THE LUMWANA COPPER PROSPECT
IN ZAMBIA

by

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of Philosophy at Rhodes University, Grahamstown.
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PREFACE

This volume was returned to the writer after perusal by the examiners in order that he might make certain changes in the manuscript. These changes have been made, and in addition the opportunity offer~~r~~ed by the inclusion of a preface has been taken to clarify the writer's viewpoint on the use of the word "ore"; and on the subjects of age of the gabbro and temperature of metamorphism at Lumwana.

The use of the terms "ore","orebody", "ore mineral" etc. is not intended to convey any indication that the copper mineralization at Lumwana has economic potential at the present time. The writer uses these terms loosely according to the definition of ore, "as a naturally occurring mineral complex which can now, or may later be profitably exploited in order to extract, use or sell one or more of its constituents". (From "Dictionary of Mineral Technology" by E.J. Pryor. Mining Publications Limited, London, 1963).

In the acknowledgments it is mentioned that many of W.G. Garlick's ideas have become the writer's own, but two important conclusions reached as a result of this research project are not shared by Garlick. The first of these concerns the age of the gabbro. Among other considerations Garlick finds it difficult to visualize why the Zambian gabbros should seek out the carbonate-bearing rocks in the folded and metamorphosed pile of strata, and hence favours intrusion during (or before ?) the Lufilian Orogeny. This and other problems concerning the gabbro need much careful investigation but on the available evidence from Lumwana the writer reaffirms his view that intrusion occurred subsequent to Lufilian folding.

The second difference of opinion concerns the temperatures of metamorphism on the Copperbelt and at Lumwana. If one accepts the postulated temperatures for formation of the transparent metamorphic minerals, one finds disagreement in what the writer believes to be established temperatures for the formation of certain sulphide minerals and intergrowths. For instance biotite is present in gangue in the Copperbelt mines and cubanite has not been reported among the sulphides. The biotite indicates temperatures in excess of 250° C (Barth, 1952), and the absence of cubanite indicates temperatures below 235° C (Edwards, 1947). While Garlick prefers to accept the theoretical temperatures of formation of the metamorphic index minerals, the writer favours the evidence of metamorphic temperatures available in the examination of sulphides. This evidence leads to the conclusion that the temperature of metamorphism at Lumwana was much lower than would have been postulated had the transparent metamorphic minerals been examined alone.

The writer is very grateful to Mr. Garlick for other criticisms which have resulted in correction or modification of various portions of the manuscript.

J. A. McGREGOR

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ABSTRACT

The Lumwana copper orebody[§] is situated 170 miles west of the Copperbelt. It is stratiform and occurs in schists regarded as part of the Katanga System older than the lower-most Copperbelt quartzite.

The discovery of copper at the Lumwana Prospect was a text book example of the success of the R.S.T. Mines Services Limited prospecting techniques. These include partial geochemical analyses of soil and drainage samples, pitting, drilling and radiometric, self potential, magnetic, resistivity and induced polarization methods of geophysical exploration.

The copper-bearing formations at the Lumwana Prospect occur in the inverted limb of a great recumbent fold within the Mombezhi Dome. Three periods of folding are recognized from the study of regional foliations and lineation, and the attitude of fold elements in individual folds. Each period of folding is regarded as a major pulse in the Lufilian Orogeny. The first-formed folds are isoclinal and have axial planes which strike at 160°, and dip southwest at 15°; the plunge is 11° in a direction 212°. The formation of first folds was accompanied by thrust faulting and the development of nappe structures including the great Lumwana recumbent fold. The second folds have axial planes which strike at 170° and dip west at 44°, the plunge is 12° in a direction of 192°, and the folds tend to be overturned. The third folds cut across the earlier folds at variable angles, they are overturned to the north and have axial planes which dip gently to the south. The formation of third folds was such that northward-acting stress was rotated from southeast to southwest, and relaxation of this stress resulted in the development in competent strata of joints which strike at 120° and dip steeply.

At the Lumwana Prospect the northward-acting Lufilian stress is thought to have been resolved into eastward acting stress during first and second folding as a result of compression near the centre of the Lufilian Arc. The third folds are the normal Lufilian folds sub-parallel to the Lugilian Arc.

Normal faulting and intrusion of gabbro along planes of these faults and the earlier thrust faults occurred in a post-Lufilian tensional phase. In recent times warping of the formations at Lumwana has occurred on east-west axes.

Statistical examination of chemical data on fifty-four composite samples of mineralized rock from drill-holes reveals that the distribution of copper, iron and sulphur is related to that of potash and soda. These relationships can be explained on sedimentological grounds since the examination of the distribution of soda and potash in these and other horizons yields no evidence of metasomatism in the mineralized horizon.

Intrusive into the mineralized schists, though not found in the ore, are thin amphibolites and a large serpentinite which contains relict olivine and bronzite. This is the first recorded occurrence of ultrabasic rocks in the Lower Roan Group of the Katanga System in this part of Zambia.

Study of all formations at the Lumwana Prospect reveals that they have been metamorphosed in the epidote-amphibolite facies of regional metamorphism. Mineral assemblages indicative of the amphibolite facies are found in sheared rocks, and metamorphism in competent parts of the Upper Roan-Mwashia has been confined to the greenschist facies. Temperatures of metamorphism are estimated to have been between 250°

[§] See Preface

and 280°C, and pressures are likely to have exceeded 6 kilobars.

Evidence of metasomatism, absent in the Lower Roan, is found in the examination of the Upper Roan-Mwashia formations. Metasomatism includes scapolitization and albitization and is related to the intrusion of gabbro into these sediments, but does not necessarily involve exogenous material.

The sulphide minerals identified are bornite, chalcocite, digenite, covellite, chalcopyrite, cubanite, valleriite, carrollite, pyrite and pyrrhotite. Intergrowths of these minerals have resulted from metamorphism at temperatures slightly in excess of 235°C.

The copper sulphides are distributed zonally in the orebody with chalcocite-bornite ore where the mineralized schist is thin, and chalcopyrite-cubanite-pyrite ore where it is thick. Vertically the body contains horizons with sulphides relatively rich in copper at the top and bottom, and an intermediate zone with sulphides leaner in copper. This zonal distribution is considered to be evidence for syngenetic deposition of copper during successive cycles of transgression and regression.

Ore genesis at Lumwana is closely related to genesis of the Copperbelt and Katanga orebodies. The Zambia-Katanga province is considered to have been enriched in copper epigenetically prior to the formation of the present-day orebodies. Reworking of these cupriferous rocks and some early-formed syngenetic deposits of which Lumwana is one, is considered to have played a major rôle in producing the present-day copper orebodies.

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ACKNOWLEDGMENTS

I thank Professor E.D. Mountain, Head of the Geology Department, Rhodes University, for his encouragement at the start of this undertaking, for his sustained interest, and for his help in the solution of numerous problems which arose in the course of the investigation.

It has been a privilege to have worked under Mr. W.G. Garlick at Rhodesian Selection Trust Mine Services Limited. The lines of thought pursued in parts of this thesis were born and developed in many discussions with Mr. Garlick, and many of his ideas have inevitably become my own.

I thank the management of R.S.T. Mine Services Limited for permission to conduct this investigation, and for its assistance in putting the company's various technical services at my disposal without cost. I am sincerely grateful to members of this company for aiding my investigations in numerous ways. These included reading of portions of the manuscript, collecting specimens, logging cores, field mapping and preparing drawings. The people to whom I am particularly grateful for their assistance are messrs. M.W. Ellis, J.E. Martin, G. Krummei, D. Ritchie, N. Bailie, N.R. Wainwright, T.C. Isted, W. Olivier, A. Mills, and A. Bosch, Dr. H. Meyer and Mrs. D. Parry.

I gratefully acknowledge the help in research techniques given me by Dr. H.V. Eales, and I thank both Dr. Eales and Mr. A. Ruddock of the Geology Department, Rhodes University, for criticizing parts of the manuscript.

I thank Mr. G. Whitfield, a post-graduate geology student at Rhodes University, for his analysis of the gabbro.

The aerial photographs used in Plates 1 and 2 were reproduced from originals owned by R.S.T. Mine Services Limted. I am indebted also to Mr. J. Salmon for taking the photograph reproduced in Plate 5, to Mr. C. Mills for the magnificent pictures presented in Plates 8 and 19, and to Dr. H.V. Eales for taking the photographs reproduced in plates 3, 15 and 16.

Finally, I thank my wife for helping to assemble the thesis and for her patience during the months of full-time research.

INTRODUCTION

The Lumwana Prospect lies on latitude 12° 12' south and longitude 25° 50' east, in the Solwezi District of the Northwestern Province of Zambia. It occurs seven miles north of the main Solwezi-Mwinilunga road, 170 miles by road from the nearest Copperbelt town, Chingola, and is nearly equidistant from the railheads of Chingola, and those of Elisabethville, Jadotville and Kolwezi in Katanga.

The prospect occurs in a saddle between two domes which together form the Mombezhi Dome. This is the central one of three domes which are the most conspicuous feature of the Mwinilunga area, being flanked by the Solwezi Dome to the east and the Kabompo Dome to the west. The mineralized beds occur in conformable schists older than the ridge forming Lower Roan quartzite, the succession being overturned and thrust beneath Basement granite. The Roan mineralized beds are exposed on the banks of the Lumwana River, the largest stream draining the northeastern lobe of the dome, and it is from this river that the prospect derives its name.

Climatically the region is classified as Tropical Savannah. It experiences cool, dry winters, with occasional frosts, a hot dry season, and then a hot rainy season. Rain falls almost entirely between the months of November and April, and totals 125 to 175 cm. per season. The mean annual temperature is about 20°C.

The area is fairly thickly forested in the manner described by Horscroft (1954), who refers to the vegetation as the Brachystegia-Isoberlinia type of woodland. Individual species may grow more commonly, or to greater heights in soils overlying particular formations.

The investigations by the writer have been concerned mainly with the mineralized formation, and the other formations have been examined only with a view to gaining a better understanding of the geology of this mineralized formation. Although a picture of the broader geological aspects has been presented, little attempt has been made to fill in obvious gaps in this knowledge.

HISTORY

Background History.

The interesting history of prospecting in Zambia, then Northern Rhodesia, has been described by Bancroft (1961) and Gunning (1961, ed. F. Mendelsohn) who emphasize the events leading up to the present development of the mines on the Copperbelt. Prospecting, however, was not confined to the vicinity of the Copperbelt, and when one considers the intensity of the early prospecting operations, it is remarkable that the Lumwana Prospect escaped detection for so long. This is particularly true as rocks brightly coloured with malachite and chalcanthite crop out on the banks of the Lumwana River, and both prospectors and indigenous Africans must at times have passed close to them.

Copper and iron were much in demand by the indigenous population, the former being the more highly prized, and very nearly all outcrops of copper occurrences were known to the local Africans when prospecting by Europeans first started in Zambia. Shallow old workings and remains of smelters are fairly common, and these led to the discovery of many copper occurrences early in the prospecting history of Zambia.

Organized prospecting started in 1895 when the Northern Territories (B.S.A.) Exploring Company sent Burnham and Ingram to prospect north of the Zambezi River. During the following fifteen years individuals, syndicates and small companies were issued with prospecting licences, one of the latter being Tanganyika Concessions Limited, which was formed in 1899. Field parties for this company under George Grey pegged Kansanshi (near Solwezi) in 1899, and under H.G. Robbins Kalaba (70 miles west of the Lumwana Prospect) in 1902 or 1903, the former actually coming into production in 1908.

From 1910 to 1923 there was little activity, and in 1922 the British South Africa Company concluded that almost nothing had resulted from exploration by individual prospectors, and it was decided to grant exclusive prospecting rights over large areas to responsible mining interests. These could afford to establish and maintain the proper staff and necessary organization to undertake a systematic and thorough search for mineral deposits.

Large concessions were granted to Copper Ventures Limited, and in 1923 Rhodesian Congo Border Concession Limited was formed to explore these concessions. From 1923 to 1940 R.C.B.C. undertook what was probably the largest and most comprehensive prospecting campaign over undertaken. In fifteen years 156,000 square miles were prospected and mapped so well that very few copper occurrences were missed and the maps have stood the test of subsequent prospecting. Little prospecting was carried out during the war years, and in 1947 Rhodesian Selection Trust Mine Serviees Limited (then Mufulira Copper Mines Limited) resumed exploration. A systematic prospecting technique was developed for the 27,000 square miles of the Mwinilunga Area, and the discovery of the Lumwana Prospect at the end of 1960 was a textbook example of the success of this technique.

Prospecting and Discovery History.

The R.S.T.M.S. prospecting technique which has been developed to cover large areas as rapidly and efficiently as possible is summarized in the following paragraphs.

Prior to commencing field-work, a camp-site is selected which forms the centre about which a radius of 40 miles is to be prospected. The results of early prospecting are examined and the relevant data transfered to aerial photograph mosaics, on which also are plotted a photographic interpretation of the geology, and physical features such as hills and clearings. The attention focused on clearings is based on a large number of known copper occurrences where the high concentration of copper in soil seems to have prevented the growth of trees. In addition anomalies in previously flown aerial geophysical surveys are noted for special attention.

The camp is occupied by a party of from five to ten geologists and field assistants, served by one or two helicopters, and the first stage of geochemical drainage reconnaissance is started. This consists of taking samples of sediments from all the streams and dambos in the area, a procedure rapidly accomplished with the aid of helicopters. These samples are tested at the R.S.T.M.S. geochemical laboratory for copper, cobalt, nickel and zinc by a chromatographic method.

The second stage consists of soil sampling along lines over previously known places of interest, clearings and all metal concentrations discovered by stream sampling. This is accomplished by pacing along traverse lines with the aid of compass and aerial photographs, the field parties being dropped and collected by helicopter at the most convenient landing point. The samples are again tested at the R.S.T.M.S. geochemical laboratory and any anomalies in the results evaluated and assigned different priorities for further investigation. The most encouraging results are left by the reconnaissance team for later detailed work by ground-crews, while the lesser anomalies receive immediate geological examination by pitting so that their potential can be better assessed.

The Lumwana Prospect was discovered by drainage reconnaissance at the end of 1960, and follow-up soil sampling revealed the extent of copper concentrations in soil. Contractors surveyed the area, resampled it and conducted a self-potential survey. The writer mapped the main "copper clearing" with compass and alidade and discovered the oxide-bearing outcrops on the banks of the Lumwana River. He put down two long trenches which gave an immediate approximation of the structure and revealed over 1% copper in weathered rock, and started pitting for further structural information.

In November 1961, when the time came to site the first drill-hole, an overturned structure dipping to the west was suspected. This hole was collared in granite and drilled through quartz-mica schists, Lower Roan quartzites, Upper Roan dolomite, dolomitic schists, and was halted in gabbro. It intersected bornite and chalcopyrite mineralization in the schists between the granite and quartzite which averaged more than 1% copper over a true width of more than 50 feet.

The success of the first drill-hole warranted extensive exploration and a large pitting and drilling programme has been completed. The structure was found to have local complexities and geophysical surveys were conducted to assist in structural interpretation, as well as for direct search for ore.

As a detailed geological picture emerged an accurate topographical map was found to be necessary, and the prospect was mapped by plane-table with drill-holes and control points coordinated by theodolite.

Surface copper concentrations were found at several other localities in the central part of the Mombezhi Dome, and eventually this whole area was surveyed, sampled and traversed by geologists. Drilling and pitting were conducted at the more promising sites and all data has been compiled to produce the geological map of the Mombezhi Dome Area. (See Figs. 1 and 2 in Folder on back cover).

STRATIGRAPHIC COLUMN OF THE COPPERBELT

KATANGA SYSTEM

SERIES	GROUP	FORMATIONS
Kundelungu	Upper.	Shale, quartzite.
	Middle.	Shale, tillite.
	Lower.	Shale. Dolomite and limestone (Kakontwe). Tillite.
Mine	Mwashia.	Carbonaceous shale, argillite.
	Upper Roan.	Dolomite and argillite. Argillite and quartzite.
	Lower Roan.	Hangingwall quartzite. Ore-bearing argillite, impure dolomite, quartzite or graywacke. Footwall quartzite. Aeolian quartzite. Conglomerate.

UNCONFORMITY

MUVA SYSTEM	Quartzite, schist and conglomerate.

UNCONFORMITY

LUFUBU SYSTEM	Schist and gneiss.

GRANITE intrusive into the Lufubu System.

GABBRO intrusive into the Upper Roan, Mwashia and Lower Kundelungu.

(From Garlick, 1954, and Mendelsohn (Ed.) 1961).

TABLE 1

STRATIGRAPHIC CORRELATION

Correlation within the Katanga System.

The formations present at the Lumwana Prospect consist of Basement granite and schists, overlain by a conformable succession from oldest to youngest of copper-bearing schists, soft epidote and kyanite schists, quartzite, and dolomite and dolomitic schists intruded by gabbro. Elsewhere on the northern and eastern flanks of the Mombezhi Dome rocks higher in the succession are found to be carbonaceous shales, limestone, and finally schistose shales at the top of the succession in this area. These formations are regarded as part of the Katanga System and it is desirable to show how they are related to the established sequences in well-known areas.

The formations at the Copperbelt, originally classified by Gray (1930) who followed the nomenclature of the Belgian Geologists in Katanga, modified by Garlick (1954) and simplified in the "Geology of the Northern Rhodesian Copperbelt" (Mendelsohn Ed. 1961) are given in Table 1.

Hatfield (1937) in the Solwezi area gave local names to various groups of beds, but Mann (1955) in the same area, and Horscroft (1954) in the Sosa Hill area nearer the Copperbelt, used the nomenclature of Garlick. The Geological Survey of Northern Rhodesia uses a three-fold subdivision of the Katanga into Upper, Middle and Lower Groups, following Phillips (1956), but also finds the use of local names necessary even in fairly recent literature (e.g. Newton 1960). It is the opinion of the writer that local names should be used only in the preliminary description of an isolated area, as faulty correlation, which can be corrected by later detailed work, is preferable to an abundance of confusing local names. As lithology and sequence of formations in the Mwinilunga Area and on the Copperbelt are sufficiently similar to permit broad correlation, the writer uses the nomenclature of the Copperbelt.

In the correlation of the Copperbelt succession with that in the Mwinilunga area, there are two horizons which occur with sufficient regularity to be regarded as markers. The first is the Lower Roan footwall quartzite which generally lies directly on pre-Katanga schists, gneisses and granite. It forms ridges around the domes which occur west of the Copperbelt, and has acted as a starting point for prospecting and geological mapping.

The ridge-forming quartzite is overlain by dolomites and dolomitic schists which together form the Upper Roan and Mwashia Groups. In the Mwinilunga area this part of the succession contains much more carbonate material than is generally the case on the Copperbelt. It includes lenticular carbonaceous shales which are not necessarily confined to the top of the Mwashia, and is the most common host-rock for emplacement of gabbroic bodies.

The schists of the Mwashia are overlain by a thick limestone which is regarded as the equivalent of the Kakontwe limestone of the Copperbelt, and is the second marker horizon. As a marker, however, it loses some of its value in that the tillite which is present at its base on the Coppbrbelt and in Katanga, is generally absent in the Mwinilunga area.

The succession above the limestone is the remainder of the Kundelungu Series of which little is known in the Mwinilunga Area, apart from the facts that the formations above the limestone are dominantly argillaceous and are apparently overlain by quartzites and basic lavas in the extreme northwest of Zambia.

At the Lumwana Prospect only the lower part of the Mine Series is present. The ridge-forming quartzite is conspicuous in outcrop on the flanks of the Mombezhi Dome and at outliers within the limits of the dome. This ridge-forming quartzite forms the basis for correlation and if it is the equivalent of the footwall quartzite of the Copperbelt, it would be expected that the cupriferous formation would occur directly above it as on the Copperbelt. This is not the case, the copper-bearing schists at the Lumwana Prospect occurring beneath the quartzite in close proximity to the granite, and doubt must be expressed as to whether the schists are in fact part of the

CORRELATION OF THE MINE SERIES

	KATANGA GENERAL	KALABA KABOMPO DOME	LUMWANA MOMBEZHI DOME	SOLWEZI SOLWEZI DOME	COPPERBELT GENERAL
MWASHIA	*Carbonaceous Shale* *Dolomite* *Sandstones & Dolomites* *R.G.S.* 1,600'	*Schists & Lenticular Carbonaceous Shales* 350'		? ↑ *Garnet schists* *Dolomites & Lenticular Carbonaceous Shales* ● *Dolomites & Dolomitic Schists* > 4,000'	*Carbonaceous Shale* *Argillite* 300 - 2,000'
UPPER ROAN	*Dolomite* *Carbonaceous Shales & Dolomites* *Dolomitic Shales* ● *Cherts & Oolites* *Dolomites* ● 800'	*Magnesite* ● *Dolomitic Limestone* 0 - 200'	*Dolomites & Dolomitic Schists* > 350'		*Dolomite & Argillite* *Argillite & Quartzite* 1,100 - 2,700'
LOWER ROAN	*R.A.T. (talcose)* *Dolomitic Sandstones* *Sandstones* *Arkoses* ↓ ? > 600'	*Soapstone* *Specularitic Quartzites* *Conglomerate* 500 - 3000'	*Talc Schist* *Specularitic Quartzite* 70 - 350' *Kyanite-Epidote Schist* 30 - 50' *Quartz-biotite Schist* ● 80 - 400'	*Talc Schist* *Specularitic Quartzite* *Kyanite-quartz Schist* ± 1,000' *Quartz-amphibole Schist* ● 0 - ?'	*Quartzite* *Argillite, dolomite, or greywacke* ● *Quartzite* *Aeolian quartzite* *Conglomerate* 700 - 2,000'
BASEMENT		*Schists* *Granite*	*Feldspathic Schists* *Granite*	*Schists* *Granite*	*Quartzite & Schist* *Granite*
● ORE HORIZONS	AFTER DEMESMAEKER (ET AL.) 1962	MCGREGOR 1960			AFTER MENDELSOHN 1961

TABLE 2.

Katanga (Mine Series), or an older series or system, particularly as they contain basic and ultrabasic intrusive material.

The writer includes the copper-bearing schists of the Lumwana Prospect in the Lower Roan Group for the following reasons:

(1) The Mine Series is so called because of the characteristic presence of copper-bearing formations, and the presence of copper minerals in these schists suggests inclusion in the Lower Roan part of the Series.

(2) There is apparently no unconformity between the schists and the overlying quartzite.

(3) The schists have not been found to be intruded by granite.

(4) Recent work on the Solwezi Dome has revealed a cupriferous formation stratigraphically comparable to that on the Mombezhi Dome (See Table 2).

The Stratigraphic Column on the Mombezhi Dome may be summarized as follows:

System	Series	Group	Formations
Katanga	Kundelungu	(Upper	Dominantly arenaceous).
		Middle	Dominantly argillaceous.
		Lower	Limestone. (Tillite).
	Mine	Mwashia and Upper Roan	Dolomitic schists and dolomites.
		Lower Roan	Quartzite. Kyanite-epidote schists ("softschists"). Copper-bearing schists.
		UNCONFORMITY	
Basement	Granite gneisses and feldspathic schists.		

Gabbro intrusives show preferred emplacement in post-Lower Roan formations.

Basic and ultrabasic intrusives and possibly extrusives in the copper-bearing schists.

CORRELATION TABLE

	Zambia	Southern Rhodesia	South Africa & South-West Africa
Recent.	Alluvium and laterite.		
Tertiary.	Kalahari Sands.		
Cretaceous.		Sandstones etc.	
Jurassic. Triassic. Permian.	Karroo.	**Karroo**	**Karroo**
Palaeozoic to Late Pre-cambrian.	Katanga. (Upper strata).	Sijarira.	Waterberg and Loskop.
Late Pre-cambrian.	Katanga.	Umkondo. Piriwiri. Lomagundi. Deweras.	Damara (Otavi).
Middle Pre-cambrian.	Muva.	Frontier. Gairezi.	Transvaal. Ventersdorp. Witwatersrand.
Early Pre-cambrian.	Lufubu.	Shamvaian. Bulawayan. Sabakwian.	Swaziland. Moodies. Gariep. Kheiss etc.

TABLE 3

The Katanga and Other Systems.

Correlation of formations in Zambia with those in Southern Rhodesia and South Africa has been attempted by various writers, but there is still scarcely enough evidence to warrant more than a tentative correlation over much of the succession. Most of the formations are unfossiliferous and have only the most general of marker horizons, and as yet only a limited number of absolute ages of particular formations have been determined. The most probable broad correlation is given in Table 3, which is based on the correlations used by the Geological Survey of Southern Rhodesia on their map of 1961, but has been modified as outlined in the following paragraphs.

The formations in the lower part of the Katanga System have ages of approximately 630 million years. This figure has been reached by eighteen age determinations of the Shinkolobwe pitchblende and is referred to as the "Katangan Cycle" by Holmes and Cahen (1955). Within this cycle fall determinations of Nkana pitchblende of about 580 million years, 500±100 million years (quoted by Holmes and Cahen), 522±15 million years (Darnley et al., 1961), and also that of 520 million years for uraninite at Mindola determined by Bowie (1960), while brannerite from Kansanshi has been dated at 503±15 million years (Darnley et al., 1961). Further south, two specimens of lead from Broken Hill gave an average of 660 million years, and radioactive tantalocolumbite from the Lomagundi north of Miami in Southern Rhodesia, has an adopted age of 615 million years. In South-West Africa galena from Tsumeb has an age of about 540 million years, while a number of determinations on lepidolites and uraninites from various localities range from 640 to 850 million years. (Ages quoted by Holmes and Cahen).

Holmes and Cahen have no hesitation in correlating the Lomagundi and Damara Systems with the Katanga on the basis of these determinations, and the presence of basic and ultrabasic igneous rocks in the lower part of the Katanga System at Lumwana suggests a correlation with the Deweras lavas at the base of the Lomagundi. The correlation of the Lomagundi and Katanga follows Macgregor's views of 1951, and the Damara-Katanga correlation is supported by Clifford (1962), and Nicolaysen (1962).

There has never been much basis for correlation of the Katanga with the Transvaal System, but Macgregor (1955) suggests correlation of the Lomagundi with the Transvaal, and Smit (1962) puts forward a similar correlation for the Damara (Otavi) and the Transvaal Systems. These correlations are impossible if the age of 1950±50 million years for the intrusion of the Bushveld Igneous Complex into the Transvaal is to be accepted (Nicolaysen et al. 1958).

To sum up, there seems to be little doubt that correlation is valid between the Katanga, Damara and Lomagundi Systems, and that they are all post-Transvaal. It is probable that with further age determinations, a correlation may be found between the upper strata of the Katanga and the Waterberg or Loskop Systems, and that the Piriwiri (regarded as pre-Lomagundi by Stagman 1959 and Wiles, 1961), will be found equivalent to the Mwashia which it resembles lithologically.

Note. Since writing I have been informed that the Muva System is dated at 1,400 - 1,000 million years and is therefore younger than the Transvaal, Ventersdorp and Witwatersrand Systems, and also probably younger than the Waterberg System which is older than 1,500 million years. The tentative correlation of the Zambian and South African Systems in Table 3 is therefore obsolete.

GEOMORPHOLOGY

The geomorphology of the Mombezhi Dome is representative of much of Zambia and analogies may be drawn equally well with the Lusaka area or the Copperbelt.

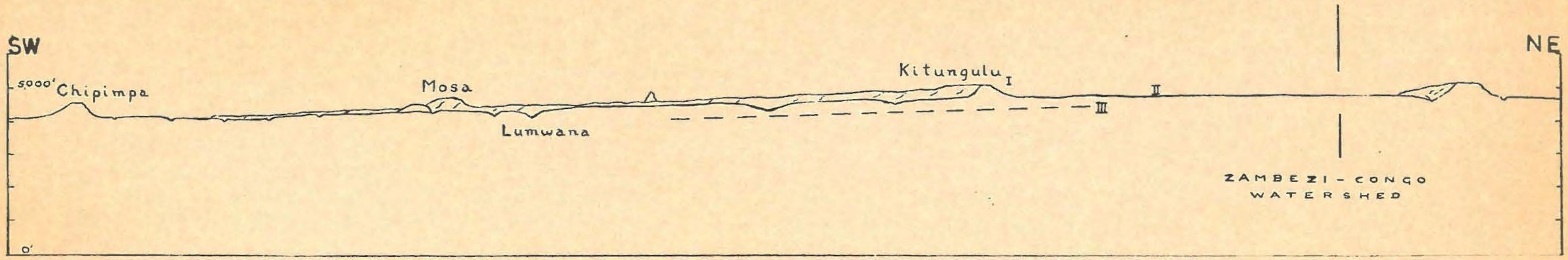
Dixey (1955) describes the Lusaka area as having an easily identifiable Miocene (mid-Tertiary) surface at an altitude of 4,200 feet, and a late-Cretaceous surface recognizable as numerous larger and smaller residuals standing up to a few hundred feet above it. In the broader valleys and depressions the end-Tertiary group of surfaces are recognizable.

Garlick in "The Geology of the Northern Rhodesian Copperbelt" (Ed. F. Mendelsohn 1961) gives the elevations of three land surfaces as follows:-

Late-Tertiary	4,000 feet
African or Mid-Tertiary	4,200 feet
Gondwana or Late-Cretaceous	4,500 feet

Although levels may differ, the topography west of the Copperbelt as far as, and beyond the Mombezhi Dome is of such similar type to that on the Copperbelt that correlation of land surfaces, without actually tracing the surfaces between different areas, is warranted. In Zambia both the mid-Tertiary and Cretaceous surfaces are considered by Dixey (1955) to have been subjected to warping, and the mid-Tertiary surface is also thought to be inclined toward the Kalahari to the southwest as a result of basin margin elevation along the Zambezi-Congo divide. He considered the elevation of this divide to date back probably at least to Jurassic times. King (1951) considers the Zambezi-Congo watershed to be relatively young and regards the African surface as being tilted to the south as a result of gentle deformation on an east-west axis.

In the vicinity of the Lumwana Prospect the most distinctive



I LATE-CRETACEOUS GONDWANA
II MID-TERTIARY AFRICAN SURFACE
III LATE-TERTIARY SURFACE

HORIZONTAL SCALE 1 INCH = 4 MILES (APPROX.)
VERTICAL SCALE 1 INCH = 4,000 FEET

FIGURE 3

feature is a surface partially cut by later erosion cycles with resultant development of gently rolling topography. This surface is well preserved on resistant formations which form ridges of concordant elevation and give rise to a monotonous skyline, broken only by the occasional steeply sloping inselberg. This surface has an elevation of 4,400 feet and although this is some 200 feet higher than at the Copperbelt or at Lusaka, the similarity of physical features suggests that it is the mid-Tertiary peneplain.

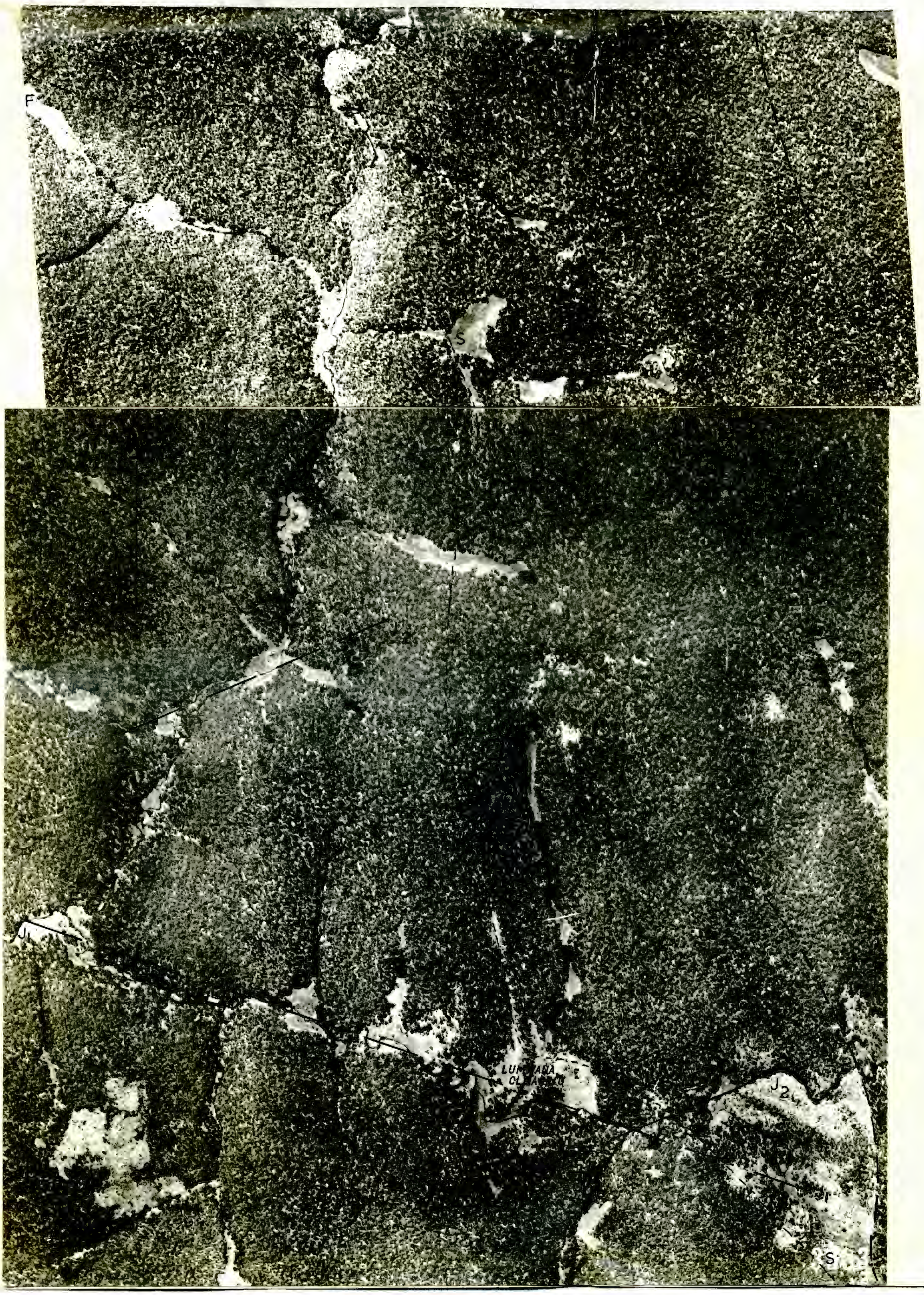
Little remains of the early Gondwana surface (Fig. 3) which is preserved some 350 feet higher than the African surface on bevelled inselbergs of resistant Lower Roan quartzite. These range from Kitungulu, a ridge on the northern flank of the dome fifteen miles northeast of the Lumwana Prospect, at an elevation of 5,159 feet, to Mosa Hill twelve miles west of the prospect at an elevation of 4,756 feet, and Chipimpa Hill fifteen miles southwest of the prospect at an elevation of 4,623 feet.

