THE GEOLOGY, GEOCHEMISTRY AND EXPLORATION OF IGNEOUS PHOSPHATES NORTHWEST OF MUMBWA (BIG CONCESSION) CENTRAL PROVINCE OF ZAMBIA

BY

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LUSAKA

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DECLARATION

This dissertation was written and submitted in accordance with the rules and regulations governing the award of Master of Mineral Sciences Degree of the University of Zambia. I further declare that the dissertation has neither in part nor in whole been presented as substance for award of any degree, either to this or to any other University. Where other peoples work has been drawn upon, acknowledgement has been made.

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APPROVAL

This dissertation of **DAVISON MULELA** is approved as fulfilling part of the requirements for the award of the degree of Master of Mineral Sciences in Geology by the University of Zambia.

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ABSTRACT

The syenites and quartz feldspar porphyries of the Mumbwa district occur as satellite bodies at the north east margin of the Hook Granite Massif, a large batholith dated 456 Ma, and intrude the pre-Cambrian Katanga metasediments.

The composition of syenitic rocks varies from hornblende biotite syenite, through leucocratic porphyritic and microsyenite to pseudo-trachyte. Within the syenites occur large xenoliths of calc-silicate rocks. The syenites are quartz-bearing linked petrologically and chemically to alkaline magmatism formed during the final development of Pan-African batholiths.

Geological, geochemical and geophysical investigations led to the discovery of a new type of phosphate deposit occurring as apatite pegmatite ore bodies N.E. Sugar Loaf, with estimated reserves of 0.22×10^6 tonnes at 12 percent P_2O_5. At Sugar Loaf Hill investigations are not complete. Resources of phosphate bearing material has been estimated in the range of $0.5 - 1.0 \times 10^6$ tonnes at 5 percent P_2O_5.

Trace element studies show that the syenites are high level intrusions that resulted from differentiation of parental magma and assimilation of country rocks. Tectonic setting of the syenites has been classified as within-plate granite, of the attenuated continental crust.

For future phosphate exploration locally and regionally, the most favourable target areas would be post-orogenic fractionated alkaline syenitic bodies occuring at the margin of large granitic batholiths associated with deep seated faults.

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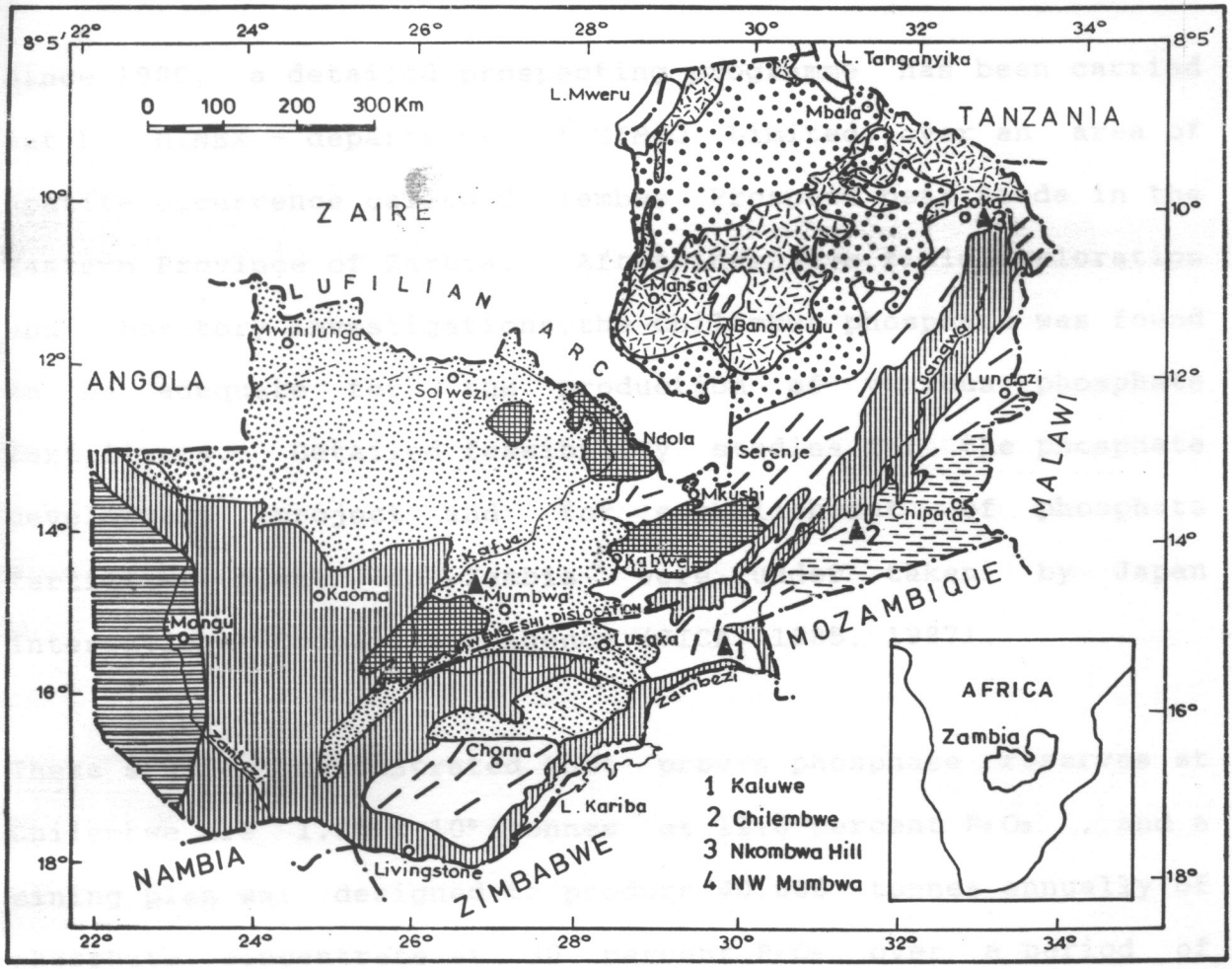
INTRODUCTION

1.1 PHOSPHATE OCCURRENCE IN ZAMBIA

Syenitic rocks are known to occur at several localities in Zambia. Their economic potential was not known until recently when discoveries of concentrations of apatite and associated sulphides in some of the syenites were made, thus generating an interest in these rare igneous rocks. There are proven deposits of raw igneous phosphate of different quality and composition in at least four areas of Zambia (fig. 1). Those areas are Kaluwe (Lusaka Province), Nkombwa Hill (Northern Province), Chilembwe (Eastern Province) and North-West of Mumbwa (Central Province).

The Kaluwe Carbonatite in the Rufunsa Valley has been thoroughly investigated and has been found to be low grade, and therefore uneconomic at present. Resources are estimated at 200×10^6 tonnes of ore, with a grade in the range of 1 to 4 percent P_2O_5.

Nkombwa Hill carbonatite near Isoka, north east of Zambia, has 220×10^6 tonnes of phosphate-bearing resources, with 4.6 percent P_2O_5 but has been found to contain a peculiar mineralogy which requires further research for effective metallurgical processing.



LEGEND

- Cretaceous system
- Karroo supergroup
- Katangan supergroup with trend lines
- Mozambique metamorphic belt
- Irumide Province: Kibaran extensively overprinted
- Undifferentiated Pre-Katanga Basement remobilized in part
- Platform sediments: Plateau Series Mbala Sandstone, Luapula-Luitikila Beds
- Granites, gneisses and volcanic rocks

BANGWEULU BLOCK

FIG.1 Location of phosphate occurrences within the framework of the geological map of Zambia
modified (after Drysdall, Thieme and Johnson 1972)

Since 1980, a detailed prospecting programme has been carried out by MINEX - department of ZIMCO Limited, over an area of apatite occurrence called Chilembwe Prospect near Sinda in the Eastern Province of Zambia. After intensive field exploration and laboratory investigations,the Chilembwe phosphate was found to be adequate for the production of various phosphate fertilizers. Detailed feasibility studies for the phosphate development project and for establishment of phosphate fertilizer plant in Zambia were under taken by Japan International Cooperation Agency (JICA, 1985, 1987).

These studies demonstrated that proven phosphate reserves at Chilembwe are 1.64×10^6 tonnes at 11.8 percent P_2O_5 , and a mining plan was designed to produce 40,000 tonnes annually of phosphate concentrate at 30 percent P_2O_5 over a period of fourteen years by a flotation process with an expected recovery rate of more than 80 percent.

The reserves are small and limited but the operation is technically feasible. However, financial analysis and economic valuation of the project illustrated that the proposed project is not viable because of low financial and economic returns on the investment under present conditions of the phosphate fertilizer industry.

Chilembwe and north west of Mumbwa prospects occur in similar geological setting. The occurrence of apatite mineralisation

at Chilembwe has encouraged the present study of phosphate mineralisation north west of Mumbwa.

1.2 PREVIOUS WORK

The history of the area north west of Mumbwa (Big Concession) dates back to the discovery of ancient copper workings in 1898. Between 1900 - 1912, the concession was surveyed, prospected and shallow development work was done on a number of small zinc, silver and copper deposits. From 1925 to 1932, most of the Big Concession was reopened to prospecting. Several parties and various claims were pegged and subsequently abandoned. In 1948 the Big Concession was acquired, without mineral rights, by a company called Kafue Concession Limited for agriculture and trading purposes.

Brandt (1955), mapped the Big Concession and published a comprehensive report on the geology and mineral resources of the area. In 1958, a drill hole at the summit of Sugar-Loaf hill by Mineral Search of Africa (Pvt) Limited indicated a rather disseminated type of copper mineralisation to a depth of 190m in weathered syenite. Occurrence of apatite mineralisation was mentioned as locally being up to 10 percent, P_2O_5. An adit was also driven through the hill for mining purposes.

Chartered Exploration Limited (Later Zamex Limited) completed an extensive geochemical drainage reconnaissance and soil sampling survey programme during the period of 1957 - 1964.

Further regional geological mapping by the Geological Survey of degree sheet 1426-SE quarter, was carried out by Cikin from 1966 to 1967. Cikin (1973) at Sugar-Loaf hill analysed 25 samples from the inner 60 metres of the 94.5 metres adit in length and gave an average of 9.6 percent P_2O_5.

The United Nations Mineral Survey Projcet concentrated their prospecting and exploration activities at Sugar-Loaf (Copper Queen) and Lou-Lou prospects between 1968 - 1972, mainly for base metals as syenitic rocks were considered as possible targets for porphyry copper deposits. Similar occurrence of apatite mineralisation was reported at Lou-Lou. Drilling failed to establish any economic deposit of sulphide and apatite.

1.3 SCOPE AND AIMS OF PRESENT WORK

In Zambia agriculture has been given a higher priority than ever since independence. According to the soil surveys, Oygard (1987), Zambia has large areas covered by low fertility and acid soils. Phosphate, the principal target, is important because it is a major plant nutrient severely lacking in many of the region's soils. The anticipated growth of agriculture

in the country has posed a great problem with the nation's fertilizer requirements and will require the establishment of fertilizer industries that can assure a sustained and uninterrupted supply.

The high cost of imported fertilizer has imposed a considerable strain on the nation's economy. In responding to the Party and its Government's interest in locating and developing a domestic phosphate source, MINEX Department has embarked on a regional project.One of the prime objectives of this project is to explore, discover and evaluate phosphate deposits, which could become the source material for phosphate manufacture in Zambia.

The present study involves a detailed survey of the syenitic rocks north west of Mumbwa with emphasis on phosphate mineralisation.Phosphate mineralisation is found to occur in three forms in local concentrations in the syenites:

1. Apatite associated with copper and iron mineralisation at Sugar loaf Hill.
2. Apatite pegmatite bodies.
3. Copper phosphates in supergene concentrations.

Syenites are rare igneous rocks and very little information is available on the phosphate mineralisation associated with them. It is hoped that this study will:-

1. assist in the recognition of possible targets for phosphate mineralisation in syenitic terrain.
2. guide, future exploration methods.
3. give a better appreciation of the economic potential of syenites as sources of phosphate.

1.4 METHODOLOGY

Field work involved geochemical soil sampling, detailed geological mapping and systematic rock sampling.Geophysical survey , pitting and trenching over phosphorus geochemical soil anomalies and mineralised outcrops were also conducted. Drilling was carried out at two of the most promising prospects Sugar Loaf Hill and N.E. Sugar Loaf.

Laboratory work involved geochemical soil and rock sample preparation, chemical analysis of soil and rock samples for phosphorus content; analysis of soil and rock samples by Atomic Absorption Spectrometry; identification of minerals by X-ray Diffraction Spectrometry; preparation of polished and thin sections for petrographic investigations; and X-ray fluorescence spectrometry analysis for major and trace elements.

1.5 GENERAL DESCRIPTION OF THE AREA

The area under study lies within the Mumbwa District of the Central Province of the Republic of Zambia. The phosphate occurrences north west of Mumbwa District lie within a roughly rectangular area measuring about 8.5 km in length and 4 km in width (figs. 2, 3 & 4). The two best known, and most thoroughly investigated occurrences are at Sugar-Loaf (also known as Copper Queen) in the south of the area, and Lou-Lou about 4 km further north. New occurrences have been found during recent investigations north west and north east of Sugar-Loaf Hill approximately 1.2 km and 1.5 km respectively.

Access to the area is by asphalt road 150 km westwards from Lusaka to Mumbwa and thereafter on an all weather gravel road to Sugar-Loaf, a distance of about 50 km on the Mumbwa-Kasempa road. Although the approach to the area from the south is relatively flat, the Sugar-Loaf and Lou-Lou prospects are located in rugged terrain. There is no road connecting Sugar-Loaf and Lou-Lou apart from a partly overgrown bush trail.

Sugar-Loaf itself is a peculiar little rocky hill rising 30-50m above the bottom of the valley in which it is situated with cliffs of ferruginous gossan at the top. Lou-Lou consists of low outcrops 1.2m high. Otherwise the mineralisation has no particular topographic expression.

1.6 TOPOGRAPHY AND GEOMORPHOLOGY

The region is part of the Central African Plateau referred to as the "End Tertiary Peneplain" (Dixey, 1944) or "African Landsurface" (King, 1951). The area forms a gently undulating plateau at an average altitude of 1,140m above sea level. The whole area is drained by tributaries of the Kafue river which forms the northern boundary and is flanked by a wide stretch of extremely flat alluvial plain. Most of the streams are sluggish and bordered by open "dambos".

The limestone terrain is flat, with dark brown clay soil which carries grassland with thickets developed in patches. A characteristic feature of the limestone terrain is the prevalence of depressions where sink holes occur and clusters of jagged rain fluted rock pinnacles about 10m in height,indicating a typical mature karst topography.

Syenite intrusions underlie a large part of the area, marked by flat open plain, sparsely and patchily forested with Isoberlina paniculata-Brachystegia woodland. Sandy soils support low grass and a very sluggish undecisive drainage. In places hills of various shapes and heights in youthful state of dissection rise abruptly from a mature plane surface. Local cappings of resistant material such as iron stones and superficial laterite are widespread.

CHAPTER TWO

REGIONAL GEOLOGY OF THE AREA

The area under study is dominated by the Precambrian, Katanga Supergroup intruded by syenites and quartz porphyries. The Katanga Supergroup is broadly divisible into the clastic sediments of Lower Roan, the calcareous sediments of Upper Roan and the shales and calcareous shales of the Kundelungu Group. The syenites and quartz porphyry intrusions occur as satellite composite bodies at the north-east margin of the Hook Granite Massif,a large batholith situated west of Mumbwa.

GEOLOGICAL SETTING OF THE AREA

The geological setting of most alkaline provinces shows that their locations are controlled by structural weaknesses in the lithosphere whose age and thickness to a large extent determine their degree of alkalinity and silica saturation. Whereas mixed and strongly undersaturated provinces are commonly associated with well defined rifts and transform faults. Over saturated provinces are related to reactivated tear fault systems in a regime of distension where lithosphere is relatively thin, either in a recently stabilized mobile belt or in regions of crustal fragmentation (Black et al, 1985).

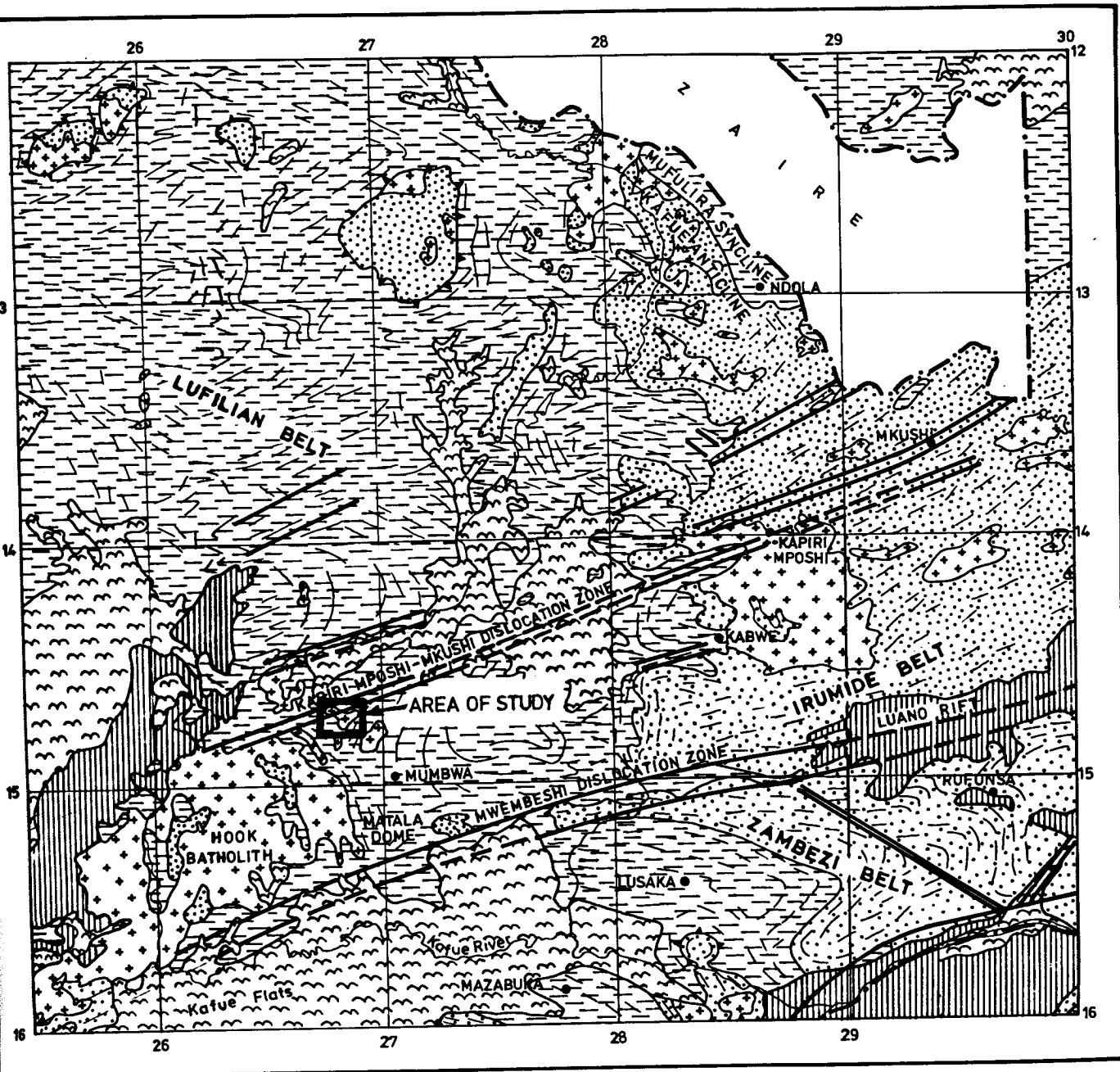
The majority of alkaline rocks in Zambia are broadly associated in space and time with the Pan-African orogenic activity .

Their development in this orogenic setting reflects the absence of subduction generated calc-alkaline magmas in the Pan-African of the Zambia region (Turner,1985).

The alkaline magmatic rocks of Zambia are generally less well known and have less extreme compositions than those of other parts of eastern and southern Africa. They are widely distributed and are of interest economically and because of their place in the crustal evolution of the region. They show a wide range of ages and belong to a variety of igneous associations. Examples are (fig. 1) the nepheline syenite - Carbonatite association of Irumide to early Pan-African age in north east Zambia, the gabbro-syenite association of early Pan-African age in central Zambia, the late Pan-African syenite-granite association in the Sinda and Mumbwa North areas and the carbonatite in the Rufunsa Valley of Karroo or post Karroo age . The salient feature in the Mumbwa region is the Hook granite Massif, marginally characterised by numerous alkaline magmatic rocks intruding the Katanga metasediments and are considered to have a close genetic relationship with Hook Granite Intrusion.

STRUCTURAL GEOLOGY OF THE AREA

Central Zambia comprises three orogenic belts (fig. 2), the Irumide belt of Kibaran age (1100 Ma),and the Lufilian and Zambezi metamorphic belts of the Pan-African age (600-500 Ma).



E X P L A N A T I O N

- Kalahari beds and Recent deposits
- Karroo supergroup
- Katanga supergroup and possible equivalents
- Basement complex
- Granite

20 0 20 40 60 80 100 Km

FIG. 2 GEOLOGICAL AND STRUCTURAL MAP OF PART OF CENTRAL ZAMBIA

modified (after de SWARDT AND OTHERS)

(1965)

The two Pan-African belts have irregular margins and are themselves separated by a major ENE trending tectonic break known as the Mwembeshi Dislocation (de Swardt, Garrard and Simpson, 1965).

The area north west of Mumbwa structurally lies within the segment of the southwest flank of the Lufilian Orogenic belt of the Pan-African age (Garlick, 1960), situated between the Mwembeshi and Kapiri Mposhi dislocation zones (fig. 2) the major planes of differential shear (de Swardt, Garrard and Simpson, 1965). The Mwembeshi dislocation zone separates rocks of different structural levels.North of the zone, the tectonics are of a thin skinned thrust type involving decoupling at the base of the Katanga sediments and in the upper levels of the basement (Coward and Daly,1984).All areas are variably affected by Pan-African metamorphism and deformation. The metamorphic grade however is low.

The Katangan rocks in the Big Concession, on the eastern margin of the Hook Granite Massif, show zones of tight folding separated by belts of gentle folding. Brandt (1955) describes complex folding in the Katangan Limestone and ascribes it to plastic flow. This deformation locally represents, locally the final event of the Lufilian orogeny (Brandt ,1955) and marks the south-western extension of the Kapiri Mposhi-Mkushi dislocation zone (fig. 2) which continues beyond the unexposed area of the Lukanga Swamp into the north west of

Mumbwa, where it is represented by one of Brandt's fold belts. Folds with vertical plunge east of Sable Antelope mine (now abandoned) represent a combination of drag and refolding of a steeply dipping succession trending north west. Near the dislocation zone itself, the old trend both north and south curves around into an east-north-easterly direction.

REGIONAL METAMORPHISM OF THE AREA

The metamorphism pattern in this part of Zambia is dominated by the Lufilian metamorphic belts. The Lufilian orogeny is continuous with the Damara Orogenic phase (900 to 450 Ma) of Namibia.

The grade of regional metamorphism varies from green-schist to the amphibolite facies. More recently evidence has accumulated indicating specific high pressure type of the Lufilian metamorphism which produced a variety of unusual kyanite-bearing mineral assemblages (Prasad and Vrana, 1972). Locally south of the Mwembeshi dislocation zone the formation or preservation of eclogite and talc-kyanite bearing assemblages (Barr ,1974; Vrana, Prasad and Fediukova,1975), in the areas of Chombwa and Sanje-Iron about 37km south of Mumbwa and east south east of Chombwa respectively are interpreted as indicating unusually high pressure conditions (Schreyer and Seifert, 1969). In the north the metamorphic grade is of green schist facies suggesting a marked contrast in pressure and

temperature condition north and south of the Mwembeshi dislocation zone.

The Mwembeshi dislocation represents vertical as well as lateral motion, exposing a much deeper sequence to the south and presenting lower Kundelungu strata to the north. With the exception of localized thermal metamorphism of predominantly pelitic assemblage in the post Katanga emplacement of the Hook Granite Massif, the metamorphic rocks of Katanga metasediments did not reach high grades.

Low matamorphic temperature gradients are indicated by high pressure assemblages and by low metamorphic grade north of the Mwembeshi dislocation and point to preceding phase of deep and rapid subsidence.

The distinct pecularities of regional metamorphism in the Pan African Orogeny is attributed to opposite vertical motion, including deformation and different radiogenic heat generation, while mantle heat flow was supposedly uniform within the orogeny and remained normal during the thermal event (Hartmann, et al, 1983).

HEAT FLOW STUDIES OF THE AREA

Heat flow studies in the central and western regions of Zambia revealed a broad heat flow anomaly, which has been previously infered to neo-tectonic activity associated with the rifting

(Chapman and Pollack, 1977). Recent interpretation of the heat flow anomaly is that, the cause is not rifting as previously considered, but the diversion of heat by a cratonic root (Pollack, 1987).This is explained by variations in heat flow from cratonic terrains through cratonic margins to mobile belts, the mobile belts, having the highest heat flow. This is characteristic of all mobile belts in Southern Africa. The diversion of heat by a cratonic root to mobile belt is attributed to thick lithosphere in cratonic areas and thin lithosphere in mobile belts. Cratonic lithospheres are higher than average seismic velocity zones.

The radiogenic heat of the crust had a predominant influence on the character and development of metamorphism in the Pan African Orogeny. Motion and particularly advection of heat must have been involved, which can be ascribed here to large scale intrusions of granite(Hartman et al, 1983).

Hot springs associated with the Hook granite Massif indicate that the area is still hydrothermally active. This view is also supported by a gravity low anomaly over the centre of the massif and the fact that is a seismically active zone (Bram, 1972).

GEOCHRONOLOGY OF THE AREA

The Lufilian Arc (840-452 Ma) forms part of the extensive system of Pan-African orogenic belts characterized by ages 600-500 Ma, Table 1.

Table 1: Chronological events in Pan African Orogeny.

Events	Age
Hook Granite Batholith	456 Ma
Lufilian Cooling	602 - 456 Ma
Lufilian Orogeny	656 - 602 Ma
Deposition of upper Kundelungu	850 - 602 Ma
Deposition of lower Kundelungu	950 - 850 Ma
Deposition of Roan	1130 - 950 Ma

Source: Cahen and Snelling et al, 1984.

It is represented by deformed rocks of the copper-bearing Katangan Supergroup which unconformably overlies the basement of Kibaran granites, Muva quartzites and schists.

There is no geochronological data on the syenites of the Central Province,North West of Mumbwa. However,a relative age of these syenites can be inferred from local field evidence.

The K-Ar, determinations on micas and hornblende from five rock samples representive of the Hook Granite Massif give an average of 456 Ma. (Abell, 1970), which is very similar to the Rb-Sr age of the biotite 465± 30 Ma. previously determined from the same province (Snelling **et al**, 1964).These could be the cooling dates of the Lufilian. It is therefore concluded that the syenites north west of Mumbwa are younger than the Katangan Supergroup deformed during an early period of deformation (Lufilian Orogeny) but are coeval with the Mozambiquan phase of the Pan-African orogeny (485 - 650 Ma) (Cahen and Snelling **et al**, 1984), whose dates in Malawi range from 400 - 700 Ma. (Carter and Bennett, 1973).

CHAPTER THREE

GEOLOGY AND PETROLOGY OF NORTH WESTERN MUMBWA

3.1 GENERAL OUTLINE

A large part of the area (fig. 3) is underlain by metasediments assigned to the upper Katangan Supergroup. To the north and east the sediments are represented by thick carbonate rocks.The metasediments of argillaceous - arenaceous facies rest conformably on the carbonates and show a very low grade of metamorphism. They contain some lenses of limestones (fig 3a).

A complex of syenitic and quartz-feldspar-porphyries intrude folded metasediments. Skarns are present in some places, especially at the contact zone with syenites. The syenites are locally contaminated by assimilated carbonates resulting in the formation of a hybrid scapolite - bearing actinolite rock (calc-silicate).

3.2 CARBONATE ROCKS

The carbonate rocks of the area are divided into lower massive dolomite and dolomitic limestone and upper bedded limestone. The lower massive dolomite and dolomitic limestone have outcrops in the north of the area around the disused Sable Antelope and Silver King mines.They also occur in the east together with the bedded limestone. The boundary between the

lower massive dolomite and the dolomitic limestone is not clear. They are both medium to coarse grained, white-grey to pale red in colour. Recrystallisation is more pronounced in the lower massive dolomite. Locally the rocks are brecciated especially at Sable Antelope. The mineralised matrix is sideritic, ankeritic, yellowish and hardened by silicification. Copper mineralisation is very closely associated with the siderite and ankerite. Calcite and dolomite are the main constituents, smaller amounts of quartz, sericite, iron and clay minerals are observed microscopically.

The upper bedded limestone conformably overlies the lower massive dolomite in the Silver King locality. Most of it is a dense, fine grained, conspicously banded rock of grey to dark or bluish grey colour and a finely crystalline texture. The banding disappears as the rock becomes massive (implying dolomitization). In places it is intercalated with shale, metasediments, and chert. The bedded limestones are also partly brecciated, sideritic and silicified.

3.3 ARGILLACEOUS - ARENACEOUS METASEDIMENTS

These rocks consist of a thick assemblage of low grade metamorphosed shales and sandstones and overlie the bedded limestone conformably. Sandstones and argillaceous rocks grade both laterally and vertically into each other.

Argillaceous rocks range from shales and mudstone to siltstones

and fine-grained sericitic sandstones. Their colour is brown, grey and yellowish. In the shales, a whitish-reddish colour is common and is probably due to weathering and oxidation of finely dispersed iron-oxides. The rocks show lamination and well developed slaty cleavage, though massive types are present.

In thin section sericite and clay material are the main constituents of the argillaceous rocks. Sometimes minute flakes of chlorite are present. Quartz as detrital grains varies in amount but increases in sandy types where magnetite and rutile are occasionally present.

Silicification is conspicous in the shales overlying the dolomitic limestones, and the silicified types are impregnated by minute veinlets of silica parallel to the slaty cleavage. A second phase of silicification also occurs filling small fractures.

Though the contact with the igneous rocks cannot be observed the effect of contact metamorphism in argillaceous rocks is very small mostly as impregnation of iron oxides. The presence of other contact metamorphic minerals in the argillaceous rocks

examined cannot generally be seen due to secondary alteration and silicification, but in bore hole UN 21 banded shales have been intersected adjacent to the syenite with streaks of muscovite, quartz and epidote.

The sandstones vary from pure quartzites and arkoses to calcareous sandstones. Siltstones are often present and appear to be a transition within the argillaceous sandstones. The sandstones are mostly medium-grained and massive, but lamination and crossbedding are sometimes well preserved. The colour ranges from pink and buff to grey and white. Reddish and greenish varieties are associated with shaly types and fine-grained sandstones grading into mudstones.

Clay minerals within the sandstone are recrystallised into sericite while calcareous material is of fine-grained calcite or dolomite. Fine streaks of hematite and magnetite are present. Magnetite occurs as scattered grains while the hematite (specular) tends to form small nests.

In thin section quartz and feldspar grains are sub-angular or rounded. Quartz grains often show an increase in size by marginal growth of grains at the expense of the groundmass. Other detrital minerals present are magnetite, ilmenite, rutile, leucoxene, tourmaline, chert and mica.

