

THE AMPHIBOLITE AT CHIBULUMA MINE

ZAMBIA

by

I. D. THOMSON B.Sc. (HONS)

Dissertation submitted for the degree of  
Master of Science at Rhodes University,  
Grahamstown.

January 1969

## A B S T R A C T

Chibuluma Mine is situated on the southern flank of the Nkana-Chambishi basin in the central section of the Zambian Copperbelt. The amphibolite at Chibuluma Mine occurs exclusively in the Upper Roan Group sediments overlying the economically important Lower Roan Group.

The amphibolite occurs in lenticular, sill-like bodies ranging in thickness from less than 10 feet to over 1,000 feet. It is concluded that these sill-like bodies are intrusive sills of basic magma. The largest sill is a multiple intrusion with two phases, both of which exhibit chilled margins. The younger phase was intruded into the older along a plane approximately 50 feet above its basal contact. Grain-size, specific gravity, and micrometric data indicate that each phase of the intrusion has undergone gravitational differentiation during crystallisation. Variations in the relative amounts of amphibole and feldspar distinguish between a lower melanocratic amphibolite, an upper mesotype amphibolite, and a zone of coarse-grained pegmatitic amphibolite schlieren.

The amphibolite consists mainly of hornblende, labradorite, albite, and scapolite, with accessory biotite, chlorite, epidote, clinozoisite, sphene, apatite, quartz, micropegmatite, and calcite. Clouding of the basic plagioclase and zoning in amphibole, plagioclase, and scapolite are features of petrological significance. The opaque minerals in the amphibolites and the adjacent sediments are magnetite, ilmenite, pyrite, chalcopyrite, pyrrhotite, cubanite, valleriite, and pentlandite. Intergrowths of these suggest that their temperatures of formation were probably in excess of 450°C.

The chemical data show a close resemblance between the amphibolite and a tholeiitic magma-type although minor spilitic characteristics are also evident. The chemical data also confirm the mineralogical evidence of fractionation and gravitational differentiation. The trend in differentiation followed in the development of the pegmatitic and mesotype amphibolite is very similar to the trends followed by other basic intrusions. The main metamorphic affect accompanying the intrusion of the amphibolite is the soda metasomatism evident in both sediments and intrusions. Some evidence exists to suggest that the amphibolites were emplaced before or during the early stages of the Lufilian orogeny when sediments were essentially horizontal.

CONTENTS

	<u>Page</u>
ABSTRACT . . . . .	i
CONTENTS . . . . .	ii
ACKNOWLEDGMENTS . . . . .	v
INTRODUCTION . . . . .	1
LOCATION OF CHIBULUMA MINE . . . . .	3
HISTORY OF EXPLORATION . . . . .	3
GEOLOGY OF CHIBULUMA . . . . .	5
STRATIGRAPHY . . . . .	6
Description of Individual Formations . . . . .	7
The Basement . . . . .	7
Katanga System . . . . .	7
STRUCTURE . . . . .	13
GEOMORPHOLOGY AND TOPOGRAPHY . . . . .	14
DISTRIBUTION OF GABBRO AND AMPHIBOLITE . . . . .	16
Copperbelt Distribution . . . . .	16
Chibuluma Distribution . . . . .	17
FORM AND STRUCTURAL RELATIONS OF THE AMPHIBOLITE BODIES . . . . .	18
The Major Amphibolite Body . . . . .	18
The Major Amphibolite Bodies . . . . .	22
A Note on the Location and Labelling of Drillholes and Structural Sections of Chibuluma Mine . . . . .	25
A Note on the Construction of the Geological Plan . . . . .	25
PETROGRAPHY . . . . .	28
GRAIN SIZE . . . . .	31
SPECIFIC GRAVITY . . . . .	34
MICROMETRIC DATA . . . . .	38
MINERALOGICAL CLASSIFICATION . . . . .	41
MELANOCRATIC AMPHIBOLITE . . . . .	42

	<u>Page</u>
MESOTYPE AMPHIBOLITE . . . . .	44
PEGMATITIC AMPHIBOLITE . . . . .	46
STRUCTURAL FEATURES . . . . .	51
Jointing . . . . .	51
Crystal Orientation along the Contacts . . . . .	53
MINERALOGY . . . . .	56
NON-OPAQUE MINERALS . . . . .	56
AMPHIBOLE . . . . .	56
FELDSPAR . . . . .	69
Lime Soda Plagioclase . . . . .	70
Soda Plagioclase . . . . .	80
Potash Feldspar . . . . .	83
MICROPEGMATITE . . . . .	84
SCAPOLITE . . . . .	85
EPIDOTE AND CLINOZOISITE . . . . .	92
MICAS . . . . .	96
Biotite . . . . .	96
CHLORITE . . . . .	98
SPHENE . . . . .	99
APATITE . . . . .	100
ZIRCON . . . . .	100
QUARTZ . . . . .	100
CARBONATES . . . . .	101
GYPSUM AND ANHYDRITE . . . . .	101
THE OPAQUE MINERALS . . . . .	102
OPAQUE MINERALS IN THE AMPHIBOLITE . . . . .	103
OXIDES . . . . .	103
ILMENITE . . . . .	103
MAGNETITE . . . . .	104
HAEMATITE AND SPECULARITE . . . . .	106
RUTILE . . . . .	106

	<u>Page</u>
SULPHIDES . . . . .	106
PYRITE .. . . .	106
CHALCOPYRITE .. . . .	107
PYRRHOTITE AND PENTLANDITE . . . . .	107
OPAQUE MINERALS IN THE SEDIMENTS . . . . .	112
In the Contact Zone . . . . .	112
In Carbonate Veins .. . . .	114
In Dolomite . . . . .	117
In Lower Roan Quartzites .. . . .	122
PETROLOGY .. . . .	123
CHEMICAL DATA . . . . .	123
Complete Rock Analyses . . . . .	123
Partial Rock Analyses . . . . .	124
Geochemical Testing . . . . .	124
THE MAGMA-TYPE . . . . .	125
DIFFERENTIATION . . . . .	128
THE ORIGIN OF THE AMPHIBOLITE . . . . .	134
METAMORPHISM AND METASOMATISM . . . . .	137
General Contact Features . . . . .	137
Soda Metasomatism . . . . .	137
Lime Metasomatism . . . . .	141
Metasomatic Affects on the Lower Roan Group . . . . .	141
Development of Asbestiform Serpentine . . . . .	142
Evidence of Metamorphism in the Opaque Minerals . . . . .	144
AGE OF INTRUSION . . . . .	145
SUMMARY OF CONCLUSIONS . . . . .	151
REFERENCES . . . . .	152
Results of Partial Rock Analyses	Appendix A.

## ACKNOWLEDGEMENTS

I thank Professor E.D. Mountain, Head of the Geology Department of Rhodes University for his interest and encouragement since he first suggested that the Chibuluma amphibolite offered a suitable subject for research.

I thank Mr. W.G. Garlick, Consulting Geologist for Roan Selection Trust Limited, for his encouragement, particularly in getting this research project under way, and for his subsequent suggestions and constructive criticisms of the manuscript.

I am particularly indebted to Dr. H.V. Eales of the Geology Department of Rhodes University for the sustained interest he has shown and the encouragement and guidance he has offered throughout this research project. Many of the views expressed in this thesis have developed from suggestions made by Dr. Eales. I also thank Dr. Eales for the help he has given me in research techniques.

I thank the managements of Mufulira Copper Mines Limited - Chibuluma Division and Roan Selection Trust Technical Services Limited for their permission to undertake this research and for the unrestricted use of technical equipment made available by their personnel. In the latter connection I would particularly like to thank Mr. O. Winfield, Chief Geologist of Chibuluma Division, and Mr. M.W. Ellis, Exploration Superintendent, and Mr. R.H. Lamb, Superintendent of Research and Development, of RST Technical Services. I am very grateful for the interest shown by Dr. J.A. McGregor and for his numerous suggestions as to possible avenues of research to be followed.

I thank Messrs. C.B. Anderson, T.C. Chisholm, D. Muirhead and L. Walker, post graduate students at Rhodes University, for their analyses of the amphibolite.

The developing and printing of the photomicrographs and preparation of the drawings are considerable tasks, and I gratefully acknowledge the help given to me in these fields by Mrs. I. van der Poll, Messrs. A. Paverd, A.H. Mills, G. Garlick, W. Olivier, and A. MacLeod. Dr. H.C. Meyer took the photograph reproduced in Plate 34.

I am particularly indebted to Mrs. B. Grobler and Mrs. J. Wainwright for their very generous assistance in typing the manuscript.

Finally, I must thank my wife for her considerable help, encouragement, and patience throughout the undertaking of this research.

## INTRODUCTION

Widespread occurrences of basic hypabyssal rocks in and west of the Zambian Copperbelt have been described and discussed by many authors since the discovery of the copper deposits. The problems related to these rocks, namely those of their age and origin, their contact phenomena, and their possible role in ore genesis, remain subjects of controversy and interest among geologists.

Prominent among early authors is Jackson who, in 1932, described in detail the gabbros, norites, olivine norites, and scapolitised amphibolites of the Nchanga district. Hall (1958 and 1963) and McGregor (1964) are among the writers who have discussed the gabbro problems in recent years.

The term "gabbro" has been used on the Copperbelt to describe a number of basic rock types, varying from rare olivine norites to granophyres and amphibolites. The predominant "gabbro" occurring at Chibuluma and over a large part of the Copperbelt is a scapolitised amphibolite (Mendelsohn, 1961, p. 51), which is generally considered to be of igneous origin. A number of geologists, however, consider that the amphibolites are possibly metamorphosed sediments. In this thesis the writer has, therefore, attempted to view all data obtained during the investigation objectively, but for consistency, the nomenclature of igneous petrology has been used in describing these rocks.

The writer has had the opportunity to study the amphibolite bodies of Chibuluma Mine since mid-1963, while employed by Rhodesian Selection Trust Mine Services Limited, and later by Chibuluma Mines Limited. He considers that the amphibolite bodies of Chibuluma Mine are particularly suitable for the study of these rock types for the following reasons:-

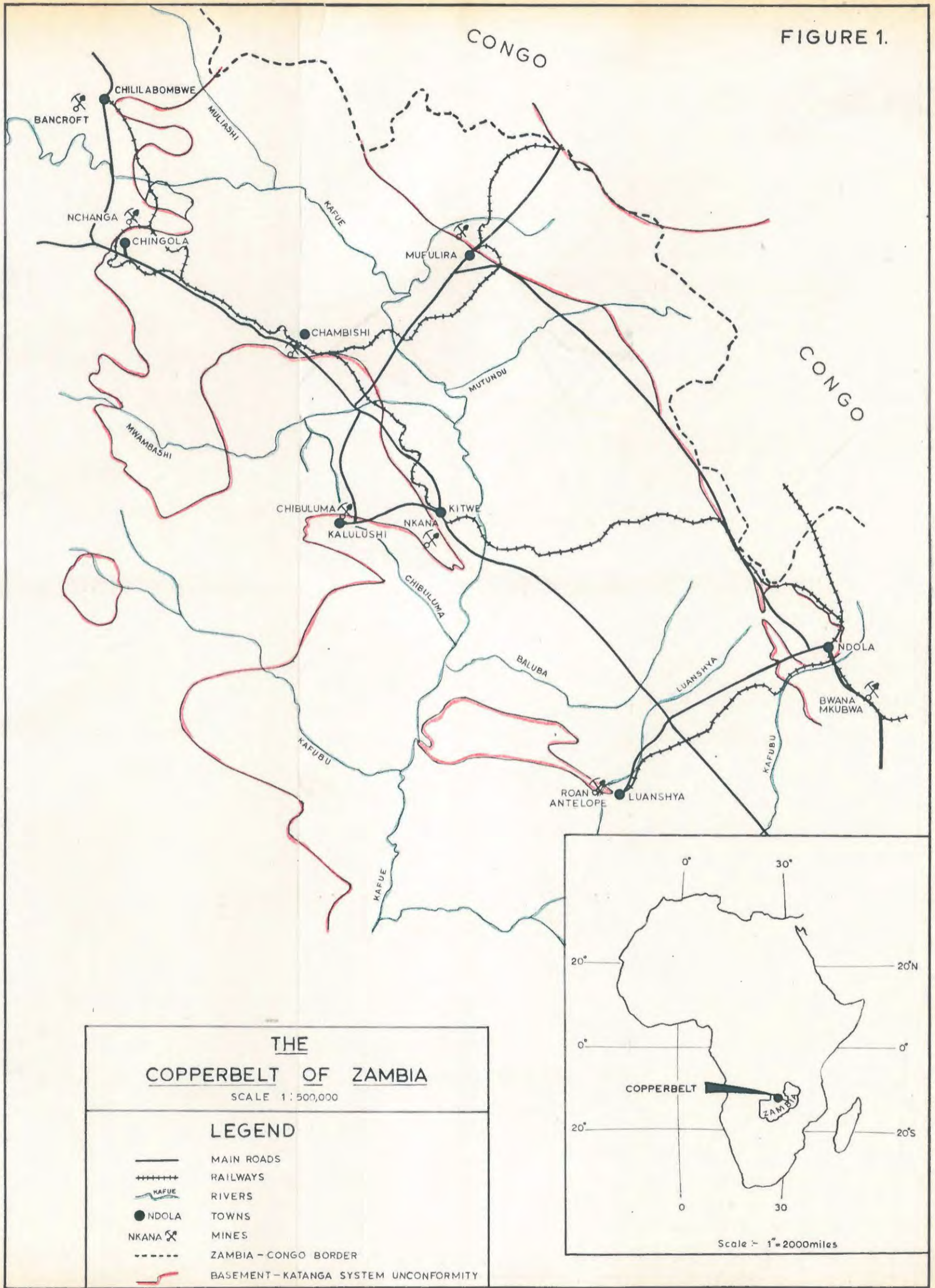
- (a) at least four sill-like amphibolite bodies exist in the formations overlying the Chibuluma orebody. These bodies occur adjacent to several different sedimentary and metamorphic rock types and, therefore, could be expected to exhibit a variety of contact phenomena;
- (b) there is a considerable range in thickness shown by the four sills. One sill is in places less than 10 feet thick, whereas another is over 1,000 feet thick. At the start of this investigation, it was considered that the thick sill, if of igneous origin, would display the more characteristic igneous textures, and because of its bulk and probable slower rate of cooling, would best exhibit suspected features of both gravitational differentiation and contact metamorphism;
- (c) the lowermost sill in the succession is in places only 40 feet above the economic copper-bearing horizon, and should provide adequate conditions for examining any relationship between the two;
- (d) a large number of "exploration drillholes" have been drilled from surface into the Chibuluma orebody, and these provide excellent intersections of the amphibolite sills. A good core recovery has been maintained in these drillholes and the original location of any piece of core can be determined accurately. The close spacing of these drillholes enables some reliable lateral correlations to be made between intersections.

The investigations by the writer were restricted to the amphibolite bodies which occur in the formations overlying the Chibuluma orebody. The country rocks have been studied in detail only in the proximity of these bodies. The investigations have been hampered by the absence of amphibolite outcrops in the area and by the fact that no amphibolite has been exposed by underground development.



2a

FIGURE 1.



#### LOCATION OF THE CHIBULUMA MINE

Chibuluma Mine and the township of Kalulushi lie on longitude 28°05' East, and latitude 12°50' South, almost in the centre of the Zambian Copperbelt (Figure 1). The Mine is approximately 6½ miles west of Kitwe and the Nkana-Mindola copper deposits. Chibuluma is linked by major roads to Kitwe and the more northern and eastern Copperbelt towns, but is not served by rail, the nearest railhead being Kitwe.

Chibuluma lies in the tropical savannah climatic zone and experiences well defined dry and wet seasons. The rainfall averages 52 inches per year and extends from mid-November to the end of March. The annual range in temperature is between an average minimum of 55°F and an average maximum of 84°F. The vegetation has been described by Trapnell and Clothier (1957) as being of the *Brachystegia-Isobertlinia* woodland variety.

#### HISTORY OF EXPLORATION

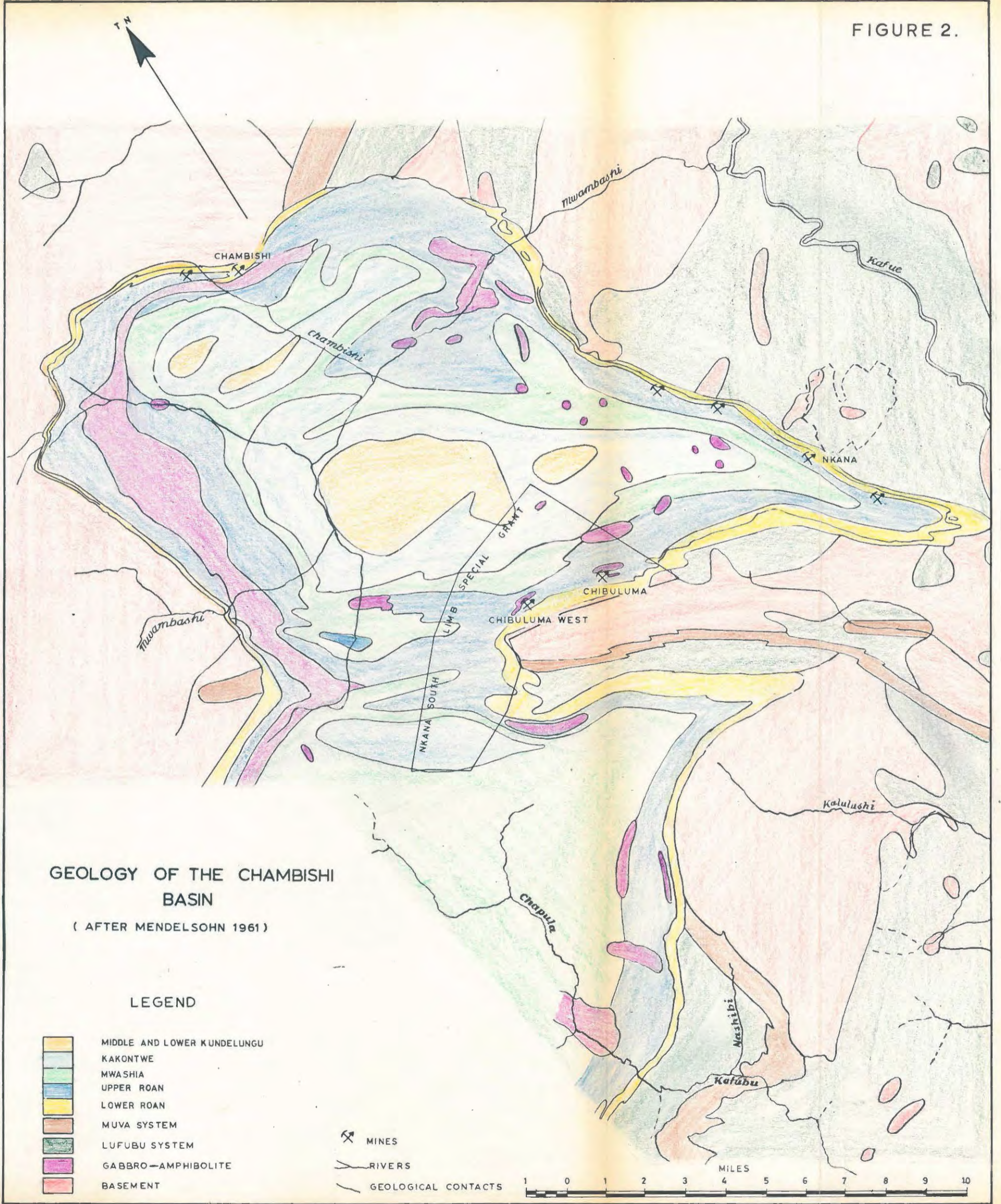
The history of early mineral exploration in Zambia, leading to the discovery between 1902 and 1923 of all but one of the currently exploited copper deposits has been well chronicled by Bancroft (1960, arranged by Guernsey) and Gunning (Mendelsohn, 1961, p. 3), and it is largely from the latter's description of "The Early Years" that the following dates and sequence of events are obtained. The earliest-discovered deposits all showed some surface indication of copper mineralisation in the form of malachite-stained outcrops, copper clearings - areas where high copper concentrations in the soil prevent tree growth - or ancient workings. These were the features that the early prospectors discovered or were shown by the local inhabitants, but not having had any surface expression, the Chibuluma orebody escaped early discovery.

The mineral rights in many parts of Zambia were controlled by the British South Africa Company from 1894 until 1964 during which time numerous individual prospectors, syndicates, and companies were engaged in the search for new mineral deposits. In 1922 the British South Africa Company considered that better results would be obtained if the larger mining and prospecting concerns, capable of organising and maintaining large-scale mineral exploration, were granted exclusive rights over large areas. Further, it had been realised at an early date that the orebodies were restricted to particular sedimentary horizons that could be correlated between the various deposits, and, although differing widely in lithology, form a distinct stratigraphic group. This increase in geological knowledge, together with the establishment of the "Exclusive Prospecting Concessions", led to widespread geological mapping as opposed to haphazard prospecting, and between 1923 and 1940 large areas of the Copperbelt and the surrounding territory were systematically mapped in considerable detail.

The Chambishi-Chibuluma-Nkana basin, together with the Roan Antelope Syncline, and parts of the Mufulira syncline, comprised part of an 1,800 square mile exclusive prospecting area known as the Nkana Concession. After the first field season, the geologists employed in mapping the area had outlined the major structural and lithological features. This led to the eventual establishment of "Special Grants" over the areas of highest mineral potential and the relinquishing of the rights over the remainder of the concession area. Subsequently, particular attention was paid to the lower successions of the Mine Series in which occurred those ore deposits already known.

The sub-outcrop of the lower succession of the Mine Series is known to occur over large areas of the Nkana South Limb Special

FIGURE 2.



Grant (Figure 2). Detailed mapping by pitting and trenching in these areas followed by diamond drilling at intervals of 6,000 feet along strike led to the discovery of the Chibuluma orebody when, in 1939, drillhole NS.10 intersected 51.1 feet true thickness of feldspathic quartzite of the Lower Roan Group assaying 5.35 per cent total copper, 0.03 per cent oxide copper and 0.22 per cent cobalt.

The Chibuluma orebody has no outcrop or surface indication. Mendelsohn (1961, p. 497) records that early surface pitting over the centre of the orebody revealed quartzite with limonite stains representing sulphides, and containing up to 0.2 per cent total copper.

Subsequent drilling at intervals ranging from 450 to 1,000 feet outlined an orebody roughly 1,400 feet on strike, and raking towards the northwest. The decision to mine the orebody was taken in 1951. The sinking of Norrie Shaft began in December, 1951 and production started in October, 1955 at 40,000 tons of ore per month.

The most recent published ore reserves are 14.88\* million tons averaging 5.00 per cent total copper, and 0.22 per cent cobalt. The current rate of production is approximately 2,000 long tons of copper (60,000 long tons of ore) per month.

Between 1939 and the present, nearly forty exploratory surface diamond drillholes have been drilled and, of these, only a few of the shallower ones failed to intersect a "gabbro-amphibolite body".

#### THE GEOLOGY OF CHIBULUMA MINE

The general stratigraphy and structure of the Copperbelt, and the correlation with the stratigraphy of other areas of the sub-continent are beyond the scope of this thesis. The writer

\*Including Chibuluma West tonnages

TABLE I

THE STRATIGRAPHIC COLUMN OF  
THE ZAMBIAN COPPERBELT

(After Garlick 1961 and Mendelsohn 1961)

SYSTEM	SERIES	GROUP	FORMATIONS AND ROCK TYPES
Katanga	Kundelungu	Upper	Shale, quartzite.
		Middle	Shale, tillite.
		Lower	Shale.  Kakontwe limestone, dolomite, and shale. Tillite.
	Mine	Mwashia	Carbonaceous shale, argillite.
		Upper Roan	Dolomite and argillite. Argillite and quartzite.
		Lower Roan	Hangingwall quartzite, argillite, feldspathic quartzite.  Cupriferous argillite, impure dolomite, micaceous quartzite, greywacke, and arkose.  Footwall conglomerate, quartzite, aeolian quartzite, and basal conglomerate.

UNCONFORMITY

BASEMENT COMPLEX

Muva		Argillaceous Arenaceous Rudaceous	Schist. Glassy quartzite, quartz-mica schist. Sheared conglomerate, quartz-mica schist.
------	--	---	---

UNCONFORMITY

Lufubu			Schists, micaceous quartzite, gneiss.
--------	--	--	---------------------------------------

Gabbro is intrusive into the Katanga System (mainly into the Upper Roan, Mwashia, and Lower Kundelungu formations).

Granite and Granite Gneiss are intrusive into the Lufubu System.

considers it desirable, however, that these fields should be discussed briefly in order to present the broad geological setting to which the local Chibuluma stratigraphy and structure can be related.

### STRATIGRAPHY

The stratigraphy of individual mines and of the Copperbelt in general has been described fully by Mendelsohn and others (1961) who followed the nomenclature originally proposed by Grey (1930) and subsequently modified by Garlick and Brummer (1951). A broad outline of the Copperbelt succession after Garlick (1961) and Mendelsohn (1961) is shown in Table I.

At Chibuluma Mine, only Granite, Lufubu System, and Mine Series formations, together with the amphibolite bodies, have been encountered in underground workings or exploratory drilling. The local succession is shown in Table II, following the descriptions of the mine geology by Garlick (1959) and Winfield (1961).

No original investigation of the Basement Complex or Lower Roan formations has been undertaken for this thesis. The brief account of the formations given below has been compiled from descriptions of the geology of Chibuluma Mine by Fleischer (1956), Garlick (1959), and Winfield (1961), together with the petrological description by Darnley (1958) and Hall (1963). The nature of the feldspars is of particular interest in the Lower and Upper Roan Groups as the variations in soda and potash contents are regarded by some writers (Darnley, 1958) as being relevant to the origin of the copper mineralisation, and possibly associated with the amphibolite intrusions.

TABLE II

STRATIGRAPHIC SUCCESSION  
AT CHIBULUMA MINE

UPPER ROAN GROUP

	<u>Thicknesses</u>	
Dolomite	0	- 400 ft.
Major amphibolite body	900	- 1100 ft.
Dolomites, argillites, shales and siltstones, with sporadic sill-like amphibolite bodies	500	- 1000 ft.
Various minor amphibolite bodies	0	- 200 ft.
Talc and chlorite schists	10	- 100 ft.

LOWER ROAN GROUP

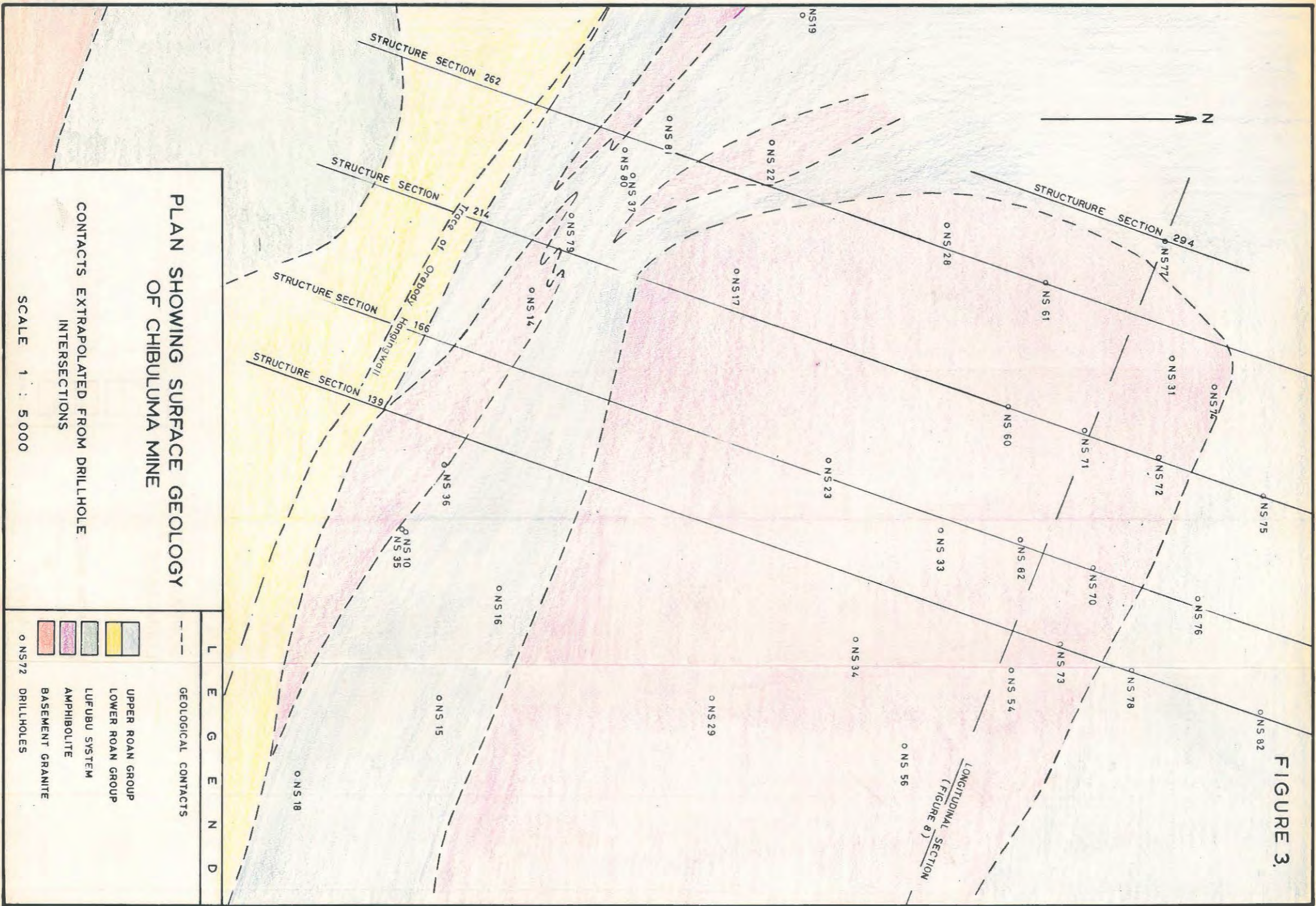
Hangingwall Conglomerate	0	- 30 ft.
Hangingwall Quartzite	0	- 30 ft.
Ore-bearing Quartzite	60	- 75 ft.
Aqueous Quartzite	10	- 47 ft.
Acolian Quartzite	50	- 400 ft.
Basal Conglomerate	10	- 15 ft.

Unconformity

BASEMENT

Lufubu System intruded by granite gneiss





**PLAN SHOWING SURFACE GEOLOGY OF CHIBULUMA MINE**

CONTACTS EXTRAPOLATED FROM DRILLHOLE INTERSECTIONS

SCALE 1 : 5000

**G E O L O G I C A L C O N T A C T S**

- GEOLOGICAL CONTACTS
- UPPER ROAN GROUP
- LOWER ROAN GROUP
- LUFUBU SYSTEM
- AMPHIBOLITE
- BASEMENT GRANITE

**DRILLHOLES**

- ONS 72

FIGURE 3.

LONGITUDINAL SECTION (FIGURE 8)

Description of the Individual Formations

(a) The Basement

Quartz-biotite schist of the Lufubu System, occurring as thick roof pendants in the intrusive granite gneiss, has been intersected in underground development and drillholes. Surface mapping and pitting have outlined large areas of both weathered schist and granite to the south of the Mine.

Muva System rocks are known to occur approximately two miles south of the Mine where a clean, glassy quartzite crops out extensively and strikes approximately west-northwest.

The pre-Katanga topography underlying the Lower Roan formations consisted of a number of small hills or ridges separated by broad shallow basins. Maximum known relief is about 350 feet, but could be considerably more.

(b) Katanga System

(i) Lower Roan Group

The Basal Conglomerate is a sheared conglomerate consisting of angular and subangular granite and Lufubu schist boulders developed locally on the flanks of the pre-Katanga hills and in the intervening valleys.

The Aeolian Quartzite is a grey to dark grey feldspathic quartzite with well developed bedding emphasized by variations in the concentration of detrital iron oxides. Large-scale cross-bedding with long curved foresets and dihedral angles of over 30 degrees has been interpreted by Garlick (1959) as an original feature of sand dunes up to fifteen feet high.

Petrographic studies have been carried out by Hall (1963) who subdivided this formation on textural and mineralogical criteria into a lower feldspathic quartzite and an upper sub-arkose. The predominant feldspar is albite which exhibits discontinuous (010) twin lamellae, a texture regarded by Hall as being due to replacement of potash feldspar by albite.

The Aqueous Quartzite consists largely of coarse-grained arkose with scattered conglomerate bands. Small-scale cross-bedding has been interpreted by Garlick (1959) to be of aqueous origin. Minor shaly interbeds occur. Hall (1963) has observed between 25 and 35 per cent albite in the arkose and has drawn attention to the abundance in this formation of tremolite associated with calcite and sphene on the western side of the ore basin.

The Ore-bearing Quartzite consists of one or more lenses of chalcopyrite-rich sericitic quartzite intercalated with and enveloped in pyritic albite-quartzite (Hall, 1963). The contacts between the sericitic and the albitic quartzite are gradational and commonly lie within the copper-bearing horizon. The quartzites exhibit blastopsammitic textures and are commonly cross-bedded. The predominant copper sulphide is chalcopyrite with bornite and chalcocite occurring locally. Cobalt occurs in carrollite and cobaltiferous pyrite. These minerals are commonly confined to narrow bands which lie within and parallel to the main orebody and which can be traced for considerable distances.

The Hangingwall Quartzite is a hard, white, poorly bedded rock consisting largely of rounded quartz and albite grains exhibiting blastopsammitic textures. Sericite and biotite occur sparsely except in minor argillite bands,

where they occur with microcline and minor calcite. The feldspar content of the rock is variable and Hall (1963) records arkose, sub-arkose, and feldspathic quartzite within these beds. Microcline and orthoclase occur in minor amounts. Pyrite is common and chalcopyrite less common in the hangingwall quartzite.

The Hangingwall Conglomerate consists of poorly sorted gritty fragments, pebbles, and cobbles of Basement rocks occurring in an albite-quartz-carbonate matrix. Albite, which forms up to 70 per cent of the matrix, also occurs towards the top of the conglomerate in segregated masses of small crystals resembling the fragments of the "albite breccias" of the Upper Roan Group. Pyrite is commonly found in the conglomerate.

(ii) Upper Roan Group

The Upper Roan formations overlying the Chibuluma ore deposit consist of a variety of rock types ranging from almost pure dolomite, through dolomitic shale and dolomitic mudstone, to shale and siltstone. The more dolomitic varieties predominate and there are only minor occurrences of quartzites. Carbonaceous shales occurring in these formations are also of limited distribution. These rock types are randomly intercalated with one another, and the individual bands of uniform composition range from approximately ¼ inch to 15 feet in thickness. Regional metamorphism has further diversified the rock types which now include clean dolomitic marble, scapolite and tremolite-bearing dolomite, talcose dolomite, and talc-chlorite schists (Winfield 1961). Most varieties have gradational contacts giving rise to intermediate types.

Garlick (1959) described broad subdivisions which were slightly amended by Winfield (1961) (Table II). Work is currently being undertaken by the former (personal communication) in order to establish the more detailed subdivisions of the Upper Roan Group. Considerable difficulty has been experienced in correlating individual formations between adjacent drillholes because of the following factors:-

- (a) the overall similarity of rock types which, as noted above, are predominantly dolomitic argillaceous sediments;
- (b) the lateral facies changes and variations in thickness of individual formations. The quartzite beds occurring 200 to 300 feet above the Hangingwall Conglomerate on the eastern margin grade westwards and northwards into siltstones and shales (Garlick 1959, p.6);
- (c) the masking effect of regional metamorphism and possible metasomatic aureoles associated with the amphibolites. Variations in the development of porphyroblasts, particularly of tremolite and scapolite, cause sediments of similar bulk chemical composition to appear very different in hand specimens. The so-called "albite breccias", commonly associated with the amphibolite bodies, do not yield very much information as to their original character;
- (d) the occurrence and in some cases irregular form of the amphibolite bodies.

Hall (1963) is the only writer to have made any detailed petrographic study of the Upper Roan formations of Chibuluma Mine. Her findings have in almost all cases

been confirmed by those of the present writer.

Hall found that the most common feldspar of the Upper Roan formations is albite which occurs generally as small, idioblastic crystals with well-developed albite, and more rarely pericline, twin lamellae. The albite content of the rocks is extremely variable with less than 1 per cent in some dolomites and more than 70 per cent in the albite breccias. In the formations between the major and minor amphibolite bodies, the occurrence of albite was found to be limited to a zone near the contact with the amphibolite.

Scapolite occurs as fresh, ovoid crystals which are commonly altered to a micaceous product. Scapolite was found only on the fringe of the albitic zones and never within the albite breccias. The scapolite occurring in argillaceous beds well away from amphibolite bodies was found to be dipyre ( $Me_{45}$ ) from refractive index determinations.

Tremolite commonly forms porphyroblasts, up to 4.5 x 0.7 cms in size. Pink to mauve anhydrite occurs very commonly in veins and in the groundmass of the carbonate rocks. Gypsum is also very common and is largely confined to veins and stringers. Veins of anhydrite up to 2 cms in width commonly occur along the contacts between the amphibolite and the sediments.

Quartz was found by Hall to vary in amount from less than one per cent in the dolomites to over twenty-five per cent in some quartz-albite-carbonate rocks. The predominant carbonate mineral is dolomite although calcite is locally abundant. Brown and greenish brown biotite,

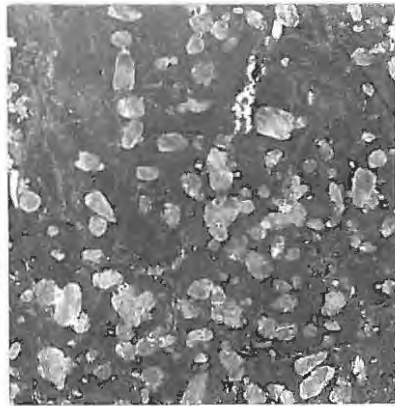


Plate 1. UPPER ROAN GROUP.

Light coloured ovoid scapolite porphyro-  
blasts in dark micaceous argillite.

NS 78, 1658'.

(x 0.84).



Plate 2. UPPER ROAN GROUP.

Argillite and dolomite. Brecciated argillite with interstitial calcite (white). Tremolite porphyroblasts are common in the dolomite.

Note the boudinage developed in the thin fractured argillite bed.

NS 76, 1592'.

(X 0.62).

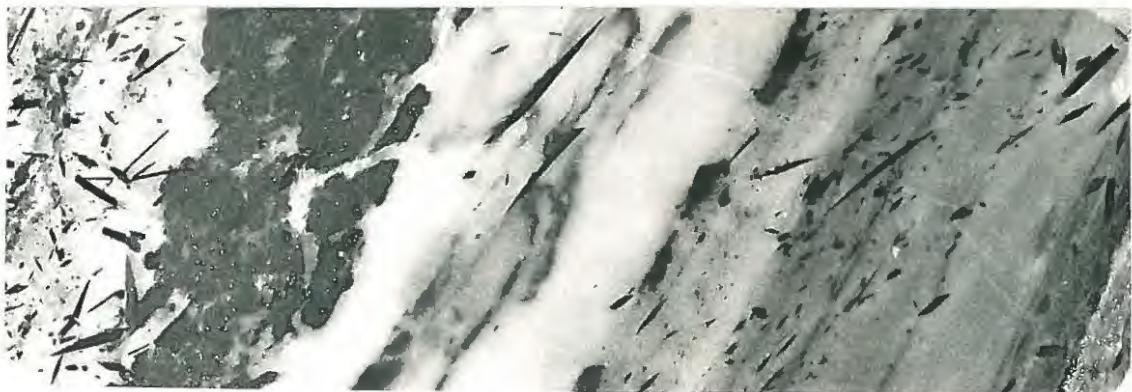


Plate 3. UPPER ROAN GROUP.

Dolomite in which tremolite porphyroblasts exhibit a common alignment at a small angle to the bedding planes. Haematite band is fractured.

NS 76, 1585'.

(X 0.70).



chlorite, and talc were found to be ubiquitous in the sedimentary formations. Other minerals recorded by Hall include sericite, sphene, apatite, zircon, rutile, goethite, pyrite, and chalcopyrite.

The writer was able to add to Hall's description of the Upper Roan sediments only as regards the megascopic study of these rocks from drillhole cores. The most striking features noted were:-

(a) that the development of large, ovoid scapolite porphyroblasts (Plate 1) is largely confined to the more argillaceous rocks. Small scapolite porphyroblasts are developed in a coarsely recrystallised marble occurring above the major amphibolite;

(b) that the tremolite porphyroblasts are developed best in the more dolomitic formations and are very common in narrow (six inches to two feet thick) beds of dolomite interbedded with more argillaceous rocks (Plates 2 and 3). Tremolite is commonly associated with epidote.;

(c) that both tremolite and scapolite porphyroblasts show a moderate degree of orientation with their crystallographic c-axes commonly lying along a plane dipping north at a greater angle than the bedding planes. This feature is noted even adjacent to the amphibolite bodies and implies that the tremolite in particular developed during regional, rather than contact, metamorphism;

(d) that argillaceous formations are almost invariably brecciated or fractured while the dolomite formations are not, suggesting that

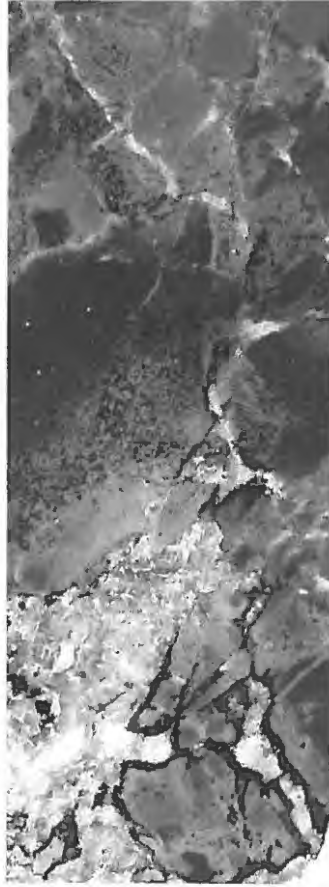


Plate 4. UPPER ROAN GROUP.

Albite breccia. Partially albitised brecciated argillite (albite - light colour, unaltered argillite - dark). Calcite and talc are developed in interstices, and biotite rims the albitised argillite fragments.

NS 72, 1332'.

(X 0.75).

the latter are less competent. The brecciated argillite commonly develops an interstitial calcite "matrix", (Plate 2) and the actual argillite fragments are fringed by a narrow zone of biotite. The development of this breccia is regarded by the author as a forerunner to the development of the albite breccias (Plate 4).

#### STRUCTURE

The Zambian Copperbelt is situated at the southeast end of a 500-mile long arcuate orogenic belt of folded Katanga sediments, termed the Lufilian Arc by Garlick (1961) following the nomenclature of Van Doorninck. The major structural feature of the Copperbelt, namely the Kafue anticline, is aligned along this arc and has an average trend of 145 degrees (true bearing). The southwest flank of the Kafue anticline consists of a series of en echelon plunging synclines one of which is the Chambishi-Nkana basin with an axial trend of approximately 130 degrees.

Chibuluma Mine is located on the southern flank of the Chambishi-Nkana basin. Immediately south of the Mine, Basement formations occupy the core of an anticline plunging to the west-northwest at a shallow angle.

At Chibuluma Mine the Katanga System sediments strike approximately east and dip to the north at an average angle of 38 degrees. The dip of the Lower Roan formations is uniform and is affected by only minor undulations. The plan section of the orebody is slightly arcuate (concave to the north) on all levels, possibly as a result of compactional folding in a small depositional basin.

Rocks displaying a major dragfold crop out one mile east of Chibuluma Mine and have been intersected by exploratory drilling at a depth of 2,500 feet below surface. This fold has influenced both Upper and Lower Roan sediments and the amphibolite bodies.

Folding at Chibuluma is gentle in the arenaceous Lower Roan formations and more severe in the brecciated dolomite and argillite of the Upper Roan. This pattern of increased intensity and amplitude of folding in the younger and less competent formations is similar to that described by Garlick (1961, p. 289) at Chambishi.

No major faulting has been recorded in the Lower Roan formations at Chibuluma. Faults with a throw of up to fifteen feet are known and smaller faults and shear zones are fairly common in competent quartzite. The inadequate correlation of the Upper Roan formations makes the recognition of faults very difficult. Following the correlation of the zones of the main gabbro sill in the west of the Mine, the writer considers that a major fault with a vertical throw of about 100 feet may exist in that area.

#### GEOMORPHOLOGY AND TOPOGRAPHY

The surface in the vicinity of Chibuluma Mine is approximately 4,200 feet above sea level and it slopes very gently to the north at between one and two degrees. This surface is a slightly modified form of the erosional surface which is considered by Dixey to be mid-Tertiary in age, and equivalent to King's African Surface (Garlick 1961, p. 11).

The topography of the area surrounding the Mine is only slightly affected by the structure and lithology of the underlying formations. The highest point (4,307 feet above

sea level) is two miles southwest of Chibuluma, where the Basement core of the plunging anticline trends on a bearing of approximately 300 degrees, and forms the major watershed. Quartzite of the Lower Roan Group, which overlies the Basement Complex, forms a subsidiary watershed trending east. This controls the drainage southeast of Chibuluma Mine where the Chibuluma stream, after which the mine is named, flows eastwards. Drainage over the Mine area is to the northeast and northwest into two streams which unite and flow north into the Mwambashi stream. Where flowing over dolomites and limestones of the Upper Roan Group and the Kundelungu Series, these streams are flanked by basin-like areas, waterlogged in the wet season and devoid of trees and known locally as "dambos". The water of the Chibuluma and the Mwambashi eventually flow into the Kafue River.

DISTRIBUTION OF GABBRO AND AMPHIBOLITE

Basic plutonic and hypabyssal intrusions are a common feature of the geology of Zambia. They are of a wide variety of types and are known to intrude Basement rocks as well as those of Katanga System. Their distribution and nature have been discussed briefly by de Swardt, Drysdall, and Garrard (1963, p. 62) who also reviewed the most notable intrusions. Of these, the basic rocks intruded into the basement formations are commonly of a schistose or gneissose structure. De Swardt, Drysdall, and Garrard note that some intrusions described by Newton have schistose margins but cores which retain the original igneous textures.

Large masses of norite and related rock types have been described by Newton (de Swardt, Drysdall, and Garrard, 1963) from east-southeast of Choma and at Chinkozia north of Livingstone. The latter is a composite and layered intrusion, and was emplaced by multiple injection. Amphibolites and metagabbros are also common as dyke-like bodies in the Basement formations.

Widespread occurrences of basic intrusions have been noted from the lower formations of the Katanga System. These intrusions appear to be of various ages as some are schistose and others in the same area exhibit undistorted igneous textures.

Copperbelt Distribution

Basic intrusions are also a common feature of the Copperbelt, where, as described by Mendelsohn (1961, p. 52), there is a general increase in the number and size of occurrences westwards across the area. This trend is well illustrated by Figure 2, showing the geology of the Chambishi-Nkana basin, which exhibits a pattern very similar to that of the Roan-Lufubu basin. Very little gabbro is known to occur in the

Mufulira syncline which forms the eastern limit of the Zambian Copperbelt whereas, scattered basic intrusions are abundant to the west (Jackson 1932, McGregor 1960, and 1964).

The Copperbelt occurrences of gabbro are almost completely restricted to the Upper Roan Group and younger formations, although some basic intrusives have also been recorded in older rocks. Garlick (1961) notes the occurrence of dyke-like basic intrusions along part of the "Phantom Fault" where it cuts the granite core of the Kafue anticline between the Mufulira and Fitwaola synclines. The Lower Roan Group has been cut by a kersantite dyke north of Mindola (Jordaan 1961) and by an irregular body of quartz-gabbro at Bwana Mkubwa. Jackson (1932) has described gabbro intruding the Lower Roan Quartzite at Sosa Hill west of the Chambishi-Nkana basin.

#### Chibuluma Distribution

The amphibolite bodies investigated by the writer at Chibuluma Mine occur only in the Upper Roan Group.

The major amphibolite body at Chibuluma is in places over 1,000 feet thick. The base of this body is between 500 and 900 feet above the base of the Upper Roan Group. About eight minor amphibolite bodies occur at irregular intervals in the Upper Roan formations below the major body. The exact number of these minor bodies is not known as lateral correlation of individual bodies over a few hundred feet between adjacent drillholes is in some cases very difficult. Only where a regular feature or trend is observed in a number of intersections can the shape and situation of the amphibolite body be interpreted with any certainty. Drilling to date has exposed only two thin amphibolite bodies in the sediments immediately overlying the major amphibolite body.

In determining the shape and extent of individual amphibolite bodies, the writer relied mainly on the geological structure-sections (1:1,000 scale) prepared by Chibuluma Mines Limited. These sections have been reduced to 1:5,000 and are presented as Figures 4, 5, 6, and 7. By superimposing the outlines of each amphibolite mass from successive structure sections the writer, in a number of cases, was able to "follow" the trend of a particular body. Isopachous lines for each separate amphibolite body were plotted on plan as a further means of defining the shape of the body. Even with all the available information at hand, the writer considers that he is not in a position to describe accurately the shape of an amphibolite body and can, therefore, only suggest the most probable form.

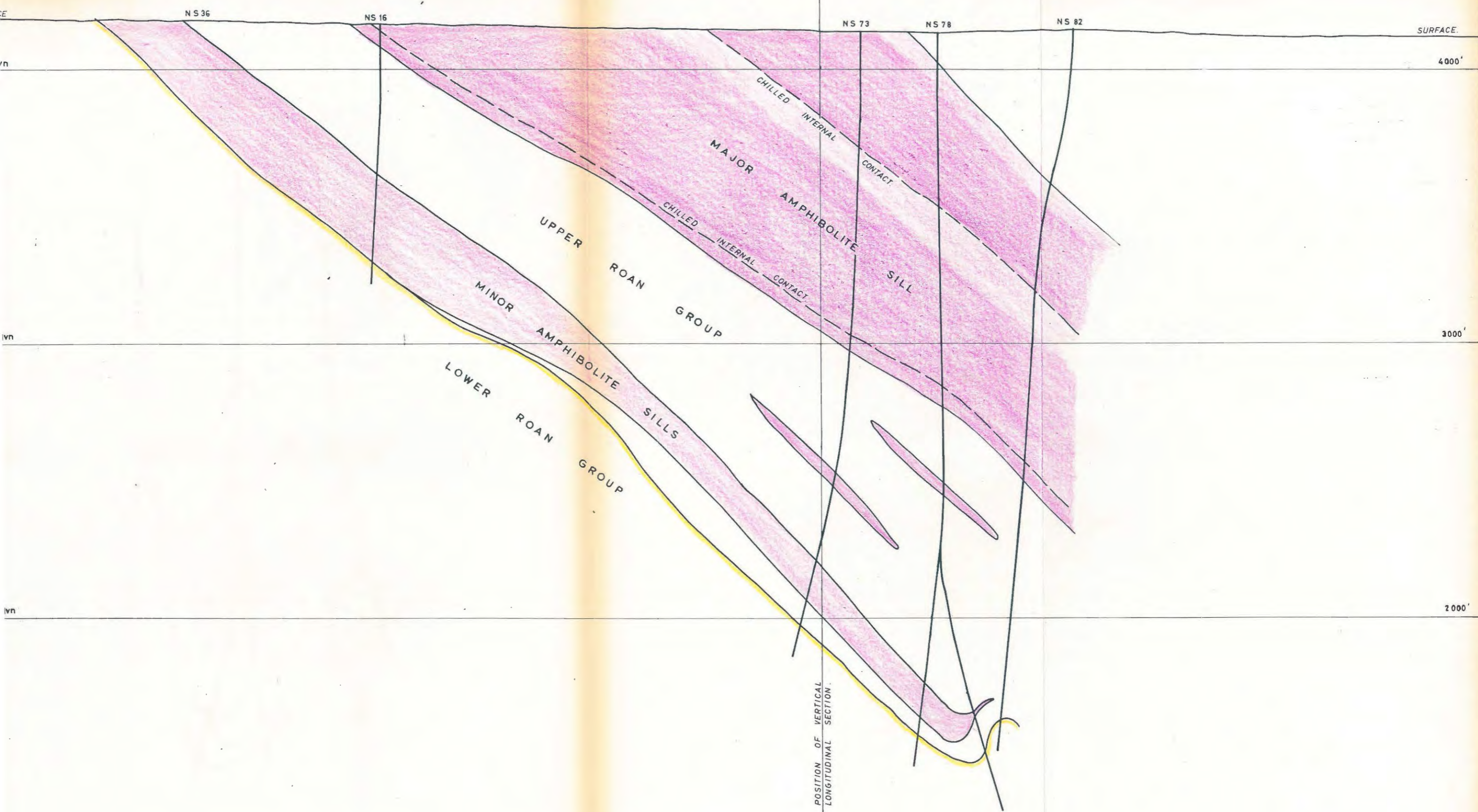
#### THE FORM AND STRUCTURAL RELATIONS OF THE AMPHIBOLITE BODIES

##### The Major Amphibolite Body

Only six surface drillholes NS. 75, NS. 76, NS. 78, NS. 82, 83, and 84 have intersected the full thickness of the major amphibolite body. The greatest known true thickness is approximately 1,020 feet in drillhole NS. 76. The extensions of the amphibolite body down dip and to the east of the mine are not known, but are at least 2,500 feet and 2,000 feet respectively. The true thickness shows very little variation although it decreases towards the north. The gradual down-dip divergence between the sill and the ore horizon appears to be due to an actual thickening of the intervening sediments.