The late-Tertiary surface is not discernible within the Mombezhi Dome, but has developed at an altitude of 3,900 feet over the less-resistant Jiundu limestone northwest of the dome.

The northeastern lobe of the Mombezhi Dome forms a drainage basin from which the Lumwana River rises and flows southeast. The tributary streams in the basin rise close against the dividing ridge of resistant Lower Roan quartzite, and in general converge inwards from the dome boundary. Locally streams are known to follow the strike of infolded schists, and to be controlled by joint and fracture patterns in the underlying rocks. (See Plate 1:F-fault; J_1 and J_2 - joint directions; S- strike of mineralized beds with "copper clearings".)

Over formations younger than the Lower Roan quartzite dambos (grassy treeless areas with the water table at, or very near the surface) are best developed over the deeply weathered dolomites and limestones, and streams show a tendency to follow these beds. Despite local variations of drainage, the major streams all flow to the south


4
5
5

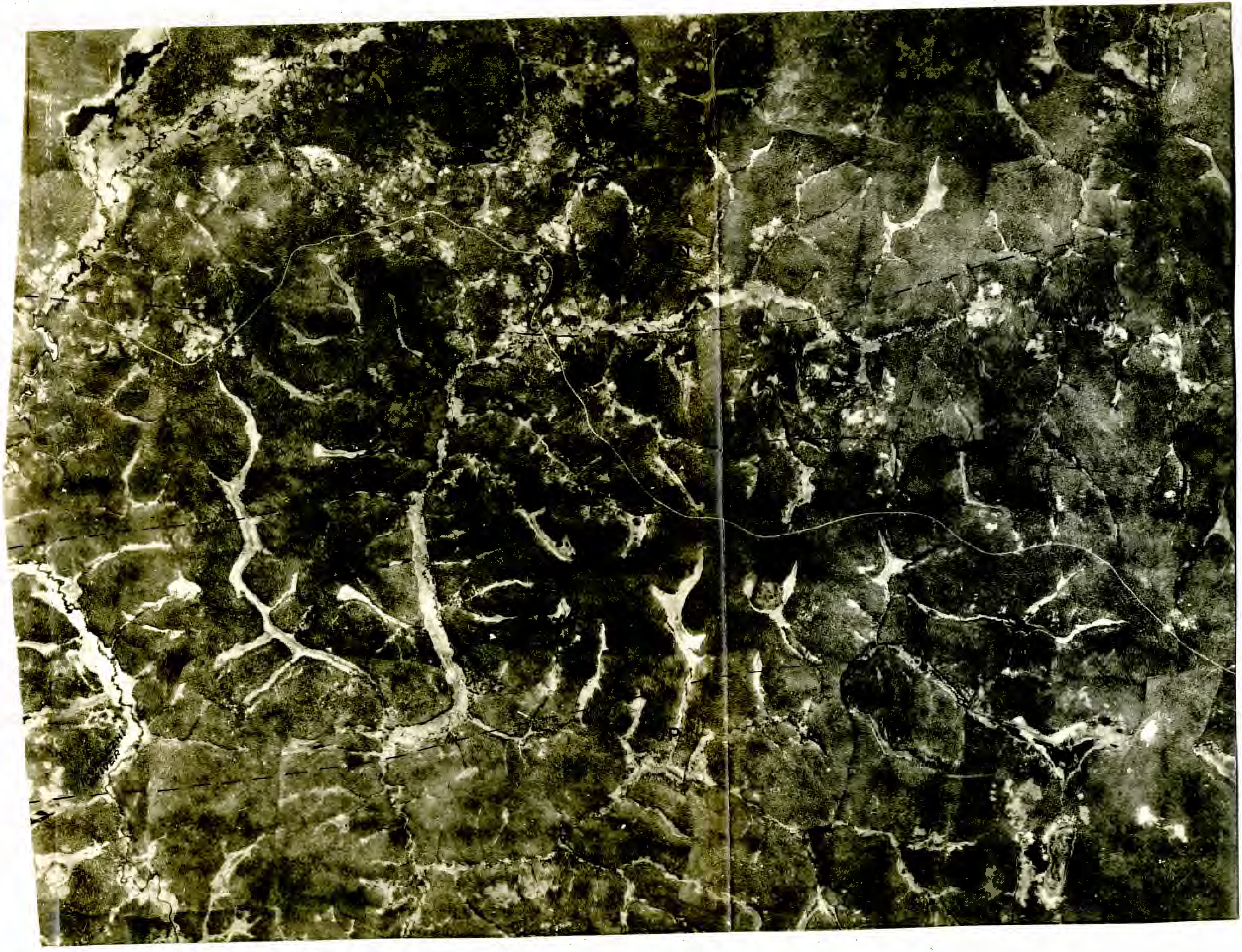

F
S
J1
LUMDANA
CLEARING
J2
S

or southwest, and are part of the Zambezi River system.

It is interesting to note that both Dixey (1955) and King (1951) draw attention to the gentle tilting of the African surface in a general southward direction from the Zambezi-Congo watershed. This fact is borne out by the drainage pattern superimposed on the African surface, but it is surprising that the altitude of this surface is the same at the Copperbelt and at Lusaka. The fact that the surface is 200 feet higher at the Lumwana Prospect than at Lusaka suggests confirmation of the southward tilt, while suggesting at the same time enigmatic eastward tilt toward the Copperbelt.

Tilting of the African surface of course means equal tilting of the earlier Gondwana surface. The elevations of the flat-topped inselbergs on the Mombezhi Dome indicate a very distinctive southward component of tilt of the Gondwana surface. This tilt is much more marked than that of the African surface and it is concluded that southward tilting of the Gondwana surface occurred before any later tilting of it and the African surface. This suggests that repeated tilting occurred in the same southward direction (or repeated elevation of the Zambezi-Congo watershed), and implies confirmation of the age of this watershed postulated by Dixey (1943).

There is evidence of warping of the African surface on the Mombezhi Dome but insufficient local data to support the following statement by Dixey (1955) concerning the late Cretaceous surface : "The late Cretaceous surface in Central Africa was subjected to much gentle warping with the result that it may actually occur below the succeeding Miocene surface (which) is also thrown into gentle folds on the lines of earlier movements". The warping of the African surface occurs on roughly east-west axes as can be seen in Figure 3. Stream incision is marked on the up-warps, in contrast to the development of dambos and meanders on the down-warps. A slight westward cant is also implied by the westward shift of both the Lumwana and Mombezhi Rivers where they enter the southern-most zone of



up-warping in Figure 3, a shift that apparently is not controlled by any structural feature in the underlying granitic rocks. Warping may explain the coincident elevations of the African surface at the Copperbelt and Lusaka, as Dixey (1955) quotes Cahen and Lepersonne (1955) as regarding the Lusaka 4,200 feet ridge as an up-warp.

Whereas the mid-Tertiary and late-Cretaceous surfaces are distinct and well developed on the Mombezhi Dome, the third major surface of Zambia, the late-Tertiary surface is absent. Its absence may be explained simply by the resistance to erosion of rocks within the dome relative to those surrounding it; recent doming however, may have occurred giving rise to rejuvenation of the late-Tertiary erosion cycle rendering it indistinguishable from subsequent cycles. Moreover, while the Cretaceous and mid-Tertiary surfaces are regarded by Dixey (1955) as true cyclic surfaces eroded with respect to sea-level as base, the late-Tertiary surface is simply the best development of a number of Tertiary and later surfaces which are mainly dependent on local bases, and correspond only approximately from one region to another.

The group of surfaces which includes the late-Tertiary one have resulted from a number of erosion cycles none of which has reached completion. Evidence for this is found in examination of stream and dambo profiles, typical examples of which can be found on the Mombezhi Dome. Characteristically a dambo is broad and concave in cross-section at the head, while down-stream it narrows and the valley sides become convex, and finally it terminates in a knick-point. Further down-stream a second or third dambo may develop and terminate in a knick-point as before.

Sheet-wash erosion today far exceeds stream-wash erosion even though much of Zambia has a thick vegetation cover, and it is likely that this relationship has been maintained during the more recent erosion cycles. These minor cycles, in the opinion of the writer have resulted in a number of pediplanes, and the topography in general may be regarded as having developed along the lines of King's "Pediplanation

Cycle" (1951). The pattern of these later cycles and the resultant surfaces is however further complicated by warping of the African surface, post-Kalahari faulting and possible doming of the Basement areas, so that local bases have developed and correlation of the late-Tertiary and later surfaces can be only approximate.

Since the main concern of the writer is the structure of the Lumwana Prospect, consideration of geomorphology may be regarded as a digression. This is true if only the academic aspects are considered, but of great importance is the conclusion that warping of the Cretaceous and mid-Tertiary surfaces has occurred. These warps may have sufficiently closely spaced axes and have sufficient amplitude to affect measurements of early structural elements, so that the direction of dip of a near horizontal formation or the plunge of a fold may be completely reversed. These warps have occurred, and though Cretaceous and Tertiary warps cannot be distinguished from each other, the writer, following Dixey (1955), has assumed that Tertiary warping has occurred on the lines of the older warps, and refers to them together in later chapters as "Fourth Folds".

GEOPHYSICS

In the search for ore in Zambia, geochemistry has so far proved itself to be a far more useful tool than geophysics, but it fails in the search for blind orebodies and in supplying structural information. This weakness of geochemistry may be overcome by drilling or by geophysics and as the former is the most expensive prospecting tool, the latter is used where possible.

The challenge to geophysics in Zambia is largely caused by the masking effect of the weathered zone of variable thickness over the various formations. This weathered zone is generally deep and as the strength of geophysical signals arising from a buried body is reduced rapidly with increase in depth of such a body, most geophysical methods have poor success on the Copperbelt of Zambia.

At the Lumwana Prospect the depth of the zone of weathering and oxidation of sulphides is considerably less than is usually encountered in Zambia, fresh sulphides having been found in drill-cores as little as forty feet beneath the surface, and therefore the application of geophysical methods has met with moderate success. The various methods used are discussed briefly in the following paragraphs.

1. Radiometric method

Minor amounts of uranium are associated with most of the Copperbelt orebodies (e.g. Nkana and Chibuluma) and also Kansanshi, and prospecting for uranium has been conducted in the hopes of finding uranium associated with copper mineralization. Starting in 1957, New Consolidated Goldfields, in collaboration with Rhodesian Selection Trust, surveyed the Mwinilunga area using a single-engined aeroplane equipped with a sensitive scintillation counter. A large number of anomalies were noted and ground checking as part of the normal reconnaissance technique, has resulted in the discovery of several uraniferous bodies, some of which have been accompanied by copper mineralization.

Anomalies in the aerial radiometric profiles occur both north and south of the Lumwana Prospect. Ground checking in 1961 showed only minor surface concentration of radio-active material, but in 1962 drill-holes on the southern and northern parts of the prospect intersected patchy disseminations and blobs of uraninite and yellow oxide.

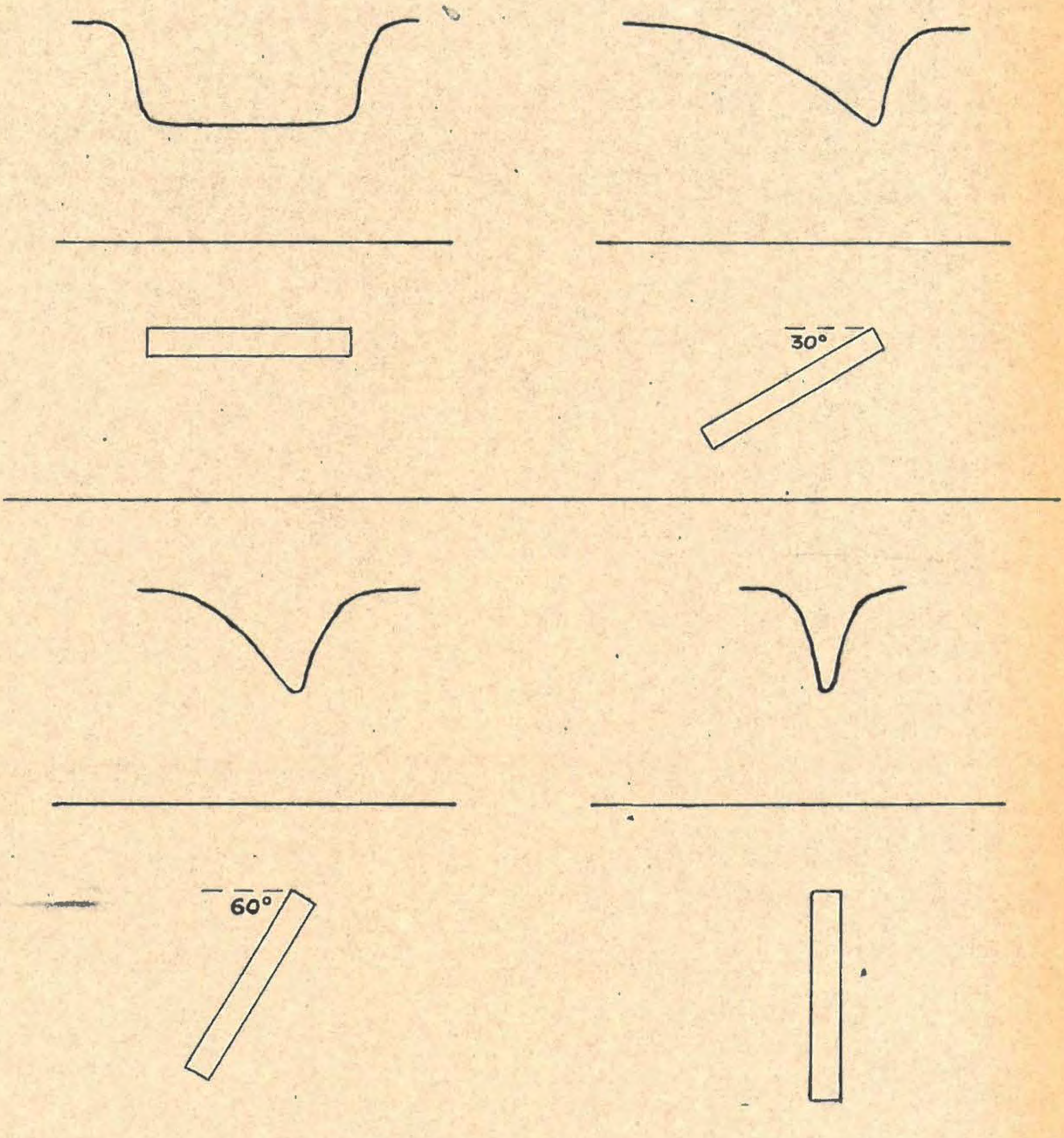
2. Self Potential method.

This method is applied by Rhodesian Selection Trust Mine Services Limited as a routine part of detailed exploration of any promising locality. It measures the electro-chemical activity generated from the upper oxidizing edge of a sulphide body, and at the Lumwana Prospect a negative anomaly was found to occur near the outcrop of the mineralized beds, agreeing remarkably with the geochemical picture. The anomaly is best developed over the central part of the mineralized beds, that is over chalcopyrite and bornite mineralization rather than over the parts with bornite and chalcocite mineralization.

3. Resistivity method

Geochemistry and the self potential method gave a clear picture of the position of the outcrop of the mineralized beds, and drilling and pitting confirmed early ideas of the structure. Drilling, however, showed up folds which are frequently not detected in pits due to the chevron pattern of folding in the noses of folds and the destruction of bedding planes by schitosity, and a resistivity survey was conducted to seek further information on the fold patterns.

The resistivity method has the advantage of measuring an actual property of the rock though only in apparent form, so that ideally a particular reading at surface indicates that a particular rock type occurs beneath the surface at that point, but it also has the disadvantage that there is often only slight resistivity contrast between different rock types. At the Lumwana Prospect, using units log $\frac{\text{ohm feet}}{2\pi}$ projected to equivalent "a" = 500 feet, granite has an apparent resistivity of 2.8 to 3.2, schist 1.8 to 2.2 and quartzite 2.6 to 3.0.



RESISTIVITY TYPE CURVES
BY EXPERIMENT
(AFTER HEILAND)

FIGURE 4

The calculation is based on "a" (the depth) as 500 feet, but in actual fact the survey reflects more closely the resistivity at the bottom of a variable depth of overburden. The survey was conducted along east-west lines in the northern part and north-south lines in the southeastern part of the Lumwana Prospect, at a line spacing of 500 and 1,000 feet.

The interpretation of resistivity follows four common methods, outlined by Heiland (1940) as follows:-

a) Qualitative methods.

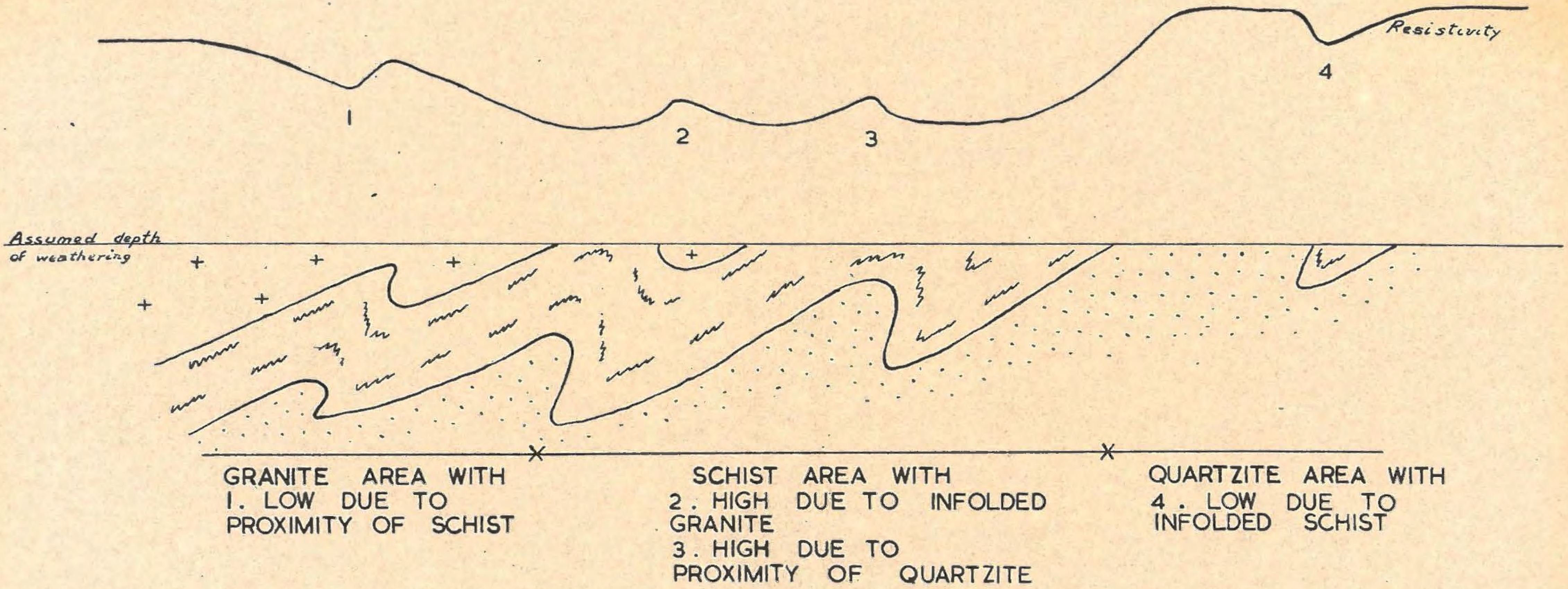
b) Quantitative methods. Analytical, direct methods of depth interpretation.

c) Quantitative methods. Interpretation by type curves. This method is based on the interpolation of theoretical curves and depends on the availability of tested and accurate field data as each area has its own particular types of curves.

d) Model experiments. These are made for checking the theoretical calculations and for simulating geological bodies whose effects cannot be calculated.

At the Lumwana Prospect the complexities of structure have precluded the use of models or mathematical quantitative methods, but the writer has attempted to use quantitative type curves in a general way, (see Figure 4) and has developed a rule of thumb method for qualitative determination. On the interpretation of resistivity by rule of thumb the writer is justified by Jakosky (1957) who says however, that it is not precise or scientific, but on the other hand the mathematical parameters cannot be evaluated with sufficient accuracy under normal field conditions to justify the assumptions necessary for a rigid mathematical basis of interpretation.

On completion of the survey, a contoured resistivity plan provided a broad picture of the distribution of the various rock types approximately at the depth of weathering. Furthermore the examination of the line profiles, combined with the known surface geology, enabled the compensating effects of the three layers upon each other to be assessed, and folds to be plotted from this information. The principle



RULE OF THUMB INTERPRETATION OF RESISTIVITY

FIGURE 5

of interpretation is shown in Figure 5.

The chief difficulty is the positioning of axial planes of asymmetrical folds, and the more asymmetrical the folds are, the more difficult the interpretation. Symmetrical folds plot directly beneath the resistivity peaks or lows, but the more inclined the axial plane of the fold, the further the trace of the axial plane from the resistivity high or low. This is caused by compensating effects of overfolding or underfolding, and is also a function of the depth of weathering. The shape of the profile indicates the dip of the beds; so where the folding is simple it is not difficult to determine the approximate shape of folds, the interpretation becoming increasingly difficult where folding is complex.

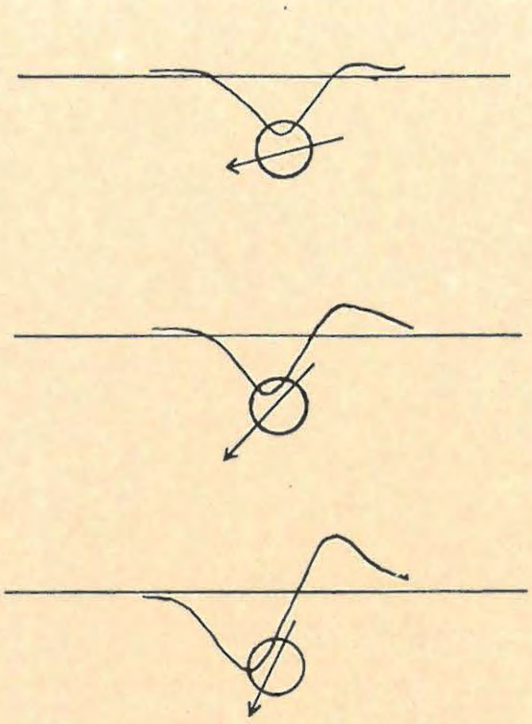
Despite the difficulties of interpretation, several folds found both in drill-holes and at surface lie at the theoretical position plotted from resistivity, and this has justified the assumption of position of other folds not yet checked by drilling.

4. Magnetic Method

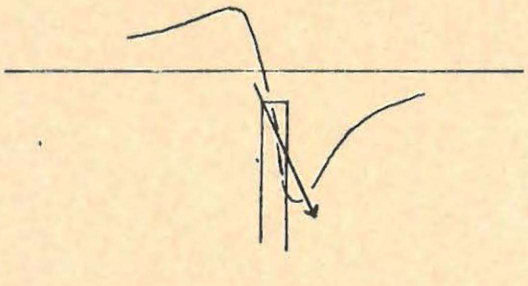
After completion of much of the drilling at the Lumwana Prospect the magnetic method was tested to attempt to obtain confirmation of general structure, and to assess the use of this method for structural correlation between Lumwana and other areas of economic potential on the Mombezhi Dome.

Although actually measuring the vertical component of the earth's field, the magnetic method may be said to measure magnetization of rock, a property which often varies considerably with different rock types. This physical property however differs from other physical properties in one fundamental respect; it is composed of two phases, (i) induced magnetism, which remains the same regardless of orientation, and (ii) remanent magnetism, which reverses its sign when the orientation is reversed.

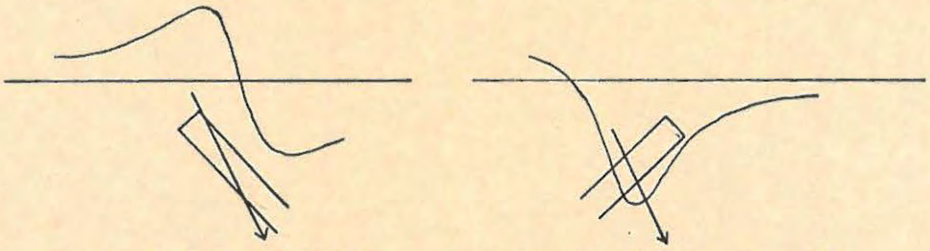
Like other physical properties magnetization is affected by the composition of the rock, especially magnetic content and acidity, but



EFFECTS OF MAGNETIC LATITUDE

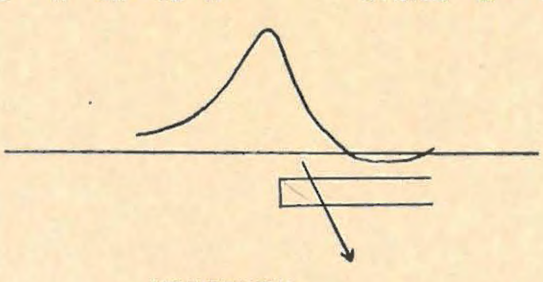


STRIKE E - W DIP VERTICAL



STRIKE E - W DIP 45° N

STRIKE E - W DIP 45° S



HORIZONTAL

EFFECTS OF DIP AND STRIKE
(AFTER HEILAND)

FIGURE 6

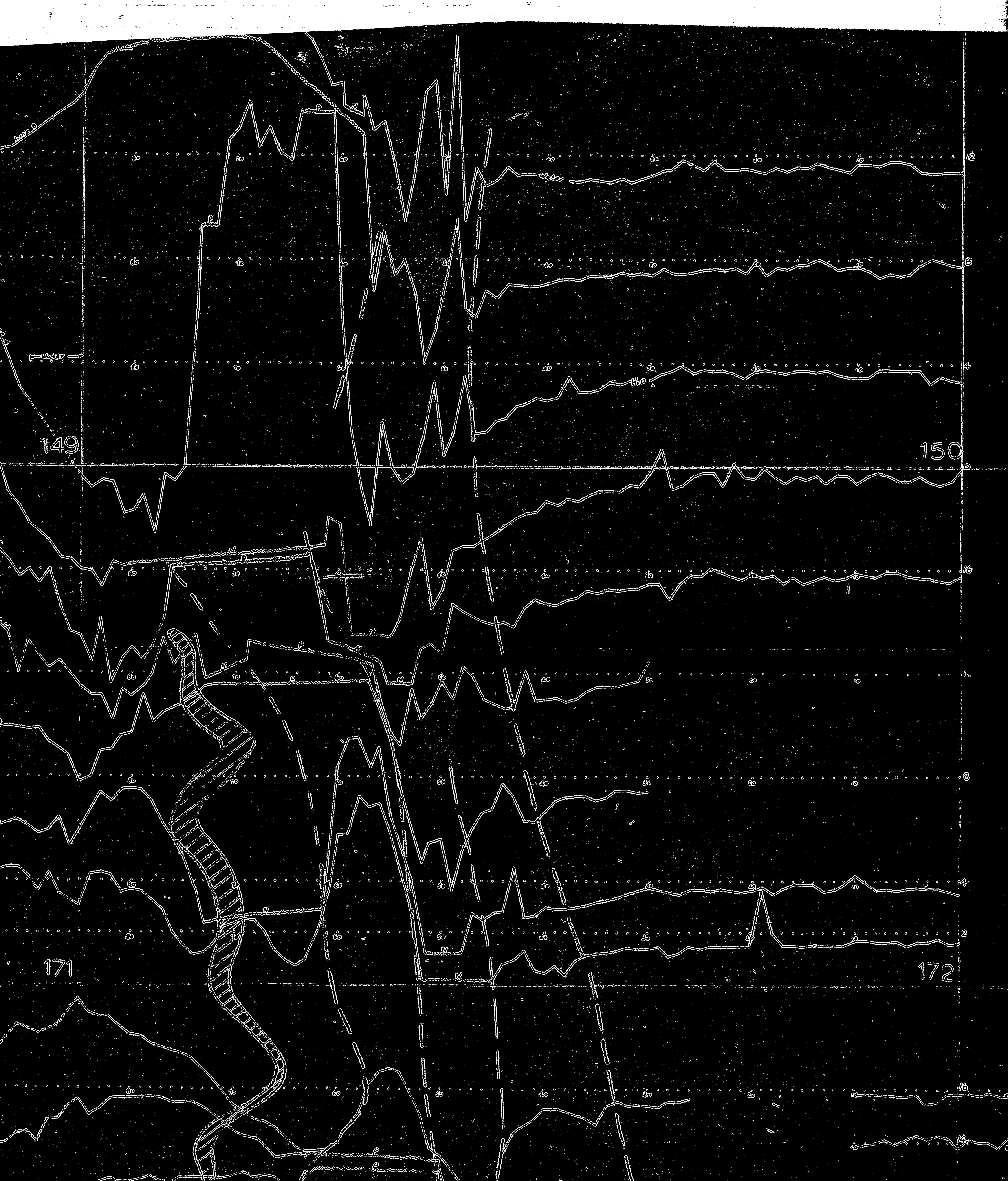
is also greatly affected by factors influencing the geological history, such as igneous intrusions, regional metamorphism, tectonic movements, mechanical and chemical concentrations, disintegration and finally lightning. In the course of geological history structural bodies may therefore gain or lose magnetism, their position may be changed, and if they have acquired remanent magnetism and been overfolded, apparent abnormal polarization may be produced (Heiland 1940).

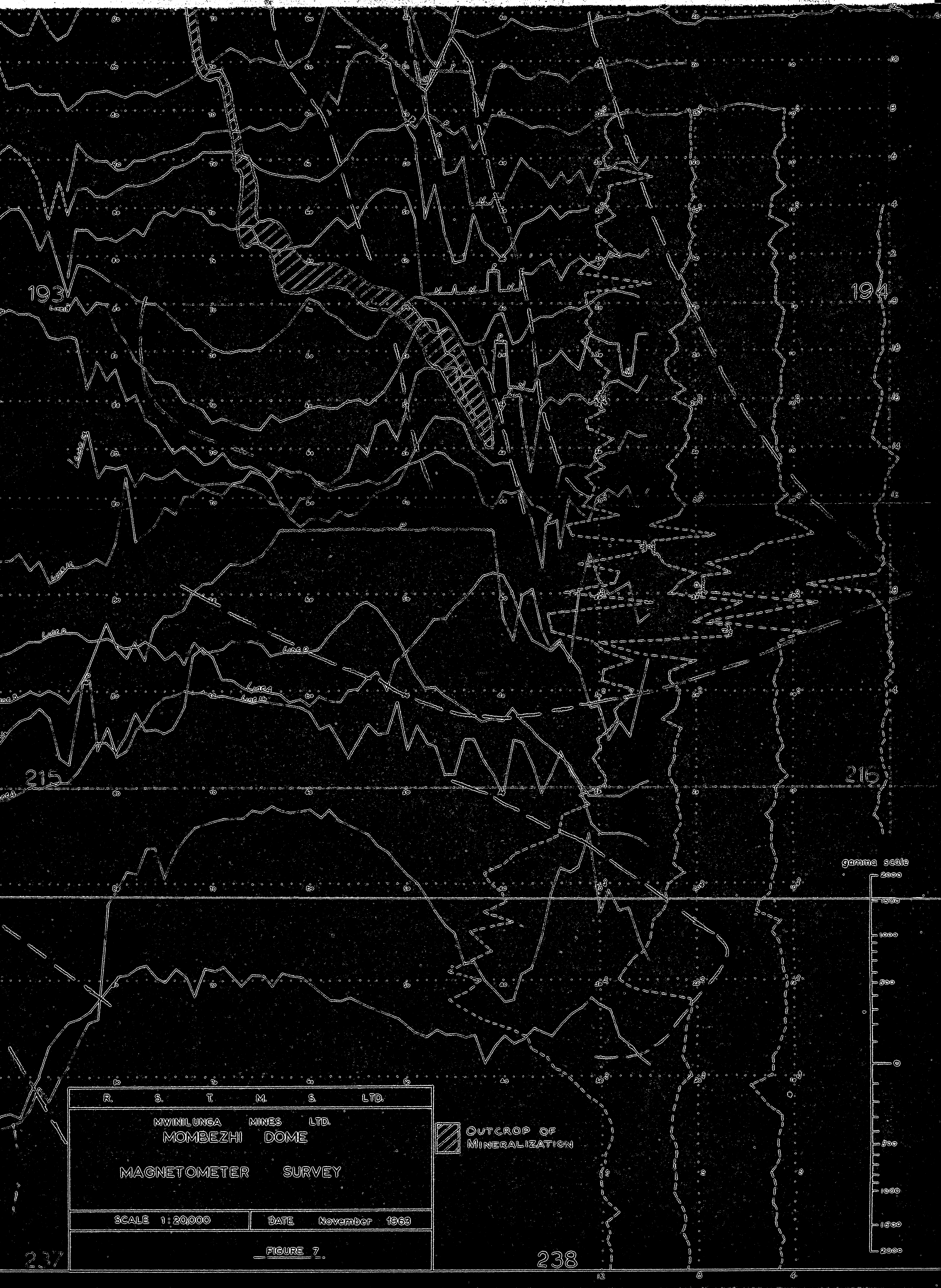
In addition to the factors causing variation in magnetization the intensity and sign of the measured magnetization are functions of the dip and strike and magnetic latitude (see Figure 6) as reinforcement or compensation may occur within the earth's magnetic field. Measurements are generally resolved into horizontal and vertical intensities and at the Lumwana Prospect measurements were confined to the former. Figure 6 illustrates the type of horizontal-intensity anomaly over magnetized bodies of various dips and strikes.