Near the contact with syenites, contact metamorphism has been noticed and xenoblastic muscovite, tourmaline and epidote

occur. Close to the contact with calcareous sandstones scapolite, amphibole and pyroxene are present. Although the actual contact cannot be observed its presence is usually marked by brecciation and veins of specularite and other iron-oxides.In some places veins of iron-oxides heavily impregnate the sandstones or cement the breccia zones.

3.4 IGNEOUS ROCKS

Igneous rocks intrude folded Katangan meta-sediments and represent a late activity near the margin of the Hook Granite Batholith. The composition of the igneous rocks in the area is very variable. The most common rocks are a series of syenitic rocks which range from very fine-grained pseudo-trachytes (rock exhibiting an almost trachytic texture) to a characteristic porphyritic syenite which was previously termed monzonite by Cikin (1973). A later quartz-feldspar-porphyry occurs sporadically on the flanks of the syenitic rocks (Fig.4 and 5).

3.5 **PETROGRAPHY OF THE SYENITES AND RELATED ROCKS**

3.5.1 SYENITE

Typical syenite in the area occurs as a fine to medium grained rock of pinkish colour, which is preserved even when the rock is affected by weathering (Plate 1a and 1b).

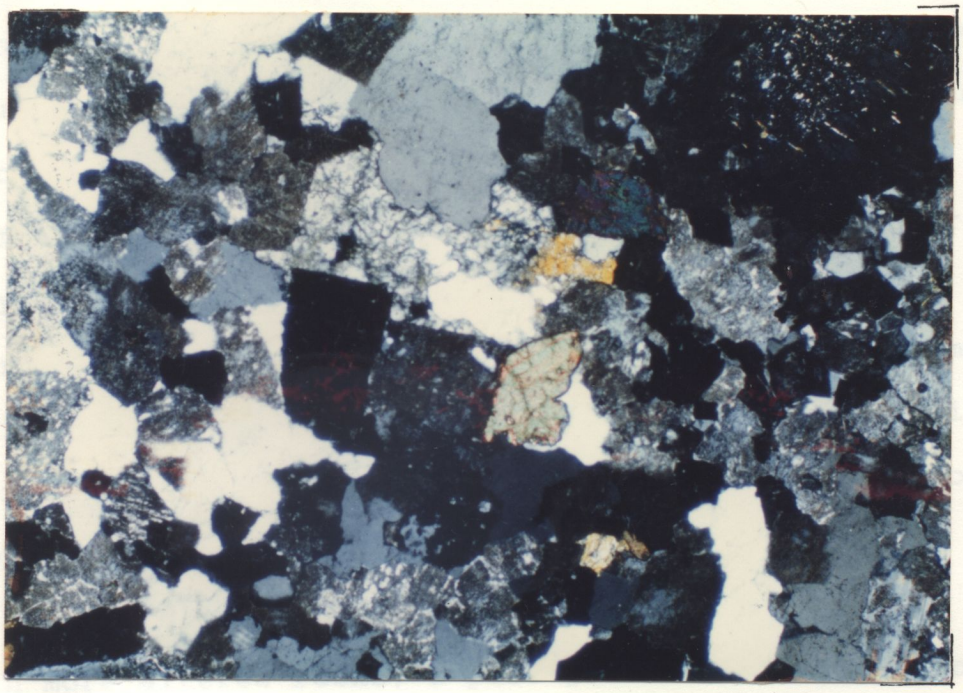


Plate 1a:

Fine to medium grained syenite showing the exsolution texture of the feldspar and interstitial quartz and epidote. Crossed nicols. x 40

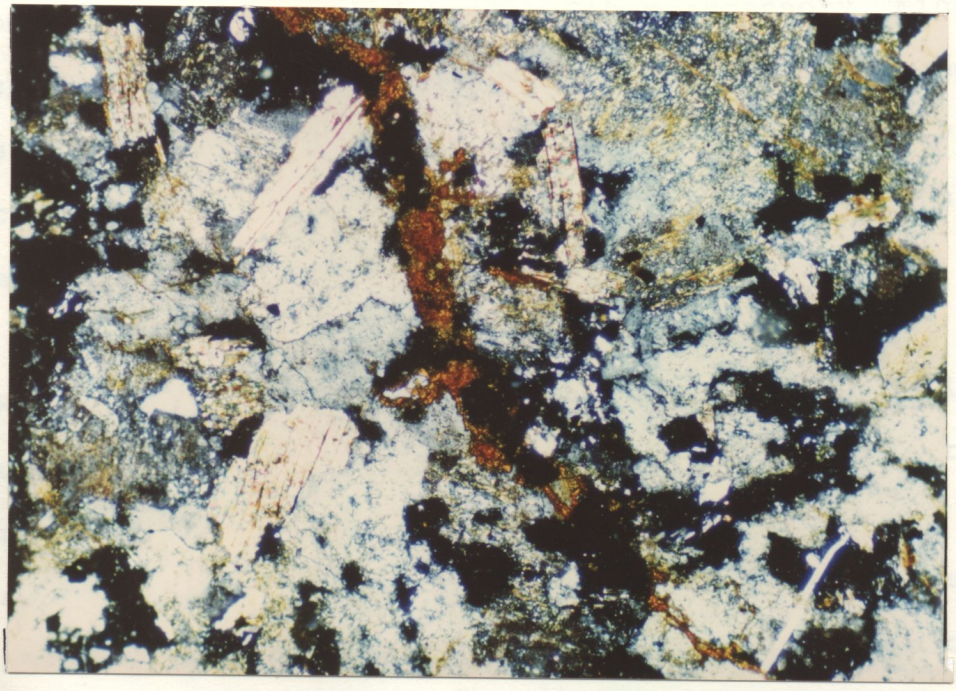


Plate 1b:

Altered syenite showing secondary quartz, mica flakes and

Orthoclase and perthite are the main constituent and occurs in normal syenite as tabular crystals or as a second generation of small, turbid crystals, forming the groundmass in the porphyritic types. Plagioclase is also tabular but often affected by sericitization. Quartz is rare or absent in syenite but when present it is intersititial and has an irregular form. The main mafic minerals are amphibole and biotite but their proportion varies. Amphibole is usually a green hornblende, some amphibole appears as pseudomorphs after pyroxene.

In more altered rocks, a pale green fibrous amphibole is formed at the expense of magmatic hornblende. Biotite occurs in large poikilitic plates and also in small ragged flakes.

Apatite is a common accessory but at Sugarloaf Hill it tends to become a prominent mineral. Other accessory minerals include sphene, scapolite, magnetite and pyrite. Secondary minerals such as epidote, chlorite, sericite, secondary quartz and carbonate, form small nests. Epidote, sericite and quartz are also present in small veins.

Within the syenite rocks, there occur large xenoliths of basic calc-silicate rocks, locally formed by assimilated calcareous rocks, especially limestones. The contamination is conspicous around Karenda Mission. The xenolithic blocks are altered into basic types of rocks rich in scapolite and actinolite. (Plate 2a and 2b).

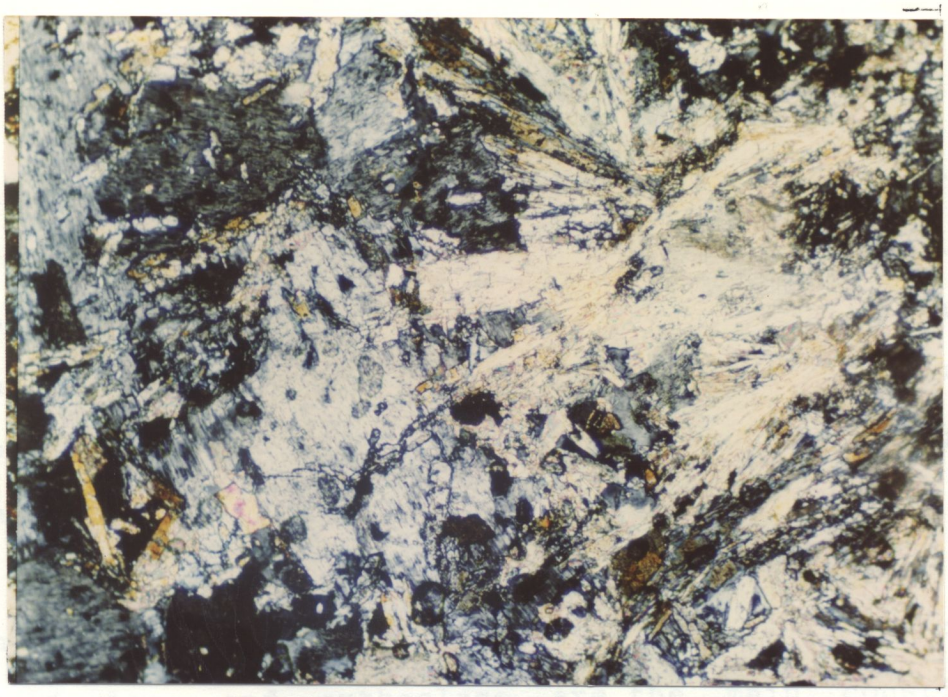


Plate 2a: Calc-Silicate. Crossed nicols, x 100
Note: Actinolite, sphene, scapolite and epidote.

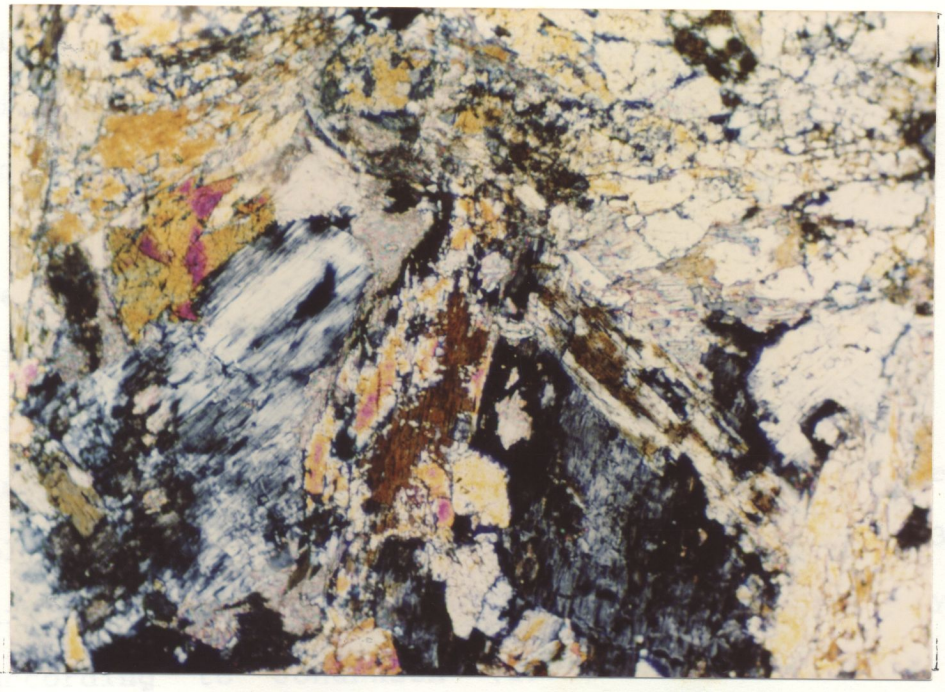


Plate 2b: Note: scapolite, calcite, and epidote replacing hornblende. Crossed nicols. x 100

Plate 2a & 2b: Calc-silicate rock showing radiating actinolite and scapolite

3.5.2 PORPHYRITIC SYENITE

The porphyritic syenites are the most abundant rocks in the area. In hand specimen the rocks are mottled pink and pale yellow-green, the latter colour being confined mainly to the phenocrysts whilst the pink colouration represents the matrix. Texturally the rocks grade from porphyritic to granular type and from fine to medium grained.

The mineral composition of these rocks is fairly uniform. Plagioclase and orthoclase are the main constituents with plagioclase phenocrysts being larger than the orthoclase and always sericitized. In some thin sections from the bore holes around Sugar-Loaf, albite-twinning and faded zoning can still be seen in a sericitized plagioclase, which has a composition of oligoclase - andesine. The presence of plagioclase led Cikin (1973) to classify the rocks as "Monzonites". (Plates 3a and 3b).

Searle (1973) disputed with Cikin on the presence of plagioclase and classified the rocks as "porphyritic microsyenites". He observed the phenocrysts with altered cores and found no evidence that, the cores represented altered plagioclase. From the chemical analysis Table 3.2 column 31, high K content classified the rock as Kalisyenite family according to Johannsen (1937). However from the present observations, some of the rocks at least contain plagioclase.

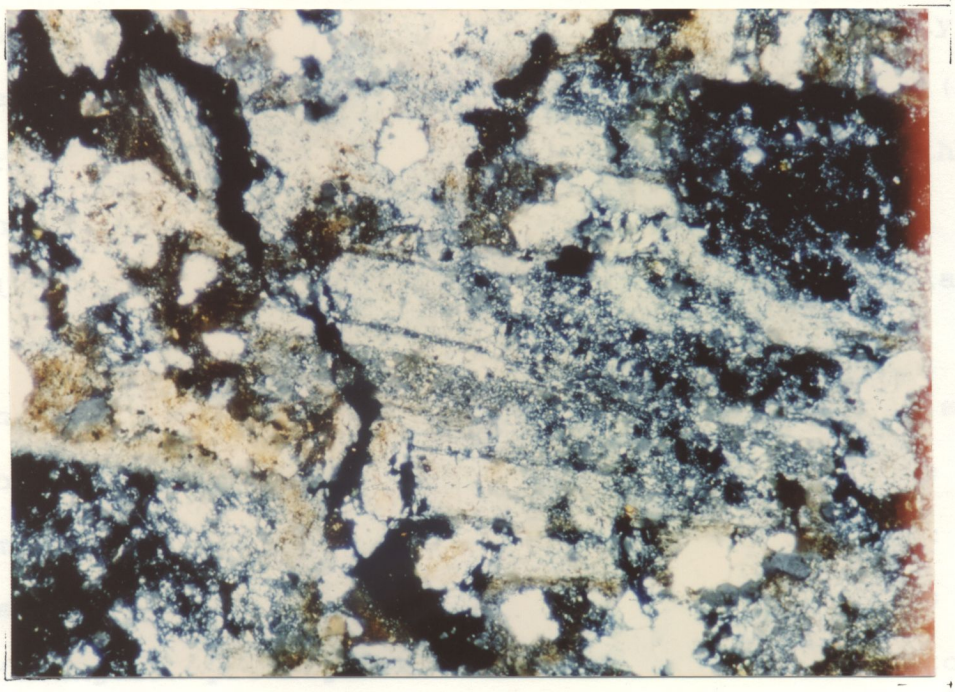


Plate 3a: Altered plagioclase in syenite.
Note: twinning in sericitized plagioclase.
Crossed nicols. x 64

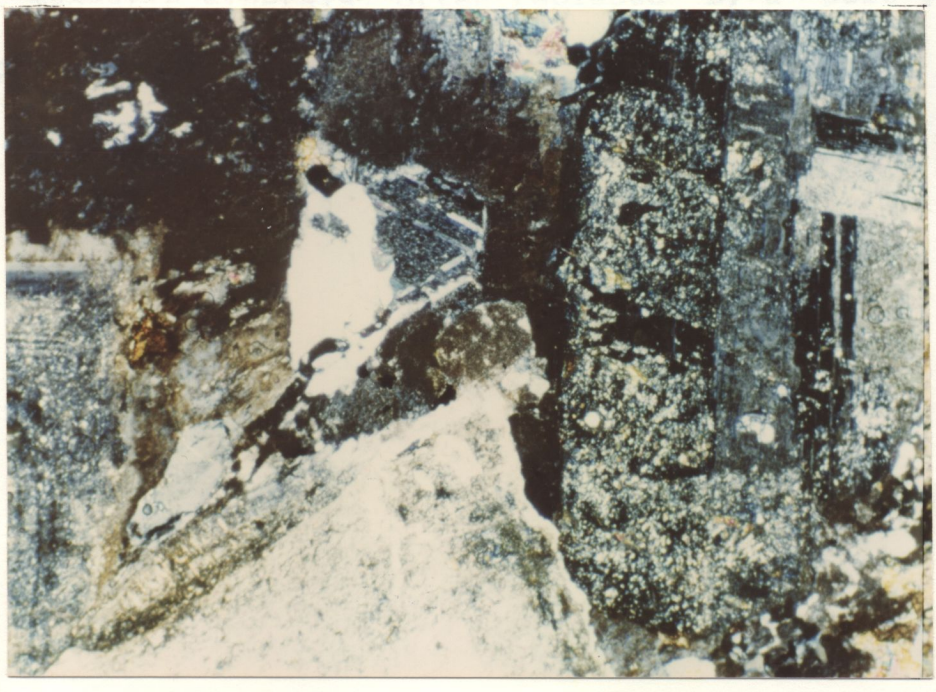


Plate 3b: Altered plagioclase in syenite. Crossed nicols.x 40
Note: zoning in plagioclase. Epidote carbonate and

In the porphyritic syenite the primary plagioclase may be replaced by a later biotite, chlorite and rarely by a fresh feldspar, as well as by sericite and quartz, (Plate 4a). Orthoclase occurs as a principal constituent of the groundmass in the porphyritic syenite and also rims the plagioclase.Tourmaline occur as blades and as radiating stars.

The quantity of mafic minerals cannot be properly estimated due to hydrothermal alteration and weathering. Some biotite and amphibole have been observed to be primary mafic minerals and usually occur as ragged blades. In places it is difficult to distinguish primary from secondary biotite due to replacement by chlorite, iron-oxides and a later stage of sericite-quartz, (Plate 4b).

Close to Sugar-Loaf hill amphiboles are preserved. They occur as magmatic minerals, often replaced by a pale-green fibrous amphibole.

Plate 4a: Altered plagioclase laths in fine grained porthyritic biotite syenite. Note training and alteration of the plagioclase. Crossed nicols. x 40.

Plate 4b: Priminary and secondary biotite flakes in altered biotite syenite, showing chlorite replacing biotite. Note high birefrigence sphene. Crossed nicols. x 100

3.5.3 AMPHIBOLE AND BIOTITE SYENITE

The amphibole syenite was intersected in drill hole UN. 32, drilled by UNDP, about 400m southwest of Sugar-Loaf, elsewhere this rock type has not been found. The amphibole syenite is an equigranular rock which consists of highly altered plagioclase and alkali feldspar laths with hornblende and apatite . Apatite occurs as euhedral to anhedral crystals 1-2 mm long which are highly fractured, (Plate 5a). The fractures are filled with hematite. Hornblende is light green to brown in colour, in places appear to be partly altered to biotite and sometimes contains inclusions of opaques. Quartz occurs as an interstitial mineral. The commonest accessory minerals are epidote, pyrite, sphene (titanite), iron-oxide and carbonate. Carbonate appears to be an alteration product of sphene, hornblende and plagioclase, (Plate 5b).

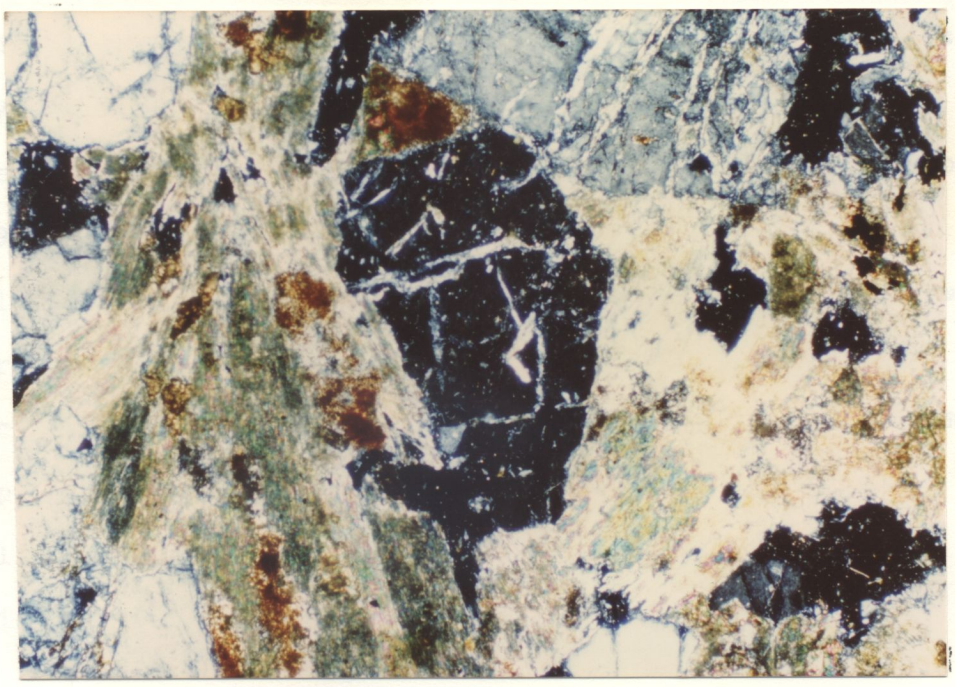


Plate 5a:

Hornblende syenite showing fractured apatite crystals. Note: sphene replacing amphibole. Crossed nicols. x 40

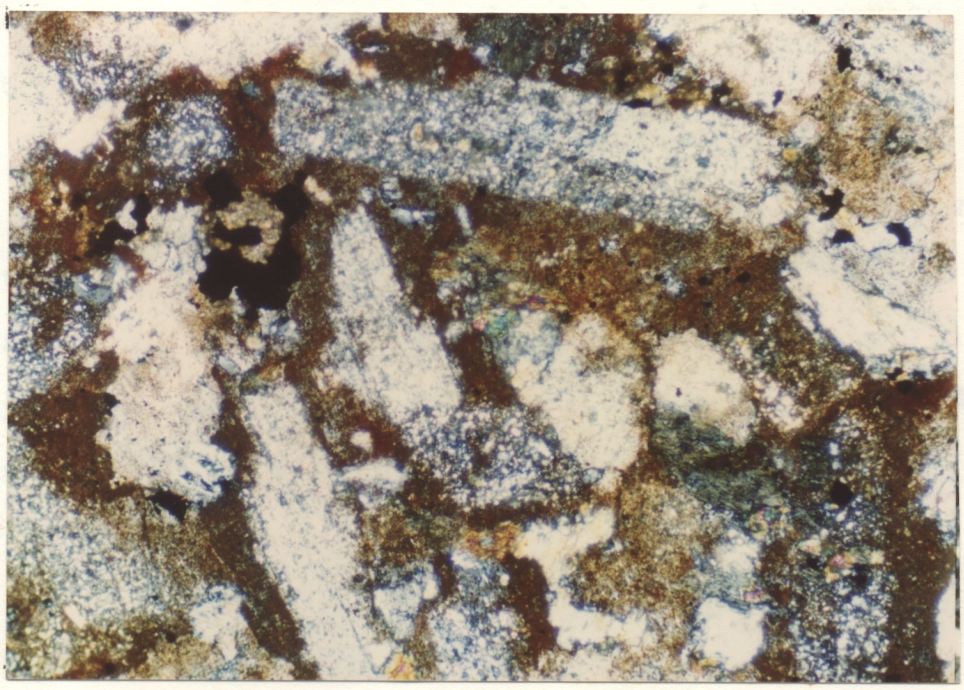


Plate 5b:

Altered porphyritic syenite showing common accessory minerals of iron oxide, epidote and sphene. Note high

There appears to be layering within the amphibole syenite shown by different mineralogical composition. This is apparent in drill hole UN. 32 5GD - 302 and 309 at depths of 76.55m and 89.40m respectively,where biotite is a predominant mineral with plagioclase and alkali feldspar while hornblende is subordinate or completely lacking and apatite is present only as an accesory mineral (Plate 6a). Other accessory minerals are epidote and pyrite. The rock is fine grained and highly altered. The feldspars are either completely altered or display sericitized cores and zoning. (Plate 6b)

3.5.4 PSEUDO-TRACHYTE

The rock is pale grey but where it has been subjected to intense alteration a green colour develops. In hand specimen the rock exhibits scattered relics of phenocrysts in a finely mottled greyish or reddish groundmass.

In thin section the fresher specimen show abundant orthoclase,and probably relics of plagioclase which occur both scattered tabular phenocrysts and as minute lath shaped crystals arranged in a divergent trachytoid groundmass giving the groundmass a bostonitic texture (Plate 7a), (Johannson, 1937).

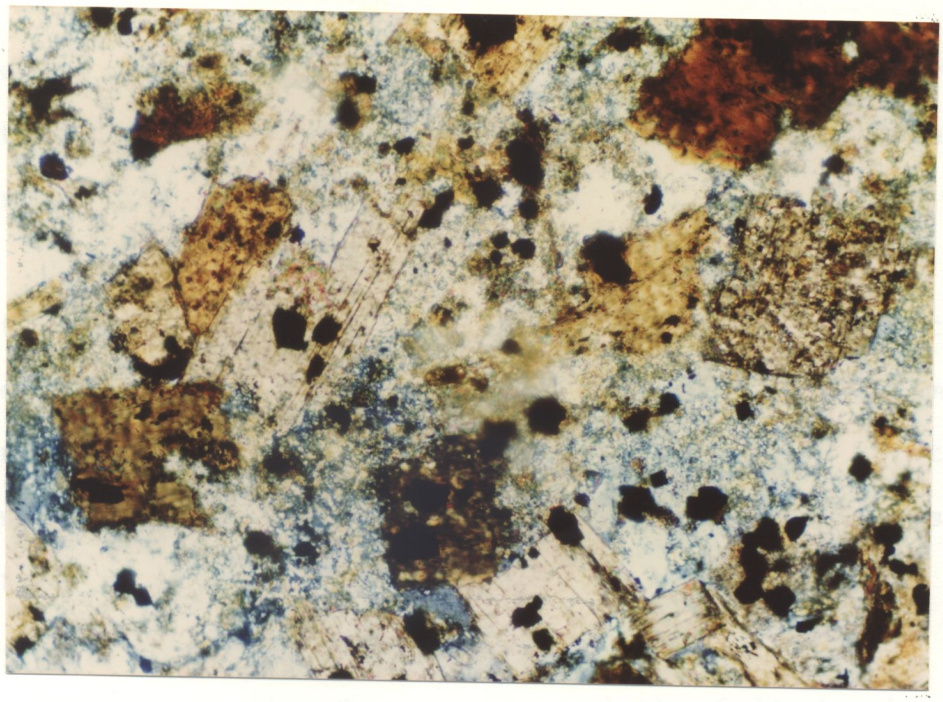


Plate 6a:

Biotite syenite showing the abundance of biotite and iron oxide. Crossed nicols. x 100

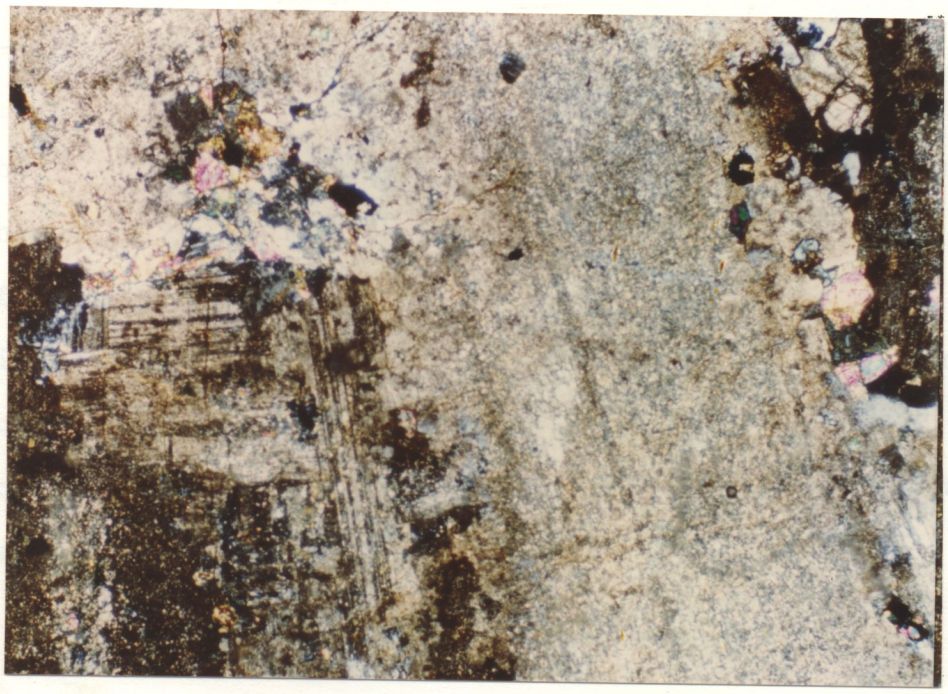


Plate 6b:

Sericitized plagioclase laths showing relict twinning and interstitial sphene. Crossed nicols. x 100

The matrix almost defies resolution but appears to be an intimate mixture of illite and orthoclase (Searle, 1973) with scattered grains of hematite and some rare quartz, (Plate 7b).

Patches of hematite and dolomite are commonly scattered, which are often veined by barytes, a mineral which may occur as larger crystals infilling small cavities. The barytes veins are usually composite with quartz lining the vein walls and barytes infilling the centre.

The nature of the phenocrysts and the felted character of the matrix suggests the rock to represent a fine-grained variety of the porphyritic micro-syenite, possibly a marginally chilled-phase.

3.5.5 QUARTZ-ORTHOCLASE PORPHYRY

The quartz-orthoclase porphyries are apparently intrusive into the syenite. The rock is easily recognizable by the presence of greyish-white quartz phenocyrsts, embedded in a matrix of fine grained pink feldspar. The quartz phenocrysts are sometimes cracked and strained, but commonly rounded and corroded and sometimes contain inclusions of magnetite which is replaced by hematite, (Plate 8a).