Towards the west the main amphibolite body terminates abruptly. Superimposition of geological structure sections shows the lower contact of the amphibolite to be remarkably

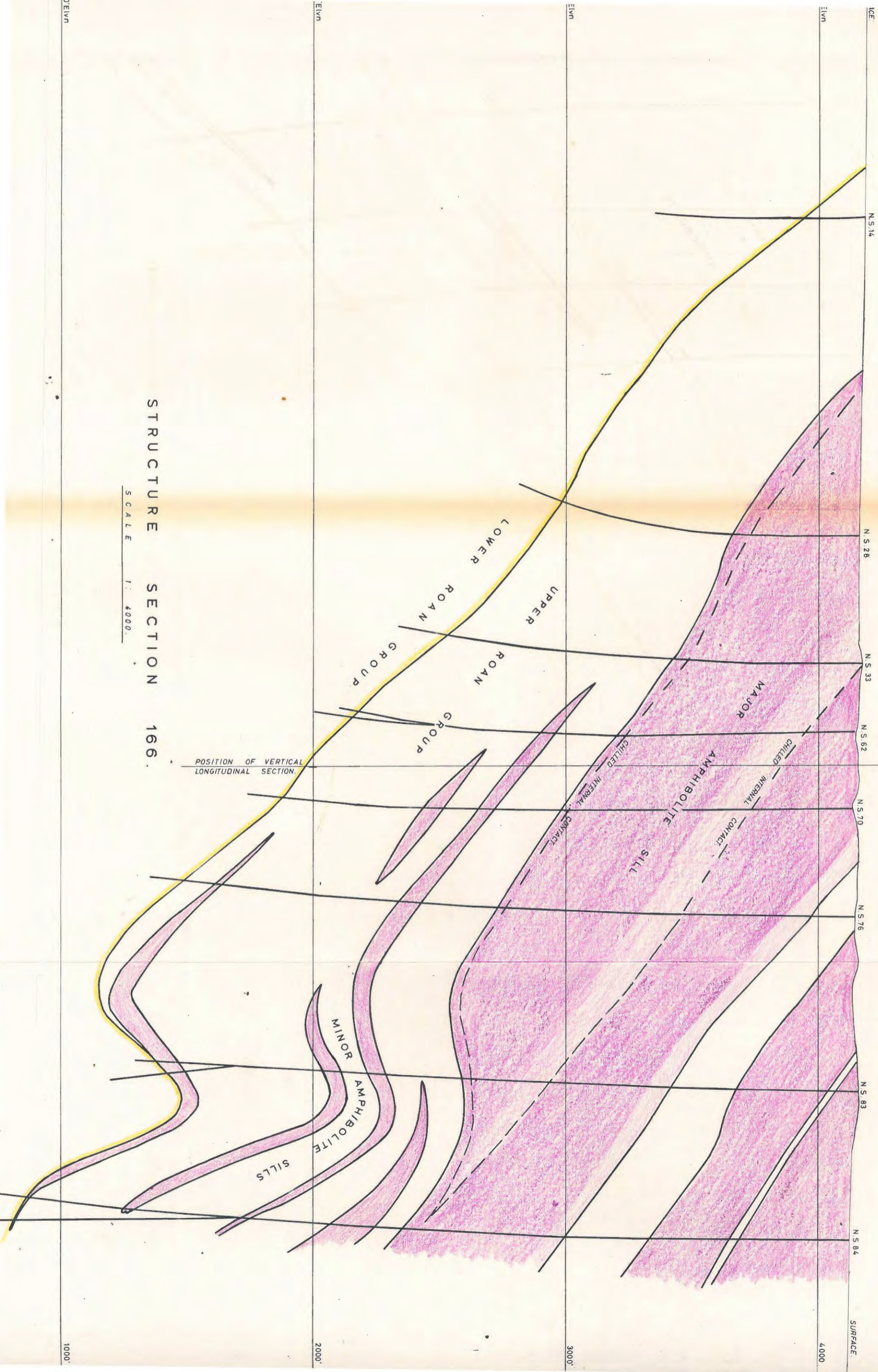




STRUCTURE SECTION 134.

SCALE 1: 4000.

FIGURE 5.



STRUCTURE SECTION 166

SCALE 1:4000

POSITION OF VERTICAL LONGITUDINAL SECTION.

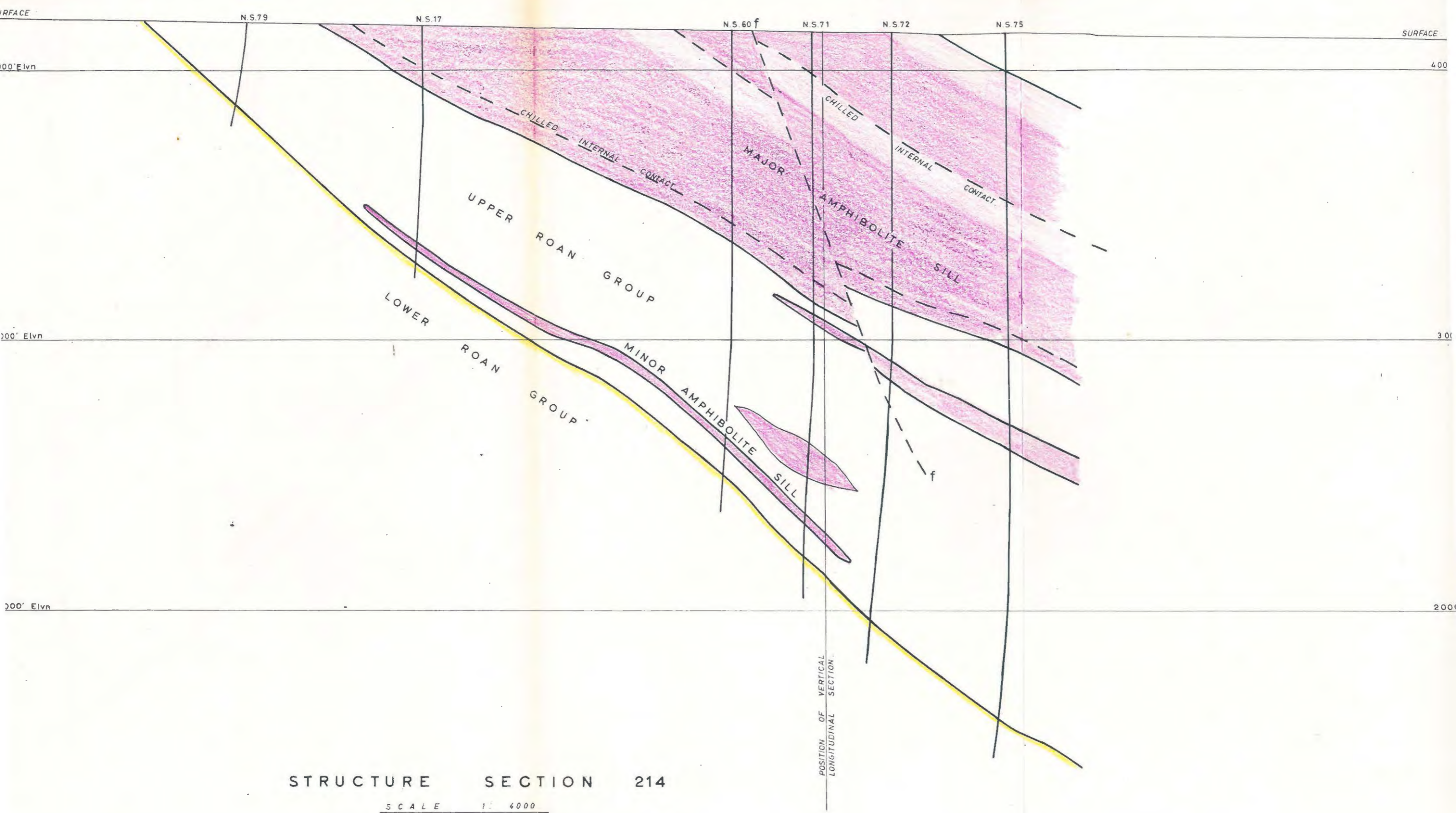
1000'

2000'

3000'

4000'

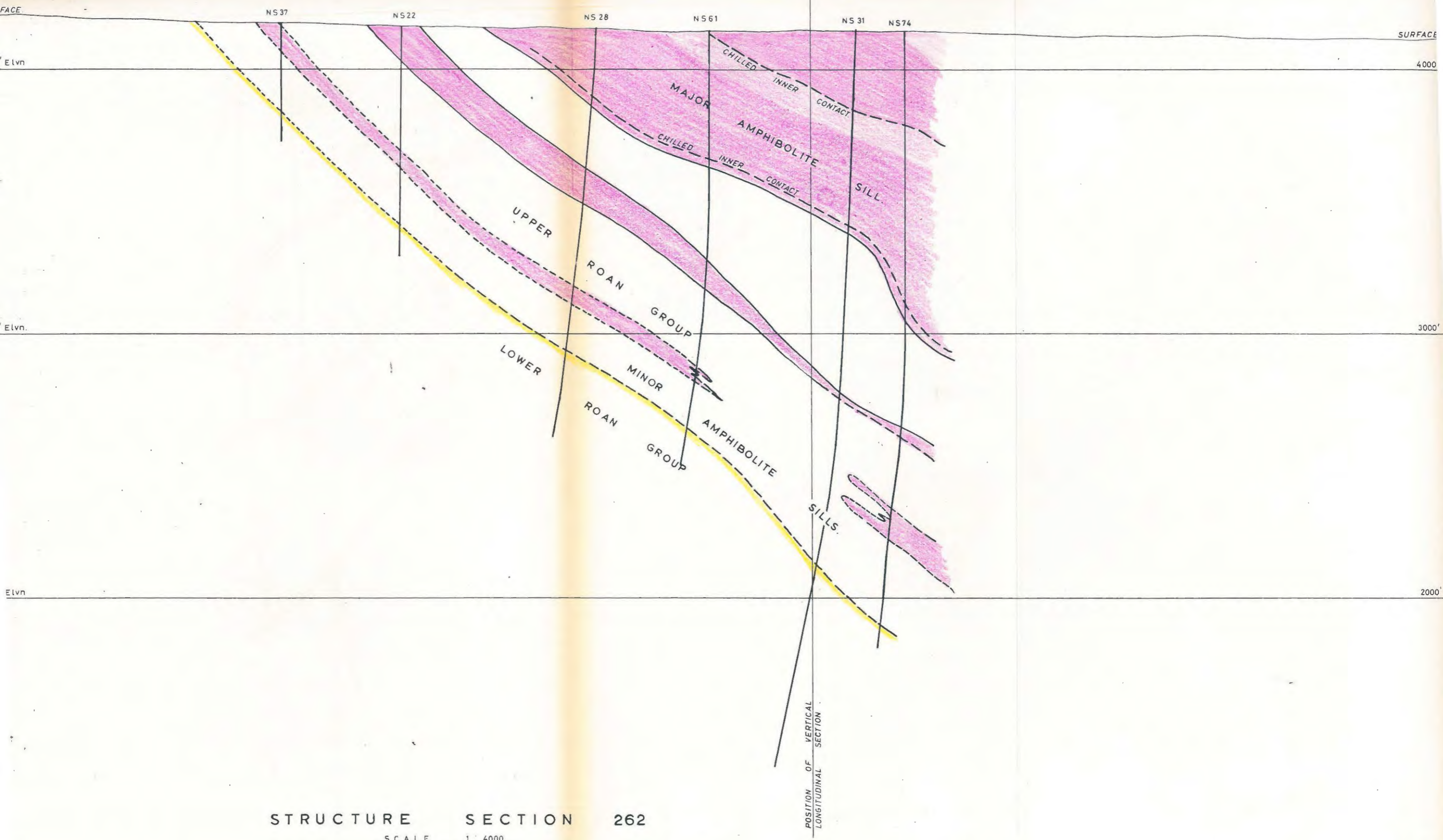
SURFACE



STRUCTURE SECTION 214

SCALE 1:4000

POSITION OF VERTICAL LONGITUDINAL SECTION



STRUCTURE SECTION 262

SCALE 1:4000

POSITION OF VERTICAL LONGITUDINAL SECTION

constant over almost the complete strike length of the Chibuluma deposit. Towards its western extremity, the base of the amphibolite body is shown to be considerably higher than that of the rest of the body. Over a horizontal distance of 480 feet between structure-sections 214 and 262, the lower contact rises about 260 feet. Drillhole NS. 77, a further 300 feet west of structure-section 262, does not intersect this amphibolite body at all. Towards the west, therefore, the amphibolite body over 1,000 feet thick, terminates abruptly within a distance of less than 780 feet.

The nature of the pre-erosional up-dip extension of the main amphibolite body is unknown. At the southwestern extremity in drillhole NS. 28 the amphibolite is interdigitated with dolomitic argillites. This is possibly a feature characteristic of the margins of the amphibolite bodies.

The upper contact of the main amphibolite body has been intersected in only five drillholes and it appears to be a uniform surface roughly parallel to the larger part of the lower contact. The precise nature of the upper contact towards the western limit is not known, but Figure 8, a longitudinal section through the major amphibolite, shows that this body has a bi-convex lenticular profile where it terminates in the west. This indicates that the overall shape is probably that of a sheet-like laccolith rather than that of a sheet-like lopolith.

The individual contacts between amphibolites and sediments are in many cases not available for study as the rocks (those of the upper contact in particular) are commonly weathered and difficult to core. In core samples where the contacts have been recovered, the contacts are always sharply defined and of a strictly conformable nature (Plate 5). The lower contact of the main amphibolite body where intersected by drillhole

FIGURE 8.



NS. 82 appeared on first examination to be discordant, with the bedding planes of the sediments terminating abruptly against the amphibolite. Closer examination, however, revealed the apparently discordant contact to be that of a xenolith or tongue of sediments with a maximum intersected dimension of 9 inches centred approximately 18 inches above the true basal contact which is conformable with the sediments.

The sediments and the amphibolite body, where interdigitated near the southwestern limit of the main amphibolite, appear to be conformable. The weathered and brecciated nature of the sediments intersected in drillhole NS. 28 resulted in very poor core recovery and consequently no detailed observations were possible.

The contact on the western extremity of the amphibolite body also appears to be conformable. The sediments intersected in drillhole NS. 77 dip at very steep angles, a feature which is in accordance with the displacement of the strata on the intrusion of a large body nearby.

A major structural feature affecting this amphibolite body towards its western extremity is an abrupt displacement of its lower contact and certain parallel internal features. This displacement is interpreted by the writer as a fault, (Figure 6), but whether it is in fact due to faulting, folding, or a step-like transgression of the amphibolite, is still an unanswered question. The amount of displacement (120 feet vertically) is nearly equal to the thickness of an amphibolite sill occurring 200 to 280 feet below the displaced section. If the major sill was emplaced before the lower sill, this would suggest that the displacement was due to faulting or folding rather than to transgression. The writer has, however, been unable to determine the sequence of emplacement of the various sills. Evidence ob-

tained by W.G. Garlick (personal communication) on correlation of the sedimentary formations also favours displacement by faulting or folding. This displacement is evident in the sediments below the smaller sill, but it decreases with depth, indicating that the fault or fold dies out in depth.

The displacement affects certain internal features of the major amphibolite body. These features, described in detail in the petrography, include the layered arrangement of different types of amphibolite, and the "internal" chilled margins which indicate that there is more than one phase of intrusion present. As these features were developed during or after the consolidation of the intrusion, the faulting or folding must be a post-consolidational feature. The writer considers that folding of a thick competent sill enclosed in incompetent dolomitic formations is unlikely and, therefore, favours displacement by faulting. The writer, with the above problem in mind, examined the core from drillhole NS. 71, but did not find any evidence to suggest either faulting or folding.

The same apparent displacement could have originated from the "transgression" of the first phase of the multiple amphibolite body if this ore intruded along a preferred plane which already had been displaced by earlier faulting or folding. The second phase which holds a preferred position in the first phase would then also have been similarly displaced.

The distribution of the amphibolite near the surface offers an interpretation of the magnetic data in the area. An abrupt change in magnetic values parallels the western limit of the major sill, and an eastward trending band of high magnetic values coincides with the sub-outcrop of a very coarse-grained magnetite-rich zone within the amphibolite.



The overall shape of the major amphibolite is one of a thick conformable sill with an average dip of 40 degrees to the north. The shape conforms with the principal morphological characteristics of a laccolith as defined by Gilbert and quoted by Daly (1933) inasmuch as it is:-

- (a) a sill-like, conformable body with only minor local transgressions;
- (b) bi-convex lenticular in profile on at least its western margin.

The bi-convex profile indicates that the roof has been lifted during intrusion, another feature of laccoliths as defined by Gilbert. This up-doming is significant in that a number of geologists (Daly 1933, p. 81) consider the emplacement of some laccoliths to be facilitated by antecedent or simultaneous upward buckling of the roof sediments under tangential crust pressure. Daly considers that intrusive bodies formed in this manner are, however, a variety of phacolith.

Lack of knowledge of the overall shape of the major amphibolite body precludes assigning any morphological term to it at this stage and the writer considers that it is adequately described as a thick sheet which probably has a bi-convex profile.

#### The Minor Amphibolite Bodies

The term "minor" is used to distinguish these amphibolite bodies from the one large body which occurs above them. A number of the minor amphibolite bodies are by no means small, the largest having a maximum known thickness of 290 feet (NS. 29) and extending for at least 3,000 feet in the direction of its greatest development. However, the majority of the

minor amphibolite bodies are between 40 and 120 feet thick and do not appear to be over 2,000 feet in length in any one direction.

All but one of the minor amphibolite bodies are conformable with the sediments, and most of the contacts are abrupt and well defined. A number appear to be gradational (e.g. NS. 76 at 2,490 feet) possibly due to contamination by the sediments. The amphibolite body intersected by drillhole NS. 15 appears to transgress the bedding at an angle of 20 degrees and is thus better described as a transgressive sheet.

The major dragfold mentioned previously on page 14 was intersected at a depth of 2,500 feet below surface in drillhole NS. 82. A minor amphibolite sill in this region has been interpreted by O. Winfield (personal communication) as being conformable with the folded sediments. Whether the emplacement of this sill pre-dates or post-dates the folding is obscure as the sill thins out considerably towards the north near the fold.

The writer experienced difficulty in interpreting the size and shape of the amphibolite bodies in cases where these bodies are intersected in one drillhole, but not in adjacent drillholes. These amphibolite intersections could represent either steeply dipping dykes or sills of limited lateral development. The fact that a number of amphibolite bodies are mantled by "albite breccias" has proved useful in some of these cases. By correlating the albite breccias in the intersections adjacent to the amphibolites the writer has been able to determine the shape of some of the amphibolites. A good example of this relationship is the amphibolite body intersected in drillhole NS. 71 at 1,600 feet, which is shown to be a sill by the "albite breccias" in adjacent drillholes.

Not enough evidence is available to establish the precise nature of the limits of the minor amphibolite sills. The most common termination of a sill-like body appears to be a simple tapering-out of the amphibolite producing a lenticular cross section. This interpretation is favoured by Garlick (personal communication) who, in correlating the Upper Roan formations, has shown that the amphibolite bodies in some cases have simply parted the sediments, presumably along a bedding plane. The total thickness of sediments in a sedimentary unit in these cases is the same, whether or not the unit has been intruded by an amphibolite, and the increase in the overall thickness of the sedimentary unit is equal to the thickness of the intruding sill. In a number of cases, the sill-like bodies have split into a number of small, separate sills which are interdigitated with the sediments (NS. 61 at 1,450 feet, Figure 7).

The slightly transgressive nature of some of the minor sills as represented in Figure 3 is of interest. The sediments strike at an average bearing of 120 degrees, which is roughly parallel to a series of sheared and leached zones intersected in the mine workings at depth. These zones, unlike the sills, have a steeper dip than the strata, but the similarity in horizontal trends suggests a structural weakness in that direction. This direction is also nearly parallel to the axial plane of the large dragfold cropping out to the east of the mine and intersected at depth by NS. 82.

A Note on the Location and Labelling of Drillholes and structural Sections of Chibuluma Mine

All surface exploratory drillholes in the Nkana South Limb Special Grant are designated by the prefix NS followed by the consecutive number of the particular drillhole, o.g. NS. 76. The surface locations of all drillholes referred to by the writer are shown on Figure 3. The depth of a sample is indicated thus - NS. 76 - 1262.5'.

The mine's survey base line, on which an arbitrary zero point has been selected to the east of the Mine, is parallel to the strike of the orebody. Mining locations including the major structural sections (Figures 4 to 7) are referred to by their distance in feet west of zero. This reference is simplified by dropping the last digit. Section 166 is located 1,660 feet west of zero. All sections are parallel to "mine north" which has a true bearing of 020 degrees.

A Note on the Construction of the Geological Plan

The detailed geological plans of the surface of the mine area existing prior to this investigation included only the area underlain by the Lower Roan Group, parts of the Basement granite and schists, and the lower formations and lower amphibolite bodies of the Upper Roan Group. The extension of the existing plans to include the major amphibolite body was, therefore, undertaken by the writer.

Outcrops are rare features in the Copperbelt landscape and the environs of Chibuluma Mine are no exception. Neither the Upper Roan formations nor the amphibolite bodies crop out and this makes direct surface mapping impossible. The only outcrops known to the writer are of Muva Quartzite and Lower Roan Quartzite.

The existing geological plan was extended by extrapolating the main contacts of each geological structure section to surface and connecting the points so obtained in the most feasible manner. A number of methods of inferential mapping were investigated briefly, and are mentioned below.

The soil types derived from amphibolites and dolomites are very similar in colour and texture (Maree 1961, p. 65) and were considered by the writer to be unsuitable for mapping purposes. M.W. Ellis of Roan Selection Trust Technical Services Limited informed the writer of earlier attempts to outline amphibolite bodies based on heavy mineral separations. The minerals considered to have originated in gabbro amphibolites, namely euhedral sphene, monazite, and zircon were however, found to occur in equal abundance in parts of the dolomites.

The writer considered pitting along the contacts of the amphibolite bodies where, particularly in the western extremity of the area investigated, further knowledge of the relationship between the sediments and amphibolite bodies would be of value. Pitting was not considered feasible, however, as apart from the expense involved, a large part of the area concerned is either covered by tailings dam or waterlogged dambo.

Four sets of aerial photographs were examined by the writer. The earliest photographs (1 : 30,000) were taken in 1947 prior to the development of Chibuluma Mine and the latest (1 : 10,000) in March, 1965. Even with a knowledge of the approximate location of the major contacts, the writer was unable to detect any corresponding features in the photographs. This was to be expected because, as is noted by Horscroft (1961, p. 79) gabbro, amphibolite and carbonate rocks have very similar vegetational covers.

Large parts of the area have been deforested within the last five to ten years, making inferential mapping from vegetation almost impossible. One plant, however, was noted to occur in profusion over both the major amphibolite of Chibuluma Mine and near the Mwambashi river bridge where gabbro-amphibolite actually crops out. This plant was kindly identified by Mr. D. Fanshaw of the Zambian Forestry Department as Aloe christianii Reynolds. Taylor (1963) describes the general Copperbelt distribution of this plant which, but for a few occurrences (e.g. Kamfinsa Hill), would appear to be closely associated with basic rock types. The writer mapped the occurrence of this aloe in the vicinity of Chibuluma Mine and found that its occurrence coincided closely with the inferred sub-outcrops of the main amphibolite body. No aloes appear to be growing over the sub-outcrops of the minor amphibolite bodies, but they occur in widely scattered clusters up to two miles north of the main amphibolite.

PETROGRAPHY

Colour and grain size are the most readily discernible megascopic features of the amphibolites. Consistent variations in these features, noted in several drillhole cores, established the existence of a number of varieties of amphibolite in the major sill. Plotting the locations of these types on dip and strike sections showed that they occur in well defined zones roughly parallel to the contacts between amphibolite and sediment. The writer considers that the petrography of the amphibolites is perhaps best undertaken by first describing those features, principally grain size, mode, and specific gravity, which were used to delimit the various types of amphibolite before describing these types individually.

The abrupt and well defined boundaries between coarse-grained and fine-grained amphibolites (Plate 6) were the first features noted by the writer, which indicated that the major amphibolite body is a multiple intrusion. These boundaries occur consistently at approximately 50 and 600 feet above the base of the major amphibolite body, dividing it into three sections. Other features described below also demonstrate the multiple nature of the sill and indicate which of the three sections is the earlier phase of the intrusion.

A sequence of zones is outlined by colour and is repeated in each intrusion. A lighter coloured zone is situated at the top of each intrusion indicating that both have undergone a similar course of events and suggesting possible magmatic differentiation. The investigation into these possibilities has developed into a major aspect of this thesis and the writer has attempted to relate all data obtained to a vertical cross section of the major amphibolite body.

The task of studying in detail some twenty four drill hole intersections in the 1,000 feet thick major amphibolite body would be a considerable one and the writer, therefore, selected only two drillhole intersections for microscopic and chemical examination. The remainder of the drillhole intersections were examined megascopically and more detailed work was carried out only where interest or importance warranted it.

Only six drillholes have intersected the full thickness of the major amphibolite body, and the two which were selected for detailed examination, NS. 76 and NS. 82, are located on the north-central and north-western parts of Chibuluma Mine. The logs of these two drillholes are briefly summarised below with particular emphasis being placed on colour and grain size of the rocks.

Drillhole NS. 76

<u>Depths in feet</u> <u>below the surface</u>	<u>Upper Roan Group</u>
0 - 178	Dolomites - and argillaceous sediments
178 - 240	<u>Mesotype Amphibolite</u> - medium-grained with a fine-grained chilled margin against the sediments.
240 - 281	<u>Pegmatitic Zone</u> - poorly developed, very coarse-grained schlieren in mesotype amphibolite.
281 - 699	<u>Melanocratic Amphibolite</u> - medium to coarse-grained, commonly scapolitised.
699 - 800	<u>Mesotype Amphibolite</u> - medium-grained with an abrupt, fine-grained chilled margin against the melanocratic amphibolite above.
800 - 864	<u>Pegmatitic Zone</u> - well developed very coarse-grained bands in both mesotype and melanocratic amphibolite.
864 - 1377	<u>Melanocratic Amphibolite</u> - medium to coarse-grained, commonly scapolitised. From 1350' down to 1377' the grain size decreases uniformly producing an abrupt chilled margin against the melanocratic amphibolite below.
1377 - 1416	<u>Melanocratic Amphibolite</u> - medium to coarse-grained, scapolitic and chloritic, with a fine-grained chilled margin against the sediment below.
1416 - 1451	Brecciated Argillite - dark green, dolomitic with abundant gypsum and anhydrite.



<u>Depth in feet</u> <u>below the surface</u>	<u>Upper Roan Group</u>
1451 - 1574	Dolomite
1574 - 1628	Interbedded dolomitic and argillaceous bands.
1628 - 1713	Argillite - brecciated and partially albitised.
1713 - 1798	<u>Melanocratic Amphibolite</u> - medium to coarse-grained, scapolitised with poorly developed chilled margins.
1798 - 2483	Interbedded dolomitic and argillaceous sediments.
2483 - 2518	<u>Melanocratic Amphibolite</u> - coarse-grained with poorly defined margins suggesting possible contamination.
2518 - 2672	Interbedded dolomitic and argillaceous sediments commonly albitised.

Lower Roan Group

2672 - 2800	Felspathic Quartzite - the highest economic copper mineralisation occurs at 2,712 feet.
-------------	---

Drillhole NS. 82

<u>Depth in feet</u> <u>below the surface</u>	<u>Upper Roan Group</u>
0 - 572	Dolomite and argillaceous sediments. The contact zone carries abundant magnetite and pyrite, especially from 568.0' to 569.5' with greater than 90 per cent magnetite.
572 - 590	<u>Mesotype Amphibolite</u> - medium to coarse-grained. From 572' to 574' - a very fine-grained chilled zone.
590 - 625	<u>Pegmatitic Zone</u> - very coarse-grained bands in mesotype and melanocratic amphibolite.
625 - 962	<u>Melanocratic Amphibolite</u> - medium to coarse-grained, scapolitic.
962 - 1023	<u>Mesotype Amphibolite</u> - an abrupt extremely fine-grained chilled contact at 962' grades downwards into a medium-grained amphibolite.
1023 - 1054	<u>Pegmatitic Zone</u> - very coarse-grained bands in both mesotype and melanocratic amphibolite.
1054 - 1587	<u>Melanocratic Amphibolite</u> - medium to coarse-grained, scapolitic. A possible chilled margin at 1,587' is poorly developed against the melanocratic amphibolite below.
1587 - 1631	<u>Melanocratic Amphibolite</u> - medium to coarse-grained with a well developed chilled margin against the sediments below.
1631 - 2059	Dolomitic and argillaceous sediments.
2059 - 2266	Brecciated and albitised, chloritic and talcose dolomites and argillites.
2266 - 2472	Well bedded but brecciated argillaceous dolomites.

<u>Depths in feet below the surface</u>	<u>Lower Roan Group</u>
2472 - 2517	Albite breccia passing downwards into albitised hangingwall conglomerate.
2517 - 2567	Lower Roan quartzites - with disseminated sulphides.

The consistent position of the two internal chilled marginal zones in the major amphibolite body, the similarity of the succession of mesotype, pegmatitic, and melanocratic amphibolite types in each phase of the multiple intrusion, and the irregular distribution of the minor amphibolite sills can be seen from these summaries.

#### GRAIN SIZE

Grain size measurements were carried out only on the feldspar laths because the sub-ophitic nature of the rocks precluded accurate and representative measurements being made on the amphibole crystals. In the measurement of these laths, the writer was influenced by the views of Lane (quoted by Alling 1936, p. 323) who recognised that thin sections represent chance sections of the rock and preferred therefore to measure only the largest grains which are the most significant in grain size studies.

The overall coarse-grained nature of the rocks prevented the writer from measuring more than from five to fifteen feldspar laths in any one section, with the exception of those of chilled facies in which fifty laths were measured. All laths were examined between crossed nicols to ensure that they were not intergrowths. The original size and shape of partially albitised basic plagioclase laths were determined from the distribution of the epidote inclusions in the albite.

AMPHIBOLITE

SEDIMENT

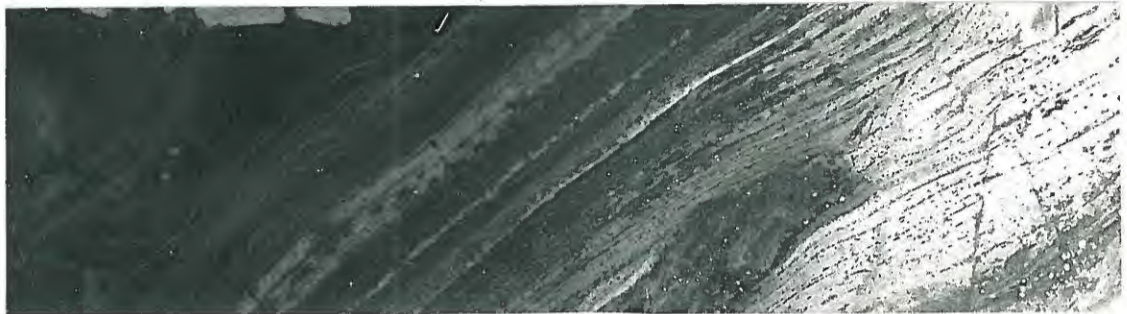


Plate 5. AMPHIBOLITE - DOLOMITE CONTACT.

A conformable basal contact of the major amphibolite sill. Magnetite and chlorite are common in the argillaceous dolomitic sediment.

NS 78, 1333'.

(X 0.75).

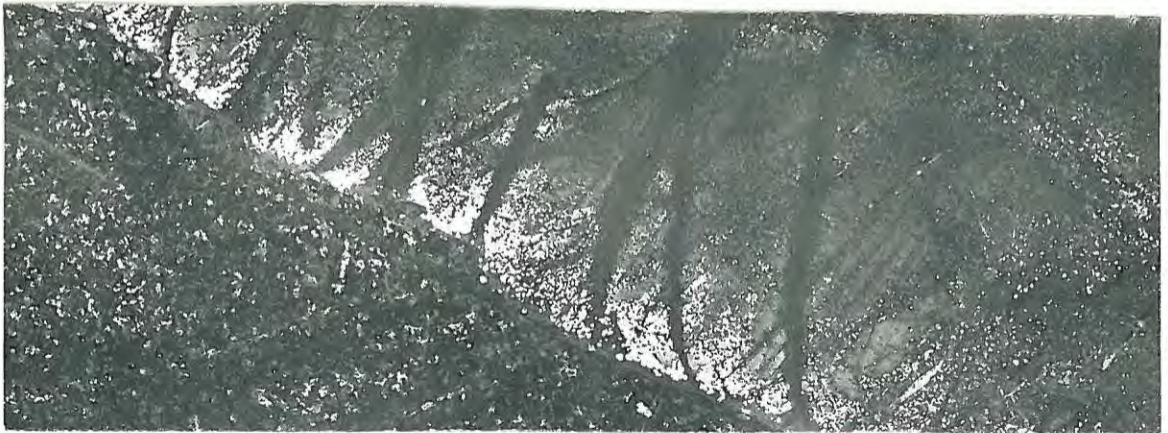


Plate 6. AMPHIBOLITE.

An 'internal' contact between the two phases of intrusion of the major amphibolite sill. The fine-grained amphibolite is considered to be the chilled contact facies of the younger intrusion adjacent to the coarse-grained amphibolite of an older intrusion. Scapolite is developed in the chilled, fine-grained, melanocratic amphibolite particularly along the contact. Joints approximately perpendicular to the contact are emphasized by chloritisation. Note the joints do not traverse the contact.

NS 62, 885'.

(X 0.78).

AMPHIBOLITE

SEDIMENT



Plate 5. AMPHIBOLITE - DOLOMITE CONTACT.

A conformable basal contact of the major amphibolite sill. Magnetite and chlorite are common in the argillaceous dolomitic sediment.

NS 78, 1333'.

(X 0.75).

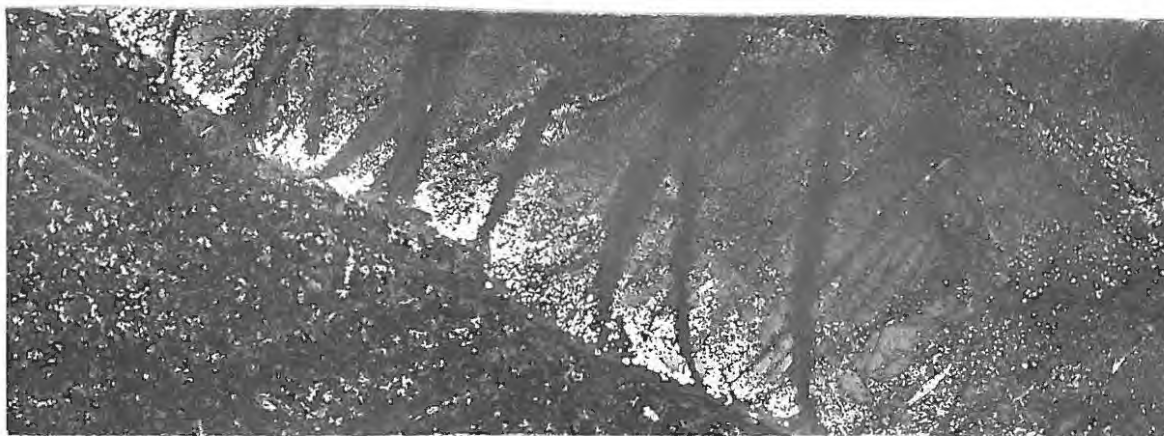


Plate 6. AMPHIBOLITE.

An 'internal' contact between the two phases of intrusion of the major amphibolite sill. The fine-grained amphibolite is considered to be the chilled contact facies of the younger intrusion adjacent to the coarse-grained amphibolite of an older intrusion. Scapolite is developed in the chilled, fine-grained, melanocratic amphibolite particularly along the contact. Joints approximately perpendicular to the contact are emphasized by chloritization. Note the joints do not traverse the contact.

NS 62, 885'.

(X 0.78).

The original size and shape of scapolitised laths could be determined only in the partially scapolitised rocks because the sub-ophitic texture of the amphibolite is completely destroyed by advanced scapolitisation. This produces an apparently coarse-grained texture in hand specimens due to the formation of large subhedral to euhedral scapolite porphyroblasts which, under the microscope, are seen to be mosaics of scapolite crystals.

In order to avoid misinterpretation of the results by the presence of long but narrow laths, the areas of feldspar crystals and not their lengths, were used for the grain size studies. The areas were calculated from micrometric measurements of their longest axes and their average widths perpendicular to these axes. The areas were then recalculated to give the diameters of circles having the same area which were plotted in Figure 9 as abscissae against the depths of the samples as ordinates.

Detailed grain size studies were carried out only on NS. 76 because certain features, although observed in nearly all intersections of the major amphibolite body are not well developed in NS. 82. The most important of these features is the chilled zone which occurs normally about 50 feet above the base of the sill; and another is the pegmatitic zone towards the top of the inner member of the multiple sill. The poor development of the latter in NS 82 is also indicated by the specific gravity curves in Figure 10.

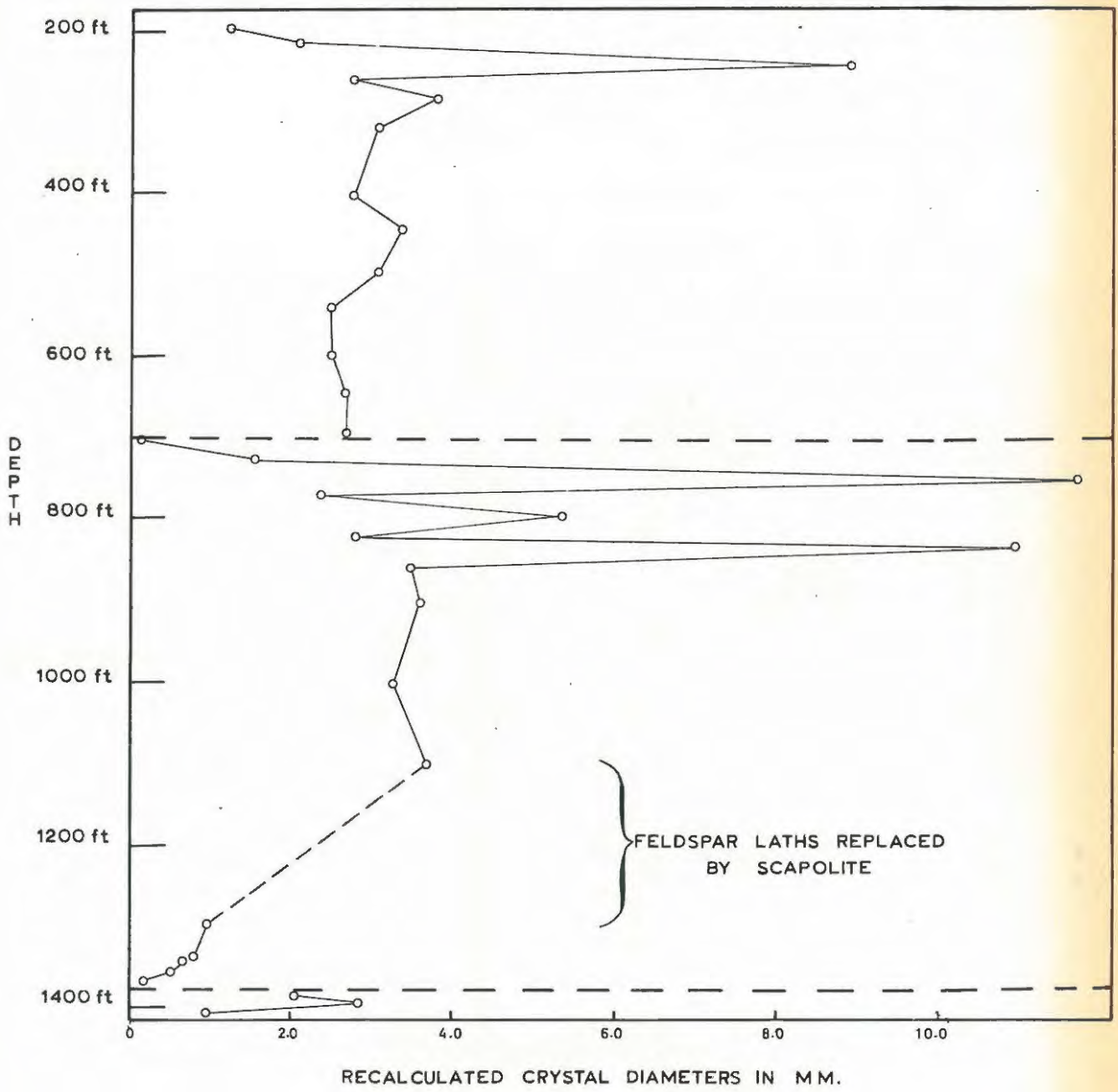
The detailed microscopic studies confirm the megascopic observations of variations in grain size and the overall coarse-grained nature of the amphibolite. Figure 9 demonstrates the presence of four fine-grained zones, and

two very coarse-grained zones in the major amphibolite body. The fine-grained zones at the external contacts are very narrow, normally less than five feet in width, and are interpreted as the chilled marginal facies of the original intrusion. The two inner fine-grained zones exhibit a gradual increase in grain size towards the centre of the amphibolite body, but there is an abrupt increase in grain size towards the outer contact of the body (Plate 6). These inner fine-grained zones (Plate 7) are also interpreted as chilled marginal facies and their presence indicates that the inner member was the second phase of intrusion of the multiple sill, and that it was intruded into the first phase after the first phase had cooled and largely solidified.

The very coarse-grained zones situated near the top of each phase of intrusion (Plates 8 and 9) represent thin pegmatitic bands or schlieren which occur in the normal medium- to coarse-grained amphibolite. Sixteen of these bands were found in the pegmatitic amphibolite zone of one member of the multiple sill, and therefore, Figure 9 showing only three coarse-grained peaks in the inner member, is not representative of individual bands, but indicates the general range of their distribution. The pegmatitic zones are better developed and more numerous in the inner member than in the outer member of the multiple sill and this is represented graphically in Figure 9 by the greater number of coarse-grained "maxima" in the inner member.

In all subsequent diagrams showing variations of certain properties with depth in both NS. 76 or NS. 82, lines have been drawn across the figures to represent the positions of the four chilled contacts described above. These occur at

DRILLHOLE NS 76



VARIATION IN SIZE OF PLAGIOCLASE CRYSTALS WITH DEPTH

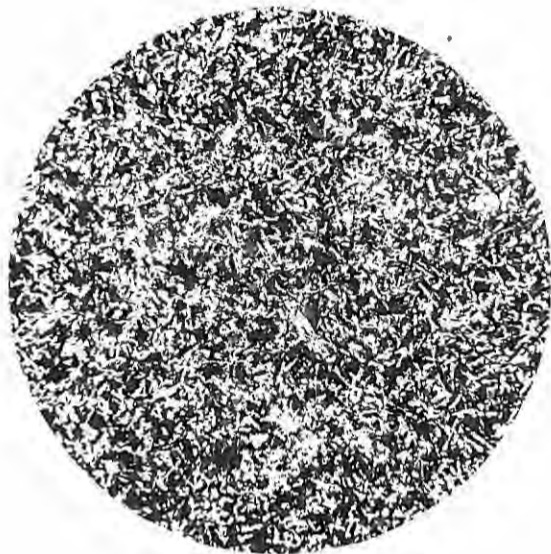


Plate 7. AMPHIBOLITE.

Fine-grained amphibolite from the chilled marginal facies. The large laths are albite. The groundmass is a felt of albite laths, amphibole, chlorite and magnetite.

NS 82, 962'.

Photomicrograph (X 25),  
Plane polarised light.





Plate 8. PEGMATITIC AMPHIBOLITE.

Coarse-grained schlieren of pegmatitic amphibolite in melanocratic amphibolite.

Skeletal crystals of ilmenite (il) coated with leucoxene and sphene (sp) are common. The light coloured mineral is largely albite (ab) and the dark mineral mainly amphibole (a).

NS 76, 848'.

(X 0.60).



Plate 9. PEGMATITIC AMPHIBOLITE.

Radiating and branching amphibole crystals (dark) with albite and micropegmatite (light).

NS 74, 243.5'.

(X 0.64).

178, 699, 1377, and 1416 feet in NS. 76 and at 572, 962, 1587, and 1631 feet in NS. 82. The middle member of the three sections has been intruded into, and thus divides, an earlier sill which now forms the upper and lower sections. The upper and lower sections are, therefore, referred to as the "first" or "earlier phase" of intrusion, or "outer members" of the major amphibolite body, and the middle section is referred to as "second phase" or "later phase" of intrusion, or the "inner member". The contacts between amphibolite and sediment are termed "external contacts" as opposed to "internal contacts" between amphibolites of different ages.

#### SPECIFIC GRAVITY

Two sets of specific gravity determinations were made on the core samples from each of the two drillholes NS. 76 and NS. 82, and the results are plotted as abscissae against the depths below the surface at which samples were intersected as ordinates (Figure 10).

The first set of determinations was carried out on pieces of core trimmed by diamond saw and weighing between 120 and 140 grammes. The samples were selected by the writer to represent a particular rock type and as far as was possible were free of veins, stringers, shear zones or above average amounts of magnetite, pyrite or scapolite. This set of determinations was carried out by the Assay Laboratory of Chibuluma Mines Limited using the immersion method with a "Mettler" balance (hence the dry weight of the samples being limited to about 150 grammes). The determinations were carried out on three samples from each location in drillhole NS. 82 and on five samples from each location in drillhole NS. 76. The results accepted for this set of determinations were the averages of results of either the three or the five samples.

DRILL HOLE NS 76

DRILL HOLE NS 82

SPECIFIC GRAVITY

SPECIFIC GRAVITY

2.8 2.9 3.0 3.1 3.2

2.9 3.0 3.1 3.2 3.3

178'

572'

699'

962'

1377'

1587'

1416'

1631'

2.8 2.9 3.0 3.1 3.2

2.9 3.0 3.1 3.2 3.3

500  
600  
700  
800  
900  
1000  
1100  
1200  
1300  
1400  
1500  
1600  
FEET IN DEPTH

• DRY WEIGHT OF SAMPLE IN AIR = 1.5 - 3.5 KILOGRAMMES  
X DRY WEIGHT OF SAMPLE IN AIR = 120-140 GRAMMES.

VARIATION IN SPECIFIC GRAVITY WITH DEPTH  
IN MAJOR AMPHIBOLITE BODY.

The results of the first set of determinations showed a definite trend in the specific gravity of the amphibolite throughout the thickness of the major sill. The writer considered, however, that the samples on which the determinations were made, being only 120 to 140 grammes, were not truly representative and that the vertical interval between samples was too large, thus necessitating a second set of determinations.

The second series of specific gravity determinations was made by the writer and two assistants, using pieces of core weighing between 3.5 and 1.5 kilogrammes. The determinations were made on a slightly modified Triple Beam Balance using the normal immersion method. The writer removed most of the air bubbles adhering to the core before weighing it underwater. Both wet and dry weights obtained were repeatable to  $\pm 5$  grammes, a variation of less than 1.0 per cent. The vertical interval between samples was dependent upon the nature of the core and ranged from 22 feet in broken core to 5 feet in hard compact core. The average interval was about 12 feet.

Both sets of specific gravity determinations included samples from the dolomitic and argillaceous formations of the Upper Roan Group and the "albite breccias". Averages of these determinations for particular rock types are as follows:-

Dolomite	=	2.74
Argillaceous dolomite	=	2.80
Albite breccia	=	2.63

The average specific gravity of the Chibuluma amphibolite is 3.02. Details of any original variations of the specific gravity within the major amphibolite body are considered to

have been largely obscured by the subsequent alteration of the rocks, in particular the development of scapolite, amphibole-rich shear zones, and magnetite and carbonate veins. The mean specific gravity curves drawn in Figure 10, therefore, represent only general trends in the variation of specific gravity with depth.

These variations are most marked in NS. 76 where the inner member of the multiple sill shows distinct maximum and minimum points approximately 120 feet and 30 feet (respectively), below its upper contact.

The maximum point, (specific gravity = 3.13) occurs in the pegmatitic zone and the minimum point (specific gravity = 2.84) in the upper part of the mesotype amphibolite. The overall shape of the specific gravity curve, with the exception of the marked maximum, is in general agreement with the typical density curve of dolerite sills presented by Jaegar and Green (1957, p. 29). Both curves show a rapid decrease in specific gravity away from the upper contact of the sill, and then a gradual increase with depth until near the chilled basal contact. Here the specific gravity decreases again, and is approximately equal to that of the chilled upper contact. These salient features appear in the density curve presented by Merriam (quoted by Shrock, 1948, p. 413) for a gabbro sill with an upper dioritic facies. In this case, however, the specific gravity figures are of a lower tenor than those of the Chibuluma amphibolite. Jaegar and Green (1957), and Merriam (Shrock 1948), interpret the variation of density with depth as indicating that some form of gravity controlled differentiation had taken place in the sills during crystallisation of the magma. The similar variations in specific gravity of the major amphibolite

body at Chibuluma, therefore, imply that a similar differentiation has taken place in this sill. Certain differences exist between the standard specific gravity curves, and those of the Chibuluma sill. The most marked of these is the high specific gravity of the pegmatitic zone, the explanation for which is found in the micrometric data that show an unusually high content of iron oxides in these rocks.