The magnetometer method is most useful in structural interpretation where the structure is fairly simple, such as the north-central parts of Figure 7. Here the magnetic profiles may be divided into a fairly flat uniform profile which may be correlated with granite and schists, an intense positive anomaly which apparently occurs mainly over the soft schist formation, and a jagged profile over the quartzite which includes both intense positive and negative anomalies.

In the northern and southern parts of the Lumwana Prospect strikes are less uniform than in the central part and the effect of the changes of strike is apparent in the change of character of the profiles over the various formations, and correlation from profile to profile is difficult. The map of smoothed magnetic profiles, (Figure 7) does show the general structure and has resulted in slight alterations to the structure interpreted from geological data only, but contacts may appear in slightly different positions due to the effect of dip and consequent proximity of adjacent formations.

The writer is not sufficiently experienced in geophysical interpretation to have gained all that could be gained from the magnetic


149
150
171
172
12
8
4
0
16
12
8
4
2
16
14
Water
H2O



▨ OUTCROP OF MINERALIZATION

R. S. T. M. S. LTD.

MWINILUNGA MINES LTD.
MOMBEZHI DOME

MAGNETOMETER SURVEY

SCALE 1:20,000

DATE November 1963

FIGURE 7

map, and future geological problems may be discovered which this method may help solve. Such a problem of correlation of geological and magnetic data occurs in the northern part of sheet 216 where magnetic trends cut across geological contacts, and there is apparent overlap of the mineralized schists onto the soft schist formation. No explanation of this is offered, but it is hoped that the solution will be found with future drilling.

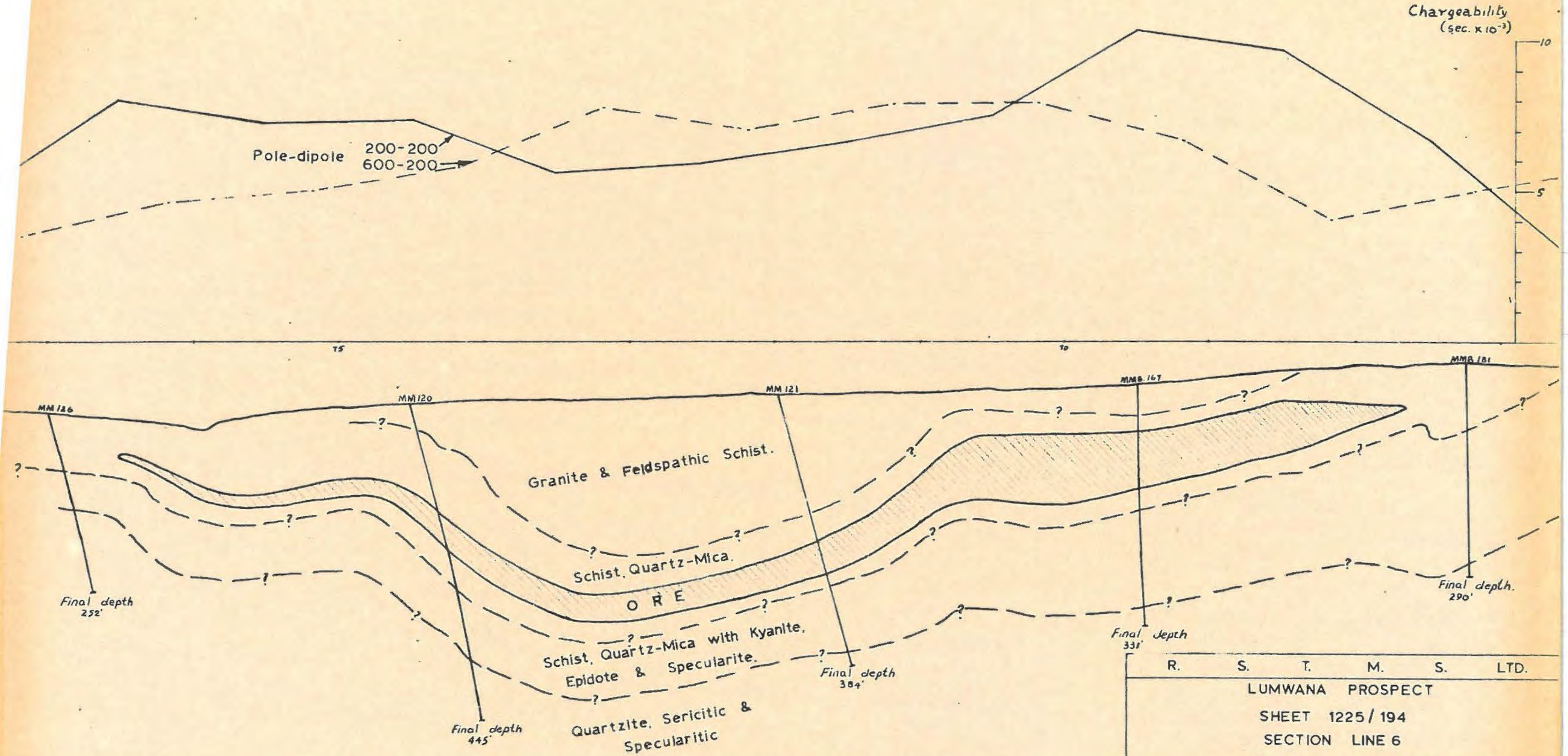
5. Induced Polarization Methods

Induced Polarization methods developed in the nineteen fifties were tested initially on the Copperbelt in 1959. Techniques were slowly improved and it was not until 1963 that R.S.T. Mine Services Limited encouraged contractors to conduct further tests in Zambia, using the Lumwana Prospect as one of the testing grounds.

Seigel (1962) has described the Induced Polarization methods simply as follows: Induced Polarization is measured in one of two ways. In the first a steady current of some secondsduration is passed and abruptly interrupted, and the slowly decaying transient voltages existing in the ground are measured after interruption. This is known as the "Time Domain" method of Induced Polarization. The second method entails a comparison of apparent resistivities using sinusoidal alternating current of two or more frequencies and is therefore called the "Frequency Variation" method.

In normal rocks the polarization effects are confined between fairly narrow limits and any large departures may be attributed to the presence of electronic conductors (sulphides, graphite etc.). Polarization effects due to non-metallic agents do occur and have been explained in part by certain clay minerals, while other spurious effects remain unexplained. Overburden causes masking due to the primary current being concentrated in the good-conducting overburden with little of it penetrating to the high resistivity bed rock, and polarization variations are caused by changes in thickness of overburden.

In order to measure I.P. effects one passes current through the



R.	S.	T.	M.	S.	LTD.

LUMWANA PROSPECT
SHEET 1225/194
SECTION LINE 6
INDUCED POLARIZATION
TIME DOMAIN METHOD

Scale 1: 2,000 | Date : January, 1964.

FIGURE 8

volume of rock by means of two electrodes and measures voltage across two other electrodes. Various electrode arrays can be selected to give adequate penetration down to the desired depth of exploration as each array has its own practical advantages in terms of both field procedures and penetration.

At the Lumwana Prospect the optimum array (200-200 feet in Fig. 8) was able to define the limits of the orebody. The degree of polarization in this array was directly proportional to grade x thickness of ore, and inversely proportional to the depth. With arrays of greater penetration the displacement of the greatest polarization effects was found to be in the down-dip direction.

From the results at the Lumwana Prospect it is concluded that I.P. methods are effective in the direct search for disseminated sulphide bodies, and in addition may be used to indicate depth and attitude of the mineralized formations.

STRUCTURE

INTRODUCTION

The Lumwana Prospect lies very close to the centre of the Lufilian Arc, and good exposures, combined with extensive diamond drilling have enabled a picture to be drawn of the local structures. These structures are significant in the understanding of the structural history of Zambia and Katanga, and these regional aspects are discussed after description of the local structures.

In literature on structural geology various writers often use the same terms in different senses, and thus most common terms have been variously defined. Other terms which at least have a common verbal usage, appear to be undefined. It is remarkable that such widely used terms as "fold axis" and "axial plane" have no standard simple definition. This deficiency in the literature is explained largely by improved understanding of the geometry of folds with time, which necessitates strict definition of terms which are used to describe this geometry, and also by a tendency for some writers to alter the usage of terms.

The early definitions of fold axis are typified by that given by Lahee (1931): "folds are bodies of three dimensions, that is, they have height, breadth and length ....The crest line of an anticline and trough of a syncline are called the axes of these folds respectively." Modern tendency is however to define the crest as the highest point of a fold (Hills, 1963), a point which need not lie on the axis, and Hills, perhaps as a result,does not succeed in finding suitable definitions of fold axis and axial plane.

The definition quoted from Lahee becomes somewhat clumsy when altered to comply with modern terminology but in the absence of anything more suitable is favoured by the writer, and may be stated as follows: considering that any fold has length, height and breadth, <u>the fold axis</u> is a line in a surface of a particular bed which traverses the length of the fold and contains the points where curvature is greatest in successive height-breadth sections across the fold.

In single folds the axis can be considered to be a straight line, which is bent only by subsequent folding or by resolution of the stresses causing folding such that yielding is inhomogeneous.

Having defined the axis for a particular folded plane (bedding plane) the best definition of the axial plane is found to be that given by Badgley (1959): the axial plane or surface is the surface containing the axes of successive folded bedding planes. Unlike the axis, the axial plane is commonly curved, curvature taking place about the axis, and the early definitions (e.g. Billings 1947) that the axial plane is the plane that divides the fold as symmetrically as possible,are inadequate.

In definition of plunge the writer follows Billings (1947) who states that the plunge of a fold is the angle between the axis and the horizontal.

Minor folds in the limbs of larger folds are often referred to loosely as "drag folds", sometimes without establishing the exact relationships between the larger and lesser folds. It is often important to confine the term drag fold to fit Rice's (1943) definition: drag folds are minor folds in the limbs of a major fold, having axial planes parallel or nearly parallel to the axial plane of the major fold, and are produced by the shearing stresses set up within the major fold by the relative movements of beds along bedding planes.

Other minor folds have been called "parasitic folds" by de Swardt (verbal communication) and in the absence of any other definition are defined by the writer as follows.

Parasitic folds are minor folds in the limbs of a major fold, having orientated axial planes and fold limbs similar to the major fold, and are produced by the same stresses as produced the major fold.

Students of structural geology are familiar with a number of terms used to describe various types of folds, but with the exception of those involving deformation by flow, folds are classified in modern usages as concentric or similar. The writer follows de Sitter (1956) in the usage of these terms which are broadly defined as follows.

Concentric folds ideally are folds in which successive bedding planes are folded about axes such that the bedding planes remain parallel, and there is no variation in thickness of each folded bed. The beds are elastically bent and the folds are produced by slip in planes parallel or nearly parallel to bedding planes. The folds do not persist in depth.

Similar folds are folds in which successive folded beds are similar, having become thickened in the crests and troughs, and thinned in the limbs. They are produced by slip in planes parallel or nearly parallel to the axial planes of the folds and flow may play a part in the mechanism of formation. The folds persist in depth.

In exploration geology involving diamond drilling, deepening and shallowing of inclined beds by folding is of economic importance, and folds causing deepening or shallowing require classification. The terms "S" and "Z folds" are used by Ramsay (1962a) for the differently orientated drag fold type of folds in opposite limbs of a larger fold, but different views of such folds result in reversal of appearance, and the principle can be applied with greater latitude by reference to the horizontal plane as follows.

Z folds are folds which result in a particular inclined bed being elevated towards the horizontal.

S folds are folds which result in a particular inclined bed being depressed away from the horizontal.

Fold elements include all data which can be obtained by field measurement of folded strata. (Hills 1963).

All directional structures are described with reference to three rectangular coordinates labelled a, b and c tectonic axes. It is standard practice to regard a as a direction of motion in the rock; thus it may coincide with a direction of compression or a direction of shearing (Hills, 1953). Since these directions are usually opposed, it is the practice in this thesis to use a for the direction of motion of shearing in similar folds, or for the equivalent direction of nascent shearing in concentric folds. The b axis is normal to the direction of motion lying in the plane of slip or nascent slip. Thus a and b lie in the axial plane of both similar and concentric folds. b is commonly orientated parallel to the fold axis, but not necessarily so, and the c axis is normal to the a-b plane, or axial plane of the folds.

In considering regional stresses consistency is maintained by using c for the direction of compression and a for the direction of increase of amplitude of any folds in the system. The a, b and c directions thus coincide respectively with the A, B and C axes of the strain ellipsoid.

In taking photographs it is the practice of the writer to place the hammer with shaft vertical and the point of the head pointing towards the north.

Folding and faulting of different ages have occurred on the Mombezhi Dome. As far as possible the ages of folding are considered in chronological order in this chapter, after description of primary structures. Faulting receives separate treatment after discussion of folds.

PRIMARY STRUCTURES

The formations at the Lumwana Prospect have been severely metamorphosed and bedding and other primary structures have for the most part become obscured by recrystallization and development of various schistosities. This destruction of primary structures occurred completely in all formations except the Lower Roan quartzite and the conglomerate which is sometimes present at the base of the mineralized schists.

The conglomerate at the base of the mineralized schists and pebbly lenses within the quartzite can be recognized as such by comparison with adjacent formations. The pebbles are recrystallized

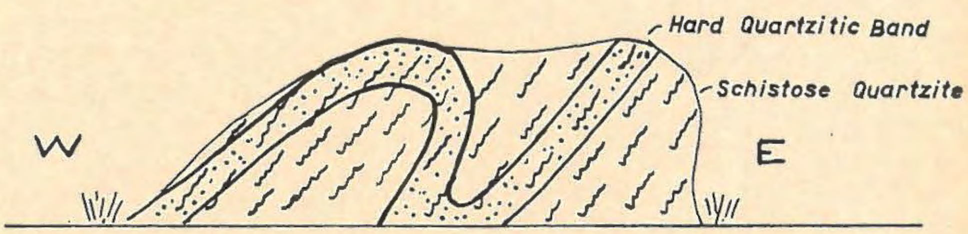


FIGURE 9a. Field sketch of fold in quartzite.

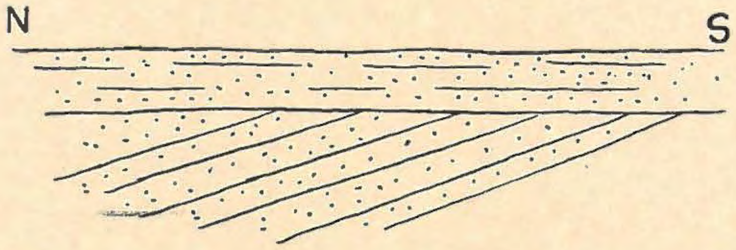


FIGURE 9b. Cross bedding.

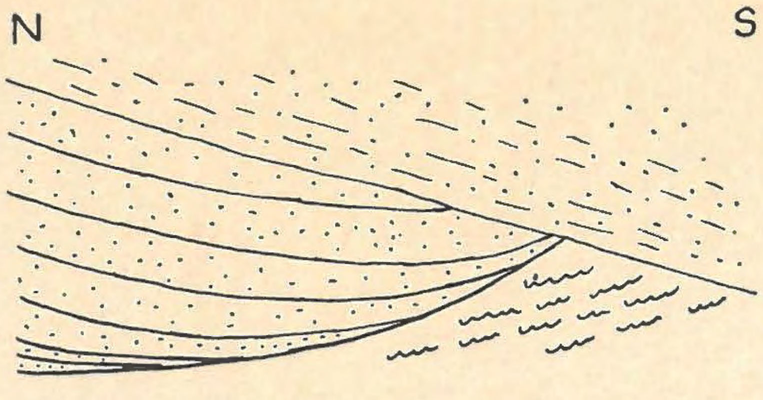


FIGURE 9c. Scour fill.

and elongated parallel to the main schistosity, but in some cases retain partial rounding. Recognizable pebbles are confined to those composed of quartz. Any pebbles that may have been granitic in composition no longer have distinct form, and there is frequently doubt as to whether feldspathic segregations are truly metamorphic in origin, or whether they were originally granite boulders or arkosic lenses.

The quartzite varies in content of quartz, micaceous minerals, and detrital minerals, and preservation of primary structures is largely dependent on the mica content. Fold characteristics may be observed in a bed rich in quartz and iron oxides while adjacent micaceous strata contain no trace of bedding, schistosity cutting across both rock types. It can be inferred therefore that bedding is preserved only in strata that have behaved competently relative to the other strata at the Lumwana Prospect, and it is in these strata only that other primary structures are likely to be preserved.

Cross-bedding was observed in a single outcrop of quartzite just north of the Lumwana River and was of the aqueous type. The bottom sets (?) were truncated at an angle of approximately 20° in one case (Figure 9b). In another the sets were seen to fill a scour hollow in schist with no visible bedding, to overlap southwards and to thicken to the north (Figure 9c). In drill-hole MMB 225 cross-bedding of the same type was observed and orientated cores permit the inference to be drawn that transport was from the south.

Bedding has not been identified in Upper Roan formations but in impure dolomitic rocks fine-grained crystalline quartz nodules are common, usually deformed parallel to the schistosity. These nodules are thought to be recrystallized chert concretions.

Other major structures in the Upper Roan Group are gypsiferous or anhydrite-rich seams, and in drill-hole MMB 226 a magnesite horizon. These beds are thought to have originated as evaporites and are likely to have played a major part in the location of shear and thrust planes in later deformation.

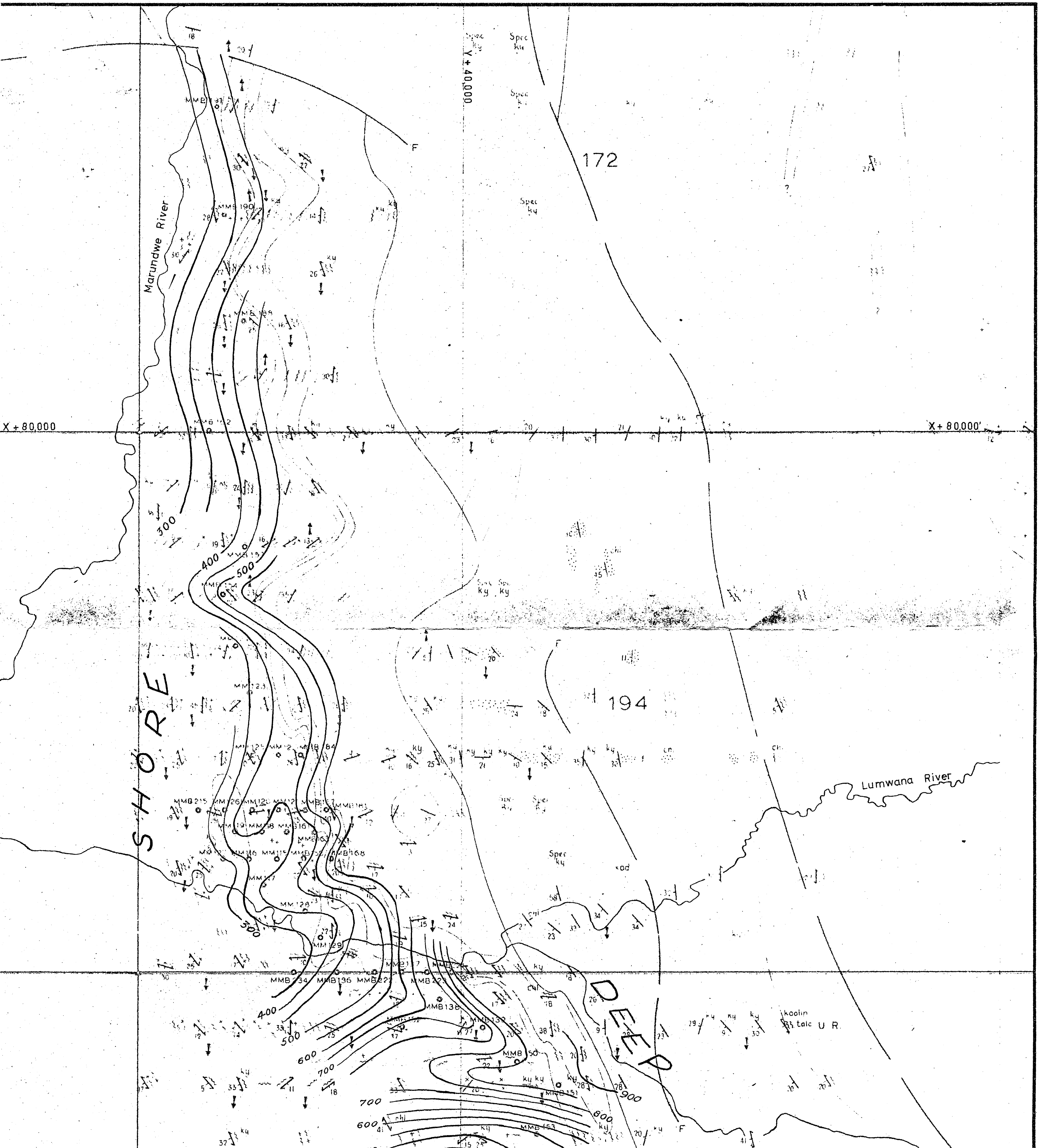
PRE-TECTONIC FOLDING.

The first folding at the Lumwana Prospect is certain to have been compaction folding during sedimentation, probably with local slump folding. Examples of slump folding have not been observed at Lumwana, but are common in similar formations at the Copperbelt mines such as Mufulira, and with the high relief of the pre-Roan landscape it is reasonable to postulate their presence elsewhere.

In Figure 10 twice the true thickness of the schist formations between the Basement unconformity and the quartzite contact has been contoured between the various drill-holes. The data are not sufficient to be able to propose that this is a true picture of the pre-Roan landscape, but if the basic assumption that the Lower Roan quartzite was deposited on a fairly flat surface is valid, then it is likely that the general contour pattern is similar to that of the pre-Roan landscape. The assumption is based on comparable thicknesses of the quartzite intersected in two drill-holes that have intersected the full thickness of this formation, and the consistent occurrence of argillo-calcareous schist beneath the quartzite. The main discrepancies are likely to be due to compaction folding.

From data presented by Krumbein and Sloss (1951) it has been calculated that muds are capable of compaction to less than a quarter of the original volume, and Garlick (1958) quotes the even more remarkable compaction ratio of 8:1. Pure sandstones on the other hand are unlikely to compact to much less than 90% of their original volume. The minimum true thickness of the schist encountered in drill-holes is 150 feet in MM127, and the maximum at least 440 feet in MMB151. If there was no compaction the difference indicates a relief of at least 290 feet, but for the purposes of Figure 10 a compaction ration of 2:1 has been assumed which gives a relief of at least 580 feet.

A further effect of compaction is the early formation of folds called compaction folds by Hills (1963). Such folds are formed by compaction of sediments deposited on an uneven surface with the result that domes are formed over hills and basins over valleys.


Y+40,000
X+80,000
X+80,000
Marundwe River
Lumwana River
SHORE
DEEP
172
194
F
F
F
300
400
500
600
700
800
900
300
400
500
600
700
MMB 190
MMB 189
MMB 192
MMB 123
MMB 215
MMB 134
MMB 136
MMB 138
MMB 130
MMB 151
MMB 153
MMB 129
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MMB 168
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chl
kod
kaolin
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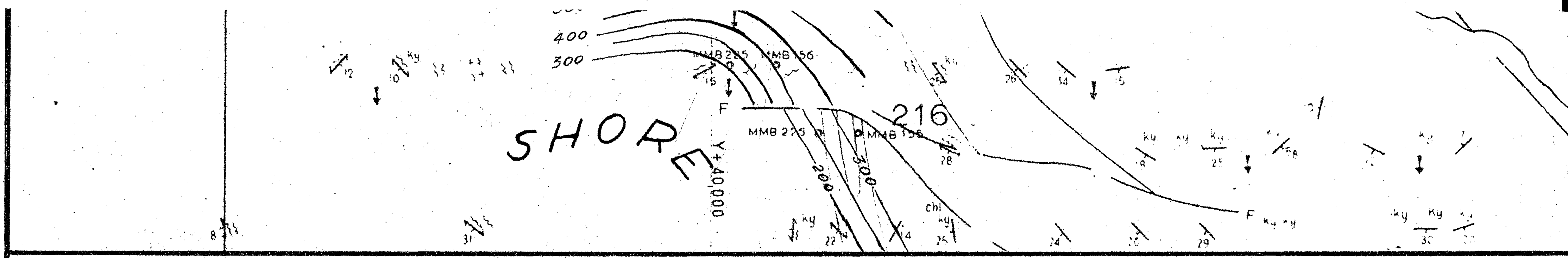

KEY TO GEOLOGICAL FORMATIONS

UPPER ROAN - MWASHIA		CARBONACEOUS PHYLLITE
	U.R.	DOLOMITE & DOLOMITIC SCHIST
LOWER ROAN		SERICITIC QUARTZITE
		SCHIST, INCLUDING MINERALIZED FORMATION
UNCONFORMITY		
BASEMENT		SCHIST
		GRANITE & GNEISS
		GABBRO (Intrusive into rocks younger than the quartzite)
		AMPHIBOLITE (Intrusives or Extrusives in rocks older than the quartzite)

Legend

Rivers & Streams
Drill-holes .... © MM 24
Field Sheets ....

215	216
237	238

GEOLOGICAL REFERENCE

GEOLOGICAL CONTACTS
FAULTS
DIP & STRIKE OF BEDS 71
DIP & STRIKE OF SCHISTOSITY 25
PLUNGE OF LINEATION

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MWINILUNGA MINES LTD.

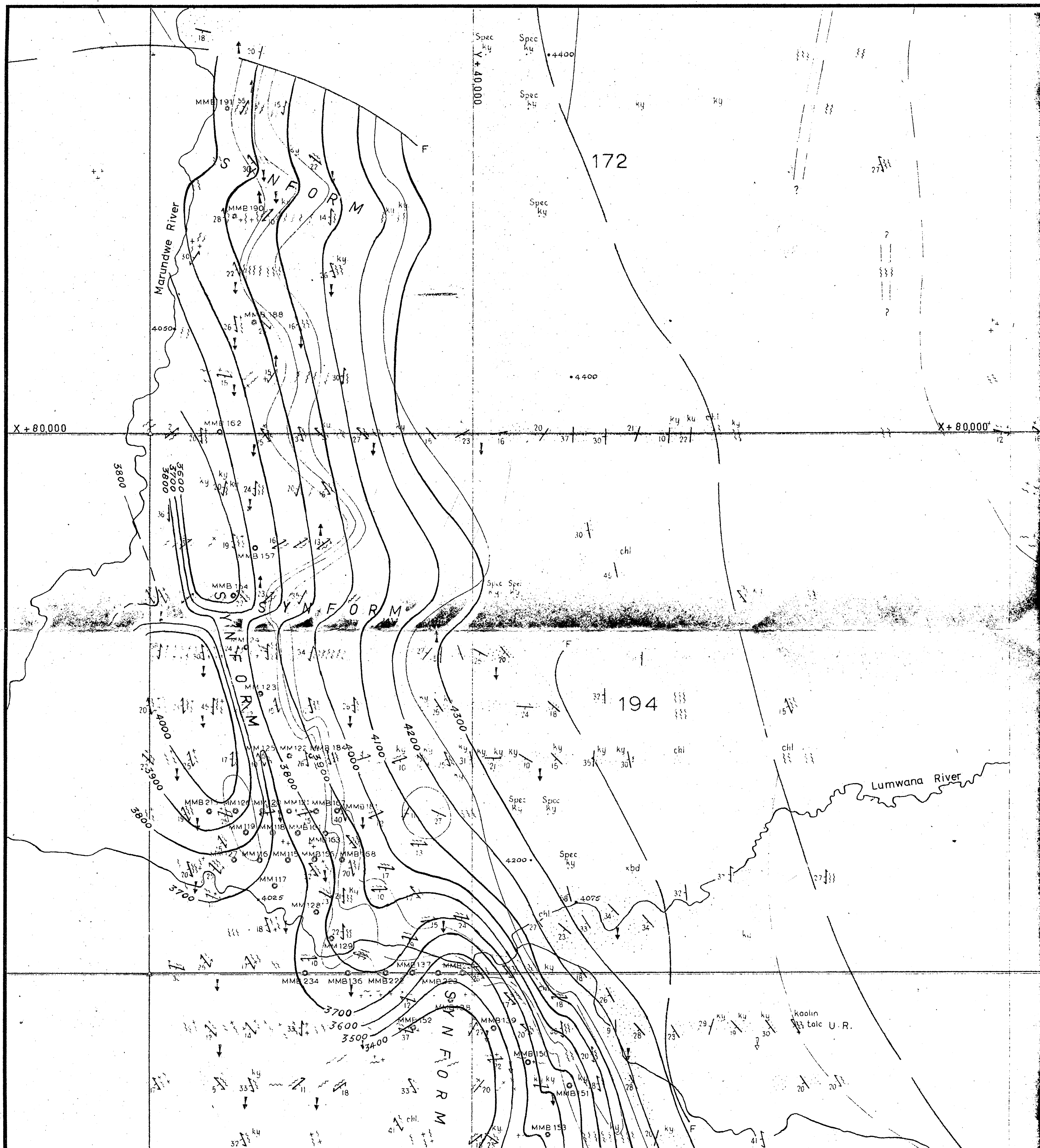
LUMWANA PROSPECT
PRE-ROAN TOPOGRAPHY

1000 0 2000 4000
Feet

SCALE 1/20,000

7 JULY 1964

FIGURE 10

Y + 40,000
X + 80,000
X + 80,000
172
194
SYNFORM
SYNFORM
SYNFORM
SYNFORM
SYNFORM
Marundwe River
Lumwana River
F
F
F
4400
4400
4050
4025
4075
4200
3600
3700
3800
3800
3900
4000
4100
4200
4300
3700
3600
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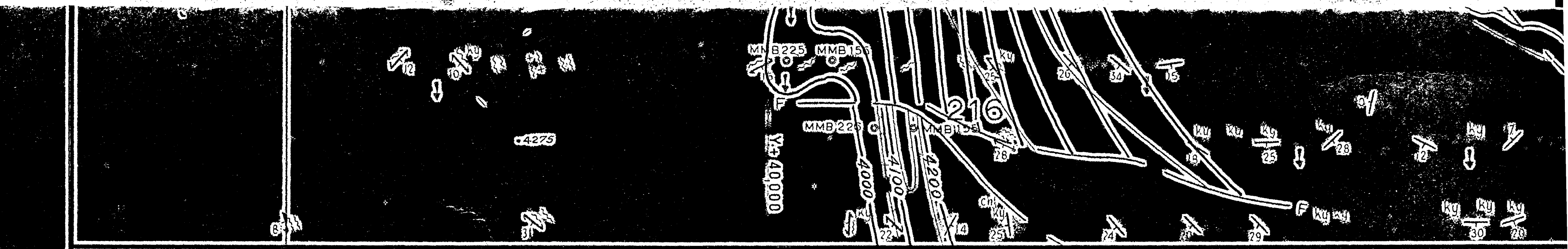
3700
MMB 191
MMB 190
MMB 188
MMB 162
MMB 157
MMB 154
MM 124
MMB 123
MM 125
MM 122
MMB 184
MMB 21
MM 126
MM 119
MM 118
MMB 161
MMB 163
MMB 168
MM 116
MM 115
MMB 155
MM 117
MM 128
MM 129
MMB 234
MMB 136
MMB 222
MMB 137
MMB 223
MMB 152
MMB 138
MMB 139
MMB 150
MMB 151
MMB 153
Spec ky
ky
chl
kaolin
talc
U.R.
xbd



KEY TO GEOLOGICAL FORMATIONS

UPPER ROAN -MWASHIA
- CARBONACEOUS PHYLLITE
- UR. DOLOMITE & DOLOMITIC SCHIST

LOWER ROAN
- SERICITIC QUARTZITE
- SCHIST, INCLUDING MINERALIZED FORMATION

UNCONFORMITY

BASEMENT
- SCHIST
- GRANITE & GNEISS

GABBRO (Intrusive into rocks younger than the quartzite)

AMPHIBOLITE (Intrusives or Extrusives in rocks older than the quartzite)

Legend

Rivers & Streams

Drill-holes ◎ MM 24

Field Sheets 215 216 237 238

GEOLOGICAL REFERENCE

GEOLOGICAL CONTACTS

FAULTS F

DIP & STRIKE OF BEDS 71

DIP & STRIKE OF SCHISTOSITY 25

PLUNGE OF LINEATION

SPOT HEIGHTS (LOCAL BASE) •4200

R. S. T. M. S. LTD.
MWINILUNGA MINES LTD.

LUMWANA PROSPEC

STRATUM CONTOURS, UPPER
QUARTZITE - SCHIST CONTAC

1000 0 2000 4
Feet

SCALE · 1/20,000

7 JULY 1964

FIGURE 11

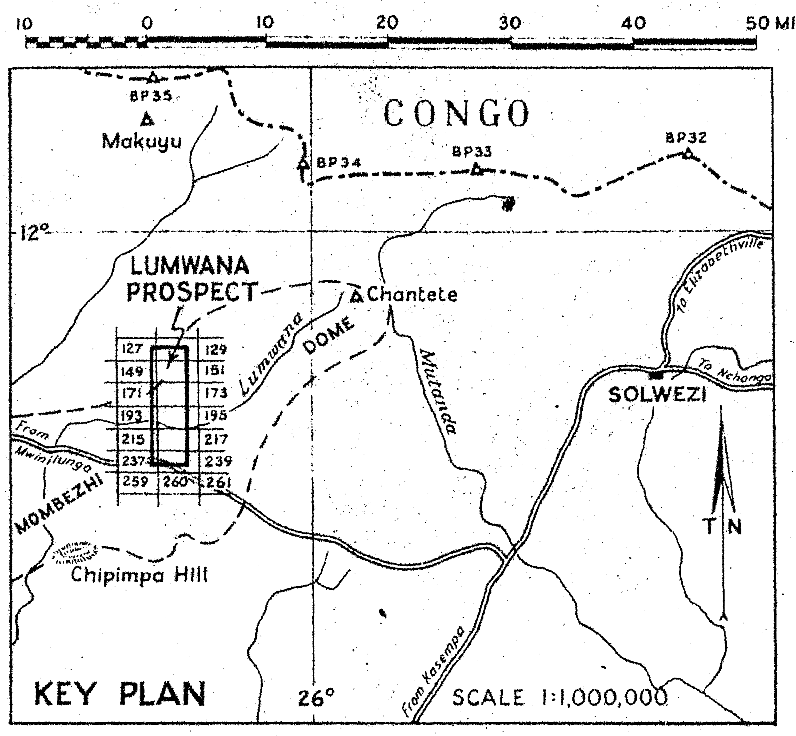
These folds are described as supratenuous by Hills because the formations are thinner at the crest of the arch than in the neighbouring troughs, and the folds die out gradually upwards. Compaction folds are not however always of this type as the higher ground is the site of shallow-water sandy sediments, while the lower ground is the site of deposition of more compactible argillaceous sediments. The result from subsequent differential compaction may be that the anticlines over hills actually have greater amplitude than the underlying hill profiles, and the folds will die out only where uniform sediments are deposited over both hills and valleys.