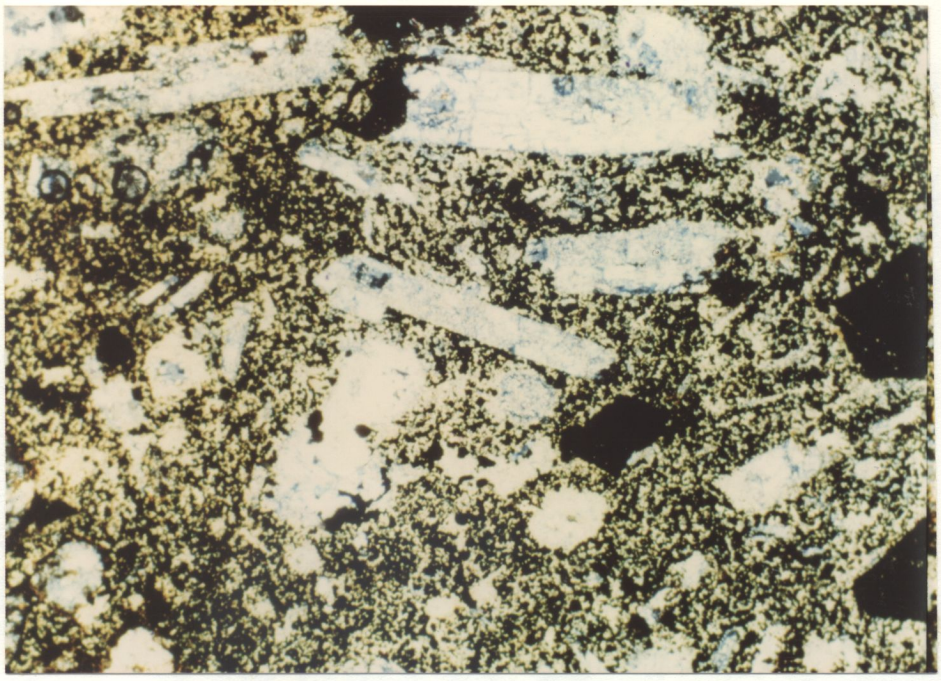


Plate 7a:

Pseudo-trachyte showing trachytic texture. Note: Scattered laths and hematite grains. Crossed nicols. x 40

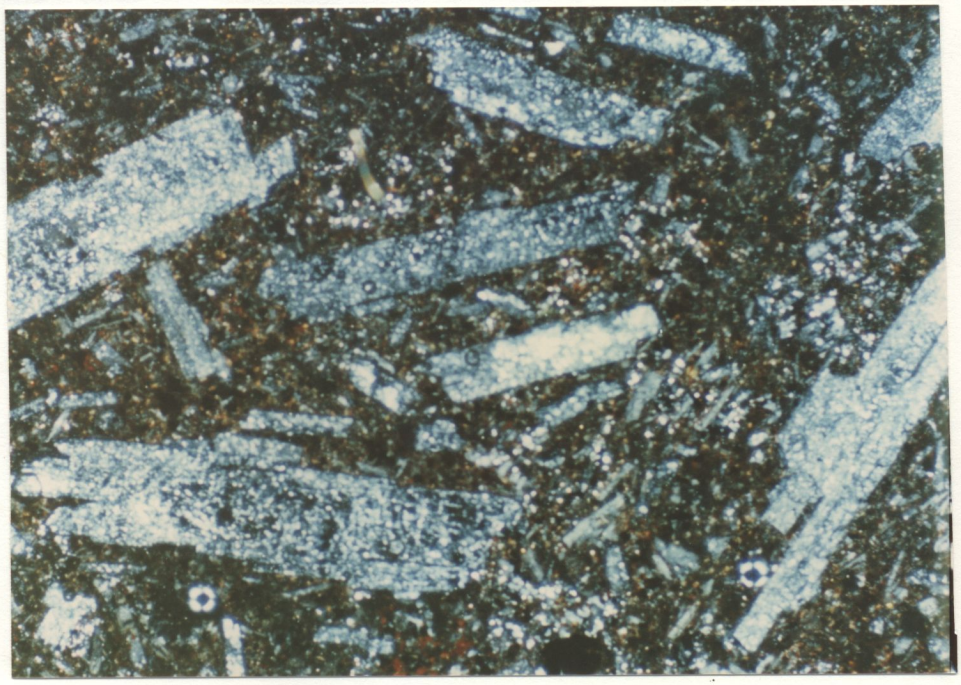


Plate 7b: Pseudo-trachyte showing flow texture.
Note: Scattered grains of hematite and quartz in the matrix. Crossed nicols. x 40

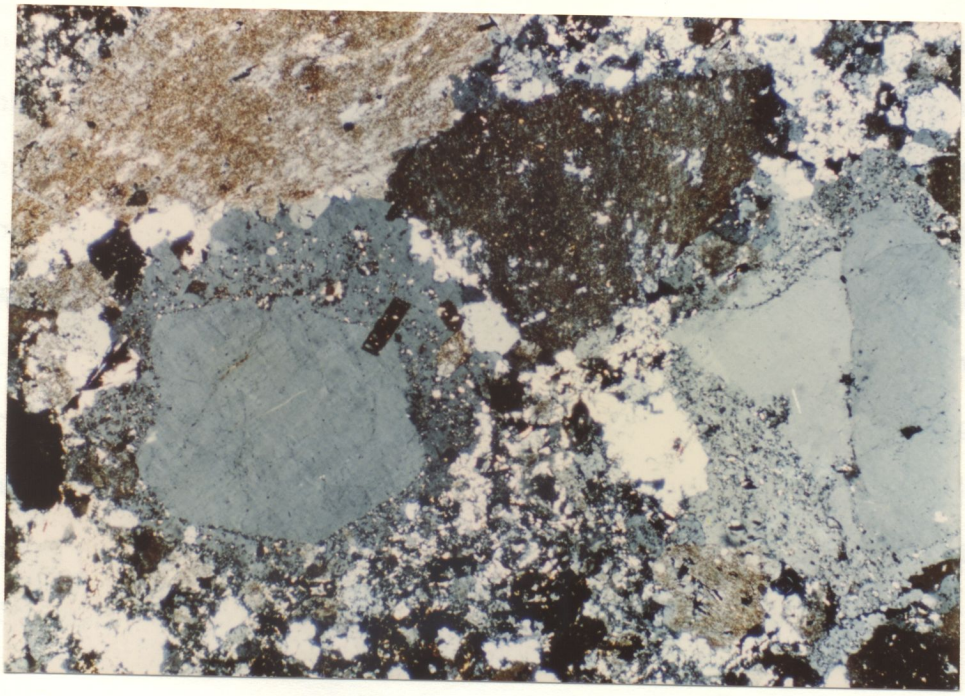


Plate 8a:

Quartz feldspar porphyry. Crossed nicols. x 40
Note: corroded quartz phenocrysts with inclusions of iron oxide.

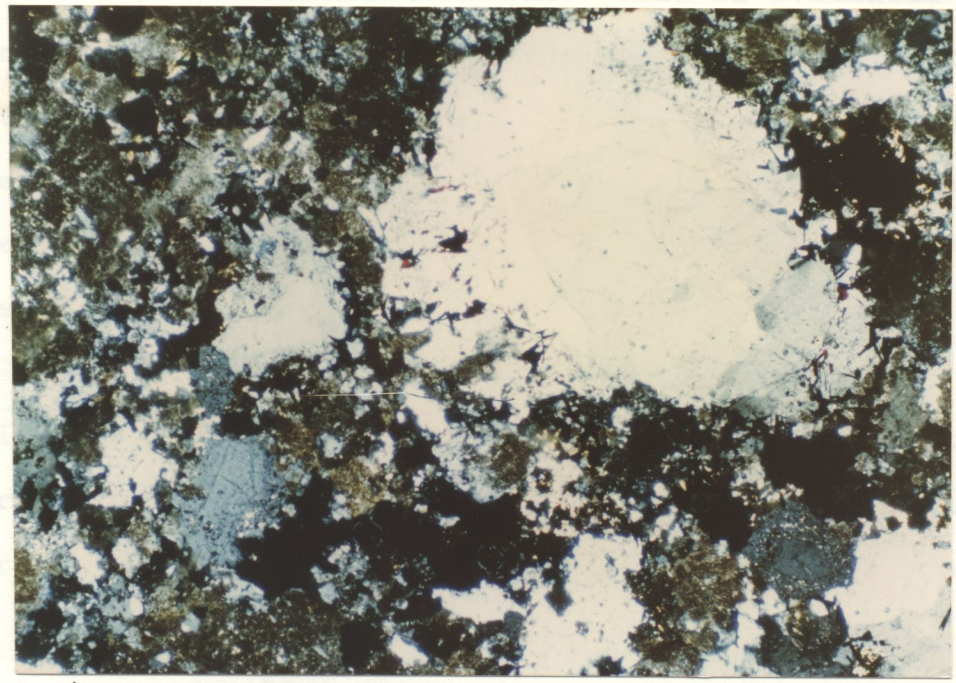


Plate 8b: Quartz-feldspar porphyry. Crossed nicols. x 40
Note: Fracturing of quartz phenocrysts.

In thin section, potash feldspar phenocrysts are subhedral to anhedral, cloudy and corroded. Some crystals show fracturing and granulation, contain inclusions of sericitized feldspar and opaques in form of clusters, represented by hematite, limonite associated with sphene, (Plate 8b). A few tourmaline grains are present with distinct dichroism. No mafic minerals are present. Alteration of the quartz-orthoclase porphyry is marked by secondary quartz and sericite, (Plate 9a). Close to the contact with the metasediment brecciation and impregnation of iron-oxide in veins is prominent.

3.5.6 ALTERATION OF THE SYENITES

Surface alteration such as weathering has almost obliterated an earlier hydrothermal alteration. This is evidenced by box work structures developed after hematite and by ferricrete and laterite observed at Sugar Loaf and Lou-lou. Weathering has been seen to a depth of 100 metres in drill holes, where the syenites are replaced by silica and goethite, an association clearly seen on the surface.

Oxidation mostly advances along fractures resulting in the formation of the oxidized zone and a leached zone in the lower part of the zone of oxidation or above the sulphides.

At Sugar-Loaf hill and Lou-Lou, atmospheric water reacting with the sulphides, formed sulphuric acid which attacked the apatite resulting in phosphoric acid. The phosphoric acid reacted with

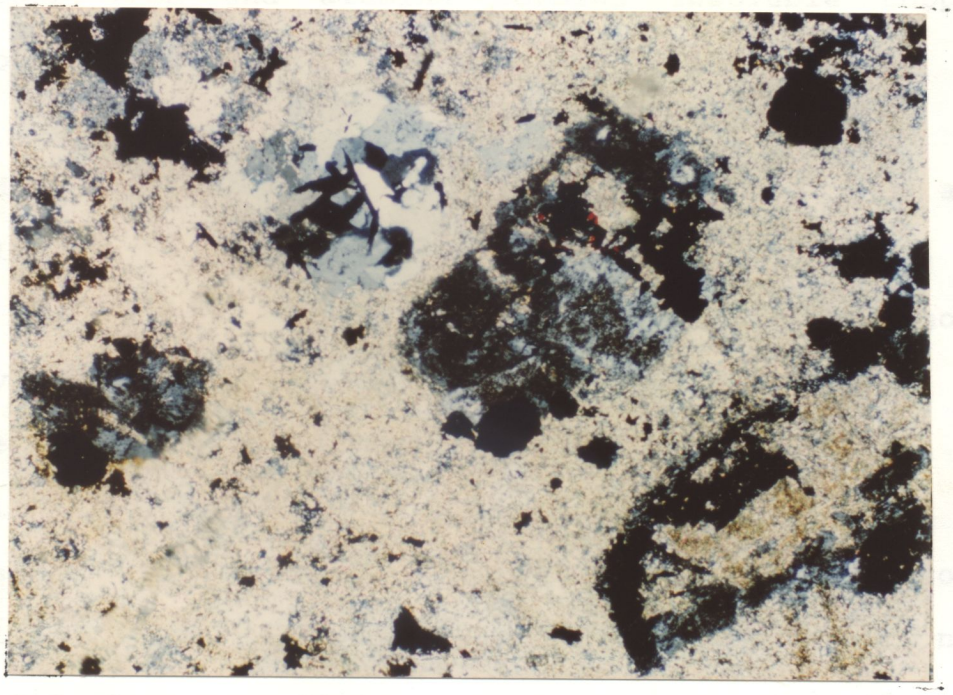


Plate 9a:

Altered quartz orthoclase porphyry showing secondary quartz and sericite. Crossed nicols. x 40
Note: relict outlines of altered feldspar and quartz.

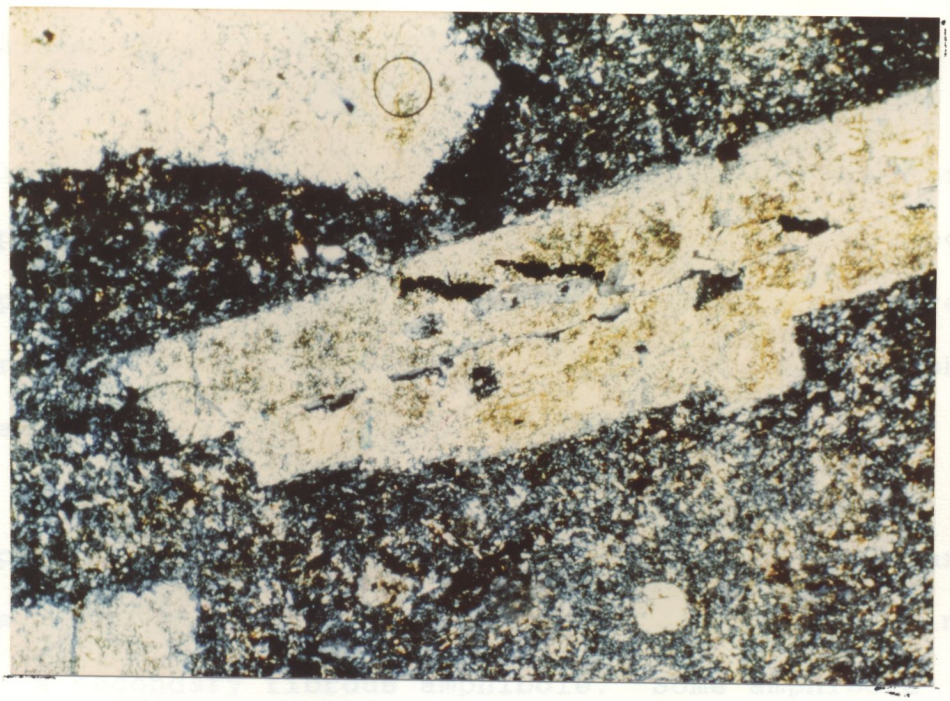


Plate 9b:
Porphyrytic syenite showing altered feldspar phenocrysts in fine groundmass of sericite and opaques. Crossed nicols. x 40

copper, iron and alumina forming insoluble copper - iron - phosphates.

Hydrothermal alteration developed in the syenites and affected all rock types. In the Sugar-Loaf and Lou-Lou area, alteration of the syenite is so pervasive that the phenocrysts are invariably turbid and partly altered or completely pseudomorphed into fine micaceous aggregates, which grow initially as fine flakes along the cleavage planes and gradually replaces the whole mineral beyond recognition and original crystal outlines becomes obscured by dense clusters of micaceous aggregates, quartz and iron oxide (Plate 9b). In porphyritic types, plagioclase cores can be seen being altered to sericite. In some places plagioclase is being replaced by carbonates. Orthoclase feldspar is also replaced by sericite or quartz-sericite veinlets dissecting the feldspar into fragments.

Chlorite is widespread around the Sugar-Loaf area and sometimes replaces most of the rock. It is usually associated with amphibole and biotite. Epidote appears as scattered grains or forms streaks. Sometimes it replaces amphibole and plagioclase.

Amphibole (hornblende) is present in the Sugar-Loaf area associated with apatite, and is rarely fresh, being replaced by a secondary fibrous amphibole. Some amphibole appears as pseudomorphs after pyroxene. (plate 10a).

Carbonates are abundant at Lou-Lou and are associated with quartz sericite veins. They replace the host rock in patchy aggregates or by veins in which the grains of carbonate are coarser (Plate 10a).Tourmaline occurs as small grains scattered through out the rock.

Magnetite is the primary oxide and alters to hematite. Pyrite is the main sulphide and occurs as disseminated small grains, small nests or patches, small or large veins. Chalcopyrite occur commonly as a rim and vein replacement of pyrite (Plate 11a and 11b). Sporadically it occurs within the post brecciation dolomite veins.Hematite is in most cases secondary, it is a constituent of cement in brecciated veins that cut even pyrite and magnetite.

The hydrothermal alterations may be summarized as widespread sericitisation of the syenites, followed by silicification and brecciation and later introduction of sulphides. This resulted in formation of several secondary minerals.

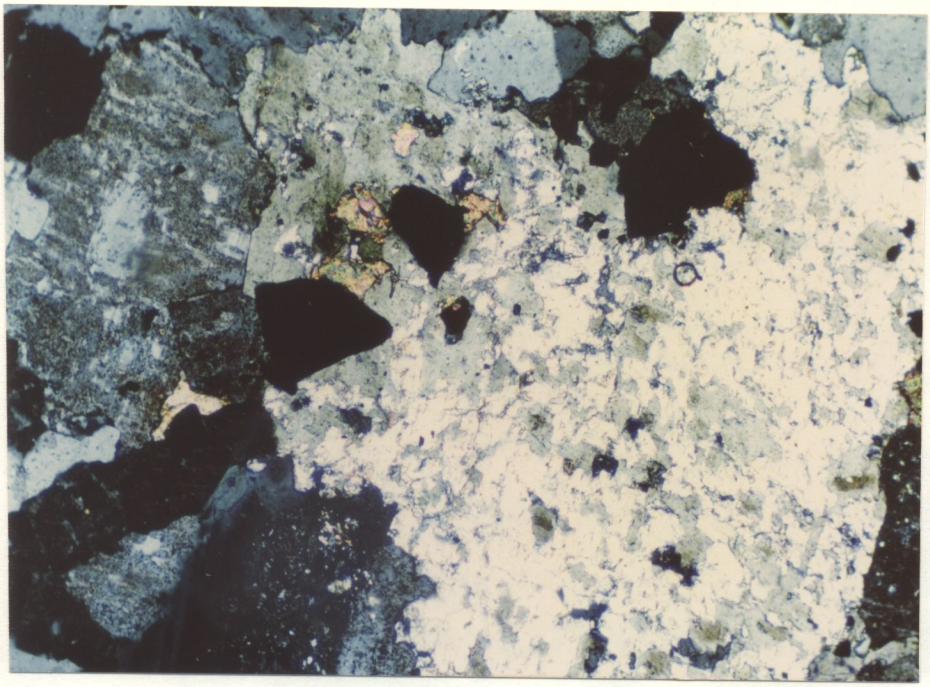


Plate 10a:

Hornblende syenite showing pseudomophs after pyroxene and plagioclase altering to sericite. Crossed nicols. x 100
Note: sphene replacing hornblende.

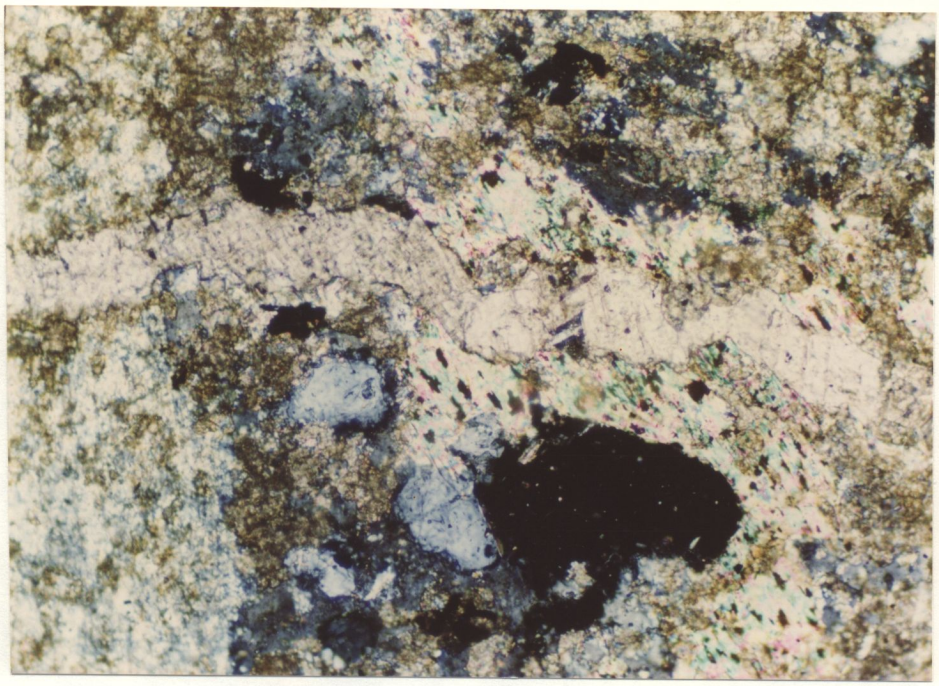


Plate 10b:

Altered syenite showing calcite vein and chlorite alteration. Crossed nicols. x 100

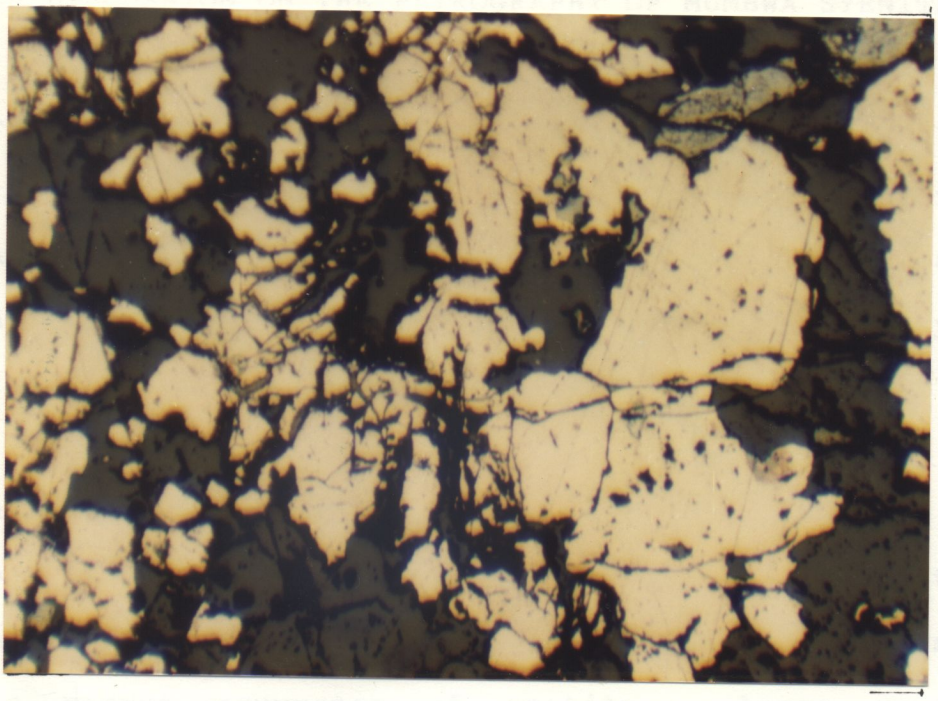


Plate 11a: Note: pyrite, hematite and covellite plane light x 120

Polished sections showing pyrite, chalcopyrite and covellite with chalcocite as inclusions.

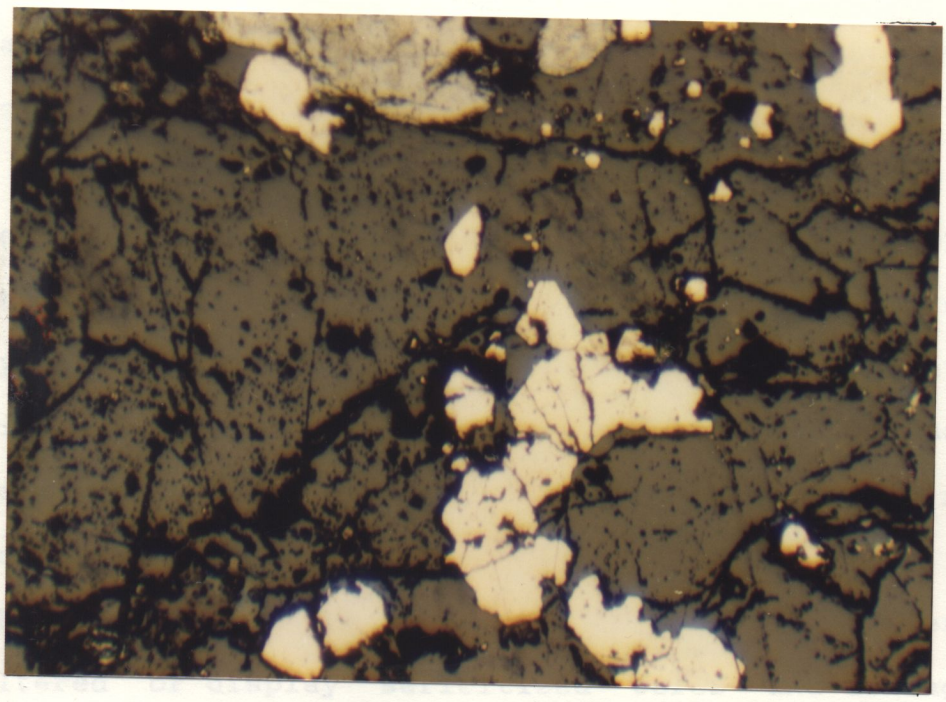


Plate 11b: Polarised light. x 120

3.6 DISCUSSION ON THE PETROGRAPHY OF MUMBWA SYENITES

From the petrographic description it is clear that there is a crystallization sequence which ranges from mafic syenites characterized by pyroxene, amphibole, biotite, alkali feldspar and plagioclase through leucocratic porphyritic syenite devoid of mafic minerals to quartz feldspar porphyry.

This mineralogical variation and the presence of sphene, apatite and opaques in mafic rocks indicate a relative increase in alkalis, volatiles and oxygen pressure with crystallization. The common occurrence of apatite as large crystals and as inclusions in ferro-magnesian minerals suggests that some syenite magmas were saturated in P_2O_5 (Plate 12a and 12b). Apatite is observed in mafic bearing syenites and is a trace in microsyenites,porphyritic syenite and completely lacking in quartz feldspar porphyry.The later magmas were no longer saturated in P_2O_5 .

Feldspar exsolution textures represented by perthitic structures indicates hypersolvus to subsolvus condition of syenite crystallization. In addition, oscillatory zoning, simple twinning in the Carlsbad law and selective sericitization outlined by plagioclase in altered rocks appears to indicate high temperature igneous origin of the syenite, (Plate 13a and 13b). The plagioclase are either completely altered or display sericitized cores and zoning reflecting metastable phase due to high rate of cooling (Rittmann, 1973).

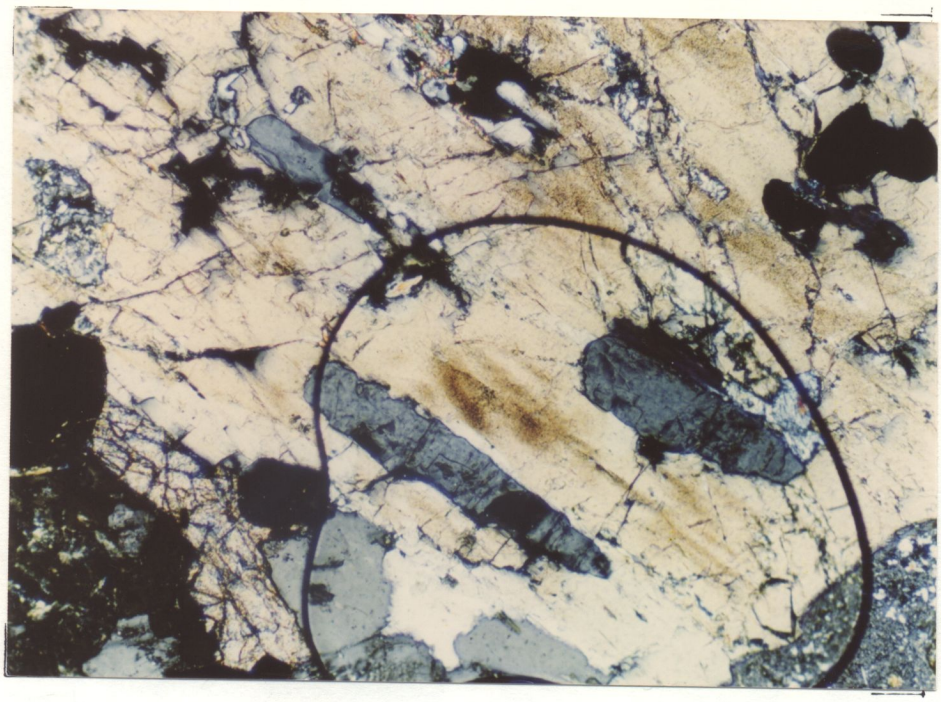


Plate 12a: Hornblende syenite. Crossed nicols. x 100
Note: Apatite as inclusions in hornblende.

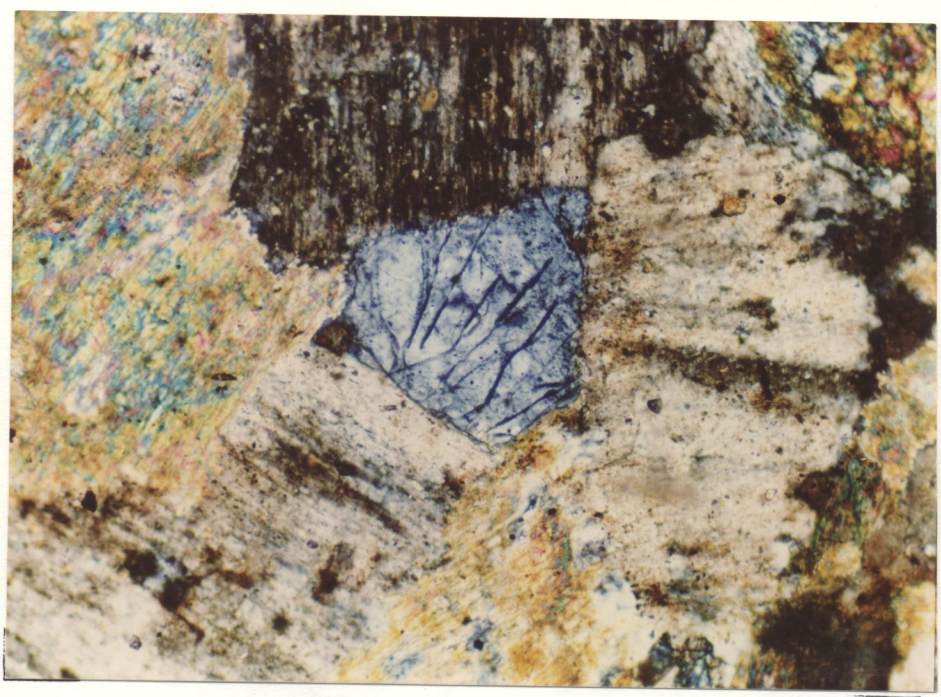


Plate 12b: Altered hornblende syenite. Crossed nicols. x 100
Note: Apatite crystal and epidote.