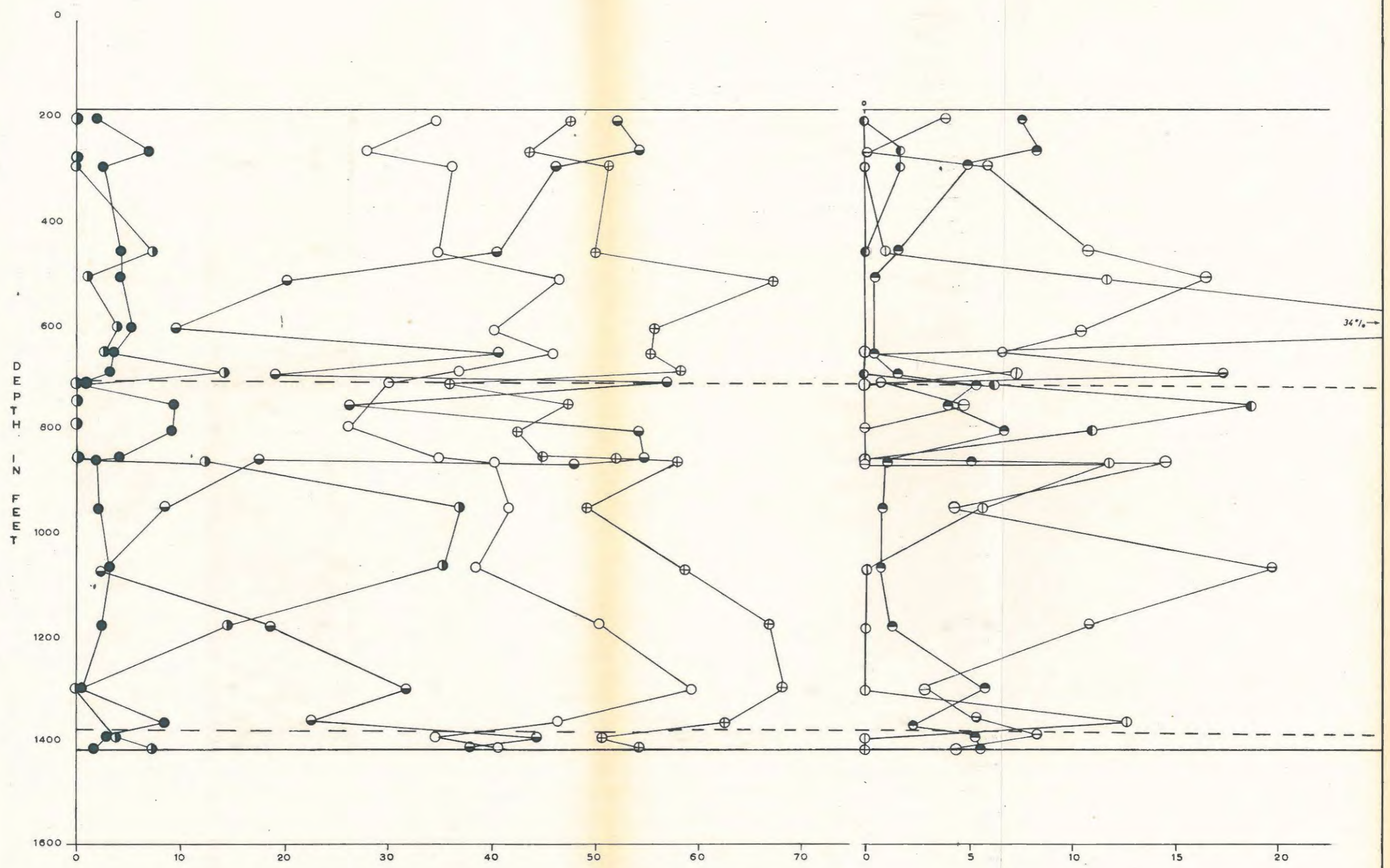
In both NS. 76 and NS. 82 the zone of high specific gravities coinciding with the pegmatitic amphibolite zone is more pronounced in the inner member of the sill than in the outer member. This possibly represents a higher degree of differentiation in the inner member which, in turn, possibly reflects a slight difference in composition between the magmas of the two phases of intrusion.

MICROMETRIC DATA

The mode of a rock is defined by Rice (1943, p. 256) after Holmes as "the actual mineral composition of a rock expressed quantitatively in percentages by weight". No modes as such were determined by the writer, but the volume percentages of the major minerals were determined from 35 thin sections of the major amphibolite body. The zoned nature of the plagioclase, amphibole and scapolite crystals, and the very altered nature of the rock, precluded any accurate determination of the densities of individual minerals and, therefore, these volume percentages have not been converted to weight percentages.

The thin sections studied were selected from drill-holes NS. 76 and NS. 82 and the analyses were carried out by means of a Cooke, Troughton, and Simms electronic particle counter used as an integrating stage. The distance traversed on each thin section was more than two hundred times the length of the largest grain traversed. The very altered nature of the rock limited the accuracy of the determinations to  $\pm 3$  per cent.

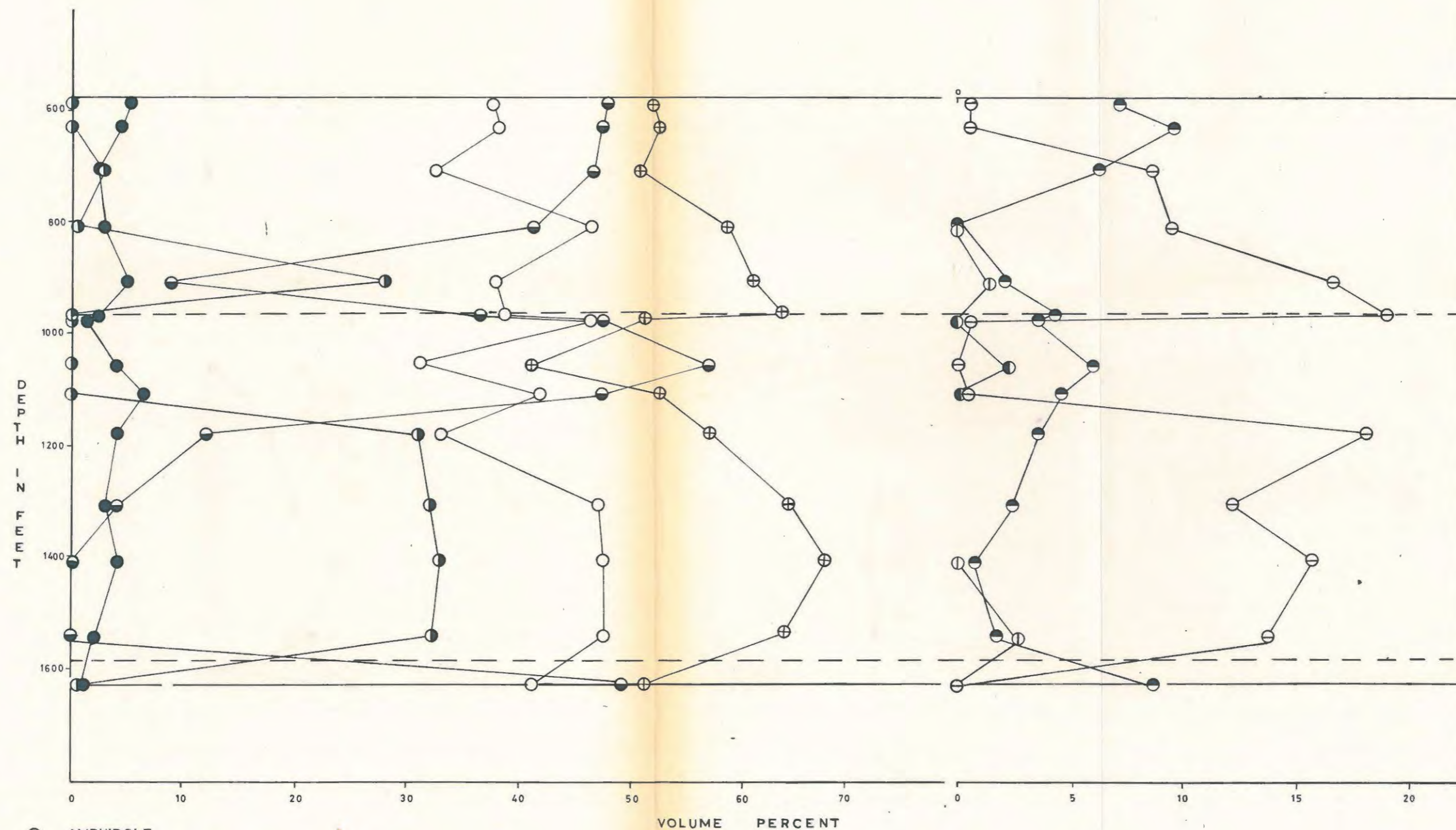
The alteration obscures the original nature of the amphibolite and, therefore, possibly obscures features which could point to differentiation within the sill. The writer, therefore, attempted to determine the colour index of the original rock which is not necessarily that of the present rock. In doing this, use was made of the original subophitic texture which is recognisable in partially scapolitised or completely albitised rocks. The volumes of the felsic minerals albite, scapolite and basic plagioclase occupying the position of the original basic plagioclase laths were determined individually and no account was taken



- AMPHIBOLE
- ⊙ BASIC PLAGIOCLASE
- ALBITE
- ⊖ SCAPOLITE
- ⊕ QUARTZ & MICROPEGMATITE
- ⊗ BIOTITE
- ⊘ SPHENE
- OPAQUE MINERALS
- ⊕ COLOUR INDEX

VARIATIONS OF MODE WITH DEPTH  
IN THE MAJOR AMPHIBOLITE BODY INTERSECTED  
IN DRILLHOLE NS 76





- AMPHIBOLE
- ① BASIC PLAGIOCLASE
- ALBITE
- SCAPOLITE
- QUARTZ & MICROPEGMATITE
- ⊖ BIOTITE
- SPHENE
- OPAQUE MINERALS
- ⊕ COLOUR INDEX

VARIATIONS OF MODE WITH DEPTH  
 IN THE MAJOR AMPHIBOLITE BODY INTERSECTED  
 IN DRILLHOLE NS 82

of the inclusions of epidote, clinozoisite, chlorite, and biotite. These minerals appear to have been formed during alteration of basic plagioclase to acid scapolite or albite.

The volume percentages of the amphibolite minerals were determined according to the following groupings:-

- (a) Amphibole - all varieties and including chlorite where it replaces the amphibole.
- (b) Original basic plagioclase - clouded, pinkish brown, polysynthetically twinned.
- (c) Scapolite - in whatever form it occurs.
- (d) Altered feldspar - albite replacing the original basic plagioclase laths and crowded with inclusions of epidote, chlorite, clinozoisite and biotite.
- (e) Quartz and Micropegmatite.
- (f) Biotite - only where it occurs as an alteration product of amphibole.
- (g) Sphene.
- (h) Opaque Minerals.

The original colour index is the sum of categories (a), (f), (g), and (h). (This is not strictly accurate as volume percentages and not weight percentages are used).

Zircon, apatite, calcite, potash feldspar, and rutile are common, but occur in only small amounts, and their percentage volumes were, therefore, not determined individually. The results of the volume percentage determination for the various minerals are represented graphically in Figures 11 and 12, the salient features of which are:

- (a) the predominant minerals are amphibole, albite, scapolite, and biotite;

- (b) the variations in amphibole content are reflected by the variation in colour index;
- (c) the colour index curve indicates a mesotype zone at the top of each phase of intrusion and a melanocratic zone towards the base of each phase thus confirming megascopic observations;
- (d) both biotite and scapolite are largely confined to the melanocratic zone;
- (e) albite and scapolite contents vary antipathetically;
- (f) the present content of original basic plagioclase varies considerably between points in a single drillhole and between equivalent positions in different drillholes. Maximum amounts recorded from drillholes NS. 76 and NS. 82 are 33.1 per cent and 2.5 per cent respectively;
- (g) the sphene content increases abruptly towards the outer margins of the amphibolite body and is also relatively high in the mesotype zones;
- (h) the opaque minerals, together with quartz and micropegmatite are most abundant in the mesotype zones.

MINERALOGICAL CLASSIFICATION

The term amphibolite is defined by Rice (1943, p. 13, after Holmes) as "a granulose or glomero-blastic metamorphic rock, consisting essentially of amphibole and plagioclase, and often containing quartz, epidote, or garnet". The Chibuluma amphibolites readily fit this description. The question whether the Chibuluma rocks are ortho- or para-amphibolites is discussed in detail in the section on petrology, but for the purpose of the mineralogical classification, the writer accepts an igneous origin for the rocks.

Detailed mineralogical classification depends upon the nature of the original igneous rock. Assuming that the feldspar laths now consisting largely of albite were originally labradorite, the mineralogical classification of the Chibuluma amphibolite, following the system of Johannsen (1931, Vol. 1, p. 141), identifies the original rocks as belonging to the gabbro family designated 2312 P. The gabbro family is subdivided according to the predominant ferromagnesian mineral and the rock type closest to the Chibuluma amphibolites is hornblende-gabbro or bojite. Johannsen (1932, Vol. 3, p. 226) defines hornblende-gabbro as consisting of primary hornblende and basio plagioclase, and differing from diorite in that it contains labradorite or bytownite instead of oligoclase or andesine. Hornblende-gabbro differs from uralite-gabbro in the primary nature of the hornblende in the former, and Johannsen prefers the name Bojite to hornblende-gabbro in order to emphasize this difference.

In the mesotype amphibolite the original plagioclase

appears to have been less basic than in the melanocratic amphibolite. This is indicated by the greater abundance of epidote and clinozoisite inclusions in the secondary albite of the latter. Johannsen's classification places this rock, in which oligoclase is the predominant feldspar and ferromagnesian minerals total less than 50 per cent of the rock by volume, in the 2212 P or diorite family. The melanocratic amphibolite in which the colour index is greater than 50 is classified in the melagabbro or 3312 P family.

Any classification beyond the broad families stated above is impracticable in that no information is available regarding the presence or amounts of original olivine and pyroxene on which more detailed nomenclature is based. It would appear therefore that while the main mass of the amphibolite body was originally a gabbro or hornblende-gabbro, more acid phases were near diorite in composition, and more basic phases were melagabbros.

The petrography of the individual types of amphibolites is described below.

#### MELANOCRATIC AMPHIBOLITE

The greater part of the Chibuluma amphibolite is a uniformly coarse-grained, dark greenish grey rock which the writer has termed the melanocratic amphibolite (Plates 6 and 10). This rock consists of amphibole, albite, scapolite, biotite and accessory chlorite, opaque oxides, and sphene, and it constitutes the lower two thirds of each member of the multiple sill. The colour index is normally between 58 and 67 but may be as low as 49 in the scapolite-rich rocks.

The melanocratic amphibolite of the major amphibolite body has a chilled lower margin, but it passes gradationally into the lighter mesotype amphibolite above. Pegmatitic amphibolite schlieren cut the rock near its upper limit.

The texture exhibited by the rock is one in which the amphibole and feldspar exist in a sub-ophitic relationship. Replacement of the original basic plagioclase by albite preserves this texture and the zoned nature of the original plagioclase is shown by varying concentrations of epidote and clinozoisite in the secondary albite. In scapolitisation however, the sub-ophitic texture is preserved only during the early stages. In the advanced stages of scapolitisation euhedral porphyroblasts of scapolite are developed at the expense of both feldspar and amphibole and the rock appears very coarse-grained and spotted and has a lower colour index than normal. Phenocrysts of feldspar are rare.

Micrometric analyses of the melanocratic amphibolite are presented in Table III, together with volume percentages of minerals in a diorite and an amphibolite as quoted by Johannsen (1932).

#### Individual Minerals

Amphibole is the most common mineral constituting 43 per cent of the rock on average. Amphibole occurs typically as short crystals averaging 4.0 mm maximum length. Zoning is pronounced in the amphiboles towards the base of the sills. These have colourless cores, green mantles and narrow blue-green rims. Twinning is uncommon.

Feldspar laths occur up to 3.5 mm in length. The amount of original basic plagioclase still present

TABLE III  
MICROMETRIC ANALYSIS OF MELANOCRATIC AMPHIBOLITE  
 (Volume Percentages)

	1	2	3	4	5	6	7	8	9	10
Amphibole	46.8	37.0	41.6	38.6	46.2	38.8	47.5	47.3	58.80	50-55
Basic Plagioclase	11.8	7.7	5.5	0.2	-	-	-	1.5	38.82	40-50
Albite	20.3	19.6	8.7	2.5	41.2	36.5	-	3.1	-	-
Soapolite	0.6	14.1	37.0	35.5	0.2	0.4	32.7	30.2	-	-
Quartz and Micropegmatite	-	-	-	-	-	-	-	-	-	-
Biotite	16.0	17.0	5.2	19.9	9.4	18.6	15.4	13.6	-	2-5
Sphene	0.3	1.5	0.3	0.3	0.1	1.6	0.3	1.5	-	Tr.
Opaque Minerals	4.3	3.0	1.9	3.0	3.0	4.1	4.1	2.8	2.40	2-4
Colour Index	65.4	58.6	49.0	58.2	58.7	63.1	67.3	65.2	60.2	60

- 1 Chibuluma amphibolite NS.76 at 501 feet
- 2 Chibuluma amphibolite NS.76 at 684 feet
- 3 Chibuluma amphibolite NS.76 at 951 feet
- 4 Chibuluma amphibolite NS.76 at 1,060 feet
- 5 Chibuluma amphibolite NS.82 at 800 feet
- 6 Chibuluma amphibolite NS.82 at 961.5 feet
- 7 Chibuluma amphibolite NS.82 at 1,399 feet
- 8 Chibuluma amphibolite NS.82 at 1,525.5 feet
- 9 Diorite Pajaro River California, Johansen (1932, Vol. 3, p. 241)
- 10 "Amphibolite" Prospect Hill, (Ibid, p. 330)

depends upon the amount of alteration of the basic plagioclase to albite or scapolite and therefore differs considerably between samples only a few feet apart. The general trend, however, is for the original feldspar to be preserved in the rocks nearest to the base of the sill. The amounts of albite and scapolite present also differ over short distances within the sill. Both biotite and chlorite occur mainly as alteration products of the amphibole.

The opaque minerals are found mainly as small crystals within the amphibole. Sphene is associated with ilmenite, and epidote and clinozoisite occur as alteration products of the basic plagioclase.

#### THE MESOTYPE AMPHIBOLITE

The upper 70 to 120 feet of each member of the multiple major amphibolite body consists of a medium- to coarse-grained mesotype rock composed largely of albite and amphibole (Plate 11) with ilmenite, sphene, quartz, and epidote as minor accessories. The relatively light colour of this rock, due largely to the abundance of white to cream feldspar laths, is a characteristic feature which readily distinguishes it in hand specimens from the other types of amphibolite and this rock is, therefore, termed the mesotype amphibolite. Colour indices range from 40 to 53.

The mesotype amphibolite is thicker in the inner member of the amphibolite sill than in the outer member, but in each member the upper contact of the mesotype amphibolite is chilled against the rocks above. There is no appreciable difference in colour between the chilled and coarse-grained rocks. The mesotype amphibolite passes downwards into the



pegmatitic amphibolite zone in which it forms a large part of the host rock for the coarse-grained segregations or schlieren (Plate 9) and passes gradually into melanocratic amphibolite by a progressive downward increase in amphibole content. The texture in the mesotype amphibolite is diabasic with discrete amphibole crystals filling the interstices between lath-shaped feldspars. With increasing amphibole content this texture is replaced by the sub-ophitic texture.

Results of micrometric analyses of the mesotype amphibolite are presented in Table IV and are compared with volume percentages of minerals in a diorite and a hornblende-gabbro quoted by Johannsen (1932).

#### Individual Minerals

Albite is the dominant mineral in the rock, occupying 40 to 55 per cent by volume. Laths of albite show no preferred orientation in the rock. More basic plagioclase is very rare but from the distribution of epidote and clinozoisite in the albite crystals, it appears that basic plagioclase formed the cores of these crystals before albitisation took place.

Amphibole content of the rock ranges from 26 to 40 per cent by volume and the crystals commonly exhibit deep blue margins but do not have colourless cores as in the melanocratic amphibolite. Biotite is present in amounts below 1 per cent and is associated with the amphibole. Quartz occurs interstitially in variable amounts ranging from 0.2 to 2.4 per cent. Scapolite is entirely absent. Sphene is very common and forms up to 9 per cent of the volume of the rock. It is associated with magnetite and ilmenite which together occupy up to 8 per cent of the rock.

TABLE IV  
MICROMETRIC ANALYSES OF MESOTYPE AMPHIBOLITE  
 (Volume Percentages)

	1	2	3	4	5	6	7	8	9	10	11	12
Amphibole	34.7	28.3	36.2	35.1	44.7	37.6	38.1	47.4	44.0	41.9	30.79	42.98
Basic Plagioclase	-	-	-	-	-	1.6	-	-	-	-	56.03	54.73
Albite	52.2	54.5	46.3	57.1	48.4	46.3	47.5	46.1	48.0	47.0	-	-
Scapolite	-	-	-	-	-	-	-	-	-	-	1.14*	0.10*
Quartz and Micropegmatite	0.2	1.7	2.4	0.3	0.2	2.0	0.2	1.5	1.3	0.4	1.39	1.34
Biotite	3.6	-	6.0	-	-	0.7	0.1	0.3	0.4	-	8.33	-
Sphene	7.8	8.2	5.4	6.1	4.5	5.7	6.5	3.5	2.9	4.6	-	-
Opaque Minerals	1.5	7.3	3.6	1.4	2.1	6.1	7.6	1.2	3.4	6.1	-	0.85
Colour Index	47.6	43.8	51.2	42.6	51.3	50.1	52.3	52.4	50.7	52.6	41.44	43.83

- 1 Chibuluma amphibolite NS.76 at 198 feet  
 2 Chibuluma amphibolite NS.76 at 258 feet  
 3 Chibuluma amphibolite NS.76 at 283 feet  
 4 Chibuluma amphibolite NS.76 at 706 feet  
 5 Chibuluma amphibolite NS.82 at 573.5 feet  
 6 Chibuluma amphibolite NS.82 at 574.5 feet  
 7 Chibuluma amphibolite NS.82 at 624.5 feet  
 8 Chibuluma amphibolite NS.82 at 965 feet  
 9 Chibuluma amphibolite NS.82 at 968.5 feet  
 10 Chibuluma amphibolite NS.82 at 1,020.5 feet  
 11 Hornblende gabbro - Johannsen (1932, vol. 3, p. 217)  
 12 Diorite, Coast Batholith, Vancouver (Ibid, p. 154)

\* Apatite

PEGMATITIC AMPHIBOLITE

Numerous, mutually parallel, very coarse-grained segregations or bands of amphibolite occur so consistently in a narrow zone from 70 to 120 feet below the upper contact of each component of the multiple sill, that a distinct unit can be recognised. This unit has been termed the pegmatitic zone, and is best developed in the inner member of the multiple sill, where its width ranges from 40 to 80 feet. Up to sixteen separate pegmatitic horizons have been noted in this zone which, in effect, constitutes a division between the mesotype and melanocratic amphibolites although the segregations themselves occur in both types. Individual bands or schlieren (Plates 8 and 9) are from three inches to four feet thick. The thickness of finer-grained amphibolite between successive pegmatitic segregations averages approximately one foot, but has been noted to be up to 15 feet. Rare intersections (NS. 76 at 850 feet) have shown that, in places, the individual segregations bifurcate.

The shape of each segregation cannot be determined accurately from drillhole cores, but by analogy with other pegmatitic differentiates of basic sheets (Walker 1953, p. 42), they are probably lens-shaped or tabular schlieren or veins possibly flattened parallel to the main contacts of the major sill. The lengths of individual schlieren are normally from two to ten feet although Eales (1959, p. 85) has described one such segregation approximately three inches thick that could be traced for 50 feet in the upper part of the Khale Dolerite sheet. The contacts between the Chibuluma pegmatitic schlieren and the host rocks are well defined, but are irregular in that they are not strictly planar.

The pegmatitic bands are strongly variable both in texture and in composition, but they consist mainly of large laths of amphibole and feldspar in intergranular to sub-ophitic relationship, with a well developed mesostasis of micropegmatite. Ilmenite is abundant and apatite, sphene, and biotite are common accessories.

Modal analyses carried out on thin sections cannot be regarded as accurate because of the extremely coarse-grained nature of the pegmatite. Megascopic modal analyses are on the other hand less accurate and can neither determine relative amounts of such minerals as apatite and biotite, nor distinguish between the felspar laths and the micropegmatitic mesostasis. Results of both methods, therefore, have been included in Table V. The average of the twelve modes of dolerite pegmatites presented by Walker (1953, p. 45), and the mode of Karroo dolerite-pegmatite from the type locality, Alewyn's Gat (Walker and Poldervaart 1949, p. 619), are also included for comparison.

The amphibole content of the pegmatite varies considerably from 26 to 37 per cent, but the more mafic varieties are rare. Feldspar, quartz, and micropegmatite are the only felsic constituents, and the colour index ranges from 43 to 52. This, when compared to the equivalent range of 33 to 46 shown by Walker's twelve modal analyses (1953, p. 45), indicates that the average Chibuluma pegmatite is a dark variety.

The opaque mineral content, particularly in the darker pegmatites, is considerably higher than that of the average or typical modes quoted in Table V. These high values are not unknown however, as Walker (1953, p. 45) re-

TABLE V

MICROMETRIC ANALYSES OF PEGMATITIC AMPHIBOLITE  
(Volume percentages)

	1	2	3	4	5	6
Amphibole	28.2	26.3	35	37	25.9*	28*
Feldspar	34.3 <sup>+</sup>	45.5	} 55	48	40.5	35
Micropegmatite and Quartz	18.2	10.8			17.3	25
Opaque Minerals	9.5	9.3	5	11	8.7	8
Sphene	5.0	6.7	5	4	} 7.4	4
Biotite	4.8	0.2	-	-		
Colour Index	47.5	43.7	45	52	42.2	40

- 1 NS.76 at 752 (thin section)
- 2 NS.76 at 798 (thin section)
- 3 NS.76 at 847 ft. (hand specimen)
- 4 NS.76 at 850 ft. (hand specimen)
- 5 Average of 12 dolerite-pegmatite modal analyses presented by Walker (1953, p. 45) (Weight percentages)
- 6 Modal analysis of dolerite-pegmatite from type locality - Alewyn's Gat. (Walker and Poldervaart, 1949, p. 619) (Weight percentages)

\* for amphibole read pyroxene

+ The feldspar includes approximately 8% basic plagioclase

corded a pegmatitic schlieren and a pegmatitic vein with 13.0 and 15.0 weight per cent iron ore respectively.

#### Individual Minerals

Amphiboles occur typically as large, curved, branched, and twinned laths up to 48 mm. long and 14 mm wide. The only preferred direction of growth noted was on the contacts with the host rock where clusters of mutually parallel amphibole laths occur perpendicular to the contact. The amphibole is typically the dark green variety and shows soda-rich rims, but no strongly zoned cores.

Feldspar laths are up to 25 mm long and 7 mm wide, and together with the amphiboles form a diverse network enclosing interstitial micropegmatite and quartz. The feldspars have been almost completely albitised and the inclusions of epidote and micropegmatite point to the basic nature of the original plagioclase. Up to approximately 15 per cent of the original clouded brown plagioclase remains unaltered in some thin sections and was determined to be andesine  $An_{44} \cdot Ab_{56}$ . Zoning in these crystals is absent or poorly developed. Albite is the only feldspar intergrown with quartz in the micropegmatite. Micropegmatite is largely interstitial and does not appear to be replacing the feldspar laths. Potash feldspar forms up to 2 per cent of the rock in some specimens and also occurs interstitially to the plagioclase.

Magnetite occurs in large masses and in clusters of small anhedral crystals typically replacing up to 30 per cent of the amphibole. Ilmenite occurs as skeletal crystals or plates which are normally surrounded by sphene selvages. Unusual "swarms" of thin, parallel sheets of ilmenite were noted in

NS. 76 at 273 feet. Individual sheets are 0.5 mm thick and occur 25 mm apart. These sheets intersect all other minerals, and are themselves cut by a later magnetite veinlet. Sphene also occurs in large masses apparently replacing amphibole.

Biotite is associated with the amphibole, but is rare. Acicular apatite crystals (with a maximum length of 4.8 mm) are a common feature of the micropegmatite masses. They do not appear to intersect any amphibole crystals and their margins are corroded in appearance. Scapolite crystals have only rarely been noted replacing the original feldspar although scapolite is a common constituent of the melanocratic amphibolite host rock.

Throughout the pegmatite bodies small inclusions of epidote and clinozoisite occur in the albitised feldspar laths and in sporadic zones they completely replace the feldspar giving rise to an epidote-amphibole rock. The pegmatitic schlieren do not appear to have affected the adjacent host rock in any manner except in the case of the melanocratic schlieren where the magnetite content of the host appears to be considerably higher than normal. This feature was noted only in megascopic observations and was not verified under the microscope. Walker (1953, p. 43) considered that there was never any alteration of the adjacent dolerite by the dolerite-pegmatite .

Although no measurements of magnetic susceptibility or intensity of magnetisation were undertaken by the writer, certain anomalous results of early surface surveys can be explained by the petrography of the amphibolites. The western limit of the major amphibolite body coincides approximately with the -200 gamma contour. This relationship is ascribed to the

generally high iron oxide content of the amphibolite compared to that of the sedimentary formations. Furthermore, a marked eastward trending band of high magnetic values coincides with the suboutcrop of the pegmatitic zone of the inner member of the multiple sill. This is due to the high magnetite and ilmenite content of the pegmatitic zone possibly resulting from the late stage concentration of iron along with the volatiles. Similar high magnetic intensities have been recorded from the pegmatitic dolerite schlieren of basic sills in Tasmania (Jaeger and Joplin, 1954, p. 10).



STRUCTURAL FEATURES

A number of structural features associated with the amphibolite sills are of interest.

The most striking of these features is the multiple nature of the sill. All evidence points to the early formed sill having been intruded by a second sill along a plane approximately fifty feet above its basal contact. That the first sill was solid or nearly so at the time of the intrusion of the second sill is borne out by the sharply defined, chilled contacts of the second sill against the first. In addition, in drillhole NS. 76, a "xenolith" of coarse-grained melanocratic amphibolite three inches in diameter occurs in the fine-grained, chilled amphibolite eight feet above the basal contact of the second sill.

Two features of the contact zones between the two phases of intrusion of the multiple amphibolite sill are of particular interest. These are the development of characteristic jointing in the fine-grained chilled margins and the orientation of feldspar laths in this fine-grained material parallel to the plane of the contact.

Jointing

The orientation of joints normal to the contacts in the fine-grained amphibolite adjacent to coarse-grained amphibolite (Plate 6) suggests that these joints are possibly a form of prismatic or columnar jointing formed during contraction of the rock (on cooling). Iddings (1909) described the causes and mechanism of columnar jointing and showed that close spacing of joints is due to rapid cooling and that curved



joints are due to different rates of cooling, at various points either on the surface of, or within, the cooling mass. The range in spacing of joints given by Iddings is from one inch or less, up to twenty feet. The spaces between joints investigated by the writer were measured on a random section perpendicular to the contact and averaged 0.7 inches with a maximum of 1.6 inches. This, from the size ranges quoted above, would be regarded as close spacing, indicative of rapid cooling.

One common megascopic method of determining earlier or later phases in a multiple or composite igneous body is by the study of their joint patterns. If, of two sets of joints, one set terminates abruptly against the mutual contact between the two igneous rocks, and the other set traverses the contact, then the rock containing the first set is usually regarded as the older as the other rock is considered to post-date this jointing. This, however, is only valid where jointing is caused by "external" tectonic stresses acting upon the igneous rocks, and does not appear to apply in the above case where jointing is caused by "internal" stresses due to cooling and contraction.

The presence of this prismatic jointing does not indicate definitely that the inner amphibolite body is the later phase of the multiple sill, as the jointing may have been developed adjacent to a contact with sedimentary rocks, and subsequent intrusion may have enveloped the first sill rather than intruded it.

In addition to the jointing in the chilled margins of the amphibolite, jointing is present throughout the rock. No analysis has been undertaken, but the joints commonly occur



Plate 10. AMPHIBOLITE.

A zone of brecciated melanocratic amphibolite. The interstitial matrix is amphibole and chlorite.

NS 70, 1621'.

(X 0.60).

in well developed parallel sets. Alteration of the amphibolite has taken place along these joints, and the minerals developed on the joint planes are calcite, prismatic amphibole, chlorite, and less commonly specular haematite, magnetite, gypsum, anhydrite, and pyrite. Different mineral assemblages on intersecting sets of joints suggests that the jointing is of diverse ages. Joint surfaces commonly exhibit slickensides which show that both thrust and normal fault movements have taken place along these planes. In drillhole NS. 82 at 1,354 feet, two superimposed sets of slickensides on a specular haematite surface show that more than one phase of movement took place. This is confirmed by the presence of bent and foliated prismatic amphibole crystals on the joint planes. In localised areas of strong differential movement within the amphibolite, breccias are developed (Plate 10). These most commonly have prismatic amphibole matrices.

#### Crystal orientation along the contacts

The orientation of feldspar phenocrysts on either side of the chilled contacts of the second phase of the multiple sill was studied in drillholes NS. 76 and NS. 82. The angle between the longest axis of each lath and the plane of the contact was measured for all laths occurring up to approximately one inch from the contact, both in the fine-grained chilled amphibolite and in the coarse-grained amphibolite.

The results have been represented graphically in Figure 13 in which the percentages of laths are plotted as

ordinates against their angular deviation from the trace of the contact as abscissae. The percentages are recorded for ranges of angular deviation such as 0-10°, 10-20°, 20-30° up to 80-90°. No regard was taken of whether the laths are orientated with negative or positive angles to the contact, and no attempt was made to undertake a three dimensional analysis. The coarse-grained and fine-grained phases have been plotted on either side of the abscissa zero to emphasize the abrupt change in degree of orientation of the laths. A second set of measurements was made on specimens of the fine-grained amphibolite from 2.0 to 3.5 feet from the contact to determine whether the orientation of laths in this rock at the contact persists throughout the second amphibolite or is limited to a narrow contact zone. These measurements are not represented in Figure 13 as the orientations of the rock sections relative to the contacts were not known. The measurements were of use, however, in that they showed that there was no preferred orientation of feldspar laths a few feet from the contact.

The contacts investigated in detail were the upper contact in NS. 82 at 961 feet and the lower contact in NS. 76 at 1,377 feet. The number of feldspar laths measured in each case is tabulated below:-

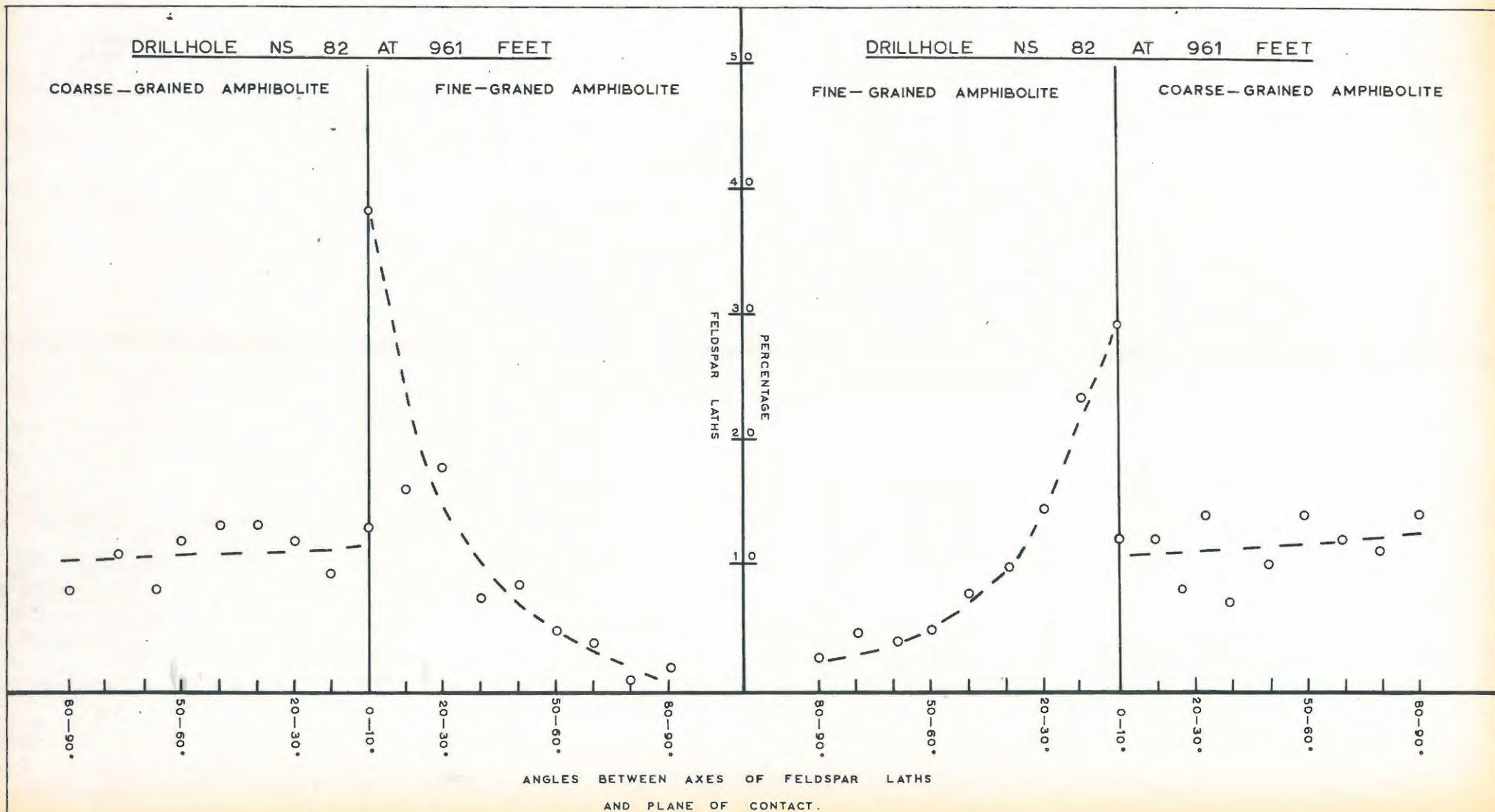
NS. 82	Fine-grained amphibolite on contact	- 106 laths
961 feet	Fine-grained amphibolite 3.5 ft. from contact	- 100 laths
	Coarse-grained amphibolite on contact	- 75 laths
NS. 76	Fine-grained amphibolite on contact	- 150 laths
1,377 feet	Fine-grained amphibolite 2.0 ft. from contact	- 100 laths
	Coarse-grained amphibolite on contact	- 75 laths

In the fine-grained rocks, no measurements were made in the ground mass which consists of a felt of very small feldspar laths with random orientation.

The investigation of the orientation of crystals near the contacts between coarse- and fine-grained amphibolites showed that the crystals are preferentially aligned parallel to the contact in the fine-grained rocks and are randomly orientated in the coarse-grained rocks. At both the upper and lower contacts between coarse- and fine-grained material the fine-grained material exhibits a preferred orientation of crystals, with at least 65 per cent of the crystals being arranged at angles less than  $30^{\circ}$  to the contact.

A few feet from the contact the feldspar laths in the fine-grained rocks are randomly orientated and exhibit a relic ophitic texture with slightly altered laths of feldspar enclosed in hornblende. The coarse-grained amphibolite adjacent to the contact also exhibits an ophitic texture with a random orientation of the feldspar laths, which is further evidence that the inner member of the multiple sill is the younger. If this were not the case, and the outer member had enveloped an inner earlier sill, then orientated feldspar laths should be expected on both sides of the mutual contact.

Apart from the orientation of feldspar laths, no linear features are apparent in the microscopic fabric of the rock. The normal sub-ophitic and diabasic textures are unstrained in appearance. A schistose or flow texture was noted in drillhole NS. 82 from 400 to 440 feet in melanocratic amphibolite, but it is a poorly developed local feature only. No fabric suggestive of rhythmic layering or banding was noted.



ORIENTATION OF FELDSPAR LATHS NEAR INTERNAL CONTACTS

FIGURE 13

## MINERALOGY

In describing the mineralogy of the Chibuluma amphibolites, the writer has not restricted himself to a simple statement of the properties of the minerals, but has included discussions on the origin and significance of those features which were considered to be of particular importance or interest. By including these discussions under mineralogy and not under petrology, where they rightfully belong, he hopes to avoid both repetition of the data and the excessive use of back references.

### NON-OPAQUE MINERALS

#### AMPHIBOLE

Amphibole is the most abundant mineral in the Chibuluma sills and is subordinate to feldspar only in the mesotype zones of the major amphibolite body. Modal analyses show that the amphibole content of the amphibolite is between thirty and fifty-five per cent by volume. The only variety found in the sills is hornblende which shows marked variations in composition and colour. Single crystals commonly exhibit zoning with colourless cores, strongly pleochroic green mantles, and narrow outer mantles of bluish green sodic hornblende. The optical properties of the hornblende are, therefore, presented on the basis of these divisions.

Identification was made using immersion methods for measurement of refractive indices and the universal stage for extinction and optic axial angles. The majority of universal stage determinations were made on basal or near-basal sections with fairly well defined cleavage traces. These could be orientated with the Y-vibration direction horizontal, enabling the writer to determine both the extinction angle and the optic axial angle.

Two further universal stage methods for determining the



extinction angles were used on a number of sections parallel to the c-crystallographic axis. These methods involved the direct measurement of the angle (c/Z) after orientating either X or Y horizontally and either the twin plane (100) or the parting parallel to the basal pinacoid (001) vertically. The extinction angle is not, however, of value in specific identification of amphiboles, and this measurement was not considered important.

The accuracy of these determinations is considered to be approximately  $\pm 2$  degrees in the case of the nearly colourless amphibole forming the cores of some crystals, but in the case of the peripheral zones, the higher absorption, strong pleochroism, and alteration, tend to obscure the exact position of extinction and the accuracy falls off.

Refractive index determinations by immersion methods were made in monochromatic light and refractive indices of oils were checked by Leitz-Jelly refractometer. The accuracy of the results is considered to be  $\pm 0.003$ .

The optical properties of the end members of the hornblende series described here may be summarised as follows:

(a) Cores

Biaxial negative (rarely positive)

$$2V_x = 85 - 93^\circ \quad c/Z = 12 - 16^\circ$$

$$N_x = 1.629 \quad X \text{ colourless}$$

$$N_y = 1.641 \quad Y \text{ colourless to very pale green}$$

$$N_z = 1.652 \quad Z \text{ colourless to very pale blue}$$

$$(N_z - N_x) = 0.023$$

Absorption  $Z = Y > X$

(b) Mantle

Biaxial negative

$2V_x$	=	$70^\circ - 85^\circ$	$c/Z = 17 - 24^\circ$
$N_x$	=	1.638	X pale yellowish brown
$N_y$	=	1.648	Y pale green
$N_z$	=	1.655	Z pale bluish green
$(N_z - N_x)$	=	0.017	

Moderate pleochroism

Absorption  $Z > Y > X$

(c) Sodic Rims

Biaxial negative

$2V_x$	=	$55 - 70^\circ$	$c/Z = 24 - 28^\circ$
$N_x$	=	1.672	X yellow-brown
$N_y$	=	1.683	Y green to brownish green
$N_x$	=	1.688	Z deep blue-green
$(N_z - N_x)$	=	0.016	

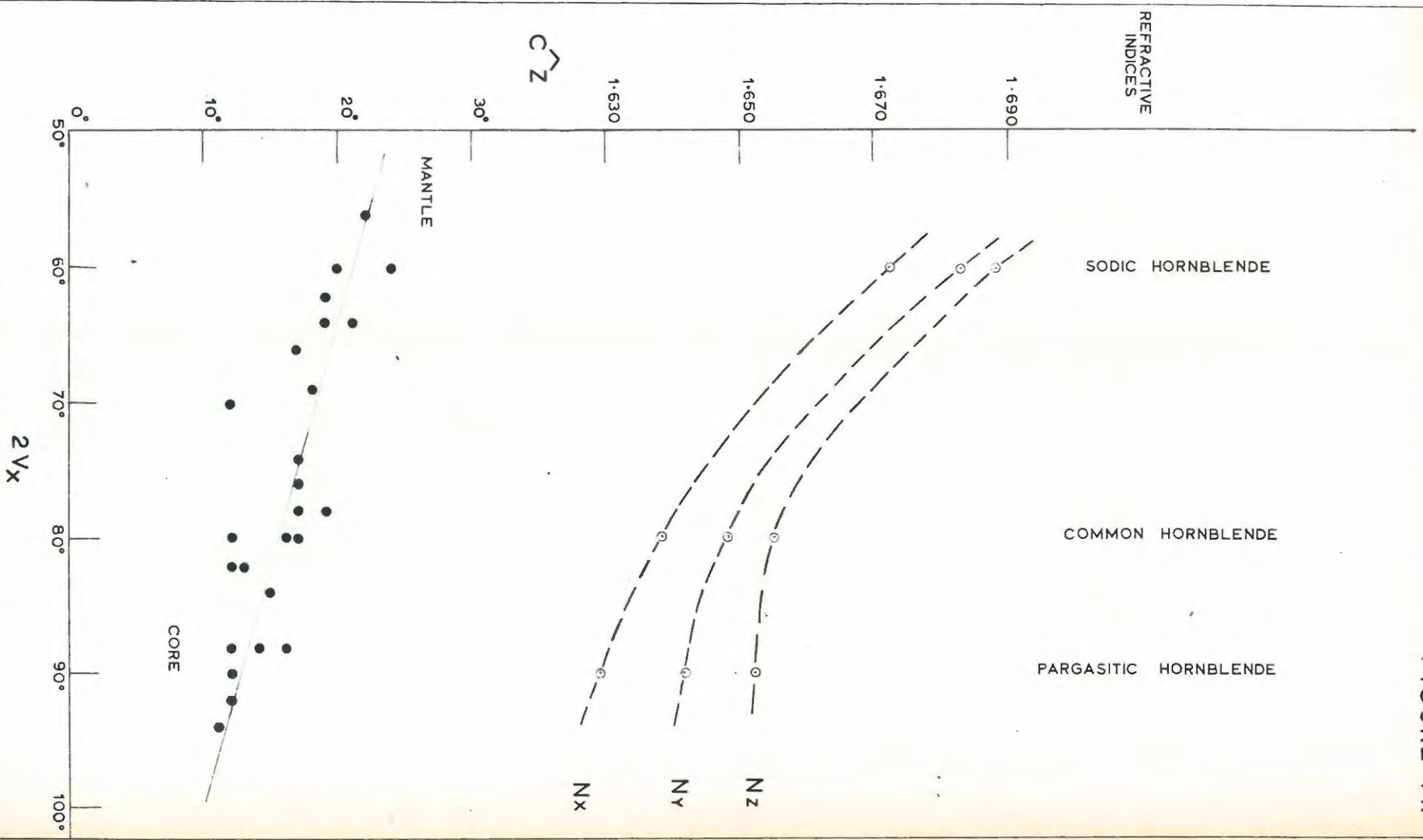
Very pronounced pleochroism

Absorption  $Z > Y > X$

The amphibole exhibits the characteristic  $56 - 124^\circ$  cleavage traces on basal sections, which show symmetrical extinction. The Y-vibration direction is parallel to the longer diagonal and the optic axial plane is parallel to (010).

Zoned crystals extinguish uniformly in sections containing Y but show a variation in extinction angles for all other sections, with a maximum variation in sections perpendicular to Y. The soda-rich rims are generally in crystallographic continuity with the cores although in many cases the soda-rich amphibole occurs in small discrete crystals scattered around the margins of large amphiboles. The zoning is considered to represent a continuous variation in composition of the amphibole in which  $2V_x$  decreases and  $c/Z$  increases outwards from the core of the crystal as is shown in Figure 14.

FIGURE 14.



OPTICAL PROPERTIES OF AMPHIBOLES

### Composition Determinations

The precise identification of amphiboles and the determination of their chemical compositions by optical properties alone is rendered very difficult by the varied and extensive substitutions which are possible within this mineral group. Deer, Howie, and Zussman (1963, Vol. 2, p. 295) consider that the only unequivocal identification is given by chemical analysis. Owing to the poikilitic texture and their high degree of "contamination", the Chibuluma amphiboles were not considered suitable for separation and analysis. In addition, the zoned nature of the amphiboles would add further difficulties to the interpretation of the results. The writer, therefore, decided to rely entirely upon the optical properties in identifying the amphiboles, bearing in mind the probable limitations of this method.

The optical properties of the amphibole given above, place the mineral in the hornblende-tremolite series. The principal diagnostic features which exclude the Chibuluma amphibole from other amphibole series are as follows. The inclined extinction indicates that it is not of the anthophyllite-gedrite series which possesses straight extinction. Its colour and pleochroism, and in the case of the colourless variety, its low refractive indices exclude the Chibuluma mineral from the cummingtonite-grunerite series. Colour also excludes the possibility of the Chibuluma amphibole's being glaucophane or riebeckite. Arfvedsonite and eckermannite exhibit smaller optic axial angles and the latter, lower refractive indices, than the Chibuluma amphibole. Both basaltic hornblende and kaersutite possess distinctive colours, different to that of the Chibuluma mineral, and barkevikite has higher refractive indices.

Deer, Howie, and Zussman (1963, Vol. 2, p. 250) consider that a continuous range in composition exists between tremolite-ferroactinolite and the pargasitic, hastingsitic and tschermakitic hornblendes. The compositions of the principal end members are

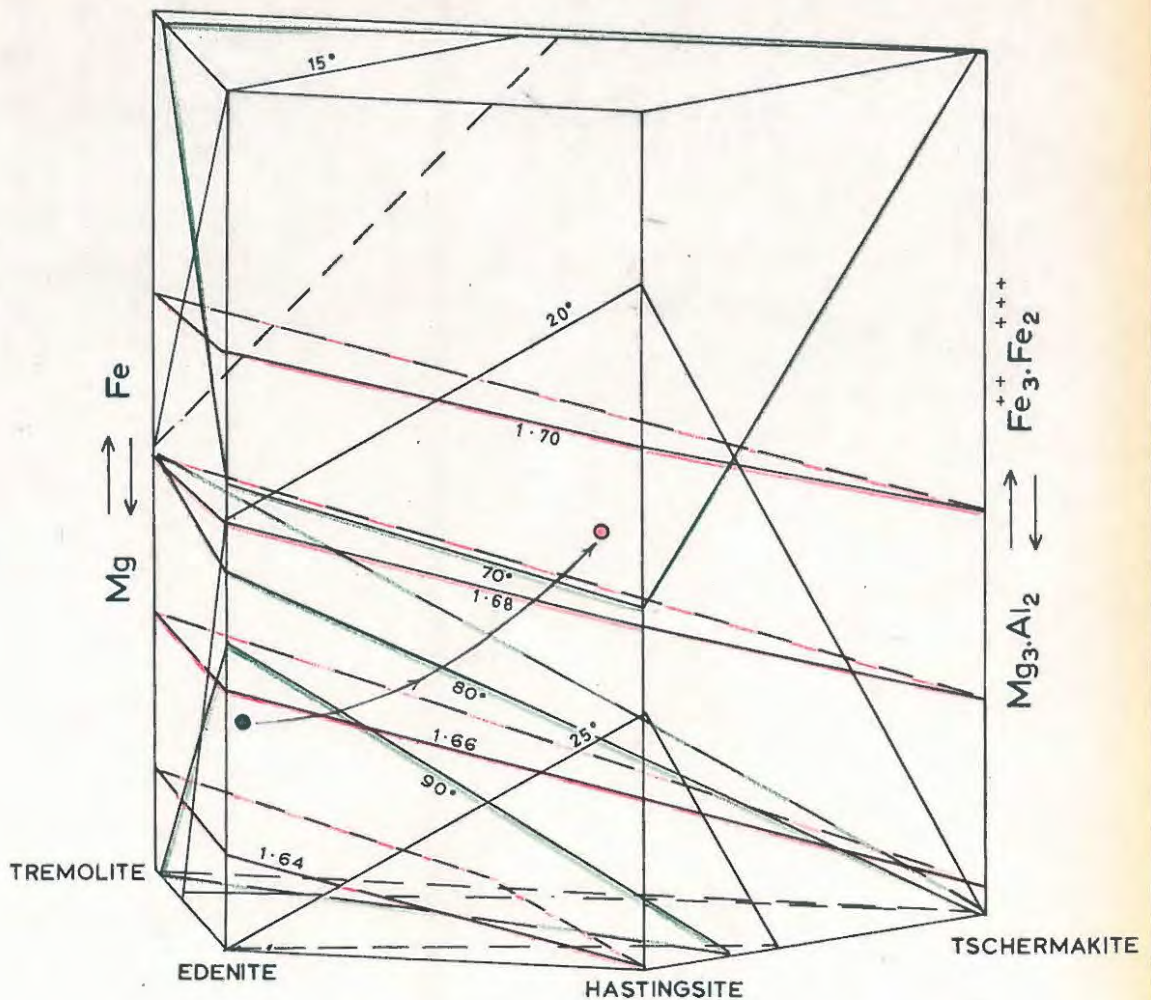
as follows:-

Tremolite	- $\text{Ca}_2\text{Mg}_5(\text{Si}_8\text{O}_{22})(\text{OH},\text{F})_2$
Ferroactinolite	- $\text{Ca}_2\text{Fe}^{++}_5(\text{Si}_8\text{O}_{22})(\text{OH},\text{F})_2$
Common hornblende	- $(\text{Ca}, \text{Na}, \text{K})_{2-3}(\text{Mg}, \text{Fe}^{++}, \text{Fe}^{+++}, \text{Al})_5$ $[\text{Si}_6(\text{Si}, \text{Al}_2\text{O}_{22})](\text{OH}, \text{F})_2$
Pargasite	- $\text{NaCa}_2\text{Mg}_4(\text{AlFe}^{+++})(\text{Si}_6\text{Al}_2\text{O}_{22})(\text{OH}, \text{F})_2$
Ferrohastingsite	- $\text{NaCa}_2\text{Fe}^{++}_4(\text{AlFe}^{+++})(\text{Si}_6\text{Al}_2\text{O}_{22})(\text{OH}, \text{F})_2$
Tschermakite	- $\text{Ca}_2(\text{Mg}, \text{Fe}^{++})_3(\text{AlFe}^{+++})_2(\text{Si}_6\text{Al}_2\text{O}_{22})(\text{OH}, \text{F})_2$

The principal variations in compositions were regarded by Hallimond (1943, p. 73) as being due to the complete diadochy of Mg and  $\text{Fe}^{++}$ , and the replacement of  $\text{Al}_4$  by  $\text{Mg}_2\text{Si}_2$  and  $\text{Si}_2$  by  $\text{Na}_2\text{Al}_2$  in various proportions. That such a continuous series exists in the Chibuluma amphiboles is shown by a number of features. Under crossed nicols, the extinction shadow moves outwards from the colourless cores of zoned crystals on rotation of sections showing maximum extinction angles. Figure 14, in which the optic axial angles are plotted as abscissae against the extinction angles as ordinates, demonstrates the simple linear relationship between the two. Although not related linearly, the refractive indices also show a similar continuous trend with the higher values occurring in the peripheral sodic material.