The effects of compaction folding in the first instance may be slight in that domes are found over hills and basins over valleys, with gentle dips in the limbsof the folds. With subsequent orogenesis, however, the topography and associated compaction folds may have far-reaching effects in location of tectonic folds early in the orogenic period. This effect is most noticeable in the comparison of Figures 10 and 11. The latter is a picture of the later fold patterns at the Lumwana Prospect based on stratum contours of the quartzite-mineralized schist contact. There is considerable parallelism between the general contour patterns of each case, and a tendency for the synclines to follow ancient valleys and anticlines to follow ridges.

It must be emphasized that the data are not sufficient to enable the writer to do more than draw attention to the probable implications of compaction folding at the Lumwana Prospect, and to illustrate the apparent pre-determination of the position of at least some of the orogenic folds by the topography prior to deposition of the now folded strata.

TECTONIC FOLDING.

The formations at the Lumwana Prospect have been folded intensely in at least three periods all of which probably are part of the same major orogeny. Folds pre-dating these three periods may be inferred from the regional geology but have not been demonstrated. Vertical move-


10 0 10 20 30 40 50 MILES
CONGO
BP35
Makuyu
BP34
BP33
BP32
12°
LUMWANA
PROSPECT
Chantete
Lumwana
DOME
Mutanda
To Elizabethville
To Nchonga
SOLWEZI
127
129
149
151
171
173
193
195
215
217
237
239
259
260
261
From Mwinilunga
MOMBEZHI
Chipimpa Hill
T N
KEY PLAN
26°
From Kasempa
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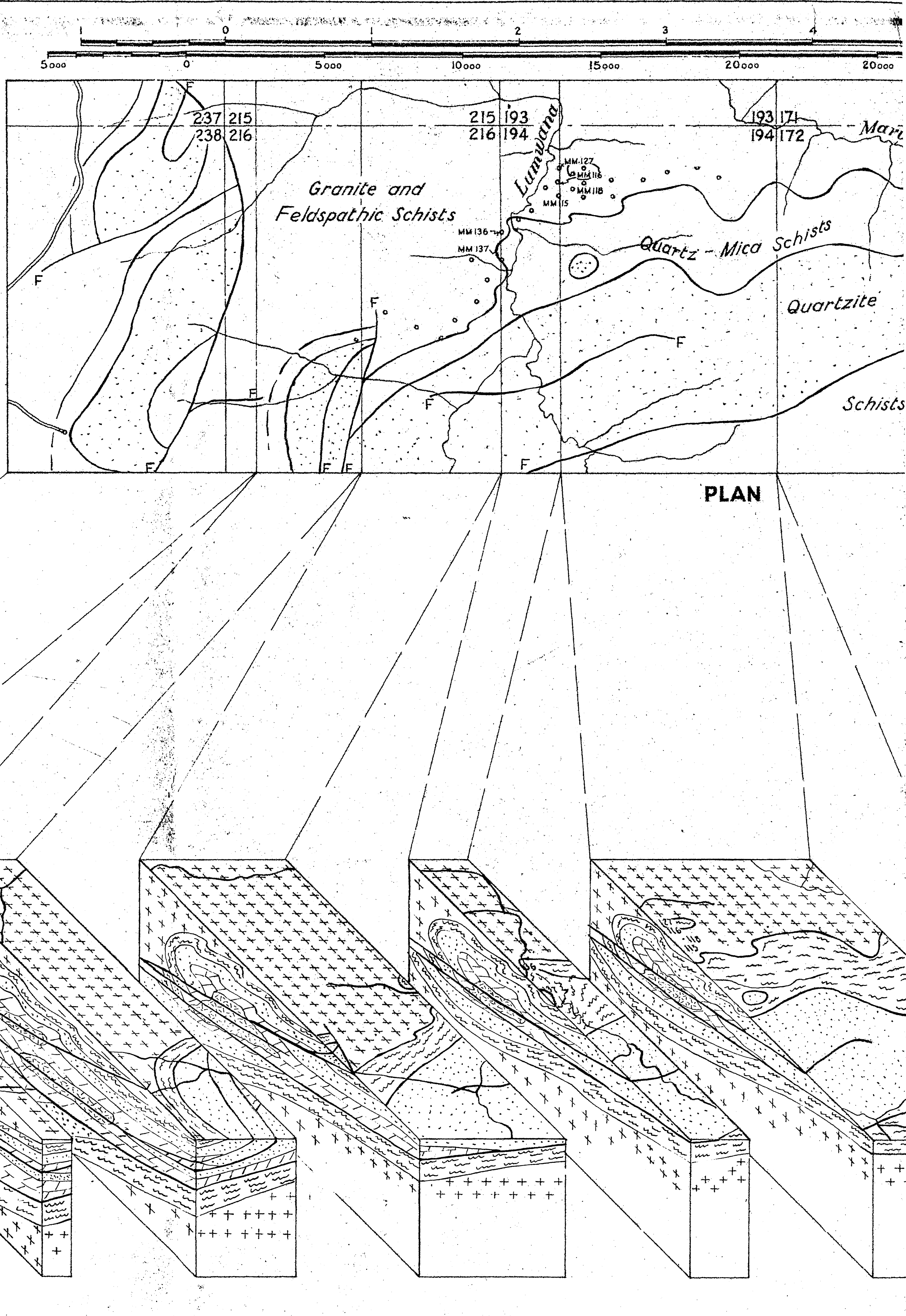

1 0 1 2 3 4
5000 0 5000 10000 15000 20000 20000
237 215
238 216
215 193
216 194
193 171
194 172
Lumwana
Mar
Granite and
Feldspathic Schists
MM 127
MM 116
MM 118
MM 15
MM 136
MM 137
Quartz - Mica Schists
Quartzite
Schists
F
PLAN
116
118
115

R. S. T. M. S. LTD.

MWINILUNGA MINES LTD.

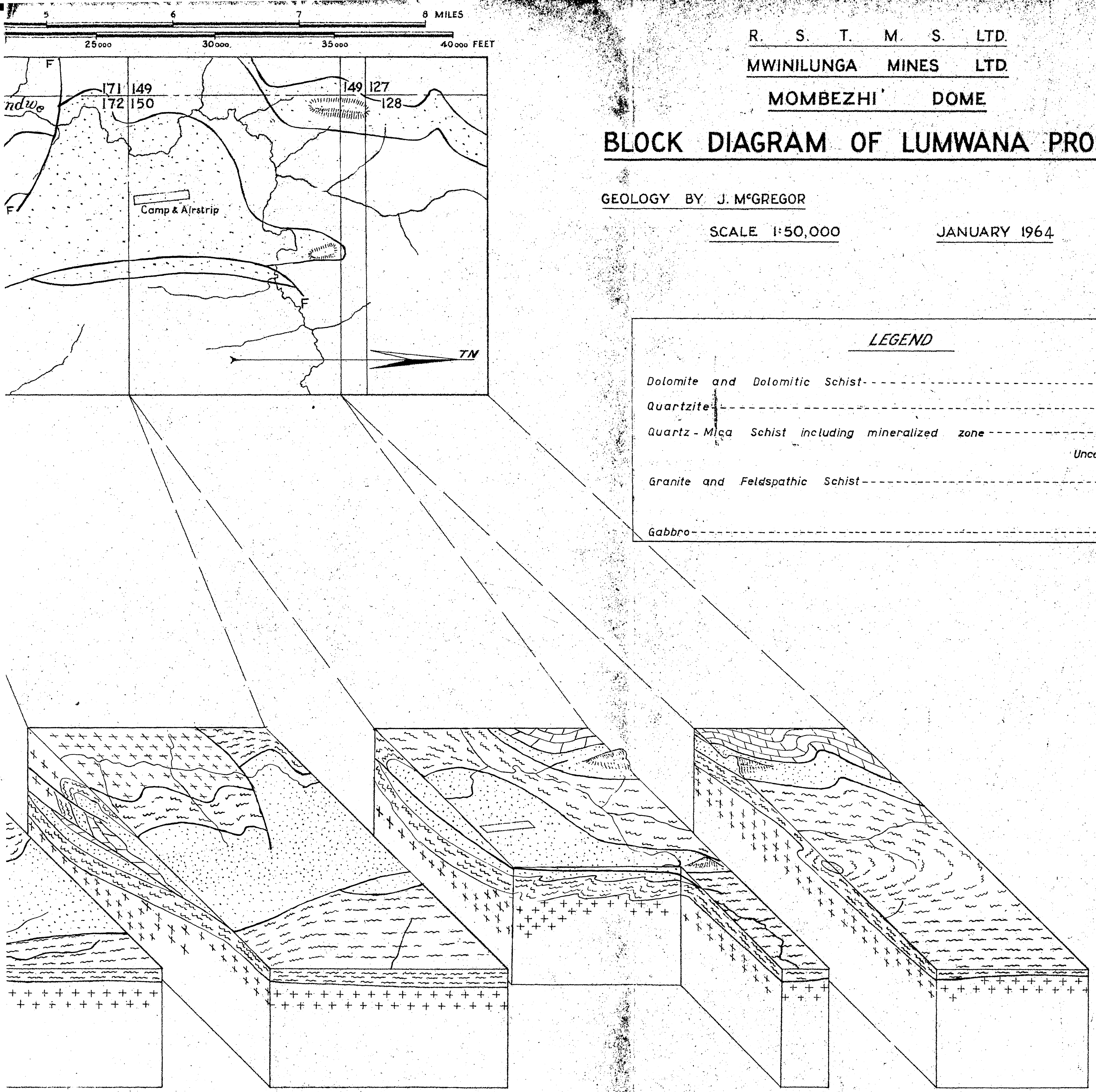
MOMBEZHI' DOME

BLOCK DIAGRAM OF LUMWANA PROSPECT

GEOLOGY BY J. McGREGOR

SCALE 1:50,000

JANUARY 1964



LEGEND

- *Dolomite and Dolomitic Schist* ▦
- *Quartzite* ⁘
- *Quartz - Mica Schist including mineralized zone* ≈
- *Unconformity*
- *Granite and Feldspathic Schist* + + +
- *Gabbro* ▨

ments have occurred and in more recent times the formations were subjected to gentle tilting and warping (Fourth period of folding.) The folds of the various periods have distinct form and when the problems of super-position are unravelled, the orientations of the fold elements are found to be arranged in an orderly fashion and are related to the larger scale features pertinent to the structure of Zambia as a whole. The four sets of folds are referred to in chronological order as first, second, third and fourth folds.

First Folds.

The sediments at the Lumwana Prospect which contain copper mineralization lie on the inverted limb of a great recumbent fold, explored by drilling for over four miles of strike, and extending for at least a further four miles, (see Figure 12). On this limb three sets of folds are superimposed. The upper normal limb of the fold has been faulted and eroded away, and is present only where the fold dies out north of the Lumwana Prospect. The lower normal limb has not been intersected in drill-holes, and its depth beneath the Lumwana Prospect is unknown.

The first folds have a highly developed axial-plane schistosity which frequently has completely obscured bedding, but which itself is folded by the later folding. Detection of the folds is generally difficult in drill-hole cores, but differential weathering of outcrops sometimes results in etching of the less-resistant iron-poor beds so that the form of the first folds can be seen and measurements made of the orientation of the fold elements. In drill-cores bands of light and dark material are assumed to represent the bedding and are folded and cut by two schistosities. The better developed schistosity is parallel to the axial plane of these folds, and the poorer schistosity is inclined across the folds and can be related to second folding.

The form of the first folds is nearly isoclinal and commonly chevron in pattern. This chevron pattern is partly due to compounding with later folds, and gives rise to patterns similar to those described by Ramsay

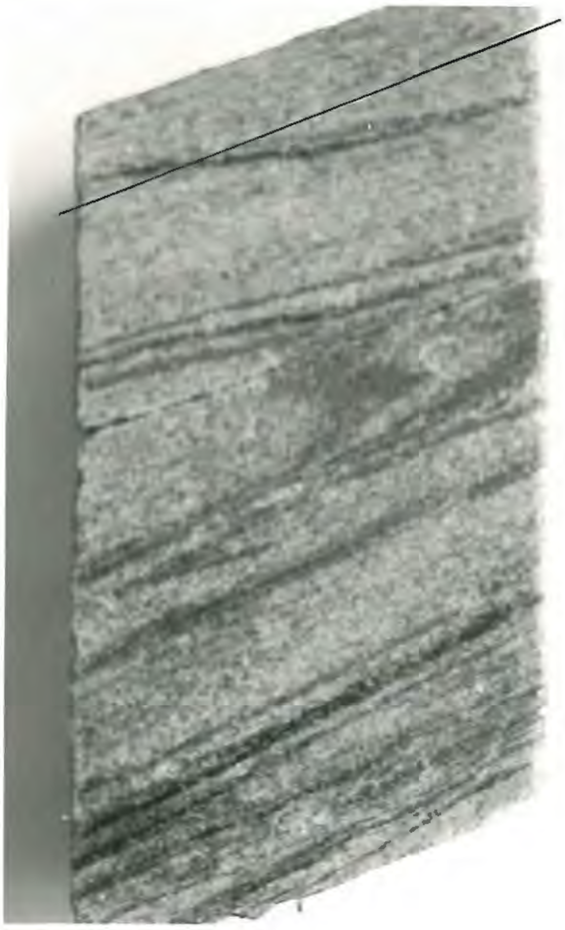


Plate 3. First fold, barely visible in Basement schist. Note well-developed axial plane cleavage cutting across upper limb. MM 121, 52'.

Plate 4. First fold in Lower Roan quartzite. Chevron type with nearly horizontal axial plane.

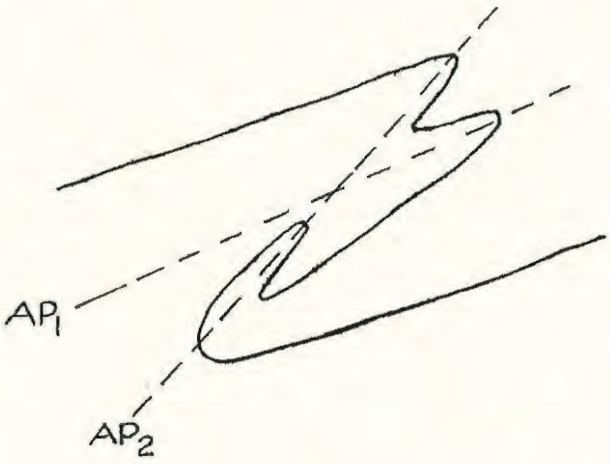
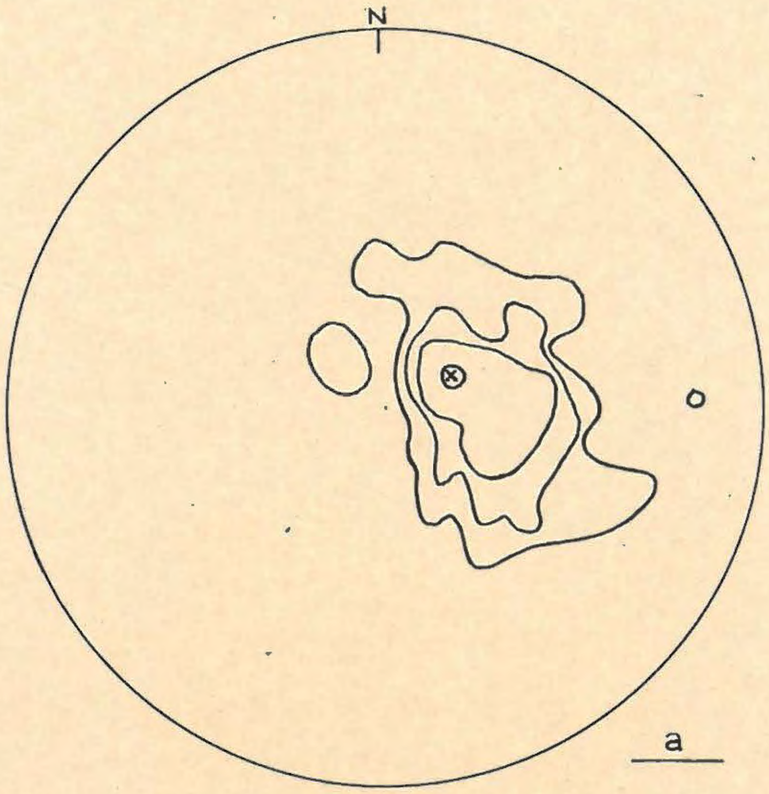
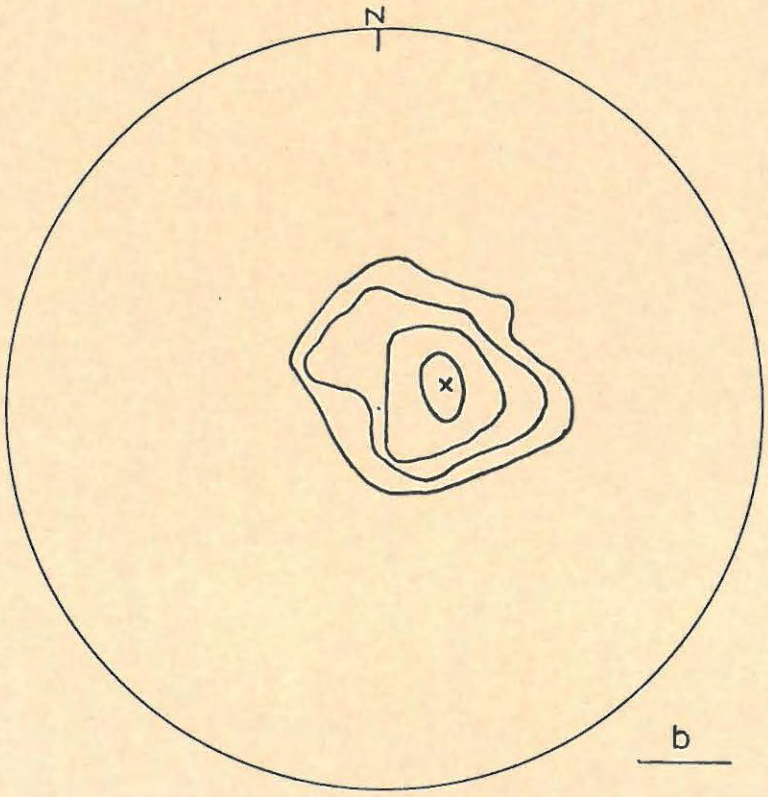


Figure 13. Compound minor fold resulting from superposition of two Z-folds.

Plate 5. Intricate compound fold in Lower Roan quartzite.

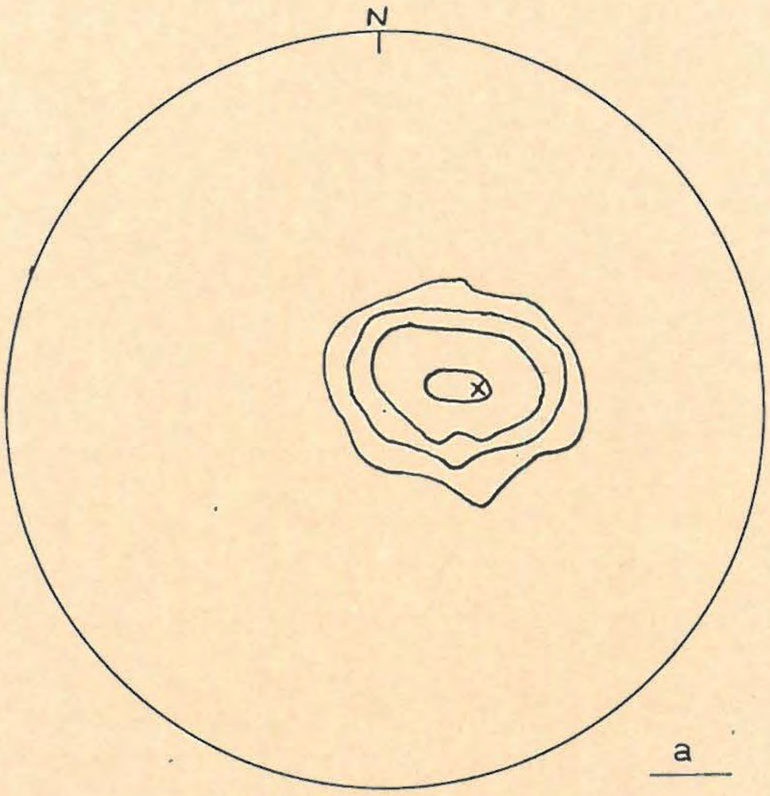


Poles of schistosity. Sheet 150.

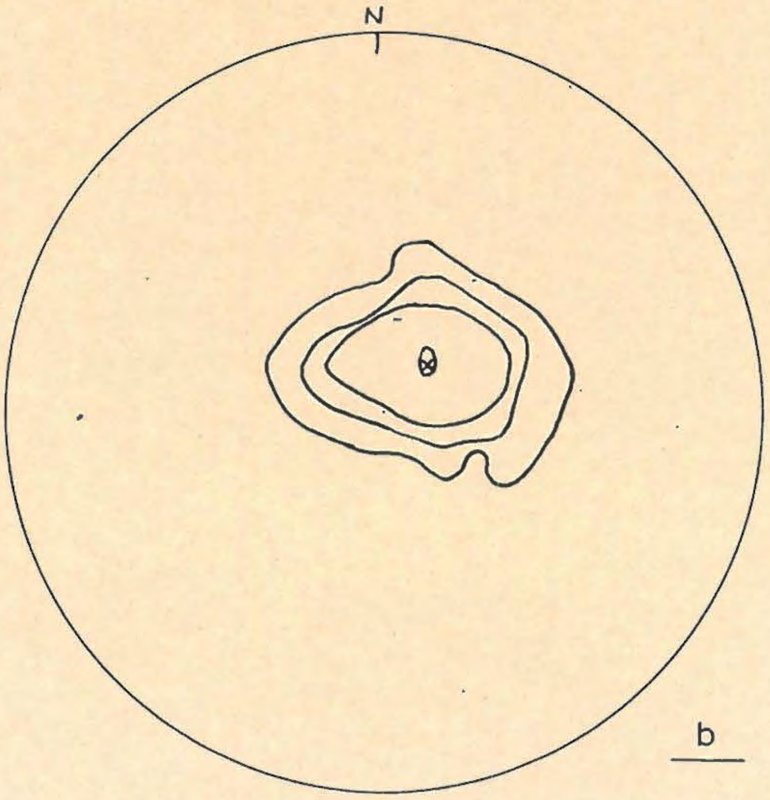


Poles of schistosity. Sheet 172.

FIGURE 14

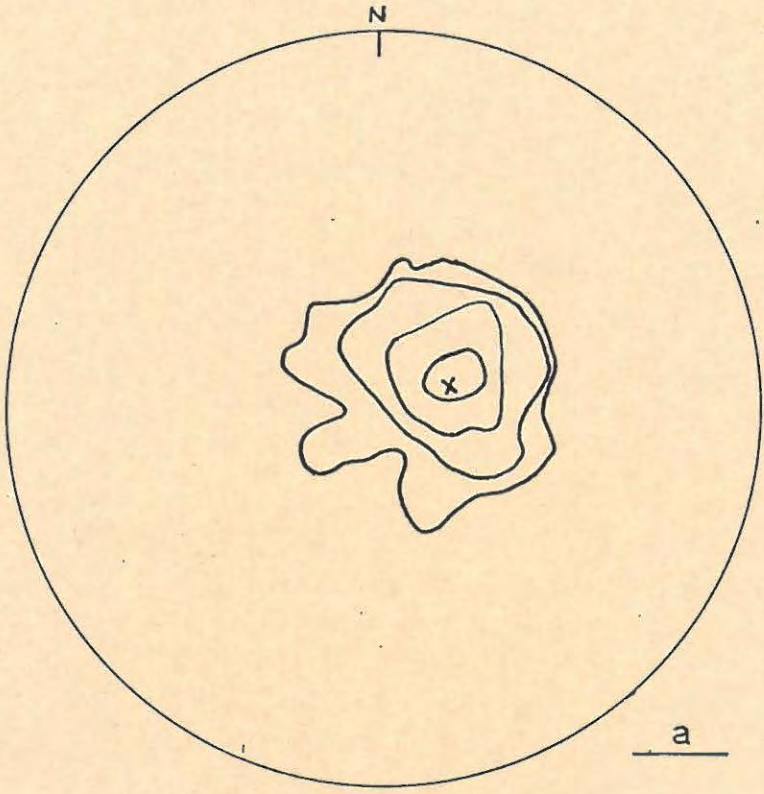


Poles of schistosity. Sheet 194 lines 6 - 20 .

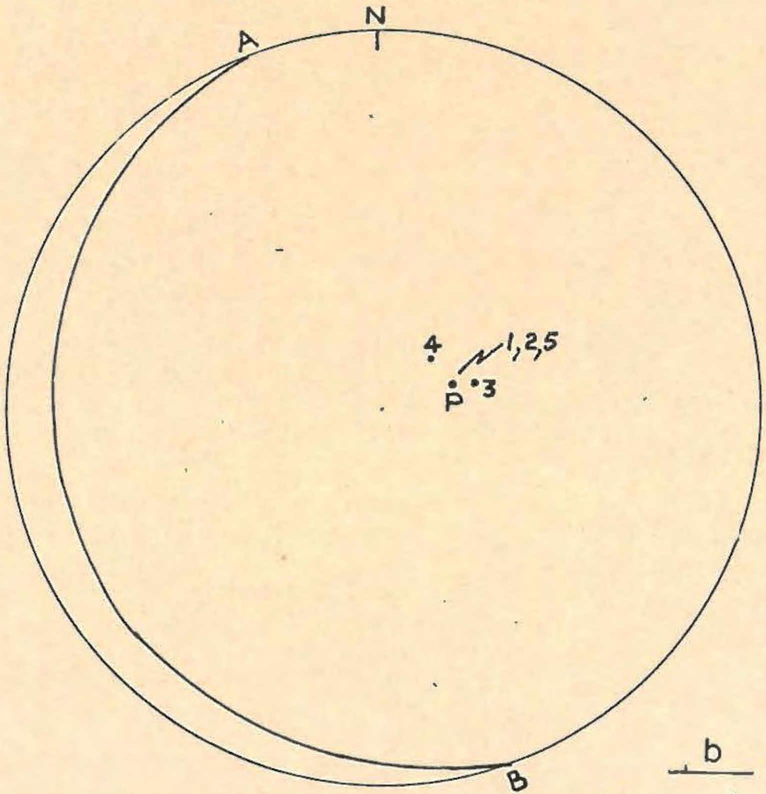


Poles of schistosity. Sheet 194 lines 0-5.

FIGURE 15

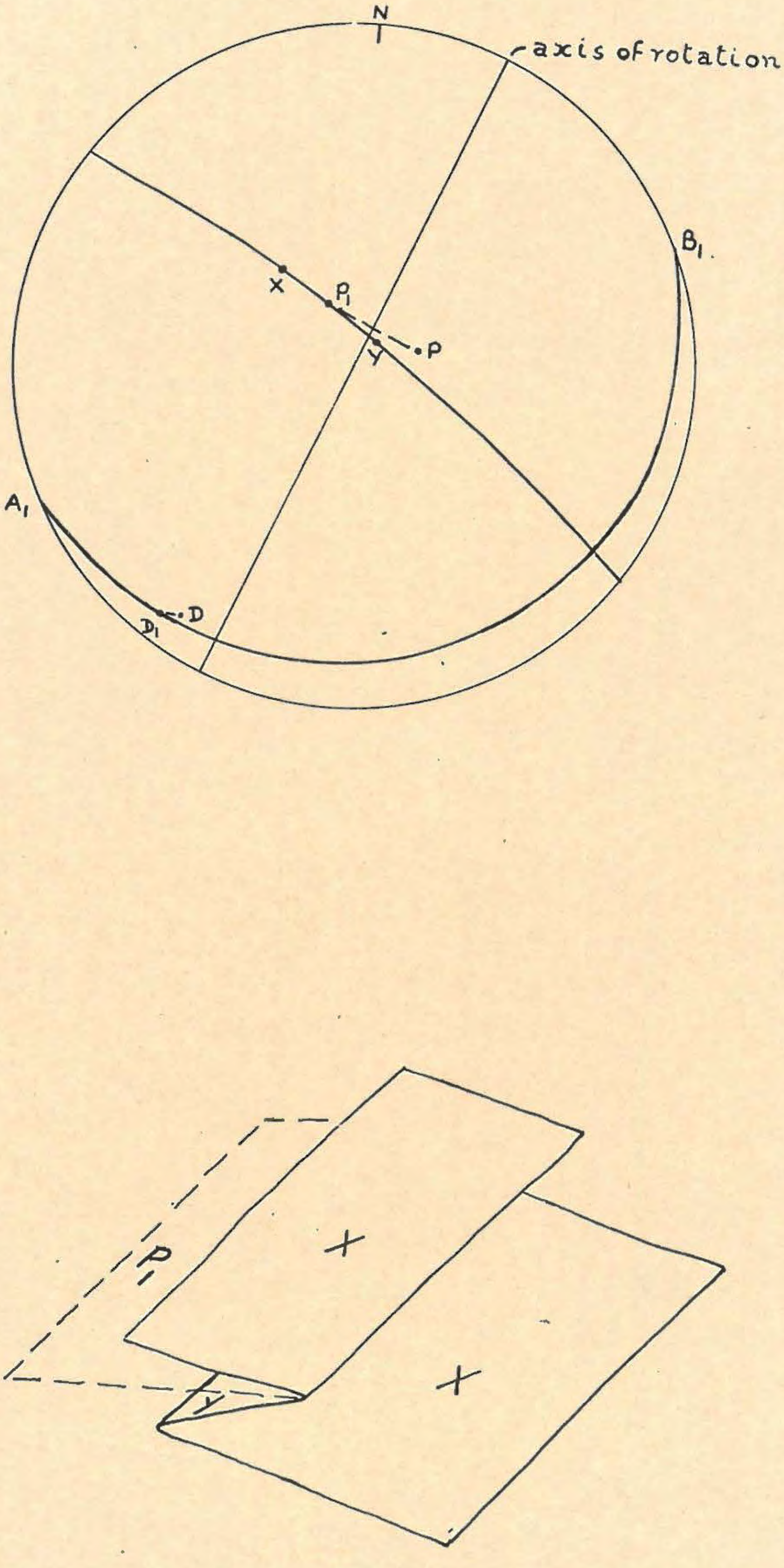


Poles of schistosity. Sheet 216.



P - Pole of axial plane of first folds (coincidence of maxima from areas 1,2 & 5).
AB - Axial plane of first folding.

FIGURE 16



Selected first fold. For explanation see text.

FIGURE 17

(1962a), (see Figure 13). Although the occurrence of compound folds complicates the examination of the form and orientation of the elements of the first folds, the near isoclinal Z fold form is characteristic, and there is no difficulty in recognizing the first folds provided that adjacent anticlines and synclines are present.

The determination of the orientation of the elements by averaging measurements taken on a large number of folds is not practicable because of the rarity of good examples, and the method adopted therefore was to use the schistosity and not the bedding in the following manner.

The area mapped was sub-divided into five smaller areas in a north-south direction so that if any east-west warping (fourth folds) had occurred it could be detected. The poles of all the schistosities were plotted on equal area nets and contoured using a 2% circle and graticule. Contours were made at intervals of 2½%, 5%, 10% and 20% and the maximum marked. In each sub-area the effects of later folding were found to be inconspicuous in the pattern i.e. the schistosity has a single maximum which dominates the pattern and other maxima are suggested only by the expansion of contours in the planes of later folds.

The stereograms opposite these pages are pantographed reductions of the original equal area nets and represent the following sub-areas.

Figure	Sub-Area.	Number of measurements.
14a	Sheet 150	70
14b	Sheet 172	171
15a	Sheet 194, lines 6 to 20	362
15b	Sheet 194, lines 0 to 5	272
16a	Sheet 216	131

A comparison of these five stereograms shows that they are remarkably similar and that the maxima are almost coincident. When one considers that these schistosity measurements were made on the inverted limb of a great recumbent fold, the similarity is so remarkable that it is concluded that the schistosity must be related to the major fold.

Although there is no accurate knowledge pertaining to the orientation of the axial plane of the great recumbent fold, this axial plane is apparently close to those of the first folds seen in the field. The great recumbent fold therefore is thought to be of the same age as the first folds, and the majority of first folds are parasitic minor folds on the limbs of the major fold.

In Figure 16b the maxima from the preceding five stereograms have been plotted, and as three of these maxima coincide, this direction is taken as the pole of the schistosity of the first folds (P), and the axial plane is A B. In order to determine the axis and plunge of the first folds a particular fold (Figure 17) was selected for examination which, while having the characteristics of first folding, was not noticeably compounded with subsequent folds. Poles of bedding planes were measured at regular intervals across the fold, and were plotted on an equal area net. The poles plot on a great circle with maxima at X and Y, and as thinning in the limbs was not appreciable, the pole of the axial plane (P_1) falls on the same great circle equidistant between X and Y. A_1B_1 is the axial plane and D_1, the axis of this fold, is the pole of the great circle XP_1Y. From Figure 16b, P is the actual position of the pole of the axial plane of the first folds. It is clear that P has been moved to P_1 by later folding, the net effect of which is rotation on an axis 23° east of north. Since P_1 is derived from P on a small circle about this axis, D is derived from D_1 on a similar small circle.