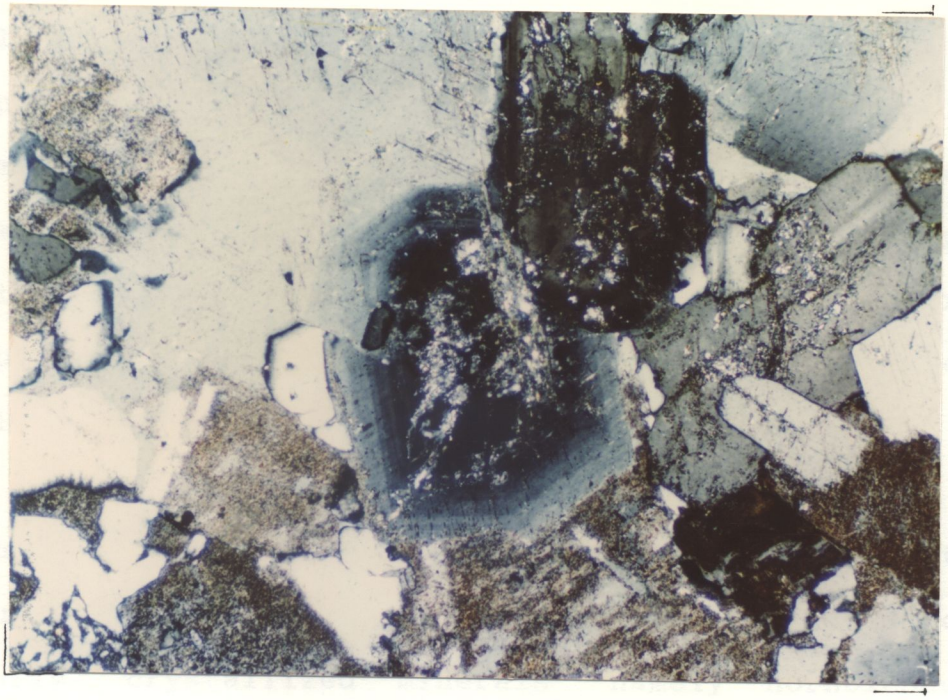


Plate 13a: Syenite. Note: Zoning in the feldspar and alteration at the centre. Crossed nicols. x 100

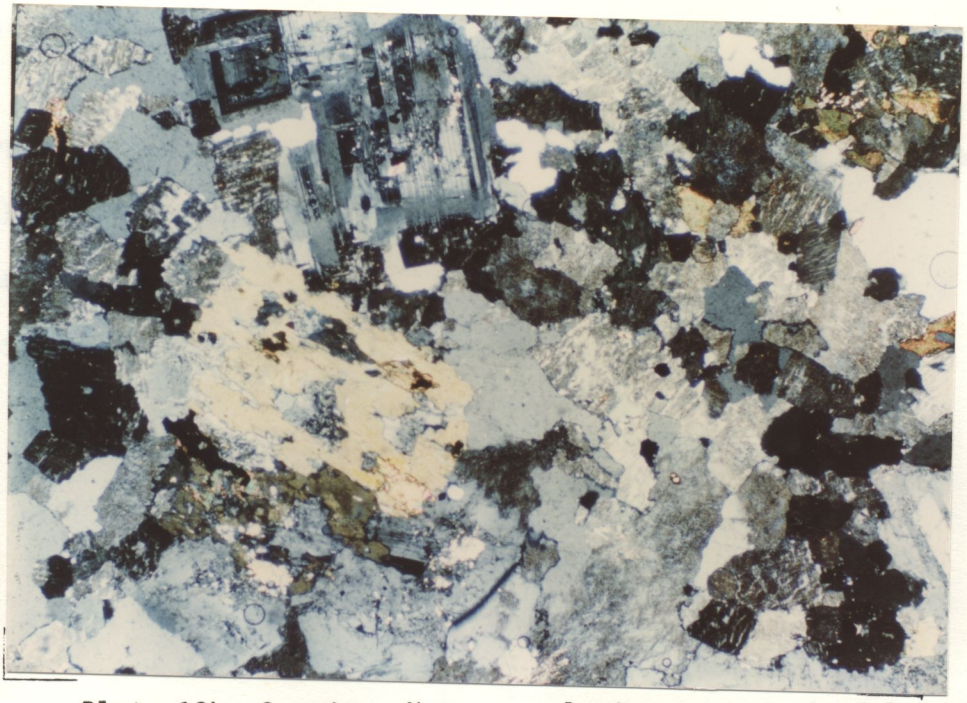


Plate 13b: Syenite. Note: exsolution texture in feldspar. Crossed nicols. x 40

Plate 13a & 13b. Syenite showing zoning and exsolution texture in feldspars.

Alteration of primary minerals is common in syenites; calcite, epidote, sericite formed at the expenses of plagioclase. Amphibole pseudomorphs after pyroxene indicate that the amphibole at least in part was formed by replacement of clinopyroxene and relicts are well preserved. Iron-oxide and sphene are accessories of secondary origin, (Plate 14a). This alteration is regarded as hydrothermal.

The apatite-bearing hornblende syenites are interpreted as cumulates which originated as a result of the accumulation of early crystallized minerals namely hornblende, apatite, feldspar and plagioclase as observed in thin sections 5GD - 303, 305A and 306 from Drill Hole UN 32 south west of Sugar-Loaf Hill, (Plate 14b). The mineralogy is consistent with the differentiation sequence of the mineral assemblages observed in the syenites.

The brecciation of some cumulates particularly apatite suggest that they were affected by tectonic activity after being emplaced into their present position and finally affected by hydrothermal alteration.

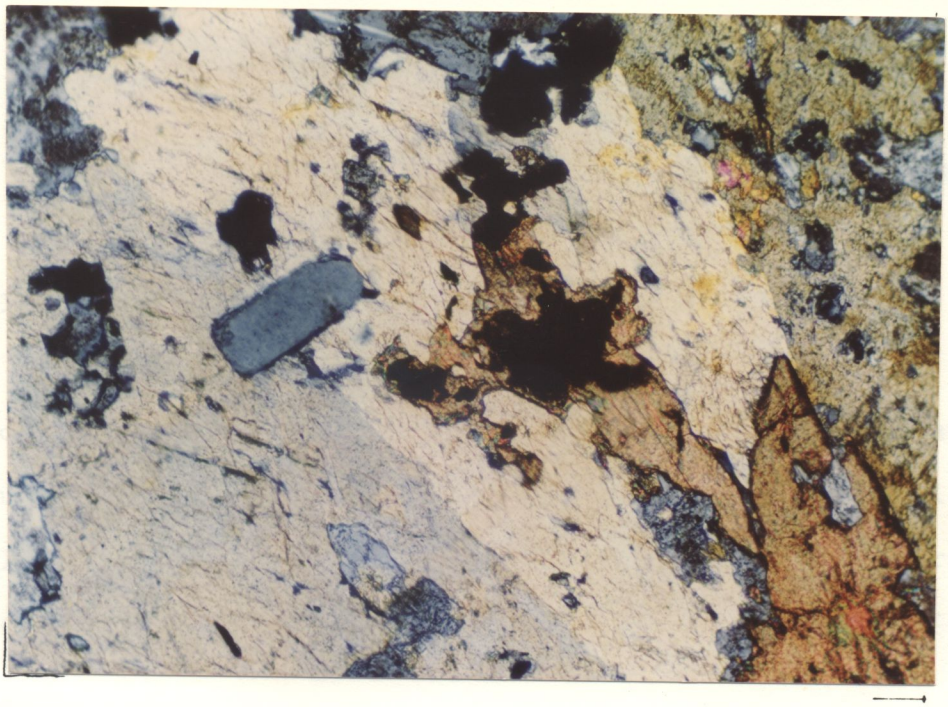


Plate 14a: Hornblende syenite. Crossed nicols. x 100

Note: Epidote, sphene replacing Hornblende and apatite euhedral crystal as inclusion.

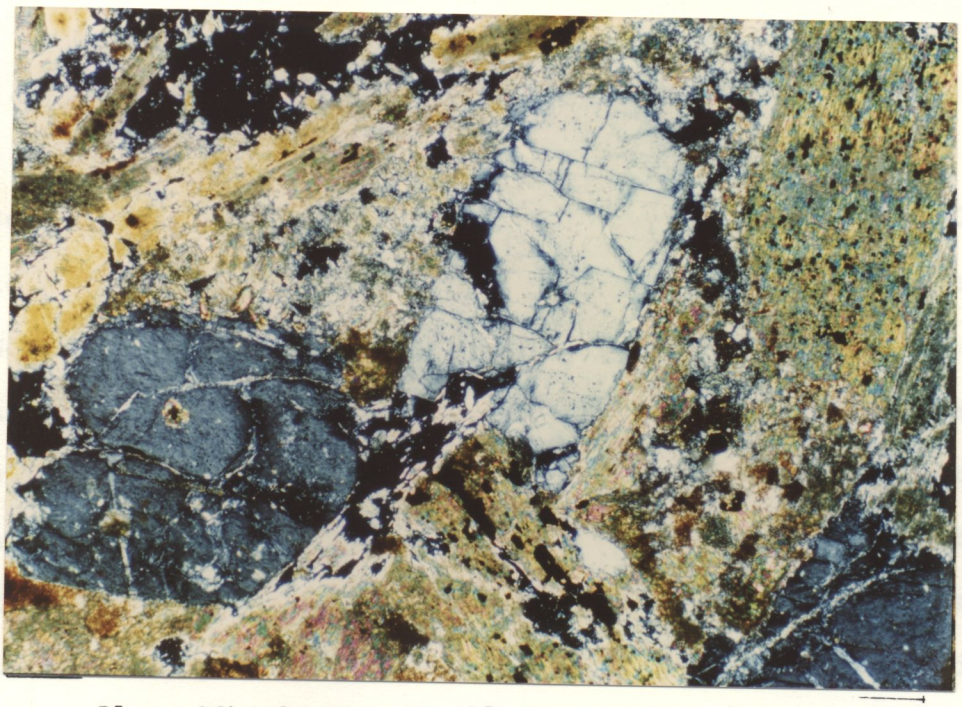


Plate 14b: Apatite Hornblende syenite. Crossed nicols. x 100

Note: Fractured cumulus apatite.

CHAPTER FOUR

GEOLOGY AND PETROLOGY OF THE PHOSPHATE OCCURRENCES

4.1 FIELD RELATIONS

Phosphate occurrences associated with copper mineralisation are found at Sugar-Loaf hill and at Lou-Lou, while pegmatite related phosphates are found at N.E. Sugar Loaf prospect. All occurrences are within the porphyritic syenite.

Due to intense weathering sets of joints and fissures patterns have been obliterated and attitudes could not be taken but the shear pattern appears to be trending in a NE-SW direction and dips between 60 and 80 degrees.

4.2 SUGAR-LOAF HILL

Sugar Loaf hill is a small prominent hill about 25 metres in height and 22 metres in diameter consisting of altered syenite. Most of the syenite is now represented by porous limonite and massive hematite accompanied by veins of the same mineral. Oxidized surfaces are filmed with greenish-blue turquoise. An adit 96m in length has been driven from the southern side of the hill and intersected only hematite-impregnated altered syenite, apart from two small basic dykes, in which iron and possibly copper appear to have been introduced along a

fracture zone. Some magnetite and sporadic patches of earthy copper-phosphate also occur, the latter being concentrated where hematite is not abundant. The highest Copper value recorded from the adit was 4.6 percent (Cikin, 1971).

Recent investigations and resampling of the adit reveals that the P_2O_5 values range from 1.3 to 30 percent with an average of 16 percent P_2O_5 for the inner 58m. Due to intense weathering it is difficult to draw detailed outlines of apatite mineralisation. According to Searle (1973), the sulphide and apatite mineralisation is essentially confined to fragmented blocks within the brecciated altered syenitic host rock.

Phosphate mineralisation occurs in altered porphyritic syenite associated with sulphides and iron-oxide. Pyrite and chalcopyrite are the common sulphide minerals. Hematite, magnetite and geothite are the major opaque minerals seen. Other secondary, copper-phosphate complex minerals have been identified (chalcosiderite-turquoise series).

Apatite varies in amount from 10 percent to 30 percent.The apatite crystals reach up to 10mm, and occur as prismatic euhedral and subhedral hexagonal crystals.From X-ray diffraction analysis,the apatite mineral was identified as hydroxyl-apatite $Ca_5(PO_4)_3OH$.Analytical procedure and X-ray charts are given in appendix II.Brecciation of apatite is prevalent due to intense fracturing. Fractures are filled with quartz, hematite and tourmaline. (Plate 15a and 15b).

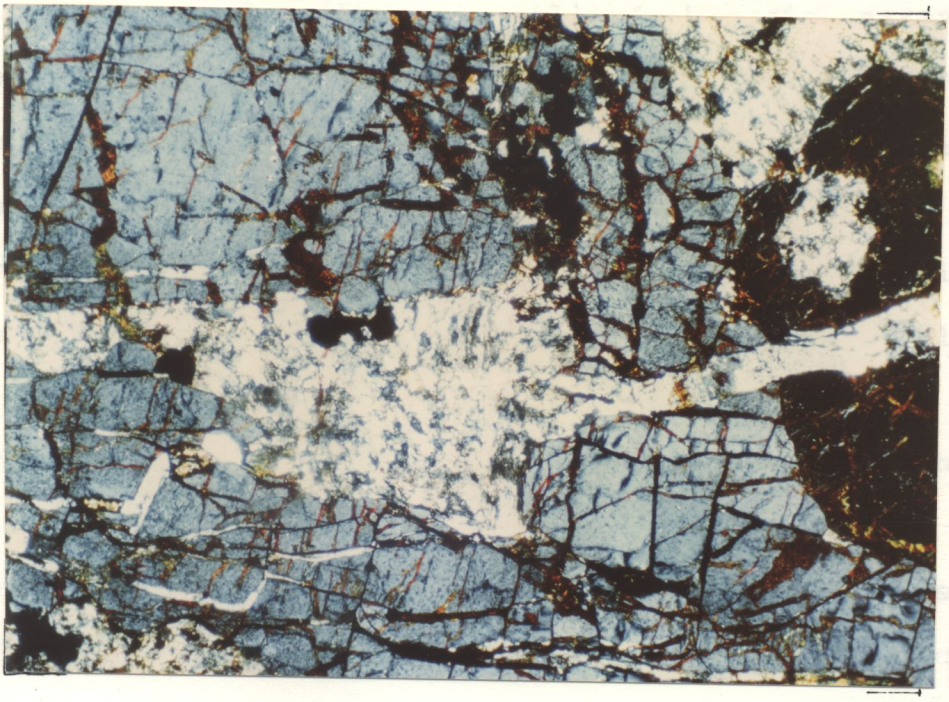


Plate 15a: Note: Brecciation of apatite, quartz vein veinlets filled with hematite. Crossed nicols. x 40

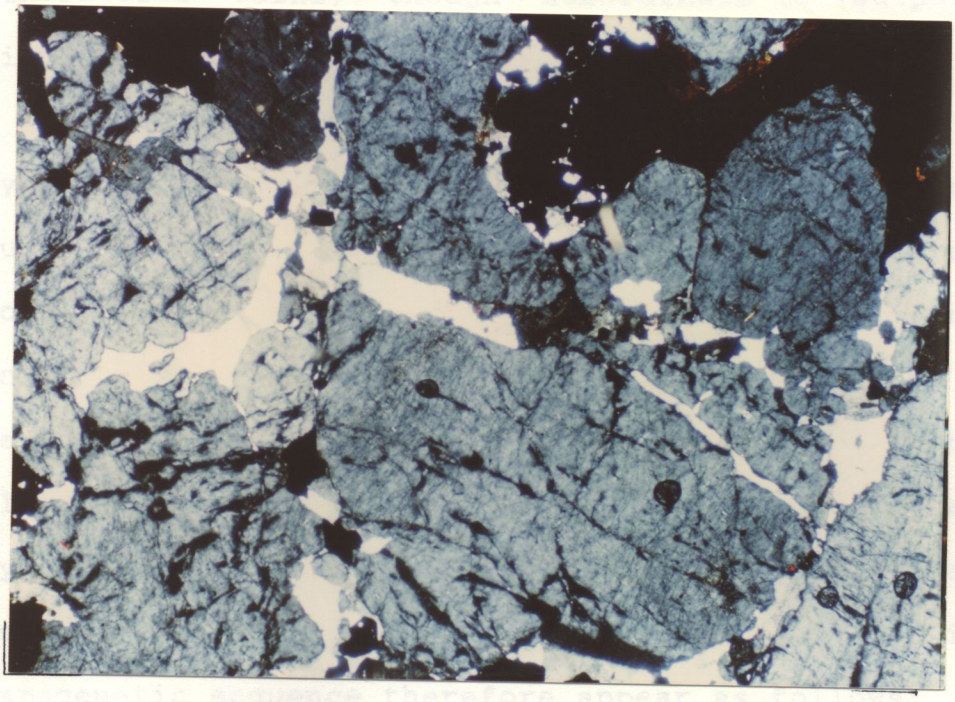


Plate 15b: Apatite rock from Sugar Loaf Hill.

Note: Quartz filling the fractures and iron oxide. Crossed nicols. x 40

The samples from the mineralised breccia assayed up to 30 percent P_2O_5, with an average of about 14 percent P_2O_5. Both apatite and copper values appear to be restricted to the ferruginous breccia and fall sharply in the host porphyritic syenite. Apatite is also found as an accessory in relatively small grains in the porphyritic syenite (Searle, 1973).

Primary magnetite occurs as cubic crystals, shows perfect cleavage and alters to hematite along cleavages. Hematite occurs in several forms or varieties. As replacement of magnetite, as late formed flakes of specularite, as colloform masses associated with tourmaline and as needles which penetrate into quartz crystals and alters to goethite. It is the most ubiquitous ore mineral occurring in a variety of forms in all rock types and is a common constituent of many mineralized veins, though subordinate to sulphides in the mineralised breccia zones.

Pyrite occurs as agglomerations of small grains, usually in a cubic form. It is a relatively late crystallizing mineral, moulding itself upon apatite. In some places cubic pyrite is encased in hematite formed from magnetite. The relationship between magnetite and pyrite is obscured by secondary alteration of magnetite. Pyrite is characteristically replaced by chalcopyrite and hematite. Chalcocite, covellite and geothite are secondary product of supergene enrichment. The paragenetic sequence therefore appear as follows:

	Primary Magmatic Phase	Hydrothermal Phase	Secondary Phase
Magnetite	I------I		
Hematite	I------I	I----------I	
Specular Hematite		I----------I	
Goethite			I------I
Pyrite	I------I		
Chalcopyrite	I------I	I----------I	
Chalcocite			I------I
Covellite			I------I
Apatite	I------I	I----------I	
Chalcosiderite-Turquoise			I------I
Quartz		I----------I	

decreasing temperature ---------->

4.3 LOU-LOU PROSPECT

Lou-Lou is situated 4km north of Sugar-Loaf hill. Surface outcrops comprise patches of limonitic gossan and associated hematite breccia, roughly oval in shape and projecting no more than 2 metres above a flat surface area of 180m by 45m aligned in a NW-SE direction. The gossanized outcrops are mottled with pale green turquoise, associated with a highly altered,

fractured syenite. The syenite appears to be in contact with a quartz feldspar porphyry, which also intrudes the shale. Copper phosphates fill boxwork structures which attain dimensions ranging up to several centimetres.

In order to clarify the mineralisation, six holes were drilled by UNDP and only one drill hole (DH.1) intersected five sulphide and apatite at depth intervals immediately below the oxidized zone within the porphyritic syenite. The highest value of copper attained was 4.76 percent (Searle, 1973).

The porphyritic syenite consists of orthoclase phenocrysts with cores replaced by illite which in turn shows incipient replacement by dolomite. The matrix is composed of fine grained feldspar and interstitial clear quartz with hematite and pyrite.

The mineralisation consists of a fine grained dark coloured sugary pyrite, specked and veined with chalcopyrite. Anhedral pyrite shows arrested growth in porphyritic syenite. Fragmented apatite and pyrite have chalcopyrite infilling cracks.

Quartz feldspar porphyry was encountered in DH.51 at Lou-Lou, in the oxidized zone. In hand specimen the rock is recognised by the presence of greyish-white quartz phenocrysts, measuring up to 5mm in cross-section and embedded in a matrix of pink and fine grained feldspar. In thin section the quartz phenocrysts

are usually anhedral. The matrix consists of small feldspar laths embedded in a fine mozaic of interlocking quartz which amounts to between 30 and 40 percent of the rock. The relationship between the quartz feldspar porphyry and the porphyritic syenite is observed in DH.56, where quartz feldspar-porphyry is replacing the porphyritic syenite (Searle, 1973).

The pseudo-trachyte was encountered in DH.54 between 20.0m and 28.5m and in DH.56 between 60.4m and 62.5m. Patches of hematite and dolomite are commonly scattered throughout the pseudo-trachytes which are often veined by baryte, a mineral which occurs also as large crystals infilling cavities.

4.4 NORTH EAST SUGAR-LOAF

Apatite-bearing pegmatites occur in highly altered porphyritic syenites as irregular bodies. Outcrops are rare, and were only seen at two places, where the fine grained apatite rock about less than 0.5m high and the weathered limonite rocks about 200m to the northeast of the fine grained apatite rocks. The pegmatites exhibit a sharp contacts with the host rock. (Plate 16a). The structure of the pegmatite bodies appears to range from irregular wedged like lenses to plug like. Near the contact with the country rock, the apatite rock is fine to medium grained, white to pinkish in colour with specks of hematite. In thin section the apatite occurs as euhedral prismatic crystals within altered feldspar. Minor magnetite is

intersititial to the apatite, and hematite occur as a secondary cementing material (Plate 16b). The fine grained apatite rock seems to represent the marginal zone of the apatite pegmatite. The pegmatite core is highly brecciated and is essentially monomineralic and rarely contain stumpy prisms of altered feldspar, which are light greenish in colour. Small veinlets of quartz and iron oxide are seen cutting through the apatite (Plate 17a) and filling in the fractures. In some apatite specimen, copper staining and iron is clearly seen filling in apatite fractures. The pegmatites are of high grade, the analyses of apatite chips are shown in table 2.

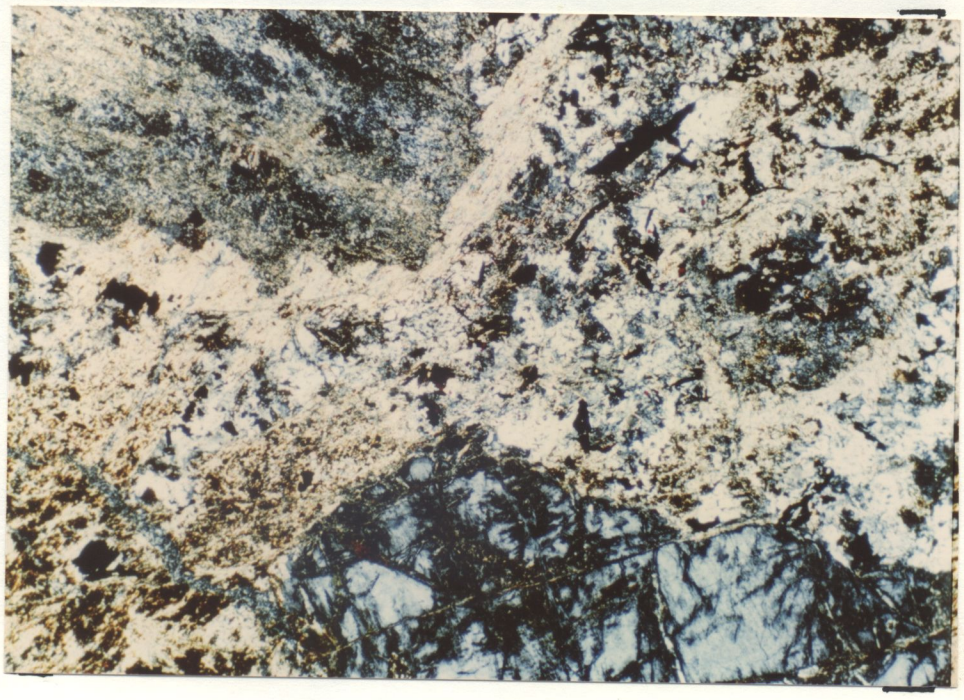


Plate 16a: Apatite-syenite contact zone.
Note: Alteration, outlines of feldspar phenocryst and apatite crystal. Crossed nicols. x40

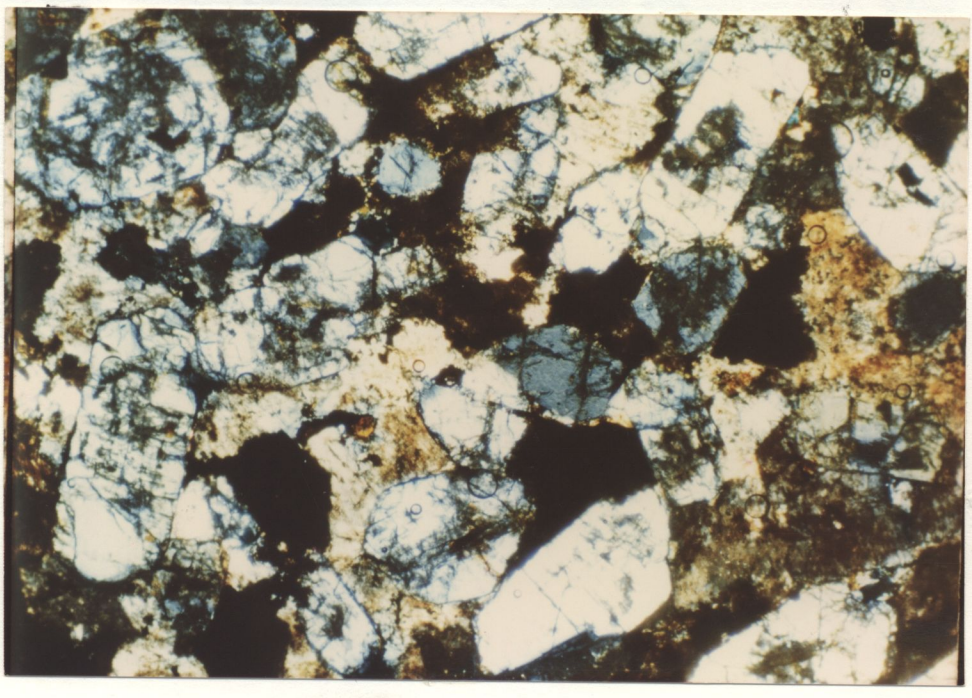


Plate 16b: Fine grained apatite rock. Crossed nicols. x40
Note: Iron-oxide and altered feldspar cementing euhedral apatite crystals.

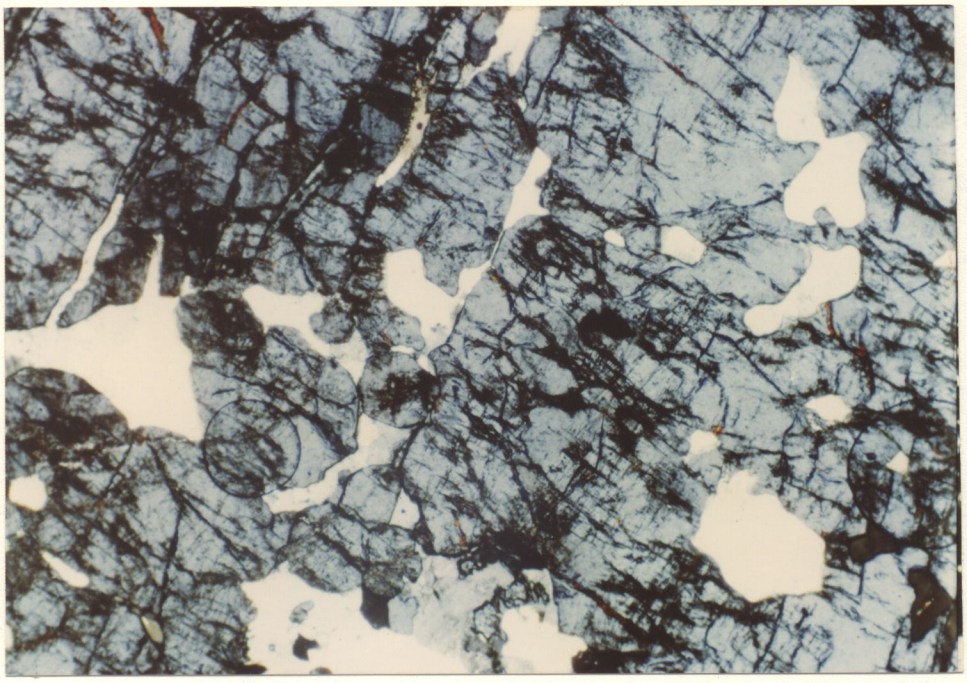


Plate 17a: Apatite pegmatite showing secondary quartz and iron filling in the fractures. Crossed nicols. x40

Plate 17b: Apatite hornblende of Sinda, orebody No. 4 Eastern Province. Note: similarly with plate 14b. Crossed nicols. X40

Table 2: Chemical analysis of apatite pegmatite.

WEIGHT %	TRENCH NO. 8	12	14	17	18	23	24
P_2O_5	40.00	12.00	20.00	36.00	38.00	38.00	7.00
Fe_2O_3	0.97	13.73	15.01	2.29	1.94	4.20	7.44
Al_2O_3	0.38	8.88	6.08	2.00	3.02	0.44	10.21
MgO	0.17	0.66	0.50	0.33	0.33	0.41	0.71
CaO	50.07	14.25	23.94	47.06	44.67	49.88	8.15
SiO_2	2.93	41.75	27.87	6.42	5.01	2.55	56.58
S	0.10	0.07	0.10	0.23	0.05	0.18	0.36
MnO	0.03	0.46	0.10	0.06	0.25	0.03	0.04
L.O.I*	1.34	5.16	4.14	2.37	3.92	1.63	7.28
CaO/P_2O_5	1.30	1.20	1.20	1.30	1.20	1.30	1.20

Determinations carried out by MINEX laboratory

P_2O_5 - by colorimetric method

CaO - by EDTA

SiO_2 - by NaOH fusion

MgO, Fe_2O_3, MnO and Al_2O_3 by AAS

* L.O.I at 1000° c

4.5 NORTH WEST SUGAR LOAF

Apatite occurs in small sporadic oval outcrops 10m diameter which have been obscured by the silicified ironstone occuring in the vicinity. Apatite forms euhedral sugary crystals in association with quartz and hematite. The country rock is porphyritic syenite. The lateral extent of these occurrences has not been established.

CHAPTER FIVE

SYENITE GEOCHEMISTRY

5.1 INTRODUCTION

X-ray fluorescence spectrometry for major and trace elements was undertaken on 31 selected rock samples.The chemical classification using CIPW Norms has been applied on 6 fresh rocks. The major and trace elements variation diagrams are discussed. Trace elements variation diagrams have been used to determine the petrogenetic evolution of the magma and tectonic setting of the rocks.Errors in the chemical analysis of major elements are introduced by the intense alteration of the rocks and matrix effect in the analysis as such the data should be considered as semiquantitative.

5.2 ANALYTICAL PROCEDURE

Major elements were analysed by X-ray fluorescence spectrometry on pressed pellets prepared by mixing 8g sample with 1g borax wax, except for Na and Mg, which were analysed by atomic absorption spectrometry. The instrument used was a Phillips PW 1410 X-ray spectrometer with X-ray tube gold target.

The UNZA internal and international geochemical standards (UZA, UZB, UZC, UZD, UZE; G-2, AGV-1, BEN-N, GA, GXR-1, GXR-4,

SARM-1, SARM-2, SARM-4, SARM-5, SARM-6, SY-2, SY-3, Rb-2 and Rb-3) were used for calibration.

The trace elements Nb, Zr, Sr, Rb, Zn, Cu, Ni, U,Th and Pb were analysed using the method of Viè le Sage et al (1979). This is a combination of the methods of Feather and Willis (1976),for correcting background and matrix by measuring an Interference Free Background (I.F.B.) or a Compton scattered peak from the tube, and correcting for the interferences Bougault et al (1977). For Nb, Zr, Y, Sr and Rb, the operating conditions were: excitation potential 80Kv and current 30mA . An Interference Free Background was taken at 15.00 degrees 2-theta. For Zn, Cu and Ni the operating conditions were, excitation potential 60Kv and current 30 mA at 32.90 degrees 2-theta, closer to the analyte lines.Detection limits were:Nb, 1ppm; Sr, Y and Rb, 3ppm; Th,8ppm; U and Pb,6ppm.

For Ba, this method could not be used, since the analyte line Ba L alpha 1, lies at the long wavelength side of the K-absorption edge of the heaviest major element Fe. Therefore, straight linear calibration was used on standards (SARM-1, SARM-5, UZE, BE-N and G-2), giving acceptable results. Since the counts were low per ppm, the results are given in tenfolds.

5.3 PRESENTATION OF RESULTS

The major elements and CIPW Norms calculations were done on six rock samples which were considered to be relatively fresh,Table

3.1.The mean of the six analyses is shown in column 7,which is compared with an average syenite shown in column 8,after Cox et al (1979).The trace elements are in ppm, both major and trace elements are shown in Table 3.2.

The totals of some composition are not 100 percent because of analytical errors, differences in the composition between the unknown and chosen standards and the intense alteration of the rock samples.