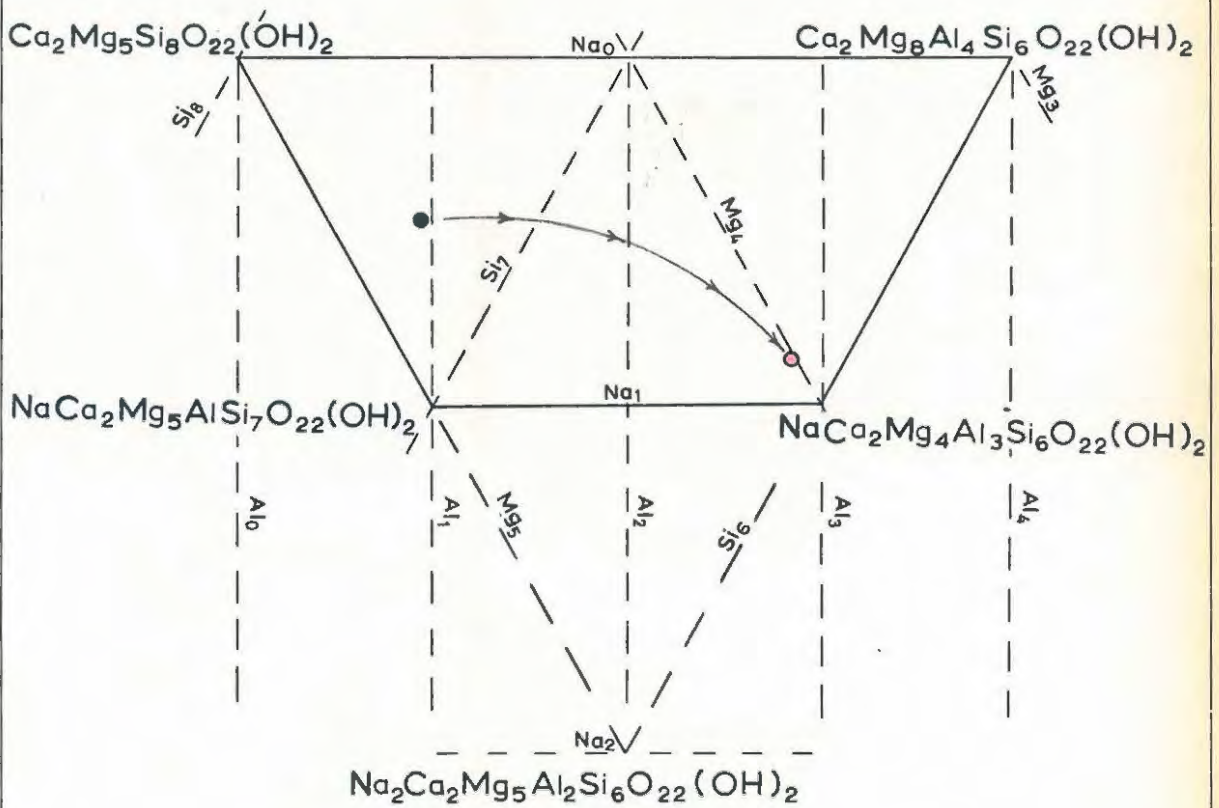
Use was made of the diagram (Figure 15) presented by Winchell (1945, p. 41) to show the variations of optical properties with composition in tremolite-ferro actinolite and the pargasitic, hastingsitic, and tschermakitic hornblendes. Winchell (p. 34) states "it is important to remember that this (partial) triangular column will not correspond to the facts in every case; indeed it will only rarely correspond with all the data - it is only an estimate of the average condition. But it is believed that it will give an approximately correct idea of the composition of a sample of amphibole belonging to this system". Variations in

FIGURE 15.



- CORE
- OUTER RIM

- 2Vx —
- Nz —
- cz —



VARIATION OF OPTIC PROPERTIES  
OF HORNBLLENDE WITH COMPOSITION

AFTER WINCHELL

the optical properties of the zoned Chibuluma amphibole indicate that the trend in composition is from a pargasitic hornblende core to a mantle, enriched in iron, aluminium and sodium. The optic axial angles and refractive indices of the Chibuluma amphibole are in close agreement with those of the common hornblende series shown in the diagram given by Deer, Howie, and Zussman (1963, Vol.2, P.296). They differ, however, in the optic axial angles and refractive indices of the pargasite - hastingsite - ferrohastingsite series given by the same authors.

#### Optic Axial Angle and Extinction Angle Relationship

Although Deer, Howie, and Zussman (1963, Vol. 2, p. 300) consider that the maximum extinction angle of amphiboles is not a diagnostic feature, the inverse linear relationship between  $2V_x$  and  $c/Z$  of the Chibuluma amphiboles merits comment. This relationship is shown in Figure 14.

A decrease in  $2V_x$  outwards from the core of a zoned amphibole is considered by Deer, Howie, and Zussman (p. 300) to be an expression of marginal iron enrichment.  $2V_x$ , in fact, increases with increase of iron content in the cummingtonite-grunerite series, the tremolite-ferroactinolite series, and in the various hornblende series. Where the extinction angle  $c/Z$  is known, this also decreases with increase in iron content. In contrast, the Chibuluma amphiboles display a normal decrease in optic axial angle towards the peripheral zones but an increase in  $c/Z$  over the same range. This inverse relationship is not unknown, however, and was recorded by Poldervaart and von Backström (1949, p. 446) in the amphibole crystals of the basic rocks of the Kakamas area. In this case the range of  $2V_x$  is only  $60 - 80^\circ$  and  $c/Z$  only  $17 - 14^\circ$ , both being considerably less than those of the Chibuluma amphiboles.

The linear appearance of this relationship is, therefore, interpreted by the writer as being indicative of a simple sub-



Plate 11. MESOTYPE AMPHIBOLITE.

Albite (ab) laths and interstitial amphibole (a) in a mesotype amphibolite. Inclusions in the albite are mainly epidote and clinozoisite. One large epidote (ep) crystal is enclosed in albite. Sphene (sp) is also present.

NS 76, 706'.

Photomicrographs (X 27),  
 (a) Plane polarised light,  
 (b) Crossed nicols.

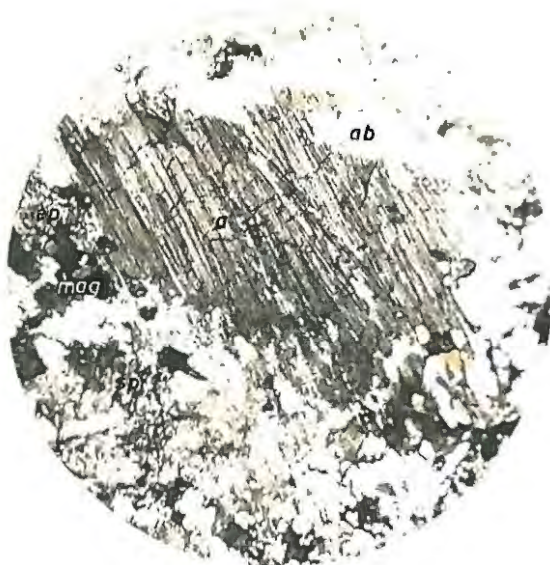


Plate 12. MELANOCRATIC AMPHIBOLITE.

Amphibole (a) crystals developed in a small shear zone in the melanocratic amphibolite. Other minerals are albite (ab), epidote (ep), magnetite (mag), and sphene (sp).

NS 76, 1378.5'.

Photomicrograph (X 27),  
 Plane polarised light.



stitution series with a progressive increase outwards from the core, of some element other than iron, probably sodium, which has a greater effect on c/Z than does the increasing iron content. In this respect, it is of interest to note the high c/Z and low  $2V_x$  values of the soda amphibole arfvedsonite, which is a common constituent of plutonic alkali igneous rocks.

To summarise, the three varieties of hornblende are considered to be:-

- (a) pergasitic hornblende, forming the cores of a limited number of crystals;
- (b) common hornblende, comprising the bulk of the amphibole;
- (c) a soda- and iron-rich variety of common hornblende, forming mantles to the majority of amphibole crystals.

### Textures

The amphiboles exhibit a wide range of textures, each of which assists in the interpretation of the origin of the mineral and hence of the rock.

The most commonly observed texture is that in which the amphibole occurs in ophitic to sub-ophitic relationship with well developed feldspar laths (Plate 11).

Small idiomorphic amphiboles are developed in the feldspars around some of the larger ophitic amphibole crystals. These small crystals are usually of soda-rich hornblende, poorly zoned, and with well developed prism and clino-pinacoid faces that give distinctive six-sided basal sections.

The amphiboles of the mesotype and pegmatitic zones are usually elongated in the direction of the c-axis, and curved and branching crystals are common (Plate 9). Fibrous amphibole was noted in the numerous shear joints (Plate 12) that exist throughout the gabbro bodies. Radiating acicular crystals



Plate 13. AMPHIBOLITE.

An amphibole (a) crystal partially replaced by chlorite and enclosing numerous small magnetite crystals (dark) arranged in a rectilinear pattern. Albite (ab) and a second generation of magnetite (mag) are also present. The former occurs in a sub-ophitic relationship with the amphibole.

NS 76, 853'.

Photomicrograph (X 35),  
Plane polarised light.



Plate 14. MELANOCRATIC AMPHIBOLITE.

A nearly basal section of a zoned amphibole crystal showing the continuity and parallelism between the two sets of cleavage planes in the pargasite (p) core and in the hornblende (hb) mantle. Other minerals are magnetite (mag), biotite (b), and sphene (sp).

NS 82, 961.5'.

Photomicrograph (X 140),  
Plane polarised light.



Plate 15. MELANOCRATIC AMPHIBOLITE.

Zoned amphibole showing the well defined curved boundaries between the colourless pargasite (p) cores and the hornblende (hb) mantles. The hornblende is slightly replaced by chlorite and has numerous magnetite inclusions.

NS 76, 1337'.

Photomicrograph (X 95),  
Plane polarised light.

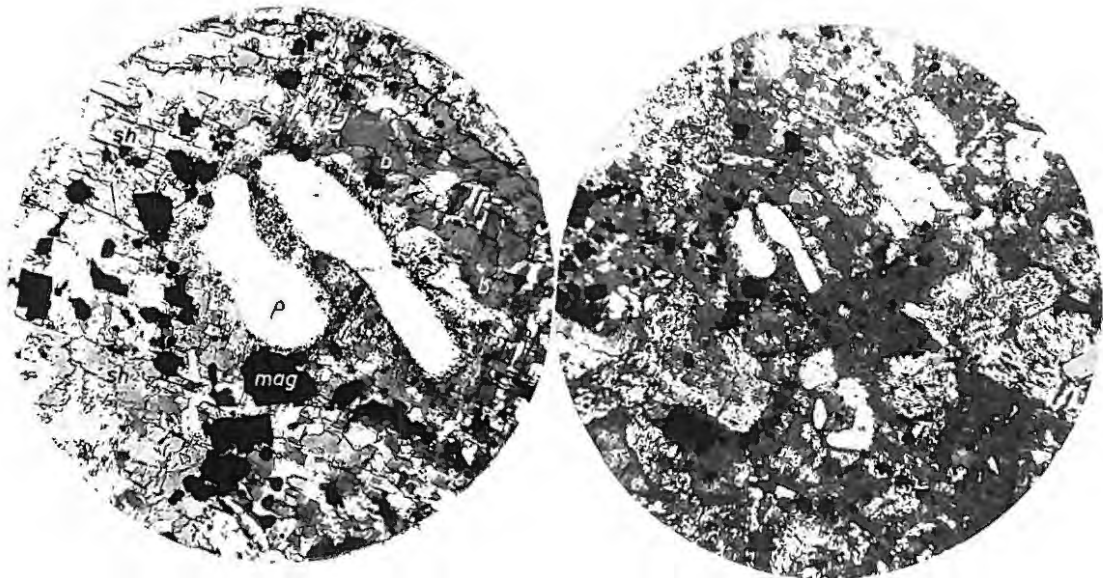


Plate 16. MELANOCRATIC AMPHIBOLITE.

Zoned amphibole crystals. Colourless pargasite (p) cores and sodic hornblende (sh) rims of amphibole crystals remain unaltered. Hornblende is largely replaced by biotite (b) and magnetite (mag). The boundaries of the rounded, colourless pargasite cores are emphasized by a 'dusting' of small magnetite crystals.

Plate 16b shows the poorly preserved sub-ophitic textural relationship between the amphiboles and albitised plagioclase laths crowded with epidote, clinozoisite, and biotite inclusions.

NS 82, 961.5'.

Photomicrographs (a X 70),  
(b X 27),  
Plane polarised light.

are found in carbonate and scapolite veins.

#### Possible Relic Textures

Magnetite and ilmenite are the most common form of inclusions in the hornblende crystals. Small rods, bars and strings of opaque iron oxides are arranged in rectangular grid-like or, in some cases, herring-bone patterns (Plate 13).

These are distinct from the pseudo-hexagonal arrangement of opaque bars and rods of the skeletal ilmenite crystals which are almost invariably surrounded by sphene. The herring-bone arrangements are rare, but the grid-like patterns are less so.

The presence of rectangular grid-like patterns of inclusions could not be explained by reference to the host amphibole crystal, which suggested that it could be a relic texture of an earlier mineral. A similar texture was reported by Jackson (1932) from the scapolitised gabbros of the Nchanga district. He found the pattern in both amphibole and hypersthene and he regarded its occurrence in the former as indicating that the amphibole was derived from the hypersthene. The herring-bone texture was also recorded by Jackson who considered that it was probably a similar relic feature. The axis of the herring-bone commonly coincides with a twin plane of the host although, in some cases, the amphibole is not twinned at all, but the postulated original pyroxene could have been.

#### Zoned Amphiboles

Zoned amphiboles are readily recognised by the differences in colour between the various types of hornblende (Plate 14). The paragonitic cores, where they occur, are invariably rounded in outline (Plates 15 and 16) and exhibit well defined boundaries with the enclosing common hornblende. In a number of crystals, cores are "composite" and consist of two or more

rounded masses of pargasitic hornblende. Inclusions of other minerals in these colourless cores are rare; a few crystals of sodic hornblende and magnetite were the only examples noted. The boundaries of the colourless core are emphasized by the pale blue-green of the common hornblende and by the band of minute opaque iron oxide inclusions which occur in the common hornblende immediately surrounding the cores. Exceptions to these generalisations have been noted; some rare pargasitic cores have idiomorphic outlines and some zoned crystals are devoid of inclusions and have gradational boundaries between zones.

The common hornblende constitutes the bulk of the amphibole and completely encloses the pargasitic cores and is itself enclosed by the sodic hornblende rims.

Inclusions of magnetite, ilmenite, sphene, and biotite are abundant in the common hornblende zone, whereas inclusions of zircon, apatite, and albite occur sporadically.

The sodic hornblende rimming the main bulk of the amphibole crystals has a very distinctive blue-green colour parallel to the Z-vibration direction. In most cases, it occurs in narrow outer zones in crystallographic continuity with the core of crystals, but it is also present as discrete euhedral crystals scattered around the margins of the main crystals. Fractures and some of the cleavages of the common hornblende crystals are lined by deep blue-green sodic hornblende suggesting late-stage formation of sodic amphibole along these surfaces.

A small number of amphibole crystals exhibit unusual zoning when rotated between crossed nicols. The extinction shadow moves in from both sides of the crystal on rotation, and the final extinction shadow at the core of the crystal resembles an hour-glass in outline. The long axis of the hour-glass is parallel to the c-axis of the amphibole crystal.

### Twinning

Twinned amphiboles are common throughout the amphibolite bodies. All twins are normal twins with the twin plane being the composition plane (100) parallel to the longer diagonal bisecting the cleavage rhomb traces on a basal section. Although the composition planes are normally simple planes, several which are stepped or ragged were noted. The twinning is unaffected by the zoning of crystals.

The most common twin consists of two individuals making up a single isolated crystal. In the pegmatitic amphibolite zone the lath-like, radiating and branching amphibole crystals are commonly twinned and exhibit an unusual effect on rotation under crossed nicols. Corresponding individual twin members of each amphibole crystal all extinguish together even where the laths are now separated from each other in the plane of the section by other minerals.

One polysynthetically twinned amphibole was observed in a slide from 1,525 feet in drillhole NS.82 and its 12 twin lamellae have an average width of 0.02 mm.

### Deformed Crystals

In addition to the well developed radiating, curved, and branched crystals in the pegmatitic amphibolite, a small number of amphibole crystals in the melanocratic amphibolite appear to have been bent during or after growth. The most striking of these is a lath 5.0 mm. long, 0.6 mm. in average width, bent through an angle of 110 degrees. Other crystals in the same slide appear to have been fractured and displaced laterally. The origin of the bent crystals of hornblende is closely related to the origin of the amphibolite as a whole, especially when considering the age of intrusion and the nature of the magma.

The significance of bent amphibole crystals in the Lumwana gabbro was discussed by McGregor (1964). The distortion of these

crystals bent through 180 degrees is similar but of a much higher degree than that of crystals from Chibuluma amphibolite and a common origin for the two is considered feasible.

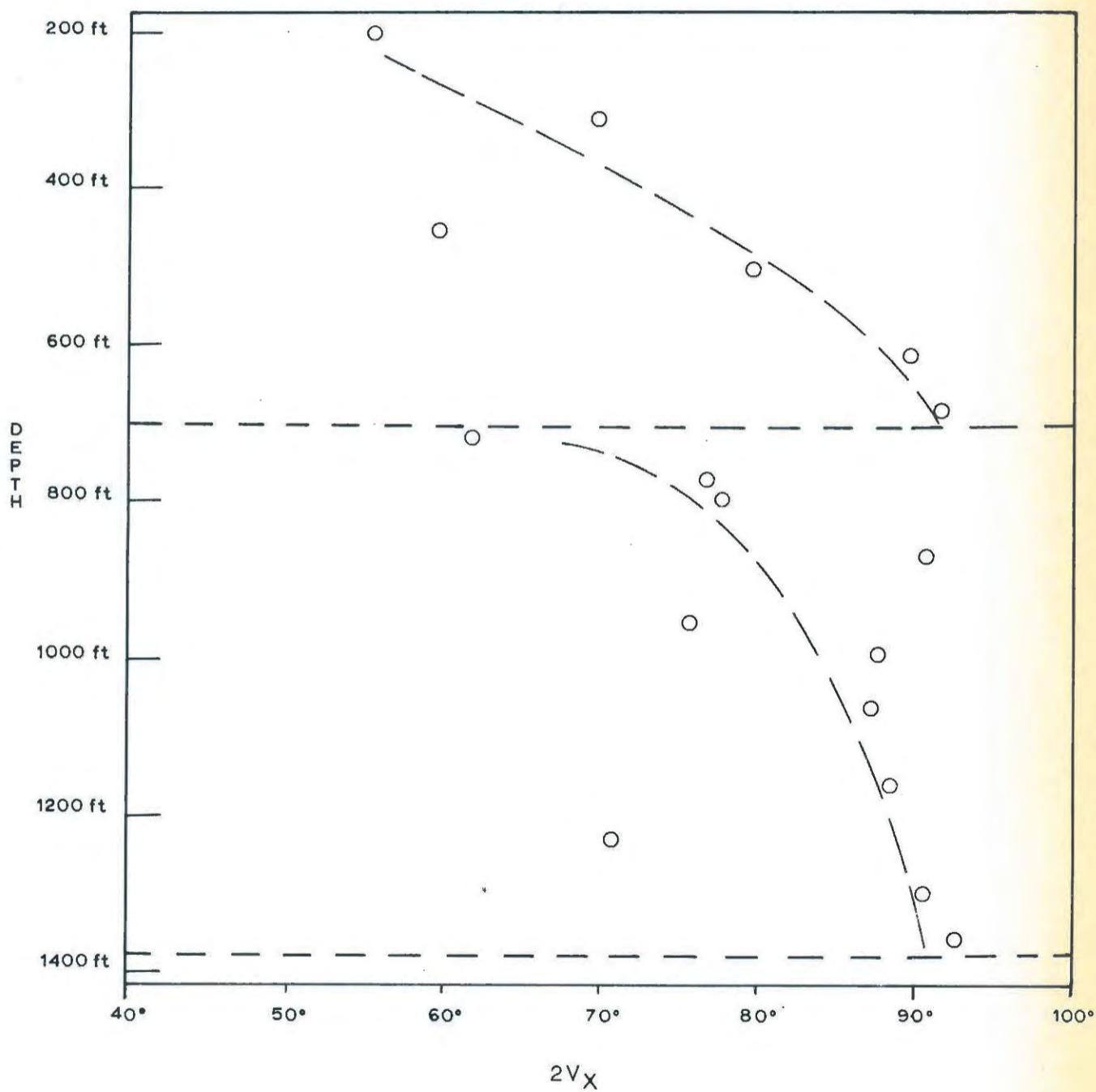
McGregor favoured the theory of origin of the bent crystals advocated by Buckley (1951, p. 516) whereby "the original narrow dendrite limbs were in some way bent as they first grew, the subsequent deposition would bring about the curved thicker limbs, as the distortion due to curvature would be spread out in a molecular manner". The bending of the original narrow dendrite, possibly caused by molecular impurities, takes place as it grows in length and not when it is a narrow full-length crystal.

The bending of an acicular dendritic crystal in a fluid medium, in the writer's opinion, is not feasible even where the relief of stresses is by flow. Any actual bending of such a crystal during flow would normally be straightened out when flow ceases and normal hydrostatic pressures prevailed once more. Any mechanical bending (this excludes crystal growth influenced by impurities) of a crystal would require both active and opposing reactive forces which are not normally possible with a liquid medium. The bending of a narrow crystal lath could conceivably take place during early stages of emplacement when differential flow due to rapid chilling and hence differing viscosities of parts of the magma, could act on the lath. The bent lath should, therefore, occur in fine-grained rock which is not, however, the case at Lumwana or Chibuluma.

Bending, therefore, probably took place in a partially crystalline medium, possibly in a crystal mush consisting of feldspar and pyroxene laths. The mechanism most acceptable to the writer is that described by Buckley (1951): "In a narrow crystal, if two straight units were forced out of alignment to the extent of only a few molecules, the gap would be rapidly bridged and healed and the repetition of this would produce an apparently true curve." The only difference between an apparently true curve and a true one would be the length of each individual straight unit.

FIGURE 16

DRILLHOLE NS 76



2V<sub>x</sub> OF AMPHIBOLES PLOTTED AGAINST  
DEPTH IN MAJOR AMPHIBOLITE SILL



Thickening of the crystal by subsequent lateral growth would preserve the curved nature of the crystal.

This theory as to the cause of bending is to some extent borne out by the presence in the same thin section of other amphibole crystals that show fractured and laterally displaced segments, features which could have been formed only in a solid or near solid medium. The nature of the curved amphibole at Chibuluma does not indicate whether or not the crystal is a pseudomorph after pyroxene. There is no indication of any bent or fractured feldspar adjacent to the amphibole. The original textures of these have been largely destroyed by alteration and replacement.

#### Distribution of Hornblendes

In addition to the zonal structure in single crystals, the different varieties of hornblende show a slight variation in their abundance with depth. In Figure 16, the highest  $2V_x$  value determined in any one thin section has been plotted against its depth in the sill. This shows that the colourless parasitic hornblendes (high  $2V_x$ ) tend to occur only near the base of each individual intrusion, and that the common green hornblende is the most Mg-rich and Na-Fe-poor hornblende present elsewhere. This feature could be interpreted possibly as being due to the gravitational settling of the early-formed magnesium-rich minerals during early stages of crystallisation of the magma. However, not all zoned amphiboles within a single section show the complete range of composition, and a number are not zoned at all, factors which, therefore, preclude the strict validity of any conclusions drawn from Figure 16.

The deep colour and strong pleochroism of the soda-rich hornblende obscures any variations in colour and pleochroism which may exist between common hornblendes from different depths in the major sill.

### Alteration

The most common alteration products of the hornblende are biotite and chlorite, formed by processes which involve further hydration. Both minerals occur throughout the sill, but chlorite predominates towards the base of each intrusion and near the contacts with the sediments. Alteration to biotite takes place preferentially in the common hornblende usually leaving the sodic hornblende rims and pargasitic hornblende cores unaltered (Plate 16). Alteration to chlorite occurs preferentially in the pargasitic and common hornblendes and normally leaves the sodic hornblende rims unaltered.

An unusual form of alteration was noted from NS.76 at 604 feet where the original amphibole core is now composed of a mosaic of albite crystals with biotite, chlorite and sphene. The sodic hornblende rim is not altered and the adjacent labradorite laths show only incipient scapolitisation.

### The Origin of the Amphibole

The well developed ophitic to sub-ophitic texture of the amphibolite bodies is a strong indication of an igneous origin of the rock. Although no pyroxene has been found in the Chibuluma sills, the writer considers that the amphibole was formed as the result of hydration of such early-formed minerals during the final stages of crystallisation of the magma.

The preservation of the ophitic texture by amphibole crystals enclosing feldspar laths, and the well formed outline of the laths, suggests that the bulk of the amphibole did not result from the reaction between plagioclase and pyroxene. This reaction, however, could account for the formation of the masses of small euhedral sodic hornblende crystals that abound in the feldspars near to and rimming the larger amphibole crystals. The more acceptable explanation is that the formation of amphibole from pyroxene was a process of alteration and hydration which preserved not only the ophitic texture, but the schiller and herring-bone textures of the pyroxene as well. The zonal arrangement in composition

of the amphibole would also be interpreted as a relic feature of the pyroxene with Mg-rich cores and Fe-rich mantles. The common occurrence of magnetite, ilmenite, and sphene in the common hornblende suggests that original pyroxene was richer in both iron and titanium than its amphibole derivative. The development of the strongly sodic rims is considered to have taken place during a late tectonic stage of crystallisation together with albitisation and scapolitisation of the basic plagioclases.

#### FELDSPAR

Three distinct types of feldspar occur in the Chibuluma amphibolites. These are lime-soda-plagioclase, soda-plagioclase and potash-feldspar. The first group constitutes the early-formed basic plagioclase, while the second group rims and replaces the first. Potash feldspar has a very limited distribution in the major amphibolite body, being largely confined to the pegmatitic zones.

The compositions of the feldspars were established by universal stage methods. Determinations of composition and twin laws were made by the Rittman zonal method (Chudoba, 1933, p. 41) on between ten and fifteen crystals in each thin section. Optic axial angles were determined by the Fedorov method (Chudoba, 1933) on between two and eight crystals in each thin section.

Potash feldspars were first detected by a feldspar staining technique described by Bailey and Stevens (1960, p. 1,020), whereby the potash feldspar is stained yellow by sodium cobaltinitrite after etching the specimen with hydrofluoric acid and treating it with barium chloride solution.

Grain size measurements carried out on feldspar laths have been described in the section on petrography. A short study of the orientation of feldspar laths was carried out on amphibolite specimens from rocks occurring near the contacts

between successive stages of intrusion, and was described in the same section.

#### Lime-Soda Plagioclase

The plagioclase described under this heading has a large range of composition from calcic labradorite to sodic oligoclase. The term lime-soda-plagioclase is used in order to distinguish this group from almost pure albite or soda-plagioclase. The crystals are typically lath-like, occurring in sub-ophitic relationship with the amphibole. The laths are normally polysynthetically twinned, strongly zoned and are a clouded brown colour in ordinary light.

#### Composition and Zoning

Zoning of the plagioclase is variable. Examples of normal progressive zoning, oscillatory zoning, and resorption and repair are common, and may all be found within a single thin section. The cores of the zoned crystals are invariably more basic than the margins. The most sodic margins are found furthest from the cores of the crystals, commonly in embayments in the surrounding ferromagnesian minerals which, therefore, appear to have limited the growth of the plagioclase. In most cases, the zoning is symmetrically arranged about the (010) median of the crystal (composition plane for the albite twin law). Zones are wider in the direction of the c-axis implying that the lath-shape was present throughout crystal growth.

The composition of the basic cores was found to vary from labradorite ( $An_{66}$ ) to andesine ( $An_{45}$ ). Within any one thin section the variation is restricted to a range of 6 per cent of anorthite. Less basic cores were noted in rocks where less than 30 per cent of the original plagioclase remains unaltered to albite, and may, in fact, be representative not of the cores, but of an intermediate

zone of the crystal intersected in the plane of the section. For this reason, the variation in composition of the basic cores of plagioclase at different levels in the major amphibolite body as presented in Figure 17 cannot be regarded as accurate. The degree of alteration or replacement of the original plagioclase is represented symbolically on one side of Figure 17 which, therefore, also indicates the vertical distribution of the remaining lime-soda-plagioclase. Bearing in mind the above limitations, interpretation of the figure shows that the anorthite content of the plagioclase increases with depth in each separate phase of the intrusion.

The range in composition from the core to the periphery of individual zoned plagioclase crystals may be as great as 60 per cent anorthite ( $An_{66} - An_{06}$ ). The composition of the peripheral zones has a greater range than that of the cores and has been found to vary by up to 28 per cent anorthite ( $An_{05}$  to  $An_{33}$ ) in one particular thin section. This is not considered to be a significant feature as the development of the more sodic margins is commonly impeded by other contiguous feldspar laths or ferromagnesian minerals.

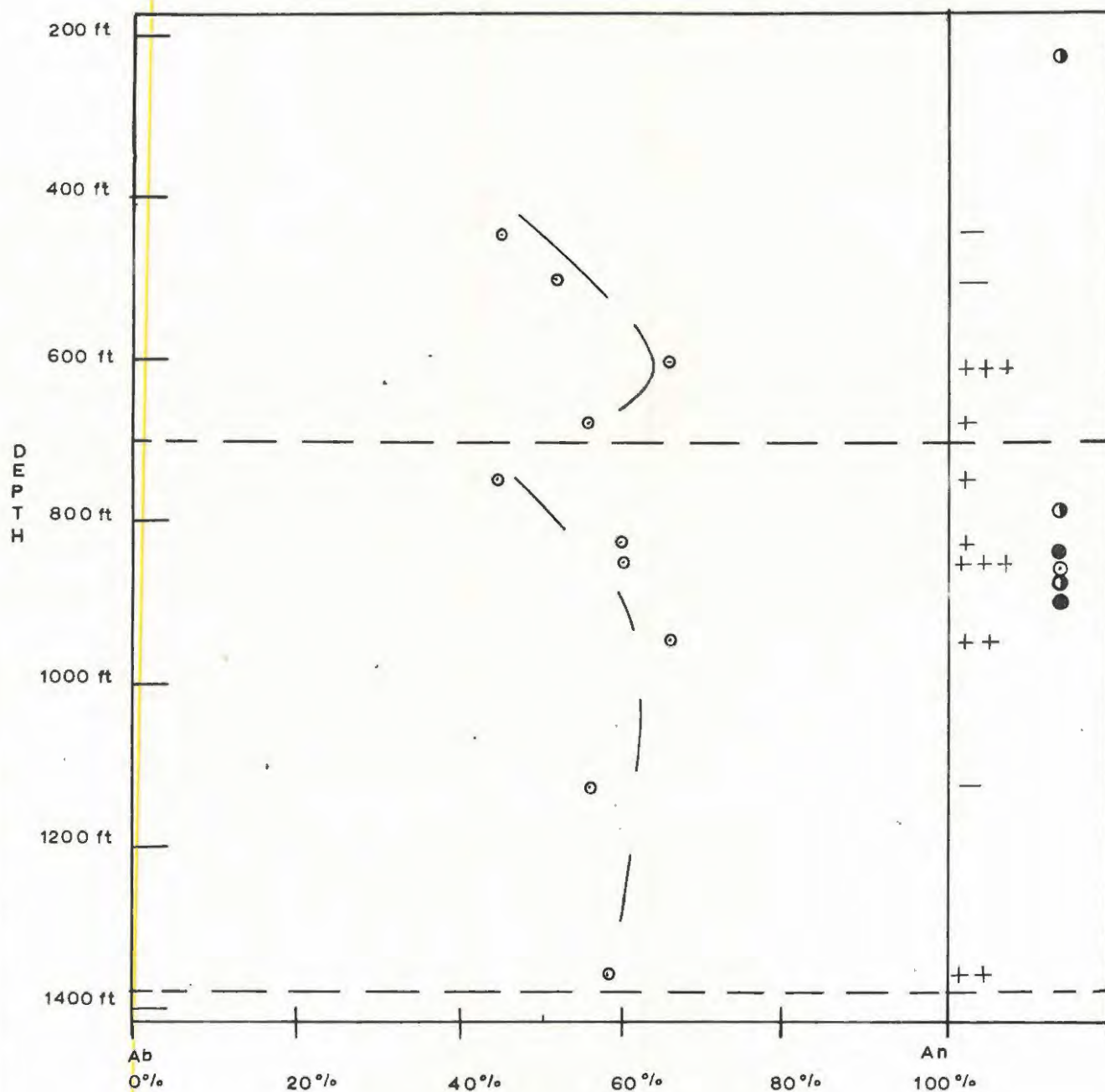
The optical properties of the extremes of the lime-soda-plagioclase range are as follows:-

	<u>Core</u>	<u>Margin</u>
Extinction angle [trace of $X/(010)$ ]	$+ 33^{\circ}(An_{66})$	$- 5^{\circ}(An_{13})$
$2V_x$	$92 - 104^{\circ}$	$87 - 90^{\circ}$
$N_y$	1.562	1.550

The identification of the plagioclase by the Rittman method is reliable and the results obtained are consistent. Identification of the plagioclase from its optic axial angles is less accurate, however, because of the large range obtained for these angles. The refractive indices used for identification are the extreme values obtained for  $N_y$ , but these do not appear to represent the extremes in

FIGURE 17

DRILLHOLE NS 76



PERCENTAGE ANORTHITE IN BASIC CORES OF ZONED PLAGIOCLASE

% BASIC PLAGIOCLASE REMAINING UNALTERED

- = < 10 %
- + = 10-30 %
- ++ = 30-60 %
- +++ = 60-95 %

DISTRIBUTION OF POTASH FELDSPAR

- = TRACE
- = 0-1 %
- = 1-3 %

composition as obtained from the Rittman method.

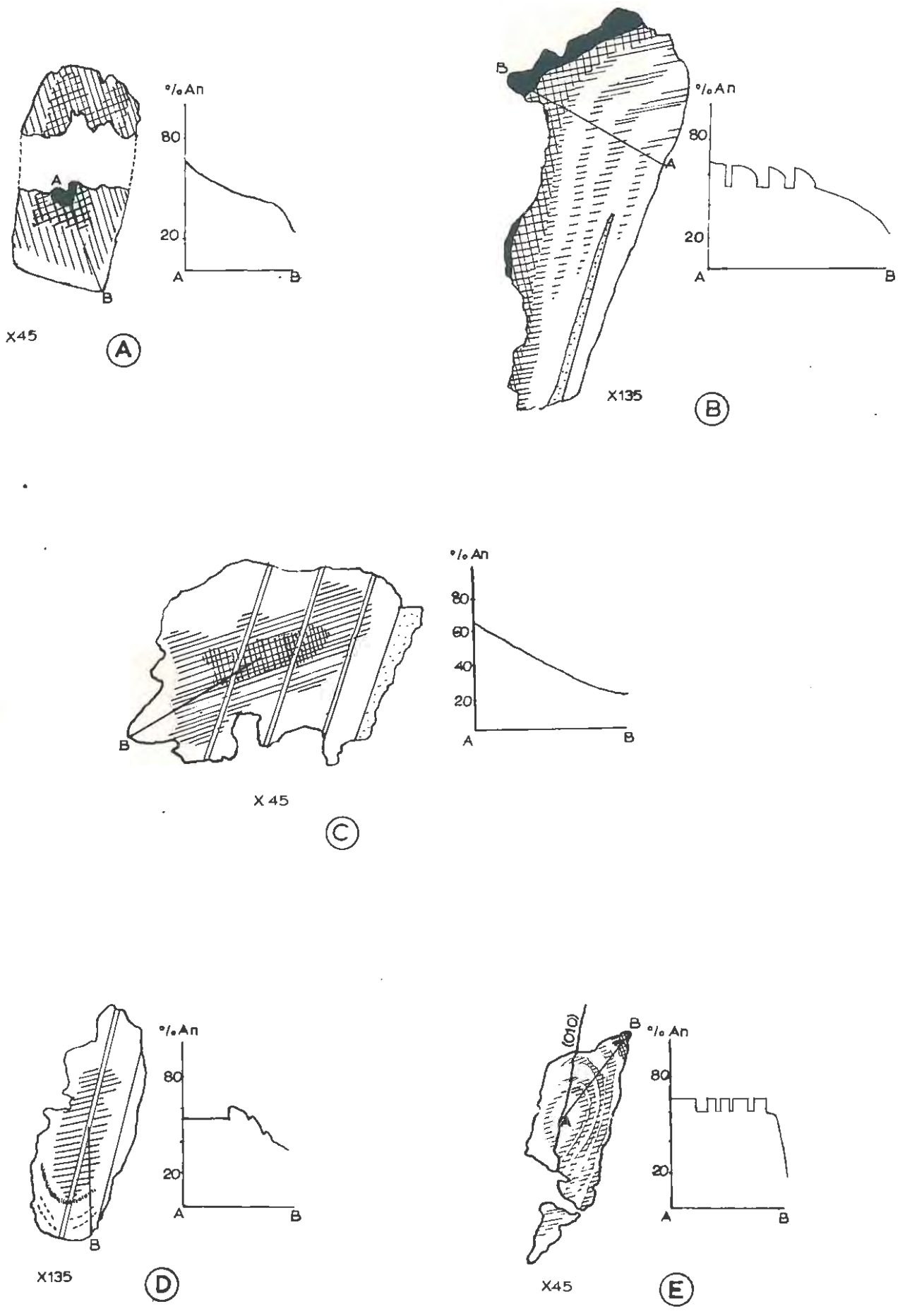
Distinction between secondary albite and the marginal albite of zoned crystals is difficult. The albite occurring interstitially with fresh basic plagioclase laths has a crystallographic orientation parallel to that of the basic laths as does the secondary albite. The early stages of alteration, which commonly take place along crystal boundaries are, therefore, difficult to recognise and the same features could be interpreted as a late stage in zoning.

The writer considers it necessary to define the terms used in describing the various forms of zoning found in the plagioclase crystals. The authority quoted in defining these terms is Phemister (1934, p. 542).

The most simple type of zoning is that where the core is calcic and the successive outer shells are progressively more sodic. This is termed normal zoning and may be of a continuous or discontinuous nature depending upon whether the change in composition is gradual or abrupt. Crystals with sodic cores and calcic margins are said to exhibit reverse zoning, which is usually discontinuous. Plagioclase crystals consisting of a number of thin shells which are alternately less and more calcic are said to exhibit oscillatory zoning. This is in effect an alternation between normal and reverse zoning. If the change in composition of each series of alternate shells is towards a more sodic periphery, then the zoning is termed oscillatory-normal. If it is towards a more calcic periphery, it is termed oscillatory-reverse.

Normal continuous zoning is the most common form of zoning found in the basic plagioclase of the Chibuluma amphibolite, and the basic cores are usually well developed. The composition changes very gradually in the centre of the crystal, but progressively more rapidly near the periphery, as shown in Figure 13A. This zoning is usually symmetrically arranged about the (010) median, but in a number of crystals this is not the case (Figure 18C). This type

FIGURE 18.



TYPES OF ZONING IN PLAGIOCLASE CRYSTALS



of crystal also exhibits uniform normal continuous zoning with no rapid increase in soda near the periphery.

Oscillatory zoning in the plagioclase crystals is rare.

The vertical distribution of these crystals does not appear to follow any particular pattern although such crystals are more common towards the base of the intrusions. Any original pattern may have been obliterated by subsequent albitisation. Most crystals exhibiting this zoning contain up to four well defined idiomorphic zones (Figure 18B, Plate 17), or concentric, rounded or "tear-shaped" zones (Figure 18E). The difference in composition between individual members of either the calcic or sodic series is only 1 - 2 per cent anorthite. The difference in composition between the alternating zones is as great as 12 per cent anorthite. Near the margins of the laths oscillatory-normal zoning was observed to pass into normal continuous zoning with a very rapid increase in soda content.

Reverse zoning is a rare feature in the Chibuluma plagioclase. Where observed it is invariably accompanied by resorption and repair features (Figure 18D, Plate 18). The cores of these crystals, commonly elongated along the c-axis, are very ragged and embayed in outline, and are enclosed in relatively basic mantles which, in one example, exhibits an euhedral outline. The change from sodic core to calcic mantle is discontinuous in all crystals studied. The mantle itself becomes progressively more sodic away from the core.

#### The Significance of Zoned Plagioclase

Plagioclase crystals exhibiting continuous normal zoning are considered by Phemister (1934, p. 543) to be the normal product of crystallisation in an undisturbed basic magma in which the rate of cooling is too rapid to allow continuous readjustment between the solid and liquid phases. The early crystallisation of calcic plagioclase would increase the soda content of the magma which, on cooling, precipitates progressively more sodic plagioclase. A feature in accordance with this process is the occurrence of the most sodic

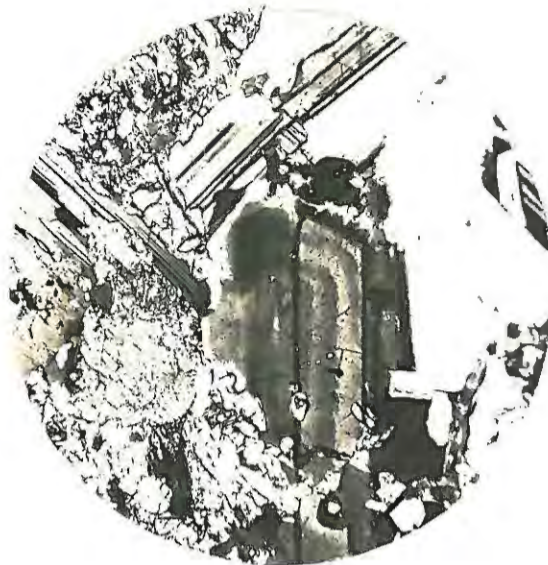


Plate 17. MELANOCRATIC AMPHIBOLITE.

Zoned plagioclase crystal showing oscillatory - normal zoning.

NS 76, 604'.

Photomicrograph (X 80),  
Plane polarised light,  
Crossed nicols.



Plate 18. MELANOCRATIC AMPHIBOLITE.

Zoned plagioclase laths - labradorite (lab) cores and albite or oligoclase rims - in a sub-ophitic relationship with the amphibole (a). Resorption and repair features are evident. The amphibole is largely replaced by biotite.

NS 76, 604'.

Photomicrograph (X 80),  
Plane polarised light,  
Crossed nicols.

plagioclase in embayments in the enclosing ferromagnesian minerals. A slower rate of cooling would enable equilibrium to be maintained between the solid and liquid phases and would result in homogeneous, unzoned crystals of intermediate composition.

Reverse and oscillatory zoning cannot be explained by the above process although the resorption or corrosion features of the sodic cores of reverse-zoned crystals indicate that equilibrium between the crystal and the liquid was in the process of being re-established when the mantle crystallised. The sodic cores of these crystals are considered by Plemister (1934, p. 545) to be the result of normal crystallisation in an isolated chamber of a soda-rich magma that possibly was mixed with the normal basaltic magma during the final intrusion. He considers the line between the zones to be comparable with an unconformity and representing a period during which corrosion and transportation may have taken place.

Oscillatory zoning in crystals reflects cyclic changes in composition or conditions of temperature and pressure during crystal growth. The various processes invoked to explain the formation of oscillatory zoning have been summarised by Plemister (p. 553) as follows :-

- (a) "Movement of crystals as in the magma, whether by gravitative settling or convection currents;
- (b) "Movement of the magma as a whole into a region where different conditions of temperature and pressure prevail;
- (c) "Irruption of additional magma into the crystallising liquid;
- (d) "Loss of volatile constituents."

The first hypothesis could be applicable to the Chibuluma plagioclase, but the fact that only a small proportion of plagioclase crystals in any one thin section exhibit oscillatory zoning implies that the zoning and growth of these crystals took place under intratelluric conditions prior to the magma's final emplacement.

Movement of the crystals to produce zoning could not, therefore, have taken place in the "magma chamber" now occupied by the amphibolites. Any such movement would have to have been repetitive in order to develop three or four alternating zones in the plagioclase crystals. Carr (1954, p. 372) considered that each oscillation in zoning in plagioclase of the Skaergaard gabbros represented a complete circuit of the crystal within the magma chamber. He considers that the calcic zone was deposited on the relief of pressure on the ascent of the crystal through a homogeneous magma. Fhemister favoured a combination of the second and the third hypotheses whereby relief of pressure consequent upon eruption caused the periodic accession of hot magma into higher chambers where crystals were forming. More calcic zones would have formed when the temperature of the magma was increased. Apart from the multiple nature of the Chibuluma major amphibolite body, and the very rare occurrence of reversed zoning in plagioclase crystals, there is no other evidence to suggest that the conditions envisaged by Fhemister prevailed at any time.

The overall character of the major amphibolite body, and in particular the albitisation of the basic plagioclase and the development of albite breccias or adinoles, is suggestive of an important role played by volatiles. It is possible that volatiles also played an important part in the development of the oscillatory zoning of the feldspars under intratelluric conditions. Fhemister (1934, p. 544) quotes experimental data showing that the melting points of the alkali feldspars are generally reduced by the presence of volatiles. At a fixed temperature, therefore, calcic plagioclase would be formed in the presence of a high concentration of volatiles and more sodic plagioclase in their absence. A decrease in the concentration of volatiles could be brought about by their upward migration through the magma or their release following any lowering of pressure. The concentration of volatiles at the top of the chamber after the final emplacement of the magma results in

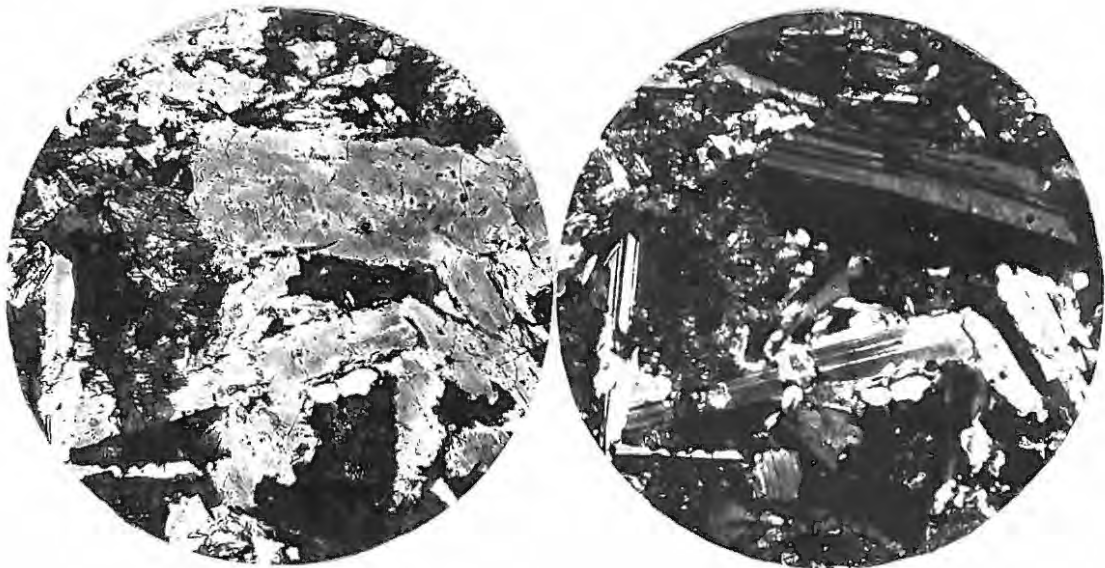


Plate 19. MELANOCRATIC AMPHIBOLITE.

Clouded plagioclase crystals. Variations in intensity of the brown clouding indicate twin planes and the zoned nature of the plagioclase.

NS 76, 604'.

Photomicrographs (X 27),  
(a) Plane polarised light,  
(b) Crossed nicols.



Plate 20. MESOTYPE AMPHIBOLITE.

Albite laths exhibiting a zoned arrangement of epidote and clinozoisite reflecting the zoned nature of the plagioclase crystals before albitisation. Epidote and clinozoisite are most abundant in the originally more basic cores.

NS 76, 715'.

Photomicrograph (X 25),  
Plane polarised light.

a protective sodic shell being formed on plagioclase near the base of the intrusion, thus preserving the oscillatory zoning. Near the top of the intrusion the volatiles facilitate the continuous repair of the plagioclase, thus the oscillatory zoning is destroyed. This distribution of the zoned feldspars is very similar to that of the Chibuluma major amphibolite body where the same effect could have been realised by the late deuteritic albitisation of the basic plagioclase near the top of the sill.

Continuous normal zoning, reverse zoning, and oscillatory zoning of plagioclase are, therefore, features which originate under apparently different sets of conditions. The presence of all three types of zoned feldspars in one thin section emphasizes the fact that the feldspars did not begin to crystallise in their present position, but were probably developed under intratelluric conditions. This is borne out by the nature of the outer-mantles of both oscillatory and reversed zoned crystals. These outer mantles all exhibit continuous normal zoning, which the writer considers was the only form of zoning to develop during the final stages of crystallisation of the magma in situ.

#### Clouding of Feldspars

A characteristic feature of the basic plagioclase laths is their pale brown to pink colour when observed in ordinary light under the microscope. This brown colour or clouding is not discernible in hand specimens. In appearance, it is quite distinct from any clouding or turbidity due to alteration or decomposition of the plagioclase.

The intensity of the brown clouding apparently varies with the composition of the plagioclase. The deeper colours occur in the more basic cores of the zoned crystals (Plate 19), whereas the albitic mantles are almost colourless. The limits of brown clouding coincide exactly with the contacts between the original basic plagioclase and albite which has partially replaced it, and this readily distinguishes any relic basic plagioclase from later albite. Clouding occurs in

large feldspar phenocrysts as well as in the smaller feldspar laths occurring in sub-ophitic relationship with the amphibole.

In polysynthetically twinned plagioclase crystals the intensity of clouding differs very slightly between individual twin lamellae which in a few crystals enables the lamellae to be seen in ordinary light. This feature was also noted by Jackson (1932) as being a distinctive feature of basic plagioclase in the gabbros and norites which he described from west of the Copperbelt.

The writer was unable to determine the cause of the clouding. Examination with a high-power objective (oil immersion x 100) and eyepiece (x 8) did not reveal any features to which the clouding could be attributed. The writer examined the clouded plagioclase from the Khale dolerite sheet, for the purpose of comparison. Eales (1959, p. 94) considered that the clouding in this intrusion was caused by numerous minute granules of a pale green or colourless transparent mineral occurring as inclusions along planes in the feldspar. The colour of the clouded feldspars in the Khale sheet and the variation in colour associated with twin lamellae and zoned crystals is remarkably similar to that of the Chibuluma clouded feldspars. The major difference between the two is that whereas the inclusions in the Chibuluma clouded feldspar are sub-microscopic, the inclusions in the Khale feldspar are at least capable of resolution. A small number of granules, superficially similar to those of the Khale feldspar, occur in the Chibuluma feldspars, but their distribution does not suggest that they are associated with the clouding as they appear in equal numbers in both acid and basic plagioclases.