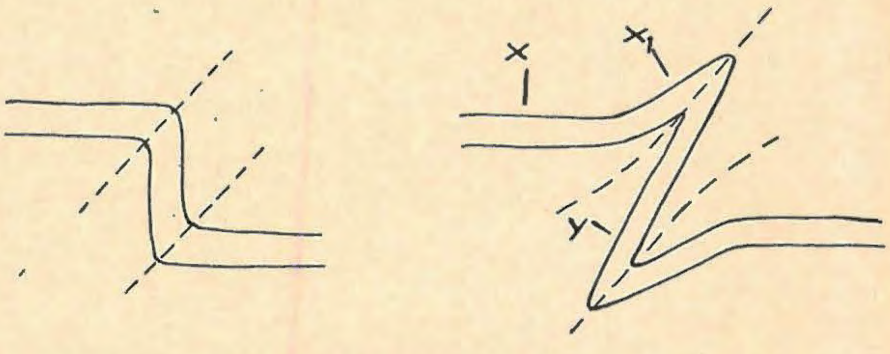
From P, therefore, the axial plane of the first folds strikes at 160° and dips southwest at 15°. From D the plunge of these folds is 11° in a direction of 212°.

Second Folds.

The second folds are similar to first folds in that both are Z folds, both have axial planes which dip to the west, and both tend to be overturned. Unlike the first folds, the presence of which is largely inferred from a schistosity which is folded, and does not belong to the later folds, the second folds are easy to see and measure both in cores

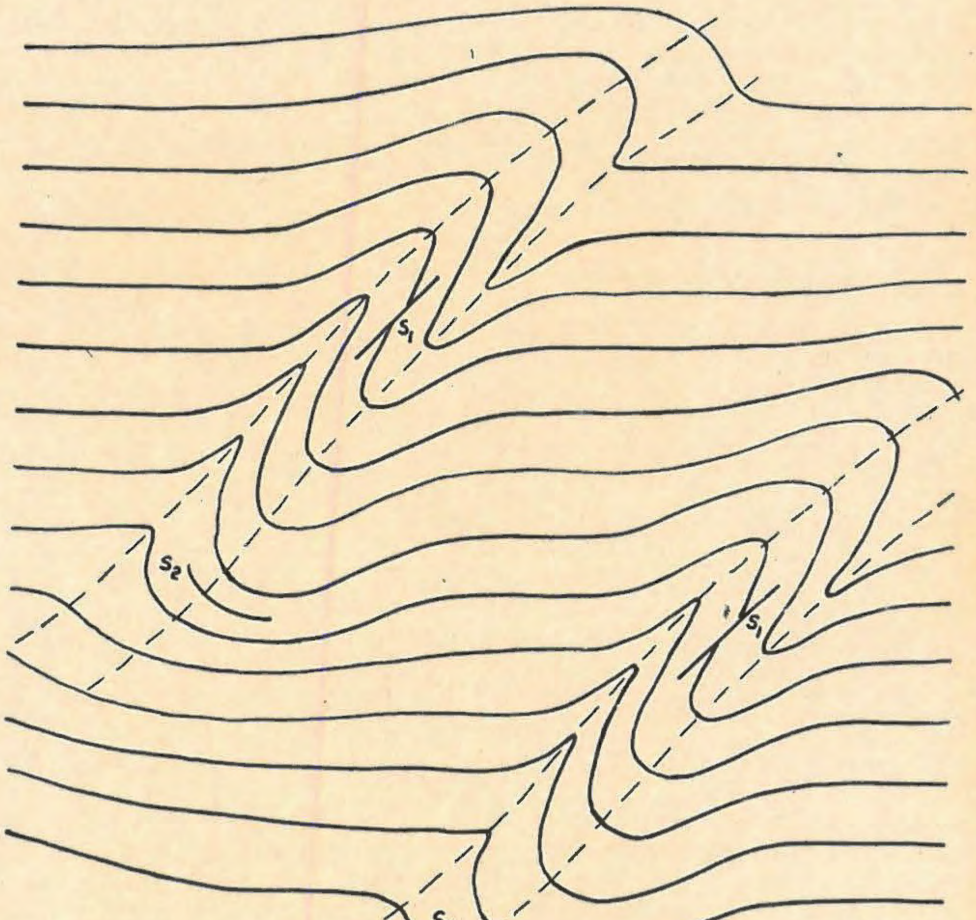
Plate 6. Second fold, axial plane dipping west.

Plate 7. Small normal faults caused by folding of a competent quartzitic bed. MM 124, 324'.



X, X_1 & Y - Pole Maxima

a



S_1 - Similar shear
S_2 - Concentric shear

b

Development of second folds.

FIGURE 18

and outcrops. The schistosity is much more poorly developed than in the case of first folds, and is found to be best developed in the noses of folds which sometimes have a chevron pattern. In addition to the characteristic folds described below, all stages in the development of shear folds are present, ranging from cases in incompetent beds where no shears are visible, to cases in more competent beds where shears oblique to the bedding are several millimetres apart looking like small normal faults.

The second folds at the Lumwana Prospect have been examined in considerable detail and their characteristics have been determined by plotting the elements of numerous simple and compound folds on equal area nets. The stereographic techniques have been found to have a much more limited application than is inferred in the descriptions by various authors in other structurally complex areas. The writer has found that the use of the stereogram must be selective, and it can be used effectively only in conjunction with careful field observations not only of the measurable elements of the folds, but also of their general form. A sketch of the fold under examination is essential in the interpretation of the statistical data, and as sketches of compound folds are difficult to make, the interpretation of statistical data pertaining to such folds is frequently questionable.

The main difficulty in the use of the stereogram is its inability to portray curved axial planes. In theory (Ramsay 1962b) a series of measurements of the poles of the folded plane (usually bedding plane) at regular intervals across the fold, plot on a great circle containing two maxima with the pole of the axial plane falling between them. In practice the second folds at the Lumwana Prospect follow theory in that the poles of the folded plane (in this case the schistosity of the first folds) lie on a great circle, but the maxima are diffuse and there are usually three maxima. The reason for the third maximum is illustrated in Figure 18a where a simple flexure is shown to become intensified with rotation of the direction of shear. The result is that the axial plane has become curved, and two maxima (X and X_1) are obtained from the normal

Plate 8. Concentric shear in a second fold. (S_2 in Figure 18b). Thickening takes place to the left of the photograph.

MM 122, 659'. (x 8)

limb. The pair of maxima pertaining to the nose of the fold have to be considered in numerous individual cases in order to determine the limits within which the curved axial plane falls. This curvature of the axial plane is an indication of close proximity to the point of rupture and rupturing occurs in the overturned limb of such a fold, causing the fold to become disharmonic with development of a curved thrust plane parallel to the axial plane of the fold.

The development of disharmonic folding of the type at the Lumwana Prospect is illustrated in Figure 18b. In the centre of the drawing the fold is symmetrical and shear takes place across the attenuated overturned limb. This is similar or shear folding, but unlike more typical examples of this type of folding, the folds do not persist but grade into a type of fold which consists of a curvate syncline paired with a carinate anticline or vice versa. Such folds have been recognized before, and have been explained by variable degrees of folding in inter-layers of variable competency being subjected to the same conditions of strain. This type of fold is very common at the Lumwana Prospect and its occurrence with more symmetrical folds in the identical host rock, and without any marked inter-layer variation in competency, puzzled the writer for some time.

The carinate portions of these folds contain intensely crumpled material which is sheared parallel to the axial plane of the fold, and which sometimes is squeezed through neighbouring beds in the shear direction. The curvate portion of the fold is less crumpled but may be drag folded on a small scale.

In the outer part of Figure 18b the fold is shown to be dying out. This is accompanied by thickening and thinning of the formations as shown in the drawing. In most cases this is accomplished by flow, but in others by multiple shearing sub-parallel to the schistosity of the first folds. This type of shearing corresponds to concentric shear and may be both parallel to the original bedding and to the folded schistosity of the first folds. The result is that small lozenge-shaped fragments

Plate 9. Second fold as in the central part of Figure 18b. Note slight drag folding in upper limb of the anticline. MM 122, 705'.

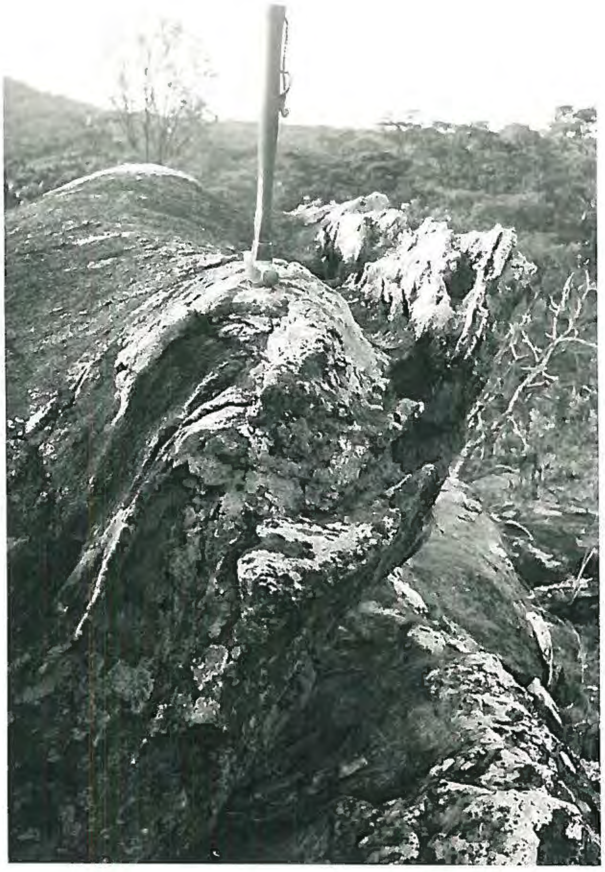


Plate 10. Second fold in Lower Roan quartzite. Characteristic form with steeply-dipping axial plane; note bending of the axis to the east.

Plate 9. Second fold as in the central part of Figure 18b. Note slight drag folding in upper limb of the anticline. MM 122, 705'.

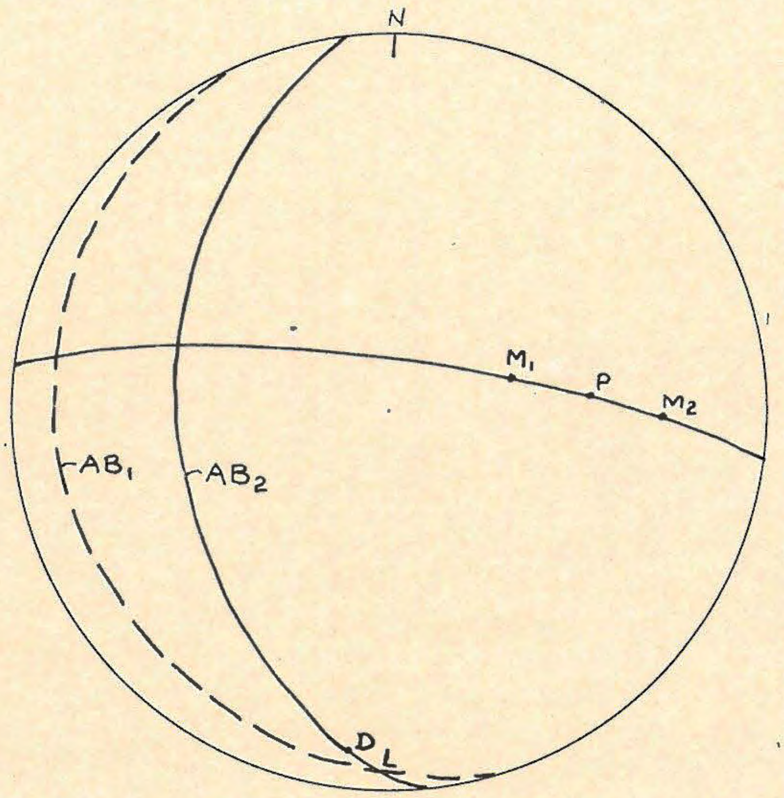
Plate 10. Second fold in Lower Roan quartzite. Characteristic form with steeply-dipping axial plane; note bending of the axis to the east.

are formed which slide upon each other from the areas of thinning to those of thickening.

The form of the second folds is so characteristic of the Lumwana Prospect that it is thought that this form is the logical outcome of folding of beds containing a previous schistosity. Concentric shear parallel to the previous schistosity must be of great importance in the development of these folds, although similar shear is unlikely to be absent.

Figure 11 shows the central part of the Lumwana Prospect where drilling has been concentrated. Stratum contours have been drawn of the quartzite-mineralized schist contact in the various drill-holes and at surface, with modifications based on the plunge of lineation and dip and strike of schistosities. The lineation is inadvertently close to the fold axes which have the greatest effect on the bedding, although the bedding itself is largely obscured by the well developed schistosity, and dips and strikes are so doubtful that they have been disregarded. The spacing of drill-holes over much of the area is such that contouring is largely a matter of personal choice, and the result is an idealized drawing which combines factual data with data inferred from schistosities and folds which cannot be seen to affect the contact plane directly, yet neglects details of overturning which cause intersection of contours and distort the overall characteristics apparent from the drawing.

The general structural pattern shown in Figure 11 is that of the major second folds. This pattern consists of folds striking roughly north-south, with axial planes dipping to the west and a tendency toward overturning. The plunge is to the south at angles varying from $3\frac{1}{2}^{\circ}$ in the central part to 14° in the southeast. Superimposed on the pattern of second folds are the more distinct of the third folds and zones of third folding. These later folds, which have axes striking at variable large angles across the main trend, cause displacement of second fold contours primarily to the east, and reversals of plunge, and are described fully later in the chapter.



M_1 & M_2	Averages of maxima of pole directions of planes folded by second folding.
P	Pole of axial plane of second folds.
D	Axis of second folds.
AB_1	Axial plane of first folds (from Fig. 16.)
AB_2	Axial plane of second folds.
L	Direction of lineation.

FIGURE 19

The method of contouring used for the quartzite-schist contact has proved adequate for obtaining the general structural characteristics of the second folds, and was used for planning drilling. This method, however, depends on the assumption that the quartzite contact was not greatly deformed either by pre-tectonic or early tectonic folding. Since it is known that such deformation did occur the pattern is in fact not that of the second folds alone, but a combination both of first and second folding with possible pre-tectonic folding, and it is only because the second folds are much the best developed that the picture corresponds approximately to that of the second folds.

In order to obtain more accurate information on the attitude of the tectonic axes of the second folds, poles of the folded schistosity in selected examples of second folds were plotted on equal area nets following the technique described earlier in the chapter. The examples selected were limited to those of symmetrical form corresponding to the central part of Figure 18b. In this way it was intended to arrive at a mean value for the orientation of the axial plane, which in fact curves approximately 8° on either side of the mean in the dip direction. The maxima derived from the poles of the first schistosity and the poles of the axial planes were plotted on a single net and averaged using the 2% circle and graticule. The result (reduced in Figure 19) shows that the axial plane of the second folds strikes at 170° and dips west at 44°. The plunge is 12° in a direction of 192°, and limbs diverge at an average of 36°. This means that the majority of second folds must be overturned, and indicates that the eastward dipping limbs of folds shown in Figure 11 consist in fact of a number of small overturned folds with a net effect of an eastward dip. Finally, point L in Figure 19 is at the intersection of the axial planes of first and second foldings, this direction is 180° with a plunge southwards of 6°, and is the direction of primary lineation. This can be seen when the rock is split along planes of either the first or second schistosities, as in each case the lineation is in the plane of schistosity and each lineation is parallel to the other. The lineation and its general plunge has proved invaluable in the orientation of drill-cores and subsequently in the unravelling of the structure, particularly as the plunge of the lineation approximates very closely to the overall plunge of the beds as shown by the stratum contours in Figure 11.

It should be borne in mind that the methods of examination of the first and second folds are dictated by the absence of bedding, and the analysis does not permit accurate definition of the geometry of the bedding after first and second folding. However since the first folds are nearly isoclinal the overall dip of the bedding is likely to be generally inclined to the west at only a few degrees less than the first schistosity. For most practical purposes the bedding is assumed to be parallel to the schistosity until accurate data on stratigraphic contacts is obtained.

Third Folds.

At the northern end of the Lumwana Prospect where the Lower Roan quartzites are well exposed, a third set of folds is found to be well developed. In contrast to the vicinity of the Lumwana Clearing where second folds are dominant, here the second folds are beginning to die out and are replaced by crosscutting S folds. In Figure 11 it can be seen that the cross-folds do affect the formations as far south as the north-central part of sheet 194, but on the whole are confined to well defined zones in which the stratum contours of the westward dipping quartzite are displaced to the east. These folds are clearly later than the first and second folds as the lineation formed by the intersection of the axial plane schistosities of the early folds is deformed, and plunges generally to the north instead of to the south.

A superficial examination of the folds reveals that the trend of the axes varies from approximately 40° to approximately 120° true bearing, and that the axes and axial planes are frequently curved. The plunge is generally to the west and the axial planes have a shallow dip which generally has a southward component. In the well exposed

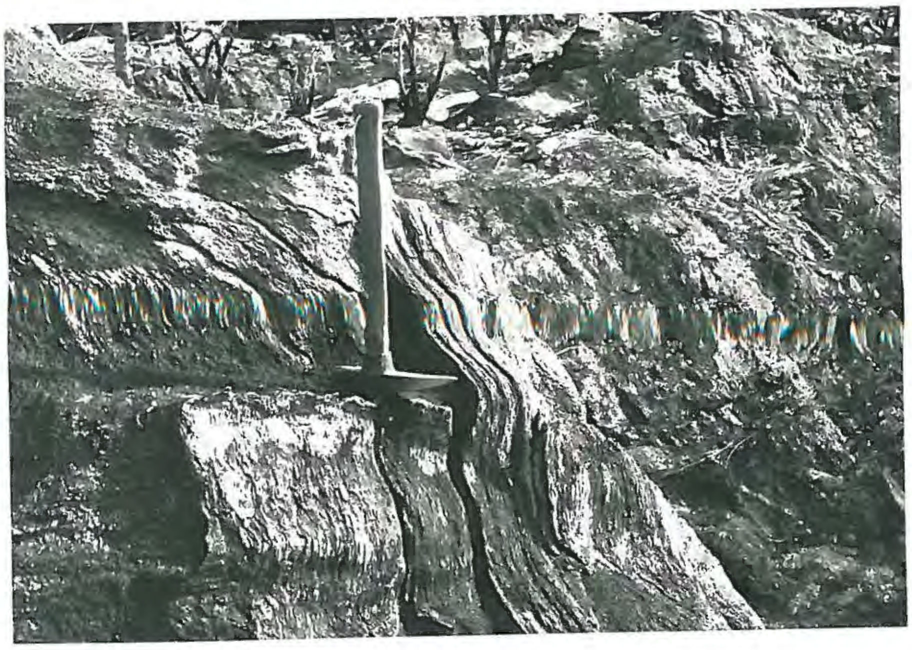


Plate 11. Third folding in Lower Roan quartzite. Note folded early lineation.

Plate 12. Third folding in Lower Roan quartzite. S-fold of concentric type partially compounded with second fold causing bending ofthe axial plane in the foreground.

quartzites these folds normally have the characteristics of concentric folds. Often they are compounded with the earlier similar folds with the result that some outcrops display remarkably twisted beds on which it may be impossible to make measurements from which the tectonic axes could be determined. Unlike the first and second folds the third folds do not have an axial plane schistosity, though it is thought that sometimes a slight cleavage has developed.

In the absence of distinct axial plane foliation and the presence of widely divergent attitudes of the formations and schistosities, it is important to observe the distinct multiple lineations trending on a bearing of 120° on the aerial photographs taken of the quartzite outcrops (see Plate 1). Field observations have shown a well developed joint system trending in this direction, the joints being inclined at steep angles, generally to the north, but sometimes to the south.

Before considering the possibilities of determination of the tectonic axes from the folds themselves, a task made difficult by the prior inclination of the folded strata, the poor preservation of bedding planes and the compounding of third folds with earlier folds, the possibility that the jointing is related to third folds must be considered.

It has been mentioned that the third folds display the characteristics of concentric folds in the quartzites, and as shown in the accompanying photographs are often very tight. It can be inferred therefore that folding of these competent beds was achieved by stress applied for a very long time. If one considers the relief of such stress it is reasonable to suppose that competent beds, folded concentrically, are more likely to show this relief of stress by the development of jointing in the plane perpendicular to the stress, than for example beds folded in a similar manner with development of schistosity planes in which the stress relief might be taken up. It is concluded therefore that the 120° joint system in the quartzites is likely to be the result of relief of stress which caused the third folds, and these joints are likely to lie in the <u>b-c</u> plane. It may further be concluded that the axial planes of the third folds strike at 120° and dip mainly to the southwest at shallow angles. It should be mentioned that locally, previously developed schistosities in the quartzite may be so orientated that the stress relief may be taken up in these schistosity planes without the development of jointing, but such orientation would be fortuitous. Furthermore in the less competent beds the third folding is likely to have been similar with development of cleavage or schistosity, and in such formations pronounced jointing is unlikely to be present.

The effect on the outcrop pattern of the two earlier sets of folds being superimposed upon each other is slight, but the effect of the superposition of the third folds is pronounced. The general form is crescent-shaped where compound folding takes place, but what is more conspicuous is the change of strike from north-south to northeast-southwest, or even east-west. This feature is due to rotation of the formations inclined to the west before third folding, about the variably orientated axes of the third folds. A further effect of this rotation is overfolding where previously absent in north-south folds, or increase in the degree of overfolding if present. Thus the traces of the axial planes of adjacent antiforms and synforms may cross one another or diverge from one another where disturbed by third folds.

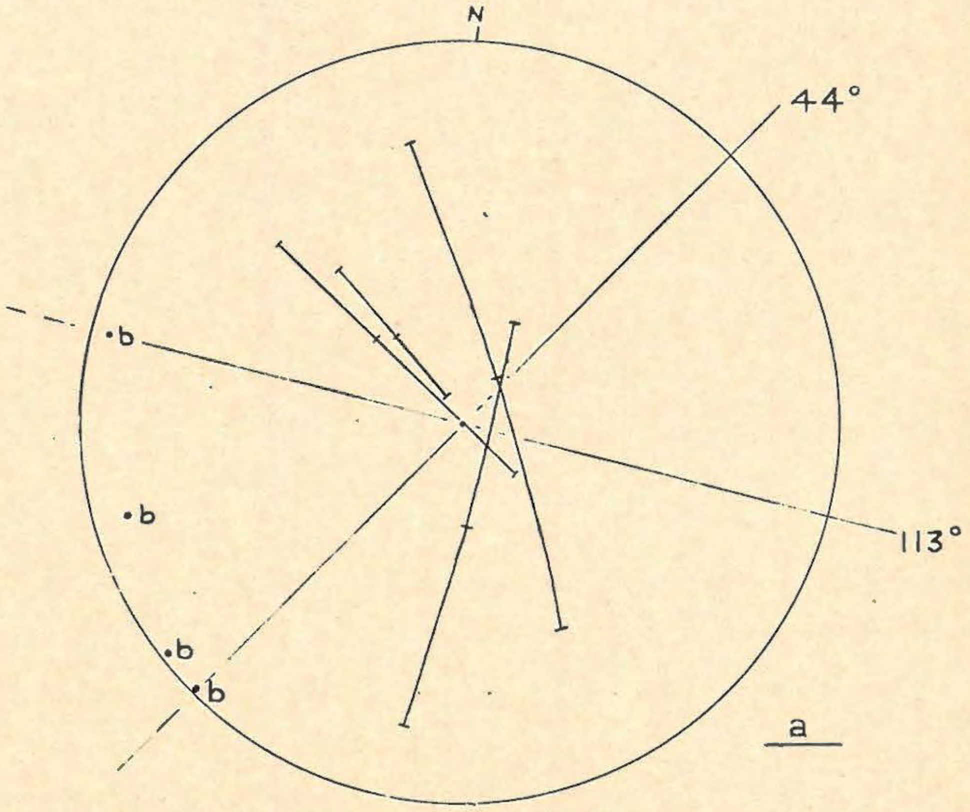
The result of the beds being inclined by first and second folding is that the tectonic axes derived from fold elements (other than schistosity which is absent) are not those of the tectonic axes to which they would normally correspond. A technique to determine the actual tectonic axes of such folds has been described by Ramsay (1960) and can be applied sometimes to the particular circumstances of the third folds at Lumwana. Ramsay describes how deformation of lineation by concentric or similar folding obeys strict laws, but queries whether it is possible to recognize a combination of the two by study of the orientations of deformed lineation. He was able to describe a sample where a history of similar folding followed by concentric folding could be postulated, but there is some doubt whether consistent results would have been obtained from a number of samples collected within an area deformed in such a manner.

In cases of lineation being deformed by pure concentric folding the angle between the fold axis and the lineation remains constant, and on a stereogram the lineations are arranged on a partial small circle about the axis. On the other hand, in cases of pure similar folding the angle between the fold axis and the lineation is variable, and the lineations are contained in a single plane which plots as a great circle on a stereogram.

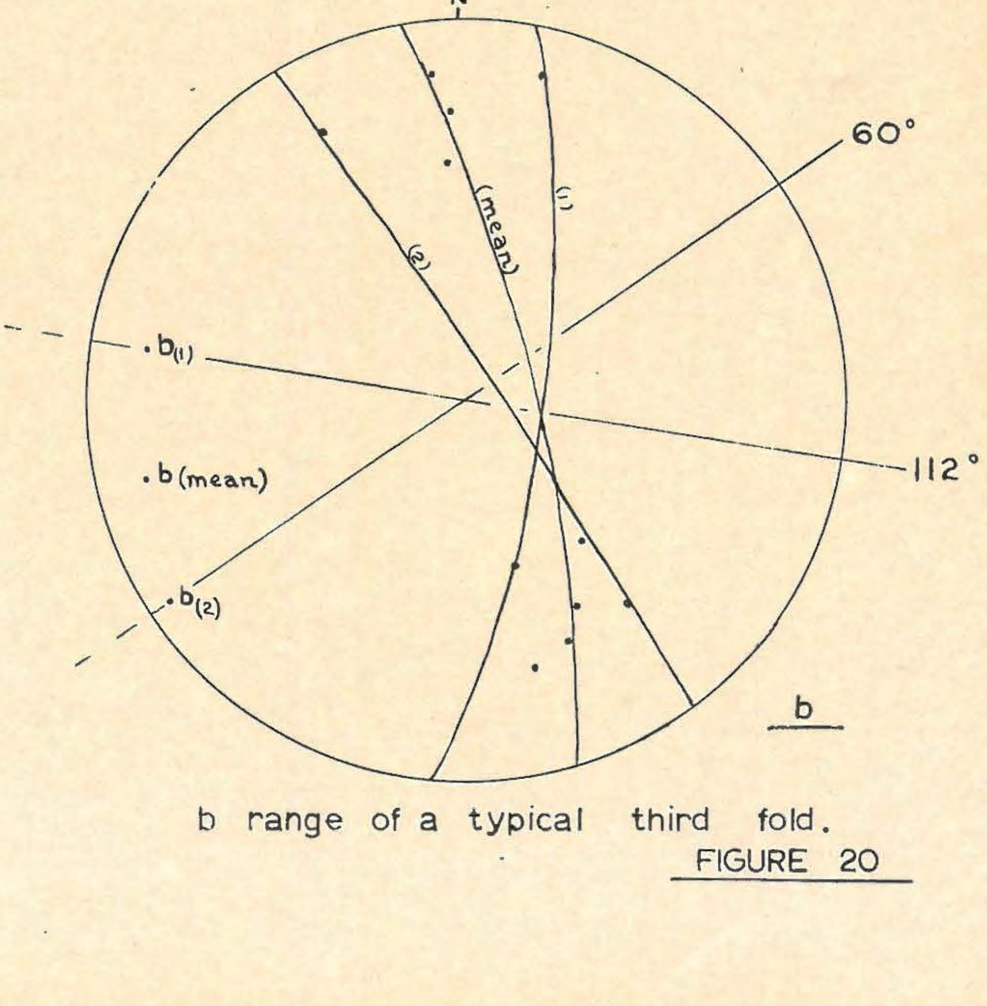
In cases of single-phase combined concentric and similar folding, that is, where part of the fold has been deformed in a concentric manner and part in a similar manner, the angle between the lineation and the fold axis is variable. This angle, however, varies only in the parts of the fold that have been deformed in a similar manner. The effect on the stereogram is that the lineations appear to be contained in two intersecting or touching surfaces, one of which plots as a great circle, and the other of which plots as a small circle.

Finally if the angle between the fold axis and the lineation neither is constant, nor does it display the systematic variation of similar folding, then it must be concluded that folding has not been confined to a single phase. This is easily recognized where fold axes are bent, but the fold axis may remain constant in cases of rotation of the axial plane about the fold axis. In such cases the lineation can be used only to determine the position of the tectonic axes if the latest folds can be "unfolded".

Since the observed a̲ and b̲ directions of a fold need not be the true a̲ and b̲ directions, that is in terms of applied stress, due to tilt of the surface prior to folding, the lineation is important as it enables the true positions of the tectonic axes to be determined. When deformation of lineation has been by similar folding the tectonic axes of the folds can be accurately determined as the plane containing the



b directions of selected third folds.



b range of a typical third fold.

FIGURE 20

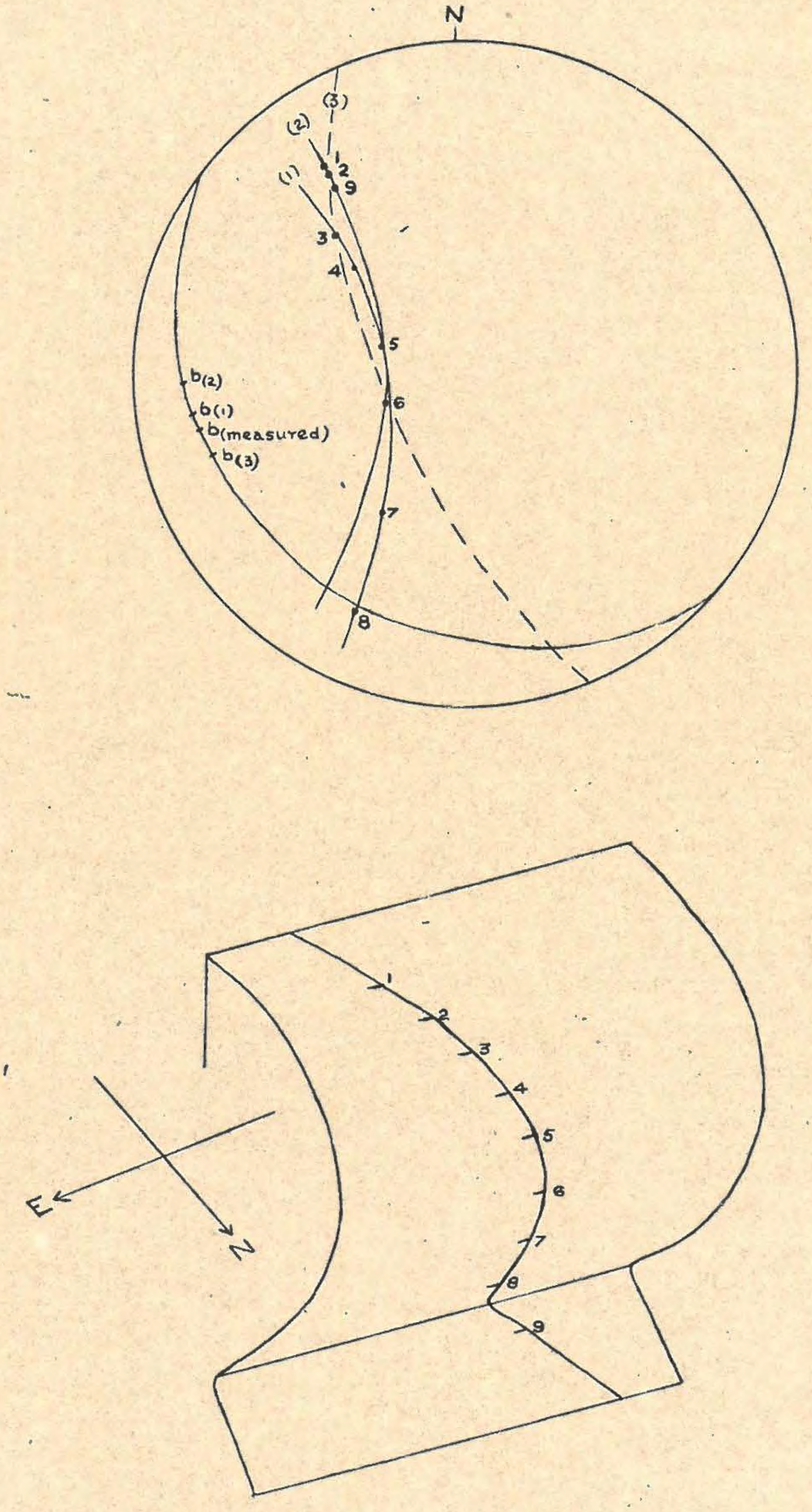
lineation is controlled by a (true), and the initial orientation of the lineation; and the axial plane of the fold also contains the true a. The intersection of these two planes therefore represents the true a and the tectonic directions b and c can be found by construction.

In the case of single-phase combined concentric and similar folding a can be determined from the intersection of the plane containing the lineations on the part of the fold deformed by similar folding, and the axial plane, and b can be determined at right angles to a in the axial plane. In addition, the second surface containing the remainder of the lineations plots as a small circle the pole of which is b, and can be checked against the previous determination.

The third folds which are exposed in the quartzite outcrops north of the Lumwana Prospect are sufficiently complex to limit the use of normal techniques in the determination of their tectonic axes except in special cases which must be selected with care.