Table 3.1: Chemical Analyses of major elements and CIPW norms of North West Mumbwa Syenites

Major Oxides (Wt %)

1	2	3	4	5	6	7	8
DM 39	DM 40	DM 41	DM 42	DM 44	DM 61	MEAN	AVERAGE SYENITE
53.97	58.10	61.12	59.58	58.36	58.37	58.25	58.58
0.67	0.80	0.66	0.72	0.66	0.96	0.76	0.84
13.82	12.00	16.73	15.15	14.87	19.22	15.29	16.
2.45	2.72	3.36	2.31	1.71	4.09	2.77	6.
0.05	n.d	0.04	0.05	0.03	0.23	0.06	0.13
1.76	1.94	1.29	1.16	1.06	0.25	1.24	1.87
6.83	5.80	3.69	4.69	5.36	0.51	4.48	3.53
6.93	3.93	3.61	3.72	3.84	0.13	3.69	5.24
0.59	4.32	4.22	4.47	4.21	12.29	5.02	4.95
0.57	0.04	0.27	0.31	0.36	1.60	0.53	0.
2.39	1.49	0.75	0.73	0.43	3.01	1.46	1.50
90.12	91.14	95.74	92.89	90.89	100.66	93.55	99.74

CIPW NORMS

1	2	3	4	5	6	7	8
1.39	10.72	15.69	13.07	11.87	10.27	10.25	0.83
n.d	n.d	0.17	n.d	n.d	5.74	n.d	n.d
3.97	28.34	26.25	28.66	27.50	73.11	32.20	29.29
66.82	36.92	32.15	34.15	35.91	1.11	33.89	44.34
5.54	2.60	17.41	12.41	12.05	n.d	11.22	7.24
n.d	n.d	3.38	0.20	n.d	0.63	1.00	4.16
10.78	11.57	n.d	6.33	6.30	n.d	5.09	5.35
5.09	3.63	n.d	n.d	1.77	n.d	n.d	n.d
0.12	0.12	n.d	0.12	0.07	0.5	0.14	1.60
2.79	3.02	3.54	2.51	1.89	4.12	3.01	4.41
1.97	2.03	n.d	1.77	1.70	n.d	1.84	n.d
n.d	n.d	0.65	n.d	n.d	0.71	n.d	n.d
1.54	1.05	0.67	0.80	0.94	3.72	1.36	0.70
n.d	n.d	n.d	n.d	n.d	n.d	n.d	0.64

Fe_2O_3* - Total Fe as Fe_2O_3.
L.I.O. - at 1000° C

1-6 - Mumbwa North syenite near Karenda Mission
7 - Mean of Mumbwa North syenite
8 - Average syenite after Cox et al (1979)
n.d - not detected

Analysis of the major elements were carried out by F.Tembo, University of Zambia, Lusaka.

Table 3.2: Chemical analysis of major and trace elemenets of North West Mumbwa

Major oxides (Wt %)

	1	2	3	4	5	6	7	8
E	DM 39	DM 40	DM 41	DM 42	DM 44	DM 61	DM 54	DM 48
	53.97	58.10	61.12	59.58	58.36	58.37	57.36	53.36
	0.67	0.80	0.66	0.72	0.66	0.96	1.06	1.36
	13.82	12.00	16.73	15.15	14.87	19.22	22.51	20.
	2.85	2.72	3.36	2.31	1.71	4.09	9.70	16.
	0.05	n.d	0.04	0.05	0.03	0.23	0.01	0.32
	1.76	1.94	1.29	1.16	1.06	0.25	0.56	0.53
	6.83	5.80	3.69	4.69	5.36	0.51	0.42	0.67
	6.93	3.93	3.61	3.72	3.84	0.13	0.13	n.d
	0.59	4.32	4.22	4.47	4.21	12.29	6.36	6.51
	0.57	0.04	0.27	0.31	0.36	1.60	0.07	0.
	2.39	1.49	0.75	0.73	0.43	3.01	3.14	2.72
	90.12	91.14	95.74	92.89	90.89	100.66	101.32	102.24

TRACE ELEMENTS (ppm)

	DM 39	DM 40	DM 41	DM 42	DM 44	DM 61	DM 54	DM 48
	38	39	36	46	40	53	36	17
	415	402	389	424	424	529	477	260
	64	64	64	68	76	121	81	49
	365	436	575	425	478	625	29	136
	43	109	110	109	100	233	301	133
	350	750	960	730	780	2280	320	710
	15	24	18	21	11	18	10	32
	n.d	10	3	18	n.d	158	150	57
	22	10	24	23	26	19	22	27
	n.d	20	8	11	8	25	29	71
	81	70	72	87	84	25	n.d	n.d
	29	30	23	20	27	20	15	n.d
r	0.12	0.25	0.19	0.26	0.21	0.37	10.37	0.98
	6.48	6.28	6.08	6.24	5.58	4.37	5.88	5.31
	n.d	3.50	9	7.90	10.5	1.00	n.d	n.d

contd.

	9	10	11	12	13	14	15	16
E	DM 63	DM 64	DM 68	DM 02	DM 60	DM 11	DM 56	DM 58
	45.65	46.41	27.17	36.16	66.71	42.85	55.25	59.03
	0.16	0.06	1.80	0.40	0.73	0.73	0.79	0.29
	1.09	2.05	2.90	2.66	16.23	15.25	24.45	24.
	6.96	5.48	3.58	13.29	4.54	25.44	6.91	2.
	0.04	0.15	n.d	n.d	0.01	0.04	0.91	0.01
	0.05	0.03	0.07	0.96	0.13	1.72	0.60	0.32
	23.53	25.65	33.66	24.94	2.13	0.57	0.41	0.42
	n.d	0.13	0.11	n.d	n.d	0.05	0.05	n.d
	n.d	n.d	0.91	0.07	8.22	2.24	10.24	12.72
	23.14	20.00	26.93	20.00	0.22	0.52	0.08	0.
	0.84	1.74	2.30	4.39	2.32	6.56	2.65	2.19
	101.16	101.7	99.43	102.87	101.24	96.00	101.62	102.24

TRACE ELEMENTS (ppm)

	DM 63	DM 64	DM 68	DM 02	DM 60	DM 11	DM 56	DM 58
	109	n.d	63	n.d	37	13	36	29
	48	32	156	2	344	227	379	470
	409	341	426	116	79	51	63	44
	384	420	890	275	75	7	70	45
	49	39	n.d	n.d	143	115	219	240
	440	26	1080	30	1010	390	1120	950
	12	12	31	44	15	96	8	4
	155	192	177	523	333	2969	85	145
	n.d	16	n.d	161	40	461	18	24
	229	135	251	137	32	36	31	n.d
	n.d	n.d	n.d	n.d	43	n.d	n.d	n.d
	n.d	12	22	n.d	36	n.d	13	16
r	0.13	0.09	n.d	n.d	1.91	16.43	3.13	5.33
	0.12	0.09	0.3	0.02	4.35	4.45	6.00	10.68
	n.d	n.d	n.d	n.d	1.3	n.d	n.d	n.d

contd.

E	17	18	19	20	21	22	23	24
	DM 49	DM 59	DM 45	DM 62	DM 14	DM 52	DM 53	DM 57
	67.14	60.35	55.55	63.32	47.88	60.65	60.56	58.80
	0.79	0.84	1.36	0.80	1.20	0.74	0.76	1.00
	24.66	21.42	34.43	20.50	16.30	19.87	17.8	19.
	2.88	5.78	6.71	3.28	12.40	3.49	4.98	6.
	0.81	n.d	0.03	n.d	n.d	0.01	n.d	1.94
	0.11	0.33	0.46	0.26	1.51	0.28	0.56	0.10
	0.38	0.39	0.38	0.38	1.48	0.43	0.38	0.43
	0.08	n.d	0.03	0.03	3.49	0.16	0.19	0.08
	5.82	10.46	9.88	6.15	6.15	8.65	11.20	9.60
	0.07	0.28	0.25	0.10	0.60	0.07	0.07	0.
	2.86	2.31	3.05	2.98	4.81	2.25	1.70	3.18
	104.80	102.16	101.13	97.80	95.82	96.60	98.20	101.99

TRACE ELEMENTS

	DM 49	DM 59	DM 45	DM 62	DM 14	DM 52	DM 53	DM 57
	51	34	30	40	31	38	25	35
	540	451	382	419	281	414	326	361
	74	81	90	41	41	46	38	42
	17	12	190	21	193	45	50	62
	165	287	295	163	139	192	154	230
	180	3020	3010	300	450	610	750	1140
	10	14	13	31	162	17	7	25
	36	100	308	96	1237	69	158	53
	25	18	14	23	251	21	17	23
	19	47	18	9	26	13	34	33
	119	n.d	n.d	109	n.d	89	n.d	26
	32	16	11	31	13	26	16	17
	9.71	1.35	1.55	7.76	0.72	4.30	3.08	3.71
	7.30	5.57	4.24	10.22	6.85	9.00	8.58	8.59
	6.20	n.d	n.d	12.10	n.d	6.80	n.d	0.70

contd.

	25	26	27	28	29	30	31	32
E	DM 55	DM 69	DM 46	DM 36	DM 50	DM 47	UN DH 51	UN DH 56
	63.73	49.47	57.16	49.83	58.43	58.14	52.83	54.35
	0.90	0.50	0.40	1.29	0.70	0.60	1.07	0.72
	19.40	5.80	18.90	15.07	20.60	16.50	19.29	12.
	3.62	2.96	4.94	9.94	3.33	7.94	11.17	16.
	0.01	n.d	n.d	0.05	n.d	n.d	0.26	0.89
	0.10	8.60	0.41	1.76	0.28	0.32	0.66	1.00
	0.37	15.00	0.41	2.14	0.35	0.38	0.67	0.63
	0.08	6.10	0.05	4.16	0.40	n.d	0.10	n.d
	8.35	0.72	10.20	2.13	12.30	10.60	9.31	4.33
	0.06	0.20	0.02	1.00	0.10	0.07	0.23	0.
	3.61	6.34	2.33	4.98	1.80	1.73	6.07	8.78
	100.2	95.69	94.82	92.35	98.29	96.28	101.66	99.35

TRACE ELEMENTS (ppm)

	DM 55	DM 69	DM 46	DM 36	DM 50	DM 47
	42	18	21	31	32	23
	476	202	418	304	355	251
	52	30	25	28	22	19
	78	206	59	366	66	n.d
	176	45	200	61	233	122
	720	110	990	590	2300	530
	18	24	11	150	8	5
	165	12	130	843	120	97
	33	18	16	187	13	15
	27	6	19	20	24	28
	89	n.d	9	n.d	10	n.d
	29	18	21	15	12	14
r	2.26	0.22	3.38	0.17	3.53	n.d
	9.15	6.73	16.72	10.86	16.14	13.20
	3.20	n.d	0.47	n.d	0.40	n.d

n.d - not detected
L.O.I - Loss on ignition at 1000° C
Fe_2O_3* - Total Fe as Fe_2O_3

Analysis:

1 - 6	Fresh syenite, near Karenda Mission
7 - 8	Pseudo-trachyte, Sugar Loaf prospect
9 - 12	Apatite rocks, Sugar Loaf propsect
13	Altered syenite, Sugar Loaf propect
14	Altered basic rock, Sugar Loaf prospect
15 - 16	Altered syenite, Sugar Loaf prospect
17	Altered syenite, Lou-Lou prospect
18 - 19	Altered syenite, Sugar Loaf prospect
20	Altered syenite Lou-Lou prospect
21	Altered basic rock, Sugar Loaf hill, DDH. 3.
22	Altered syenite, Lou-Lou prospect
23	Altered syenite, Sugar Loaf prospect
24	Altered syenite, Lou-Lou prospect
25	Altered syenite, Sugar Loaf prospect
26	Calc-siliceate near Karenda Mission
27	Altered basic rock, Sugar Loaf prospect
28	Altered basic rock, Sugar Loaf hill, DDH.1.
29	Altered syenite, Sugar Loaf prospect
30	Altered syenite, Lou-Lou prospect
31	Porphyritic microsyenite, UN.DH.5I, Lou-Lou prospect
32	Pseudo-trachyte UN.DH.56, Lou-Lou prospect.

Analysis of the major elements were carried out by F. Tembo while trace element analysis were done by Mr. H.W. Nugteren both of the University of Zambia, School of Mines Laboratory.

5.4 CHEMICAL CLASSIFICATION

Table 3.1 gives chemical compositions and CIPW Norms of six of the representative fresh syenite investigated. From inspection of the norms, most of them are nordmarkites. Chemically they plot in the alkali feldspar member series in the Q-Ab-Or and An-Ab-Or ternary systems. (Figure 6). The alkali feldspar is therefore mainly orthoclase microperthite or microcline.

A simple alkalinity ratio devised by Wright (1969), in form of a variation diagram (fig.7), by plotting it against SiO_2 on a log - linear scale was used to classify the Mumbwa syenites as mildly alkaline with transitions into calc-alkaline field, Alkali Syenite of Johannsen (1937).

The total alkalis-silica variation diagram (fig. 8) was also used to classify the same rocks as belonging to the alkaline basalt family with transitions into subalkaline rocks. These conclusions are based on the cluster of data on the variation diagrams.

5.5 CHEMICAL VARIATION IN THE MUMBWA SYENITES

Chemical variation diagrams show the relationship between the elements and give an indication of the state of differentiation. Rocks from different rock series generally

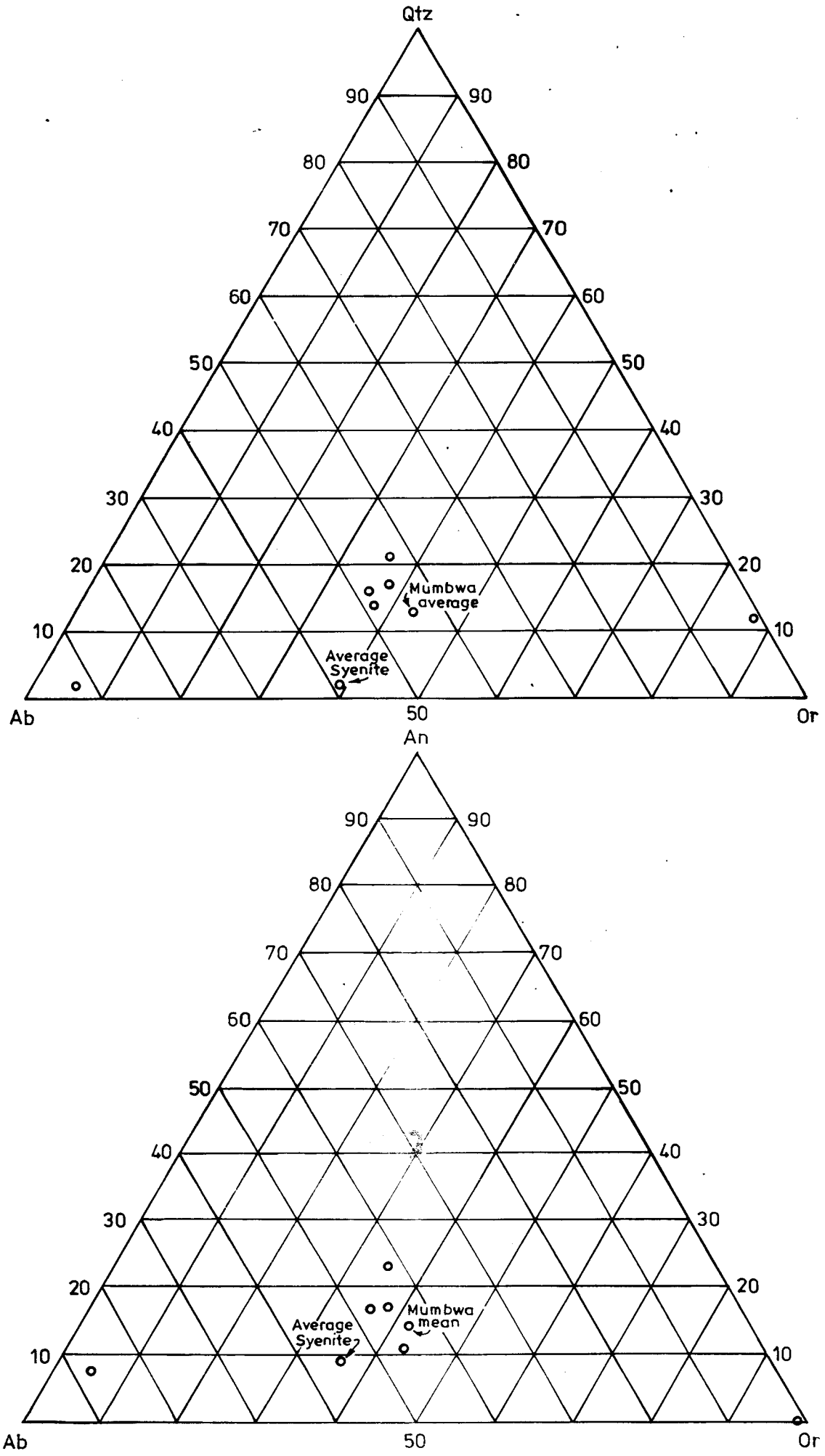


Fig.6 Normative compositions of Mumbwa Syenites
Ab - An - Or and Ab - An - Qtz

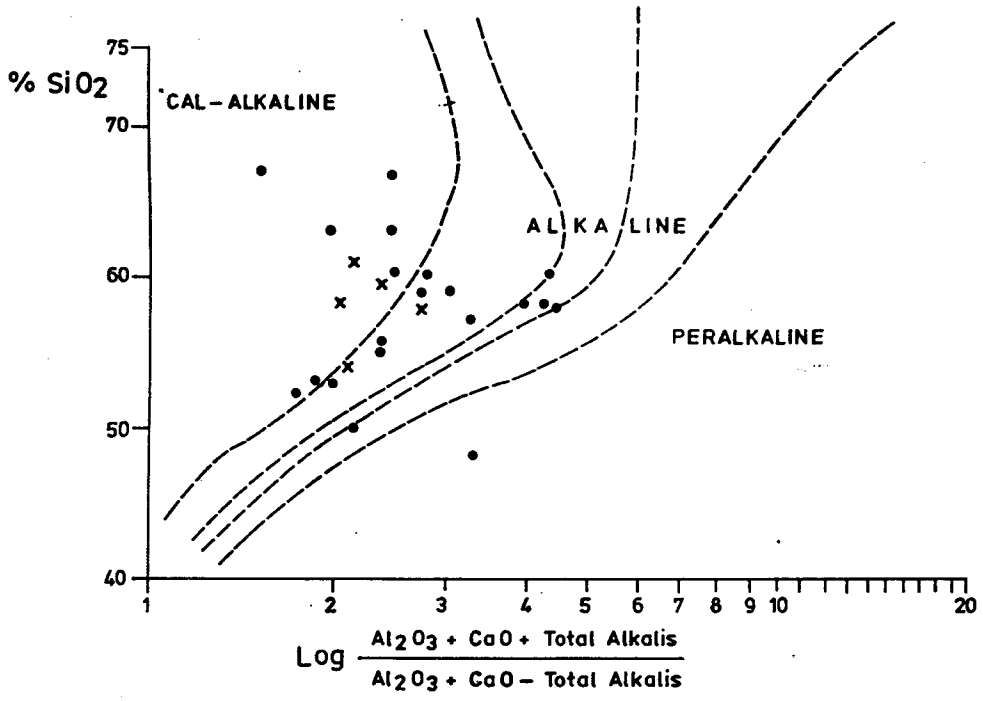


Fig. 7 Alkalinity ratio Vs SiO_2 Variation diagram for North-West Mumbwa Syenites (After Wright, 1969)

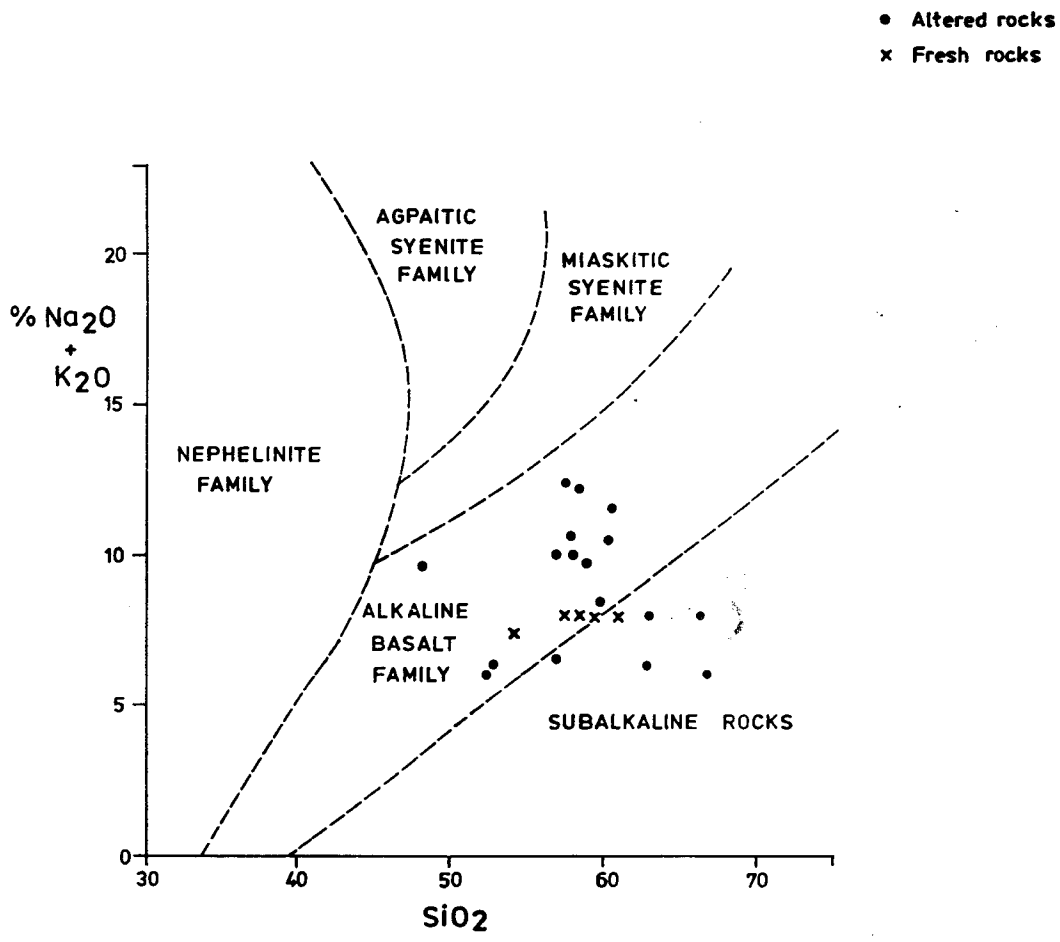


Fig. 8 Total alkalis Vs SiO_2 Variation diagram for North-West Mumbwa Syenites (After Currie, 1976)

show diverse variation diagrams. Variations in major elements are directly affected by differences in the crystallizing mineral assemblage (Anderson and Gottfried, 1971). A quantitative mineralogical understanding of such differences depends upon the physical significance of the parameters of chemical differentiation.

Causes of chemical variation include crystallization differentiation, progressive partial melting, magma mixing and assimilation (Turner and Verhoogen, 1960; Hamilton, 1964; Green and Ringwood, 1968). Post-magmatic alteration is widespread phenomenon and is a result of interaction with groundwater or hydrothermal fluids. Common effects include the leaching and removal of some constituents, the oxidation of Fe^{2+} to Fe^{3+}, and introduction of water and CO_2 to produce hydrated minerals and carbonates.

Any element which is largely excluded from the minerals and stored in the liquid can serve as an approximate indicator of the amount of crystallization (Anderson and Greenland, 1969). Of several potentially useful elements such as P,K,Ti, phosphorus is prefered because appears less susceptible to deuteric transport than potassium, and because it enters less readily than titanium into pyroxene and than potassium into plagioclase. Mumbwa syenites are not fresh, the feldspar phenocrysts are invariably turbid, or completely pseudomorphosed by sericite. Plagioclase alter to finely aggregates of sericite and it is often notable that the centres

of crystals are more affected than the edges.

5.6 MAJOR ELEMENTS

Chemical variations of the major elements on the Harker variation diagrams (fig 9a and 9b) show increases in K_2O, Al_2O_3 with increasing SiO_2. This probably reflects the abundance of clay minerals due to alteration. Extremely low Na_2O, CaO, and MgO in altered rocks relative to fresh rocks indicates the leaching of elements during alteration processes because they are soluble. The general decrease in P_2O_5 with increasing SiO_2 confirms the observation by Watson (1980) and Green and Watson (1982), that apatite solubility declines as temperature decreases and silica increases.

TiO_2 shows a generally flat trend with a slight scatter in the individual data points. No considerable concentration of titanium in alkaline rocks is found and the most alkaline rocks contain the least amounts of the element. The alkaline geochemical province of the Kola Peninsula in the U.S.S.R. seems to be anomalous because its nepheline syenite contains nearly twice as much titanium (0.53 percent) as the global nepheline syenite (0.30 percent). The average titanium content in alkaline rocks of the earths crust is 0.35 percent (Beus, 1976).

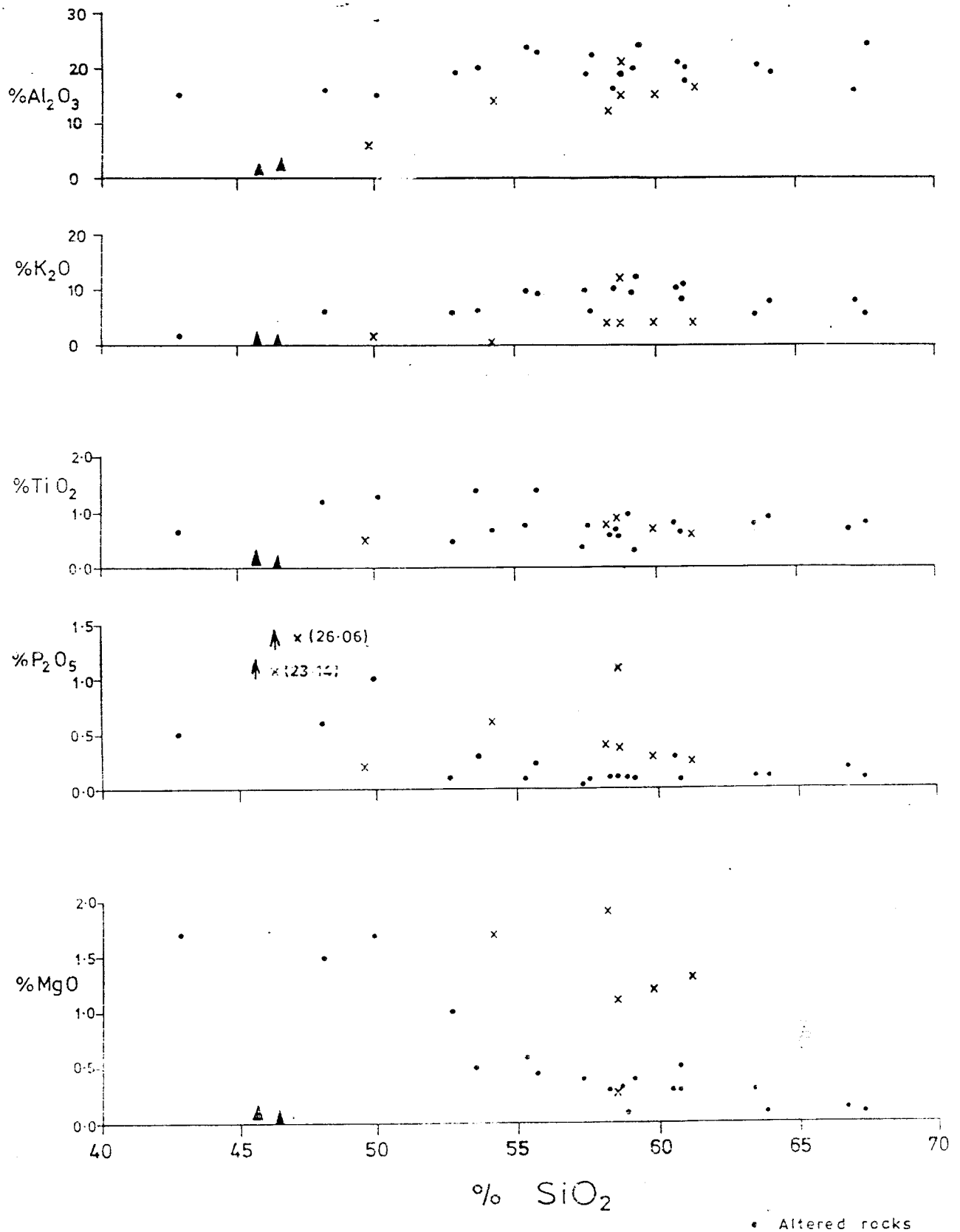
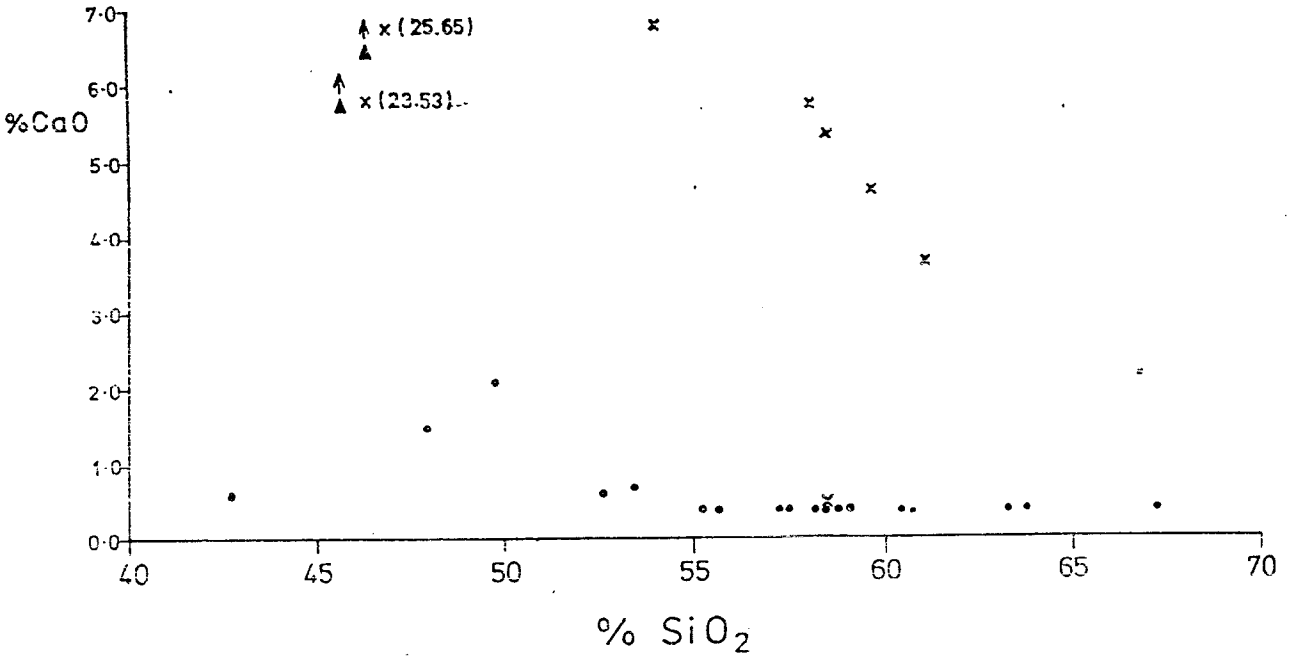


Fig. 9a Harkers variation diagrams for the North West Mumbwa Syenite



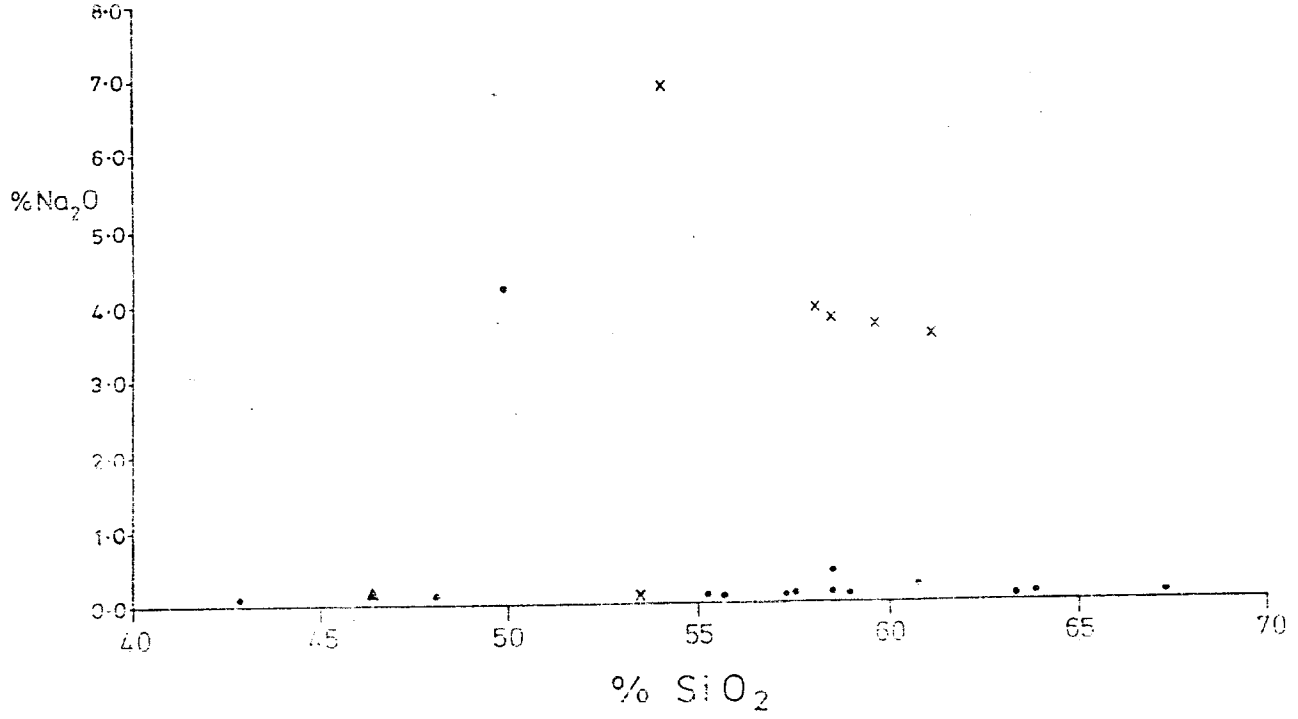


Fig. 9b Harkers variation diagrams for the North West Mumbwa Syenite

P^{5+}, and Ti^{4+} are small, highly charged ions which may be expected to form complex anionic groups in silicate melt. Such complexes may be sensitive to minor variations in the major element composition and possibly may change with subtle variations in crystallization conditions.