Clouded feldspars occur mainly in the melanocratic amphibolite zones of the major amphibolite body. They are found in both phases of the intrusion, but are more common in the second phase. The clouded feldspars have a greater vertical distribution in NS.76 than in NS.82, and this is thought to be due to the greater replacement by albite and scapolite in the latter. Both Jackson (1932) and Hall (1958 - Slide No. 110) considered that the clouding of the

feldspars is due possibly to incipient alteration of the plagioclase to scapolite. The former writer also recorded that the intensity of brown clouding increased with increase in scapolite content of the rock. This relationship was not observed by the writer in any of the Chibuluma scapolitised amphibolites.

MacGregor (1931, p. 524), and Poldervaart and Gilkey (1954, p. 75), have summarised the various causes of clouding in feldspars which, they conclude, is due to numerous microscopic or sub-microscopic inclusions of various minerals within the feldspar crystal. These writers differ, however, in their views as to the origin of these inclusions, and they do not specify whether the typical brown colour of the clouding is due to absorption, scattering of light, or related phenomena. The consistent colour of the clouded feldspars described by these authors suggests that it could be a scattering phenomenon caused by innumerable minute inclusions or cavities in the feldspar. This is also suggested by the fact that the inclusions of the brown clouded feldspars of the Khale sheet were observed by Eales (1959, p. 94) to consist chiefly of green or colourless granules with a small proportion of opaque grains. The identification by MacGregor (1931, p. 536), and Poldervaart and Gilkey (1954, p. 78), of the inclusions as opaque iron oxides and ferromagnesian minerals may indicate that the brown clouding is largely an absorption phenomenon.

The sub-microscopic dimensions of the "inclusions" does not definitely exclude the possibility of the clouding effect being caused by the scattering of light from numerous minute cavities within the crystal. Cook, quoted by Jackson (1932), suggested that such cavities could be the cause of clouding in feldspars from norites and gabbros west of the Copperbelt. However, the remarkable similarity, under low power objectives, between the clouded feldspar of the Khale sheet and that of Chibuluma amphibolite influences the writer in favour of scattering caused by minute inclusions rather than by minute cavities.



Macgregor (1931, p. 536) proposed that the clouding effect in certain feldspars is caused by minute inclusions of iron oxides which were exsolved from the feldspars during thermal metamorphism. In support of this hypothesis and as an explanation for the clear sodic rims of these feldspars, he cited feldspar analyses which indicate a higher percentage of iron oxides in oligoclase-andesine-feldspars than in albite- or potash-feldspars. If the Chibuluma clouded feldspars were restricted to either one of the two phases of intrusion, then possibly Macgregor's hypothesis would be applicable. The feldspars of the earlier phase could then have been "clouded" when subjected to thermal metamorphism during the intrusion of the second phase. The fact that the feldspars occur in both phases of the intrusion and the fact that regional metamorphism is of low greenschist facies both militate against Macgregor's hypothesis.

An alternative origin for the micro-inclusions has been suggested by Poldervaart and Gilkey (1954, p. 87), who consider that whereas exsolution may produce a mild form of clouding, intense clouding is caused by minute inclusions (principally iron oxides) which have formed from extraneous material that has diffused into the feldspar after the formation of the feldspar. Their prerequisites **for** the formation of clouded feldspars are:-

- (1) "the existence of an adequately high temperature for a sufficient length of time;
- (2) "the presence of an aqueous pore fluid;
- (3) "the presence of iron bearing minerals in the original rock."

The proposed introduction of the ions is mainly by migration down concentration gradients along surfaces of physical discontinuity within the unmixed crystal. Poldervaart and Gilkey point out (p. 87) that, where recognised, the inclusions are invariably the same minerals that occur outside the plagioclase,

indicating equilibrium between the interior and exterior of the crystal. With a lowering of temperature, magnetite will crystallise out from the pore fluid producing the clouding effect. The simultaneous crystallisation of magnetite in the surrounding rock will reverse the concentration gradient within the feldspar, and the mantles will be cleared of inclusions by the outward migration of iron. The complete clearance of these inclusions is inhibited by the time factor.

Poldervaart and Gilkey (1954, p. 88) conclude that although clouded plagioclases are common in contact metamorphic aureoles, they are not confined to rocks subjected to thermal metamorphism as a high grade of regional metamorphism could produce the same effects. Significant in considering the clouding of feldspars of the Chibuluma amphibolites is their suggestion (p. 88) that "a prolonged iron-rich deuteric phase in the basic intrusives, as might result from magmatic incorporation of water and pelitic material upon emplacement, may also produce clouding of pre-existing or newly-formed plagioclase which cannot then be attributed to later thermal or regional metamorphism." A similar origin for clouded feldspars of quartz-gabbro and eucrite of Ardnamurchan, north-west Mull, has been proposed by Richey and Thomas (1930, quoted by Macgregor 1931, p. 534). These writers consider that the clouding is in some cases caused by the permeation of late granophyric material and is, therefore, a deuteric effect.

#### SODA-PLAGIOCLASE

Soda-plagioclase is the most common felsic mineral of the amphibolites, occurring throughout the major body, and especially in the mesotype amphibolite.

The predominant soda-plagioclase is almost pure albite  $An_{(01-04)}$ . Variations in composition are very limited, the most calcic type being  $An_{08}$ . The optical properties are as follows:-

Extinction angle on sections  
perpendicular to the a-crystallo-  
graphic axis -15 to -12° (An<sub>0</sub> - An<sub>08</sub>)

$$2V_x = 104 \rightarrow 111^\circ$$

Refractive Index  $N_y = 1.534$

Birefringence - low

Refractive index determinations made on specimens from different types of amphibolite, were found to range from  $N_y = 1.530$  to  $N_y = 1.537$ . These values, together with the optic axial angles imply that the soda-plagioclase throughout the major amphibolite body is almost all of the low temperature albite series.

Albite occurs in four main forms. These are:-

- (i) large polysynthetically twinned laths occurring mainly in the mesotype amphibolite;
- (ii) polysynthetically twinned crystals partially replacing basic plagioclase;
- (iii) the outermost mantles of zoned basic plagioclase crystals. This is an uncommon occurrence and exhibits the complete range of plagioclase feldspar from labradorite to albite;
- (iv) intimate intergrowths with quartz in micropegmatite.

The first and second forms can be considered to have originated in a similar manner as all stages of replacement of the basic plagioclase by albite have been observed.

#### The Alteration of Plagioclase

The lime-soda-plagioclase is very commonly replaced by albite and both these feldspars may in turn be replaced by scapolite. These reactions are regarded by Ramberg (1952, p. 267) as autometasomatic although Deer, Howie, and Zussman (1962, Vol. 1, p. 208) consider that albitisation is a low temperature hydrothermal alteration of the basic plagioclase. Jackson (1932) thought that scapolitisation may be the result of normal saussuritisation in the presence of a

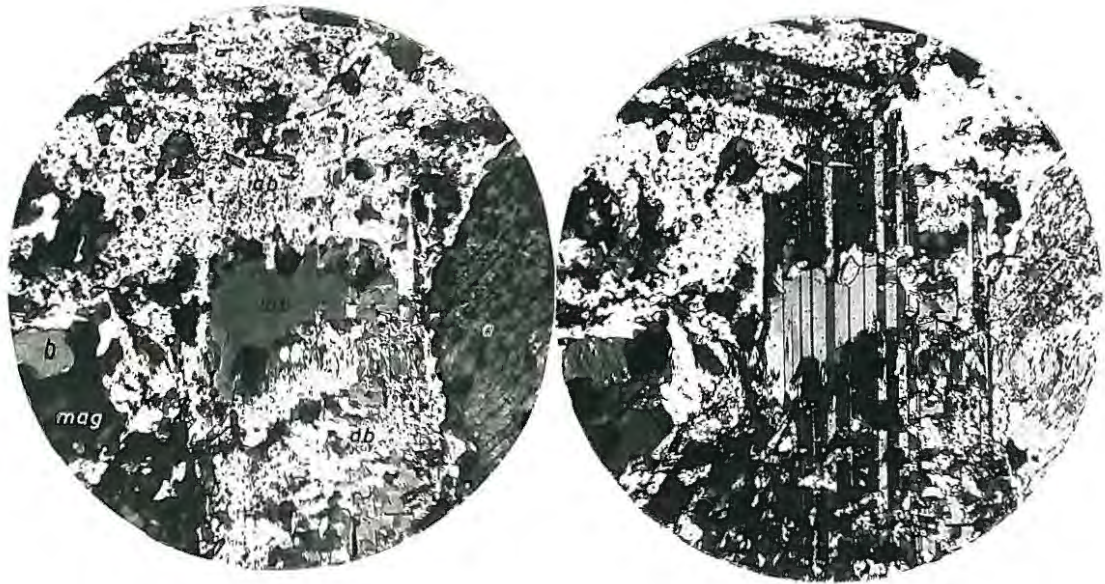


Plate 21. MELANOCRATIC AMPHIBOLITE.

Partly albitised basic plagioclase lath. Clouded labradorite (lab) free of inclusions is enclosed in albite (ab) with abundant epidote, clinozoisite, and biotite inclusions. Plate 21b exhibits the crystallographic continuity between the basic plagioclase and the albite as is shown by the unbroken twin lamellae. Other minerals are amphibole (a), biotite (b), and magnetite (mag).

NS 76, 853'.

Photomicrograph (X 75),  
(a) Plane polarised light,  
(b) Crossed nicols.



Plate 22. PEGMATITIC AMPHIBOLITE.

Micropegmatitic intergrowth of quartz (q) and albite (ab) radiating out from the corner of a feldspar lath. The lath has been albitised and is crowded with epidote and clinozoisite inclusions. The quartz is in the extinguished position. The albite in the micropegmatite is in optical continuity with that of the lath. Other minerals are amphibole (a), biotite (b), and apatite (ap).

NS 76, 752'.

Photomicrograph (X 27),  
Plane polarised light,  
Crossed nicols.

saturated sodium chloride solution.

The two processes, spilitisation or albitisation, and scapolitisation appear to be closely related although in the amphibolites, scapolitisation is generally later than albitisation. Albitisation, however, does not always result in later scapolitisation nor is it a prerequisite of scapolitisation.

Incipient alteration of the original plagioclase to albite commonly occurs in the already sodic mantles of the crystals and is indistinguishable from normal zoning. With further replacement, the colourless albite is readily seen in embayments in the margins of the light brown clouded basic plagioclase. This replacement is always accompanied by the development, especially towards the more calcic core of the plagioclase, of inclusions of epidote, and clinozoisite, and small amounts of calcite, (Plates 11 and 20), which occur commonly along cleavage planes within the albite.

The crystallographic orientation of a feldspar is unchanged by the replacement of labradorite by albite. Twin lamellae in the brown basic plagioclase are continuous with those of the colourless albite. As a result of the opposed extinction angles of labradorite and albite, an unusual feature is seen in certain positions of the partially replaced crystal between crossed nicols (Plate 21). In this phenomenon the extinguished lamellae of the unaltered feldspar give way along their length to unextinguished lamellae of albite and vice versa.

In examining thin sections of completely albitised rocks with ordinary light, the shapes of the original laths of basic plagioclase can be seen from the distribution of the inclusions in the albite. The proportions of albite to epidote, clinozoisite, and calcite, in any one crystal vary considerably even within a single thin section. The general trend is for albite crystals in the mesotype amphibolite zone to be relatively clear whereas those in the melanocratic amphibolite zone are crowded with inclusions. Two interpretations are possible. The first, and more probable, is that the

original feldspar laths in the mesotype amphibolite zone were never as calcic as those in the melanocratic zone, possibly as a result of some form of differentiation during crystallisation. The second interpretation is that a late migration of lime into the gabbro took place in the melanocratic zone only. Lime metasomatism did, in fact, take place, as is shown by the zoned scapolites, but this only affected the lowest 100 feet of the major amphibolite body and not the bulk of the melanocratic amphibolite zone.

#### Twinning

No investigations were carried out by the writer during laboratory study to determine the relative importance of the various twin laws of the feldspars. This is perhaps unfortunate as Turner and Verhoogen (1960, p. 590) consider the relative abundance of the various types of twinning to be indicative of the igneous or metamorphic origin of the feldspars. The most common twins observed were those twinned on the Albite, Pericline, Carlsbad, Acline, and Ala laws. Sporadic albite crystals, which, from their interstitial occurrence and fresh nature, were considered to be late in the crystallising sequence, exhibit a "checkerboard" twinning with discontinuous albite twin lamellae. Hall (1963) considered this texture to be indicative of albite having replaced potash feldspar both in the Lower Roan quartzites and in a minor amphibolite body (Hall, 1958).

#### POTASH FELDSPAR

The presence of potash ions in the felsic minerals of the amphibolite is indicated by the common occurrence of minute biotite flakes scattered through the secondary albite. At the start of this investigation, the writer had no knowledge of whether the potash occurred as a distinct feldspar or whether it merely replaced soda ions in the original plagioclase, and therefore, the writer undertook the staining technique mentioned previously. It was found that potash feldspar occurs in a limited zone in the major amphibolite body where it constitutes up to a maximum of approxi-

mately two per cent of some of the rock specimens.

In vertical distribution, the potash feldspar (shown on Figure 17) is limited to the pegmatitic amphibolite zones and the upper 50 feet of the scapolitic amphibolite zone of the inner amphibolite body. Within these zones, the potash feldspar occurs in small discrete anhedral grains up to 1.7 mm in diameter. These grains normally occur interstitially to the plagioclase laths. One stained specimen shows a string of plagioclase crystals partially replaced by the potash feldspar.

Under the microscope, the potash feldspar is seen to be associated with coarse-grained quartz and quartz-albite micropegmatite. Crystals are clear and fresh and, in some cases, have well developed cleavage traces. The optic axial angle is moderate to small, and the optic sign is negative. No refractive index determinations were made. Microperthitic texture was observed in a small number of the crystals.

#### MICROPEGMATITE

Micropegmatite is common in the Chibuluma amphibolites and has been recorded by Hall (1958 and 1963) from a number of intersections of the minor sills, and by the writer from the lowermost minor sill intersected in drillhole NS.76. In the major sill, micropegmatite is largely confined to the upper mesotype amphibolite and the pegmatitic amphibolite zones. Quartz, on the other hand, although not common, occurs throughout the sill in small, irregular, interstitial crystals.

The term micropegmatite is used to describe all forms of intergrowth between alkali feldspar and quartz, including both granophyric and micrographic intergrowths. The intergrowths almost invariably occur interstitially to the plagioclase laths in the major amphibolite sill, although in a number of cases, large growths of quartz appear to have grown into the laths. Feldspar laths were

seen to have been completely replaced by quartz-albite intergrowths in a number of thin sections from the minor amphibolite bodies.

The only feldspar observed in micropegmatitic intergrowths is albite. It commonly occurs in optical continuity with either the sodic periphery of the zoned basic plagioclase crystals, or the whole feldspar lath where albitised. In nearly all cases, the albite is untwinned. The quartz extinguishes uniformly over large areas of each intergrowth. Two or three such areas commonly exist in any one intergrowth.

The quartz component of the intergrowths exists in a variety of shapes. These are rod-like, triangular, subgraphic, vermiform, or irregular. The smaller quartz grains consist of a higher proportion of angular to irregular grains. Strings of quartz grains in an albite groundmass are commonly developed in a radiating manner and are usually centred on an edge or corner of a feldspar lath as shown in Plate 22. The grain size and the relative amount of quartz in the intergrowth increase away from the lath.

The relationship between micropegmatite and potash feldspar was not clearly established. Although they occur in similar interstitial positions, in no case does the micropegmatite appear to have replaced the potash feldspar in the manner typical of a myrmekitic texture. The characteristic vermiform growths of quartz in myrmekite are rare and are not associated with the potash feldspar.

Albite of the micropegmatitic intergrowths is normally free of inclusions other than quartz, and is fresh and unclouded in appearance. Alteration of plagioclase to scapolite most commonly affected the basic plagioclase before the albite. Later stages of scapolitisation altered only the albite, and the quartz of the micropegmatitic intergrowths has retained its graphic texture within the scapolite.

#### SCAPOLITE

Scapolite, an uncommon mineral in most parts of the world, is very common throughout the Copperbelt and northwestern Zambia (Mendelsohn, 1961, p. 109 and McGregor, 1964, p. 120), where it is



most commonly found associated with metamorphosed argillaceous or dolomitic sediments and gabbro-amphibolite bodies. In view of its uncommon occurrence elsewhere, the writer considers it necessary to mention briefly the broader aspects of the scapolite group of minerals.

According to Shaw (1960, p. 242), the scapolites form an isomorphous series between two principal end-members, chloride-marialite ( $\text{MaCl}$ ) and carbonate-meionite ( $\text{MeCO}_3$ ). These end-members are the chemical equivalents of 3 Albite + NaCl and 3 Anorthite +  $\text{CaCO}_3$  respectively. The simplest general formula is  $W_4(\text{Al}_{3-6}, \text{Si}_{9-6})\text{O}_{24} \cdot \text{R}_{1-2}$ , where W includes mainly Ca and Na with some substitution by K, Mg, Fe, Mn, and Ti; R includes  $\text{CO}_3$ ,  $\text{HCO}_3$ , Cl, F,  $\text{SO}_4$ ,  $\text{HSO}_4$ , and OH. Dipyre and mizzonite are two intermediate varieties of scapolite, the former being the more sodic of the two.

The optical properties depend chiefly on Ca, Na and K content. The mean of the two refractive indices  $\frac{E + W}{2}$  termed nm and the birefringence termed dn both increase linearly with increase in calcium content. Shaw (p. 253) presents this data graphically as a means of identifying members of the scapolite family by their refractive indices.

In thin section, scapolite is readily recognised by its colourless nature, low to moderate birefringence, straight extinction, negative elongation, and uniaxial negative optical character. The distinct cleavages on (110) intersect at right angles on basal sections. Longitudinal sections present a very marked flash figure in convergent light.

Scapolite occurs scattered throughout the Upper Roan formations where it forms large white ovoid idiomorphs or poikiloblastic anhedral crystals. The most common occurrence is in the more argillaceous rocks, scapolite being conspicuously absent from the purer dolomites, talc schists and albite breccias. Scapolite is best-developed in the melanocratic amphibolite where it forms up to

37 per cent of the rock. It is very rare in the mesotype amphibolite zones and is present in variable amounts in the pegmatitic granophyric amphibolite. It is a common constituent of veins in the more basic zones of the amphibolite.

The scapolite of the major amphibolite body was identified as dipyre ( $Me_{35}$ ). The average refractive indices are  $E = 1.545$ ,  $W = 1.560$ ,  $nm = 1.5525$ ,  $dn = 0.015$ . The range in meionite content of scapolite samples selected from large idiomorphs occurring at different depths in the major amphibolite body was found to be less than fifteen per cent. Jackson (1932) recorded a larger variation in composition ( $Me_{25}$  to  $Me_{50}$ ) in the scapolite of gabbroic rocks of the Nchanga district. Scapolite occurring as large (2.2 cm) crystals in a vein, together with pyrrhotite, pyrite and chalcopyrite (NS.56 at 718 feet), was found to be dipyre ( $Me_{33}$ ,  $E = 1.545$ ,  $W = 1.556$ ).

Scapolite occurring in the lowest minor amphibolite body intersected by NS.76 at 2,509 feet was found to be a more calcic dipyre. Refractive indices are  $E = 1.551$ ,  $W = 1.568$ ,  $nm = 1.559$  and  $dn = 0.017$  indicating a composition  $Me_{45-49}$ , (The values for  $dn$  and  $nm$  giving different compositions). Under the microscope, these scapolites were seen to be very strongly zoned with very lime-rich margins, and on examining the drillhole core, the sill in question was found to have no definite contact with the sediments, but instead, a gradational contact with "hybridization" of the rocks. For these reasons, the writer considers that the composition of this dipyre cannot be regarded as truly representative of the amphibolite.

Scapolite from the Upper Roan dolomitic argillite of NS.82 at 440 feet is also dipyre ( $Me_{45-50}$ ) in composition. Refractive indices are  $E = 1.551$ ,  $W = 1.570$ .

No qualitative or quantitative chemical tests have been carried out on the Chibuluma scapolites. The finely "contaminated" nature of the poikiloblastic scapolite makes their clean

separation almost impossible, even after fine grinding. The presence of abundant gypsum and anhydrite in the Upper Roan sediments implies that the scapolite could contain a high proportion of the sulphate radical.

Textures exhibited by the scapolite of the major amphibolite body point to its being a very late mineral. All degrees of development from labradorite-amphibolite, carrying less than 1 per cent scapolite, to an amphibolite where it forms the only felsic mineral, constituting over 30 per cent of the rock by volume, occur within the same sill. In the progressive replacement of albite by scapolite, the first formed scapolite grains are typically anhedral or rounded in outline. Their development is almost exclusively at the expense of feldspar and most commonly within the interstitial soda-rich varieties.

An exception to this tendency was noted in the coarse granophyric zone where micropegmatite occurs interstitially to the feldspar laths, and where the scapolite has completely replaced the laths without altering the quartz-albite intergrowths. Scapolite crystals do not exhibit any preferred orientation within the feldspar laths which they have replaced. Early development of scapolite commonly takes place along small cracks and fractures, but not along twinning or cleavage planes within the feldspar.

During subsequent growth, the subhedral to rounded outline of the scapolite is retained, but this becomes embayed by the partial enclosure of the numerous epidote and clinozoisite inclusions in the earlier albite. This embayed outline and poikiloblastic texture is the most characteristic form of scapolite and has been termed fleecy, cauliflower-like, or bulbous by various authors.

Further growth results in the whole of the original feldspar lath being replaced by a mosaic of scapolite crystals. With the exception of sphene, lime-bearing inclusions in the feldspar are largely absorbed or expelled by the scapolite. In addition to sphene, magnetite and zircon inclusions are retained. A rare occurrence of calcite within the scapolite was noted from NS.82 at



Plate 23. MELANOCRATIC AMPHIBOLITE.

Basal section of an euhedral scapolite (s) crystal. Prismatic cleavage traces are evident. Dark minerals enclosing the scapolite are hornblende and biotite.

NS 76, 1177'.

Photomicrograph (X 35),  
Plane polarised light.



Plate 24. MESOTYPE AMPHIBOLITE.

A subhedral skeletal crystal of ilmenite (il) in mesotype amphibolite. Amphibole inclusions within the ilmenite are in optical continuity with amphibole crystals outside of the ilmenite.

NS 76, 604'.

Photomicrograph (X 80),  
Plane polarised light.

895 feet. A large, white, subhedral mass in a minor amphibolite sill (NS.76 at 1,760 feet) which in the hand specimen appears to consist of homogeneous scapolite phenocrysts, under the microscope is found to consist mainly of aggregates of scapolite, calcite, and quartz.

In the final stages of scapolitisation, scapolite develops markedly euhedral outlines at the expense of the amphibole (Plate 23), which it appears to have replaced since growth fractures are not observed around the scapolite. Shaw (1930, p. 282) considered that any claims of scapolite replacing hornblende or pyroxene are probably based on erroneous textural interpretations. Deer, Howie, and Zussman (1963, Vol. 4, p. 333), on the other hand, quote Verbitski who described sodium-rich diopside formed from both plagioclase and amphibole in metadiabase. As in the case of the Chibuluma amphibolites, the conversion of plagioclase to scapolite was observed in all states of development. It is of interest to note that Verbitski considered that scapolitisation took place during a period of hydrothermal and tectonic activity subsequent to the consolidation of the diabase,

The Chibuluma scapolite contains numerous inclusions of amphibole which could possibly be remnants of larger crystals enveloped in scapolite on the destruction of the ophitic and sub-ophitic textures. Furthermore, skeletal ilmenite rods and bars are found completely enclosed in scapolite. In non-scapolitised amphibolite, these skeletal crystals are almost completely restricted to the interiors of amphibole or sphene crystals and are not found within plagioclase laths. Their occurrence in scapolite, in the writer's opinion, is a feature which supports the view that scapolite has replaced the amphibole.

No definite relationship could be determined between the chemical composition of the scapolite and that of the feldspar it has replaced. The common form of zoning of scapolites of the

amphibolite bodies described below is possibly caused by a similar zoning of the original basic plagioclase - both have calcic cores - but the difference in lime content between the core and margin is greater in the plagioclase than in the scapolite. This difference is also expressed by the relative amounts of epidote and clinozoisite inclusions within the scapolite crystal. These, where they occur, are more abundant nearer the core of the crystal as is the case in the secondary albite laths, but they are more common in the albite than in the scapolite.

#### Zoning in Scapolite

Zoning in scapolite crystals would appear to be rare judging from the reference by Shaw (1960, p. 228) to "one of the few records of zoned scapolite" as being that described by Tomlinson from a vein associated with altered diabase. This scapolite had a lime-rich periphery.

Zonal variations in the lime-alkali ratio within scapolite crystals of the Chibuluma amphibolite are common and are readily recognised by the resulting changes in birefringence. McGregor (1964) made use of this zoning in interpreting the migration of lime and soda in the later stages of crystallisation of the Lumwana gabbro bodies. He found that the peripheral zones of scapolite crystals occurring within the gabbro near the contact were enriched in lime relative to their cores, whereas scapolite occurring in the sediments near the contact were enriched in soda. He considered (p. 137) that this intimate relationship between the scapolite of the sediment and that of the gabbro implied that their crystallisation was simultaneous and showed late migration of lime into the gabbro and soda into the sediments.

Following McGregor's lead, the writer studied the zonal relationships of the scapolites from the Chibuluma amphibolite and

the following are the salient features observed:-

- (i) most of the scapolites of the major amphibolite body exhibit soda-enriched margins. The exceptions are those occurring within approximately a hundred feet of the base of the sill, which exhibit narrow, but well defined lime-rich mantles;
- (ii) without exception, the scapolite developed in the minor amphibolite bodies has strongly developed lime-rich rims. The thickest of these sills investigated by the writer is, however, only 85 feet thick;
- (iii) most of the scapolite within the sediments has poorly developed soda-rich margins; an exception to this is in the proximity of the amphibolite bodies where well developed, but narrow lime-rich margins are common;
- (iv) scapolite occurring in veins within the major amphibolite body shows weak soda-enriched rims, whereas that of veins in the sediments shows strongly developed lime-rich rims;
- (v) in nearly all zoned scapolites, those displaying late soda enrichment are only weakly zoned whereas those displaying late lime enrichment normally are strongly zoned with narrow but well defined mantles. The greatest difference in birefringence encountered between core and mantle of the soda enriched crystals was approximately 0.004, representing a change in composition of  $Me_{10}$ . The equivalent difference in birefringence of the lime enriched crystals was 0.012, representing a difference of  $Me_{25}$  in composition.

The different strengths of zoning exhibited by the lime-rich and the soda-rich margins might indicate that the more stable form of scapolite under the prevailing temperature-pressure conditions was nearer meionite than marialite in composition. However, if this were the case, the writer considers that in the presence of excess

lime, the scapolites of sedimentary formations would be more calcic than they are. The main cause of the differences in degree of zoning is possibly the ionic concentrations in the media in which migration took place, the Ca and CO<sub>3</sub> components being more plentiful than either Na or Cl.

In the case of the Lumwana gabbro (McGregor, 1964), the dividing line between lime enriched and soda enriched scapolites coincides with the contact between gabbro and sediment. The equivalent dividing line of the Chibuluma scapolite occurs approximately 50 feet below the major amphibolite. The scapolite in the lime-rich sediment near the contact shows lime-enriched margins similar to those within the amphibolite which are, therefore, possibly of the same origin. The displacement of this dividing line relative to the amphibolite contact precludes the simultaneous exchange of Ca for Na across the contact. The outward migration of soda during the late stages of crystallisation of the gabbro appears to predate the opposing migration of lime.

#### EPIDOTE AND CLINOZOISITE

Epidote occurs throughout the Chibuluma bodies as numerous small inclusions in albite and scapolite crystals, as large discrete idiomorphic crystals, and as aggregates of crystals in veins. Clinozoisite is limited in its occurrence and was observed only as small euhedral inclusions in the altered feldspar laths.

##### (i) Inclusions in Albite and Scapolite

A common feature of the feldspar crystals as seen in hand specimens is their pale green core and cream to white margin. Under the microscope, this feature is seen to be caused by numerous small, pale yellow-green laths and irregular masses of epidote, together with lesser amounts of clinozoisite and calcite concentrated towards the cores of polysynthetically twinned albite crystals. The laths are up to 0.3 mm long, and in some crystals, are aligned with the cleavage planes of the albite. A similar



arrangement of epidote laths was found to occur in scapolite crystals which do not, however, exhibit greenish cores in the hand specimen.

The proportion of epidote inclusions to albite or scapolite host is very variable. Albite of the mesotype amphibolite zone commonly contains less than 10 per cent epidote, whereas towards the base of the major amphibolite, and in parts of the minor amphibolite bodies, the feldspar laths have been almost completely replaced by epidote, in spite of which, the original sub-ophitic texture of the rock is still discernible.

(ii) Large Idiomorphic Crystals

A small number of brilliant, yellowish green to colourless epidote crystals with idiomorphic to sub-idiomorphic outlines, occur in the mesotype and pegmatitic amphibolite zones of the major amphibolite body (Plate 11). Crystals average 0.5 mm in length, but some 2.4 mm long were noted. The well formed crystal faces are developed adjacent to albite which contains approximately 5 to 10 per cent epidote and clinozoisite as small inclusions. One large epidote crystal partially encloses a single hornblende crystal.

(iii) Epidote-rich veins

Epidote is a major constituent of veins within both the major and minor amphibolite bodies. Common associates of the epidote are calcite, biotite, hornblende, albite, and quartz. Crystals up to 12 mm in length were observed in a calcite vein in the melanocratic amphibolite zone.

Veins rich in epidote are particularly common in the pegmatitic amphibolite zone and are in most cases surrounded by zones from 3 inches to 3 feet wide in which all feldspars have been replaced by epidote. Where a number of veins occur close together, the resulting rock consists almost entirely of amphibole and epidote. The epidote crystals of veins are commonly euhedral to subhedral laths.

### Properties

Epidote was recognised by its high relief when enclosed in albite, its distinctive colour and strong pleochroism, and its high to moderate birefringence. The principal optical properties determined are as follows:-

$2V_x$	=	75 - 85°
X	=	pale greenish yellow to colourless
Y	=	greenish yellow
Z	=	brilliant yellow green

Birefringence approximately 0.015 to 0.030

Absorption  $Z > Y > X$

Optic axial angles were determined by universal stage methods on large crystals from the mesotype amphibolite zone, and on the largest inclusions in albite crystals. No refractive index determinations were made.

Clinzoisite occurring as inclusions within the albite laths was recognised by its low birefringence, with anomalous interference colours, and large optic axial angle (low to moderate in zoisite). The optic axial angle and the refractive indices of the clinzoisite were not determined accurately.

### Zoning Within Epidote Crystals

According to Deer, Howie, and Zussman (1962, Vol. 1, p. 197), the principal substitution taking place within the epidote crystal is between  $Fe^{+++}$  and  $Al^{+++}$ . Any resulting variations in the composition of the epidote crystals are readily observed by the accompanying changes in colour and birefringence, both of which increase with ferric iron content.

No marked zoning was noted in the small epidote inclusions within the albite or scapolite crystals, but the large idiomorphic crystals of epidote show marked differences in colour and birefringence between different parts of each crystal. These variations are

haphazard and "patchy" in their distribution within each crystal although iron-rich zones commonly occur at either end or at one side of a crystal. Boundaries between the iron-rich and iron-poor zones are gradational.

The epidote crystals occurring in veins commonly show iron-enriched peripheries although this is not always the case. "Patchy" zoning is also a common feature of these crystals. One epidote crystal from a depth of 1,290 feet in a melanocratic amphibolite zone of NS.76 showed a form of "oscillatory zoning" with four concentric shells alternately iron-rich and iron-poor.

#### Origin of the Epidote

The large numbers of epidote inclusions in albite and scapolite appear to have been formed, together with clinozoisite and calcite, during the alteration of original basic plagioclase to either of the host minerals. The greater abundance of the inclusions towards the centre of the host crystals resulted presumably from the zoned nature of the original plagioclase which possessed relatively lime-rich cores. The formation of epidote, calcite, and albite in place of calcium-rich plagioclase at low metamorphic temperatures is regarded by Deer, Howie, and Zussman (1962, Vol 1, p. 202) to be associated with the increasing activity of  $Fe^{+++}$  relative to  $Al^{+++}$ . The small iron content inherent in the more basic plagioclases possibly played a part in determining whether clinozoisite or epidote was formed originally, but the haphazard distribution of iron-rich zones within the larger epidote crystals, and the iron-rich rims of epidote in veins, suggests late introduction of ferric iron.

The large idiomorphic epidote crystals in the pegmatitic and mesotype amphibolite zones appear to be late products of magmatic crystallisation. Deer, Howie, and Zussman (p. 208) consider this

paragenesis to be consistent also with the increased hydroxyl and ferric iron activity during the final stages of the magma crystallisation process.

These writers (1962, Vol. 1, p. 207) report that "epidote is a common product also of dislocation metamorphism of basic igneous rocks", an origin which could possibly apply to some of the vein-like occurrences of epidote at Chibuluma, although the association with magnetite and calcite suggests that this epidote was also formed in a late deuteritic or hydrothermal phase of crystallisation.

#### MICAS

Biotite was the only variety of mica recognised by the writer in the amphibolite bodies. Hall (1958, Slide No. 219) has described a white mica (paragonite) in a minor amphibolite body.

#### BIOTITE

Biotite occurs throughout the amphibolite sills, but is especially common in the melanocratic amphibolite zones of the major amphibolite body. The most common form of biotite is small flakes and clusters of squat prismatic crystals with a maximum intercept of 6 mm, occurring in and around the amphiboles. The biotite flakes within the amphibole crystals commonly exhibit a preferred orientation relative to that of their host whereas those surrounding the amphibole are arranged at random.

Clusters of magnetite, ilmenite, and sphene crystals are commonly enclosed in a single large biotite crystal or are surrounded by a number of smaller crystals of biotite.

Very small flakes of biotite occur scattered with random orientation in both albite and scapolite which have replaced original plagioclase. These biotite flakes are both paler and smaller than those associated with the amphibole, and they are especially common adjacent to amphibole crystals which contain large

amounts of magnetite. Biotite is the most common mineral observed in the numerous small veins and is associated mainly with epidote, albite, and basic hornblende.

Properties

The properties by which biotite was identified are as follows:-

$$2V_x = 0 - 5^\circ$$

Extinction parallel to a perfect cleavage = length slow

$N_x$  not determined X very pale yellow to yellow-brown

$N_y$  = 1.650 - 1.661 Y) dark chocolate-brown

$N_z$  = 1.650 - 1.660 Z) to reddish brown

$$N_z - N_x = 0.05 - 0.04$$

Absorption  $Z = Y > X$

Interference colours on sections showing cleavage traces show slight irregularities in bands perpendicular to the cleavage. No twinning or zoning was observed.

The refractive indices indicate that the mica contains at least 25 weight per cent of  $FeO + 2 (Fe_2O_3 + TiO_2)$  and the mineral is, therefore, nearer biotite than phlogopite in composition (Deer, Howie, and Zussman, 1962, Vol. 3, p. 57).

The biotite throughout the amphibolite body is commonly fresh and unaltered. A number of thin sections showed a green-brown variety of biotite which could possibly represent incipient alteration of the biotite to chlorite with which it is also associated. This greenish brown mica was distinguished from chlorite by its high interference colours.

Pleochroism in the green-brown micas is

X = pale greyish brown

Y = olive-green to brown

X = deep orange-brown

Inclusions in mica crystals are common. In addition to the coarse aggregates of sphene, magnetite, and ilmenite mentioned earlier,

thin blades of magnetite were noted parallel to the basal cleavage planes of biotite. Acicular crystals of amphibole and magnetite or platy ilmenite occur in the biotite crystals in planes parallel to the percussion figure, i.e. those inclusions that lie parallel to a vibration direction on the basal plane are parallel to the slower ray. One such arrangement of ilmenite plates was noted in an otherwise clear crystal of scapolite and was thought by the writer to indicate replacement of the biotite by the scapolite.

Pleochroic haloes are common and well developed within the biotite. The cores of the haloes are considered to be small zircon crystals. The dark zones are highly absorbent to light vibrating in the Z-vibration direction.

#### CHLORITE

Pale green chlorite was found throughout the amphibolite bodies, constituting less than 1 per cent in the mesotype amphibolite rocks, but almost completely replacing the amphibole crystals in parts of the melanocratic amphibolite and in the minor sills.

Chlorite occurs most abundantly as an alteration product of amphibole in which it occurs in a haphazard arrangement of laths and plates which, in some cases, are curved or bent. Alteration appears to have taken place most readily in the relatively soda-free amphibole as relic amphibole crystals commonly consist of a parasitic core, chlorite, and a soda-amphibole margin. The parasitic core has been altered in preference to the soda-amphibole during the final stages of chloritisation.

Subordinate modes of occurrence include small idiomorphic plates of chlorite which have developed in the feldspar crystals adjacent to partially chloritised amphibole crystals, and the fibrous chlorite replacing amphibole crystals in shear zones. Chlorite was noted also to have replaced biotite.

Properties

The chlorite is a much paler green than the common amphibole and was recognised by the following optical properties:-

$2V_z$	=	$0 - 3^\circ$
Well developed cleavage with negative elongation.		
$c/x$		$0 - 3^\circ$
$N_x = N_y$	=	1.594 - 1.598, X = Y = pale green
$N_z$		not determined, Z = colourless to very pale green
$N_z - N_x$	=	0.005 - 0.008
Pleochroism	X = Y > Z	

The refractive indices and birefringence indicate that this chlorite is an iron-rich variety of clinocllore.

SPHENE

Sphene is a very common constituent of the amphibolite bodies of Chibuluma Mine, where it occurs as a yellow-brown mineral recognised by its very high relief and birefringence, and poor extinction, and a sphenoidal outline in some crystals.

The principal modes of occurrence of sphene in the amphibolite are:-

- (i) as small, anhedral, rounded crystals occurring singly or in clusters, mainly in amphiboles, but also in altered feldspar and scapolite;
- (ii) as large masses ( up to 4.5 mm diameter) of unorientated crystals which the writer considers to be pseudomorphs after original pyroxene crystals.

These masses of sphene commonly contain rods of ilmenite which are in a grid or herring-bone arrangement, considered to have been inherited from the pyroxene. Large masses of these crystals appear also to have largely replaced amphibole crystals in some sections;

(iii) as discrete euhedral sphenoidal crystals up to 0.5 mm long occurring in either amphibole or feldspar.

These crystals may or may not enclose grains of ilmenite;

(iv) as large aggregates of subhedral crystals enclosing clusters of ilmenite grains or rods;

(v) as a thin layer of subhedral crystals surrounding large crystals of ilmenite.

Sphene is a common accessory mineral throughout the amphibolite bodies, and is considered by the writer to have been formed largely by the alteration of ilmenite during the later stages of crystallisation. The increase in proportion of sphene near the outer margins of the major amphibolite body suggests that the lime assisting the formation of sphene may have migrated into the amphibolite from the sediments.

Ilmenite, calcite, and rutile are the minerals most commonly associated with sphene.

#### APATITE

Apatite is a relatively common accessory throughout the amphibolite bodies. The hexagonal outline is recognisable, but is not well developed in all crystals. Prismatic sections are commonly up to 4.8 mm in length. Crystals are uniaxial in character.

#### ZIRCON

Numerous small, colourless to very pale green inclusions, considered to be zircon, were noted, particularly in biotite crystals where they were surrounded by well developed pleochroic haloes. These inclusions exhibit a very high relief and very high interference colours. Prismatic sections show parallel extinction.

#### QUARTZ

Quartz, although uncommon, was observed throughout the amphibolite bodies where it occurs interstitially to the feldspar



laths in discrete anhedral crystals up to 2 mm in diameter. It occurs with albite in micropegmatitic intergrowths which are limited to the pegmatitic amphibolite zone in the major sill. Quartz veins are rare, but where found, the mineral is normally associated with epidote and albite (NS.78 at 871 feet).

#### CARBONATE

No carbonate other than calcite was noted from the amphibolite bodies. Calcite is a minor accessory mineral throughout all the amphibolite bodies. It is most commonly associated with epidote and clinozoisite in irregular anhedral inclusions in albite crystals. Rare occurrences of large (3.0 mm) calcite crystals were observed in the melanocratic amphibolite zone of NS.76.

Calcite is most commonly associated with epidote, amphibole, magnetite and specular haematite, in numerous veins in all of the amphibolite bodies. A calcite vein six inches in width occurs in NS.75 at 191 feet, and consists of an equigranular aggregate of subhedral calcite crystals which are approximately 5 to 10 mm in diameter.

#### Properties

Calcite was recognised in hand specimens by its effervescence in dilute hydrochloric acid, and under the microscope, by its well developed cleavage, high relief, birefringence and its uniaxial negative character. Refractive index determinations of calcite from veins in the melanocratic amphibolite zone were made on selected crushed fragments with their optic axis vertical, and gave  $W = 1.661 - 1.664$ .

#### GYPSUM AND ANHYDRITE

Gypsum is common in joints and fractures near the outer margins of the major amphibolite body, and throughout the minor bodies. Mauve to pink anhydrite is very rare, but has been noted in veins in minor amphibolite bodies.

### THE OPAQUE MINERALS

The most abundant opaque minerals in the amphibolite bodies are the iron-bearing oxides which are scattered throughout the amphibolite groundmass and which also form prominent veins and segregations. The most common of these are ilmenite and magnetite; haematite, specular haematite, and rutile are less common. Sulphides are largely restricted to veins and sheared zones, and are very subordinate to the oxides in the groundmass of the rock. In the order of decreasing abundance, the sulphides of the Chibuluma amphibolites are pyrite, chalcocopyrite, pyrrhotite, and pentlandite.

A number of interesting occurrences of opaque minerals are found in the dolomitic formations of the Upper Roan. These are apparently associated with the amphibolite bodies and include magnetite, pyrite, pyrrhotite, chalcocopyrite, cubanite, valleriite, and pentlandite.

Identification of the opaque minerals was carried out largely by means of their optical properties. Reflectivity determinations were made in white light using an Eel micro-reflectometer unit, incorporating a selenium photocell and amplifier unit, run off a Phillips A.C. stabiliser delivering a current of 232 volts, stabilised to within  $\pm 0.1$  per cent. A Wild 6 volt, 18 amp, high-intensity tungsten-ribbon lamp supplied the illumination. Experience with this apparatus has shown that results are repeatable to within  $\pm 0.3$  per cent in white light. All measurements were made by illuminating a circular area with a diameter of  $40\mu$  in the centre of the field. Pyrite, with reflectivity of 54.4 per cent, was used as a standard and the results obtained were compared with figures given by Cameron (1961, p. 269) for confirmation of mineral identification. Microchemical tests were carried out when optical properties were inadequate.

OPAQUE MINERALS IN THE AMPHIBOLITE

OXIDES

ILMENITE

Ilmenite was recognised by its strong grey to pinkish grey colour pleochroism, its strong anisotropism, and from its association with sphene. The reflectivity of unorientated specimens was determined to be 19.2 to 19.9 per cent, which lies well within the range of 17.8 to 21.1 per cent given by Cameron (1961, p. 268).

Ilmenite occurs most commonly as anhedral to subhedral skeletal crystals, rods and bars, which have a strong tendency to be arranged in triangular patterns (Plates 24, 25, 26, and 27), and which are invariably enclosed in narrow sheaths of sphene. These crystals are up to 8 mm in length and although they occur scattered throughout the amphibolite, they are most common and better developed in the pegmatitic zone. In the chilled marginal phases, ilmenite occurs only in short, discrete rods.

In NS.76, at 272 feet, unusual "swarms" of up to 15 thin (0.5 mm) parallel plates or sheets of ilmenite, with a maximum length of 60 mm, cut through all other minerals in the rock. The plates themselves are intersected by a later magnetite veinlet.

The alteration of ilmenite to sphene has produced curved boundaries between the two and, where the process is far advanced, the ilmenite occurs as isolated spheroidal grains in masses of sphene. Rutile is also a minor constituent in the sphene and, as it was not observed in fresh ilmenite, it is also considered to be an alteration product. Alteration in some cases has taken place along preferred planes within the ilmenite producing a cross-hatched appearance.

Lamellae twinned parallel to rhombohedral ( $10\bar{1}1$ ) planes in the ilmenite are very common (Plate 27). The lamellae average 0.02 mm in width. No intergrowths between magnetite and



Plate 25. MELANOCRATIC AMPHIBOLITE.

A skeletal crystal of ilmenite in melanocratic amphibolite.

NS 82, 675'.

Photomicrograph (X 12),  
Reflected light.

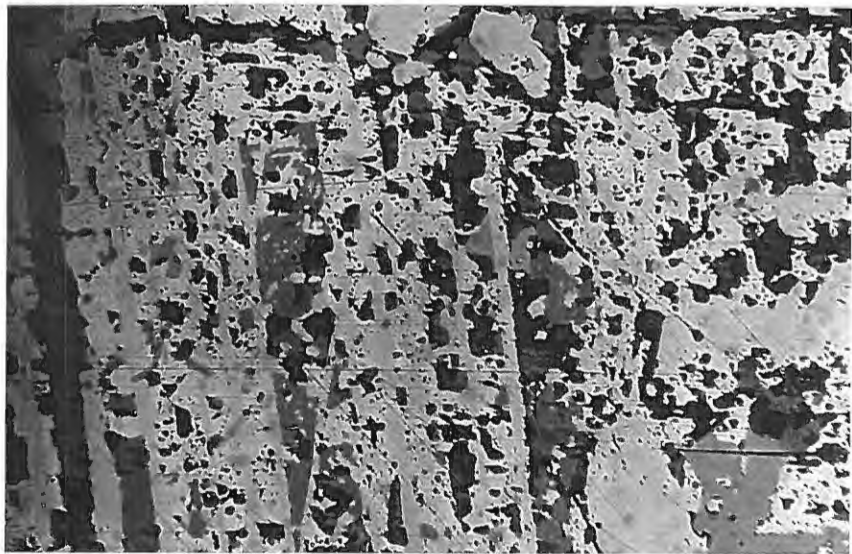


Plate 26. MELANOCRATIC AMPHIBOLITE.

Detail of a skeletal crystal of ilmenite showing rods and bars of ilmenite (light) with interstitial sphene (dark).

NS 82, 675'.

Photomicrograph (X 150),  
Reflected plane polarised  
light.

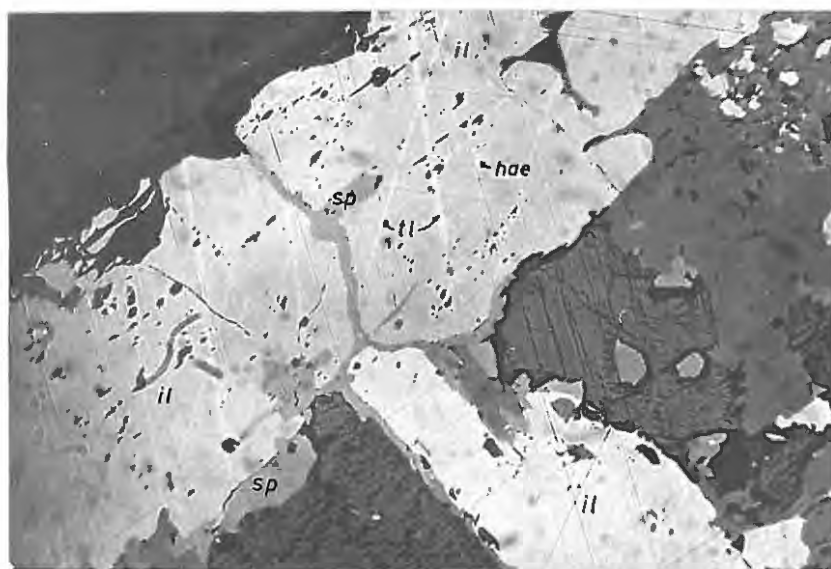


Plate 27. MELANOCRATIC AMPHIBOLITE.

An ilmenite (il) crystal with thin twin lamellae (tl) and minute exsolved haematite (hae) bodies. The ilmenite is enclosed by a selvage of sphene (sp).

NS 82, 675'.

Photomicrograph (X 150),  
Reflected plane polarised  
light.

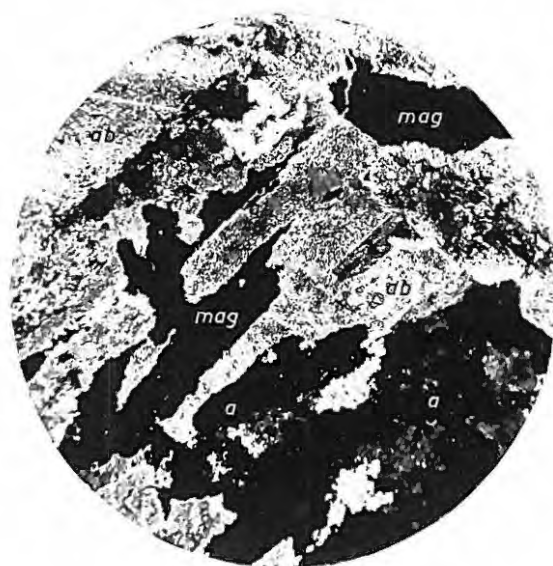


Plate 28. MESOTYPE AMPHIBOLITE.

Amphibole (a), occurring interstitially to albite (ab) laths. The former have been largely replaced by magnetite (mag).

NS 76, 798'.

Photomicrograph (X 27),  
Plane polarised light.

ilmenite were observed, but numerous very small orientated bodies of haematite occur throughout the ilmenite (Plate 27). The regular disposition and ubiquitous nature of these bodies suggests that they originate through exsolution rather than replacement processes. They average only 0.005 mm in diameter, although in most ilmenite crystals, the exsolution bodies have coalesced to form patches of haematite up to 0.02 mm in diameter. The presence of exsolved haematite indicates a high temperature of formation which, according to Edwards (1954, p. 70), would be "somewhat above 600°C".

The skeletal crystals of ilmenite enclose both amphibole and feldspar crystals in optical continuity with the amphibole and feldspar crystals surrounding the ilmenite. This suggests that the oxide is the later-formed mineral. From the moderately high tenor of  $TiO_2$  values but low tenor of  $Fe_2O_3$  values in the rock, (Table VI) this would appear to be in agreement with the views held by Wager and Deer (1939, p. 311). They consider that in a basic magma these minerals (magnetite and ilmenite) "will be amongst the first to crystallise if the amounts of  $Fe_2O_3$  and  $TiO_2$  exceed about three and a half and two and a half per cent respectively; if under these amounts there will be no primary precipitation until these values are obtained".

#### MAGNETITE

Magnetite was distinguished from ilmenite mainly by its isotropism and the absence of any associated sphene. Where these two opaque minerals occur together, magnetite is slightly less pink than ilmenite. The reflectivity of magnetite, which Cameron (1961, p. 269) gives as 21.1 per cent, was determined by the writer as 20.2 per cent.

Magnetite occurs in two main forms in the amphibolite bodies. The first is in numerous rods, bars, and subhedral crystals disseminated in amphiboles (Plates 13 and 28).

These grains have an average diameter of approximately 0.05 mm

and the rods are rarely greater than 0.1 mm in length. As described previously in the mineralogy of amphibole, these grains and rods are commonly arranged in an orderly grid-like manner within the amphibole crystal or, in some cases, form well defined bands around the colourless amphibole cores.

The second main occurrence of magnetite is in veins. Veins are up to six inches in width and, in some cases, consist entirely of magnetite although calcite, epidote, chlorite, and amphibole are normally present as gangue. The magnetite appears to have crystallised before all the gangue minerals except amphibole. The veins occur throughout the gabbro, but are particularly common in the pegmatitic and mesotype amphibolites. The individual grains of magnetite show a large size range between 7.0 mm and 0.5 mm in diameter. The crystals are normally subhedral to euhedral. Rare, very well developed octahedral crystals were found in a carbonate vein.

An unusual occurrence of magnetite was noted in the chilled margin at 962 feet in NS. 82, where large (40 mm diameter) euhedral crystals poikilitically enclose the feldspar laths and appear to have developed at the expense of the ferromagnesian silicates. The groundmass between these magnetite porphyroblasts is almost devoid of magnetite.