It has been mentioned that the axes of the third folds trend approximately between 40° and 120° true. This trend is apparent in the examination of different folds in which the axes are straight, and also in individual folds where the axis is curved between these limits, as illustrated by the technique of plotting the poles of bedding planes in Figure 20. In the first stereogram four separate folds, selected because their axes were not curved, have different positions of the pole of the axial plane and the b direction of the fold. In the second stereogram the actual poles of the bedding plane of a fold with a visibly curved axial plane are plotted, and the result is that there is no fixed pole of the axial plane and no fixed position of b. On both figures it can be seen that b ranges in direction between the approximate limits of 40° and 120° and plunges at shallow angles to the west. A large number of folds would have to be examined in order to establish the range of b accurately, and no attempt has been made to do this because of scarcity of suitable exposures.

The variation in position of the tectonic axes can be illustrated



Lineation deformed by third folding.

FIGURE 21

also by examination of the deformation of the early lineation. If the orientation of the tectonic axes had remained constant the deformed lineations, when plotted on a stereogram, would have obeyed the laws of similar or concentric folding, or both. In actual fact the lineations do not exhibit these simple phenomena as illustrated in a very simple case (Figure 21). Here the lineations lie on two small circles, the poles of which give two positions of b. In more complex examples interpretation becomes increasingly difficult as multiple small circles may be drawn and often one or more great circles as well (see dashed line in Figure 21). The b direction is found to range about a mean direction approximately 10° south of west, and to plunge consistently in this direction.

The data concerning the tectonic axes of the third folds may be summarized as follows:

(a) The b axis is not constantly orientated, but its direction has a locus between 40° and 120° true bearing.

(b) The b axis plunges west at small angles.

(c) The a axis, in general, plunges to the south at fairly small angles.

It is concluded that the third folds have resulted from stress acting originally from the southwest on a bearing of approximately 40°, and rotating gradually through an arc to a final bearing of 120° true. Relief of stress in the last stages has resulted in the development of a system of joints in the quartzite, which are perpendicular to the stress. The third folding in the quartzite has been mainly of the concentric type, but deformation of the pre-existing lineation indicates that in some folds all or part of the deformation has been in a similar manner.

The orientation of these tectonic axes applies to folds situated immediately north of the Lumwana Prospect, where exposures have permitted examination in some detail. This does not mean however that the tectonic

EARLY DOMING

SUPERIMPOSED THIRD FOLDING

CONTINUED DOMING AND THIRD FOLDING

ADVANCED DOMING AND THIRD FOLDING

FIGURE 22

axes of the third folds are orientated similarly elsewhere on the dome, and in fact this is not the case. In a similar manner to the schistosity of the Copperbelt described by de Swardt (1962), the axial planes of the third folds dip quaquaversally off the dome at steeper angles to the bedding in the south, and shallower angles to the north (see Figure 22). Furthermore the b axis plunges west on the western side of the dome, and to the east on the eastern side of the dome. This clearly indicates that at least part of the doming has occurred after the third folds.

The writer (McGregor 1960) previously drew attention to the thinning of the Upper Roan formation towards the margins of the domes indicating an early start to doming, and also to the geomorphological evidence which indicates late doming movements. It is the opinion of the writer that doming has a long history commencing possibly as early as during deposition of the Roan succession, and continuing at various stages until post-Tertiary times.

Fourth Folds.

As outlined in the chapter on geomorphology, a fourth set of folds, or rather warps, has been superimposed on most of Zambia. These warps, the most conspicuous of which is the Zambezi-Congo divide, are on east-west axes. Their effect at the Lumwana Prospect is not noticeable although steepening of the plunge of the lineation to the south of the Lumwana Clearing may be explained by these movements.

FAULTING AND JOINTING.

Faulting and jointing on the Mombezhi Dome are considered together as they appear to be mutually related. They fall broadly into two sub-divisions namely those that were formed during or immediately after folding, and those that are unrelated to Lufilian folding.

First folding was accompanied by extensive thrust faulting (See Figure 12). The largest of these thrusts at the Lumwana Prospect separates the overturned limb of the great recumbent fold from the lower limb over most of the known strike. At the northern end it dies out together with the fold and at the southern end it is split into, and accompanied by several other large thrusts. Evidence for the existence of these thrust faults was limited to the lack of outcrop of the Upper Roan formations and gabbro known to be present at depth, until drilling of hole MMB 226. In this drill-hole some of the beds in the inverted limb were repeated three times before the hole was halted at a depth of 1700 feet. The repetitions mentioned are those clearly recognizable because they include the Lower Roan quartzite, and other possible repetitions may occur within the Upper Roan but cannot be postulated with certainty.

All the formations are suitable host rocks for thrusting though thrust planes have greater development in the Upper Roan than in the Lower Roan formations. In the Lower Roan the faults cut steeply across the competent quartzites and are confined close to the schistosity in the talcose beds. In the Upper Roan talc is less conspicuously present than in the Lower Roan, but gypsiferous beds are not uncommon, and are likely to have been the sites of considerable thrusting. In addition faulting has occurred in the impure dolomites. Here, these beds have usually recrystallized into biotite- and dolomite-rich bands, but sometimes they have behaved competently and become brecciated so that pieces of impure schistose dolomite up to six inches in size have been observed enveloped in recrystallized dolomite. These large fragments may be undeformed or exhibit slight concentric folding. Other smaller fragments have been rolled and broken into yet smaller bits which trail comet-like behind a larger fragment in the recrystallized matrix.

A further effect of interest is brecciation of gabbro over a few feet of core in MMB 226. The brecciated gabbro is fine grained and is enveloped in coarse-grained gabbro showing only a few gash cracks. This type of brecciation differs from that in the dolomites as the fragments are in place and the fractures between fragments are filled with the later gabbro, or massive amphibole. The brecciation of the gabbro is not regarded as being related to thrust faulting, but to later tensional movements.

Plate 13. Fault breccia. MMB 156, 597'.

Plate 14. 120° jointing in Lower Roan quartzite.

Brecciation in rocks other than the gabbro indicates that thrust faulting occurred in several periods of time and that thrusting occurred in different planes in these different periods. Thus thrusting was probably sometimes confined to lubricating host rocks and sometimes included brecciation adjacent to these host rocks, or even on the thrust planes themselves.

The most unusual feature of the Lumwana thrust faults is that they apparently are located well down the overturned limb, that is, they are nearer to the axial plane of the syncline than the anticline. Normally, according to de Sitter (1956), overfolds of the Lumwana type would be accompanied by thrusting high up the overturned limb. De Sitter in fact quotes the Lumwana type of overfolding as being suggestive of gravitational gliding. The lubricating media for such gliding are present and it is highly likely that movement initiated under compression was completed under the action of gravity, and that later folding and doming have prevented the determination of the original attitude of these thrust or glide planes.

At the Lumwana Prospect the thrust faults strike more or less north-south, and are inclined to the west at fairly shallow angles. The thrust planes have been folded by second and third folds, but their surface traces cannot readily be picked up in the field as the formations close to the thrust planes are very poorly exposed. To the south of Lumwana the trend of these faults swings to the east which suggests close relationship between the east-west compression and the normal northward acting stress.

No large faults are known to be associated with second folding, but small scale faulting in competent strata does occur. The small scale faults include décollement faults and also small normal faults in the limbs of some folds.

The 120° jointing and its relationships with third folding have been discussed earlier. In drill-hole MMB 156 a minor fault was intersected which included a fault breccia. Unlike the earlier breccias

Plate 15. Lateral-secretion vein. MM 197, 670'.

Half size.

Plate 16. Small open gashes attributed to post-Lufilian tension. MM 197, 837'.

Half size.

this material was consolidated but not recrystallized, and contained a fragmented feldspathic vein. Shear planes in the breccia, oriented from the lineation in neighbouring unbrecciated rock, suggest that this fault is parallel to the 120° jointing and hades south at 70°. It is concluded that some normal or tensional faulting occurred at the close of third folding.

The recognition of the tensional phase at the close of third folding is of very great importance as it is to this age that many of the tensional features can be ascribed. These include the normal faults on the east flank of the Mombezhi Dome, as well as minor tear faults, gash veins, and lateral secretion veins. One of the most interesting of these minor tensional features is multiple minor tear faults, each about 1 cm long, intersected in drill-hole MM 197. These small tear faults are open and are most unlikely to have remained in this state if a compressional phase had followed the tensional state in which they were formed. It is also likely that this is the age of intrusion of gabbro. The gabbros are commonly associated with faults, and it is probable that the normal faults formed after third folding were channel-ways of ingress of the intrusive material. In addition it is probable that older fault planes and to a lesser extent schistosity and bedding planes, were the sites for emplacement. Thus gabbro occurring in the centre of the Lumwana recumbent syncline is likely to have been intruded after folding along the post-third folding normal faults, and along the thrust planes. Furthermore local brecciation of the gabbro in MMB 226 was probably due to renewed movement along the later faults and not along the thrust planes.

Periods of tension occurred later in the history of Zambia. One of these was during the Jurassic when syenites were intruded, and another was the late- or post-Tertiary age of rifting, but neither syenites nor rifting is present in the vicinity of the Lumwana Prospect, and they are not the concern of the writer in this thesis. At Lumwana, however, there is a set of joints which trend at approximately 60° true bearing. This set of joints is less well developed than the 120° set, but nevertheless exhibits striking control over drainage. The consistency of orientation of these joints indicates a late age of formation, and it is likely that they are related to one of these later periods of tension.

THE POSITION OF THE LOCAL STRUCTURES IN THE REGIONAL SETTING.

The generally accepted name for the major orogeny in Zambia and Katanga is the Lufilian Orogeny, although it has also been called the Kundelungu Orogeny (Robert 1933-4) and the Katanga Orogeny by various members of the Northern Rhodesia Geological Survey. Earlier and later movements are subdivided by the writer into Pre-Lufilian and Post-Lufilian movements.

Pre-Lufilian Movements.

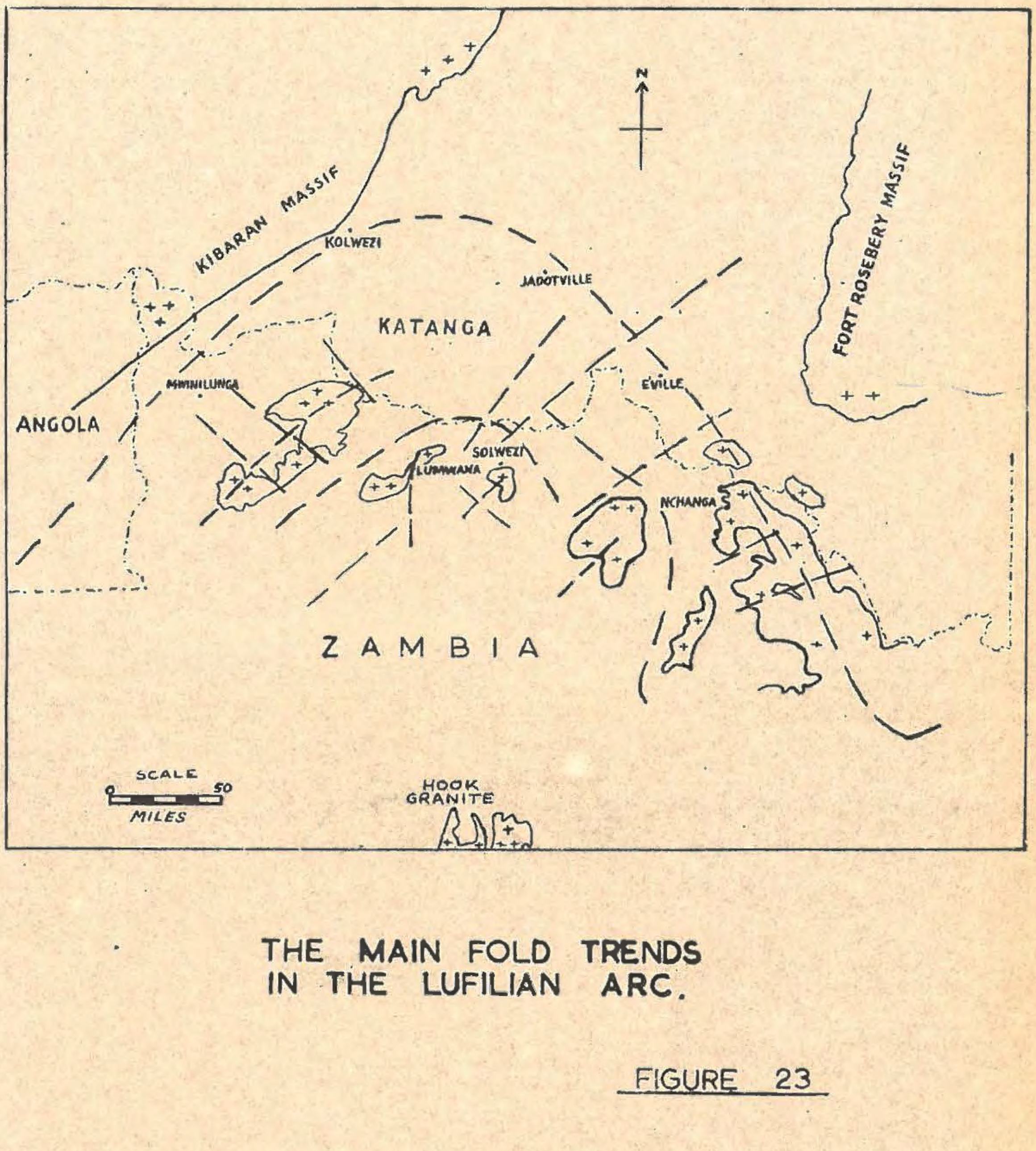
At the first meeting of African Geological Surveys (Dixey et al. 1931) it was generally agreed that the Muva System displays north-south axes. This probably indicates folding on north-south axes prior to deposition of the Katanga System. The only effect of this early orogeny is that the resistant Muva quartzite tended to form ridges on the pre-Katanga land surface. This effect, if any, has not been detected at the Lumwana Prospect.

After deposition of the Katanga System folding on north-south axes was repeated, probably following the ancient trends in many cases. The north-south pattern of the pre-Lufilian folds has been deformed by Lufilian folding so that these early folds now radiate from the centre of the Lufilian Arc, axes trending near 45° on the Copperbelt and 135° at Mwinilunga. The original north-south direction may be preserved in the centre of the arc at Lumwana and in un-arced formations against the Fort Rosebery Massif west of Mkushi (de Swardt 1962).

No faulting of this age has been observed.

Lufilian Movements.

This orogeny has given rise to a great arc of intensely folded



THE MAIN FOLD TRENDS
IN THE LUFILIAN ARC.

FIGURE 23

Plate 17. Structural model of the Lufilian Arc.

Plate 18. Flow structures in gabbro. From outcrop northwest of the Lumwana Prospect.

sediments which runs from the Copperbelt in the east, through Elisabethville, Jadotville and Kolwezi in Katanga, and re-enters Zambia at Mwinilunga in the west (Figure 23). This arc of folding has been caused by northward movement of a great mass of sediments between two relatively stable massifs in the Kibaran Massif to the northwest and the Fort Rosebery Massif to the northeast (Robert 1933-4, Garlick 1954).

In the outer part of the arc, as expected, folds are overturned outwards, but toward the centre a more complex pattern emerges as a result of east-west compression. This can be illustrated easily with a handkerchief puckered into east-west folds and then arced to the north. In this simple experiment an overturned fold on a north-south axis is invariably formed at the centre of the arc. At the Lumwana Prospect, lying at the centre of the arc, overfolding on near north-south axes can be expected and in fact occurs. This type of folding should also be expected anywhere on a line south of Lumwana.

Two hundred miles to the south, along the line southwards from the Lumwana Prospect is the extensive Hook Granite, and a further hundred miles to the south is a second large granite area known as the Kaloma Granite. Occurring as they do on the line bisecting the Lufilian Arc, the writer feels that their presence is likely to be related to Lufilian folding. The obvious interpretation is that these are intrusive granites, and that either intrusion caused arcuation to the north, or intrusion took place in a zone of weakness between more rapidly moving masses to the north and less rapidly moving masses to the south. That the Hook Granite is intrusive into the Katanga System, has been postulated for so long that it is almost an accepted fact (Murray-Hughes 1929, Guernsey 1950 and Phillips 1955, 1956, 1958a, 1958b). However, nowhere is there any strong evidence that it is in fact intrusive, Murray-Hughes and Guernsey both fail to be convincing in their argument that the granite intrudes upper members of the Katanga System, and Phillips bases his views on the intrusion of gabbros and syenites into the Katanga System, rocks which he regards as marginal to the Hook Batholith. Phillips regards scapolitization, uralitization, chloritization and the abundance of garnets as evidence of contact metamorphism, together with calc flinta, skarn deposits and iron oxide deposits. All these features are so wide-spread that apart from some local contact effects in the vicinity of gabbros and syenites they must be regarded as the outcome of regional metamorphism (see chapter on Metamorphism). Phillips (1958b) explains this regional aspect by postulating an enormous extent for his Kafue Granite (Hook Granite)including the southern portion of the Kabompo Dome, which the writer regards as pre-Katanga granite (McGregor 1960), and the Kaloma Granite which Hitchon (1956) regards as pre-Katanga. The writer is forced to the conclusion that on the present evidence the Hook Granite is not intrusive, but that it and the Kaloma Granite are exposed in anticlines or domes related to the Lufilian Arc of folding.

To avoid confusion it must be emphasized that the gabbros and syenites described by Phillips are intrusive into the Katanga, but far from being marginal to the Hook Granite, are wide-spread throughout Zambia and probably were intruded as isolated stocks in the case of the syenites, and as various dikes, sills and irregular masses in the case of the gabbros.

Syenite or quartz-monzonite has been seen by the writer as far north as the eastern flank of the Kabompo Dome, and sodic syenites (included in the Hook Suite by Murray-Hughes, 1929), occur near the Katanga border north of the Mombezhi Dome, (the latter being described by Adams and Osborne, 1934). Syenites are wide-spread in Malawi where they have received considerable attention from the African Research Unit at Leeds University, (Mallick and Vail 1962, inter alia). These are generally regarded as Jurassic in age which agrees with the age of 138±14 million years of the Chilwa Alkaline Province determined by Bloomfield (1959). Cox, Vail, Monkman and Johnson (1961) have also drawn attention to the resemblance of S.E. Southern Rhodesian complexes to those found in Damaraland. If any correlation between these syenites and those of the Northwestern Province of Zambia can be made, then the Zambia syenites would be post-Lufilian.

Gabbros are very common throughout Zambia, generally showing preferred emplacement in calcareous or dolomitic formations, and are generally thought to have been intruded after folding, (Hatfield 1937, Jackson 1933). Hall, however, is quoted in the "Geology of the Northern Rhodesian Copperbelt" (F. Mendelsohn 1961) as regarding the intrusions as having taken place at an early stage in the Lufilian Orogeny, and that alteration was due to dynamic metamorphism during the orogeny, while Robert (1933-34) regards intrusion as having occurred during folding. Hatfield drew attention to the association of gabbros with faults, a feature that is conspicuous on the Mombezhi Dome. As in the case of the syenites, the gabbros do not have any foliation or schistosity, yet frequently have well-preserved flow structures. This lack of schistosity and the association with faults suggests that the gabbros were intruded during a tension phase after folding, but prior to the intrusion of syenites.

Movements from south to north, with general overturning to the north occur elsewhere in Southern Africa in formations regarded as being of the same age. These include the northwest folds in Katanga formations near Mazabuka (Newton 1960), northwest folds superimposed on earlier northeast folds in the Lomagundi (correlated by MacGregor 1951 and Stagman 1955) of the Kariba area (Hitchon 1958), and of the Mhavare, northwest Lomagundi (Workman 1961), and east-west folds in the Damara of South-West Africa (Smit 1962) which is correlated with the Katanga by Clifford (1962). It seems that the northeast folds which have movement from northwest to southeast in the pre-Katanga Piriwiri beds at the Sanyati Mine (Bahnemann 1961), and in the Lomagundi of the Mangula Copper Deposits (W. Jacobsen 1965), can be related to pre-Lufilian folding, while the relationship of the movement from north to south in the Lomagundi at the Alaska Mine is not clear (J. Jacobsen 1965). It seems likely therefore that if these correlations are valid, the formations of the same age have undergone similar orogenic movements characterized by an extremely widespread northward movement.

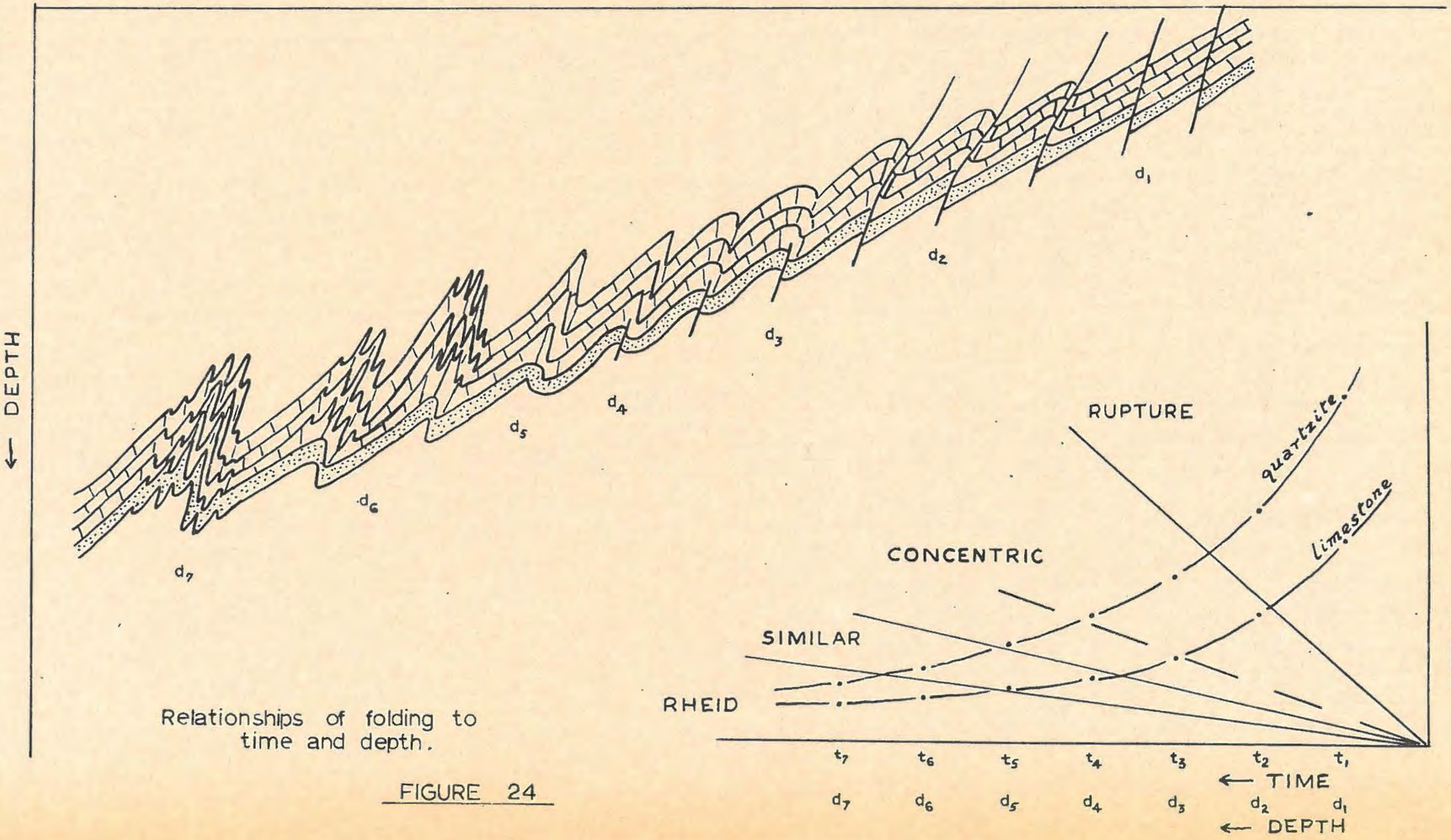
At the Lumwana Prospect the first and second folds (perpendicular to the regional east-west pattern due to compression at the centre of the arc) have given rise to a great recumbent fold, overturned and thrust to the east, as well as to many lesser folds of a similar pattern. These folds die out approximately ten miles north of the Lumwana Prospect where they are replaced by the normal arcuate folds of the orogeny. Although doming originated during deposition of the Roan succession and has continued until post-Kalahari times, the position and general shape of the Mombezhi Dome was determined by Lufilian folding, hence its parallelism to folds west of the bisector of the Lufilian Arc. The third folds at Lumwana indicate rotation of the Lufilian front in the vicinity in which these folds were examined. This rotation was such that stress applied to the northwest resulted in folds on axes trending at 40°, subparallel to the elongation of the Mombezhi Dome, but north of Lumwana this stress was rotated continuously or in stages to a final northeasterly direction so that the last folds formed have axes which trend on a bearing of 120°. This rotation may be a strictly local feature or it may be characteristic of the stress causing the entire Lufilian Arc.

The three sets of folds are all part of Lufilian folding and as each is clearly later than the preceding stage, it must be inferred that the Lufilian arcuation did not take place in one movement but in at least three major pulses. Rotation of the effects of stress have been observed, and rotation of the actual stress causing arcuation may have occurred, but as has been illustrated by Tanner (1962) any definite conclusion regarding rotation is very difficult to reach.

Faulting of Lufilian age is regarded as negligible or absent on the Copperbelt (Mendelsohn 1961), while in Katanga deformation has taken place predominantly by thrust faulting and gliding (Demesmaeker,

<u>Plate 19</u>. Rheid folding in Itawa limestone.

(x 1.5)



Relationships of folding to time and depth.

FIGURE 24

Francois and Oosterbosch, 1962). In fact between the centre of the Lufilian Arc and its outer edges all stages may be observed between yielding by folding and faulting alone. This variation is directly related to competency of the rock, to metamorphism and to depth of burial during orogenic movements, as is outlined in the following paragraphs.

The grade of metamorphism increases from the Katanga southwards (Garlick 1954). The formations at the edge of the Lufilian Arc exhibit only the lowest stages of the greenschist facies, while similar formations south of the centre of the arc are in the amphibolite facies and approach the granulite facies (McGregor 1960). This increase in grade of metamorphism is due to a large degree to greater depth of burial in the south, a factor which has also played a part in determining the types of folding and faulting to be found. In Figure 24 this relationship is illustrated diagramatically for two different rock types namely quartzite and limestone, as each would behave differently under the same conditions of burial subjected to the same strain for the same time. On a graph of time against strain four main fields of characteristic deformation are recognized, although considerable overlap undoubtedly occurs. The fields of rupture, concentric and similar folding fall within the field of elasticity following de Sitter (1956), and the remainder is the field of rheidity. This term is that proposed by Carey (1953) for a behaviour which is wholly fluid, although the substance has finite strength being below its melting point.

Although "rheid" behaviour has not been observed at the Lumwana Prospect itself, it does occur in the limestone equivalent to the Kakontwe of the Copperbelt, and is illustrated in the accompanying photograph (Plate 19) taken of a sample collected near the Copperbelt. The mechanism of rheid folding, which has also been called flow folding, is closely related to pure similar folding. Pure similar folding without flow involves no actual shortening, i.e. each rock slice between shear planes moves relative to the next adjacent slice without change of shape, and thus the shear planes are constantly orientated parallel to one another, as are the axial planes of the folds. Rheid folding develops from similar folding as soon as the individual rock slices are flattened or change their shape by flow, a mechanism which necessitates narrowing of the gap between shear planes. Rheid folding thus occurs with shortening, and as the amount of flow depends on competency it is clear that the shear planes are closely spaced in incompetent beds and more widely spaced in more competent beds. Furthermore shear planes are parallel only where the competency is constant, and are curved wherever they are influenced by nearby more competent beds. Axial planes of adjacent folds in interbedded competent and incompetent beds are curved and not parallel to one another.

In the southern part of a north-south section across Zambia and Katanga, all the formations including the Basement granite have behaved incompetently, as granite is found in the cores of folds at Lumwana. Folding is predominantly similar, although limestones exhibit rheid flow, and quartzites are often folded concentrically. Moving away from the central area of deep burial the granite and the overlying Lower Roan quartzite become competent and may be regarded as frozen together. Concentric folding and décollement faulting of these basal formations with similar folding of the overlying argillaceous strata takes place after the manner of the Alpine Jurassic folds (Heim 1921 quoted by de Sitter 1956), and the Boule and Bosche Ranges of the Canadian Rocky Mountains (O'Brien 1960), and is found on the Solwezi Dome. Here and even on the Copperbelt the limestones still yielded in a predominantly rheid manner. Further to the north in Katanga the whole succession becomes competent with the exception of two talcose horizons, the "roche argilo-talqueuse" (R.A.T.) beneath the ore horizon and the "roche gréseuse supérieure" (R.G.S.) above, and whereas folding to the south is mainly similar, folding here is concentric, so that beds retain their original thickness. Faulting in Katanga started as décollement thrusts in the lowermost beds, and developed into low angle thrusts in the talcose formations which broke through the overlying competent rocks. Movement along these planes probably took place partly by gravitational gliding, lubricated by the talc formation squeezed into fault and fracture planes, so that the final result is a jumble of blocks, which retain their original thickness, and are enveloped in the talc formation. The peculiar extrusion faults of Katanga seem to be a variation of the diapir. De Sitter (1956) states that the asymmetrical break through of a concentric fold is the thrust fault, and the symmetrical one a diapir, so that in Katanga a loosened block, enveloped in the lubricating talc formations would be extruded by load of the surrounding strata. Carey (1953) in his rheid approach to the subject of diapirism regards extrusion as occurring because the intruding medium has a lower rheidity. The easiest relief of the stress difference due to orogenic pressures is vertical which causes flow of the rheid upwards until diapiric break-through causes relief of stress. The significance of this concept is that even though the folds are markedly asymmetrical, the axis of the diapir is vertical, and as the process is exactly similar to that of a drop of oil rising through a basin of water, the location of the diapir need not necessarily be determined by a previous zone of weakness.

At the Lumwana Prospect the Lufilian stresses resulted in north-south striking thrust faults which swing to the east, south of Lumwana. This change in strike may be due only to later folding of the thrust planes, but it is likely that these faults illustrate the intimate relationship between the compressive forces at the centre of the Lufilian Arc and the stress acting from the south. Thus all three sets of folds can be regarded as Lufilian in age with some degree of certainty.

Lufilian folding and faulting have resulted in the local development of a wide variety of joint systems. The 120° joints at Lumwana are tension joints which have had some movement along them giving rise to brecciation. They are regarded as having formed in a tensional phase following the repeated compressional phases of the Lufilian Orogeny, and are associated by the writer with normal faults elsewhere on the Mombezhi Dome.

To sum up, the picture of the Lufilian Orogeny at the Lumwana Prospect is one of successive stages of deformation as follows:

(1) At least two major pulses of similar stress operating over a similar period of time, so that the same type of folding in particular environments was repeated in each of the pulses. At the Lumwana Prospect the northward acting Lufilian stress was resolved into eastward acting stress in both of these pulses with development of similar folds overturned to the east, and in the first pulse considerable thrusting as well.

(2) A third accelerated pulse which resulted in concentric folding where previously it had been similar. Stress causing this folding at Lumwana acted originally from the southeast and was rotated continuously or in stages during this pulse to a final position where it acted from the southwest.

(3) When the stress causing Lufilian folding ceased to be applied tension joints and faults were formed, and basic igneous rocks were intruded along the new fault planes.

Post-Lufilian Movements.

These movements are broadly subdivided into Karroo, Tertiary and Recent.

Karroo folding in Zambia generally has been of a minor nature. Movements of this age have not been detected at the Lumwana Prospect, but have been described in the Upper Luangwa Valley by Dixey (1937). Some tension faulting may be of Karroo age, and as mentioned, the intrusion of syenites is regarded as having occurred in late-Karroo times (Jurassic).

The rift faults of Africa are generally attributed to late-

Tertiary age. One such rift occurs on the southern flank of the Kabompo Dome where Tertiary Kalahari sands are found in the rift valley. The formation of the normal faults which trend in easterly or east-northeasterly direction may be attributed to this age of movement where they do not have associated gabbro intrusions. The 60° jointing of the Lumwana area may have formed at this time.

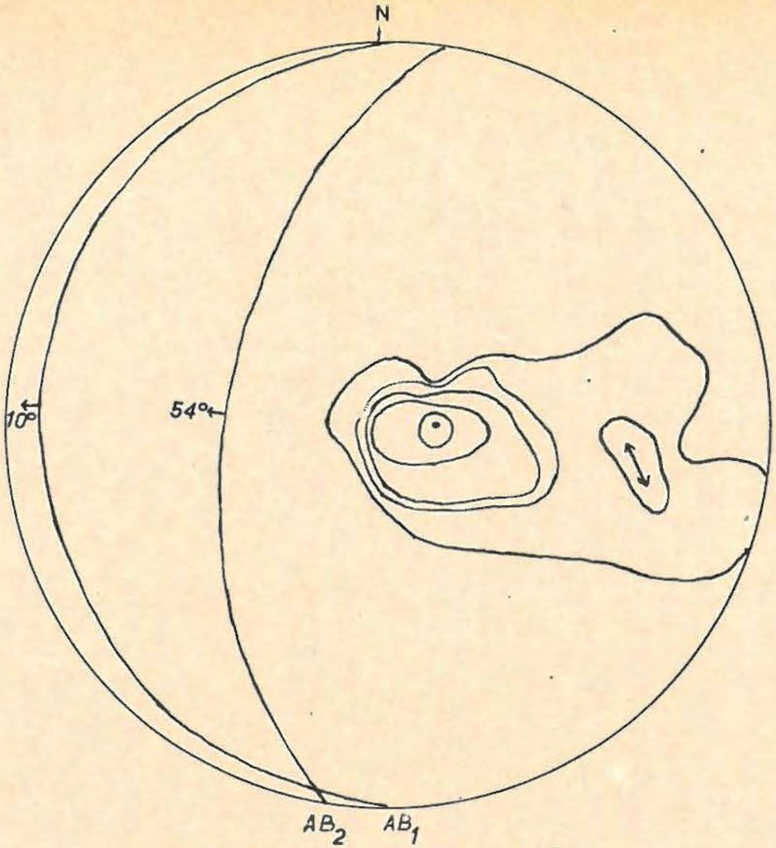
Recent movements in a number of cycles have affected Zambia, the most conspicuous being the east-west warps (fourth folds). Recent doming is also considered likely on geomorphological grounds, and although largely post-third folding, there is evidence for a start to doming as early as during deposition of the Roan succession.