The principal host minerals of Ti and P in plutonic rocks are amphibole, biotite, sphene, magnetite, ilmenite and apatite. Variations of P and Ti with crystallization depend chiefly upon these minerals. The stages of crystallization of apatite, oxides, amphibole, biotite and sphene depend upon major element composition, temperature, pressure, redox potential and water pressure (Anderson and Gottfried, 1972).

Prior to crystallization of the above host minerals P and Ti should behave coherently with other elements, whose host minerals crystallize at the same or later stage such as feldspar.

The mineralogical variations observed in Mumbwa syenites such as the presence of sphene, biotite, apatite, hornblende and feldspar seem to confirm that these minerals some how crystallized under similar conditions as mentioned above.

5.7 TRACE ELEMENTS

It is well known that the major elements normally used to

classify igneous rocks are mobile to varying degrees. Variable mobility of the major elements during hydrothermal alteration and poor preservation of phenocrysts phases whose compositions are required for geochemical modelling, hamper more detailed petrogenetic interpretations.

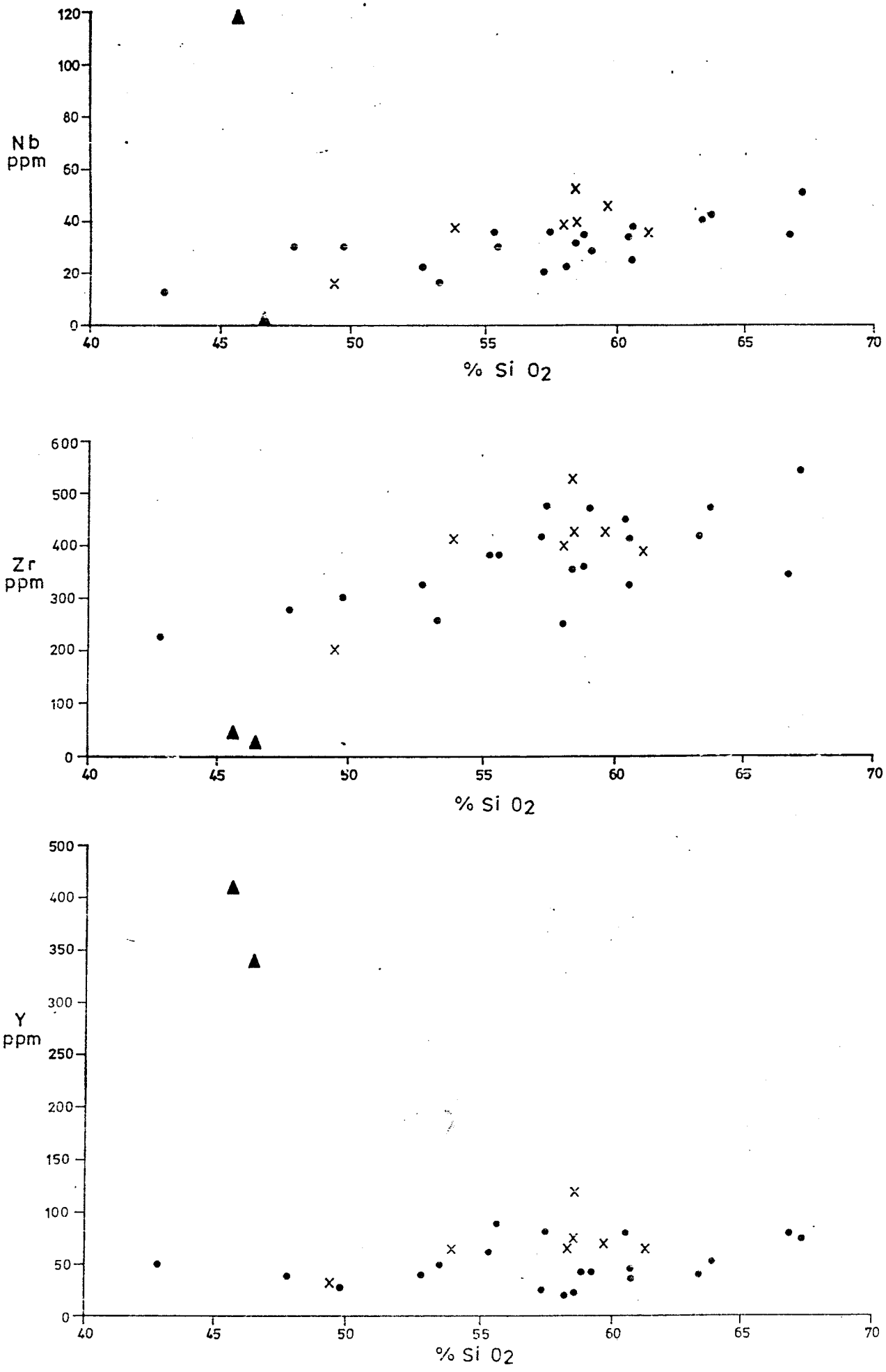
Certain elements may be strongly affected by weathering processes. The elements affected become enriched or impoverished in the altered igneous rocks, because they are mobile e.g Rb, Sr and Ba. On the other hand Ti, Y, Zr, Nb and heavy REE are extremely resistant to alteration such that petrogenetic models and rock classification can be based on these elements for altered and metamorphosed rocks (Pearce and Cann, 1973; Winchester and Floyd, 1976).

The Mumbwa syenites show an increase in Y, Rb, Nb and Zr with increasing SiO_2, and a decrease in Sr with increasing SiO_2 on Harkers variation diagrams, (Fig. 10a and 10b) particularly for altered rocks. For fresh rocks Sr increases with increasing SiO_2 (fig. 10a and 10b).

The anticipated effect of crystal fractionation would be extreme depletion of compatible elements in the later liquid. The differentiation involving plagioclase results in the depletion of Sr and to a lesser extent Ba, which becomes truly compatible once K-feldspar crystallizes (Drake and Weill, 1975)

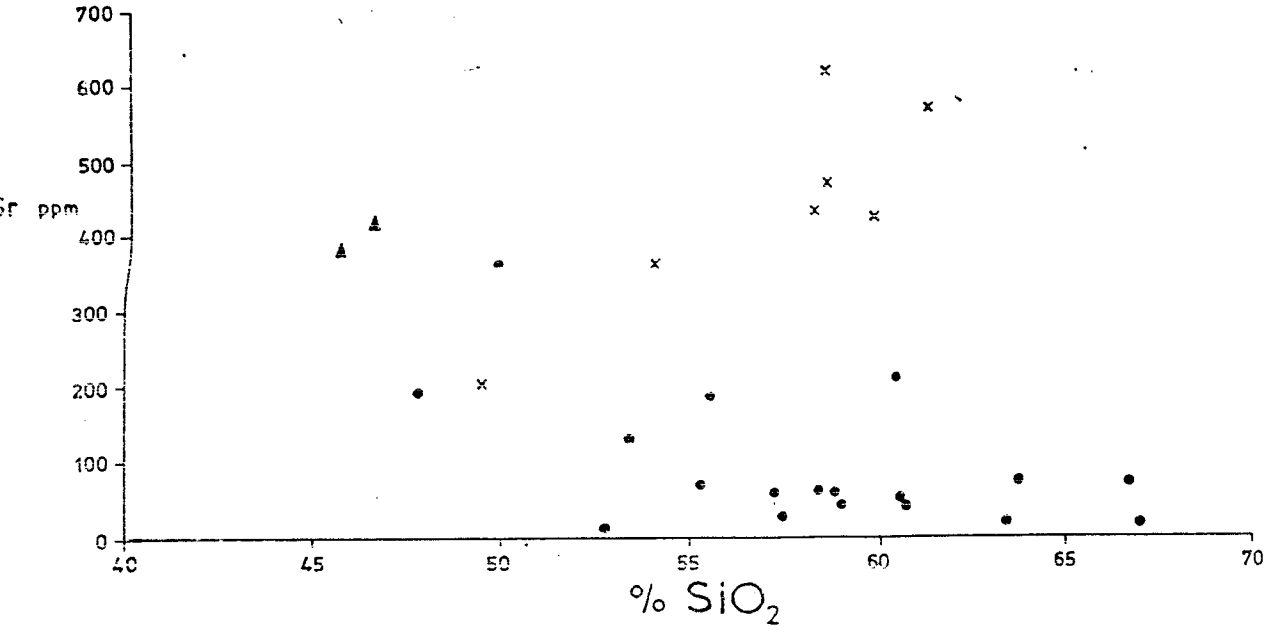
At low pressure, plagioclase can be expected to be a stable

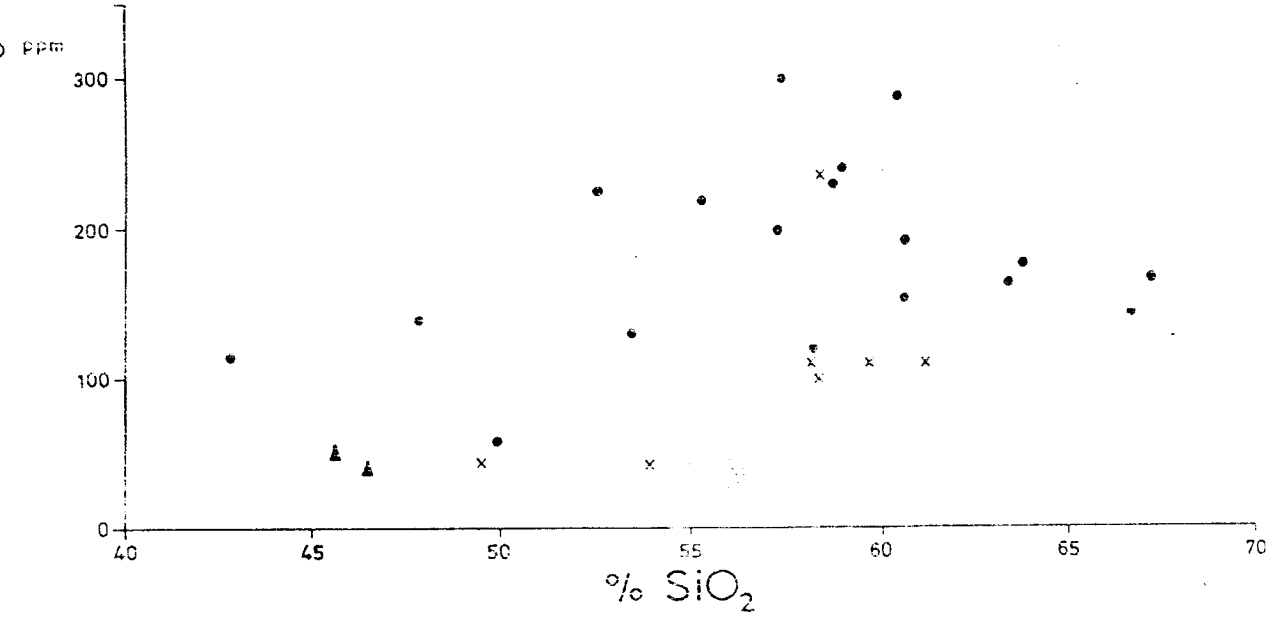
phase and will exert significant control on the trace element pattern because its distribution coefficient for rare-earth, Sr and Ba differs markedly from other common igneous rocks.



Trace element variations in the Mumbwa North Syenite

Fig. 10a





• Altered rocks
× Fresh rocks
▲ Apatite rocks

Fig. 10b Trace element variations in the Mumbwa North Syenite

The Mumbwa syenites in general exhibit a markedly coherent behaviour as manifested in the close clustering shown by Nb, Zr and Y, (fig. 10a) This coherence is absent in the case of Rb and Sr, (fig.10b) where two subgroupings are apparent.The fresh syenites are characterized by relatively high Sr and Ba which reflect cumulus plagioclase and alkali feldspar. This confirms the petrographic observation of cumulus felsic minerals.

Apatite rocks are characterized by high Nb, Y, Sr, (fig. 10a and 10b) high U and low Zr, Rb and absence of Th. The high field strength elements (Zr,Nb,Y) show a positive correlation with each other, increasing with higher SiO_2 content. These elements do not readily substitute for the major elements because of their relatively high ionic potentials, hence concentrate in the residual liquids (Taylor, 1965). There is evidence that apatite is residual during generation of granitic rocks in the lower crust (White and Chappel, 1977). Apatite is one of several minerals which strongly concentrate the rare-earth elements and strontium, relative to co-existing liquids (Henderson, 1980; Deer et al ,1962).

The apatite rocks contain high Y content because the Ca structural sites are 9 or 7 co-ordinated, the later probably affording the most suitable site for Y (Nash, 1972; Mc Connel, 1973 and Watson and Green, 1981).

Yttrium rejecting minerals include calcite, augitic clinopyroxene, plagioclase and kaersutite (amphibole). For

Calcite, it has been observed that, the Ca ion occupies a fairly regular octahedron and that trivalent ion substitution is effectively non-existent by reason of impossibility of valency balance (Lambert and Holland, 1974).

Plagioclase has cationic sites which are variously described as being of 7 or 8 co-ordination, the inter-ionic distances cover a considerable range but vary according to composition and temperature of structural equillibration of individual minerals. The significant factor governing yttrium in plagioclase appears to be the inability of the structure to accept trivalent ions.

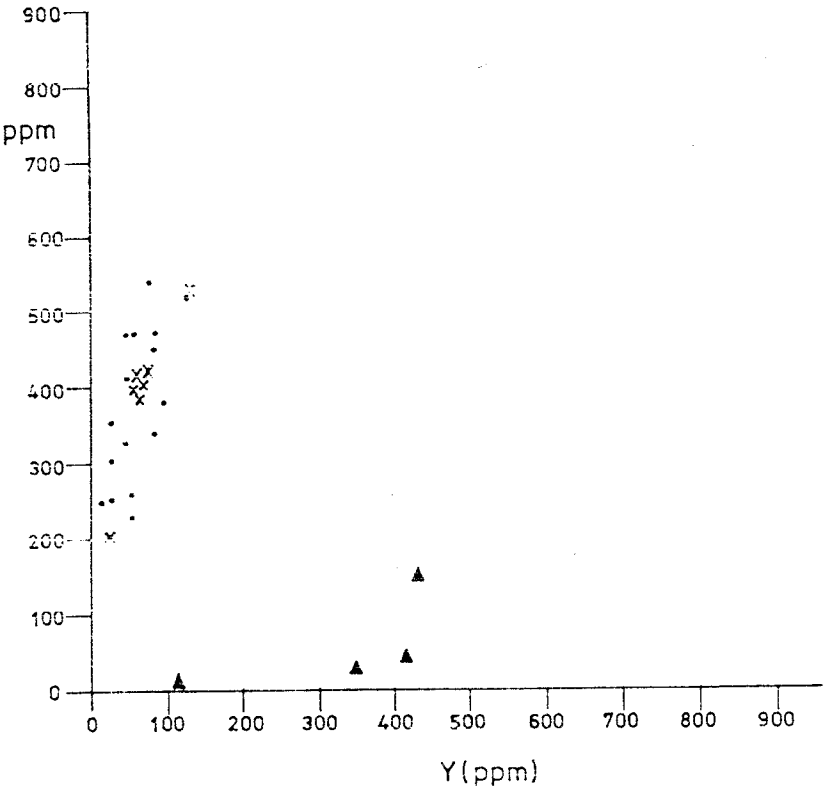
The list of yttrium acceptor Ca-minerals is comparatively long; hornblende, epidote, allanite, sphene, apatite and garnet. Among Ca-poor minerals K-feldspar, biotite, muscovite, riebeckite and aegirine-augite all contain enough yttrium. It has been shown above that yttrium is controlled in individual minerals by the details of physical dimensions of lattice sites and by electrostatic balance considerations between them accounting for the situation in most but not in all minerals.

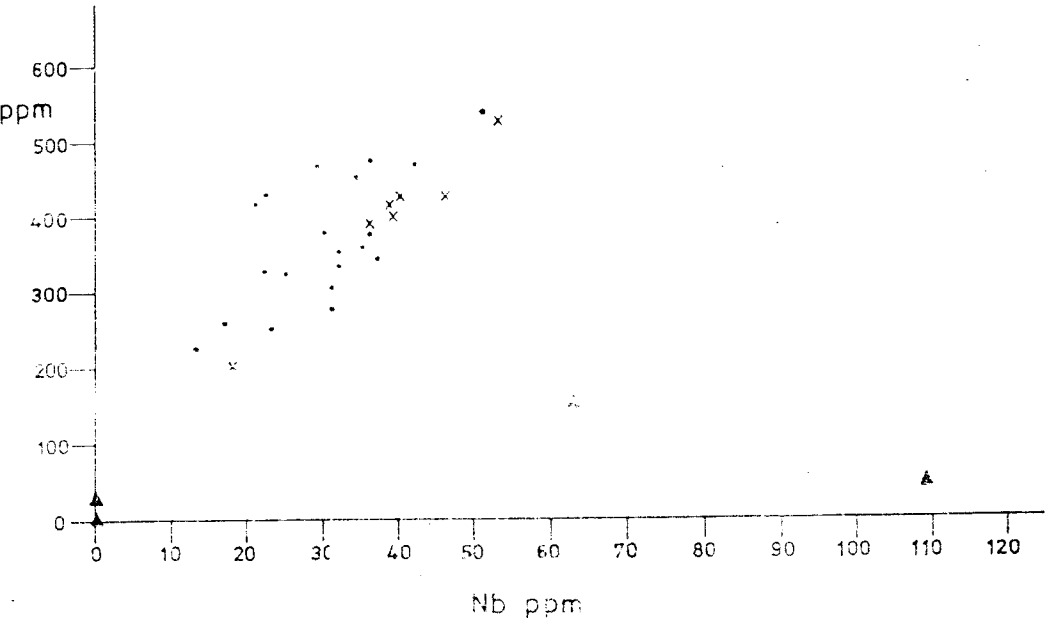
The Y^{3+} ion shows amphoteric behaviour in aqueous solution and it is to be expected that this kind of behaviour will extend into the silicate melt. It may be that the concentration of yttrium into pegmatitic fluids to the point where it precipitates in yttrium minerals may be due to decreasing pH of residual fluids as F^-, Cl^-, OH^- concentrations increase.

When trace element data are plotted against one another, assimilation data will define a straight line. The plots of Zr vs Y and Zr vs Nb are shown in (fig. 11a). However, other igneous processes such as partial melting and fractional crystallization can also result in approximately linear plots between pairs of trace elements. Plotting ratios is more diagnostic, but these usually show less variation and are sometimes subject to large analytical errors. Langmiur et al (1977b), have shown that plotting ratios for mixing models gives a hyperbolic curve. Testing the mixing model on the Mumbwa syenites using the Rb/Sr vs Zr/Y gives a feasible hyperbolic curve (fig. 11b). Chemical variation could be due to assimilation of metasediments by syenite leading to formation of calc-silicate.

High concentrations of Cu,Ni,Zn and low Pb have been observed at Sugar Loaf hill associated with the basic rock. The bivalent transition metal ions are extracted in order of Ni, Cu, Fe^{2+} and Zn according to octahedral site - preference energies in ferromagnesian minerals. The basic rock therefore might have introduced the bivalent transition metals.

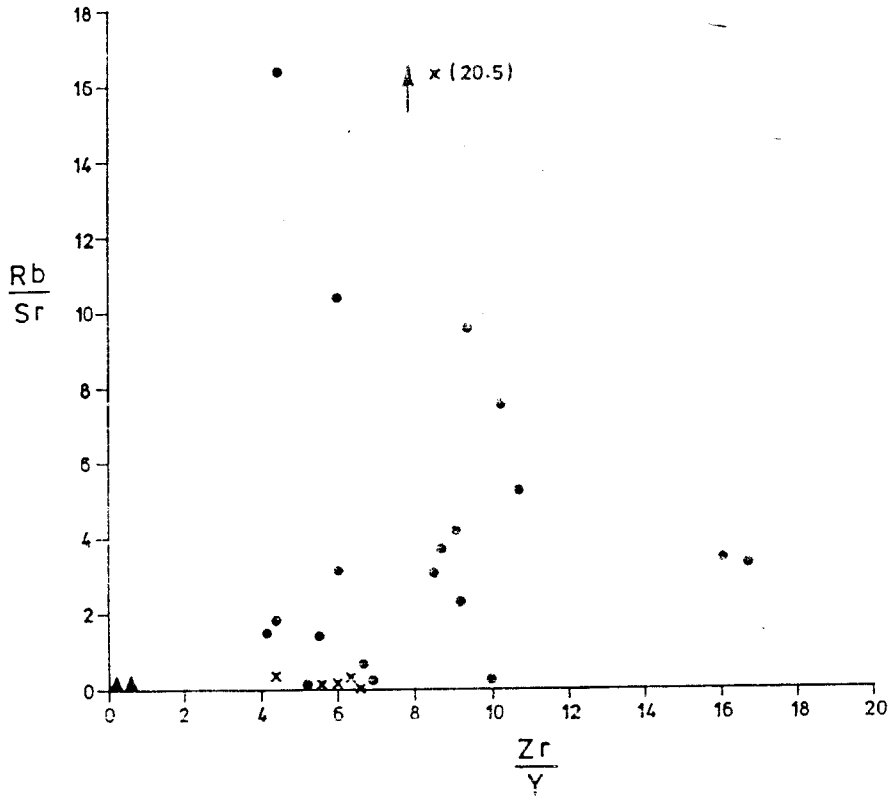
Uranium and thorium may be partly present as complex ions in alkali magma. They tend to concentrate in REE minerals (high Th/U ratios) and Zr minerals which favour the smaller U ion and





• Altered rocks
x Fresh rocks
▲ Apatite rocks

Fig. 11a Trace element variations in the Mumbwa North Syenite



Trace element variations in the Mumbwa North Syenite

Fig. 11b

have low Th/U ratios. Uranium and thorium increases rapidly with fractional crystallization in alkalic magma, perhaps less so in calc-alkaline series where early crystallization of apatite, zircon and sphene may extract them. All apatite rocks have high U and Cu content (Table 3.2, analyses 9, 10, 11 and 12). Thorium has not been detected. It is therefore concluded that radioactivity of apatite rocks is due to uranium.

5.8 TECTONIC SETTING

Trace element discrimination diagrams have been used as a means of classifying the tectonic setting of granitic rocks. Discrimination of ocean ridge granites (ORG), volcanic arc granites (VAG), within plate granite (WPG) and collision granite (COLG) based on the mineralogical and geochemical characteristics is most effective in Rb-Y-Nb space, particularly in projections of Nb-Y and Rb- (Y + Nb) (Pearce et al, 1984).

The elements chosen for tectonic discrimination of granites are those that behave incompatibly during fractionation of basaltic magma to acidic composition and most likely considered to be alteration independent. ORG - normalized geochemical patterns reveal systematic trace element differences between many tectonic groups. The most significant are high Y and REE in ORG and WPG; high Nb and Ta in many WPG and high Rb in syn-COLG.

In an attempt to classify the tectonic setting into which North West Mumbwa syenites were intruded, trace elements were plotted on the Nb-Y and Rb-(Y + Nb) discrimination diagrams.In the Nb-Y diagram (fig. 12a) the fresh rocks forms a cluster in the WPG field while altered rocks show a scatter in both WPG and V.A.G. fields. The scattering could be attributed to alteration since both Y and Nb are reduced during K-silicate alteration owing to dilution by added quartz. Separation between V.A.G, and WPG has not been achieved effectively by the Nb-Y discrimination diagram.

The Rb-(Y + Nb) discrimination diagram indicates that most of the altered rocks plot in the upper part of the WPG field and most of the fresh rocks plot in the middle part of WPG (figure 12b).This reflects the aparent Rb-enrichment which is a likely consequence of K-silicate and sericitic alteration due to the growth of secondary biotite and muscovite. Contamination due to assimilation particularly at the margins of intrusions could cause a WPG intrusion to be classified as VAG intrusion or Syn COLG. This is evidenced by the calc-silicate rock and a few others which plots in the VAG field (fig. 12a and 12b). The discrimination diagram in the Rb- (Y + Nb) space therefore achieved the separation of VAG and WPG.

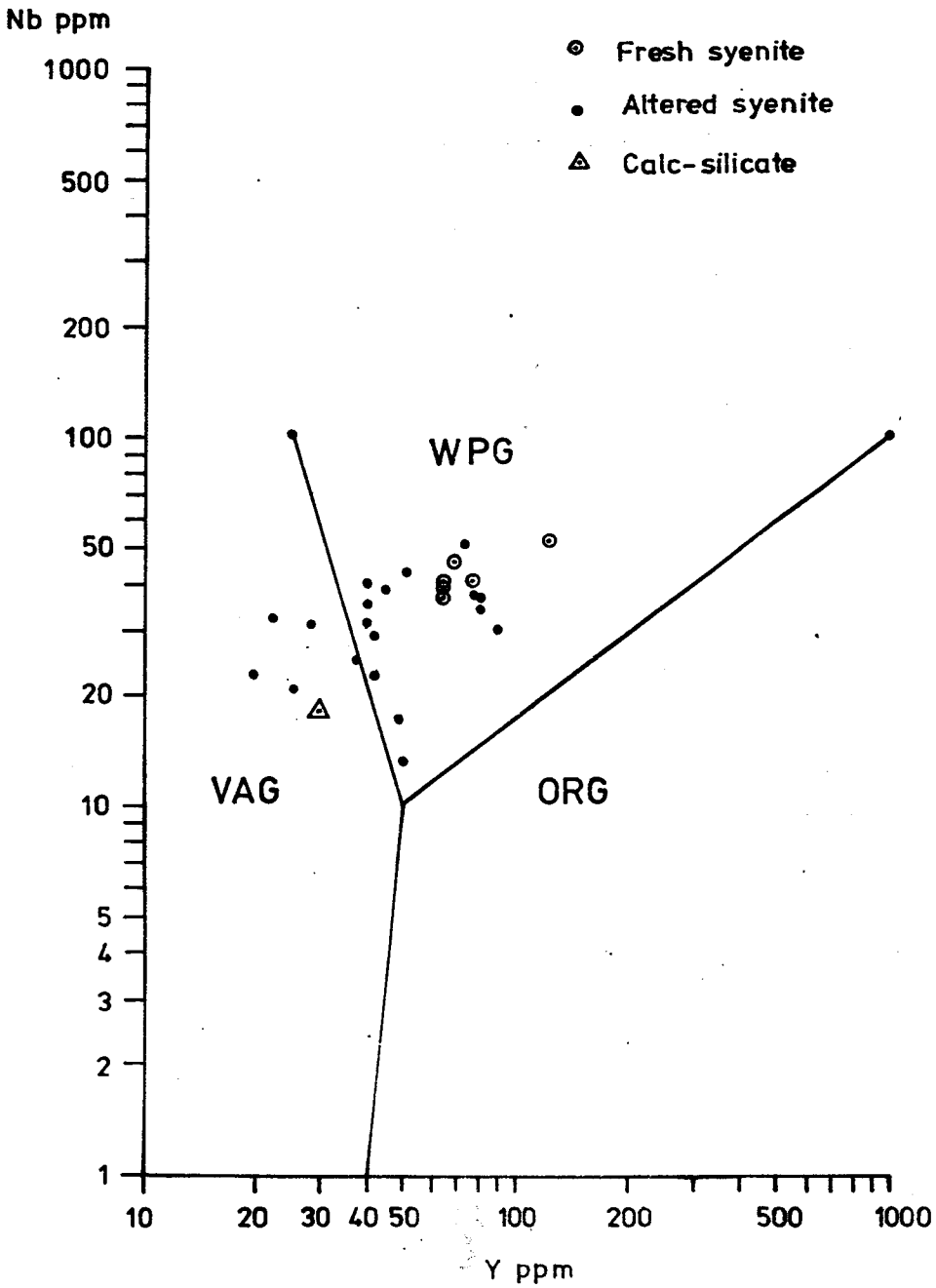


Fig.12a. Y – Nb discrimination diagram for Mumbwa Syenites
(after Pearce J.A. et al 1984)

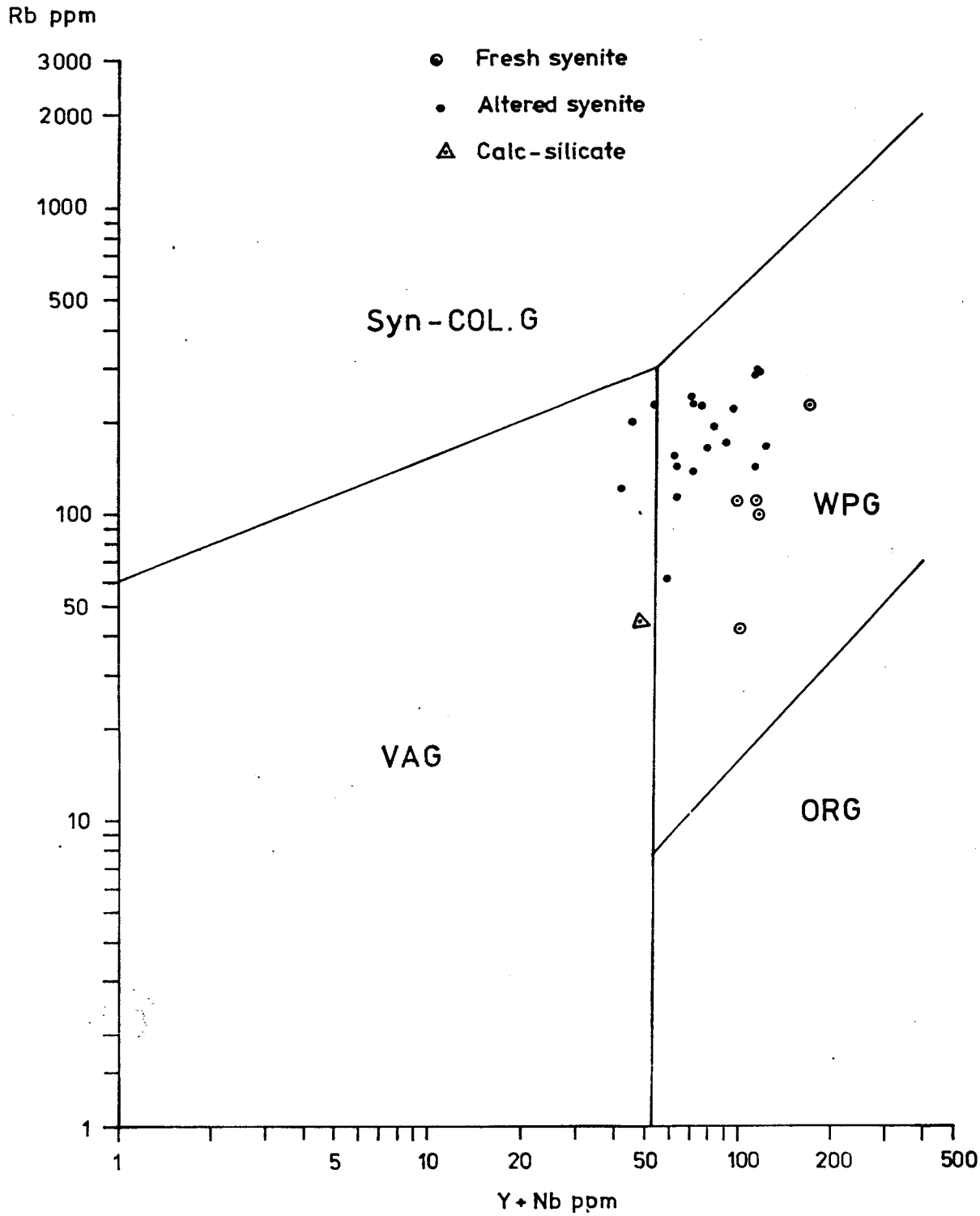


Fig.12b Rb-Y-Nb discrimination diagram for Mumbwa Syenites

(after Pearce J.A. et al 1984)

The observed discrimination diagrams can be explained by derivation of within plate granites from enriched mantle source with fractionation at the intermediate composition combined with assimilation. The North West Mumbwa syenites were intruded within plate granite, of the attenuated continental crust.