No twinning or exsolution textures were noted in any of the magnetite crystals. No chemical analysis was made of the magnetite, but the rare occurrence of sphene in some slightly weathered veins suggests that the vein magnetite may have a small titanium content.

The two principal forms of magnetite described above differ in origin. The small grains scattered throughout the amphiboles are considered to have originated during or prior to the formation of the amphibole from an original pyroxene. This is to some extent corroborated by the arrangement of the magnetite grains in rectangular or schiller-like patterns, and implies that the outer mantles of amphiboles are considerably

less rich in iron than were the outer mantles of earlier pyroxenes. In addition, considerable replacement of amphibole by magnetite has taken place (Plate 28). Parts of branching amphibole crystals from the pegmatite zone consist entirely of magnetite. The writer considers the magnetite-bearing veins to be segregation veins which represent a very late stage in the crystallisation of the magma. They are important in that they indicate a possible trend in fractionation of the intrusion.

#### HAEMATITE AND SPECULARITE

These oxide minerals are not common and occur mainly in carbonate veins, together with epidote, chlorite, and pyrite, and rarely with chalcopyrite. The carbonate veins have been the loci of late movements within the amphibolite bodies and the oxides in the veins commonly exhibit slickensides.

Specularite rarely shows twin lamellae which are, however, well developed in one carbonate vein at 936 feet in NS.78. Minute exsolved bodies of haematite also occur in ilmenite crystals (Plate 27).

#### RUTILE

Rutile occurs mainly as minute grains in sphene. It is also found with magnetite and pyrite on cross fractures in a carbonate-quartz vein. Under the microscope, it was recognised by its characteristic red-brown internal reflections, and a similar reflectivity to magnetite.

### SULPHIDES

#### PYRITE

Pyrite is the most abundant sulphide. Although it is only a minor accessory in the amphibolite groundmass, it is very common in veins and shear zones throughout the amphibolite bodies. Pyrite was recognised by its characteristic colour and hardness, its isotropism, and by its normally well developed euhedral form.



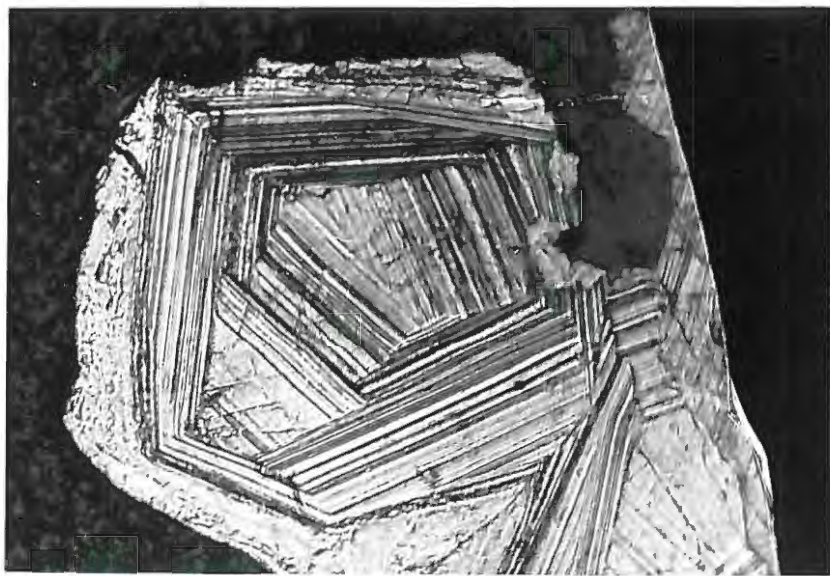


Plate 29. MELANOCRATIC AMPHIBOLITE.

A zoned pyrite crystal from an amphibolite shear zone. Etched with concentrated hydrochloric acid and potassium dichromate solution.

NS 82, 675.5'.

Photomicrograph (X 75),  
Reflected plane polarised  
light.

In veins, pyrite occurs in single cubes or pyritohedra, or in clusters of crystals associated principally with calcite, magnetite, epidote, and chlorite. In shear zones, pyrite occurs both in euhedral crystals and in anhedral masses, together with chalcopyrite, amphibole, and chlorite. Inclusions of the associated minerals are common in pyrite. The average size of crystals is approximately 8 mm but individual crystals occur up to a maximum of 40 mm in diameter. Euhedral pyrite crystals from a depth of 675.5 feet in NS.82 exhibit concentric growth zones (Plate 29) when etched with concentrated hydrochloric acid and potassium dichromate. This zoning is outlined by a string of inclusions around the inner zone which was less bright than the outer zone during the early stages of polishing but is indistinguishable except for the inclusions, in well polished sections.

#### CHALCOPYRITE

Chalcopyrite is not common. It is found mainly in chloritic and amphibolitic shear zones where it occurs interstitially to the radiating acicular amphibole crystals. It also occurs with pyrrhotite, pyrite, and scapolite in veins, and in very small, uncommon anhedral crystals scattered sporadically through the amphibolite groundmass. These chalcopyrite crystals normally occur next to or near either ilmenite, magnetite, or pyrite crystals.

Chalcopyrite was identified by its colour, hardness, and weak anisotropism. The reflectivity was found to be between 41.4 and 42.5 per cent. Cameron (1961, p. 270) records a mean reflectivity of 44.0 per cent and a range of reflectivity values between 42.0 and 46.1 per cent. The discrepancy between the writer's values and the standard is probably due to the slightly lower degree of polish obtained on the Chibuluma sample.

#### PYRRHOTITE AND PENTLANDITE

These two minerals are intimately associated in their occurrence and are, therefore, described together.

Pyrrhotite, a common sulphide of basic igneous rocks, occurs very sparsely in the Chibuluma amphibolite. Jackson (1932) did not record the mineral in his description of the gabbros and norites of the Nchanga district, but J.B. Lee-Potter has informed the writer of its relatively common occurrence in the amphibolites of the Roan Antelope basin.

Only three occurrences of pyrrhotite were noted during the examination of the drill cores from the amphibolite bodies and in all three, the pyrrhotite occurs in veins in the melanocratic amphibolite, and is associated with pyrite and chalcopyrite. Pentlandite occurs mainly as exsolved lamellae in the pyrrhotite. Gangue minerals are scapolite, calcite, chlorite, and amphibole.

Pyrrhotite was recognised under the microscope by its characteristic pinkish brown colour, its anisotropism, and weak colour pleochroism, and by its being harder than chalcopyrite. This last property distinguishes it from cubanite, which is very similar in colour, but nearly equal in hardness to chalcopyrite. A further distinction between the two is the fact that pyrrhotite shows a definite brown stain on etching with 40 per cent KOH, whereas cubanite does not react. Pentlandite was recognised by its colour (which is slightly more yellow than pyrite, but considerably whiter than chalcopyrite), its isotropism, its hardness (being softer than pyrrhotite), and by its exsolution textural relationship with the pyrrhotite.

Pyrrhotite is best developed in a vein intersected by NS.56 at 719 feet, where it occurs in the interstices between large and well formed euhedral scapolite crystals. The largest pyrrhotite crystals have a maximum diameter of 15 mm. This occurrence is of particular interest and importance with regard to paragenesis and temperature of formation of the sulphides and is, therefore, described in detail below.

The vein material consists mainly of euhedral scapolite crystals and interstitial pyrrhotite. However, along the contacts between these two minerals, pyrite has replaced scapolite and gangue minerals have replaced pyrrhotite (Plates 30, 31, and 32). The gangue thus forms a selvage between 0.1 mm and 0.5 mm in width around the pyrrhotite, separating it from the pyrite. The pyrite preserves the euhedral outline of the original scapolite crystals, but because of the random orientation of pyrite cubes, an irregular contact is formed between the pyrite and the remaining scapolite. Pyrite also replaces scapolite along internal fractures and cleavages. The gangue minerals replacing the pyrrhotite consist of chlorite with lesser amphibole, calcite, and biotite. The boundaries between the gangue and the pyrrhotite, exhibit common replacement features being normally serrated and irregular with short tongues of one mineral penetrating the other.

Pentlandite occurs in short lamellae or spindle-shaped rods up to 0.01 mm in width and 0.1 mm in length in both pyrrhotite and chlorite gangue (Plates 32 and 33). In places, these rods or lamellae are concentrated in narrow bands in which they anastomose or are arranged en echelon. Irregular bodies of pentlandite are uncommon, and occur only along the "outer margin" of the chlorite gangue adjacent to the pyrite (Plate 34). The arrangement of the pentlandite in the pyrrhotite strongly suggests that it has been exsolved, and a number of features suggest that the pentlandite in the gangue is of similar origin; the originally enclosing mass of pyrrhotite having been subsequently replaced selectively by the gangue. These features are:-

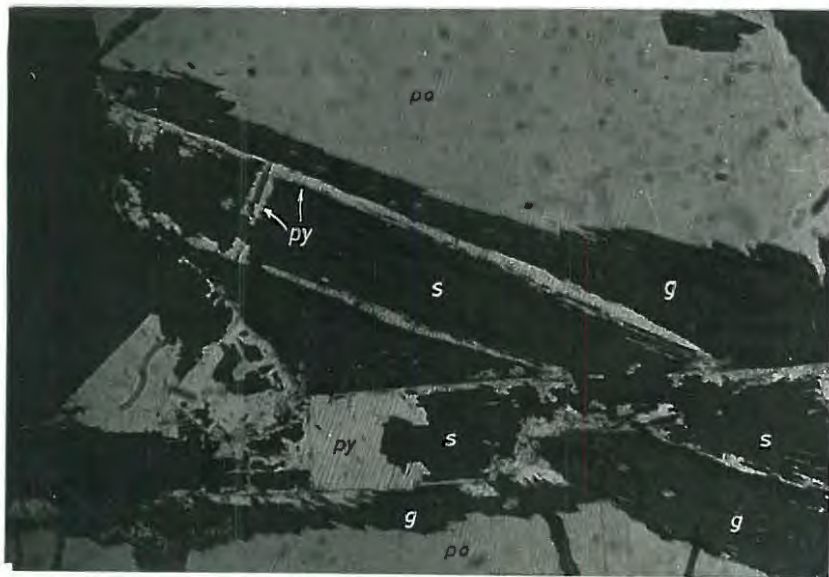


Plate 30. VEIN IN MELANOCRATIC AMPHIBOLITE.

Euhedral scapolite (s) and interstitial pyrrhotite (po) from a vein in the melanocratic amphibolite. The light coloured parallel zones outline a longitudinal section through an euhedral scapolite crystal in which pyrite (py) has replaced the scapolite in the peripheral parts of the crystal and along transversal basal cleavage planes. A gangue (g) of calcite, chlorite, and amphibole is developed between the pyrite and the pyrrhotite.

NS 56, 719'.

Photomicrograph (X 70),  
Reflected plane polarised  
light.

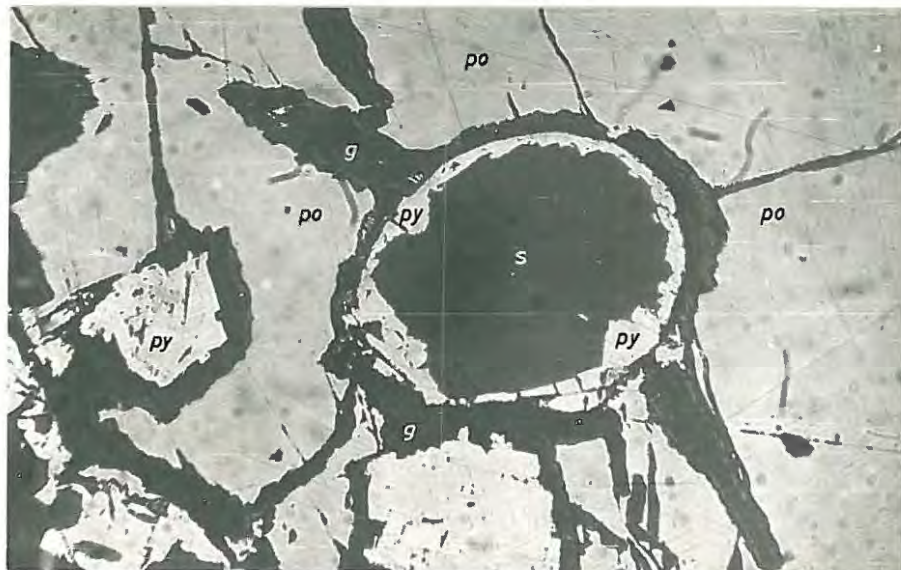


Plate 31. VEIN IN MELANOCRATIC AMPHIBOLITE.

A near - basal section of a subhedral scapolite (s) crystal set in pyrrhotite (po). Pyrite (py) has replaced the peripheral parts of the scapolite, and chlorite, calcite, and amphibole gangue minerals (g) occur between the pyrite and the pyrrhotite.

NS 56, 719'.

Photomicrograph (X 78),  
Reflected plane polarised  
light.



Plate 32. VEIN IN MELANOCRATIC AMPHIBOLITE.

Pyrrhotite (po) occurring interstitially to euhedral scapolite (s) crystals which have been replaced marginally by pyrite (py). The gangue (g) contains numerous small, mutually parallel, laths or lamellae of pentlandite (pn).

NS 56, 719'.

Photomicrograph (X 70),  
Reflected plane polarised  
light.

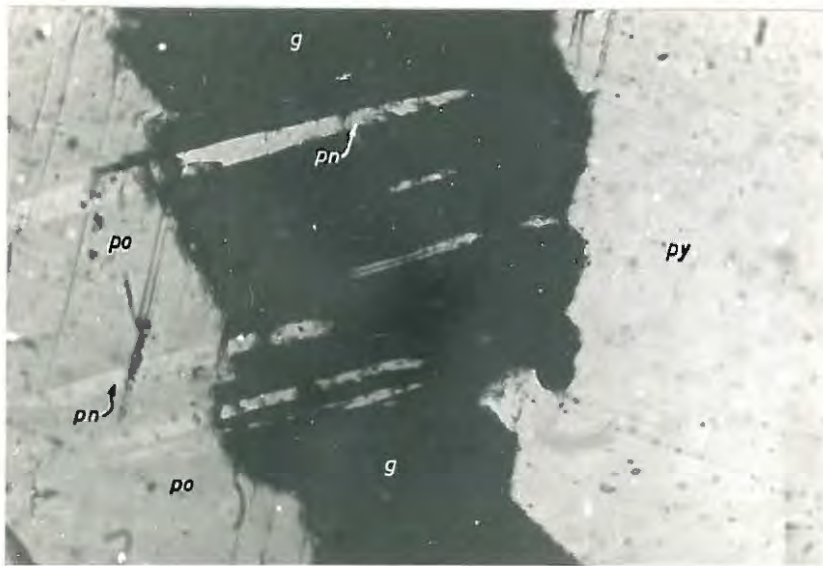


Plate 33. VEIN IN MELANOCRATIC AMPHIBOLITE.

Pentlandite (pn) laths or spindles traversing the boundary between pyrrhotite (po) and gangue (g) without any deflection or change in width. The pentlandite laths do not penetrate the pyrite (py).

NS 56, 719'.

Photomicrograph (X 700),  
Reflected plane polarised  
light.

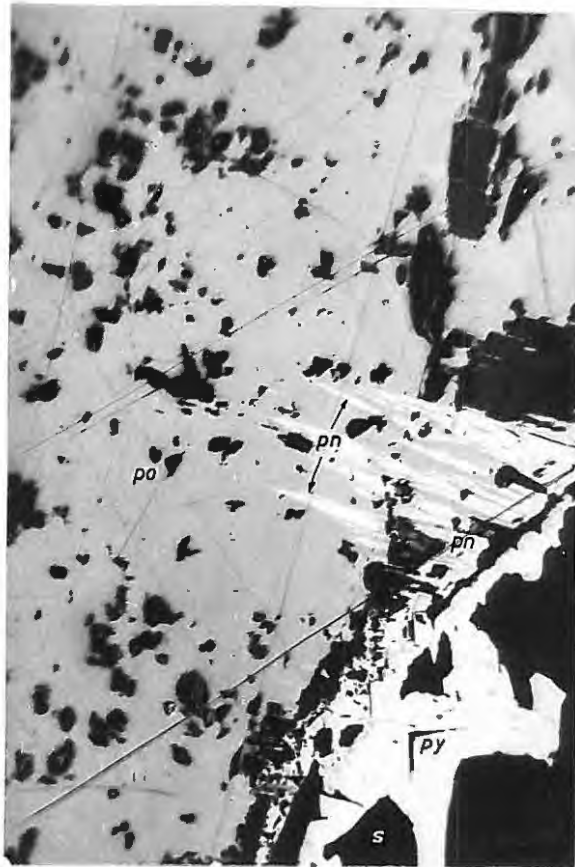


Plate 34. VEIN IN MELANOCRATIC AMPHIBOLITE.

Pentlandite (pn) occurring in flame-like spindles near the margin of a pyrrhotite (po) crystal. Discrete crystals of pentlandite also rim the pyrrhotite. Pyrite (py) replaces scapolite (s).

NS 56, 719<sup>i</sup>.

Photomicrograph (X 500),  
Reflected plane polarised  
light.

- (a) all the laths, lamellae, or spindles of pentlandite in any one pyrrhotite crystal, and in the gangue surrounding that crystal, are parallel. This parallel arrangement is characteristic of the exsolution of pentlandite from pyrrhotite, which according to Edwards (1954, p. 108), takes place parallel to the basal plane (0001) of pyrrhotite;
- (b) a small number of pentlandite laths traverse the boundary between gangue and pyrrhotite without deflection or change in width (Plate 33);
- (c) pentlandite in the gangue shows no constant structural relationship to the gangue minerals and, in particular, is in no way associated with the cleavage planes of the chlorite, amphibole, or calcite;
- (d) pentlandite lamellae are more abundant in the gangue and towards the boundaries of the pyrrhotite than in the centre of the pyrrhotite. This feature, together with the irregular masses of pentlandite on the pyrite-gangue boundaries, is characteristic of an advanced stage of exsolution (Edwards, 1954, p. 108) in which the iron-nickel sulphide migrates towards grain boundaries and there forms rims about the former host pyrrhotite, the texture being described as "rim texture".

Pyrite replacing the scapolite was probably derived from the pyrrhotite during replacement of the latter by chlorite gangue.

Large euhedral pyrite crystals up to 12 mm in diameter occur in the same vein. These crystals are normally surrounded by chalcopyrite or pyrrhotite, and, where fractured, are veined by pyrrhotite.

The chalcopyrite forms veins in the pyrrhotite and apparently replaces it. Clusters of small pyrrhotite grains occur in the chalcopyrite near the main chalcopyrite-pyrrhotite boundary, and appear to be unreplaced relics of the former.

The sequence of events within these veins appears therefore to have been as follows:-



- (a) crystallisation of euhedral pyrite and scapolite;
- (b) development of interstitial pyrrhotite, which was followed, on cooling, by exsolution of pentlandite. This exsolution is considered by Hawley and Haw (1957, p. 133) to be controlled to some extent by the variation in sulphur content of pyrrhotite with temperature. The migration of pentlandite to grain boundaries of the pyrrhotite possibly suggests a slow rate of cooling, although Edwards (1954, p. 108) and Hewitt (1938, p. 318) both consider that this migration is rapid at high temperatures;
- (c) replacement of pyrrhotite and possibly pentlandite by chalcopyrite. The stage at which this process took place cannot be determined accurately as chalcopyrite does not contain any pentlandite. The exsolution of pentlandite may have occurred simultaneously with the replacement of nearby pyrrhotite by chalcopyrite as Hawley and Haw (1957, p. 138) consider that the "later invasion of copper-rich fluids to form a late chalcopyrite may also have aided in the sulfur rearrangement and hence the ex-solution of pentlandite";
- (d) selective replacement of pyrrhotite by chloritic gangue minerals which resulted in their enclosing the relic pentlandite lamellae. This was possibly accompanied by replacement of scapolite by pyrite formed largely from the materials of the displaced pyrrhotite.

The paragenesis in the vein is, therefore, scapolite and an older generation of pyrite, pyrrhotite (and pentlandite), chalcopyrite, chloritic gangue, and finally, a younger generation of pyrite. It is of interest to note the probability of there being two generations of pyrite. This paragenesis is in agreement with that obtained by Schwartz (1937, p. 53) in his summary

of the paragenesis of pyrrhotite. He considered pyrite to be normally earlier than pyrrhotite; pentlandite contemporaneous with it; and chalcopyrite later than it. He also considered (p. 38 and p. 53) that a later generation of pyrite, resulting from the alteration of pyrrhotite, was of common occurrence.

The presence of pyrrhotite, particularly in basic igneous rocks or hydrothermal veins, is commonly regarded as an indication of a high temperature of formation. Deer, Howie, and Zussman (1962, Vol. 5, p. 153), however, quote the occurrences of authigenic pyrrhotite in sediments, and pyrrhotite inclusions in calcite crystals believed to have formed between 25 and 40°C. The presence of this sulphide alone is, therefore, not sufficient evidence to indicate high temperature of formation, but the presence of exsolved pentlandite offers more definite information.

From the behaviour of pentlandite and pyrrhotite under heat Hewitt (1938, p. 311) established that pentlandite goes into solution in pyrrhotite between 425 and 450°C, and may exsolve again only on cooling from above 800°C. Slow cooling from temperatures between 450 and 800°C did not bring about any such separation. This sets a lower limit for the temperature of formation of the sulphides at 425°C, but suggests that it is, in fact, considerably higher.

#### OPAQUE MINERALS IN THE SEDIMENTS

Brief investigations were carried out on some of the occurrences of opaque minerals in the sedimentary formations, where it was considered that they were possibly related to the amphibolite bodies.

##### (a) In the Contact Zone

A common feature of the contacts between an amphibolite and sediment is the development of abundant magnetite and pyrite in the dolomitic sediments.

Magnetite is particularly abundant in the sediments of the upper contact of the major amphibolite body intersected at a depth of 572 feet in NS.82. For a distance of up to thirteen feet above the contact, the greenish grey chloritic dolomite and dolomitic shales contain strings and clusters of subhedral to euhedral magnetite crystals, concentrated in bands parallel to the bedding planes, constituting approximately 30 to 40 per cent of the rock by volume. A narrow band from 568 to 570 feet in depth consists of an estimated 90 per cent by volume of magnetite, with the remaining 10 per cent being talc, chlorite, and dolomite. The parallelism of octahedral cleavage planes of the magnetite in this band demonstrates that large numbers of small crystals occur in parallel orientation.

Clusters of well formed euhedral pyrite crystals also occur in bands parallel to the bedding planes, but are very subordinate to the magnetite. An interesting feature is that pyrite crystals developed in the more argillaceous sediments are normally fractured, whereas those developed in the purer dolomite are not. This is possibly due to the more competent nature of the argillaceous rocks which are themselves brecciated whereas the incompetent dolomites are not, and would imply that the stresses causing the fracturing in the shale and argillites were applied after the formation of the pyrite. If the pyrite is considered to be a contact phenomenon then these stresses are also later than the intrusion of the amphibolite.

The magnetite of the contact zones is normally brittle and friable, and therefore very difficult to polish. Poorly polished sections did not reveal any opaque minerals other than magnetite and pyrite.

Magnetite is indisputably associated with the amphibolite bodies as, in the sediments away from the contacts, both magnetite and pyrite are normally present in minor amounts only, and pyrite is normally the more abundant of the two. Exceptions to this

generalisation are certain dolomite horizons in which pyrite is relatively common. Near the contacts, opaque minerals occur in bands parallel to undisturbed bedding planes and appear to have been introduced metasomatically after the emplacement of the amphibolite. This marked banding suggests that the magnetite either replaced a mineral occurring in bands in the original sedimentary rock or that the metasomatising material migrated predominantly along bedding planes. Magnetite and pyrite of metasomatic origin are common constituents in skarn deposits (Deer, Howie, and Zussman, 1962, Vol. 5, p. 76 and p. 139) and, in the contact zones of the Chibuluma amphibolite, these minerals may be the only remnants of a skarn which was formed during the emplacement of the amphibolite, but which was subsequently affected by retrogressive metamorphism. Evidence of the temperature obtained during contact metamorphism is lacking in the opaque minerals of the contact zone.

(b) In Carbonate Veins

Chalcopyrite, cubanite, and pyrrhotite occur together in a thin carbonate vein intersected at a depth of 1,385 feet in NS.78 (Plate 35). The vein, approximately 1.3 inches in width, is in the dolomite only 45 feet below the major amphibolite body.

The chalcopyrite occurs in irregular anhedral crystals up to 15 mm in diameter which contain numerous well developed intersecting lamellae of cubanite. At least three sets of lamellae exist and these are, therefore, probably parallel to the (111) planes of the chalcopyrite (Edwards, 1954, p. 104). Cubanite constitutes approximately 30 per cent by volume of the sulphide intergrowth. Small grains of pyrrhotite occur around the boundaries of the chalcopyrite crystals and constitute less than five per cent of the sulphides. A few pentlandite intergrowths occur on the outer margins of the pyrrhotite.



Plate 35. VEIN IN UPPER ROAN GROUP.

Intersecting ex-solution lamellae of cubanite (cb) in chalcopyrite (cp). Pyrrhotite (po) rims the chalcopyrite in places.

Stained with hydrochloric acid and chromic oxide.

NS 78, 1385'.

Photomicrograph (X 50),  
Reflected plane polarised  
light.

The sulphide assemblage, chalcopyrite-cubanite-pyrrhotite, is of interest in that it is regarded by McKinstry and Kennedy (1957, p. 381) to be an early, stable phase assemblage of the Cu-Fe-S system. These writers based their findings on observed mineralogical textures and reported that "cubanite commonly, if not invariably, occurs intergrown with either chalcopyrite or pyrrhotite, presumably representing unmixing of a solid solution stable above 400 or 500°....." In a mineral assemblage, "presumably formed at lower temperatures, pyrrhotite and chalcopyrite occur together but cubanite is usually lacking". Cubanite is, therefore, a valuable mineral in geological thermometry and the writer considers it necessary to mention briefly some salient features of the chalcopyrite-pyrrhotite solid solution series. Most of the data presented below are from Edwards (1954, p. 104) who quotes mainly Borchert, and Merwin and Lombard.

Cubanite is formed mainly from the transformation of chalcopyrrhotite on cooling below 235°C. The chalcopyrrhotite itself exsolves from chalcopyrite or pyrrhotite at temperatures between 550 and 255°C depending upon the composition of the original homogeneous phase. This temperature range is that over which the chalcopyrrhotite is stable. In a cooling system, the presence of the cubanite exsolution lamellae in chalcopyrite indicates that the temperature of formation of the assemblage was above 235°C. The relative proportions of these two minerals also give a rough indication of the temperature at which exsolution of the original chalcopyrrhotite began. From Figure 19 (Borchert's diagram, Edwards, p. 106), it can be seen that a small amount of either chalcopyrite in cubanite or vice versa, suggests that this temperature was only slightly above 235°C, whereas the low chalcopyrite:cubanite ratio of 2:1 in the Chibuluma carbonate vein suggests that this temperature was near 400°C.

FIGURE 19

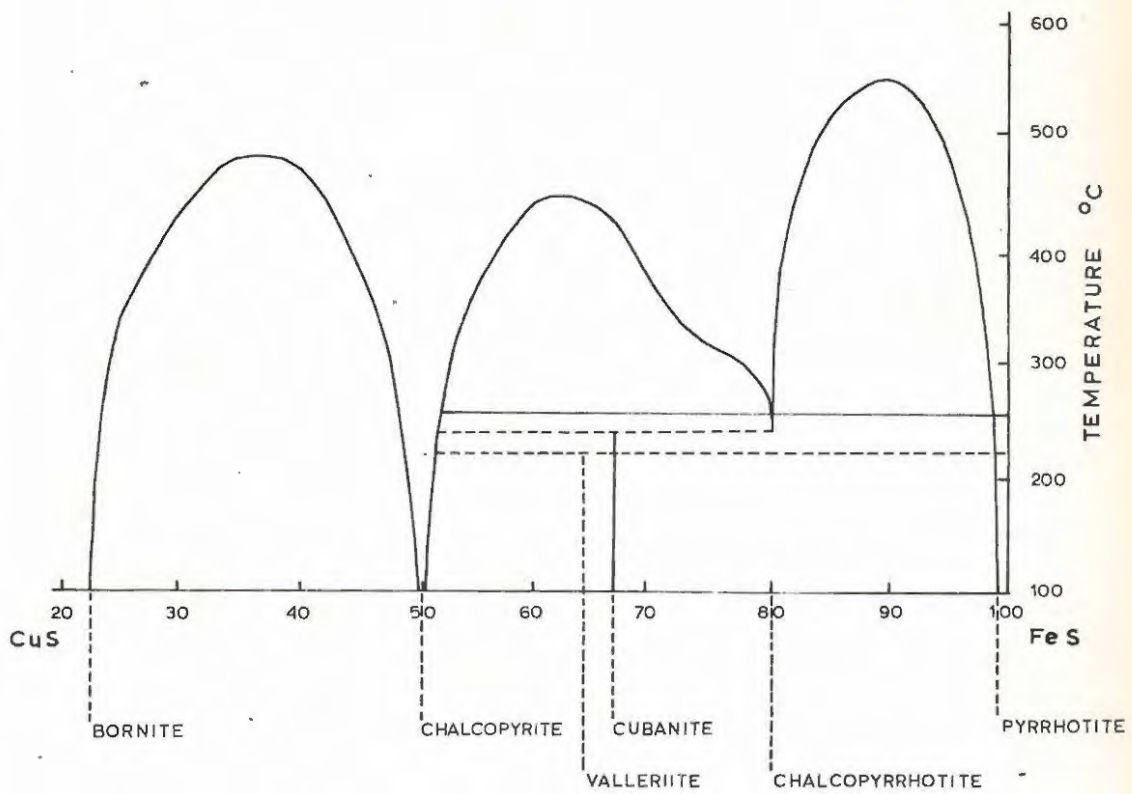


DIAGRAM ILLUSTRATING THE UNMIXING RELATIONS  
AND STABILITY REGIONS OF THE SYSTEM

Cu - Fe - S

After Borchert (quoted by Edwards, 1954)

Schwartz, also quoted by Edwards (1954, p. 105), has shown that on heating, cubanite forms a solid solution with chalcopyrite only above 450°C. These figures imply that in order to form a solid solution of either cubanite or chalcopyrrhotite in chalcopyrite, from which chalcopyrrhotite and subsequently cubanite can form, a Cu-Fe-S system must be heated to above 450°C. An exception to this is the limited solid solution or diffusion of pyrrhotite in chalcopyrite which takes place at temperatures over 300°C and, according to Hewitt (1938, p. 326) produces only a restricted aureole of a chalcopyrrhotite-chalcopyrite intergrowth around residual pyrrhotite on cooling.

Valleriite is also formed from unstable chalcopyrrhotite on cooling but at a slightly lower temperature, than cubanite (225°C as opposed to 235°C). Chalcopyrrhotite commonly has FeS in excess of that required for the formation of either cubanite or valleriite and this excess is exsolved as pyrrhotite on the transformation of the chalcopyrrhotite. The pyrrhotite rimming the chalcopyrite-cubanite intergrowth (Plate 35) could possibly be of such an origin, which would, therefore, imply that pyrrhotite had a greater rate of diffusion than the cubanite, and that the cubanite and chalcopyrite lattices completely expel pyrrhotite at low temperatures.

The minimum temperature that can be inferred from the presence of a chalcopyrite-pyrrhotite intergrowth is not definitely established. Most authors are particularly noncommittal on this point although in most of the literature studied by the present writer, the authors favoured temperatures of 450°C or greater. The notable exception is Ramdohr (1960, p. 581) who considers that the unmixing of cubanite occurs between 250 and 300°C, and that earlier estimates of 450°C are much too high.

However, from Borchert's diagram (Figure 19) and the fact that the chalcopyrite-cubanite ratio in the Chibuluma intergrowth is approximately 2:1, the writer favours a high temperature of formation





Plate 36. UPPER ROAN GROUP.

Ovoid clusters of magnetite (grey) with an eccentric concentration of sulphides (white) occurring in a fine-grained, argillaceous dolomite. Note the 'spongy' nature of the magnetite 'blebs' and the similar situation of the sulphides in each bleb. The sulphides in the intergrowth and scattered through the gangue are mainly pyrrhotite and chalcopyrite.

NS 56, 1097'.

Photomicrograph (X 11),  
Reflected light.

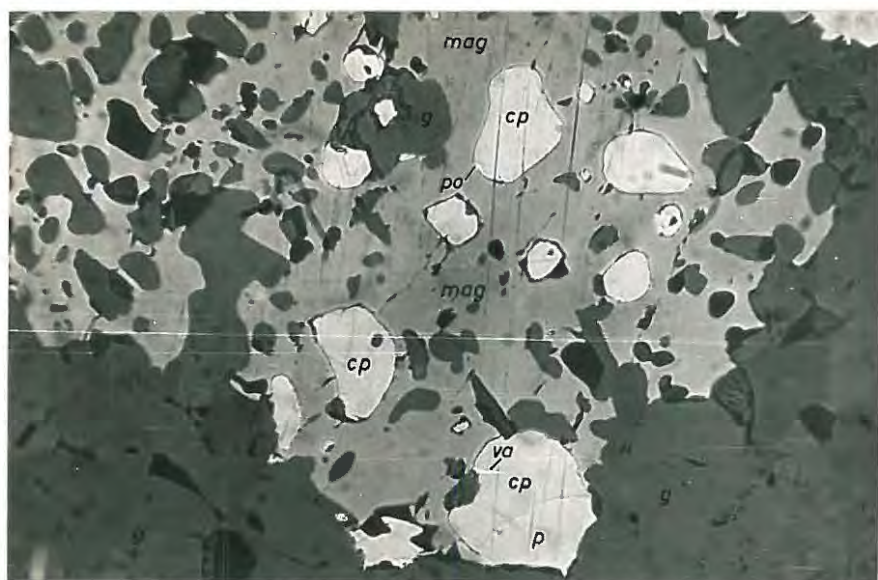


Plate 37. UPPER ROAN GROUP.

Detail of a magnetite - sulphide assemblage shown in Plate 36. Magnetite (mag) encloses chalcopyrite (cp), pyrrhotite (po), and valeriite (va). The gangue (g) is mainly carbonate.

NS 56, 1097'.

Photomicrograph (X 77),  
Reflected plane polarised  
light,  
Crossed nicols.

for the assemblage. That this is in excess of 425°C (Hewitt, 1938, p. 311) is confirmed by the presence of characteristic exsolved grains of pentlandite in the pyrrhotite which rims the chalcopyrite-cubanite intergrowths.

(c) In Dolomite

A noteworthy occurrence of magnetite intergrown with an unusual assemblage of sulphides occurs at a depth of 1,097 feet in NS.56 approximately ten feet (true thickness) below the lower contact of the major amphibolite body. These opaque minerals are locally confined to a narrow band of argillaceous dolomite approximately nine inches in width. Magnetite and pyrite are abundant in the dolomite up to three feet from the contact and are sparsely disseminated elsewhere. Magnetite occurs also along fractures and bedding planes in the dolomite.

The magnetite in the narrow band occurs in spheroidal or slightly elongated ovoid blebs between 5.0 mm and 1.5 mm in diameter. The sulphides, mainly chalcopyrite and pyrrhotite, occur largely as smaller blebs clustered in and around one end of each magnetite bleb (Plates 36 and 37). Cubanite, pentlandite, valleriite, and pyrite are closely associated with the chalcopyrite and the pyrrhotite. The relative volumes of these minerals in the blebs as roughly estimated in polished sections are magnetite 75%; pyrrhotite 12%; chalcopyrite 10%; valleriite  $\frac{1}{2}\%$ ; cubanite 1%; pentlandite  $\frac{1}{2}\%$ ; pyrite 1%.

As in the case of the amphibolite bodies, all opaque minerals were identified by their optical properties which have been described above. Valleriite, however, was not observed in the amphibolite, and in this occurrence it was identified by its pronounced grey to pink pleochroism, its very strong bireflectence, and its hardness, which is only slightly greater than that of chalcopyrite. The identification of pentlandite was confirmed by reflectivity measurements which, in four separate determinations, ranged from 52.1 per cent to 52.6 per cent and average 52.3 per cent. Cameron (1961, p. 270) gives the reflectivity for pentlandite as 52.0 per cent.

The dark magnetite blebs in a pale dolomite host rock produce a spotted appearance in the hand specimens. Cut surfaces readily reveal that the concentrations of sulphides at the ends of all the magnetite blebs are in similar position on the down-dip sides of each bleb. Each bleb, therefore, exhibits some symmetry about its longest axis, which is inclined at a steeper angle than the bedding planes. The average size of the magnetite blebs decreases downwards through the nine-inch band in which they occur. Near the top of this band they have an average diameter of approximately 4.0 mm and a maximum diameter of 5.0 mm. Towards the bottom of this band the average diameter is 1.5 mm and the maximum diameter is 2.0 mm.

The host rock is a fine-grained recrystallised chloritic dolomite with minor thin shale layers. It is no different in appearance to the unmineralised dolomite on either side of it. Under the reflecting microscope, each magnetite bleb is seen to be a spongy crystal containing abundant ovoid inclusions of the gangue minerals. It is not known, however, whether each bleb is a single crystal or a mosaic of crystals. The overall spheroidal or ovoid nature of the magnetite blebs was confirmed by dissolving away the host rock in dilute hydrochloric acid.

Spheroidal masses of sulphide up to 0.5 mm in diameter are completely enclosed in the magnetite. Larger masses (maximum diameter 1.3 mm) occur on the boundaries between the magnetite blebs and the enclosing gangue, and these exhibit smooth spheroidal or curved boundaries against the magnetite but irregular boundaries against the gangue. The paragenetic relationship between the magnetite and the sulphides was not indicated in any of the boundary features observed. A slightly serrated magnetite-sulphide boundary suggests that the latter mineral could be replacing the former, but the same feature was noted on magnetite-carbonate

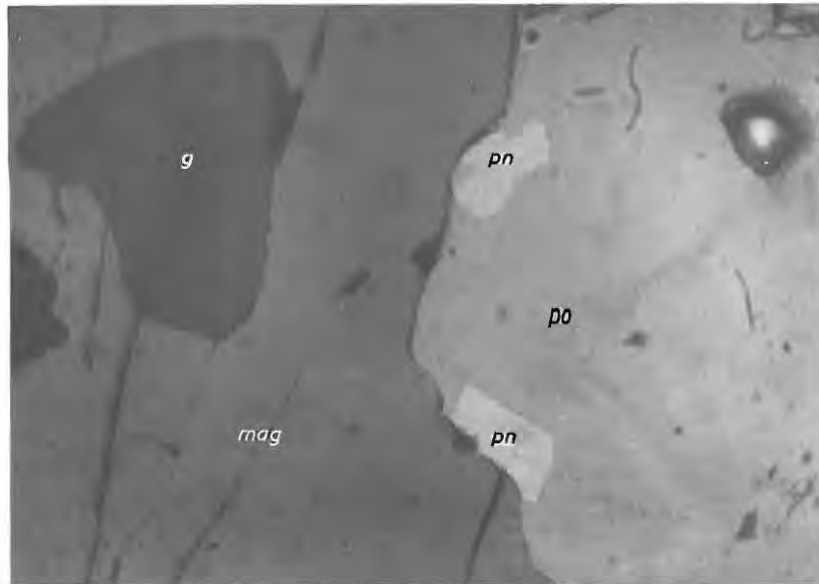


Plate 38. UPPER ROAN GROUP.

Pyrrhotite (po) with exsolved subhedral pentlandite (pn) crystals near the pyrrhotite - magnetite (mag) boundary. The gangue mineral (g) is a carbonate.

NS 56, 1097'.

Photomicrograph (X 700),  
Reflected plane polarised  
light.

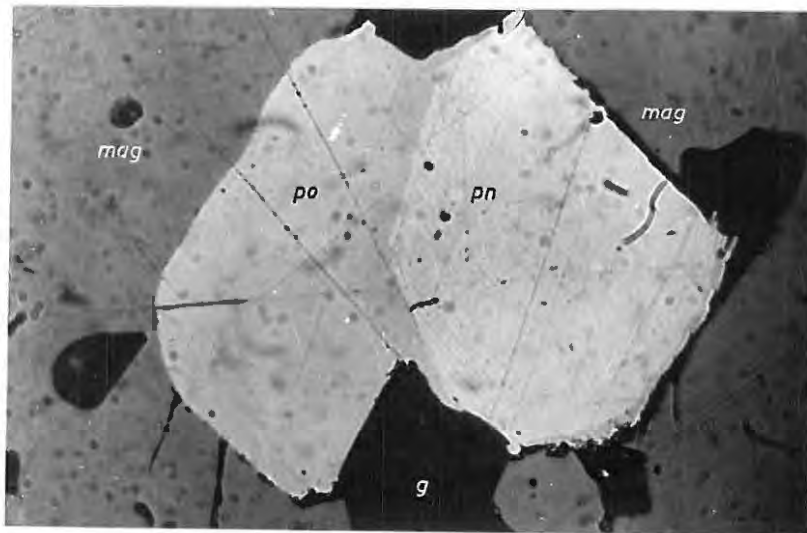


Plate 39. UPPER ROAN GROUP.

Pentlandite (pn) and pyrrhotite (po) exhibiting a mutual straight line boundary. The salient angles on the pentlandite side of the boundary suggest that this mineral was the first formed. Both sulphides are enclosed in magnetite (mag) and carbonate gangue (g).

NS 56, 1097'.

Photomicrograph (X 700),  
Reflected plane polarised  
light.

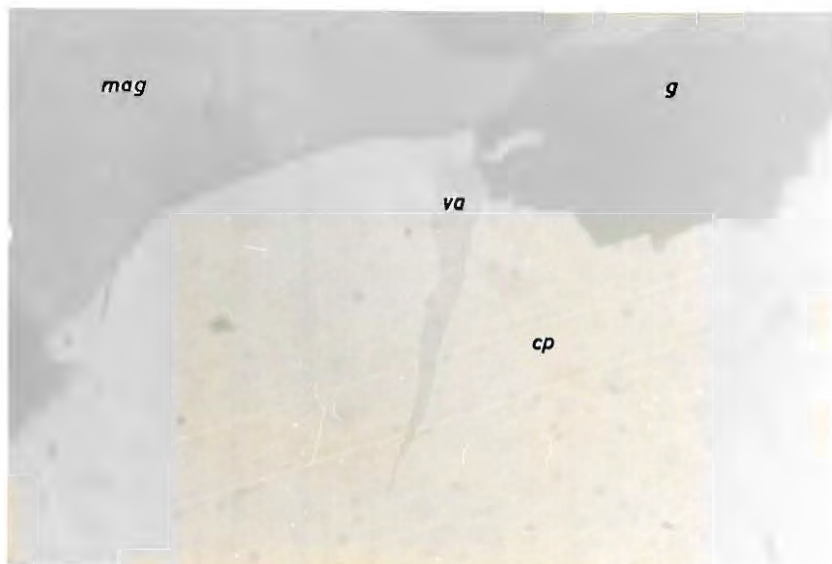


Plate 40. UPPER ROAN GROUP.

Detail of plate 37 showing an irregular wedge-shaped body of valeriite (va) enclosed in chalcopyrite (cp) together with magnetite (mag) and gangue (g).

NS 56, 1097'.

Photomicrograph (X 770),  
Reflected plane polarised  
light,  
Crossed nicols.

boundaries and, therefore, could not be used in determining the magnetite-sulphide paragenesis.

Similarly, no features indicate which of the two main sulphides, pyrrhotite or chalcopyrite, is the earlier-formed mineral as they exhibit a "mutual boundary" texture (Edwards, 1954, p. 133). Pyrrhotite in some cases may be the earlier-formed mineral as it commonly occurs along the boundaries of spheroidal masses of chalcopyrite, and, in one occurrence an euhedral crystal was observed enclosed in chalcopyrite.

Pentlandite occurs mainly in small (maximum diameter 0.02 mm) subhedral crystals near the outer margin of the pyrrhotite from which it appears to have been exsolved (Plate 38). One large crystal of pentlandite (diameter 0.08 mm) occurs together with pyrrhotite in an irregular spheroidal bleb enclosed in magnetite. These two sulphides are, in this case, separated by straight line boundaries and the pentlandite with the convex outer boundary is possibly the earlier-formed mineral (Plate 39). It would appear, therefore, that there are two generations of pentlandite. Small euhedral pyrite crystals appear fractured and are veined by and enveloped in pyrrhotite.

Cubanite and valleriite are both closely associated with the chalcopyrite. Cubanite, the less common of the two, occurs as characteristic exsolution lamellae in the chalcopyrite. Valleriite is also considered to be an exsolved mineral, and it occurs mainly in small wedge-shaped masses roughly perpendicular to the grain boundaries of the chalcopyrite (Plate 40).

With no definite data on the paragenesis of these opaque minerals, any theories concerning the formation of the magnetite blebs with a concentration of sulphide at one side, can be tentative only. Two factors, however, are established. The first is that magnetite is abundant in the contact zone of the major amphibolite body and that it was probably introduced metasomatically subsequent to the emplacement of the amphibolite. The second is that the temperature of formation of the sulphides and, therefore, possibly

that of the associated magnetite, was relatively high. As discussed above, the exsolution of cubanite and valleriite in chalcopyrite and of pentlandite in pyrrhotite all indicate that this temperature was probably at least 400 to 450°C.

A variety of explanations for the origin of these magnetite-sulphide intergrowths is possible. The first is that the sulphides existed in the small band of dolomite prior to the emplacement of the amphibolite. The migration of iron-bearing emanations away from the amphibolite, together with the rise in temperature may have caused magnetite to be precipitated on the "up-current" side of the sulphide which simultaneously developed high-temperature exsolution textures. A second explanation is that all the components necessary for the intergrowth existed in the rock either as blebs or fine disseminations, prior to the emplacement of the amphibolite. This emplacement caused the growth of the blebs, if the components were present as fine disseminations, and the partial expulsion of the included sulphides to the side of the bleb furthest from the amphibolite. A third possibility is that the magnetite itself is the result of oxidation of some pre-existing sulphide. The ovoid shape of the blebs could have resulted from their growth under stress conditions. It is interesting to note the similarity in the orientation of the blebs and that of the tremolite porphyroblasts which is attributed to regional metamorphism. McGregor (1960, p. 79) described ovoid aggregates of pyrite in soapstone at Kalaba. These ovoids are elongated in the plane of schistosity of the host rock, and McGregor, therefore, attributes their shape to their having grown under conditions of stress. If the ovoid shape of the Chibuluma blebs is due to their having developed as sulphide aggregates under conditions of stress during regional metamorphism and the oxidation of the sulphide is associated with the emplacement of the amphibolite, it follows that the emplacement of the amphibolite must post-date regional metamorphism.

Establishing any of these theories as the correct one is difficult with the limited information available and the writer can

only indicate the features which may favour one or the other. The apparently stratiform nature of this mineralised band is thought to be a feature due to the original bedded disposition of the sulphide minerals, the most striking feature of the Copperbelt deposits. It does not appear that these minerals were derived from amphibolite as they are not common in veins or in the contact zones. The amphibolite is considered to be concordant with the bedding and the fact that the axes of symmetry of blebs are at only a small angle to the bedding suggests that the direction of migration of magnetite or a possible solvent aiding in the expulsion of the sulphide, was not perpendicular to the contact, but was controlled to some degree by the bedding planes.

The existence of apparently metasomatic magnetite in the contact zone and the decrease in size of the magnetite blebs down through the mineralised band are features in favour of the first of the above theories of formation. It appears that the magnetite-forming solutions migrating away from the contact and down bedding planes precipitated magnetite on the "upstream" side of the first available sulphide. The magnetite bleb would grow in the direction of the source of magnetite-forming solutions which would, therefore, result in an eccentric distribution of sulphides. Iron that escaped deposition as magnetite on the "front line" of blebs was deposited on the sulphides below, but as the supply of iron to these was relatively limited, smaller blebs developed. The existence of magnetite-free sulphide crystals in the dolomite between large blebs may indicate that some mineral other than chalcopyrite or pyrrhotite caused the initial precipitation of magnetite, or that the magnetite migrated along definite "channels", or that sections showing these sulphides without magnetite are just chance sections.

A different explanation is suggested in that the ovoid and spheroidal masses of sulphides within the magnetite are very similar in shape and size to the more abundant gangue inclusions. The implication is that some sulphides may have been redistributed



after the formation of the spongy magnetite crystals.

The only conclusion the writer can draw from these intergrowths is that they were formed at high temperatures during contact metamorphism following the emplacement of the amphibolite.

(d) In Lower Roan Quartzites

A short study was made of a number of sulphide samples from the Lower Roan quartzites to ascertain whether they exhibit any features which might be attributed to their having been heated during the emplacement of the amphibolite. The samples, selected from surface drillholes NS.76 and NS.70 and underground drillholes 108 and 708, were of the upper part of the orebody in areas where it occurs within forty feet of the overlying minor amphibolite body. In all, sixteen separate samples were cut, roughly polished and studied under the microscope.

It is of interest to note that because of the extremely brittle nature of cubanite, exsolution lamellae of this mineral in chalcopyrite are more readily seen on roughly polished or matte surfaces than on well polished surfaces.

The minerals observed were chalcopyrite, pyrite, bornite, and carrollite. None of these exhibits any textures which could be attributed to contact metamorphism. In drillhole NS.70 at 2,285.0 feet, pyrrhotite occurs in a vein with the above minerals. The presence of pyrrhotite increases the possibility of there being cubanite in these specimens which were, therefore, carefully polished. Cubanite was not found, but it was noted that the pyrrhotite was, in places, veined by later bornite. According to McKinstry and Kennedy (1957, p. 382) this is an unstable assemblage. The presence of the pyrrhotite could possibly be attributed to contact metamorphism, but the replacement of pyrrhotite by bornite could not, and this therefore, possibly represents some later redistribution of the sulphides.

## PETROLOGY

Many aspects of the amphibolite normally considered under the heading of petrology have been included in earlier sections of this thesis. The petrological significance of the variations in grain size, specific gravity, and mode have already been discussed in describing the multiple nature of the major sill, and in indicating the possibility of differentiation having taken place within the sill during crystallisation. In addition, a number of pertinent features such as the clouding of feldspars, zoning in feldspars, scapolites, and amphiboles, and the replacement of original basic feldspars by albite and scapolite have been considered in detail in dealing with the mineralogy of the amphibolite. This section on the petrology of the amphibolites consists, therefore, of a study of the chemical data, comments on the associated metasomatic and metamorphic effects, and a discussion on the age and probable origin of these bodies.

### CHEMICAL DATA

The chemical data on the Chibuluma amphibolites may be placed in three categories. The first consists of three complete rock analyses, the second of twenty-six partial analyses, and the third, a minor category, consists of data made available by the routine geochemical testing of drill-hole cores.

#### Complete Rock Analyses

Three new analyses of Copperbelt amphibolites are presented in Table VI. These are the analyses of a typical mesotype amphibolite (No. 1), a pegmatitic amphibolite (No. 2), and a typical melanocratic amphibolite (No. 3). The norms and C.I.P.W. classifications for these rock types are also given in Table VI. Analyses of three amphibolites, a norite, two granophyres from the Copperbelt area, and a contaminated

TABLE VI  
CHEMICAL ANALYSES

	(1) <u>Mesotype</u> <u>Amphibolite</u>	(2) <u>Pegmatitic</u> <u>Amphibolite</u>	(3) <u>Melanocratic</u> <u>Amphibolite</u>
SiO <sub>2</sub>	52.57	52.68	49.75
Al <sub>2</sub> O <sub>3</sub>	17.28	15.40	13.46
Fe <sub>2</sub> O <sub>3</sub>	1.29	0.23	1.10
FeO	6.46	8.39	9.19
MnO	0.03	0.03	0.06
MgO	4.97	5.45	9.66
CaO	9.29	10.12	10.59
Na <sub>2</sub> O	4.10	2.31	3.62
K <sub>2</sub> O	0.28	0.63	0.92
TiO <sub>2</sub>	3.35	3.00	1.27
S	-	0.46	-
P <sub>2</sub> O <sub>5</sub>	0.05	0.30	0.24
H <sub>2</sub> O + )	0.53	0.98	0.34
H <sub>2</sub> O - )			0.07
	<u>100.20</u>	<u>99.98</u>	<u>100.27</u>

NORMS

Quartz		1.92	7.63	-
Orthoclase		1.67	3.90	5.57
Albite		34.62	19.41	22.55
Anorthite		27.82	29.77	17.81
Nepheline		-	-	4.26
Diopside	Wo	7.67	7.67	13.71
	En	5.02	4.42	8.33
	Fs	2.11	2.90	4.62
Hypersthene	En	7.33	9.14	-
	Fs	3.17	6.47	-
Olivine	Fo	-	-	11.12
	Fa	-	-	7.13
Magnetite		1.85	0.23	1.62
Ilmenite		6.37	5.77	2.43
Apatite		-	0.66	0.66
Pyrite		-	0.84	-
Water		0.53	0.98	0.41
		<u>100.08</u>	<u>99.79</u>	<u>100.22</u>

C.I.P.W. CLASSIFICATION

Class	II	III	III
Sub-Class	1	1	1
Order	5	4	5
Rang	3	4	3
Sub-Rang	5	4	4

- (1) Mesotype Amphibolite: Drillhole NS.76 at 757 feet.  
Analyst: Mean of two analyses by C.B. Anderson and L.Walker,  
Rhodes University.
- (2) Pegmatitic Amphibolite: Drillhole NS.76 at 850 feet.  
Analyst: T.C. Chisholm, Rhodes University.
- (3) Melanocratic Amphibolite: Drillhole NS.76 at 1,174 feet.  
Analyst: D. Muirhead, Rhodes University.

gabbro from Lumwana are given for comparison in Table VII. Typical analyses of a tholeiitic basalt, an alkaline olivine-basalt, and a spilite are also included. An analysis of a dolerite pegmatite from Alwyn's Gat (Walker and Poldervaart, 1949) is included for comparison with the pegmatitic amphibolite.