MICROFABRIC ANALYSIS.

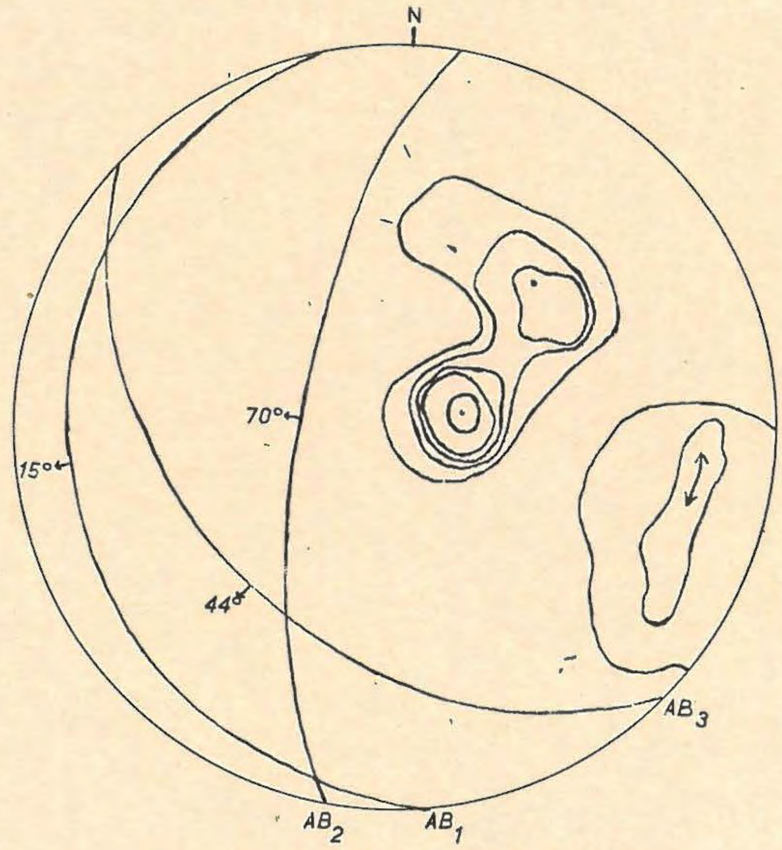
In this thesis the analyses of macro- and microfabric of rocks respectively are considered to be separate methods by which the solution of tectonic problems may be achieved. In general the foliation on which analysis is based is visible equally well in both hand specimens and thin sections, and there is little point in repeating techniques with thin sections that have been used successfully after megascopic study. In this connection de Sitter (1956) points out that one often gets a much clearer picture from megascopic study than from microscopic analysis, though the latter method may present the data in greater detail.

The fabric of the Lumwana tectonites lends itself to various possible types of microfabric analysis. Such analysis is usually commenced by assuming tectonic axes from macrofabric examination, and then cutting sections normal to these axes. This method is not well-suited to Lumwana as the three major sets of tectonic axes have different orientations in different sections. A second method is to orientate sections parallel to visible foliation, while a third is to cut sections normal to lineation. Both these methods are suited to examination of the orientation of prismatic minerals lying with their long crystallographic axes in the plane of foliation and possibly parallel to fold axes. Finally a fourth method is simply to orientate sections horizontal or vertical using geographical coordinates. This method has the advantage that the data are directly comparable with those gained from megascopic study, and is quite adequate for general-purpose microfabric analysis of the micas.

The statistical analysis of the orientation of phlogopite was conducted by the writer in two thin sections collected from outcrops of the mineralized schist at the Lumwana Clearing. These were selected because phlogopite is ideally suited to petrofabric analysis, having perfect cleavage perpendicular to the crystallographic c axes, while the colour is not dark enough to mask interference colours when the



Lumwana Clearing Trench B.



Lumwana Clearing, Western Edge.

c AXES OF PHLOGOPITE

FIGURE 25

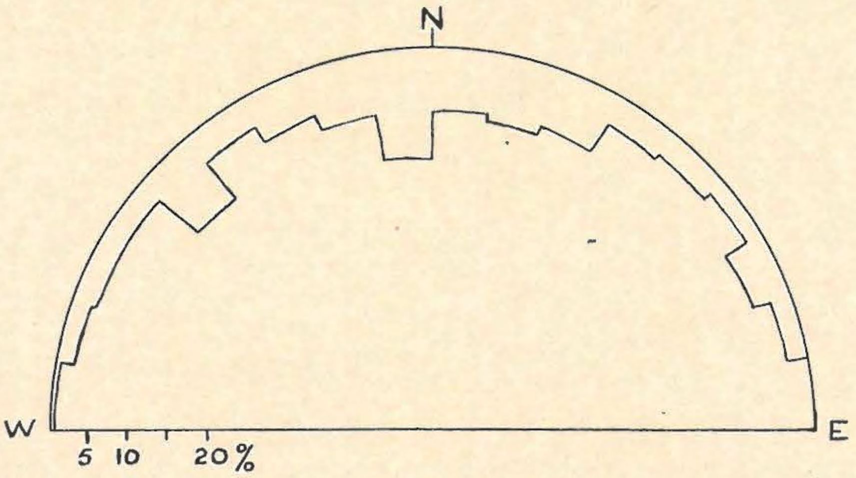
c axis is not quite vertical. The analysis was conducted with the universal stage, but without the aid of a parallel guiding slide, in the following way.

The slides were cut horizontal and orientated with geographical coordinates parallel to the edges of the slide, care being taken not to invert the section during preparation. The orientation of the sections on the universal stage was achieved by including a strip of plastic tracing material, long enough to reach the horizontal graduated scale, between the cover-slip of the slide and the upper hemisphere. The strip was orientated parallel to the long edge of the glass slide (made north-south), along the north-south cross-wire of the microscope eye-piece, and for convenience on the zero reading of the horizontal scale. Successive measurements were then made by moving the slide in the north-south direction until a traverse was completed. The slide and the plastic strip were then moved east or west and a second north-south traverse completed, and so on.

In practice measurements of the crystallographic c. axes of the phlogopite grains were made by direct measurement when the grains were orientated with c nearly vertical, or by measurement of the cleavage plane where c was nearly horizontal.

The results of the two analyses were plotted on a Schmidt net and contoured in the usual way with a 2% circle, and are presented in Figure 25. They show one well-developed orientation which appears to be normal to the axial plane of first folds, a second direction of preferred orientation much less distinct than that related to first folds, which is probably normal to the axial plane of second folds, and thirdly, in one analysis only, a distinct preferred orientation which is probably that normal to the axial plane of third folds.

The agreement between the two analyses and the data from macrofabric examination is quite good, although the bearing of the strike of the proposed third fold axial plane (132°) is greater than normal, and dips of the second and third fold axial planes are steeper than usual.



c axes of kyanite. Section parallel to foliation.
MM 115, 600′.

FIGURE 26.

In addition to the micas the prismatic minerals, especially kyanite, lie in the main foliation plane, and there is a tendency towards parallel orientation not always distinct in hand specimens. A section from a depth of 600 feet in drill-hole MM 115 was cut parallel to the foliation and north was assumed parallel to the lineation. The orientation of the kyanite crystals was then measured with the aid of a Dollar stage, tilt of the mineral grains being neglected. The results (Figure 26) show a wide spread in the orientation with a distinct preference towards the direction of lineation.

From these examinations it is concluded that in order to obtain the tectonic axes in a complexly folded area such as Lumwana, a large number of sections would have to be examined from all over the area, and the data averaged for the most accurate results. Single sections give data whichare pertinent only to the immediate vicinity from which the section is chosen, and all the periods of deformation need not be represented by the preferred orientations found in any one section.

At Lumwana the orientation of minerals with respect to the axial planes of first folds is dominant, and it is probable that orientation related to second and third folding resulted from reorientation of minerals already in existence. Thus it is implied that the highest grades of regional metamorphism were reached during first folding.

In addition to the statistical approach to microfabric examination, certain features visible under the microscope are of interest as they enhance the understanding of the mechanism of deformation. The terms competent and incompetent are widely used to describe rock behaviour, and although less frequently used, they also describe some mineral behaviour. Thus minerals with no cleavage, of which quartz is typical, often are cracked or fractured where they have behaved competently, while they may also flow and recrystallize following Riecke's principle where they behave incompetently. On the other hand minerals with a good cleavage are unlikely either to flow or fracture provided that deformation can occur by slip on cleavage planes. A particularly good example

Plate 20. Cracks in amphibole filled with chlorite. Upper Roan dolomite-hornblende hybrid. MMB 226, 1428'. Photomicrograph, x 23.

Plate 21. S-shaped bending of cleavage flakes of chlorite filling cracks in hornblende - see Plate 20. Photomicrograph, crossed nicols x 271.

<u>Plate 22</u>. Dolomite crystal deformed by gliding, now contained in a later-formed dolomite grain. Dolomite breccia in the mineralized horizon, MMB 156, 597'.

Photomicrograph, crossed nicols x 60.

<u>Plate 23</u>. Large untwinned oligoclase porphyroblast crowded with inclusions of hornblende. From a one-foot thick amphibolite in the Upper Roan, MMB 234, 451'.

Photomicrograph, crossed nicols x 23.

illustrating this point occurs in drill-hole MMB 226 at a depth of 1428 feet. The rock is a very coarse dolomite-hornblende hybrid in which some of the hornblende is traversed by irregular cracks which are filled with chlorite. Stress has caused differential movement of the amphibole fragments assisted by lubrication of the chlorite in the cracks. The result is that similar folding occurs in the chlorite so that axial cleavage planes are bent into a gentle S, and with crossed nicols the inter-cleavage flakes have the same extinction position in the upper and lower parts of the S, but a different position of extinction in the centre. Presuming that the amphibole originated after orogenesis, post-orogenic movement must have caused the fractures, the chlorite filling occurred under low-grade metamorphism, and additional movement caused bending of the cleavage planes.

Some minerals such as the carbonates and plagioclase feldspar accommodate stress by secondary twinning or gliding and the commonness of twins of these minerals indicates that minor stresses are usually active during or after crystallization of rocks. The occurrence at Lumwana of both these minerals in untwinned form in Upper Roan rocks is therefore remarkable, particularly in view of the tectonic history. In the case of dolomite, some grains are twinned in the middle of the grain and not on the margins, which suggests that twinning was present, but has been largely destroyed during recrystallization. The plagioclase grains on the other hand are either twinned or not; secondary twinning as defined by Vance (1961) is absent, and it is suggested that since the time of formation of this mineral, stress has not been particularly active, or in other words the feldspathization of the Upper Roan rocks occurred after orogenesis.

PETROLOGY

BASEMENT GRANITE.

The granite at the Lumwana Prospect is a pale pink, coarse-grained alkali granite.

In hand specimens the feldspar (oligoclase and pink microcline) and quartz are seen to be coarsely crystalline, the latter frequently being transparent. The average grain size is 3mm. but both quartz and feldspar tend to form clusters of minerals often more than 5mm. in size. Accessory biotite flakes are generally aligned in a common plane giving the rock a gneissic texture, but books up to 4mm. in size are scattered through the rock. In thin sections the microcline is strikingly twinned and usually constitutes most of the rock. The plagioclase is also twinned, and whereas the microcline is fresh, the plagioclase is partly sausuritized. Accessory minerals muscovite, chlorite and apatite are generally present together with minor amounts of magnetite or limonite, and tourmaline, hornblende, epidote and zircon may occur.

Coarse quartz-feldspar veins are common in both the granite and the Basement schists, cutting through schists and granite without truncation. These veins range in size from stringers to pegmatites several feet across. Quartz and feldspar are coarse and books of mica may reach 6 cm. in diameter. Idiomorphic tourmaline and rutile have been observed and coarse sulphide mineralization is sometimes present. Pyrite is the most common sulphide occurring in cubes up to 3 cm. in size, and chalcopyrite and bornite have been observed.

The term "alkali granite" is preferred to the simple term "granite" in the description of this rock as can be seen from the following tabulated alkali analyses.

Plate 24. Microcline granite. MM 115, 116'.
Photomicrograph, crossed nicols x 23.

a b

Plate 25. Euhedral epidote and magnetite in feldspathic quartz-biotite schist from the Basement. Note zoning and rare cruciform twin of epidote. MM 115, 155'.

Photomicrographs, a polarized light x 23,
b crossed nicols.

	Source	Number of analyses	K_2O	Na_2O
Lumwana Granite		3	5.42	4.31
Daly's Granite	Shand(1952)	546	4.11	3.48
Daly's Alkali Granite	"	12	9.0	
Copperbelt Grey Granite	Mendelsohn(1961)	5	4.03	3.09
Nchanga Red Granite	"	1	3.08	5.01

The Lumwana granite is similar in total alkali content to Daly's "alkali granite" while it is distinctly alkaline in comparison to his "granite". The Lumwana granite also contains considerably more potash and soda than the Copperbelt Grey Granite, which is the common granite of the Copperbelt area.

As both are pre-Katanga in age, and without evidence to the contrary, the Lumwana granite is regarded as being contemporaneous, though not necessarily strictly synchronous, with the Copperbelt Grey Granite. The chemical differences may have resulted from alkali contamination of the original magma, or from later metasomatism, but it is thought likely that the Lumwana granite is one of a number of autogenous phases of the regional pre-Katanga granite.

As the distribution of the alkalies has received considerable attention in recent years, particularly with respect to the Roan sediments which are discussed in detail later in this chapter, it is of interest to note that although the Copperbelt Grey Granite does not differ greatly from Daly's "Granite" in the quantity of alkalies, it is lower in each case. The deficiency in soda can be explained by regarding the Red and Grey Granites as differentiates of the same magma, but if this was the case the quantity of potash would still be low. The importance of these observations lies in consideration of possible later potash and soda metasomatism in the Katanga sediments; if such metasomatism has occurred in the sediments, it does not appear to have occurred in the Grey Granite of the Copperbelt, which, being pre-Katanga in age, must have been present at the time of metasomatism.

BASEMENT PARAGNEISS AND SCHISTS.

The formations classified as Basement at the Lumwana Prospect range from schist to gneiss. They are closely associated with, and intruded by the granite, and are separated from the Katanga System of rocks by an unconformity.

The Basement schists and gneisses are regarded for the most part as originally having been sediments, but some foliated feldspathic rocks may equally well be sheared granite.

Megascopic examination of the Basement formations reveals considerable variation in appearance and petrology largely due to the quantity of feldspar present, and in consequence the rock types are subdivided broadly as follows:

Paragneiss
Feldspathic schists
Quartz-mica schists.

Paragneiss.

The banded gneissic rocks in this group are composed largely of feldspar and in hand specimens are usually white or mottled pink and white. In thin sections orthoclase and microcline accompanied by oligoclase and quartz constitute most of the rock. Biotite is always present, and epidote, sphene, magnetite, chlorite, muscovite, hornblende and apatite are common accessories. The gneisses may occur adjacent to granite, but appear to be equally common as bands or segregations in the schists.

The occurrence of microcline and orthoclase together is suggestive of a different origin for the two minerals. As microcline is abundant in the granite its presence in the gneisses and schists is best explained by detrital deposition after weathering of an early granite. The orthoclase, absent in the granite, is metamorphic in origin.

Note. Microcline and orthoclase are distinguished by twinning. In addition, the microcline (except in the granite) is much more altered to sericite than is the orthoclase.

Feldspathic Schists.

The Basement schists are all generally feldspathic, but distinction is made between the very feldspathic types and the micaceous types which are susceptible to shearing.

The feldspathic schists include rocks which were originally arkoses and conglomerates, in which case the feldspar is probably largely detrital. Any sedimentary features originally in these rocks have been obscured by later tectonic foliations, but pebbles can be recognized in the conglomeratic sections. In contrast to these coarse-grained rocks, but still included in the same group, are crystalline schists of moderate grain size which contain feldspar probably mainly of metamorphic origin.

In general the feldspathic schists are grey, moderate to coarse-grained rocks with distinct schistose appearance. They may be equigranular, distinctly porphyritic, or contain deformed pebbles several inches in size. Quartz, oligoclase, orthoclase and brown biotite are always present, and epidote, muscovite, sphene, magnetite, chlorite and apatite usually occur. A few grains of microcline are often present and in some sections both orthoclase and oligoclase appear to be of two generations, an early generation of partly altered material accompanied by a later one of fresh mineral. This association points to a detrital origin for the microcline and some of the other feldspar, and a metamorphic origin for the remainder. The detrital microcline and some of the oligoclase may have been derived from an early granite, but if derived from a local source, the orthoclase could have come only from Basement gneiss or schist. This points to a long and complex history of metamorphism and reworking of the Basement rocks probably to the accompaniment of intrusion and remobilization of various granites.

Three samples of the feldspathic schist from drill-hole MM 115 were analysed for potash and soda. With the wide variation in quantity of feldspar in the Basement schists it is not surprising that abnormal variation was found in the quantity of the alkalies in the three samples.

	Depth	K_2O	Na_2O
Feldspathic Schist	98-99'	4.46	4.89
	130-131'	6.15	1.32
	154-155'	5.18	1.46
Average		5.26	2.56
Lumwana Granite, (Average)		5.42	4.31

The above analyses show that the potash content of the Basement sediments tends to be in equilibrium with the intrusive granite, while in two of the three analyses soda is found to be considerably less than in the granite. The recrystallized and foliated nature of the Basement schists prevents any explanation of these phenomena being anything but surmise as neither a metasomatic nor a sedimentary explanation can be criticized.

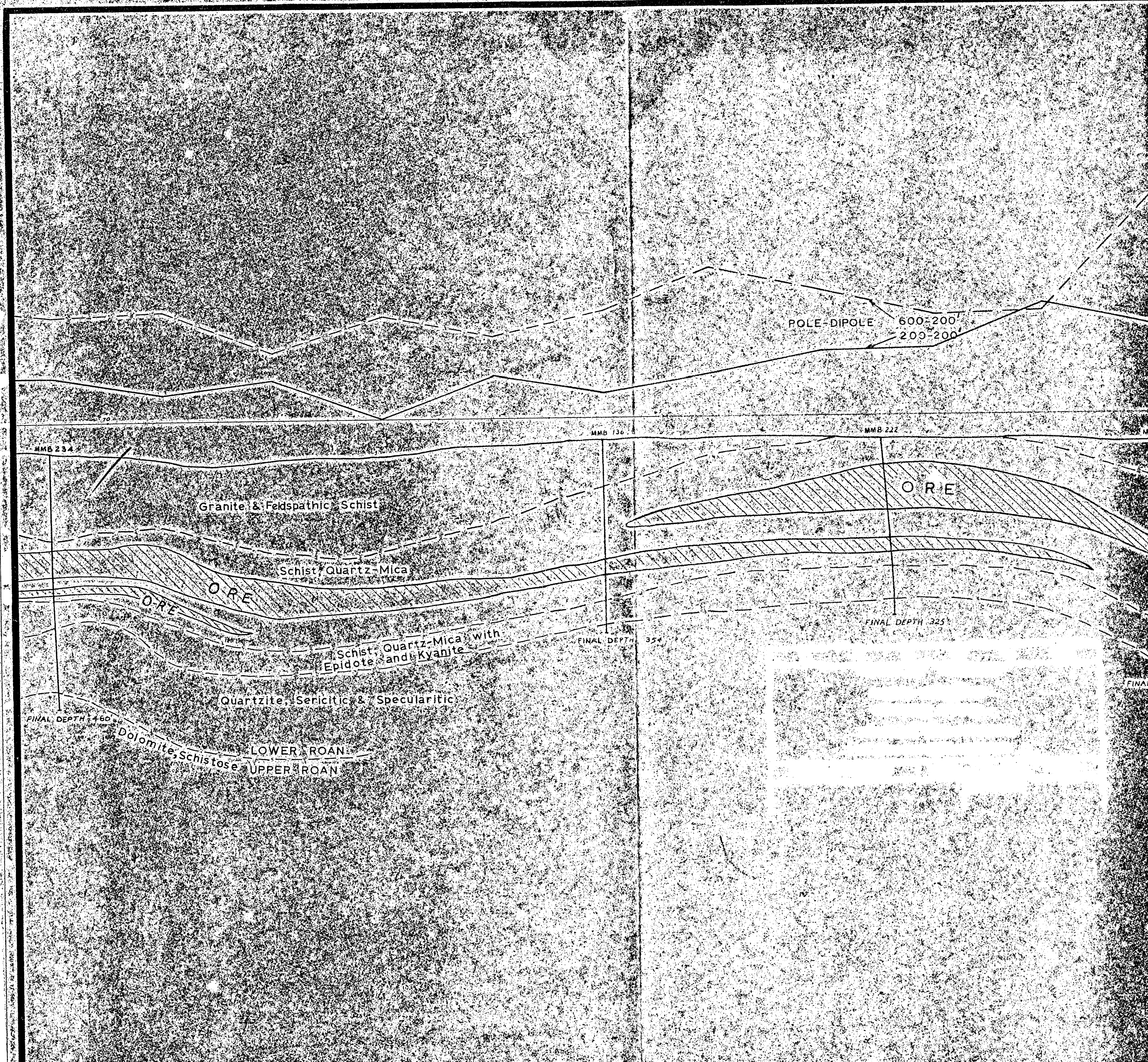
The equilibrium between schist and granite in the case of the potash may have been reached by feldspathization processes during intrusion of granite, or by later metasomatism of both the granite and the schist. The disequilibrium in the case of the soda, however, suggests that although soda enrichment of the schists could have occurred as a result of feldspathization during intrusion, it is unlikely that later soda metasomatism of both the granite and the schist occurred.

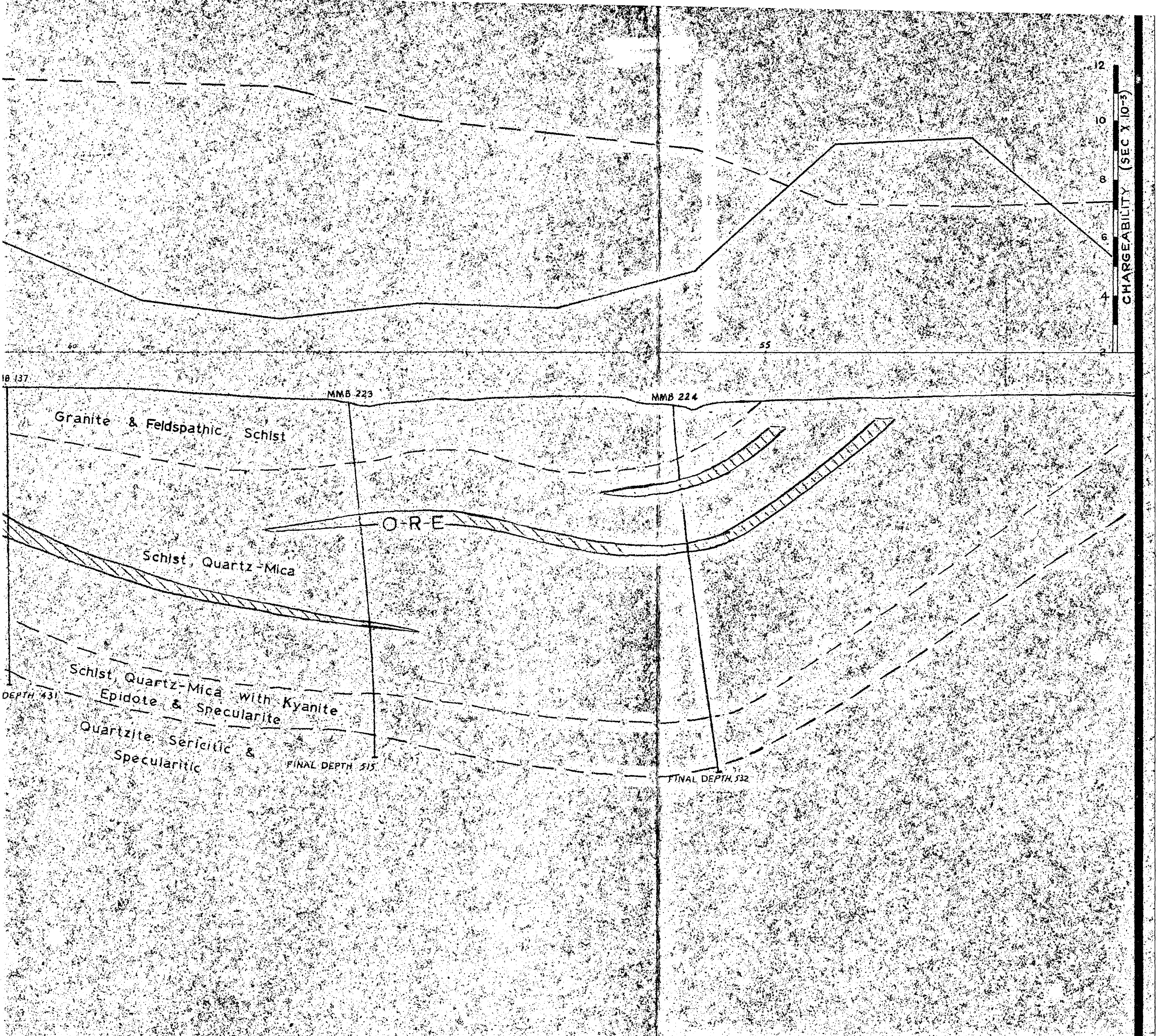
From the sedimentary viewpoint it is probable that the granite seen today is a remobilized and recrystallized older granite, so that the source of the Basement sediments is likely to have been similar in composition to the local granite. The variable composition of the Basement schists can be explained by normal operation of the geochemical cycle of potash and soda (see Rankama and Sahama, 1950), and in part is a function of the distance between the source and the site of deposition. Those sediments deposited close to the source retained a similar composition to the source rock, while those deposited further from the source lost progressively greater amounts of soda into solution, and the potash was deposited detritally, colloidally and by fixation in clay minerals.

Quartz-Mica Schist.

In the same way that the most feldspathic members of the Basement sediments are grouped together, so are the most micaceous members. The quartz-mica schists may have resulted in part from original sedimentary iron and clay concentration, or from redistribution and concentration of the constituents of the micaceous minerals during orogenesis and metamorphism. The location of much of the shearing and folding in the Basement appears to have been determined by the prevalence of micaceous bands, though in some cases the converse may well be true.

In hand specimens these schists are dark in colour as a result of the predominance of biotite over the other minerals. Quartz, orthoclase, oligoclase, chlorite, and muscovite are present in minor amounts. The quartz and to a lesser extent the feldspar, are often segregated from the micas into veins or lenses parallel to the schistosity, so that nearly mono-mineralic bands of biotite and quartz characteristically interfinger in this formation. Magnetite and epidote are often abundant in the biotite-rich bands, and occur as well-formed crystals. Mineralogically the biotite is of interest as, although brown in some specimens, it is more usually a dark olive-green variety with fairly high refractive indices ($n_Z = 1.631$). The green colour according to Deer, Howie and Zussman (1962) results from high ferric iron and low titania, the colour not being dependant on absolute values but the ratio between the two. The highish refractive indices are an indication of moderately high iron content. The epidote accompanying the green biotite is frequently twinned (polysynthetic and cruciform) and zoned with low-birifringent optically positive clinozoisite ($2V = 84^{\circ}$) forming cores on which more strongly birifringent clinozoisite or even epidote (optically negative with $2V = 88^{\circ}$) has formed. Both the cores and rims have a natural pale yellowish green colour and are slightly pleochroic.


POLE-DIPOLE
600-200'
200-200'
70
MMB 234
MMB 136
MMB 222
Granite & Feldspathic Schist
ORE
Schist, Quartz-Mica
ORE
ORE
Schist, Quartz-Mica with Epidote and Kyanite
Quartzite, Sericitic & Specularitic
FINAL DEPTH 460'
FINAL DEPTH 354
FINAL DEPTH 325'
Dolomite, Schistose
LOWER ROAN
UPPER ROAN



R. S. T. M. S. LTD.

LUMWANA PROSPECT
SHEET 1225/194 SECTION LINE 0
INDUCED POLARIZATION
TIME DOMAIN METHOD

SCALE 1:2,000 DATE MARCH, 1964

FIGURE 27

LOWER ROAN MINERALIZED SCHISTS.

The formations between the Basement unconformity and the distinctive overlying epidote and kyanite schists differ locally in lithology but display overall characteristics which enable them to be grouped into a single unit.

The thickness of the mineralized schists varies from 80 to 420 feet in the holes drilled at the Lumwana Prospect. In other areas on the Mombezhi Dome it is absent, while elsewhere, notably east of the Lumwana Prospect, it is over 1000 feet thick.

Stimulated by the economic interest, these formations have received special attention, and a separate chapter is included on the special features related to the ore minerals. It is however, impossible to divorce the special features from the more general description of this formation, and the following summary is included for clarity.

In the mineralized schists there are three main sulphide-bearing horizons separated by low grade mineralization or barren rock. Each overlaps upon another so that only rarely are all three found in the same drill-hole. Where drilling is widely spaced, correlation between drill-holes is sometimes doubtful, but in sections where investigation has been more detailed (e.g. Figure 27) the relationshipsbetween the different ore-horizons can be drawn with more certainty. It is found that distribution of the sulphides is zonal and systematic and that it is related to the thickness of the mineralized schist as a whole. Since the thickness is thought to have been determined by the topography prior to deposition of these schists, the distribution of the sulphides is thought to have been determined by the depth of the part of the basin in which deposition took place. Similar relationships are postulated for distribution of the uranium and cobalt minerals.

For descriptive purposes the ore-bearing schists are subdivided in the following pages into unmineralized and mineralized facies.

Unmineralized Facies.

The unmineralized facies in the ore-bearing schists include a lower facies (i.e. between the Basement unconformity and the first mineralization), and facies between and above the various mineralized horizons. The lower facies differs in lithology from the other barren facies and is therefore treated separately.

The lower facies is a coarse feldspathic schist containing bands with quartz augen several inches in diameter. It is regarded as originally having been an arkose with local interbedded conglomerates, but recrystallization and shearing have resulted in the destruction of sedimentary characteristics with the exception of a few pebbles which have retained a rounded shape. The facies varies from 0 to 50 feet in thickness so that mineralization can occur directly on the old land surface, and as this facies is probably largely residual in origin it is difficult to pin-point the Basement contact except where pebbles can be distinguished.

A sample of the lower facies from drill-hole MM 115 assayed 3.55% soda and 3.37% potash. Both figures are slightly lower than those of the average Lumwana granite, but whereas the potash is a little lower than in the average Basement schist from the same drill-hole, the soda is a little higher. This sample could be regarded as having been derived from the granite alone, with partial loss of alkalies by solution and abrasion during a short period of transportation from the source. It is more likely however, that the facies was formed from material derived from both the granite and the Basement schists with local variations depending on the relative exposure of the different Basement formations on the old land surface. The quantity and proportion of the alkalies in the resultant formation would therefore depend on the amount of each feldspar lost by solution and abrasion during transport, and the amount of dilution of granite detritus by the relatively soda-poor schist detritus. Since soda is lost into solution far more readily than potash, and yet the soda content is very high relative to the overlying

Plate 26. Heavy mineral concentrate containing zircon (z), rutile (r) and tourmaline (t) from the lower barren schists. Lumwana Clearing, trench B.

Photomicrograph, x 60.

Plate 27. Widely spaced shear planes in amphibolite. Calcite (colourless) and recrystallized hornblende in shear planes. MMB 225, 679'.

Photomicrograph, x 23.

formations, it is concluded that the lower barren facies consists of material transported only a very short distance from the Basement source.

In thin sections the lower barren schists are seen to consist mainly of quartz, oligoclase, orthoclase and biotite. Muscovite, chlorite, apatite and magnetite are usual accessories, and sphene, epidote and pyrite are less common. Zircon is abundant, and when examined after concentration by panning is found usually to be frosted, though clear crystal faces are not uncommon. The concentrate containing the zircon also contains small amounts of tourmaline and rutile.

In addition to the lower barren schists, barren rock occurs in thick bands between the various major mineralized facies, and in a band which varies from 0 to over 100 feet in thickness between the uppermost mineralized horizon and the over-lying epidote and kyanite schists. Lithologically the barren rock has a fairly uniform composition with three notable exceptions.

The normal barren rock is a quartz-biotite schist consisting of quartz, orthoclase, oligoclase, green or brown biotite and often garnet. Muscovite, apatite, sphene, chlorite and kyanite are common accessories and either magnetite or pyrite is usually present in small amounts. In some localities epidote is quite common while in others it is absent, and a little hornblende may be present. The barren rock differs from the mineralized facies mainly in the ratio of total iron to magnesia. This is illustrated by the characteristic association of mineralization with the light-coloured sericite or phlogopite schists, while the barren rocks are dark coloured and contain much biotite and garnet, and the hornblende where present. In some cases there is gradation between barren and mineralized formations whereupon small amounts of chalcopyrite may persist in what are regarded as barren formations.

The first exception to the normal occurs between the lower two mineralized horizons where present in some drill-holes. This barren formation differs from the other barren rocks in that it is very feldspathic and relatively coarse grained. Both oligoclase and orthoclase are present in quantities similar to those found in the lower barren schists, and it seems likely that after deposition of the lowest mineralized horizon there was local repetition of the cycle so that deposition of arkose preceded deposition of the second mineralized horizon.

The second type which is an exception to the normal has very local distribution and is assumed to occur as lenses. It is characterized by the abundance of magnetite. Magnetite is generally present in small amounts in the barren rocks, but in this rock type it occurs as a coarse dissemination over a few feet. These magnetite bands are thought to have resulted from iron concentration in the original sediment, concentration either by local detrital action or precipitation in a short-lived favourable environment. The coarsely disseminated character has undoubtedly resulted from metamorphic redistribution. It should be mentioned that these magnetite horizons are most common in barren rock well above the mineralized formations, and under no circumstances can these magnetite disseminations be regarded as replacements of sulphide disseminations or vice versa.