The volatite rich phase played an important role in distorting the patterns of micro and porphyritic rocks (Pearce **1et al**, 1984).

CHAPTER SIX

ORIGIN OF THE PHOSPHATE OCCURENCES

6.1 PHOSPHATE GEOCHEMISTRY

Phosphorus is a minor element widely distributed in the earth's crust which contains about 0.23 percent P_2O_5. Phosphorus, like aluminium, titanium and calcium, is fused from the mantle and concentrates mainly in basic and intermediate rocks (Beus, 1976). Most phosphorus occurs in minerals of the apatite group represented by the general formula $Ca_5(PO_4, CO_3, OH)_3$ (OH, F, Cl) with F, Cl and OH capable of mutual substitution to form an isomorphous series presented by pure end members fluorapatite, chlorapatite and hydroxyapatite. Hydroxy- fluorapatite, $Ca_5(PO_4)_3(OH, F)$, is the primary apatite mineral of most igneous deposits.

The structure of apatite is such that small amounts of VO_4^{3-}, AsO_4^{3-} and SO_4^{2-} substitute for PO_4^{3-}, and Na^{+}, Sr^{2+}, U^{2+}, Th^{4+} and the rare-earths (Lanthanides and Yttrium) may substitute for Ca in the apatite. The rare-earths form a solid solution in the structure of apatite.A comparison of silicate and phosphate mineral structure, along with description of anionic species in silicate melts indicates that phosphate and silicate anions have very similar structure in which both Si^{4+} and P^{5+} tetrahedrally coordinate oxygen (Ryerson and Hess, 1979).

This indicates that both the cations are capable of forming chain and ring structures. The major difference between these anionic species is that one of the four phosphate-oxygen bonds is a double bond which limits cross-linking of phosphate anions (fig. 13)

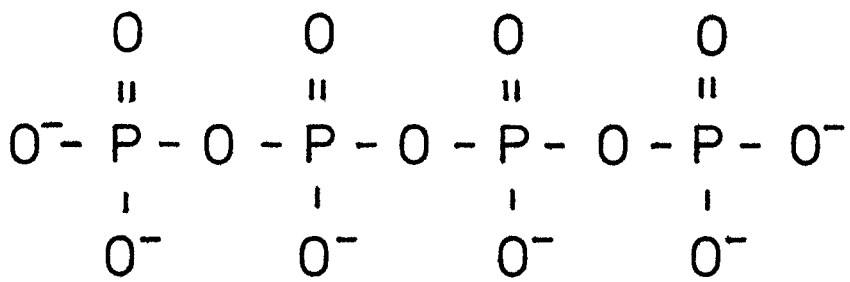


Fig. 13 Diagram of a chain of phosphate tetrahedra which indicate double bond. (After Ryerson and Hess, 1980).

Crystalline phosphates bear a close resemblance to crystalline silicates. The crystalline structure of the inorganic phosphates are based on the PO_4^{3-} tetrehedral group, which by sharing corners polymerizes to form chain, ring and sheet structures. The structure of metal-rich phosphates are very similar to those of neso-silicates and soro-silicate phases. Phosphate and silicate ions therefore have similar structure. Unlike silica, pure P_2O_5 does not form a strong cross-linked network structure but rather occurs as discrete molecules with very low melting point. Thus, the comparison of phosphate and silicate is justified only if the P_2O_5/MO ratio is not much greater than unity (Hess, 1980).

The similarity of cationic radii for Si^{4+} (0.42A°) and P^{5+} (0.35A°) indicate that these cations are capable of co-polymerization; P^{5+} substitutes for Si^{4+} in the silicate anion thereby enhancing stability of the melt (Koritnig, 1965). The decrease in activity of SiO_2 denoted by the pronounced freezing point depression of silica polymorphs, must be due to this substitution as well as the disruption of the network structure of silicate melt produced by the phosphorus - oxygen double bond (Hess, 1979).

6.2 CRYSTALLIZATION OF PHOSPHATES IN IGNEOUS ROCKS

During the crystallization of basaltic magmas, P_2O_5 is not incorporated in early precipitated crystalline phases. Therefore the P_2O_5 is enriched in late stage residual liquids in which it is eventually depleted due to crystallization of phosphate minerals. In this regard, P_2O_5 may play an important role in the geochemical evolution of late stage magmas, and in detailed understanding of basic magmas and the geochemical characteristics of mantle source regions (Watson, 1980; Ryerson and Hess, 1978).

Experimental studies on apatite and phosphorus in mantle source regions indicate that fluorapatite the most common igneous apatite mineral (Deer et al, 1966), is stable to conditions at least as high as 1350°C and 25 Kbar, so it could be present in unmelted regions of upper mantle (Watson, 1980; Beswick and

Carmichael, 1978). However, the solubility of apatite in basic magmas is so high that even a small degree of melting will result in its consumption; i.e. residual apatite in magma source regions is uncommon. Regarding the role of residual apatite in the mantle, Watson and Green (1981) noted that the apatite/basalt partitioning values chosen by Beswick and Carmichael (1978), and by Watson (1980), are considerably too high.

The onset of apatite crystallization in magmatic liquids depends systematically on three main factors; i.e. temperature, SiO_2 content and P_2O_5 content (Watson, 1979, 1980; Green and Watson, 1982). This systematic behaviour sufficiently shows that near liquidus, saturation in apatite is unavoidable in granitic magma, probable in andesites and possible but not common in basic magmas. There is evidence that apatite is residual during generation of granitic rocks in the lower crust (White and Chappel, 1977). The only circumstances that could promote apatite saturation in basic magma are:-

1. high P_2O_5 content attained either by extensive crystal fractionation or by extremely small degree of melting, and or

2. depression of the solidus by the presence of volatiles.

These factors are probably responsible for the occurrence of apatite phenocrysts in the K-rich basic lavas (Carmichael,

1967). Apatite will crystallize from magma when the chemical potential of the apatite component in the magma is equal to that of the apatite component in crystalline apatite. Hence, apatite saturation is a function of the activities of CaO, P_2O_5 in magma as well as the fugacities of CO_2, H_2O, Cl_2 and F_2 (Ryerson and Hess 1980).

The P_2O_5 solubility indicates that the activity coefficient of P_2O_5 and CaO is lower in non differentiated melts than in differentiated melts (Ryerson and Hess, 1975, 1978; Watson, 1976). Therefore for a constant P_2O_5 content, the activity of P_2O_5 is higher in a differentiated melt than in an undifferentiated melt. For a given activity of CaO and fugacities of H_2O, CO_2 Cl_2 and F_2, apatite is expected to crystallize from a differentiated siliceous melt, at lower P_2O_5 content than from a more SiO_2 - poor undifferentiated melt. Parental magma undersaturated in apatite like any basic magma,differentiates towards the syenite composition.The evolution of magma at this stage delayes the increase in silica content,therefore delayes apatite crystallisation so that the syenite becomes enriched in phosphate.

The difference in composition at which various liquids reach apatite saturation may have interesting effects upon the variations in incompatible element concentration that follow. On the basis of this model we could expect that apatite crystallization will have a much greater effect upon the trace element characteristics of suites which show SiO_2 enrichment .

This is because apatite saturation will occur earlier in the fractionation sequences of siliceous magmas and apatite concentrates REE and actinide elements to a greater extent in intermediate rocks. Frey et al (1980), concluded that the strong correlation of P_2O_5 and REE abundances does not imply that P_2O_5 and REE-rich magmas are derived from more refractory sources than the source of magmas with lower P_2O_5 and REE contents.

The relationship between the activity coefficient of P_2O_5 in the magma and the SiO_2 content also suggest that basic magmas can reach apatite saturation by assimilating siliceous country rocks (Ryerson and Hess 1979). The introduction of siliceous material will increase the number of bridging bonds in the melt, thereby increasing the activity of P_2O_5. Depending upon the amount of material assimilated and the proximity to the apatite saturation surface prior to its addition, the hybrid magma may become saturated in apatite without any enrichment in P_2O_5.

6.3 PHOSPHATE IN SURFACE ENVIRONMENT

Apatite is relatively insoluble in alkaline or neutral environments, and its solubility increases as acidity increases and temperature decreases. Although apatite may be residually concetrated in the first stages of weathering processes, it enventually breaks down and may be redeposited locally. In

limestone terranes, apatite is again formed, in igneous terranes, aluminium phosphate (variscite $AlPO_4.2H_2O$) and iron phosphate (strengite $FePO_4.2H_2O$) are formed; and in clay soils aluminium phosphate, wavellite $Al_3(PO_4)_2.(OH)_3-5H_2O$ and crandallite $CaAl_3(PO_4)_2.(OH)_5.H_2O$ are formed.

Phosphorus is carried to the sea as phosphate minerals adsorbed in iron or aluminium hydroxides or clays, or dissolved organic compounds, or in solution. The ocean is nearly saturated with phosphate, but the phosphate content is variable.

Deep cold water contains about 0.3 ppm PO_4 and warm surface water contains about 0.01 ppm. The solubility of phosphate in upwelling waters decreases as temperature and pH increase near surface, and apatite may then be precipitated by organic or inorganic processes. Phosphorites and the accompanying rocks in the environment of upwelling - black shale, chert and limestone are depositional products from seawaters that change in composition as a result of physical, chemical, and biologic processes.

6.4 ORIGIN OF NORTHWEST MUMBWA PHOSPHATES

6.4.1 Formation of apatite orebodies

Previous concepts on the origin and mode of occurrences of Copper and phosphate mineralisation at Sugar-Loaf, range from a possible carbonatite by Mineral Search of Africa (unpublished report), roots of a mineralised orebody (Brandt, 1955); a skarn type of deposit (Drysdall in Cikin, 1971); to a fragmented blocks of a previous vein network consisting essentially of pyrite and apatite with minor amounts of chalcopyrite (Searle, 1973).

According to Brandt, the primary sulphide veins were emplaced mostly at a higher level in the crust. In the course of steady erosion the volume of oxidized or enriched sulphide ore increased progressively at the expense of primary sulphide as the oxidation front moved downward. Where rich oxide ore rests on barren rock, as at Sugar-Loaf hill, it can be assumed that the whole of the primary deposit which existed at a higher level than the present land surface, has been eroded through to the bottom. Therefore Sugar-Loaf represents the supergene enrichment of a small primary sulphide deposit that no longer exists.

According to Searle, the sulphide and apatite mineralisation occur in detached, rootless and highly fragmented blocks within a brecciated and fragmented syenitic host. The close

association of apatite and sulphide suggests that before brecciation, they occupied a vein network in certain parts of the porphyritic syenite then during and immediately subsequent to the explosive phase, were highly shattered, fragmented, and displaced forcefully by the explosions to their present, rather scattered positions. The sulphide therefore is essentially confined to these fragmented blocks; the blocks, or group of blocks are separated from each other by barren breccia, and give rise to the prospects known as Sugar-Loaf and Lou-Lou.

As a result of recent investigations in the area, N.E Sugar-Loaf was discovered, where apatite mineralisation is represented by pegmatite bodies which occur as brecciated irregular, lenticular to plug-like structures. Quartz and iron-oxide is seen infilling the fractures. Individual apatite crystals in the core of the pegmatite measure upto several centimetres. In certain parts of the pegmatite light green copper staining is seen filling in the apatite fractures.

It is therefore suggested that mineralisation at Sugar-Loaf hill and Lou-Lou is similar to the occurrence at N.E Sugar-Loaf. The most characteristic features of the Mumbwa phosphates are: brecciation, apatite coarse texture, mineralogy and irregular mode of occurrence of apatite bodies in syenite. The only major difference is that N.E. Sugar-Loaf apatite ore body do not contain primary magnetite and was not affected by late stage sulphide mineralisation in terms of intensity in

comparison to Lou-Lou and Sugar-Loaf hill. The sulphides observed at all localities are of late stage, hydrothermally introduced into fractured pegmatites. The vertical structure of Sugarloaf ore body and horizontal structure of Lou-Lou mineralisation are both recorded at N. E. Sugar-Loaf. The pegmatites therefore appears to be structurally controlled locally.

Abundant apatite has been observed in the hornblende biotite syenite rock in drill hole DH UN 32 near Sugar-Loaf hill. Syenites in the area of study contain average 0.53 percent P_2O_5 (average of 6 samples) see colum 7. Average syenite contain 0.29 percent P_2O_5 (Cox et al,1979). It is evident that North West Mumbwa syenites contain higher P_2O_5 than average syenite. Crystal fractionation could have enhanced the formation of apatite in hornblende syenite. The apatite pegmatites in terms of provenance are considered to have been derived from residual and volatile rich syenite melt.

Primary phosphates with essential OH^- and F^- in their structures appears to be high temperature phases, whose refractory structures appears as traps for these volatile anionic fractions (Cerny, 1982).

6.4.2 Evolution of apatite bearing syenites

There are several different possibilities that could have led to high phosphate content in the North West Mumbwa syenites.

Firstly, magmatic evolution, leading to build up of phosphate content at the syenite stage of the composition of the magma. The parental magma undersaturated in apatite like any basic magma is differentiated towards the syenite composition. The evolution of the magma at this stage delays the increase in silica content, for reasons of physical and chemical conditions, therefore the delays apatite crystallisation, so that the syenite became enriched in phosphate. This crystallisation is delayed in more alkaline-volatile systems where $(PO_4)^{3-}$ complexes are more soluble (Bailey, 1979).

Secondly, high P_2O_5 in the source of magma. Little can be said about the high content of P_2O_5 in the source of magmas due to lack of data on the stability of apatite coexisting with basaltic melt in the upper mantle. However, mafic syenite magmas are considered to be derived by either fractional crystallisation from a more mafic source such as an alkaline basalt or by partial melting of an ultramafic source in the upper mantle (Wyllie, 1971).

Thirdly, assimilation of siliceous material. Basic magmas can reach apatite saturation by assimilating siliceous country rocks. The introduction of siliceous material will increase the number of bridging bonds in the melt, thereby increasing the activity of P_2O_5. Depending on the amount of material assimilated, magmas may become saturated in apatite without any enrichment in P_2O_5 (Ryerson and Hess, 1979).

There is little evidence that some assimilation took place locally in Mumbwa syenite. Hybrid rocks (calc-silicates) are found in the skarns of the syenites and these could have possibly formed by the assimilation of the country rocks by syenitic magma. Chemical variation diagrams of trace elements and their ratios seem to suggest assimilation of country rocks.

Neither of the three possibilities appears to be independent. It is therefore suggested that the evolution of magma and assimilation of country rocks are preferred as the possible means which led to high phosphate content in the North West Mumbwa syenites.

PART II

EXPLORATION AND ECONOMIC GEOLOGY OF THE PHOSPHATE OCCURRENCES

CHAPTER SEVEN

GEOCHEMICAL PROSPECTING

7.1 INTRODUCTION

Igneous phosphate deposits related to syenites have been discovered in the course of geochemical prospecting. Detailed geochemical and comprehensive geological investigations have been applied to locate phosphate mineralisation.

A stream sediment reconnaissance survey was undertaken in prospecting for phosphates in Chilembwe, eastern province of Zambia and was found useful in locating the source area of mineralisation (Mujogyatwoki, 1982).

In Mumbwa, where the drainage pattern is poor and sluggish, streams flow during the rain season only. Stream sediment sampling could not be conducted. The geochemical survey therefore relied on soil and rock sampling.The exploration methods and economic geology of the phosphate occurences are discussed.

7.2 SOIL SAMPLING

A soil survey success is based on the assumption that during the process of weathering and leaching,anomalous concentrations

of elements from underlying rocks or mineralisation may be incoporated in the overlying soils and other weathering products. Soils generally display a profile or layering, and the individual horizons differ from each other in mineralogy and trace element composition, so that varying results can be obtained by sampling different horizons.

There are many major factors which affect chemical weathering or soil formation. These include climate, vegetation, parent material, topography and time. All these factors have important implications for exploration geochemistry because they determine the secondary environment, the optimum horizon of sampling, the extent of secondary dispersion and the analytical method to be used.

In view of the outmost importance of secondary environments and soil sampling in exploration geochemistry it is necessary to stress that elements in soil profiles vary with depth, soil type and size of fraction. A detailed account of chemical weathering and chemical mobility in the secondary environment is given by Levinson (1974), and for secondary dispersion patterns by Hawkes and Webb (1962).

Soil geochemical investigations have been successfully utilized in outlining sedimentary phosphate deposits in northern and southern parts of Venezuela, characterized by tropical rain forests with heavy vegetation underlain by tertiary limestones and shales, covered by a thick soil with few outcrops

(Rodriquez, 1981).

The area under investigation is located morphologically in a flat terrain with scattered syenitic hills, sparsely and patchily forested with a very sluggish, indecisive drainage. Outcrops are rare particularly in flat areas and soil cover is thick. Superficial cobbles of ironstones and laterite are wide spread.

7.3 SAMPLING PROCEDURE

Traverse lines of approximately 4.0km long were cut at an interval of 100m apart. Soil samples were collected from the B horizon at depth of 30 - 50 cm. The soils are generally reddish-brown and clayey. The samples were dried, crushed in a mortar with a pestle and sieved through -80 mesh size then analysed for P_2O_5 by visual colorimetry method. The same soil samples were later analysed for other elements by spectrographic and Atomic Absorption Spectrometry methods.

7.4 ROCK SAMPLING

Rock surveys are based either on the analysis of a whole rock or individual minerals within the rock. Rocks are usually obtained from outcrops or from drill cores. On regional reconnaissance basis, rock surveys have great potential for outlining favourable geochemical (metallogenic) provinces and determining some geochemically diagnostic features that permit

the recognition of rocks which are associated with mineralisation and their distribution from barren ores.

7.5 SAMPLING PROCEDURE

In this investigation, detailed rock sampling was conducted during the routine detailed mapping along the grid lines. Rocks were collected approximately 50m apart depending on the availability of outcrops. More attention was paid to careful recognition of different rock types especially that, the rocks are highly altered, as this information was needed for proper correlation with analytical data.

The major objective of rock sampling in this study was to locate previously unknown apatite mineralisation and to determine the extension of known apatite occurrences. Rock samples were crushed, sieved through -80 mesh and analysed for P_2O_5 by visual colorimetry, for base-metals by Atomic Absorption Spectrometry and for 24 trace elements by complete spectrographic analysis.

Due to intense alteration some drill cores and rocks were analysed by X-ray fluorescence technique for both trace and major elements.

7.6 PRESENTATION OF RESULTS

7.6.1 LOU-LOU PROSPECT

a. Phosphate results in Soil

A total of 1911 soil samples were analysed for P_2O_5 by colorimetric method. The P_2O_5 results were plotted on a map of 1:10,000 (fig.14). The observed values in soil range from 0.10 to 1.20 percent P_2O_5, with a background value of 0.30 percent P_2O_5, and a threshold value of 0.50 percent P_2O_5. At Lou-Lou where apatite mineralisation is known to be present in outcrops, the observed value in soil is 0.65 perecent P_2O_5 and this value has been taken to be anomalous.

Most of the P_2O_5 high values appear to be closely associated with soils overlying the hematite gossans and lateritic rubbles.

b. Copper - Lead - Zinc and Silver in Soil

Soil samples were analysed by Atomic Absorption Spectrometer method for copper, lead, zinc and by spectographic method for silver. The results were plotted on the map of 1:10,000 (fig. 15).

Copper values range from 100 ppm to above 1000 ppm, with a

threshold of 300 ppm. Most of the copper anomalies are associated with gossans and/or ironstones, while some are associated with secondary dispersion halos concentrated in the northwestern part of the area (fig. 15).

Lead and Zinc values range from 10 ppm to 300 ppm Pb and 250 ppm Zn respectively. For both elements the value of 100 ppm was considered to be anomalous. Spectrographic analysis of soils revealed high concentrations of silver, ranging from 0.1 to more than 1.0 ppm Ag and the value of 0.5 ppm Ag was taken as anomalous in soils.

There exists an overlap of lead-zinc and silver anomalies north of Lou-Lou (fig. 15). These anomalies occur in a relatively flat terrain over a blanket of laterite which overlies the shale. Shale fragments are found in the laterite.

c. **Copper - Lead - Zinc in Rocks**

Rocks were collected over the Copper-Lead and Zinc soil anomalies. Copper values ranged from 10 ppm to 4,000 ppm. Most of these anomalies are associated with the gossans and ironstone cappings. Only values above 1000 ppm Cu and above 300 ppm Pb and Zinc were plotted (fig. 15).

7.6.2 SUGAR-LOAF PROSPECT

a. Phosphate results in Soil

A total of 1,599 soil samples were collected and analysed for P_2O_5 by visual colourimetry method. The values range from 0.10 to 3.50 percent P_2O_5. The background value of 0.30 percent P_2O_5 and threshold of 0.50 percent P_2O_5 were determined.

At Sugar-Loaf hill a locality where apatite mineralisation was first reported, the values range from 0.60 to 35 percent P_2O_5.The results are reported on the map (fig. 16) and the most prominent anomalous areas were delineated north and north-west of Sugar-Loaf. Two isolated anomalies north- east of Sugar-Loaf were identified with values of 1.20 and 2.70 percent P_2O_5 respectively. Scattered areas with P_2O_5 in the range of 0.50 - 0.70 percent occur south-west of Sugar-Loaf. The distribution of P_2O_5 in soils shows close association with ironstones.

b. Copper results in Soil

The most significant copper anomalies occur at Sugar-Loaf hill reaching up to 20,000 ppm. A broad low copper anomaly occurs north of Sugar-Loaf trending north-easterly (fig.17). Scattered copper anomalies occur north-west and south-west of Sugar-Loaf. Insignificant lead and silver anomalies occur in

the south west corner of the map (fig.17).

There exists a general overlap of P_2O_5 and Copper anomalies in soil samples in certain areas, at Sugar-Loaf and at Lou-Lou (fig.14 and 16). The overlap of P_2O_5 and copper could be attributed to the occurrence of secondary copper-phosphate minerals, notably the turquoise- chalcosiderite series.

7.7 PITTING OPERATIONS

Pits were dug to approximate depth of 3m at locations were P_2O_5 values in soil samples were anomalous at both Sugar-Loaf and Lou-Lou Prospects. Priority of pitting was given to areas with dense distribution of P_2O_5 rather than isolated anomalies. The pits were logged and channel sampled at an interval of 50cm.

The results of P_2O_5 in pits varies from 0.40 percent to 3.0 percent except for pit 2w/12.5S (fig.18 and 19) where the P_2O_5 attained a value of 8.0 percent. From the pits it is evident that the distribution of P_2O_5 is related to hematite veins e.g.(fig. 18 and 19). Pits 7W/3.0 N; 7W/4.0 N; 8W/0.5S and 3W/20.0S. The P_2O_5 anomalies in altered syenite, pit 2W/12.0S and 2W/12.5S (fig.19), can be attributed to the probable existence of small apatite veins which could not be mapped because of intense weathering.

7.8 TRENCHING OPERATIONS

Trenching was conducted north-east and north-west of Sugar-Loaf, a distance of approximately 1 - 1.5 km apart where rock sampling indicated phosphorus mineralisation. The trenches were logged and sampled. Results of phosphorus distribution in trenches are shown in (fig.20).

7.9 DRILLING AT SUGAR-LOAF HILL

Prior to diamond drilling at Sugar-Loaf hill, detailed surface rock sampling was conducted at on a Grid of 5 metres. An adit about 96 metres in length driven into the hill by previous workers was re-sampled and analysed for phosphorus. The results of the surface rock and adit samples are shown in (fig. 21 and 22). Rock sampling at Sugar-Loaf hill revealed high but variable phosphorus mineralisation with values up to 30 percent in the summit area. In the adit, the values range from 1.30 - 30 percent P_2O_5. The grade averages to 16.0 percent P_2O_5 for the inner 58 metres. From the rock sample results it is evident that phosphorus mineralisation trends in a north-east direction.

On the basis of these results, three drill-holes DDH No.1, DDH No. 2 and DDH No. 3 were sited and drilled in the NW direction normal to the mineralisation at an inclination of 60 degrees to a depth of 70 metres, 100 metres and 80 metres respectively. The distribution of phosphorus and copper in

core samples is shown (fig.23).

The drill holes gave P_2O_5 values range from less than 1 percent to 30 percent. The best results were in the middle hole (DDH No. 2) under the summit which gave an average of 14 percent P_2O_5. The other holes averaged 2-5 percent P_2O_5 in mineralised zones. From the results, it appears that there is a close correlation between copper and phosphorus suggesting a close mineral association.

Elsewhere in the area about 400 metres south west of Sugar-Loaf, close to drill-hole UN-32, DDH No.6 gave P_2O_5 grades in the range of 0-18 percent, with an average of 3.5 percent. The maximum depth drilled was 63.8 metres. Other drill holes namely DDH No. 4, DDH No. 5 and DDH No. 7 were barren of P_2O_5 mineralisation.

7.10 DISCUSSION AND CONCLUSIONS

The soil survey failed to locate any apatite-rich occurrence. This failure could be attributed to extremely low mobility and solubility of phosphorus in the environment and to the thickness of superficial material on the bedrock.

The observed distribution of phosphorus in pits near the surface and at shallow depths appears to be related to secondary surficial weathering processes that resulted in an enrichment of phosphorus which seems to be related to the rate

of erosion, superficial material and to topographic features.

Barbour (1973), in his study of phosphorus distribution in iron-ore deposits showed a relationship between weathering , alteration and the contents of phosphorus that appear to be related to fixation of phosphorus by surface reactions, adsorption and ion exchange which takes place on clay minerals developed by weathering of intrusives and on hydrated iron-oxide (goethite).

From the pits and trenches it is apparent that the bedrock surface is a paleo-erosion surface that has been stripped of the insitu material by erosion processes and re-covered by colluvium comprising clayey soil with granules and large cobbles of ironstone and trachytic rocks. This trachytic material probably slumped from ridges approximately 400 metres away where similar rocks are exposed. The colluvium reaches up to 3 metres thick and covers a wide area. On the basis of the exposures in the trenches it is also evident that the apatite rock is less weathered and altered than the apatite-free country rock and the two lithologies have sharp contacts.

On the basis of the drilling data at Sugar-Loaf hill it is apparent that the main intersections with greater than 5 percent P_2O_5 in DDH No.1 is 40 metres and 75 metres in DDH No. 2. The P_2O_5 in DDH No. 3 fluctuates with essentially no intersection with P_2O_5 greater than 5 percent that would be economically mineable. The first 20 metres in both drill holes

were almost barren.

It is therefore concluded that the limits of the Sugar-Loaf "Ore body" are not well established to warrant ore reserve estimation as some parametres are not known to achieve greater accuracy and confidence. It is recommended that more detailed drilling be carried out at closer spacing to accurately establish the ore-body, grade and cut-off grade.

Application of geochemical methods for phosphate prospecting in general can succeed only if the area is well drained and outcrop abundance is fairly distributed.

CHAPTER EIGHT

GEOPHYSICAL PROSPECTING

8.1 INTRODUCTION

The uneven distribution of outcrops puts a severe limitation on rock geochemistry as a means of outlining the areas with phosphate mineralisation. With these limitations in the geochemical methods, it was decided that geophysical methods might be of use, indirectly, in locating and outlining concealed phosphate mineralisation.

Radiometrics was an obvious choice with regard to geophysical methods. From a purely theoretical point of view, an igneous environment such as found in Mumbwa North area is favourable for the occurrence of rare-earth and uranyl phosphate which are radioactive. A reconnaissance survey with a scintillometer showed that all areas with known phosphate mineralisation gave rise to anomalous radioactivity.

8.2 RADIOMETRIC SURVEY

Radioactivity was measured using a scintrex gamma-ray spectrometer(Model GLS-5) in the total count mode (Muyovwe, 1987). Using a count time of 3 seconds, five readings were recorded at each sampling point. The average of these five

readings was taken as the total radioactivity count at the respective sampling point. A total of 16 605 reading were recorded during the survey on a Grid of 100 x 25 metres.

8.3 RESULTS

On a regional scale it is possible to discern three quite distinct zones on the basis of their levels of radioactivity; namely low background radioactivity, medium and high background radioactivity. The geological implications of these zones are not clear,because the low, medium and high radioactivity zones are respectively underlain by quartz-orthoclase porphyry, pseudo-trachytes, and a suite of porphyritic syenite, microsyenites and quartzites some of which are enriched in iron-oxides (specular heamatite)

On a local scale, the areas with known phosphate mineralisation show consistently high levels of radioactivity. There are, however some anomalies, which do not show any correlation with high P_2O_5 content in rocks. With such results, it became apparent that there was a need to try and distinguish the radioactivity anomalies indicative of P_2O_5 mineralisation from those not related to P_2O_5 mineralisation.