#### Partial Rock Analyses

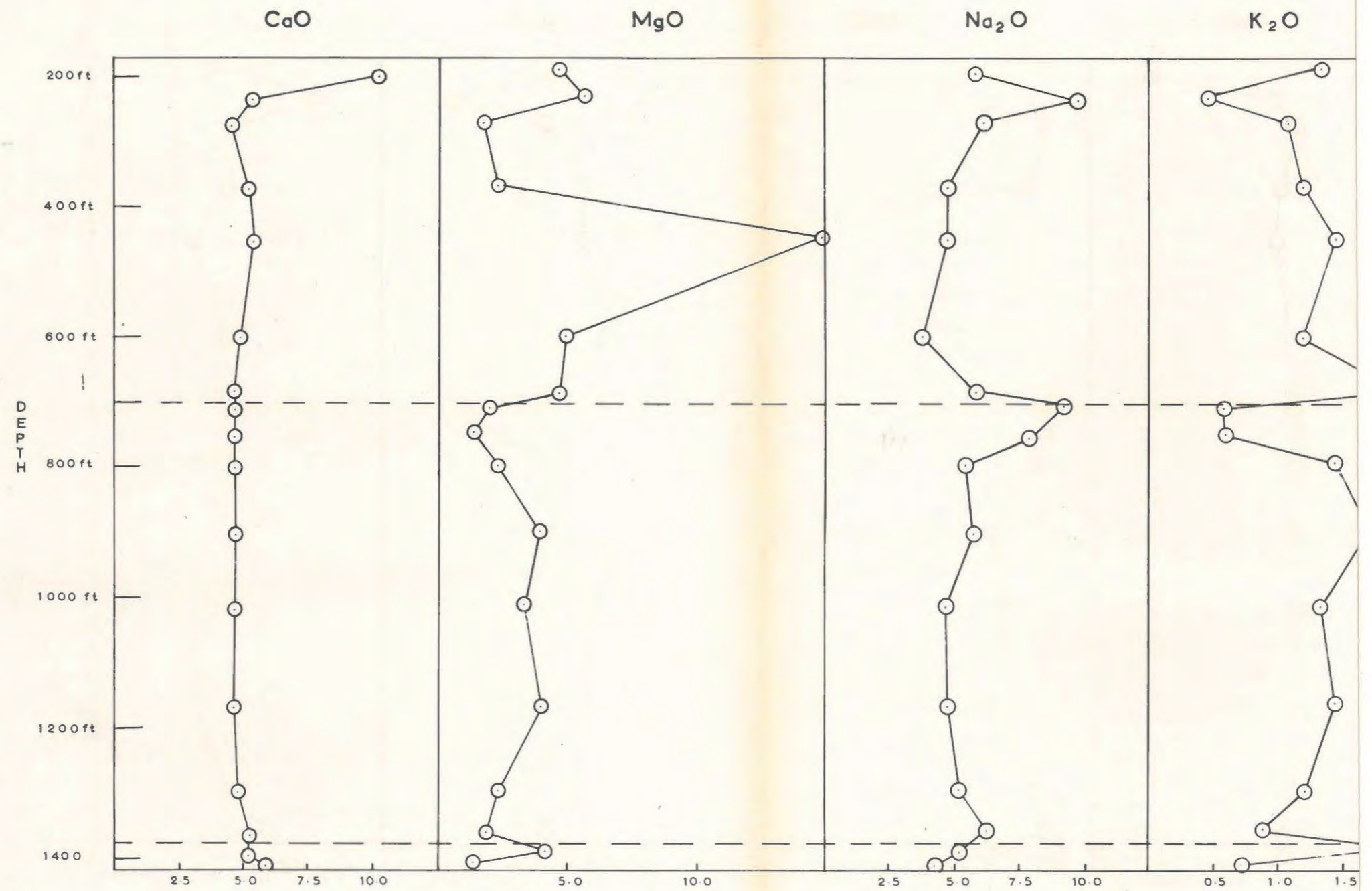
Twenty-six samples from the major amphibolite sill, together with eight samples from the adjacent sediments were selected from drillholes NS.76 and NS.82, and assayed for calcium, magnesium, manganese, total iron, titanium, and carbon dioxide by standard wet methods. Cobalt, zinc, nickel, silver, copper, lead, antimony, and bismuth were determined spectroscopically and potash and soda were determined by flame photometer.

All analyses, except those for alkalis, were carried out by the research laboratory of RST Technical Services Limited. The alkali analyses were made by Mufulira Copper Mines Limited. Each sample submitted for partial analysis consisted of a split length of core at least five feet long and weighing in excess of 2,000 grammes. These samples were crushed to minus  $\frac{3}{8}$  inch, and a portion of this material was ground to minus 200 mesh (74 MICS, 0.0029 inch).

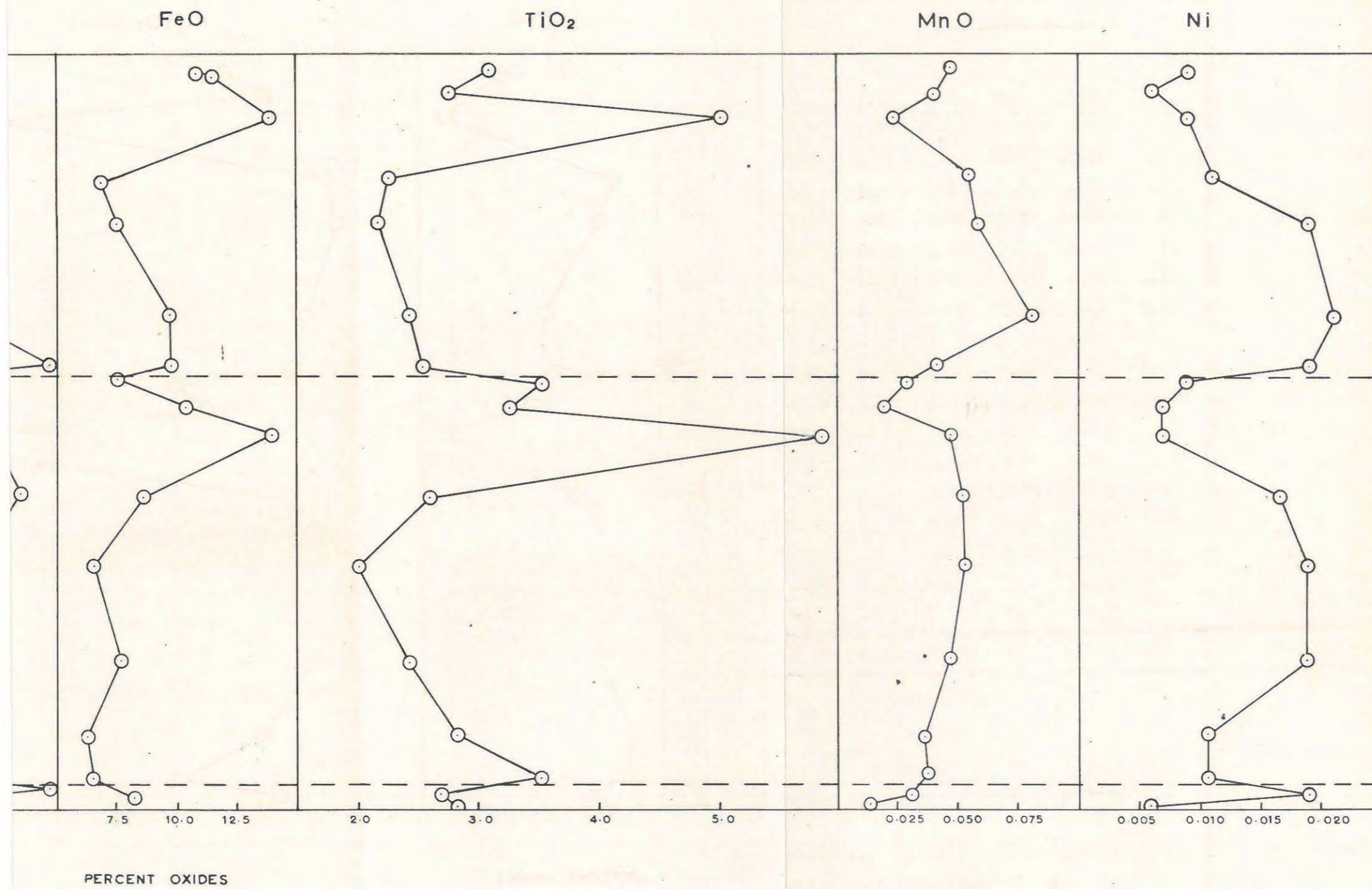
The results of the analyses are tabulated in Appendix A. The values obtained for calcium, magnesium, iron, titanium, manganese, potassium, and sodium have been re-calculated as oxide weight percentages and presented graphically as oxide profiles through the major sill (Figures 20 and 21).

#### Geochemical Testing

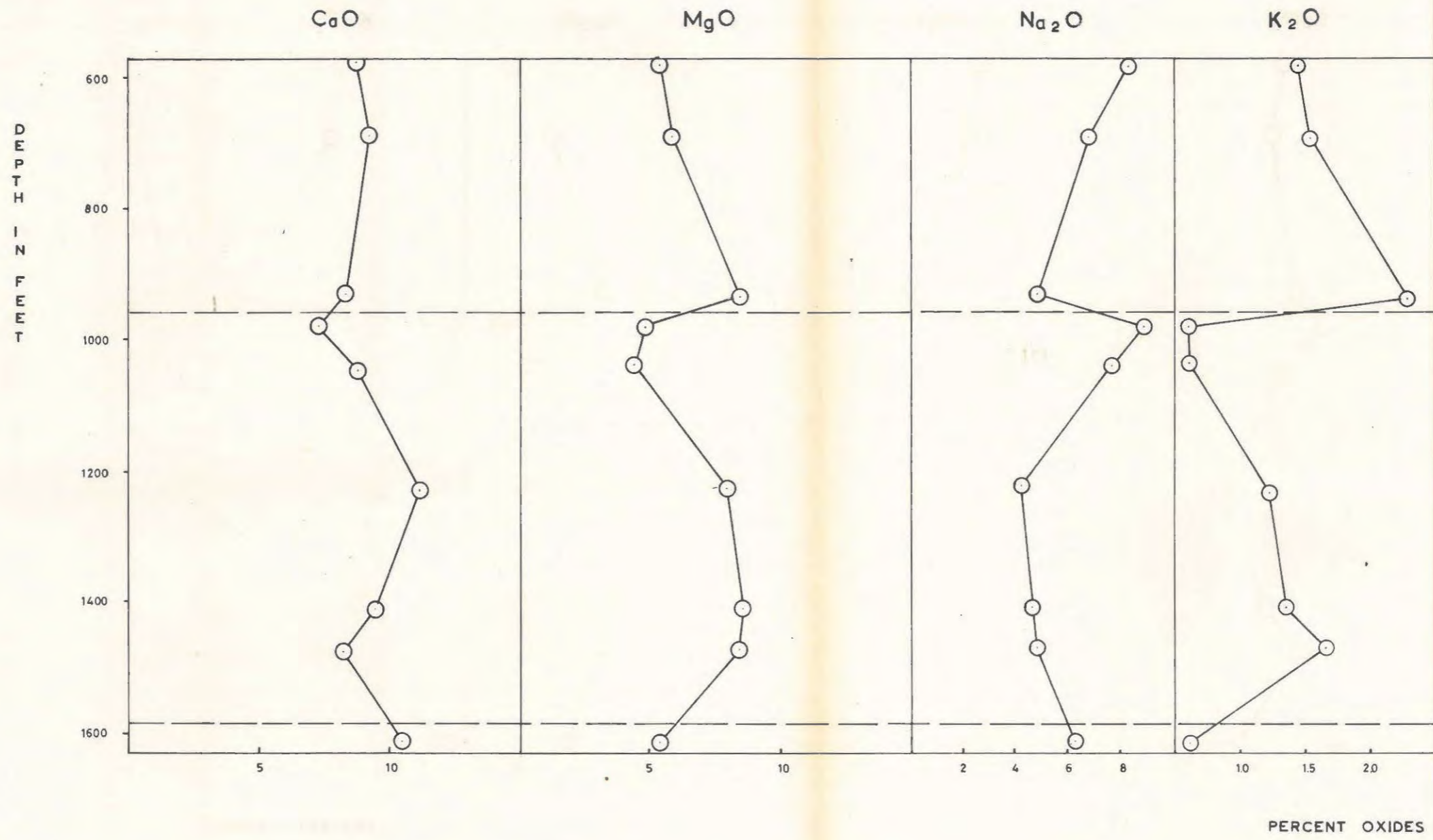
Geochemical testing for copper, cobalt, nickel, and zinc is carried out as standard procedure on all drillhole cores. Chip samples normally representative of a five foot



DRILL HO  
THROUGH

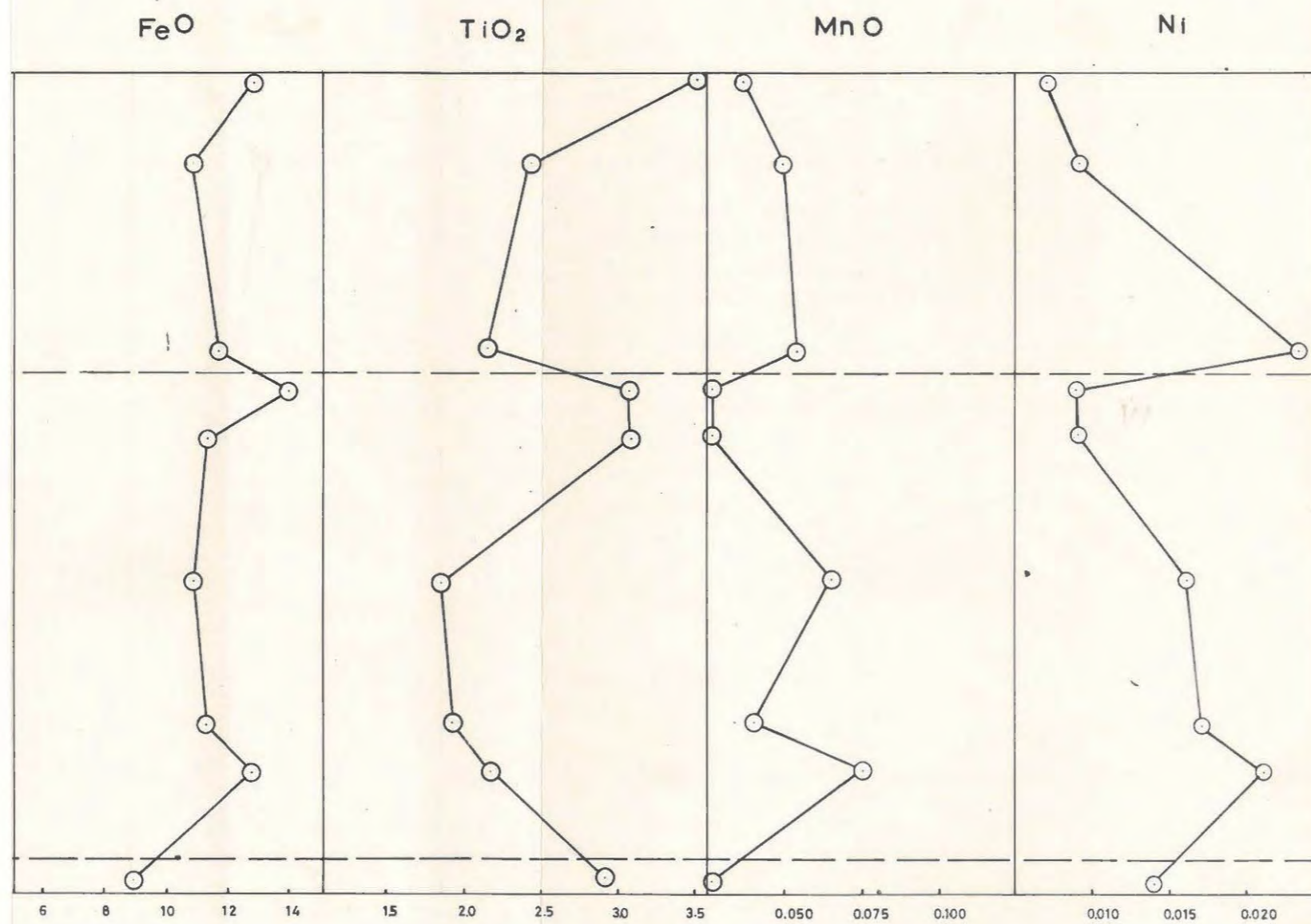


DLE NS 76 OXIDE PROFILES  
THE MAJOR AMPHIBOLITE SILL



DRILLHOLE NS 82 — OXIDE  
 THROUGH THE MAJOR AM

FIGURE 21



E PROFILES  
PHIBOLITE SILL.



TABLE VII  
CHEMICAL ANALYSES

	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
SiO <sub>2</sub>	46.85	47.87	48.19	49.41	46.75	52.68	50	45	51.22
Al <sub>2</sub> O <sub>3</sub>	15.87	14.53	14.53	12.71	14.87	13.12	13	15	13.66
Fe <sub>2</sub> O <sub>3</sub>	3.33	4.50	4.13	2.18	1.22	2.14)			2.84
FeO	7.40	9.05	7.18	10.07	10.62	10.62)	13	13	9.20
MnO	0.11	0.15	0.12	0.14	0.16	0.23	-	-	0.25
MgO	8.61	6.13	6.66	6.93	6.51	5.13	5	8	4.55
CaO	7.29	6.12	9.00	10.46	13.16	9.44	10	9	6.89
BaO	-	-	-	0.03	-	-	-	-	-
Na <sub>2</sub> O	3.65	2.95	4.25	2.46	3.25	2.68	2.8	2.5	4.93
K <sub>2</sub> O	2.50	1.55	1.40	0.80	0.62	0.89	1.2	0.5	0.75
TiO <sub>2</sub>	nd	nd	nd	2.67	1.24	1.97	-	-	3.32
P <sub>2</sub> O <sub>5</sub>	0.15	0.37	0.17	0.46	0.06	0.22	-	-	0.29
H <sub>2</sub> O <sup>+</sup>	1.43	3.35	1.73	0.85	0.41	0.97	-	- )	
H <sub>2</sub> O <sup>-</sup>	0.10	0.26	0.07	0.12	0.06	0.08	-	- )	1.88
CO <sub>2</sub>	nd	nd	nd	0.06	0.18	-	-	-	0.94
FeS <sub>2</sub>	0.17	0.20	0.28	Tr.	0.24	-	-	-	-
Cl	nd	nd	nd	0.38	0.33	-	-	-	-
	97.46	97.03	97.71	99.65	99.68	100.17	95.00	93.00	100.72

EXPLANATION OF TABLE

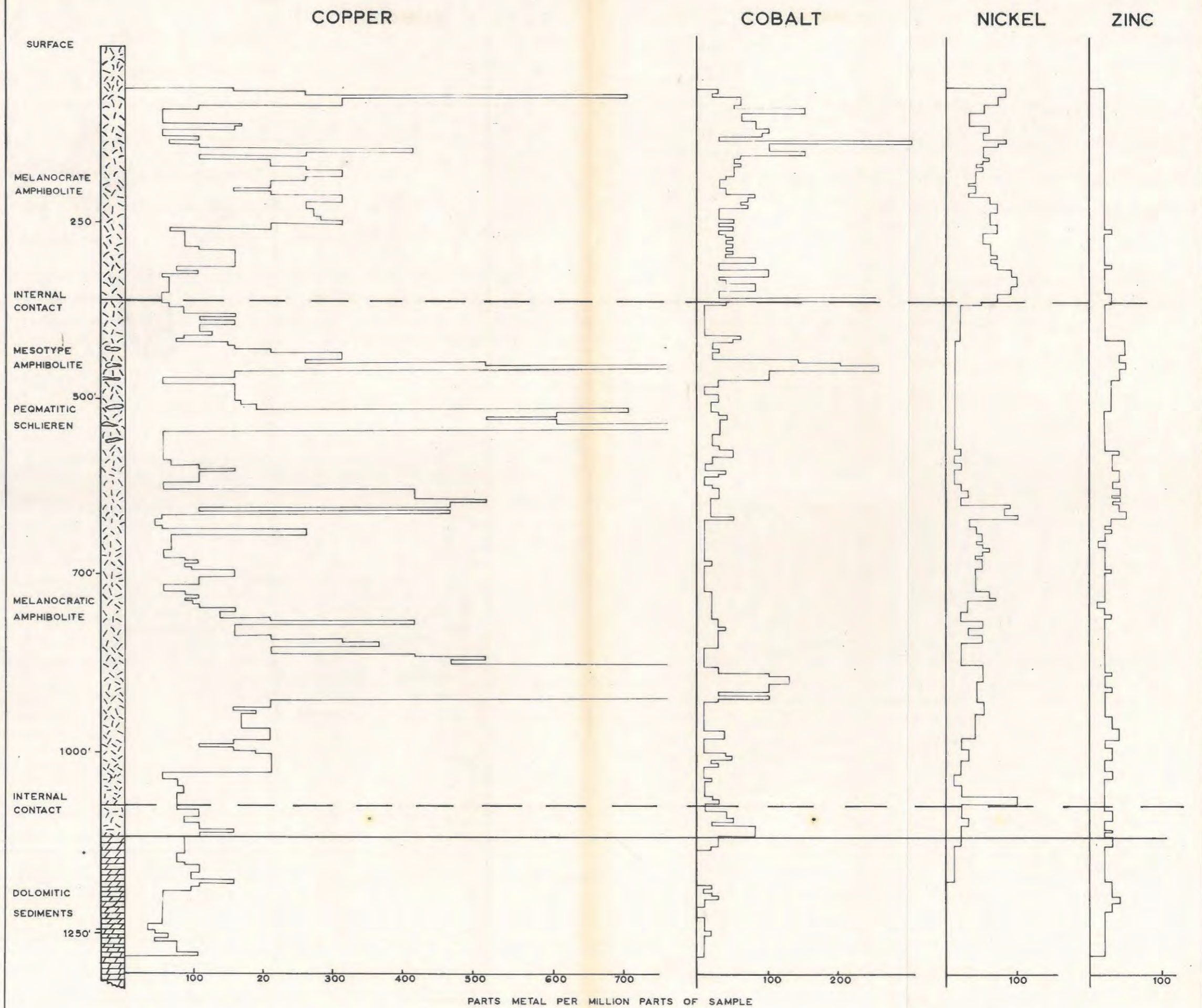
- (4) Amphibolite, Chambishi. Analyst A. Kruger (Mendelsohn 1961, p.493)
- (5) Amphibolite, Chambishi. Analyst A. Kruger (Ibid).
- (6) Amphibolite, Chambishi. Analyst A. Kruger (Ibid).
- (7) Norite, Lufupu River, south west of Chibuluma (Jackson, 1932).
- (8) Contaminated gabbro, Lumwana. Analyst G. Witfield (McGregor, 1964, p. 118, Table 5).
- (9) Dolerite pegmatite, Alewyn's Gat (Walker and Poldervaart, 1949).
- (10) Tholeiitic magma-type (W.Q.Kennedy) Quoted by Turner and Verhoogen (1960, p. 208, Table 15).
- (11) Olivine-basalt magma-type (W.Q.Kennedy) Quoted by Turner and Verhoogen (1960, p. 208, Table 15).
- (12) Average Spilite (N. Sundices) Quoted by Turner and Verhoogen (1960, p. 271, Table 26).
- nd Not determined.

length of core, are collected from broken surfaces of the core. Because of this, and the fact that in the amphibolites the copper sulphides are concentrated along shear zones on which the core readily breaks, the geochemical copper values in the amphibolite are not considered representative. Geochemical profiles for the above metals in the drillhole NS.74 are plotted in Figure 22.

#### THE MAGMA-TYPE

In the absence of an analysis of amphibolite from a chilled contact zone, it has been assumed that the analysis of the melanocratic amphibolite, the type which constitutes by far the greatest portion of the Chibuluma sill, is the closest to the composition of the original magma. Chemically, the melanocratic amphibolite (Table VI, analysis No. 3) is remarkably similar to the three Chambishi amphibolites, the Lufubu River norite, and to a lesser degree, the contaminated Lumwana gabbro (Table VII, analyses Nos. 4 to 8).

McGregor (1964, p. 118) has commented on the striking similarity between the chemical composition of the Copperbelt gabbro and the world plateau basalts. The widespread occurrence and uniform nature of the Zambian gabbros suggests that they did, in fact, originate from such a magma-type. It is not readily apparent which of the two types of plateau basalt magmas the melanocratic amphibolite most closely resembles in composition. The silica content of the melanocratic amphibolite is similar to that of the average tholeiitic basalt (Table VII, analysis No. 10), but the high MgO/CaO ratio of the amphibolite is typical of alkaline-olivine-basalts (Table VII, analysis No. 11), (Turner and Verhoogen, 1960, p. 207). In the case of the Chambishi amphibolites, the silica content (average 47.64%) lies between that of typical tholeiitic basalt and typical alkaline-olivine-basalt and the range in MgO/CaO



GEOCHEMICAL PROFILES THROUGH PART OF THE MAJOR AMPHIBOLITE SILL — DRILLHOLE NS 74

ALL METALS DETERMINED BY CHROMATOGRAPHIC METHODS IN THE GEOCHEMICAL

ratio for the Chambishi rocks extends beyond the typical ratio for both magma-types.

The presence of the silica-deficient normative minerals, olivine and nepheline, is a strong characteristic of the alkaline-olivine-basalts. (Turner and Verhoogen, 1960, p. 208). However, the formation of late silica-rich differentiates such as the mesotype and pegmatitic amphibolite with low MgO/CaO and MgO/FeO ratios is a definite characteristic of a tholeiitic magma-type. The low  $Fe_3O_4$  and high  $TiO_2$  of the amphibolite are also characteristic of a tholeiitic magma-type.

The development of adinoles in the argillites adjacent to the amphibolites, the abundance of albite within the sills, and the characteristic association of the amphibolites with marine sediments along the Lufilian orogenic arc are features which could possibly point to the amphibolite being spilitic in origin. This view is supported by the high soda content of the amphibolites. Spilites in general have soda in excess of 4.5 per cent (Turner and Verhoogen, 1960, p. 262) and although in the three complete rock analyses tabled above the soda content is less than this, it is greater than 4.5 per cent in 23 of the 26 partial analyses. Further, the CaO/Na<sub>2</sub>O ratios obtained from the partial analyses range from 0.47 to 2.55, and average 1.16 whereas this ratio for tholeiitic and alkaline-olivine-basalts is commonly between 3 and 5 (Turner and Verhoogen, 1960, p. 267) and for a spilitic magma-type approximately 1.5. Mineralogical features, however, show that the spilitic characteristics have been developed after the crystallisation of the magma which was, therefore, not necessarily a primary spilitic magma-type.

Assuming that the melanocratic amphibolite is characteristic of the Copperbelt amphibolites, it appears from the available chemical and mineralogical data that the regional

parent magma was closer in composition to the tholeiitic basaltic magma-type than to the alkaline-olivine-basaltic magma-type and that after the crystallisation of the magma, soda metasomatism gave rise to the spilitic features in the rock.

McGregor (1964, p. 118) draws attention to the differences in soda content between the Lumwana gabbro and the Copperbelt (Chambishi) amphibolite. He suggests that there may be a progressive increase in the soda in gabbros westward from the Copperbelt. The average of 4.77 per cent soda of three analyses on Lumwana gabbro lies well within the range of soda content exhibited by the Chibuluma amphibolite. These variations, therefore, appear to be local features only, an alternative suggestion also made by McGregor.

McGregor (1964, p. 123) also draws attention to the low water content of the Lumwana gabbro. This is also a feature of the Chibuluma amphibolites in which the total water content ranges from 0.41 per cent in the melanocratic amphibolite to 0.98 per cent in the pegmatitic amphibolite. The low water content of the rock reflects a low  $H_2O$  content of the amphibole. This, as stated by McGregor, is not an unusual occurrence, but it does, however, also indicate that the water content of the original magma was low. This could have considerable effect on the subsequent trend of differentiation followed by the crystallising magma.

Osborne (1962, p. 220) suggests that the partial pressure of oxygen, which is dependant upon the water content of the magma, is the main controlling factor in determining whether the trend in differentiation of the magma is towards iron enrichment (low  $pO_2$ ) or alkali and silica enrichment (high  $pO_2$ ) as in the calc-alkali series. On this basis, it would appear that the Chibuluma amphibolite should have become enriched in iron as differentiation proceeded.

### DIFFERENTIATION

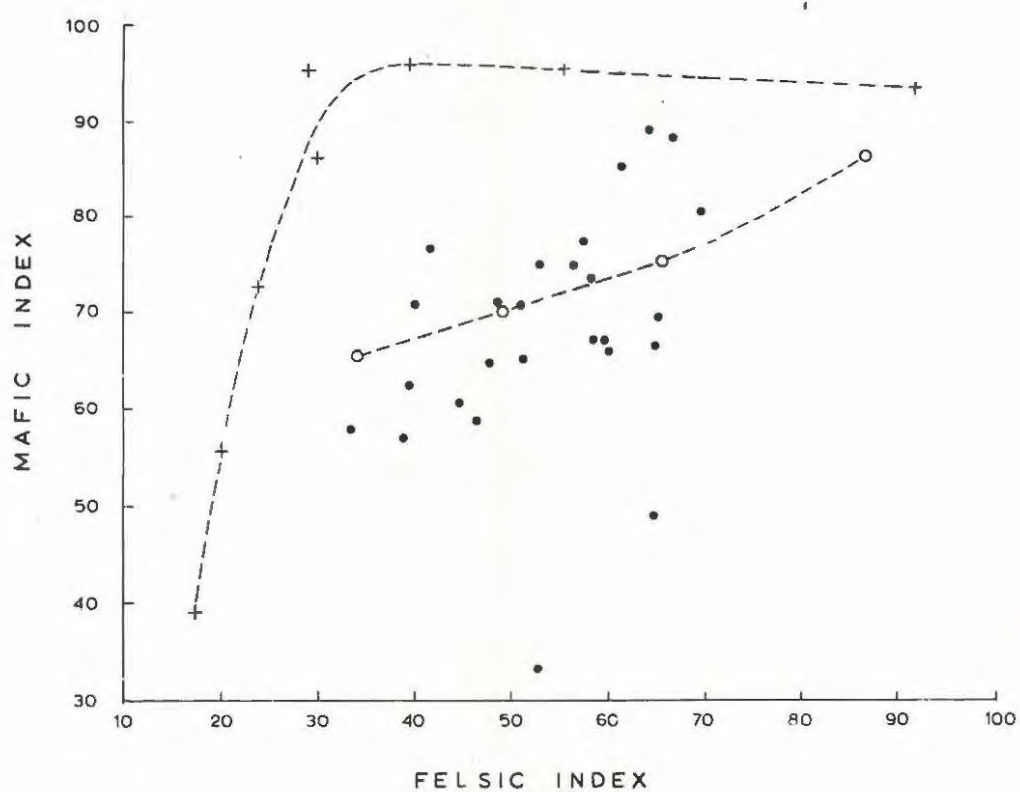
A number of petrographic features of the major amphibolite sill suggest that differentiation has taken place during its crystallisation. The most striking of these features is the distribution of rock types; in each member of the multiple sill a large mass of melanocratic amphibolite is capped by a lesser thickness of mesotype amphibolite. Other features are the well developed zoning in the original feldspar and the amphibole, and the variations of specific gravity and grain size with position in the sill. Walker and Poldervaart (1949, p. 650) consider that the "differentiation of the Karroo magma was effected by the following processes, acting singly or jointly;

- (i) crystal fractionation,
- (ii) gravitational effects,
- (iii) segregation of volatile-rich phases as pegmatitic schlieren,
- (iv) acquisition of resurgent volatiles from wall rocks or xenolithic inclusions, and
- (v) assimilation or metasomatism of sediments."

It is possible that all these processes have played a part in the magmatic history of the Chibuluma amphibolites. Trends in differentiation suggested by both microscopic and megascopic observations need confirmation that is best made by reference to the chemistry.

Crystal fractionation is the main process in the differentiation of a basaltic magma and it operates within the two contrasted mineral series, the felsic series and the mafic series. Fractionation within the felsic series is represented by the zoning of plagioclase crystals in which early lime-rich cores are surrounded by relatively soda-rich mantles. This relationship between lime and soda is partially preserved in a completely albitised basic plagioclase by the distribution of lime-bearing epidote and clinozoisite. The

FIGURE 23



- • CHIBULUMA AMPHIBOLITE
- +---+ SKAERGAARD.
- o---o CALC - ALKALINE SERIES (AFTER DALY)

DIAGRAM OF MAFIC AGAINST FELSIC INDEX

felsic index, which is the ratio  $\frac{K_2O + Na_2O}{K_2O + Na_2O + CaO} \times 100$  is,

therefore, acceptable even in the case of albitised amphibolite. Fractionation within the mafic series is represented by the zoned amphibole crystals with magnesia-rich cores and iron-rich margins. The mafic index, which is the ratio

$\frac{FeO + Fe_2O_3}{FeO + Fe_2O_3 + MgO} \times 100$ , is applicable to the Chibuluma

amphibolites. Both indices increase as fractionation proceeds.

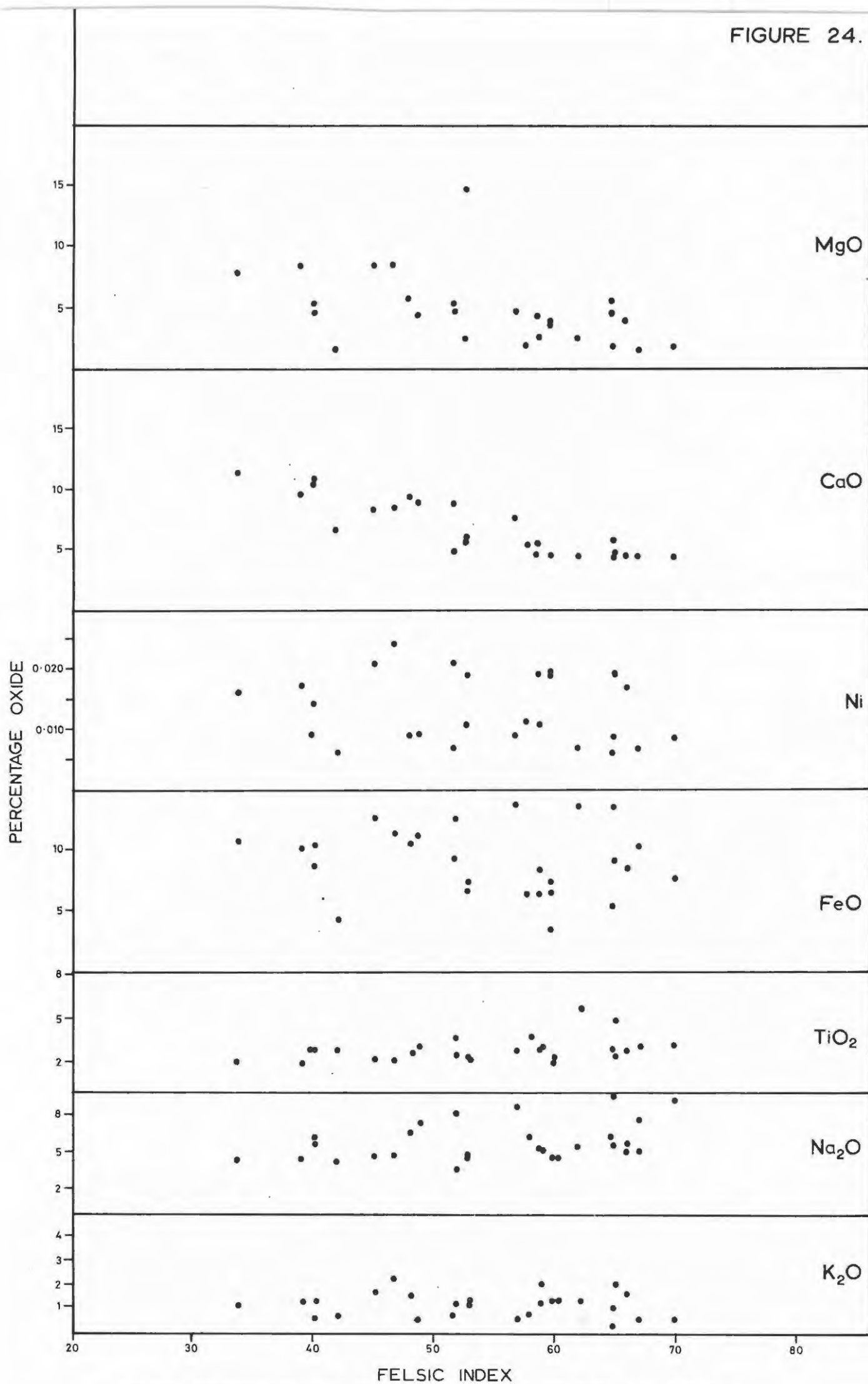
In Figure 23, the mafic indices are plotted against the felsic indices in order to indicate the relative importance of fractionation within the two mineral series (McDougall, 1962, p. 298). The points plotted are scattered, but they do indicate a general sympathetic variation between the two, ranging from a mafic index of 50 and a felsic index of 30 to a mafic index of 90 and a felsic index of 70. This implies that fractionation was not predominant in any one mineral series during crystallisation. (The high soda content of the amphibolite has resulted in higher than normal felsic indices).

Figures 24 and 25 show oxide percentages from the partial analyses plotted against the felsic and mafic indices. Nickel is plotted as percentage metal. As is the case in Figure 23, the plotted points lie in scattered zones, but some trends are discernible. Lime, magnesia, nickel, and potash decrease with increasing felsic and mafic indices, whereas soda, titania, and total iron increase with increase of the indices.

These relationships are also apparent in Figures 20 and 21, showing the oxide profiles through the major amphibolite sill intersected by drillholes NS. 76 and NS.82. These figures indicate the sympathetic variation of MgO, K<sub>2</sub>O, MnO and Ni which have pronounced minimum values in each of the mesotype amphibolite zones below which the values

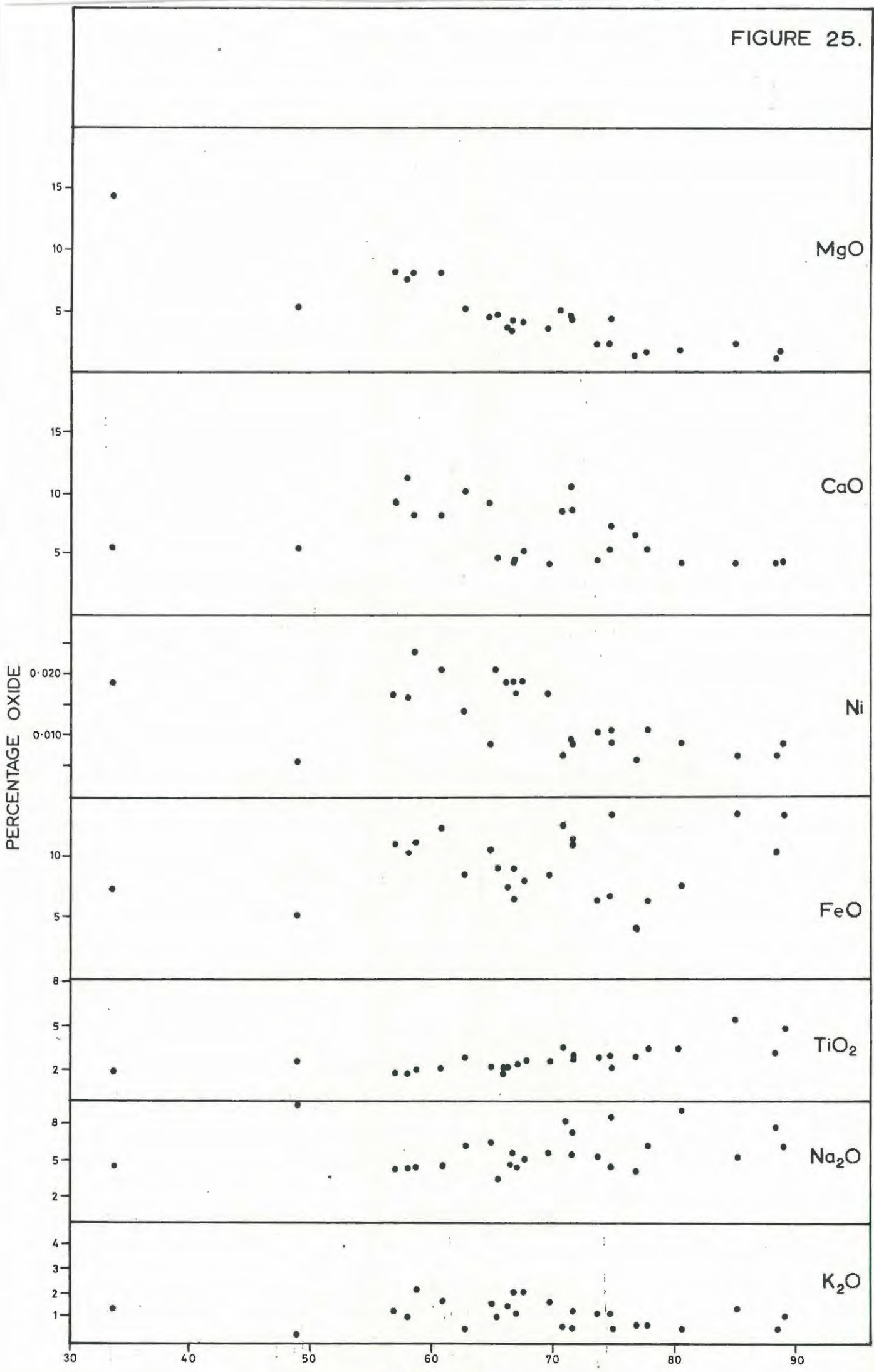


FIGURE 24.



OXIDE PERCENTAGE PLOTTED AGAINST FELSIC INDEX

FIGURE 25.



OXIDE PERCENTAGE PLOTTED AGAINST MAFIC INDEX

increase abruptly, and are high in the melanocratic amphibolite. The values for these oxides are slightly lower in the lowermost 50 feet of the sill. Variations in  $\text{Na}_2\text{O}$ ,  $\text{FeO}$  and  $\text{TiO}_2$  are antipathetic to  $\text{MgO}$ ,  $\text{K}_2\text{O}$ , and  $\text{MnO}$ . The lime content shows little variation throughout the sill, particularly in NS.76. Near the upper and lower contacts the lime content of the amphibolite increases slightly, suggesting that some migration of calcium has taken place into the sill. However, the ratio  $\text{CaO}/\text{Na}_2\text{O}$ , indicative of fractionation within the plagioclase (Appendix A) shows a steady increase downwards through each member of the multiple sill.

Nickel is the only trace element of those determined in the partial analyses which shows any variations in amount that can be related to variations in type of amphibolite. The profiles of nickel content through the major amphibolite sill (Figures 20 and 21) show pronounced minimum values (0.006 to 0.009) per cent Ni) in the mesotype and pegmatitic amphibolites, and high values (0.016 to 0.024 per cent Ni) in the melanocratic amphibolite. The same variations in nickel content are shown by the geochemical profiles through the sill (Figure 22). This concentration of nickel in the more basic rock types agrees with the distribution pattern of nickel in differentiated basic rocks (Wager and Mitchell, 1951).

Results of the partial analyses are plotted on a triangular variation diagram (Figure 26B) in order to portray the trends in fractionation in the amphibolites. No ferric iron determinations were made and the apices of the triangle are  $\text{MgO}$ , total iron as  $\text{FeO}$ , and  $(\text{Na}_2\text{O} + \text{K}_2\text{O})$ . As in the figures described above, the points plotted are fairly scattered and any trends indicated by these points are vague.

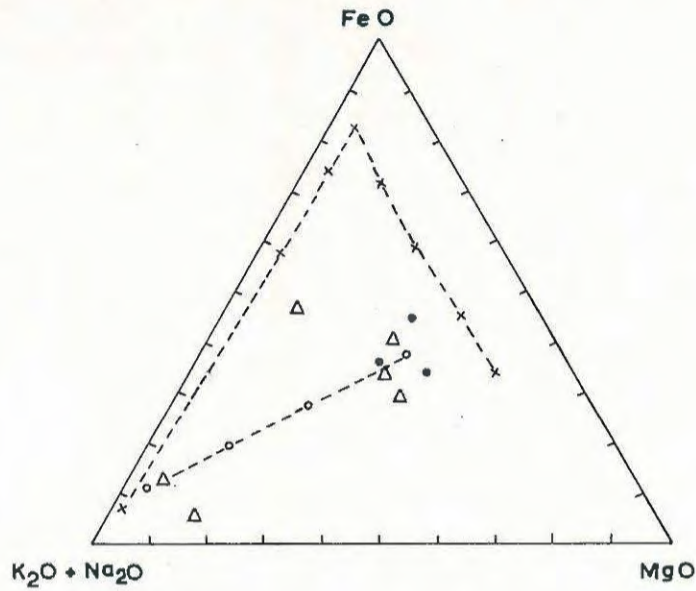
Both iron enrichment and alkali enrichment occur during the early stage of fractionation, the former being the more pronounced. Subsequent stages of fractionation result in

increased alkali enrichment and decreased iron enrichment. The iron enrichment in the amphibolite is not as pronounced as that of the Skaergaard suite (Wager and Deer, 1939, p. 313) nor is the alkali enrichment as pronounced as that of Daly's calc-alkaline series. The general trend in fractionation, as shown in Figure 26B, therefore, lies between the trends in fractionation in these two types.

No differentiated rocks exhibiting strong alkali enrichment occur at Chibuluma, but albite-granophyres with these characteristics are associated with the Chambishi amphibolite (Mendelsohn, 1961, p. 492). Data from the Chambishi "suite" are plotted together with data from the three Chibuluma analyses on a  $MgO - FeO - (Na_2O + K_2O)$  variation diagram (Figure 26B). It can be seen from this figure that the general trend in fractionation is one of early iron enrichment and late alkali enrichment. This is very similar to the trend in the Skaergaard rocks except that the early stage enrichment in iron and impoverishment in magnesia is more pronounced in the Skaergaard rocks. The trend in differentiation shown by the Copperbelt rocks does not resemble that shown by the calc-alkali series.

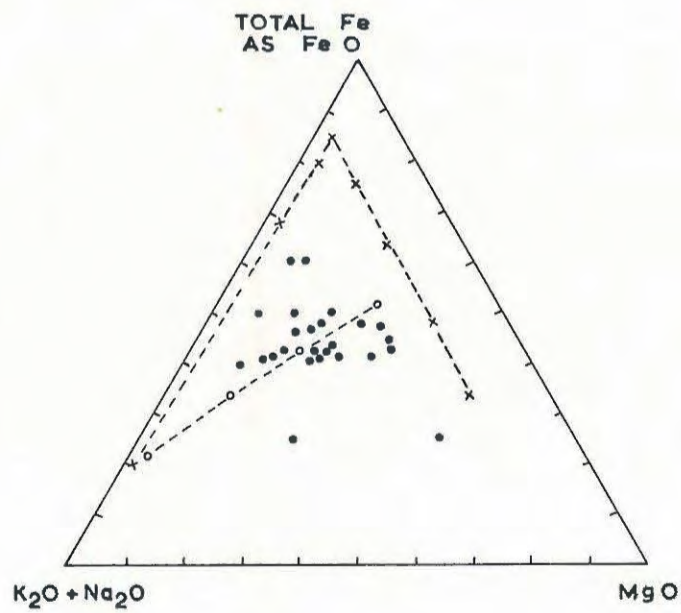
Any trends in differentiation that may be apparent in the three complete rock analyses (Table VI) should, on the basis of the mineralogical characteristics of the rocks, proceed from the melanocratic amphibolite (analysis No. 3) to the mesotype amphibolite (No. 1) to the pegmatitic amphibolite (No. 2). Silica is the only oxide that shows such a trend and this is emphasized by the amounts of normative quartz present in the pegmatitic and mesotype amphibolites, and the presence of normative olivine and nepheline in the melanocratic amphibolite. The lack of any such trend in the soda content of these rocks could have been brought about by the late-stage albitization, but the fact that a number of oxide values of the

A



MgO-FeO-( $K_2O + Na_2O$ ) diagram for  
COPPERBELT GABBROS

B



MgO-(TOTAL Fe as FeO)-( $K_2O + Na_2O$ ) diagram for  
CHIBULUMA AMPHIBOLITES

- CHIBULUMA AMPHIBOLITES
- + - - - + SKAEGAARD
- o - - - o CALC-ALKALINE SERIES (AFTER DALY)
- Δ CHAMBISHI GABBRO AND ASSOCIATED ROCKS (Mendelsohn, 1961)

pegmatitic amphibolite are intermediate between the equivalent oxide values in the mesotype and melanocratic amphibolite, requires explanation. The oxides which conform to this fact are  $\text{Al}_2\text{O}_3$ ,  $\text{TiO}_2$ ,  $\text{FeO}$ ,  $\text{CaO}$ ,  $\text{MnO}$ ,  $\text{MgO}$ , and  $\text{K}_2\text{O}$ . The reason for this apparent reversal in the normal trend of differentiation is not known. As described above (p. 46), the pegmatite schlieren occur in both mesotype and melanocratic amphibolites. The analysed pegmatitic amphibolite occurs in the latter, and it is possible, therefore, that the unexpected basic characteristics of this pegmatite are related in some way to this association.

Chemically, however, the pegmatitic amphibolite and the mesotype amphibolite are very similar. The apparent trend in differentiation from the melanocratic amphibolite to these two rock types, showing an increase in silica, soda (only in the mesotype amphibolite), alumina and titania, and a decrease in lime, magnesia, and ferrous iron, is in agreement with the normal variation of oxides in the differentiation of a basic magma. This is supported by the striking similarity between the chemical compositions of the Aléwyn's Gat dolerite pegmatite and the Chibuluma pegmatitic amphibolite.

Some of the differences in chemical composition between dolerites and their pegmatitic differentiates are apparent in Table VIII (after Eales, 1959, p. 106), which shows analyses of these rocks from the Palisades, Goose Creek, and Khale.

The variations in chemical composition with differentiation in the Chibuluma amphibolite are similar to the variations shown in all but one of the oxide values for the basic rocks and their pegmatitic differentiates. This confirms, on a chemical basis, the pegmatitic nature of the coarse-grained schlieren in the amphibolite. The one oxide value that shows the opposite variation is potash, which varies

TABLE VIII

Analyses of Pegmatites and Parent Rocks and their Ferric and Ferrous  
Iron Ratios

	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	FeO	MgO	Na <sub>2</sub> O	K <sub>2</sub> O	$\frac{\text{Fe}_2\text{O}_3}{\text{FeO}}$
1	51.46	16.24	3.04	9.58	3.47	3.01	0.87	0.317
2	52.50	18.28	1.97	7.61	2.58	3.78	1.03	0.259
3	51.56	13.81	0.96	11.32	7.40	2.08	0.96	0.088
4	52.94	14.80	0.16	12.00	5.42	1.98	1.50	0.013
5	50.59	14.22	2.66	11.10	5.35	2.59	0.91	0.239
6	51.24	16.01	1.42	12.94	3.24	3.21	1.00	0.109
7	49.75	13.46	1.10	9.19	9.66	3.62	0.92	0.120
8	52.68	15.40	0.23	8.39	5.45	2.31	0.63	0.027

1. Diabase, Palisades, (Walker).
  2. Diabase pegmatite, Palisades, (Walker).
  3. Diabase, Goose Creek, (Shannon).
  4. Diabase pegmatite, Goose Creek, (Shannon).
  5. Dolerite, Khale, (Eales, 1959, p. 106).
  6. Dolerite pegmatite, Khale, (Eales, 1959, p. 106).
  7. Amphibolite, Chibuluma.
  8. Pegmatitic amphibolite, Chibuluma.
- } Quoted by Eales  
(1959, p. 106)

antipathetically with soda, and has its highest concentration in the melanocratic amphibolite (Figures 20 and 21). The greatest concentration of potash-feldspar is, nevertheless, in the pegmatitic amphibolite. The writer considers that the potash in the melanocratic amphibolite occurs mainly in biotite which constitutes up to 18 per cent of the rock. A small amount of potash is probably also contained in scapolite.

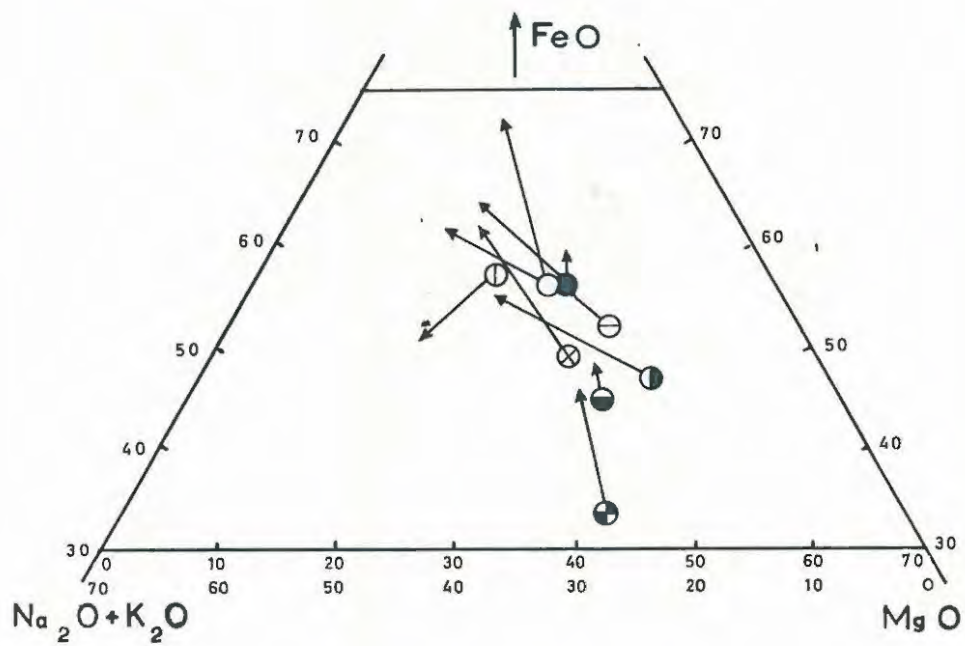
The ratio of ferric to ferrous iron is lower in the pegmatitic amphibolite than in the melanocratic amphibolite. In this respect, the Chibuluma amphibolite resembles the Palisades and Goose Creek diabases and the Khale dolerite (Table VIII). These variations in this ratio are the opposite of the general trend in dolerites and their pegmatitic differentiates as recognised by Walker (1953, p. 51), and Walker and Poldervaart (1949, p. 663). Eales (1959, p. 108) in describing the Khale sheet drew attention to the contradictory evidence and suggested that Walker's diagram, showing the ratios of ferric iron to total iron in dolerite pegmatites and parent dolerites, could be revised.

In figure 27 (after Walker, 1953, and Eales, 1959) the trend in differentiation towards the pegmatitic amphibolite is compared, in terms of variations in magnesia, ferrous iron, potash and soda contents, with the trends shown in other dolerite-dolerite pegmatite associations. The figure shows that the marked enrichment of ferrous iron relative to magnesia, shown by the pegmatitic amphibolites, is a common feature of basic pegmatitic differentiates.

A small degree of lateral variation in chemical composition is evident from the results of the partial analyses. Lime, magnesia, and total iron contents are generally higher in NS. 82, than in NS. 76. This is shown diagrammatically by plotting these oxide values against the nickel contents which are similar in both holes (Figure 28). Alkali and titania contents are similar in both drill holes.



FIGURE 27



### DIFFERENTIATION OF DOLERITES

( AFTER WALKER AND POLDERVAART, 1949 , AND EALES, 1959 )

POINT OF THE ARROW REPRESENTS DOLERITE PEGMATITE,  
AND THE BASE REPRESENTS THE PARENT DOLERITE.

- ⊖ HANGNEST
- ⊕ ALEWYNS GAT
- MOUNT ARTHUR
- ◐ ELANDSBERG
- ⊙ PALISADES
- ⊗ WHIN SILL
- KHALE
- ⊙ CHIBULUMA AMPHIBOLITE

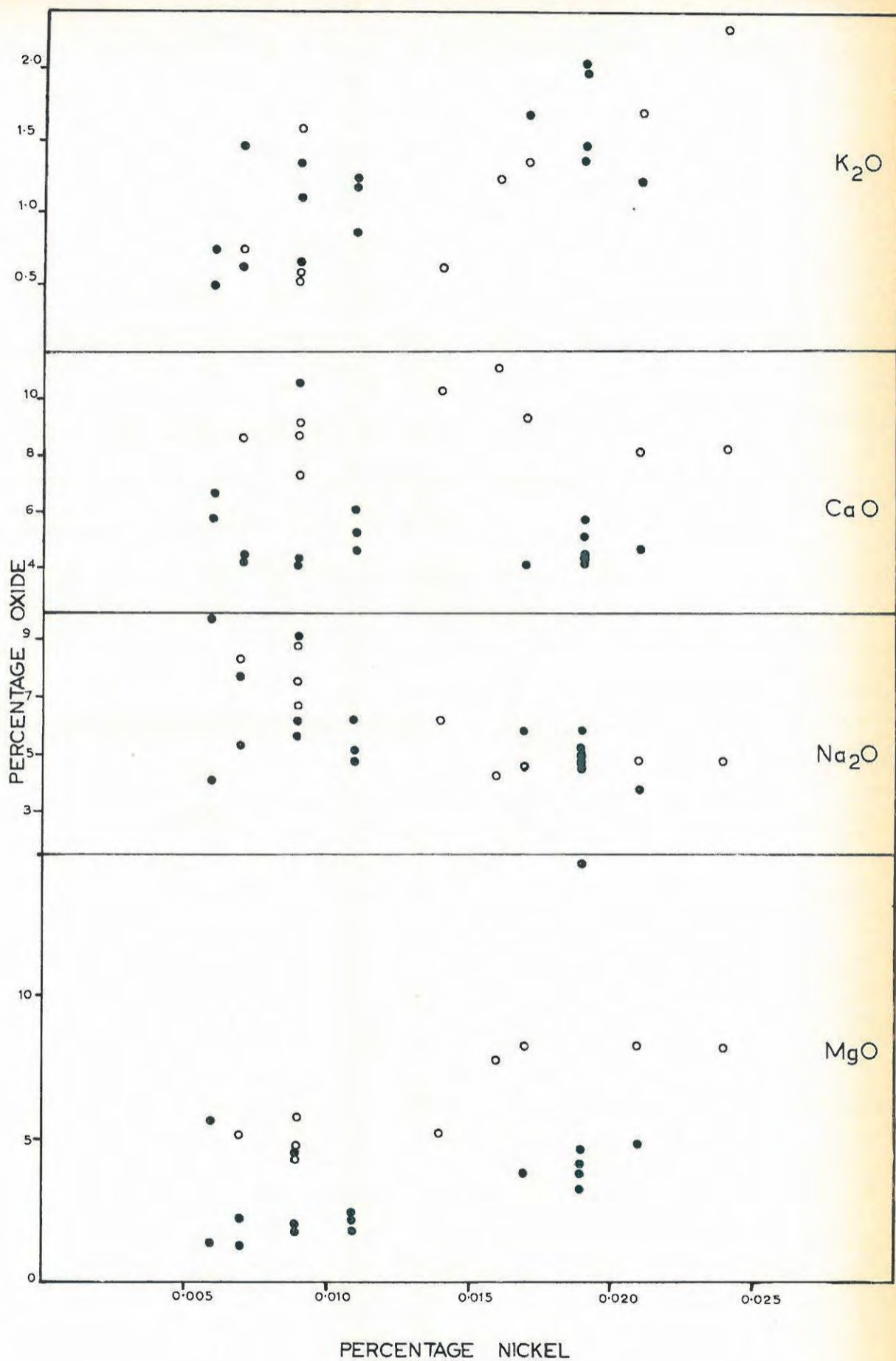
Drillhole NS.82 is located 500 feet northeast of drillhole NS. 76. Because of the attitude of the sill, intersections in NS.82 are made 600 feet down dip (300 feet in vertical difference) from the equivalent intersection in NS.76. The higher concentrations of the chemical components of the early-formed minerals, occurring in the deeper intersections of the amphibolite sill suggest that there was a small component of gravitational differentiation down towards the present down-dip side. However, considerably more chemical data than are available at present would be required to confirm this. On the basis of field evidence, in particular the fairly uniform distribution of the mesotype amphibolite, and the presence of the pegmatitic amphibolite at a constant and characteristic "stratigraphic" position within the sill both at depth and near the surface, it appears that the main component of gravitational differentiation was normal to the upper and lower contacts of the sill.

There are no apparent differences in the chemical compositions of the two members of the multiple sill. On the basis of mineralogical data, however, it would appear that the inner or later member is more acid than the outer member. The pegmatitic schlieren are more common, and the mesotype amphibolite is thicker in the inner member. A number of minor amphibolite sills have micropegmatitic mesostasis indicating that they are more acid than the major amphibolite body, and that some differentiation of the magma may have taken place under intratelluric conditions.

#### THE ORIGIN OF THE AMPHIBOLITE

The primary assumption throughout this thesis has been that the amphibolites themselves are of igneous origin. This is the view held by most authors, but it has been suggested (Mendelsohn, 1961, p. 52) that the gabbro (amphibolite) may be

FIGURE 28



OXIDE PERCENTAGE PLOTTED AGAINST NICKEL

- NS 76
- NS 82

a metamorphosed sediment. He writes:-

"The gabbro is confined to the Upper Roan group; a mixture of dolomite and argillite would have a chemical composition somewhat similar to the gabbro; there are abrupt and irregular changes in grain size and texture in the gabbro and also in places there is a gradation from gabbro to dolomite. The typical skarn type minerals found in limestones intruded by gabbros, such as garnet, pyroxene, and lime silicates, are not found in the wall rock, the main alteration products in the wall rock being amphibole (tremolite) and scapolite. Amphibolite formed from argillaceous dolomite or similar rocks is similar to that formed by the alteration of basic rocks."

This statement is not entirely accurate in that the gabbro and the sediments do differ chemically, particularly in respect of their titanium contents which in the sediments are generally less than 1.0 per cent (Mendelsohn, 1961, p. 488). A number of other features, however, can be explained only by invoking an igneous origin. The present writer follows McGregor (1964, p. 114) who considered that although the metamorphic amphibolites may resemble the intrusive gabbro in chemical and mineralogical composition, they differ from intrusive gabbros in texture. The Lumwana gabbros exhibit an interlocking texture which McGregor regarded as being igneous in origin. The ophitic, sub-ophitic, and diabasic textures of the Chibuluma amphibolites are also characteristic of intrusive rocks, particularly gabbros and dolerites. In addition, grain size variations, notably the development of the well defined chilled margins and the coarse pegmatitic schlieren, are typical of intrusive sills. Some scapolite-rich amphibolites are coarse-grained and spotted in appearance and have no ophitic textures. The development of the "spots" and the breakdown of an original ophitic texture can be seen from thin sections to be due to increasing scapolitisation. The coarse-grained, spotted

appearance of these rocks is not, therefore, a true reflection of grain size. Variations in chemical composition, specific gravity and mineralogy within the major amphibolite body, are in accordance with differentiation of an igneous magma.

The contacts between the amphibolite and the sediments are usually sharp although a number of the smaller sills have apparently "gradational contacts". No ophitic textures were observed in thin sections from the gradational contact zones, but ophitic texture was observed in the centres of these sills. Scapolite in this zone commonly has lime-rich margins suggesting that the gradational contact zones may be hybridized rocks formed by the assimilation of lime-rich sediments.

The absence of any amphibolite sills in the Lower Roan formations is a feature of their distribution that may favour a metamorphic origin. However, recent diamond drilling in Kalulushi Special grant, four miles south of Chibuluma Mines, has intersected an apparently transgressive gabbro body in Lower Roan formation (J. B. Lee Potter, personal communication). No argillaceous or dolomitic formations occur in the equivalent stratigraphic positions in adjacent drillholes and this amphibolite is unlikely to be metamorphosed sediment. Knowledge of this amphibolite is limited, but it appears to take the form of a feeder dyke.

The preference for emplacement of the gabbro in dolomitic formations could be accounted for by the possibility that the gabbro was able to intrude these formations with greater ease than either quartzite or argillite. Walker (1957) describes a suite of dolerite dykes which cut granite, Malmesbury System formations, and Lower Table Mountain Series flagstone, but stop abruptly against the first massive quartzite horizon they encounter. The lithology of the Mine Series was probably the main factor that generally restricted

the gabbro to the dolomitic formations between the arenaceous Lower Roan group and the Mwashia shales.

From the above considerations, the writer concludes that the Chibuluma amphibolites are magmatic and intrusive.

#### METAMORPHISM AND METASOMATISM

The amphibolite is closely associated with metamorphic and metasomatic features of great interest and significance. The predominant features are the development of adinoles in the argillaceous sediments near the amphibolite, and the albitisation and scapolitisation of the amphibolite itself. No detailed study of metamorphic and metasomatic effects of the intrusion on the sediments has been undertaken by the present writer.

#### General Contact Features

The lack of the usual silicate minerals characteristic of contact metamorphism in the argillaceous carbonate-rich sediments invaded by the Copperbelt gabbro, has been reported by Mendelsohn (1961, p. 52) and Hall (1963). The former notes that the main alteration products of the wall rock are tremolite and scapolite. Hall, on the other hand, records albite, biotite, and pyrite and an absence of scapolite in the contact zone. The writer's general observations agree with those of Hall. In addition to albite, biotite, and pyrite, abundant magnetite and chlorite occur in the contact zones. Tremolite is very common in Upper Roan dolomites and as it occurs both near the contacts and well away from them its occurrence does not appear to be related to the amphibolites. Scapolite is not generally found in sediments close to the amphibolite bodies.

#### Soda Metasomatism

Both the amphibolites and the surrounding sediments have been affected by soda metasomatism, resulting in the

development of albite and scapolite.

The occurrence of scapolite is of particular interest. It has been noted in the Upper Roan formations and gabbro-amphibolite bodies both on the Copperbelt (Mendelsohn, 1961, p. 109) and the areas to the west of it, (McGregor, 1964, p. 115). This widespread regional distribution of a mineral which is normally rare suggests that the Upper Roan of Zambia is part of a "scapolite province" similar to that described by Edwards and Baker (1953, p. 1) as occurring in the Cloncurry district of northwest Queensland. Jackson (1932) remarked on the similarity in this respect, between the Copperbelt and the Kiruna district of Sweden. The relatively common occurrence of scapolite, therefore, makes the knowledge of its genesis and chemistry important when considering the metamorphic or metasomatic histories of the local rocks.

Shaw (1960, p. 279) summarised the main modes of occurrence of scapolite as follows:-

- "(a) in blocks ejected from volcanoes and by contact volcanic action;
- "(b) in contact skarns or tactites, where sedimentary marbles have been influenced by nearby plutonic bodies;
- "(c) in altered igneous rocks, especially gabbro and diabase, by the effect of hydrothermal or pneumatolytic fluids (possibly also by groundwater action ...)" ; and
- "(d) in metamorphic rocks of regional distribution, especially marbles, greenstones, calcareous gneisses, and granulites, but also in pelitic and psammitic varieties;
- "(e) in fissure-fillings (veins) in various regionally metamorphosed rocks;
- "(f) in metamorphosed salt deposits ...".

Shaw considers that scapolite is typically a metamorphic mineral, unable to form in sedimentary environments, and that it is not a product of primary magmatic crystallisation.

He notes that scapolite is not restricted to a narrow range of metamorphic conditions, but occurs with a wide variety of common minerals in rocks ranging from the zeolitic facies to granulitic and sanidine facies. This is equivalent to a temperature and pressure range of 200°C to 1,100°C and 0 to 10,000 Kg/cm<sup>2</sup>. The wide range of conditions in which scapolite is able to form should result in a more widespread occurrence of the mineral than is the case. Shaw (1960, p. 282) considers that because of its complex constitution, the occurrence of scapolite is limited to zones of suitable chemical composition in which the "materials of plagioclase", in particular, are possibly a necessary pre-requisite to its formation which, in all cases, is coupled with pegmatitic, pneumatolytic, or hydrothermal action.

Scapolitisation of basic igneous rocks, both on the Copperbelt and elsewhere, has been ascribed to auto-metasomatic processes resulting from the reactions between the residual fluids, formed during the final stages of crystallisation of the magma, and the early-formed feldspars. Jackson (1932) analysed gabbros exhibiting different degrees of scapolitisation and found that Na, Cl, Fe<sup>+++</sup>, and H<sub>2</sub>O contents increase with scapolitisation. He regarded auto-scapolitisation as due to the residual "juices" rich in these elements reacting with the crystallised magma in a "heated aqueous phase". Shaw (1960, p. 283) considers that only carbon dioxide need be added to a typical gabbro in order to produce a chemical environment in which scapolite could form.

Albitisation of a basic plagioclase involves the addition of soda and silica, and scapolitisation, the further addition of chlorine or carbon dioxide. In an amphibolite, therefore, albitisation could, in fact, be a late-stage auto-metasomatic process, but scapolitisation is possibly not, as it could involve the addition of an anion radicle.



Albitisation or spilitisation of basic intrusive rocks is discussed by Turner and Verhoogen, (1960, p. 268), who suggest that the soda and silica required for the process may be provided by connate waters, either by intrusion of the rock into wet sediments, or by the upward migration of these waters during compaction. The close relationship between the Chibuluma amphibolites and the albitised zones surrounding them suggests that the amphibolite itself is the source of the soda, although the connate waters or evaporites may have supplied the anions required for scapolitisation. Autometamorphism may have been facilitated by intrusion into wet sediments resulting in the quick chilling of marginal rocks, and the consequent retention of volatiles which would otherwise have escaped.

Edwards and Baker (1953, p. 30) consider that scapolitisation of calcareous shales in the Cloncurry district of northwest Queensland is simply an intermediate stage of albitisation by soda metasomatism. The scapolite in this district has a restricted range of composition (Me 30 - Me 25). The limit of the range towards the lime end member of the scapolite series is thought to be controlled by the original aluminium content of the rock. The lime-rich varieties of scapolite contain considerably more Al than do the soda-rich varieties as variation in composition involves replacement of Na and Si by Ca and Al. Increased lime content of the shale is achieved only by an increase in calcite or dolomite content, thereby reducing the amount of aluminium present, so that beyond a certain lime content of the rocks, there would be insufficient alumina to form the more lime-rich scapolites. The limit towards the soda end member of the scapolite series is restricted either by the availability of chlorine or by the possibly greater stability of albite under the prevailing conditions.

The distribution of albite and scapolite in the Upper Roan sediments of Chibuluma Mine suggests that the formation of these minerals was controlled by the same limiting factors. Both minerals occur preferentially in argillaceous beds, and the albite breccias, or adinoles, are invariably close to the amphibolite bodies, whereas scapolite, with a few exceptions, occurs at some distance from these bodies (Hall, 1963). The scapolite in the amphibolite bodies formed later than the albite which it replaces. It is possible, therefore, that there are two generations of scapolite, the first having formed in the sediment during an outward migration of soda and the second having formed in the amphibolite during an opposing migration of chlorine or carbon dioxide. This is, in part, in agreement with the views held by Hall (Mendelsohn, 1961, p. 52) that scapolitisation in the amphibolite is due to dynamic metamorphism during the Iufilian orogeny.

#### Lime Metasomatism

Evidence that lime metasomatism has taken place is found in the well developed lime-rich rims of the scapolite crystals occurring in both amphibolite and sediments near the lower contact of the major amphibolite sill. This is substantiated by the increase in lime content of the amphibolite near the contacts with the sediments (Figure 20). The distribution of the zoned scapolite suggests that the lime metasomatism took place after soda metasomatism.

#### Metasomatic Effects on the Lower Roan Group

The amphibolite appears to have had very little effect on the Lower Roan sediments and the copper mineralisation therein. Darnley (1959) in discussing the alkali metasomatism in these rocks considered that the amphibolites could be the source of the soda. This does not appear likely, however, because although the amphibolites are the cause of some soda

metasomatism, the rocks affected by it are restricted to the proximity of the sills. Hall (1963) also refutes Darnley's suggestion and shows that potash-rich layers occur between the amphibolite and the soda-enriched Lower Roan formations. Hall considers that a large proportion of the albite is authigenic and that connate waters are the source of the soda.

There is no apparent relationship between the copper mineralisation in the Lower Roan and the amphibolite sills as was suggested by Sales (1960). Apart from the considerable evidence showing the copper in the orebodies to be syngenetic, the distribution of the copper in the amphibolite does not indicate it to be a source of the metal. Copper is not common in the amphibolites and, where it occurs, it is largely restricted to late shear zones showing that it has undergone some mobilisation. In spite of this, it is an uncommon mineral in the adjacent sediments and, where it occurs in these, the copper sulphides show some indications of a high temperature of formation which are absent from the copper sulphides in the orebodies.

#### The development of Asbestiform Serpentine

An interesting but uncommon feature of the basal contact of the major amphibolite body is the presence of a number of small "veins" of asbestiform serpentine in the dolomite. The largest development of the asbestos is in drillhole NS.72 at 1,023 feet, only one foot below the contact, where, unfortunately, the precise form of the vein has been obscured by poor core recovery. This vein is at least 2 inches in width, and it is thought to dip at approximately 30 degrees, but it is not known if the vein is truly parallel to the amphibolite contact above it. The fibres lie approximately parallel to the walls of the vein and in this particular vein are remarkably long,

being at least 3 inches in length (i.e. the full diameter of the NXC core). The more common length of fibres in other veins is from ¼ to 1 inch.

The fibres from drillhole NS.72 are very fine, with a silky lustre, and have the following optical properties.

Straight extinction, positive elongation

$N_x = 1.522$  pale greenish grey

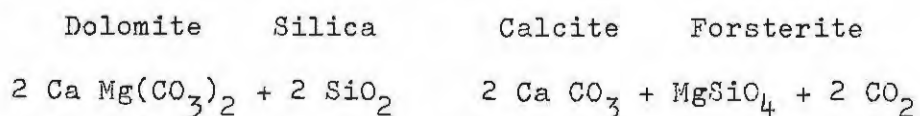
$N_y =$  not determined

$N_z = 1.553$  bright golden brown

$N_z - N_x = 0.031$

These properties distinguish the fibres as chrysotile. All of the fibrous amphiboles have  $N_z$  greater than 1.58, and the majority have inclined extinction. The value obtained for  $N_x$  is lower than the chrysotile range ( $N_x = 1.532 - 1.549$ ) recorded by Deer, Howie, and Zussman (1962) who state that ionic substitution is very limited in natural specimens, and, therefore, do not suggest any relation between optical properties and composition. This low refractive index results in the high birefringence, which could not be verified by the interference colours, as no reference mineral of standard thickness was available in either crushed fragments or in the thin section prepared.

The presence of serpentine in the dolomite near the contacts with the amphibolite bodies suggests a possible explanation for the absence of any typical skarn silicate minerals in these zones. A possible reaction suggested by Deer, Howie, and Zussman, (1962, Vol. 3, p. 185), for the serpentinitised dolomitic rock associated with diabase sills in the Transvaal is as follows:-



The originally siliceous dolomite is transformed to forsterite which is subsequently serpentinitised during retrogressive

metamorphism.

The fibres, although usually occurring as cross fibres orientated perpendicular to the vein walls, in a few cases, occur as slip fibres which are very oblique and even parallel to the walls, a feature which indicates some degree of stress during their growth. Poldervaart (1950, p. 243) considers that the development of chrysotile deposits in dolomite near dolerite sills is unrelated to crustal movements and stresses as the fibres in these deposits are usually cross fibres. He considers any disturbances of this cross fibre pattern are likely to have been caused by later earth movements. The faulting known to exist in the west of the major amphibolite body and brecciation within the amphibolite itself indicate that considerable stresses did exist after the consolidation of the amphibolite. These stresses are possibly responsible for the development of the slip fibres.

#### Evidence of Metamorphism in the Opaque Minerals

Both magnetite and pyrite are very common minerals in the sediments adjacent to the major amphibolite sill. Concentrations of magnetite, in particular, constitute greater than 90 per cent by volume of the rock in zones up to three feet in width. The proximity of these minerals to the amphibolite suggests that they were formed during the intrusion and cooling of the magma and that their occurrence is, in fact, a contact phenomenon. Unfortunately, the pyrite and magnetite do not exhibit any textures from which an estimate of their temperatures of formation could be made.

Copper-bearing sulphides are uncommon in the contact zone, but where they do occur, their textures give some indication of the temperature of their formation. The chalcopyrite-cubanite textures are particularly significant. As discussed under the heading of the mineralogy of the opaque minerals, the relative proportions of these minerals suggest

that temperatures of 450°C were obtained. The exsolution of pentlandite in pyrrhotite suggests that even higher temperatures were reached.

Contact metamorphic phenomena of the albite-epidote-hornfels facies or even of the lower hornblende-hornfels facies would be expected at these temperatures. The mineral assemblages of the albite-epidote-hornfels phase of contact metamorphism, however, are very similar to those of the greenschist facies of regional metamorphism (Turner and Verhoogen, 1960, p. 570) and, if present, would be difficult to recognise. Biotite, tremolite, and possibly chrysotile (as an alteration product of forsterite) on the other hand are the only minerals that suggest that a mineral assemblage of the lower hornblende-hornfels facies was ever developed.

It appears, therefore, that either the temperature of the amphibolite was not sufficient for the formation of higher contact mineral assemblages, or that these minerals were formed, but were subsequently altered by retrogressive metamorphism, possibly during a stage of regional metamorphism. The fact that chilled margins were developed in the amphibolite shows that considerable differences in temperature existed between the magma and the sediments at the time of intrusion. If the sediments were wet, however, the resulting increase in water pressure would have lessened the effect of the temperature in the formation of silicate minerals (Turner and Verhoogen, 1960, p. 509).

#### AGE OF THE INTRUSION

To the writer's knowledge, no absolute age determinations have been carried out on the Copperbelt gabbros. However, as the gabbros are intruded almost exclusively into the Katanga System sediments which are themselves affected by the Lufilian orogeny, the absolute ages of both the sediments

and the orogeny are of interest. A review of relevant absolute age determinations is presented by Snelling, Hamilton, Drysdall, and Stillman (1964, p. 961), and it is from this review that the following data were extracted.

Post-tectonic uranium mineralisation in Katanga dates the Lufilian orogeny as being older than  $620 \pm 20$  million years. Age determinations made on the Lusaka granite, regarded as being intrusive into the Katanga system, and contemporaneous with the late stages of the Lufilian orogeny, tentatively date the orogeny, and set a younger limit for the age of the Katanga system sediments at 725 million years. This figure is doubtfully substantiated by age determinations made on galena from Katanga and Zambia giving values which range from 712 million years to 760 million years. The rise of the Kafue anticline, and the accompanying doming and tensional faulting, are dated by the associated development of the Nchanga red granite, at 570 million years.

The chronological sequence of the emplacement of the gabbro bodies, and the Lufilian orogeny is a controversial subject which has been discussed by a number of early writers. Jackson (1932) attributed the unstrained and unaltered appearance of the gabbros of the Nchanga district to their having been intruded after regional folding. Horscroft (1954, p. 14) in agreement with Jackson, considered that in the Sosa Hill area, faulting causing a displacement of Lower Roan quartzites, but not effecting an equivalent displacement of a large gabbro mass, indicated that the intrusion of the gabbro was post-faulting. He further considered that the faulting was of two ages, the older closely following the main period of orogeny, and the younger, definitely post-folding. Hatfield (1937) considered the gabbros in the Solwezi district (approximately 100 miles west of the Copperbelt) to be post-regional folding in age and to be closely associated with faults. McGregor

(1964, p. 126) after investigating the gabbro intrusions at Lumwana (170 miles west of the Copperbelt) concluded that they had been emplaced after the Lufilian orogeny and were associated with post-Lufilian tensional faults.

The above writers favoured a post-Lufilian emplacement of the gabbro, but a number have expressed different views. Garlick (quoted by Mendelsohn, 1961, p. 52) considered that the emplacement took place at an early stage in the orogeny because the intrusions favoured the Upper Roan formations, which, as an incompetent formation between competent Lower Roan and Mwashia groups, would have been the locus of differential movements. Hall (quoted by Mendelsohn, 1961, p. 52) considered that the amphibolite was formed as an alteration product of the original gabbro, which "was intruded at an early stage of the Lufilian orogeny". Hall regarded the scapolitisation, uralitisation, and saussuritisation of the amphibolite as being due to the dynamic metamorphism associated with the orogeny. Winfield (1961, p. 334) regarded the correlation between gabbro and amphibolite schists in the folded Chibuluma West area as suggesting that "the gabbro was introduced before post-Roan folding".

It is possible that there were, in fact, a number of phases of igneous activity and that gabbros were emplaced before, during, and after the Lufilian orogeny. The apparently opposing views mentioned above may all be valid within each particular locality described. De Swardt, Drysdall, and Garrard (1963, p.62) briefly note the existence of two phases of igneous activity in basement rocks described by Newton, as being represented by amphibolites on the one hand and by post-tectonic metagabbros on the other. A similar situation could be present in the basic intrusives of the Katanga system whereby the degree of alteration or uralitisation of the original gabbro or norite could possibly reflect the period during which the rock was subjected



to the dynamic metamorphism of orogenesis. In this manner, the Chibuluma and Chambishi amphibolites which are apparently pre-orogenic contain no relict pyroxene or olivine, whereas the gabbros and amphibolites described by Jackson(1932) and McGregor(1964) west of the Copperbelt contain relics of one or both of these minerals, and are apparently post-orogenic.

On mineralogical evidence, it appears that the major amphibolite body at Chibuluma Mine was emplaced before or during the early stages of the Lufilian orogeny when the strata intruded were predominantly horizontal. The main reason for arriving at this conclusion is the parallelism exhibited between the upper and lower contacts of the conformable amphibolite sill and the internal zones of various types of amphibolite produced as a result of fractionation and gravitational differentiation.

On the basis of chemical data, it appears that the sill was possibly inclined at a slight angle to the horizontal during the consolidation of the magma. The overall tenor of the magnesia and lime contents in samples from drillhole NS.82 is higher than that in samples from drillhole NS.76, but these differences are small compared with the variations of these oxides in individual drillholes and the angle of inclination was probably small. Drillhole NS.82 intersects the amphibolite sill down dip from the NS.76 intersection and the chemical data, therefore, indicates that the slight inclination of the strata during the consolidation of the magma was in the general direction in which the sill is inclined today. This might imply that the sill was intruded at an early stage of the folding that produced the Chambishi-Nkana syncline.

Structural evidence in the form of faults, joints, and zones of sheared or brecciated amphibolite, shows that considerable tectonic stresses were operative after the consolidation of both phases of the multiple intrusion. These

stresses could be associated with the Lufilian orogeny or subsequent doming, and are possibly those responsible for the slip-fibres developed in the serpentine on some contacts.

The absence of typical contact metamorphic effects in the wall rocks, in spite of some evidence suggesting that moderately high temperatures existed there at the time of the intrusion, could be explained by assuming a pre-Lufilian emplacement of the amphibolite. The contact effects could have been largely destroyed by local retrogressive metamorphism during the regional metamorphism accompanying the Lufilian orogeny. The "dynamic metamorphism during the orogeny" invoked by Hall (Mendelsohn, 1961, p. 52) to explain the development of the amphibolite from an original gabbro is also a form of retrogressive metamorphism.

The fresh, unaltered and unstrained nature of some gabbros intrusive into schistose sediments has been considered by Jackson (1932) and McGregor (1964) to be indicative of a post-Lufilian emplacement of the gabbro. This is probably a valid conclusion in the areas these writers described, but as the Upper Roan sediments at Chibuluma are of a low facies of regional metamorphism only, the fresh, unstrained, nature of the Chibuluma amphibolite does not mean that they are post-Lufilian in age. The Chibuluma amphibolite is not known to be intrusive along any fault and, therefore, cannot be dated by such means as used by Horscroft (1954) and Hatfield (1937) in areas west of the Copperbelt.

The slight upward doming of the upper contact of the major amphibolite sill suggests that the emplacement took place during a period of crustal compression (Daly, 1933, p. 81). Such a period would have existed during the initial stages of the Lufilian orogeny whereas the subsequent period of doming was a period of crustal tension. The writer considers, therefore, that the amphibolite sills at Chibuluma Mine were emplaced

shortly before or during the initial stages of the Lufilian  
orogeny.

SUMMARY OF CONCLUSIONS

The main conclusions drawn from these investigations on the Chibuluma amphibolite are summarised below:-

- (i) The amphibolites are igneous rocks, intruded as sill-like bodies into the Upper Roan Group sediments;
- (ii) The major amphibolite body is a multiple intrusion in which the younger of two phases is intruded along a plane approximately 50 feet above the base of the older phase;
- (iii) Each phase of the major amphibole body has undergone fractionation and gravitational differentiation during consolidation;
- (iv) On a chemical basis, the amphibolite bears a close resemblance to a tholeiitic magma-type. Minor spilitic characteristics are evident;
- (v) Soda metasomatism has occurred in both the amphibolite bodies and the surrounding sediments, as evidenced by the development of albite and scapolite in the former, and adinoles or "albite breccias" in the latter. The adinoles are the main metamorphic affect produced in the sediments by the intrusions;
- (vi) No relationship could be detected between the emplacement of the amphibolite bodies and the development of the economic copper mineralisation in the Lower Roan Group;
- (vii) The amphibolites are considered to have been intruded before or during the early stages of the Lufilian orogeny, when sediments were essentially horizontal.

REFERENCES

- ALLING, H.L. (1936). Interpretive petrology of igneous rocks. McGraw-Hill, New York, 353 p.
- BAILEY, E.H. and STEVENS, R.E. (1960). Selective staining of K-feldspar and plagioclase on rock slabs and thin sections. Amer. Miner., 45, 1020 - 1025.
- BANCROFT, J.A. (1961). Mining in Northern Rhodesia. Arranged by T.D. Gurnsey. Sidney Press, England.
- BUCKLEY, H.E. (1951). Crystal growth. John Wiley and Sons, New York, 571 p.
- CAMERON, E.N. (1961). Ore microscopy. John Wiley and Sons, New York, 393 p.
- CARR, J.M. (1954). Zoned plagioclases in layered rocks of the Skaergaard intrusion, east Greenland. Miner. Mag., 30, p. 367.
- CHUDOBA, K. (1933). The determination of the feldspars in thin section (Translated by W.Q. Kennedy). Murby, London, 61 p.
- DALY, R.A. (1933). Igneous rocks and the depths of the earth. McGraw-Hill, New York.
- DARNLEY, A.G. (1958). The petrology of some Rhodesian Copperbelt orebodies and associated sediments. Ph.D. thesis, University of Cambridge.
- DEER, W.A., HOWIE, R.A. and ZUSSMAN, J. (1962 and 1963). Rock forming minerals. 5 vols. Longmans, London.
- DE SWARDT, A.M.J., DRYSDALL, A.R., and GARRARD, P. (1963). Precambrian geology and structure in Central Northern Rhodesia. Memoir No. 2, Geological Survey of Zambia, Government Printer, Lusaka.
- EALLES, H.V. (1959). The Khale dolerite sheet. Trans. geol. Soc. S. Afr., 62, 81 - 111.
- EDWARDS, A.B. and BAKER, G. (1953). Scapolitization in the Cloncurry District, northwestern Queensland. J. geol. Soc. Austr., 1, 1 - 33.
- EDWARDS, A.B. (1954). Textures of the ore minerals and their significance. Second edition. Austr. Inst. Min. and Met., Melbourne, 242 p.
- FLEISCHER, V.D. (1956). Geology of Chibuluma Mine. Paper presented to Northern Rhodesian Branch of Inst. Min. and Met.
- GARLICK, W.G. and BRUMMER, J.J. (1951). The age of granites of the Northern Rhodesian Copperbelt. Econ. Geol., 46, 478 - 497.
- GARLICK, W.G. (1959). Geology of Chibuluma Mine with notes on lithology and sedimentation. Contribution to International Geological Congress - symposium on geology of copper in Africa. Copenhagen, July 1960.

- GARLICK, W.G. (1961). Contributor to "The geology of the Northern Rhodesian Copperbelt", ed. Mendelsohn. Macdonald, London. 523 p.
- GREY, A. (1930). A correlation of the ore-bearing sediments of the Katanga and Rhodesian Copperbelt. Econ. Geol., 25, 783 - 801.
- GUNNING, H.C. (1961). Contributor to "The geology of the Northern Rhodesian Copperbelt", ed. Mendelsohn. Macdonald, London. 523 p.
- HALL, A.J. (1958). Petrographic descriptions of rocks. Unpublished Company reports (RST Technical Services Limited).
- HALL, A.J. (1963). The petrography and petrology of the Chibuluma Basin. Unpublished Company report (RST Technical Services Limited).
- HALLIMOND, A.F. (1943). On the graphical representation of the calciferous amphiboles. Amer. Miner., 28, No. 2, 65 - 89.
- HATFIELD, W.C. (1937). The geology of the Solwezi District, Northern Rhodesia. Quart. J. geol. Soc. Lond., 93, pt. 2, No. 370.
- HAWLEY, J.E. and HAW, V.A. (1957). Intergrowths of pentlandite and pyrrhotite. Econ. Geol., 52, 132 - 139.
- HEWITT, R.L. (1938). Experiments bearing on the relation of pyrrhotite to other sulphides. Econ. Geol., 33, 305 - 338.
- HORSCROFT, F.D.M. (1954). A contribution to the geology of the Katanga System in the Nchanga District, Northern Rhodesia. M.Sc. thesis, Wits. Univ.
- HORSCROFT, F.D.M. (1961). Contributor to "The geology of the Northern Rhodesian Copperbelt", ed. Mendelsohn. Macdonald, London. 523 p.
- IDDINGS, J.P. (1909). Igneous rocks. Wiley, New York.
- JACKSON, C.G.A. (1932, B). The geology of the Nchanga District. Quart. J. geol. Soc. Lond., 88, 443 - 514.
- JAEGER, J.C. and JOPLIN, G. (1954). Rock magnetism and the differentiation of dolerite sills. J. geol. Soc. Austr., 2, 1 - 19.
- JAEGER, J.C. and GREEN, R. (1957). A cross section of a tholeiite sill. Paper presented at symposium on dolerite at University of Tasmania.
- JOHANNSSEN, A. (1931 and 1932). A descriptive petrography of igneous rocks. 4 vols. University of Chicago Press.
- JORDAAN, J. (1961). Contributor to "The geology of the Northern Rhodesian Copperbelt", ed. Mendelsohn. Macdonald, London. 523 p.
- MACGREGOR, A.G. (1931). Clouded feldspars and thermal metamorphism. Miner. Mag., 22, 524 - 538.

- MARIE, S. (1961). Contributor to "The geology of the Northern Rhodesian Copperbelt", ed. Mendelsohn. Macdonald, London. 523 p.
- McDOUGALL, I. (1962). Differentiation of the Tasmanian dolerites: Red Hill dolerite - granophyre association. Bull. geol. Soc. Amer., 73, 279 - 315.
- McGREGOR, J.A. (1960). The geology of part of the Katanga System in the Kalaba area, Northern Rhodesia, with special reference to copper-bearing magnesite. M.Sc. thesis, Rhodes Univ.
- McGREGOR, J.A. (1964). The Lumwana copper prospect in Zambia. Ph.D. thesis, Rhodes Univ.
- MCKINSTRY, H.E. and KENNEDY, G.C. (1957). Some suggestions concerning the sequence of certain ore minerals. Econ. Geol., 52, 379 - 390.
- MENDELSON, F. (1961). The geology of the Northern Rhodesian Copperbelt. Macdonald and Co., London. 523 p.
- OSBORNE, E.F. (1962). Reaction series for subalkaline igneous rocks based on different oxygen pressure conditions. Amer. Miner., 47, 211 - 226.
- PHEMISTER, J. (1934). Zoning in plagioclase feldspar. Miner. Mag., 23, 541.
- POLDERVAART, A. and VON BACKSTRÖM, J.W. (1949). A study of an area at Kakamas (Cape Province). Trans. geol. Soc. S. Afr., 52, 433 - 495.
- POLDERVAART, A. (1950). Chrysotile asbestos produced by dolerite intrusions in dolomite. Colon. Geol. miner. Resour., 1, 239 - 245.
- POLDERVAART, A. and GILKEY, A.K. (1954). On clouded plagioclase. Amer. Miner., 39, 75 - 91.
- RAMBERG, H. (1952). The origin of metamorphic and metasomatic rocks. Univ. Chicago Press. 317 p.
- RAMDOHR, P. (1960). Die Erzminerale und Ihre Verwachsungen. Akademie Verlag, Berlin. 1089 p.
- RICE, C.M. (1943). Dictionary of geological terms. Edwards Bros., Michigan, 465 p.
- SALES, R.H. (1960). Critical remarks on the genesis of ore as applied to future mineral exploration. Econ. Geol., 55, 805 - 817.
- SCHWARTZ, G.M. (1937). The paragenesis of pyrrhotite. Econ. Geol., 32, 31 - 55.
- SHAW, D.M. (1960). The geochemistry of scapolite. Parts I and II. J. Pet., 1, 218 - 285.
- SHROCK, R.R. (1948). Sequence in layered rocks. McGraw-Hill, New York. 507 p.
- SNELLING, N.J., HAMILTON, E., DRYSDALL, A.R., and STILLMAN, C.J. (1964). A review of age determinations from Northern Rhodesia. Econ. Geol., 59, 961 - 981.

- TAYLOR, H.K. (1963). The occurrence of aloes in western Copperbelt of Northern Rhodesia. (part 2). Journal of naturalist Soc. of Cent. Afr., 3, p. 118.
- TRAPNELL, C.G. and CLOTHIER, J.N. (1957). The soils, vegetation, and agriculture of Northwestern Rhodesia. Report of Ecological Survey, Government Printer, Lusaka.
- TURNER, F.J. and VERHOOGEN, J. (1960) Igneous and metamorphic petrology, 2nd ed., McGraw-Hill, New York. 694 p.
- WAGER, L.R. and DEER, W.A. (1939). Geological investigation in east Greenland, Part III. The petrology of the Skaergaard intrusion, Kangerdlugssuaq, east Greenland. Meddel. om Grøn., Bd. 105, Nr. 4.
- WAGER, L.R. and MITCHELL, R.L. (1951). The distribution of trace elements during strong fractionation of basic magma - a further study of the Skaergaard intrusion, east Greenland. Geochim. et Cosmoch. Acta., 1, p. 129 - 208.
- WALKER, F. (1953). The pegmatitic differentiates of basic sheets. Amer. J. Sci., 251, 41 - 60.
- WALKER, F. (1957). Recent work on the form of dolerite intrusions in sedimentary terrains. Paper presented at symposium on dolerite at University of Tasmania.
- WALKER, F. and POLDERVAART, A. (1949). Karroo dolerites of the Union of South Africa. Bull. geol. Soc. Amer., 60, 591 - 706.
- WINCHELL, A.N. (1945). Variations in composition and properties of the calciferous amphiboles. Amer. Miner., 30, 27 - 50.
- WINFIELD, O. (1961). Contributor to "The geology of the Northern Rhodesian Copperbelt", ed. Mendelsohn. Macdonald, London. 523 p.



APPENDIX A  
RESULTS OF PARTIAL ROCK ANALYSES

DRILLHOLE AND DEPTH (FEET)	Mg%	Ca%	Fe%	Ti%	Na%	K%	CO <sub>2</sub> %	Mn%	S%	Cu%	Co%	Ni%	Zn%	Pb%	Sb%	Bi%	MAFIC INDEX	FELSIC INDEX	CaO Na <sub>2</sub> O	REMARKS
NS.82, 481-489	11.20	10.56	0.72	0.05	1.0	0.1	29.6	0.050	0.09	0.042	0.003	0.006	0.002	0.005	0.013	0.005				Sediments
547-553	10.06	12.87	2.09	0.05	1.0	0.2	25.3	0.088	0.02	0.010	0.003	0.004	0.002	0.005	0.013	0.005				Sediments
559-567	10.89	7.31	8.47	0.35	1.1	1.2	5.44	0.052	0.07	0.009	0.009	0.011	0.003	-	0.008	0.002				Sediments
574-584	3.19	6.21	9.94	2.10	6.2	0.6	0.25	0.029	0.27	0.006	0.008	0.007	0.003	-	0.004	0.002	70.72	51.12	1.04	Outer member
691-701	3.46	6.51	8.26	1.45	5.0	1.3	0.05	0.039	0.18	0.006	0.008	0.009	0.003	-	0.004	0.005	64.91	47.73	1.35	of Multiple Sill
927-936	5.00	5.97	9.01	1.30	3.6	1.9	0.05	0.041	0.17	0.028	0.008	0.024	0.003	-	0.008	0.002	58.30	46.10	1.72	
974-984	2.85	5.27	10.86	1.85	6.6	0.5	0.15	0.021	0.45	0.005	0.011	0.009	0.002	0.005	0.004	0.005	74.75	56.31	0.83	Inner member
1038-1048	2.67	6.25	8.60	1.85	5.6	0.5	0.30	0.021	0.43	0.005	0.009	0.009	0.002	-	0.004	0.005	71.40	48.26	1.16	
1221-1228	4.72	7.88	8.39	1.10	3.2	1.0	0.02	0.050	0.14	0.018	0.005	0.016	0.003	0.005	0.008	0.005	57.98	33.39	2.55	
1410-1419	5.03	6.67	8.57	1.15	3.4	1.1	0.05	0.031	0.09	0.020	0.005	0.017	0.002	0.005	0.008	0.005	56.92	38.79	2.03	
1475-1484	5.01	5.77	9.86	1.30	3.6	1.4	0.05	0.058	0.11	0.031	0.008	0.021	0.003	-	0.008	0.005	60.41	44.77	1.66	Outer member
1615-1621	3.18	7.39	6.87	1.75	4.6	0.5	0.10	0.021	0.26	0.012	0.005	0.014	0.003	-	0.004	0.005	62.62	39.69	1.67	
1804-1814	7.75	9.54	1.24	0.05	0.8	0.8	13.80	0.031	5.22	0.003	0.003	0.004	0.002	0.005	0.008	0.005				Sediments
1970-1980	3.32	7.68	4.71	0.35	0.1	4.0	5.05	0.037	1.52	0.002	0.005	0.011	0.002	0.005	0.008	0.002				Sediments
2000-2010	4.23	1.63	1.36	0.01	6.8	0.2	4.76	0.044	0.05	0.003	0.002	0.007	0.002	-	0.004	0.002				Sediments
NS.76, 195-200	2.77	7.52	8.88	1.85	4.2	1.1	0.35	0.041	0.34	0.003	0.011	0.009	0.003	-	0.008	0.002	71.33	39.93	1.86	Outer member
229-233	3.35	4.17	4.10	1.65	7.4	0.4	0.25	0.035	0.51	0.002	0.020	0.006	0.002	0.005	0.008	0.002	48.71	64.19	0.58	of Multiple Sill
267-272	1.05	2.89	10.74	3.00	4.6	0.9	0.05	0.023	0.36	0.004	0.009	0.009	0.003	-	0.008	0.002	88.61	64.29	0.65	
366-371	1.42	3.95	5.38	1.35	3.6	1.0	0.05	0.048	0.10	0.013	0.005	0.011	0.003	-	0.008	0.002	74.65	52.29	1.14	
445-451	8.97	4.12	5.82	1.30	3.6	1.2	0.05	0.050	0.09	0.019	0.008	0.019	0.003	0.005	0.008	0.005	33.47	52.24	1.19	
598-605	2.96	3.37	7.11	1.45	2.8	1.0	0.05	0.057	0.09	0.010	0.009	0.021	0.004	-	0.004	0.002	65.05	51.34	1.25	
680-686	2.77	3.13	7.14	1.50	4.4	1.7	0.05	0.037	0.11	0.005	0.008	0.019	0.003	-	0.004	0.005	66.67	64.59	0.74	
712-715	1.17	3.09	6.08	2.10	6.8	0.5	0.30	0.027	0.29	0.006	0.009	0.009	0.003	-	0.004	0.002	80.12	69.31	0.47	Inner member
753-758	0.84	3.01	7.94	1.95	5.8	0.5	0.30	0.021	0.40	0.004	0.011	0.007	0.003	-	0.008	0.002	88.02	66.69	0.54	
798-805	1.41	3.05	10.82	3.40	4.0	1.2	0.15	0.041	0.14	0.034	0.008	0.007	0.003	0.005	0.008	0.005	64.98	61.60	0.79	
895-902	2.29	2.87	6.70	1.55	4.4	1.4	0.05	0.045	0.10	0.036	0.008	0.017	0.003	-	0.008	0.005	69.40	65.49	0.68	
1015-1021	1.97	3.05	5.05	1.20	3.6	1.1	0.10	0.046	0.07	0.013	0.008	0.019	0.003	-	0.008	0.005	66.50	59.18	0.88	
1171-1178	2.37	3.03	5.93	1.45	3.6	1.2	0.10	0.041	0.11	0.012	0.008	0.019	0.003	-	0.004	0.002	66.00	59.81	0.87	
1295-1301	1.39	3.25	4.90	1.70	3.8	1.0	0.05	0.033	0.18	0.004	0.009	0.011	0.002	-	0.004	0.005	73.26	58.18	0.89	
1366-1370	1.13	3.75	5.00	2.10	4.6	0.7	0.10	0.035	0.19	0.007	0.008	0.011	0.002	0.005	0.004	0.002	77.47	57.32	0.85	
1392-1398	2.42	3.67	6.36	1.60	3.8	1.7	0.10	0.029	0.17	0.004	0.009	0.019	0.002	-	0.008	0.005	67.10	58.28	1.00	Outer member
1408-1413	0.81	4.75	3.33	1.70	3.0	0.6	0.10	0.014	0.25	0.003	0.008	0.006	0.002	0.005	0.004	0.005	76.50	41.77	1.64	
1420-1427	2.64	6.07	1.06	0.38	1.0	0.7	10.3	0.033	4.27	0.004	0.003	0.004	0.002	0.005	0.008	0.005				Sediments
1478-1486	10.53	6.41	0.57	0.25	0.4	0.6	39.1	0.062	0.24	0.002	0.003	0.004	0.002	0.005	0.013	0.002				Sediments

Alkali determinations made by Mufulira Copper Mines Limited  
All other elements determined by RST TS Research and Development Laboratory

POSTSCRIPT

Recent deep exploratory drillholes have exposed further features of the amphibolite sills in the vicinity of the fold referred to on pages 14 and 23 of this thesis. These features have been added to Figure 5.

The inner member of the major amphibolite thins out rapidly towards the north, resulting in an overall reduction of the true thickness of the sill in that direction. It is not clear whether this change in thickness produced a zone of structural weakness in the rocks which in turn facilitated the development of a fold at this point, or whether the presence of the fold prevented further intrusion of the younger phase northward within the older phase of the intrusion.

The minor amphibolite sills appear to occupy typical phacolithic positions which could imply their intrusions during or after the folding.

I.D.T.  
Kalulushi  
December 1968.