It was decided that by analysing for the abundances of K,U and Th over each of a chosen number of anomalies, a pattern might show up which could lead to the isolation of those anomalies indicative of phosphate mineralisation.

8.4 QUANTITATIVE ANALYSES OF THE ANOMALIES

About seventeen anomalies were chosen for the quantitative analysis. The gamma ray-spectrometer (G1S-5 model) was placed in contact with the ground at the peak of each of the anomalies and measurements of total count; K + U + Th, U + Th and Th counts were made using a three minute sampling interval. Five consecutive readings at each energy level were averaged to get the counts for every three seconds and hence, the counts per second. The background radioactivity was also measured in a similar manner. Tables 4, 5 and 6 show the measured radioactivity (anomalous; background and radioactivity corrected for background).

Table 4: Measured radioactivity at each sampling site for radiometric assaying

SITE NO	LOCATION	TOTAL COUNT C/S	K+U+Th C/S	U+Th C/S	Th C/S	REMARKS
1.	11E-10.5S	433.1	12.9	6.9	2.8	
2.	11E-11.0S	653.7	21.3	12.7	2.4	Apatite
3.	11E-16.25S	536.7	13.8	7.4	2.3	
4.	10E-11.0S	776.8	23.1	14.9	4.0	Apatite
5.	3E-15.0S	471.6	11.7	7.6	2.3	
6.	0 - 1.0S	542.1	14.0	7.7	2.2	
7.	4W- 7.5S	932.2	29.6	17.1	3.4	
8.	5W-13.75S	688.5	19.2	13.6	2.7	Apatite
9.	5W-19.5S	778.4	24.4	15.2	4.2	Apatite
10.	6W- 4.5S	545.8	12.5	6.6	1.5	
11.	6W-15.75S	1237.4	34.8	23.0	5.5	Apatite
12.	10W-11.25S	2027.3	39.1	20.3	1.7	Apatite
13.	10W-13.25S	925.7	17.8	9.7	2.3	
14.	11W- 9.0S	627.4	14.3	8.0	1.7	
15.	12W-14.75S	856.7	18.6	8.2	1.4	
16.	8W- 5N	1235.0	30.5	18.4	3.6	
17.	12E- 9.5S	546.5	16.3	9.3	2.9	Apatite

Table 5: Background radioactivity for radiometric assaying.

SITE NO.	LOCATION	TOTAL COUNT C/S	K+U+Th C/S	U+Th C/S	Th C/S	REMARKS
1.	11E-10.5S	325.5	7.1	6.0	1.8	
2.	11E-11.0S	405.2	10.4	6.5	2.1	Apatite
3.	11E-16.25S	325.5	7.1	6.0	1.8	
4.	10E-11.0S	405.2	10.4	6.5	2.1	Apatite
5.	3E-15.0S	405.2	10,4	6.5	2.1	
6.	0 - 1.0S	443.9	10.5	6.1	1.9	
7.	4W- 7.5S	394.0	9.9	5.7	1.9	
8.	5W-13.75S	437.7	13.4	8.5	2.0	Apatite
9.	5W-19.5S	388.9	9.5	6.7	1.8	Apatite
10.	6W- 4.5S	398.1	9.2	5.7	1.5	
11.	6W-15.75S	437.7	13.4	8.5	2.0	Apatite
12.	10W-11.25S	438.5	9.0	5.7	1.5	
13.	10W-13.25S	465.3	11.1	4.3	2.0	
14.	11W- 9.0S	438.5	9.0	5.7	1.5	
15.	12W-14.75S	465.3	11.1	4.3	2.0	
16.	8W- 5ON	427.3	10.6	6.9	1.5	
17.	12W- 9.5S	405.2	10.4	6.5	1.2	Apatite

Table 6: Radioactivity corrected for background.

SITE NO.	LOCATION	TOTAL COUNT C/S	K+U+Th C/S	U+Th C/S	Th C/S	REMARKS
1.	11E-10.5S	107.6	5.8	0.9	1.0	
2.	11E-11.0S	248.5	10.9	6.2	0.3	Apatite
3.	11E-16.25S	211.2	6.7	1.4	0.5	
4.	10E-11.0s	372.6	12.7	8.4	1.9	Apatite
5.	3E-15.0S	66.4	1.3	1.1	0.2	
6.	0 - 1.0S	98.2	3.5	1.6	0.2	
7.	4W- 7.5S	538.2	19.7	11.4	1.5	
8.	5W-13.75S	250.8	5.8	5.1	0.7	Apatite
9.	5W-19.5S	389.5	14.9	8.5	2.4	Apatite
10.	6W- 4.5S	147.7	3.3	0.9	0	
11.	6W-15.75S	799.7	21.4	14.5	3.5	Apatite
12.	10W-11.25S	1588.8	30.1	14.6	0.2	
13.	10W-13.25S	460.4	6.7	5.4	0.3	
14.	11W- 9.0S	188.9	5.3	2.3	0.2	
15.	12W-14.75S	391.4	7.5	3.9	0	
16.	8W- 5N	807.7	19.9	11.5	2.1	
17.	12E- 9.5S	141.3	5.9	2.8	0.8	Apatite

Data was analysed by C. Muyovwe, MINEX Department.

The results of the analysis show that phosphate mineralisation is characterized by either relatively low U and K, and high Th or high U and Th and low K. A detailed radiometric survey was conducted over an apatite orebody on a grid of 10 x 5 metres, with the aim of delineating concealed apatite orebodies. Very prominent anomalies were obtained which accurately delineated the apatite orebody (fig.24). Percussion drilling over these anomalies confirmed the existance of apatite. The minerals which give rise to the radioactivity are not known. It has been noticed that copper stained rocks are highly radioactive. In this case the presence of uranyl phosphates, such as torbenite - $Cu\ (UO_2)_2(PO_4)_2\ 8\text{-}12H_2O$) can be one of the possibilities. Monazite - (Ce, La, Th) PO_4 is another mineral which can be expected to occur with apatite pegmatite as observed from levels of Th in radiometric assays.

Trace elements results table 3.2 analyses 9,10,11,12, shows a coincidence of high U and Cu with P_2O_5 content,which confirms the presence of torbenite - $Cu(UO_2)(PO_4)_2nH_2O$.
Thorium concentration is high in syenites and is below detection limit in phosphates, suggesting that thorite or Monazite is responsible for radioactivity in syenite.

CHAPTER NINE

CHEMICAL CHARACTERISTIC OF MUMBWA PHOSPHATES

9.1 INTRODUCTION

Phosphate rock has many uses and nearly 90 percent of the total production is for fertilizer manufacture. Phosphate rocks vary widely in P_2O_5 content, reactivity, quality, and require different processing techniques. The production of various types of fertilizers has been characterized by the complexity of processes and each process, however, has certain advantages with respect to agronomic requirement and process economics. Assessment of the quality of phosphate rock for use as a fertilizer material must take account of several factors in addition to adequate phosphorus content. The amenability of a phosphate to beneficiation and its suitability for use as a fertilizer material depends on the constituents other than P_2O_5. The effects of some chemical quality factors of phosphate rock for production of fertilizer will be discussed, taking into consideration the chemical composition of Mumbwa phosphate in view of the overall evaluation of the economic potential of phosphate ore.

9.2 CHARACTERIZATION OF ORES

Preliminary investigations have shown that Mumbwa phosphates occur both as apatite and turquoise-chalcosiderite series, minerals of secondary origin (Vrana, 1972; Kuhnel, 1984).

The evaluations usually begin with a detailed mineralogical petrographic and chemical study of a representative sample of each ore type occurring in a deposit. The chemical and mineralogical studies indicate the principal constituents in the ore and their mode of occurrence. These data establish the phosphate grade of the ore and its chemical quality based on the non-phosphate constituent present.

Due to intense alteration of the Mumbwa phosphate rocks, the minerals are unidentifiable in hand specimen, but chemical analysis indicated high phosphorus content.It has been difficult to establish whether, the phosphorus observed in chemical analysis is associated with apatite or secondary phosphate minerals, prior to detailed petrographic studies. This presentation summarizes the rapid, preliminary method used to examine apatite containing ores.

The simplest, rapid and most effective approach was to calculate the coefficient of correlation in the available data sets of samples, according to Pearson product - moment coefficient of correlation given by (r) Haper (1971).

$$r = \frac{(xy - N\,\bar{x}\,\bar{y})}{N\sigma_x\,\sigma_y}$$

where:

N - Number of date for each compenent

x , y - components

σ_x , σ_y - standard deviations of x,y components.

$\bar{x}$, $\bar{y}$ - arithmetic mean of x, y components.

The primary objective here is to determine how certain key impurities are distributed between phosphorus and gangue mineral fractions, then deduce, some conclusions on the mineral paragenesis.

This evaluation has been applied to the phosphate rock samples to demonstrate how chemical quality factors can be rapidly estimated. From this, it is possible to determine the potential benefits of further upgrading by physical methods to improve the chemical quality of phosphate raw material. The results of the evaluation is shown in table 7.

Table 7:Coefficient of correlation for phosphates rock sample from Sugar Loaf Hill.

	Al_2O_3	CaO	MgO	P_2O_5	Cu	Fe	S
Al_2O_3	-	-0.5	-0.2	-0.5	0.3	-0.2	-0.2
CaO		-	-0.1	0.9	0.3	-0.1	0.3
MgO			-	0.2	-0.2	-0.3	0.0
P_2O_5				-	0.4	0.4	0.2
Cu					-	-0.1	0.5
Fe						-	-0.3
S							-

Statistical analysis of available data on the Mumbwa phosphates led to the following main conclusions:

1. There exists a significant perfect positive correlation between CaO and P_2O_5 of about 0.9. Therefore it may be assumed that most of the phosphorus is related to CaO in form of the mineral apatite - $Ca_5(PO_4)_3OH$.

2. The positive correlation of about 0.4 between P_2O_5 with Cu and Fe confirms the preliminary investigations on the occurrence of turquoise - $Cu(Fe)_6(PO_4)\ 4(OH)_8\ 5H_2O$.

3. The negative correlation of about 0.5 between CaO and Al_2O_3 may represent other gangue minerals such as feldspars, clays and secondary phosphate minerals.

4. The Positive correlation of 0.5 between Cu and S could represent the mineral chalcopyrite - $CuFe_2S$.

It has to be emphasised that these are assumptions deduced from statistical treatment of analytical data, because crystallochemical investigations have shown that, the structure of apatite seems to be remarkably stable, permitting a number of rather unusual types of substitutions involving a considerable number of ions (McConnell, 1973).

One drill core sample was sent to Sweden for chemical analysis and results are presented in table 8.

Table 8 Analysis of drill core from Sugar Loaf Hill DDH No. 2

(Depth Interval 91.50-92.70m)

	Wt%
P_2O_5	11.00
Al_2O_3	1.20
Fe_2O_3	48.00
MgO	2.60
CaO	13.80
SiO_2	8.80
CO_2	0.03
FeO	2.70
S	3.80
L.O.I.	4.50 (at 1000° C)
TOTAL	96.43
CaO/P_2O_5	1.25

Determinations carried out by MINPRO Laboratory.
Strassa - SWEDEN

The total composition of the analyses are not 100 percent becausethe drillcore contain sulphide minerals of Cu, Pb, Zn and Co. This is reflected in the high sulphur content.

In all phosphate rock types the sources of chemical impurities are isomorphous substitutions in the apatite structure (primarily divalent cations, carbon dioxide, and minor amounts of oxy-metal anions) and impurities derived from accessory minerals remaining in the ore.

In the production of wet-process phosphoric acid (W.P.A.) the CaO: P_2O_5 weight ratio ranks above all others in importance because of its major effect on process economics with regards to sulfuric acid consumption. (McClellan and Amitava, 1987). When the CaO: P_2O_5 weight ratio is significantly greater than 1.6, the sulfuric acid requirement may become uneconomical. The CaO: P_2O_5 weight ratio of the apatite mineral ranges from 1.31 up to 1.61 so that nearly total removal of all other Ca-bearing minerals by beneficiation may be required, and this may not be technically or economically feasible, particularly with carbonate type ores.

Phosphate concentrates with iron and aluminium above 2 - 3 percent are unattractive for phosphoric acid production since they decrease the plant capacity and often decrease the P_2O_5 recovery. An accepted (Fe_2O_3 + Al_2O_3): P_2O_5 ratio, by industry standards, is about 0.05 or less (Kouloheris, 1977).

An increase in magnesium content of the rock causes it to precipitate with aluminium and iron and blind the filter cloth. Magnesium also increases the scale formation in the concentration equipment. The desired (Fe_2O_3 + Al_2O_3 + MgO):

P_2O_5 ratio in the rock for WPA production is 0.1 or less, (Lawver **et al**, 1982). Filtration problems may arise from the presence of finely divided quartz or silica gel. Silica in the form of coarse, angular quartz grains acts as an abrasive that may erode plant equipment.

In the analysis carried out in Sweden, the CaO: P_2O_5 ratio is 1.25 suggesting that at least most of the P_2O_5 is in apatite (Jack, 1984). This confirms results of statistical analysis on the same rocks.

The iron content of the rocks is very high which confirms visual identification of hematite, magnetite and pyrite. As earlier mentioned in the phosphate rock for feed to a fertilizer plant, the ratio

$$(Fe_2O_3 + MgO + Al_2O_3) / P_2O_5$$

should not exceed 0.1. In this case, the ratio is 4.7. The analyses show that, the Mumbwa North phosphate at Sugar-Loaf hill would require substantial beneficiation to lower the Fe content.

CHAPTER TEN

SUMMARY AND CONCLUSIONS

As a result of geochemical, geological and geophysical investigations carried out in an area northwest of Mumbwa (Central Province, Zambia) a new type of igneous phosphate pegmatite was discovered with estimated reserves of 0.22×10^6 tonnes at 12 percent P_2O_5 (Mulela, 1988).
Phosphate mineralisation is found to occur in three forms in local concentrations within syenitic rocks:

(a) as apatite associated with copper and iron mineralisation of Sugar Loaf Hill.

(b) as apatite-bearing pegmatite bodies.

(c) as a series of copper phosphates in supergene concentrations.

The syenite occur in a mobile orogenic environment marginal to a granite batholith of late Pan African age and intrude the Precambrian metasediments assigned to the upper Katanga Supergroup. The metasediments of argillaceous-arenaceous facies rest conformably on the carbonate rocks. The grade of regional metamorphism varies from green-schist to amphibolite facies.

There is evidence of a differentiation sequence which ranges from mafic syenites characterised by augite, hornblende, biotite, alkali feldspar and plagioclase through leucocratic syenite devoid of mafic minerals to quartz-feldspar porphyry. The mineralogical variations and the presence of titanite (sphene),apatite and opaques in mafic rocks,indicate a relative increase in alkalis and volatiles content and oxygen pressure during crystallization processes. The common occurrence of apatite as large crystals and as inclusions in ferro-magnesian minerals suggests that some syenite magmas were saturated in P_2O_5. Apatite is completely lacking in the quartz-feldspar porphry indicating that the later magmas were no longer saturated in P_2O_5.

Feldspar exsolution textures represented by perthitic structures indicates the hypersolvus to subsolvus condition of syenite crystallization.

Alteration of primary minerals is common in syenites; calcite, epidote, sericite formed at the expenses of plagioclase. Hornblende pseudomorphs after an unidentified clinopyroxene indicates that the hornblende at least in part was formed by replacement of clinopyroxene.

The brecciation of some apatite crystals suggest that they were affected by tectonic activity after being emplaced into their present position and finally affected by hydrothermal

alteration. Hot springs associated with the Hook granite massif indicate that the area is still hydrothermally active. This view is also supported by a gravity low anomaly over the centre of the massif and the fact that the area is seismically active.

Phosphate mineralisation occurs in altered porphyritic syenite associated with sulphides and oxides. The apatite mineral is identified as hydroxylapatite $Ca_5(PO_4)_3$ OH. Pyrite and chalcopyrite are the common primary sulphide minerals. Other iron-bearing minerals include magnetite, hematite, specular hematite and goethite. The complex of secondary, copper-phosphate minerals belong to the turquoise-chalcosiderite series. Apatite-bearing pegmatites occur in highly altered porphyritic syenites as irregular bodies ranging from irregular wedged like lenses to plugs.Near the contact with the country rock the apatite is fine-grained and apparently represents the marginal zone of the apatite pegmatite. Veinlets of quartz and iron oxides are seen to cut through the apatite and form filling in fractures.

Trace element studies show that the phosphate rocks are characterised by high contents of Nb, Y, Sr and U; and low contents of Zr, Rb. There is little evidence that some assimilation took place locally in the syenite. Calc-silicate assemblages are found in skarns of the syenite and they could have possibly formed by the assimilation of the country rocks by syenitic magma.

The syenites are high-level intrusions having resulted from the differentiation of parental magma and assimilation of the country rocks which led to high phosphate content in the syenites. Tectonic setting has been classified as within plate granite (WPG) of the attenuated continental crust.

Apatite deposits within Zambia occur in syenite intrusion near Chilembwe in the Eastern Province, along the eastern margin of the Sinda batholith. The Chilembwe syenites have a anhydrous, high temperature mineralogy (augite, hornblende) which indicates deep level of origin through fractional crystallization (Tembo, 1986). The Mumbwa syenite are similar to those of Chilembwe, in that they occur in a mobile orogenic environment marginal to the granite batholith.

The association of iron ore, copper and apatite in syenitic rocks is known in several environments world wide. The nature and significance of this association is not clear. They seem chemically inappropriate as a source for important iron mineralisation, although the differentiated syenite sills of the Adirondack region, U.S.A. are evidence that iron ore may form as segregations from magmas that yield syenitic rock as their final products.

Moorehouse (1959) stated that syenite may form during hydrothermal or deuteric alteration of granites resulting in the elimination of most of the quartz (desilication) and its replacement by other minerals.

Magnetite mineralisation are found replacing syenites of the country rock adjacent to them. The most out standing example of the association is the Kiruna type deposits in northern Sweden composed of magnetite, apatite and actinolite and typically associated with intermediate composition plutons and Na_2O metasomatism. Mineralisation tend to occur above the roof of the magma bodies. This rules out an origin by iron-phosphate-silicate melt immiscibility as suggested by Philpotts (1967), because iron-phosphate melts are much denser than silicate melt. Instead are interpreted as products of high-temperature, chlorine-dominated fluids, generated during volatile exsolution (Hilderbrand, 1986).

In northern Ontario and Quebec in Canada, syenite porphyries form the host rock of gold ores, as in the Metachewan and Kirkland Lake area. Syenites also host copper mineralisation in western British Columbia. On the other hand syenitic pegmatites may contain either pegmatitic mineralisation, such as apatite, phlogopite, lithium-bearing minerals and radioactive minerals either within or adjacent to themselves.

For future phosphate exploration locally and regionally, the most favourable target areas would be post orogenic fractionated,alkaline, syenitic bodies at the margins of larger granite batholith and associated with deep seated faults. Such mobile, orogenic environment may perhaps provide zones of weakness, through which mantle magmas, generally of mildly

alkaline character, accessed the crust. Such magmas underwent fractionation and caused crustal melting to give rock types ranging from gabbro, through syenite to alkali feldspar granite.

Conventional geochemical exploration methods such as stream and the follow-up litho-geochemical survey, can be suitably employed for such deposits. The results of this project however suggest that soil surveys are unsuitable as a tool to indicate phosphate mineralisation. This is because of low mobility in secondary environment. Supplementary geophysical radiometric survey at close intervals would assist to delineate concealed apatite ore-body where such apatite mineralisation contain traces of radioactive elements provided the overburden is not too thick. This however is dependent upon the thickness of the overburden.

Finally it is hoped that this study will now assist in the recognition of possible targets for phosphate mineralisation in syenitic terrains.

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APPENDIX 1

DETERMINATION OF PHOSPHORUS IN SOILS, STREAM SEDIMENTS AND ROCKS BY VISUAL COLORIMETRY

INTRODUCTION

Most of the phosphorus minerals are readily attached by either fusion with alkalis or digestion with strong acid. For practical reasons, the phosphorus content in a sample is usually quoted as diphosphorus (P_2O_5), this being the important quantity in the fertilizer industry. From the analytical point of view, all phosphorus in the sample solution should be present as ortho-phosphate, PO_4^{3-}.The reason is that only ortho-phosphates form characteristic yellow precipitates with ammonium molybdate in acid solution which is used for determination, whereas chain (poly) and ring (meta-) phosphates do not show this behaviour. This means that chain and ring phosphates must be degraded by either fusion with alkalis or digestion with hot strong acid to ortho-phosphate.

Musatwe (1977), in his comparative study of the alkalis fusion and perchloric acid digestion methods in the determination of phosphorus came to the conclusion that, although the fusion method extracted ortho-phosphate more efficiently, the strong perchloric attack (with an efficiency of 92 percent) was preferred for fast routine geochemical analysis.

Analytical technique

Determination of phosphorus by colorimetric method was first proposed by Mission (1908). It depends on the reaction of ortho-phosphate with a mixture of vanadate and molybdate in acid solution. The yellow complex formed, presumably molydivanadophosphoric acid, provides the basis for colorimetric measurements.

The method described below for determination of phosphorus is based on colorimetric method given by Peachey et al (1973). It depends on the reaction of ortho-phosphate with a mixture of molybdate and vanadate in acid solution, to form a yellow phosphovanado-molydate complex, which provides the basis for phosphate determination. The method has been modified to meet field work requirements as well as the production rates by replacing the colorimeter measurements with visual comparison of the yellow colour with an adequately prepared standard series. Details on the reagents and procedure are given in appendix.

Discussion of the method and results

The method is semi-quantitative, fast, with a production of about 200 determinations per man shift. For quantitative phosphorus determinations, the yellow colour complex is intensified by extraction of the complex into methyl isobutylketone (MIBK) and the absorbance is measured on a

colorimeter. The method is relatively free from interference. It should be noted that the colour produced varies slightly with the acidity of the test solution. The pH-value therefore has to be controlled because it affects the colour development (Kitson and Mellon, 1944).

The results obtained by this method are fully acceptable in geochemical prospecting and agree closely with those obtained from outside laboratories. Kemira Oy, Finland, checked on 20 samples. The precision calculated by the method of Harworth and Thompson (1973) at the 2 precent P_2O_5 level and higher, is better than +15 percent at the 95 percent confidence level. The lower limit of detection is approximately 0.1 percent.

The rock samples re-assayed in Japan gave the following correlation coefficient and regression equation:

$$r = 0.98$$

$$y = 1.29\ x\ -0.59$$

$$v^2 = 4.45$$

where: r - the correlation coefficient
y - assay value obtained by this method
x - assay value obtained in Tokyo, Japan
v - unbiased estimation of covariance

The value of the method is in the direction of an exploration programme where quick and reasonably accurate results are

required, having the advantage of a high productivity and simplicity which makes it suitable even for field laboratories.

PROCEDURE

REAGENTS

Perchloric acid, $HClO_4$, concentrated (60%)

Nitric acid, HNO-3 concentrated

Ammonium vanadate, $NH_4\ VO_3$ Analar

Ammonium molybdate, $(NH_4)_6 Mo_7 O_{24}\ 4H_2O$

Dipotassium hydrogen phosphate, K_2HPO_4, Analar

PREPARATION OF REAGENTS

Nitric acid, 0.8M: Dilute 50ml HNO_3 to 1 litre with water.

Vanadate - molybdate reagent:

A. Dissolve 1.25 g ammonium vanadate (NH_4VO_3)

B. Dissolve 50 g ammonium molybdate

$(NH_4)_6\ MO_7O_{24}.4H_2O$

in 300ml of water combine solutions A and B, dilute to 1 litre with water and mix.

Standard phosphorus solutions:

stock, 1000mg/ml P_2O_5 Dissolve 2.45g

K_2HPO_4 500ml of water

Add 50ml of concentrated HNO_3 and dilute to 1 litre with

water.

Mix well before using.

Working standard solution; 100ml/ml P_2O_5 :

dilute 10ml of the stock solution to 100ml with 0.8M HNO_3 .

1. Weigh 0.1g of sample into a dry test tube, calibrated at 10ml.

2. Add 1 ml of acid mixture (1:1 HNO_3 - $HClO_4$) and digest on a sand bath for 1 hour.

3. Remove the tube from the sand bath, cool, dilute to 10ml with water and mix well leave to settle.

4. Transfer an aliquot of 1ml of the clear sample solution to a test tube calibrated at 5ml.

5. Make up to 5ml mark with metal free water.

6. Add 2ml of reagent solution, mix well for 30 seconds

7. After 15 minutes, compare the yellow developed with that of a simultaneously prepared standard series.

8. Calculate the phosphorus cancentration in the sample according to the formular:

   $\%P_2O_5$ = 0.001 g x Volume alkali x 100 divided by 0.5g.

using the relationship:

1ml of standard alkali solution = o.ool g P_2O_5

(=0.436 mgP) corresponding to.

23 moles of NaOH = 1 mole P.

where "Volume Akali" is the volume of a alkali solution used to dissolve the precipitate.

3. PREPARATION OF STANDARD SERIES

1. Transfer, respectively, 0, 0.3, 0.5, 1.0, 2.0, 3.0, 4.0ml of the working standard solution of 100mg/ml P_2O_5 to 7 test tubes calibrated at 5ml.
   This standard series will contain 0, 30, 50, 100, 200, 300 and 400 mg P_2O_5

2. Make up to the mark with 0.8m HNO_3

3. Add 2ml of reagent solution, mix well for 30 seconds

4. Leave for 15 minutes for the colour to develop.

These standard will correspond to the phosphate concentration in the samples as follows:-

0	Mg	P_2O_5	--	0.00%	P_2O_5
30	"	"	--	0.30	"
50	"	"	--	0.50	"
100	"	"	--	1.00	"
200	"	"	--	2.00	"
300	"	"	--	3.00	"
400	"	"	--	4.00	"

APPENDIX II

IDENTIFICATION OF APATITE BY X-RAY DIFFRACTION METHOD

X-ray Diffraction method was applied on three apatite rock samples to determine the X-ray Diffraction patterns. The instrument used was a Phillips P.W.14-10.X-ray Diffractometer with a Cu tube and a Ni filter. The operating conditions were at 40KV excitation potential and 28MA current.

PROCEDURE

The patterns were recorded on the diffractograms shown in this Appendix. After the patterns of the unknown samples were prepared, the spacing - "d" corresponding to each peak on the pattern was obtained from tables which give "d" spacing as a function of 2 various characteristic wavelengths. On a diffractometer recording, the intensity is taken as maximum intensity measured peak above the background.

An identification procedure is by examining the Mineral Power Diffraction File Search Mannual (1980), using the strongest reflection to locate the Hanawalt group in the Hanawalt Search Mannual. The second strongest reflection was used to locate the position within the Hanawalt group. Since a preliminary identification was achieved, then the experimental pattern was compared with all "d" spacings and relative intensities on the

Mineral Power Diffraction File-Data Book (1980). Variations in "d" spacing in range of $\pm$ 1% were considered.

On File No.9-432 reproduced there is a good agreement in the d_1, d_2, d_3 and d_4 corresponding to 2.814, 2.778, 2.712 and 3.44 respectively. (see X-ray charts)

From the X-ray Diffractometer analysis the apatite from Northwest of Mumbwa has been identified as a Calcium phosphate hydroxide - $Ca_5(PO_4)_3 . OH$. Other minerals such as hematite, quartz and feldspar were identified.

d	2.81	2.78	2.72	8.17
I/I_1	100	60	60	11

$CA_5(PO_4)_3$ 1/2$[CA(OH)_2 \cdot 3CA_3(PO_4)_2]$
CALCIUM PHOPHATE HYDROXIDE (HYDROXYL-APATITE)

Rad. $CuKa_1$ 1.5405 Filter Dia. 114.6MM
Cutoff 50 I/I_1 PHOTOMETER (GUINIER CAMERA)
Ref.DEWOLFF, TECHN.PHYS,DIENST,DELFT HOLLAND

Sys. HEXAGONAL S.G. ($P6_3/M$ (176)
a_o 9.418 b_o c_o 6.884 A CO.7309
a B r Z2 Dx 3.16
Ref. IBID

a nwB Sign
2V D 3.08 mp color
Ref.

I/I_1 ARE PEAK VALUES FROM A PATTERN WHICH SHOWS SLIGHT BROADENING OF PRISM REFLECTIONS. INDICATED BY HODGE C.S., IND. ENG. CHEM. ANAL. ED. 10156 (1938)

dA	I/I_1	hkl	dA	I/Ib_1	hkl
8.17	12	100	2.040	2	400
5.26	6	101	2.000	6	203
4.72	4	110	1.943	30	222
4.07	10	200	1.890	16	312
3.88	10	111	1.871	6	320
3.51	2	20	1.841	40	213
3.44	40	002	1.806	20	321
3.17	12	102	1.750	12	410
3.08	18	210	1.754	16	402,303
2.184	100	211	1.722	20	004,411
2.778	60	112	1.684	4	104
2.720	60	300	1.644	10	322,223
2.631	25	202	1.611	8	313
2.528	6	301	1.587	4	501,204
2.296	8	212	1.542	6	420
2.262	20	310	1.530	6	331
2.228	2	221	1.503	10	214,421
2.148	10	311	1.474	12	502
2.134	4	302	1.465	4	510
2.065	8	113	PLUS	ADDITIONAL	LINES

Adopted from: Selected powder diffraction data for minerals
Data book First Edition, 1974

APPENDIX III

DEFINITIONS OF TERMS AND NOMENCLATURES

Apatite - is a calcium phosphate minerals of the apatite group. Members of this group are represeted by the general formula $Ca_5(PO_4, CO_3 OH_3)$ (OH, F, Cl) with F, Cl and OH, capable of mutual substitution to form an isomorphous series represented by pure end members. Fluorapatite, chlorapatite and hydroxyapatite.

Phosphate - is a mineral compound. Characterized by a tetrahedral ionic group of phosphate and oxygen, $(PO_4)^{-3}$.

Phosphate rock - is defined as any rock (igneous, metamorphic or sedimentary) that contains one or more phosphatic minerals of sufficient purity and quantity to permit its commercial use as a source of phosphatic compound or elemental phosphorus. The term is normally applied to rock containing more than 20 percent P_2O_5, on an economic basis.

Sphene (Titanite) - $CaTiSiO_4$ (O, OH, F) A common accessory mineral of granitic rocks. Occurs in abundance in Zr, Ti, Nb rich alkali syenite and their pegmatites.

Scapolite - A group of minerals intermediate in composition

between marialite and meionite isomorphous series and resembles feldspar when massive but having a fibrous appearance. Scapolite minerals characteristically occur in calcium-rich metamorphic rocks (associated with impure limestone) or in igneous rocks as a product of alteration of calcic plagioclase.

Hornblende - is a member of the calcic, clino-amphibole group in which the standard composition contains $(Ca + Na)_B > 1.34$ and $Na < 0.67$.

Tourmaline - A complex boron - aluminum silicate of sodium and iron. It is a typical mineral of granite pegmatites and pneumatolytic veins and is a common product of boron metasomatism in metamorphic rocks.

Leucoxene - A general term for fine grained, opaque, alteration of ilmenite or titano-magnetite.

Chert (Flint) - A cryptocrystalline variety of quartz.

Specularite (Specular hematite) - A grey metallic variety of hematite.