The third exception is that of rock rich in tourmaline. Such concentrations are uncommon but one about three inches thick was observed between mineralized beds in drill-hole MMB 234. The tourmaline occurs in abundant prismatic crystals up to 1 cm. in length together with biotite, muscovite and quartz, and with no sulphides in the immediate vicinity of the tourmaline. The tourmaline itself is an iron-poor schorlite, pleochroic brown to very pale yellow, and devoid of inclusions. It is identical to tourmaline observed in a coarse quartz-tourmaline vein which crops out on the Lumwana Clearing and is presumed to occur high up in the orebody. It is also identical to very much smaller prismatic tourmaline grains which are scattered throughout the succession.

The occurrence of tourmaline in the Roan succession at the

Copperbelt has received attention in recent years from Davis (1949) and Darnley (1960) in particular. Both agree to the presence of detrital Mg-tourmaline in the succession which commonly has overgrowths of very pale authigenic mineral, and in addition both draw attention to interstitial prismatic tourmaline. Both authors favour a hydrothermal metasomatic origin for this tourmaline, but Davis does consider that it need not be introduced. At Lumwana consistency of composition and lack of overgrowths in all occurrences examined indicates that the tourmaline has homogenized to what is probably a stable form. The origin is not reflected in the present-day form and although a metasomatic origin is thought unlikely by the writer, speculation into tourmaline syngenesis at Lumwana would be futile.

Igneous Rocks.

In addition to the unmineralized rocks already described, dark, usually schistose, amphibolites are quite common between the granite and the ridge-forming quartzite. These amphibolites at the Lumwana Prospect vary from a few inches to a few feet thick and although usually found above the mineralized formation, they also occur beneath and between mineralized horizons.

On microscopic examination the amphibolites are found usually to consist almost entirely of hornblende. Calcite and garnet occur frequently, and a little oligoclase, quartz and biotite are sometimes present.

In the absence of any discovered pyroxene and lime feldspar, there is perhaps doubt whether these amphibolites have in fact an igneous origin. The mono-mineralic occurrences and narrowness of the bands makes a metamorphic origin unlikely; it is possible, however, that they were formed by a process of metamorphic differentiation in which the amphibole was concentrated as all extraneous material was drawn away to be emplaced elsewhere. Metamorphism usually causes minerals to form into clusters and such clusters could have become bands during subsequent deformation. The amphibolites occur between obvious

Plate 28. Alteration of olivine (o) and bronzite (b) to serpentine (s). Other minerals are tremolite (a), talc (t) and magnetite. Serpentinite, MM 197, 324'.

Photomicrograph, x 23.

Plate 29. Strained oligoclase enclosing biotite flakes sub-parallel to twin planes. Large dark grains are biotite and the subhedral colourless grains are quartz. Quartz-mica schist, MM 197, 407'.

Photomicrograph, crossed nicols x 60.

sedimentary facies and if formed by metamorphism, why is there not concentration of other minerals by differentiation?

A sedimentary origin for the amphibolites would require an original composition of the sediment close to that of the amphibole mineral, and this is considered unlikely.

By excluding a sedimentary or metamorphic origin there remains only an igneous origin for the amphibolites. This is favoured by the writer, and the narrowness of the bands suggests that the amphibolites are more likely to have been extrusives than intrusives.

Although there is little evidence for an igneous origin for the amphibolites in the overturned limb of the major Lumwana anticline, a thick body of basic and ultrabasic rocks is present in the equivalent normally dipping strata in the northeastern part of the Lumwana Prospect. The best intersection of this body occurred in drill-hole MM 197, the petrology of which is summarized below.

Depth	
0-300'	Quartz-mica schist.
300-420'	Serpentinite, talc schist and amphibolite.
420-650'	Quartz-mica schist with pyrrhotite.
650-750'	Quartz-mica schist with chalcopyrite.
750-816'	Interbanded schist and amphibolite.
816-934'	Gneiss and feldspathic schist. (End of hole.)

Twelve thin sections cut from cores of this drill-hole have the following composition (mineral identifications from data presented by Deer, Howie and Zussman, 1962-63).

Depth	
301'	Talc-biotite schist from the upper contact of the igneous body. Section composed largely of dark brown biotite and pale brownish talc, with subordinate quartz, oligoclase and orthoclase.
305'	Talc-anthophyllite schist. Mainly talc with porphyroblasts of anthophyllite up to 6mm. long.

324' Serpentinite. Original olivine (optically positive 2V=85°, Fo_{95}) and bronzite (optically positive 2V=80°, En_{83}), largely serpentinized, occupy most of the section. Talc is abundant, and although not plentiful, magnetite is common in the section. Idiomorphic secondary tremolite is also common (colourless, refractive indices Z=1.640 and X=1.614, composition 82% tremolite - 18% ferroactinolite) and a few large porphyroblasts of a very pale chlorite occur.

350' Serpentinite. The section contains serpentine, talc and magnetite only.

356' Serpentinite. The section is similar to that cut at a depth of 324'. It contains less relict olivine and bronzite and more serpentine and talc. Magnetite, tremolite and chlorite are also present.

381' Amphibolite. The rock is composed of coarse (7mm.) hornblende with subordinate biotite and magnetite. Also present in this section is approximately 5% apatite.

391' Talc schist. The section is composed mainly of talc and chlorite. Magnetite, serpentine and calcite are present in small amounts.

400' Amphibolite. The section is composed of coarse hornblende through which are scattered porphyroblasts of biotite reaching 8mm. in size. A very small amount of orthoclase is also present.

407' Quartz-biotite schist. Cut from the lower contact of the main intrusion, this section contains quartz, oligoclase, orthoclase, biotite and a little hornblende. Clinozoisite (positive 2V= 74°) is common and apatite and magnetite are also present. A feature of the section is porphyroblastic oligoclase enclosing flakes of biotite which sometimes lie in twin planes of the plagioclase. The plagioclase is generally strained and sometimes bent.

417' Amphibolite. This section was cut from a second intrusive band, and was found to contain hornblende and a little biotite.

427' Quartz-biotite schist. The section, cut from typical schist below the intrusive bodies, resembles that from between the intrusions at a depth of 407'. It contains oligoclase, orthoclase, quartz, biotite and hornblende. Clinozoisite, magnetite, apatite and a little microcline are also present.

780' Amphibolite. Section from below the mineralized horizon. It consists of abundant hornblende together with garnet, biotite, oligoclase, orthoclase, magnetite, quartz, apatite and a little chlorite.

From these few sections it is clear that there are two principal rock types in the main igneous body - a saxonite type and a more acid amphibolite type. Although the saxonite occurs above the amphibolite the exact relationships between the two types have not been established. Other facts which have a bearing on the history of emplacement of these rocks are:- that the amphibolite lower part of the intrusion includes some intercalated schists, and that the composition of these amphibolites is similar to other amphibolites one of which occurs beneath the mineralized zone in drill-hole MM 197, and others being found in other drill-holes at roughly the same stratigraphic level.

A possible history is that an original magma was differentiated into ultrabasic and more acid fractions, and that the more acid fractions, emplaced or extruded first were followed by a final stage in which the saxonites were intruded.

As mentioned earlier the igneous rocks occurring in the mineralized facies are usually schistose and for this reason are regarded as having been emplaced prior to orogenesis. Evidence supporting this view is twinning and straining of plagioclase.

The possibility that these igneous rocks are of the same age as the gabbros (scapolite amphibolites) of the Upper Roan has been considered, but differences of size of intrusion, texture, grain size and acidity, together with mineralogical differences such as the twinning and absence of twinning in feldspar, the absence and presence of scapolite, chlorite and the colourless amphiboles, and the occurrence of magnetite in the one case and ilmenite in the other, make such a view untenable.

Mineralized Facies.

(a) Major constituents.

The ore-bearing schists include members ranging from those rich in sulphide through progressively leaner types to barren schists. This variation is presumed to occur gradually as the ore dies out laterally, but vertically rock rich in sulphide often gives way to barren rock within a few millimetres. The sulphides tend to be confined to three main bodies within the ore-bearing schist, but where the formation is thick additional small sulphide-bearing horizons, lenses or segregations are quite common.

The primary copper sulphides occur in pairs as follows:-

Plate 30. Large kyanite porphyroblast (k) displaying typical sieve texture. Other minerals are quartz (q), phlogopite (p) and tourmaline (t). Lower barren schist, Lumwana Clearing.

Photomicrograph, x 23.

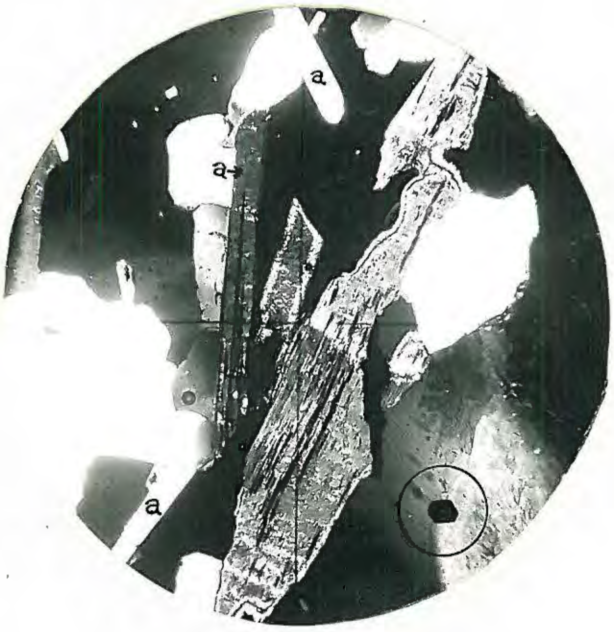


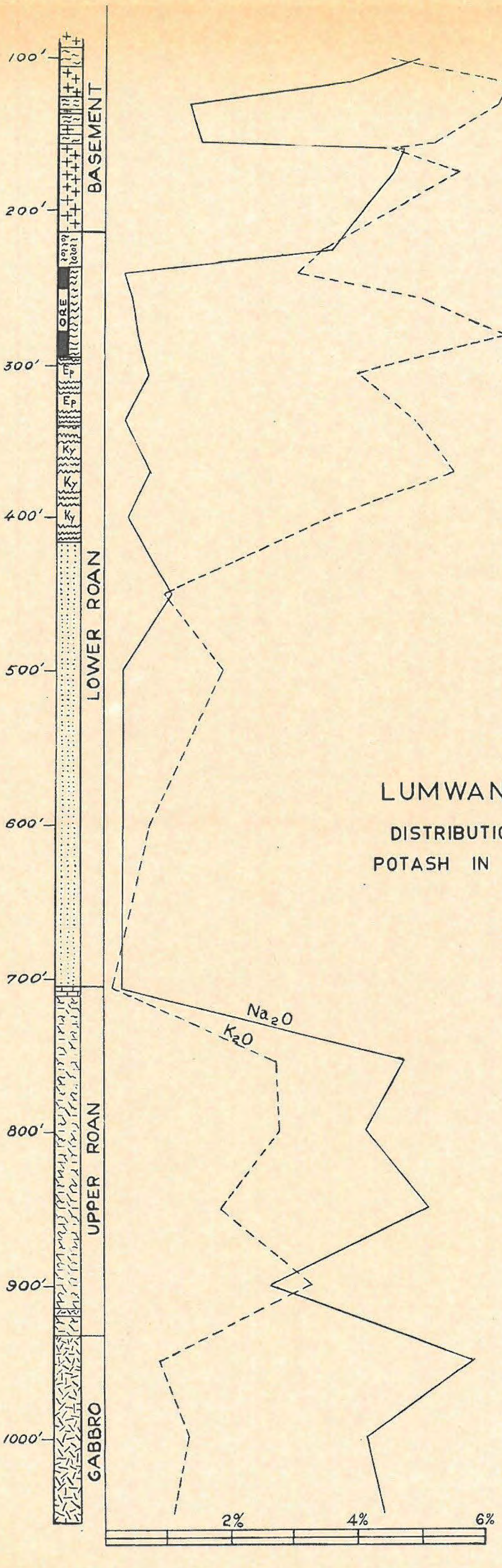
Plate 31. Mineralized quartz-phlogopite schist containing anthophyllite (a). Note small euhedral bornite crystal. MM 115, 280'.

Photomicrograph, crossed nicols x 60.

chalcocite plus bornite, bornite plus chalcopyrite, and chalcopyrite plus cubanite. Occasionally some pyrite is found with the copper-rich pairs, and chalcopyrite and cubanite occur with both pyrite and pyrrhotite. The sulphides occur disseminated in the rock in bands varying from inches to tens of feet in thickness, with the result that the grade can be highly variable over narrow widths or fairly constant over quite large widths. Coarse mineral aggragates of over three centimetres are common, but much of the sulphide occurs as grains less than 0.5 mm. in size.

There are distinct relationships between the nature and distribution of the gangue minerals and the copper sulphides. Most noticeable among these is the occurrence of the best mineralization in association with light-coloured micaceous rocks containing either muscovite or phlogopite. In contrast, good copper mineralization is absent in the hard dark rocks rich in biotite, garnet and amphibole. In addition to the pale micas quartz is always present, and kyanite and orthoclase are common in the mineralized schist; biotite and garnet occur in moderate to small amounts and microcline, oligoclase, anthophyllite, chlorite, apatite, tourmaline, zircon and sphene have been observed. A typical sample from surface was found to be made up of quartz 45%, phlogopite 40%, kyanite 14% and limonite, chlorite and apatite making up the remainder.

It has been mentioned that whereas copper occurs in light-coloured micaceous rocks, the dark rocks rich in garnet and iron minerals are barren or only poorly mineralized. This feature is quite apparent in megascopic study of the rock and no analyses are needed to show that iron in minerals other than sulphides is very much higher in the unmineralized formations than in the mineralized formations. However, within the ore itself the variations in composition are slight by comparison and without chemical analyses cannot easily be observed.



LUMWANA PROSPECT

DISTRIBUTION OF SODA AND
POTASH IN DRILL-HOLE MM 115

FIGURE 28

During the course of investigations of the Lumwana Prospect composite samples of assay rejects were thoroughly blended and used for concentration and flotation tests. Portions of heads, concentrates and tails were partially analysed as required. Most of the composite samples were made up between selected assay cutoffs, but wherever distinct mineralogical changes occurred separate samples were prepared. The result was that in some drill-holes the entire orebody was included in a single sample; in others two or three consecutive samples were used to cover the orebody, usually where high grades were separated by low grades; and the remaining samples were of two orebodies in the same drill-hole with unsampled material in-between.

In addition to analyses of composites one drill hole was selected for systematic alkali analysis. This was drill-hole MM 115, selected because it was one of two holes which were drilled through the Lower Roan into Upper Roan formations, because it was centrally situated and because it was typical of the central part of the prospect. Each sample from this hole was a one foot length selected at intervals down the hole to ensure a true picture of the vertical distribution of the alkalies with at least three determinations from each major lithological group. The results of these analyses are presented in Figure 28.

In this diagram there is little variation between the potash content of the granite and Basement schists, the lower barren schists, the orebody, and indeed the overlying epidote and kyanite schists. There has therefore been no enrichment of potash in the orebody. The soda content on the other hand, which is high in the lower barren schists, drops off abruptly in the orebody and remains low through the Lower Roan succession.

On the Copperbelt the high potash content of the shale type orebodies has received considerable attention in recent years mainly as a result of work by Darnley (1960) and Vaes (1960). The most striking examples taken from "The Geology of the Northern Rhodesian Copperbelt" (Mendelsohn 1961) are as follows.

	Cu	K_2O	Na_2O
Roan ore-shale	3.15	9.88	0.34
Roan impure dolomite	1.1	4.4	0.3
Chambishi ore-shale	3.43	7.51	0.19

Both authors postulated large-scale soda and potash metasomatism in the Copperbelt orebodies and Darnley was severely criticized in the discussion following his paper by a number syngeneticists, especially Garlick and Davis. Garlick maintained that the shale orebodies are enriched in potash primarily because of fixation of potash in clay minerals, and it follows therefore that the quartzitic orebodies poor in clay minerals such as that at Lumwana would not exhibit this enrichment. The potash content of this type of orebody would depend more on the amount of detrital potash minerals present, than on the clay content.

The factors controlling distribution of potash come into play during textural breakdown of potash-bearing rocks, with chemical alteration. Without alteration the final product would be composed of the original constituents. Chemical alteration involves the agency of water, either acting on the rock in situ, or on grains weathered by means other than chemical. This alteration is most marked in feldspars which with quartz constitute most of the rock.

Dana (1958) notes that orthoclase is frequently altered with removal of potash and formation of kaolin, and that albite may alter to kaolin and sericite. This is apparently not in accordance with the chemistry, as potassic sericite can hardly be formed from a mineral containing no potash, and it is more likely that sericite is formed as a result of breakdown of potash feldspar. Rogers and Kerr (1942) draw attention to the frequent occurrence of microcline in detrital sediments, but make no mention of detrital plagioclase. In addition to feldspar, detrital mica is a source of potash, probably a major source. Moore (1963) draws attention to the abundance of biotite in bottom sediments, and a number of writers (Rankama and Sahama, 1950, among others) refer to the formation of glauconite by diagenetic alteration of biotite. To what extent the micas are responsible for metal fixation and concentration is unknown, but it is established that clay minerals fix metals such as copper and cobalt as well as potassium, and clay minerals and mica are closely related by decompositional and metamorphic reactions, as well as by structure. The potash content of sediments other than evaporites depends mainly on the content of detrital potash minerals, the content of clay minerals which contain or absorb potassium, and on the processes of weathering and deposition. These processes are important because they cause the variations in clay content which in turn are the main control of potassium distribution, and in addition, according to Rankama and Sahama (1950), potassium may be removed by plants and formed into insoluble organic compounds.

It is clear that the processes are very complex as leaching of potassium is not accomplished only by plants, but is normal in rock alteration. If this alteration is accompanied by weathering of feldspar the potassium released from biotite may be fixed immediately by the clay minerals the formation of which is illustrated in the following equations:

(1) $\underset{\text{albite}}{Na_2O.Al_2O_3.6SiO_2} + 2H_2O \rightarrow \underset{\text{clay}}{2H_2O.Al_2O_3.2SiO_2} + 4SiO_2 + Na_2O$

(2) $\underset{\text{orthoclase}}{K_2O.Al_2O_3.6SiO_2} + 2H_2O \rightarrow \underset{\text{clay}}{2H_2O.Al_2O_3.2SiO_2} + 4SiO_2 + K_2O$

(3) $\underset{\text{orthoclase}}{3(K_2O.Al_2O_3.6SiO_2)} + 2H_2O \rightarrow \underset{\text{muscovite (or sericite)}}{2H_2O.K_2O.3Al_2O_3.6SiO_2} + 12SiO_2 + 2K_2O$

In these equations soda and potash go into solution and the potash is fixed immediately or soon after by adsorption onto the clay minerals. Finally the muscovite or sericite from (3) and primary muscovite may be deposited detritally with some potash feldspar, or may also be broken down to clay minerals as follows:

(4) $2H_2O.K_2O.3Al_2O_3.6SiO_2 + 4H_2O \rightarrow 3(2H_2O.Al_2O_3.2SiO_2) + K_2O$

Metamorphism of the formations at Lumwana is discussed elsewhere, but it is pertinent to point out that the reactions given above are capable of proceeding in the reverse direction during metamorphism. Those involving the formation of feldspar probably take place at higher grade than those in which mica is formed, the latter possibly commencing under load of sediment only. The formation of biotite is more complex than that of muscovite, and probably takes place from clay minerals with adsorbed potassium and iron from any of several sources; or it may be formed directly from glauconite, greenalite, chamosite or similar minerals. Muscovite under higher grades of metamorphism and particular conditions may be altered to kyanite, andalusite or sillimanite as well as to potash feldspar as follows:

$$H_2O.K_2O.\ 3Al_2O_3.6SiO_2 \rightarrow K_2O.Al_2O_3.6SiO_2 + 2(Al_2O_3.SiO_2) + H_2O$$

Soda once in solution does not readily form rich deposits except in evaporites, and the full understanding of its distribution in sediments will not be obtained without vast research.

According to Rankama and Sahama (1950) when sodium and potassium are extracted from rocks sodium is removed in solution while potassium, although it goes first into solution, is adsorbed by and even enriched in clays. The adsorption which starts as soon as the potassium goes into solution is completed in the sea, whereas the sea becomes enriched in sodium. From this it can be correctly concluded (A) that during the history of the earth the sea has become progressively richer in sodium, or that in early times (late- Precambrian for the purpose of the thesis) the sea had less sodium than it has today. Rankama and Sahama also state that the difference in behaviour during weathering of soda and potash may in part be due to the greater resistance of potash feldspar, and it can be further concluded (B) that soda content of sediments other than evaporites depends almost entirely on the content of detrital soda minerals.

Deposition of sediment involves the inclusion of water which is expelled during compaction and lithification. The words "almost entirely" in conclusion (B) make provision for the trace of soda which would unavoidably be left behind when the connate waters were expelled.

In considering the validity of conclusion (B) the composition of sediments in general provides surprising facts. Consider first an arkose which, if conclusion (B) is correct, would normally be the sediment with the highest soda content. Soda-rich arkoses are common and can therefore be regarded as one end member of this part of the classification of sediments. Since arkose is coarse-grained and deposited close to the source, it is reasonable to assume that the other end member would be a fine-grained sediment deposited far from the source, e.g. shale or mudstone, and the soda content would decrease with grain-size reduction and distance from the source. This assumption is not true and it will be shown in the following paragraphs that the shale end-member is surprisingly rich in soda, and the rock types intermediate between shale and arkose are poorer in soda than either end-member.

Considering that any difference in composition between arkose and granite is negligible, the average composition of 546 granites (Daly quoted by Shand 1952) includes 3.48% soda, which, if all the soda is in albite is equivalent to nearly 30% albite in the average arkose.

The average composition of 78 shales (Clarke quoted by Shand 1952) includes 1.31% soda, 3.25% potash and 15.47% alumina. Using data from Dana (1958) for the composition of albite, orthoclase and kaolin, and assuming 11.6% potash in mica (combined muscovite and biotite), these figures can be broken down as follows and compared with the average clay composition (Lewis quoted by Shand 1952):

	Na_2O	K_2O	Al_2O_3	Shale	Clay
Albite	1.31	-	2.16	11%	12.3%
Orthoclase	-	1.86	2.03	11%	
Mica	-	1.39	4.60	12%	-
Kaolin	-	-	6.68	17% (Clay silicates)	43.9%
Quartz				49%	31.3%
Calcite, limonite, Apatite, etc.					12.5%

Orthoclase is assumed to be equal to albite because if the plagioclase is present as a detrital mineral, it is likely that potash feldspar will be present in greater or at least equal amounts.

The tabulation shows that Lewis' figures include very much less feldspar than the breakdown of the average shale, and more clay silicates even if the mica in the shale is regarded as clay minerals with adsorbed potassium. There is reasonable agreement between the remaining constituents. In order to achieve a better balance between the two sets of figures it is necessary either

(1) to regard all or nearly all the feldspar as albite, or

(2) to include some soda in the clay minerals.

Since there is no reason to suppose that soda feldspar is likely to be more abundant as a detrital mineral than potash feldspar, it is necessary to revise conclusion (B) to read "that soda content of sediments other than evaporites depends on the content of detrital soda minerals, and the content of clay minerals which contain or adsorb sodium."

Support for this conclusion was obtained from study of sediments of the Gulf of Paria, west of Trinidad, by Hirst (1962). The results of his analyses were as follows.

	Number of analyses.	%Na	%K
Delta sands	3	0.43	0.74
Platform sands	12	0.88	0.95
Clays	12	1.67	1.87

The unusually low potassium is explained by removal and fixation of potassium by plants in the heavily vegetated Orinoco Basin, and although this explains slight sodium enrichment, it does not explain the sympathetic sodium-potassium variation with rock type. Hirst concluded that soda is present in montmorillonite and also in the intersheet positions in illite. No "soda illite" was identified and the presence of sodium in illite, and the relatively low potassium content of the sediments are attributed to degradation of illite either at the source or during transit. The failure to replace the sodium in the illite by potassium after deposition was attributed to potassium deficiency in the gulf waters; or the rates of sedimentation may be too great to permit geochemical equilibrium being attained.

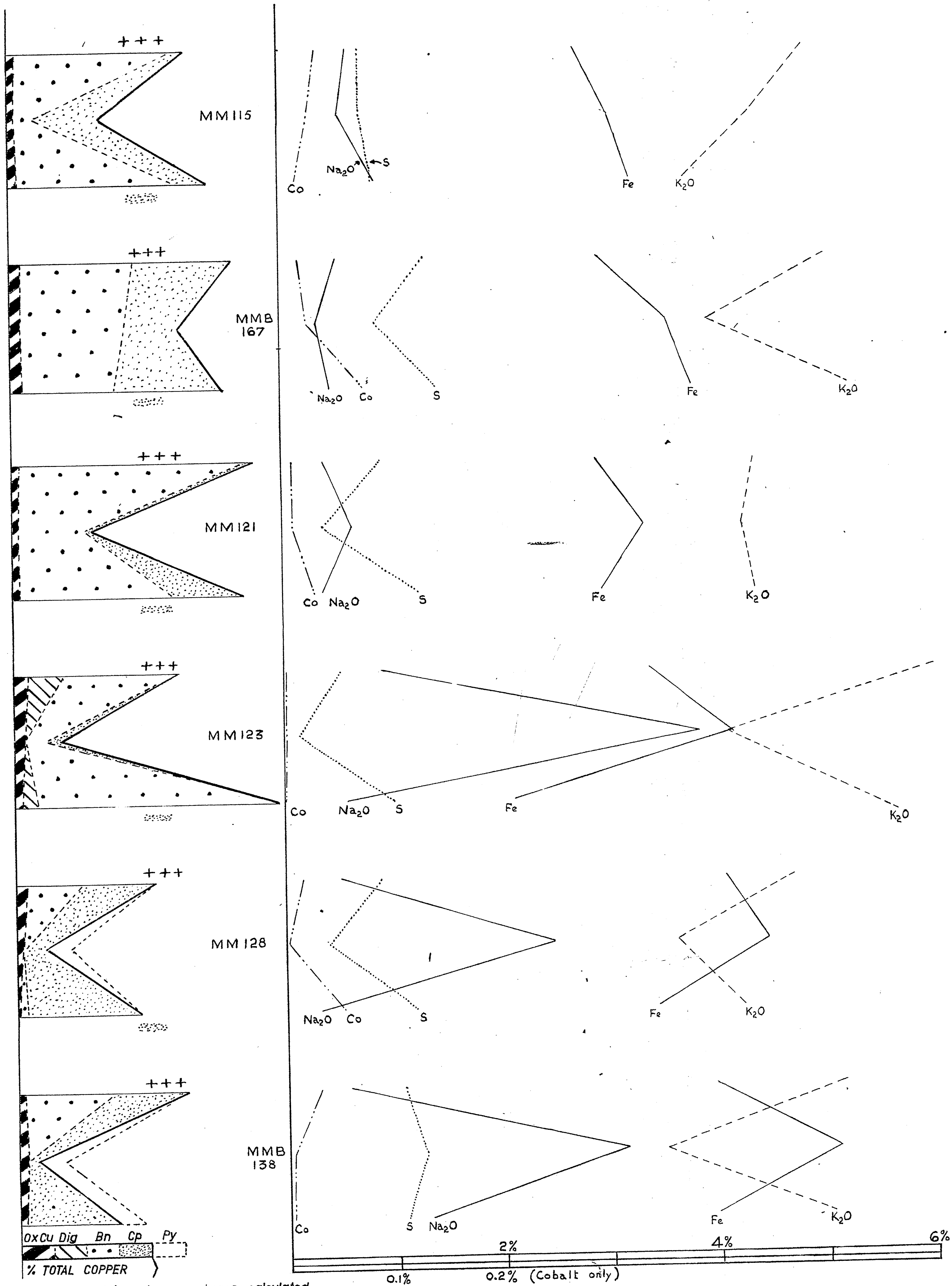
A problem in these investigations is the preparation of samples; if the water is allowed to evaporate the dried salts will enrich the samples in soda; washing may break loose bonds and remove constituent ions, and dehydration by suction may assist such a breakdown. In a letter to the writer Hirst states that he is not of the opinion that simple washing with distilled water would remove sodium from intersheet positions, and describes how his samples were prepared by washing the disaggregated material with distilled water using a suction filter until the effluent was chlorine-free. Among others who record high soda in present day sediments.Welby (1958) points out that in his samples water ranged from 1/5 to more than twice the dry weight of the sample, and where an equal amount of water was present 1.07% sodium was left on evaporation (Na_2O = 1.44%). Because of the wide variation in water content, depending on the amount of clay present in the sediments it is impossible to apply a constant correction to analyses, and as far as can be ascertained the analyses below include dried salts.

Source	Rock Type	%Na_2O	%K_2O
Moore (1963)	Proto-arkose	2.2	2.4
	Feldspathic sand (source 1)	1.6	1.6
	Feldspathic sand (source 2)	0.9	1.0
	Proto-graywacke	2.8	3.0
Welby (1958)	East Gulf of Mexico sediment	3.47	2.93
	West Gulf of Mexico sediment	3.06	2.85
	Globigerina Oozes	3.57	2.11
Bradley and others (1942)	Sea-floor near Ocean City, Maryland	1.97	1.74
	North Atlantic Deep	1.80	1.02
	Bartlett Deep	1.41	0.64

The tabulation above illustrates the diversity of alkali content in present-day sediments. Those samples analysed by Eddington and Byers (in Bradley and others, 1942) are low in both soda and potash when compared with those from the Gulf of Mexico, which in turn are abnormally high in soda even if a correction of 1.44 for soda in sea water is subtracted. The Gulf of Mexico may be abnormal as no definite relationship was established between alkali content and depth, although a general correlation between soda and potash was found to exist. The abnormality of these samples arises from the quantity of silt brought into these waters by the Mississippi River. This silt is remarkable in that it contains 1.5% soda, 2.3% potash and only 8.5% alumina (average of 235 analyses by Steiger quoted by Shand 1952), and if the assumptions used previously are applied once again the composition includes 13% albite, 13% orthoclase, less than 1% mica and 14% kaolin. That the calculated composition is peculiar indicates that the actual composition is peculiar, and the most likely reason for this is that of abundant albite relative to orthoclase.

The figures quoted by Moore from Buzzards Bay, Massachusetts, are of great interest as they illustrate sympathetic distribution of soda and potash from the shallow water proto-arkose through the feldspathic sands to the deeper water proto-graywacke. Furthermore the soda and potash are richest in the deep water sediment. Moore states that the feldspar content is largely related to the type and distance of the source rock (which can be submarine), and the deeper water sediments consist of abundant clays, micas, fine grained quartz and feldspar, accessory minerals and small rock fragments. It seems likely that as in the Gulf of Paria, soda and potash increase with clay content, as well as with feldspar content.

The most important factor, and that which is most difficult to assess, in the study of the distribution of soda in ancient sediments is the amount of connate water remaining in the rock at the time of metamorphism. The connate waters in ancient sediments are likely to have contained less soda than in present-day sediments in the same way that the sea was likely to have contained less soda than it does today. Sea water may have had a greater affinity for soda than today, breaking the weak bonds that apparently exist today between soda and the clay minerals. Low grade metamorphism or even diagenesis during compaction may have resulted in the formation of soda silicates long before the connate waters were completely expelled, while on the other hand much of the sodium held in intersheet positions of clays would probably be expelled with the connate waters (a view shared by Hirst in a letter to the writer). In this connection it is interesting to note the conclusions of Engelhardt and Gaida (1963) that montmorillonite has a diffuse double layer of cations between the layers and the outside. Thus under compression a clay will reach a state where it contains a nearly salt-free pore solution, but complete homogenization is never attained as small droplets of salt solution are trapped and surrounded by clay particles with interrupting double layers. Similarly clay bands can halt the flow of salt water and cause concentration in porous sandstones within the clays. It is therefore



Mineral percentages calculated from Cu/S ratios

DISTRIBUTION OF MAJOR CONSTITUENTS

FIGURE 29

necessary to revise conclusion (B) yet again to read "that soda content in sediments other than evaporites depends on the content of detrital soda minerals, the content of clay minerals that contain or adsorb sodium, and the content of connate waters at the time of metamorphism."

It remains only to establish the composition of sediments poor in alkalies and the average of 253 sandstones (Clarke quoted by Shand 1952) included 0.45% soda, 1.32% potash and 4.78% alumina. Using the same basis as before, the composition is albite 5%, orthoclase 5%, mica 4%, kaolin 4%, and quartz + heavy minerals + minor constituents 82%.

In the case of the Lumwana orebody, soda is normally 0.53% of the rock, a figure only slightly higher than that of the average sandstone. Any local high soda could occur in:

(1) evaporites or

(2) detrital accumulations, or

(3) clay concentrations, or thin sandstones between clay rich beds.

In the preceding section the lower barren schists were described as soda-rich arkoses and conglomerates, and in addition, barren rock occurring between orebodies was regarded as similar in origin to the lower barren schists. It seems likely therefore that a tendency existed for at least one repetition of a cycle of arkosic sediments followed by ore-bearing sediments, the latter being soda-poor. The alternative view that the sodic sediments were derived from evaporites is untenable because of the lack of any typical evaporite minerals, (gypsum and anhydrite are well preserved elsewhere in the succession), while aluminous minerals tend to be associated with copper ore rather than with barren or low grade rock.

In Figure 29 the vertical distribution of the alkalies can be compared with that of copper in six drill-holes. In each, consecutive samples were made up into three composites which were blended and analysed, selection being made on the basis of ore grade and on the nature of the sulphide minerals present. In each drill-hole zones of good grade copper mineralization are separated by a zone of lower grade, and while in the first three examples the grade in the middle is not much lower than the outer zones, in the remaining three it is considerably lower. There is also a tendency for the higher grades to contain a greater percentage of sulphides rich in copper than the middle zone of lower grade.

In the first three examples there is little variation in the soda content, but in the remaining three there is striking increase in soda in the middle zone relative to the adjacent zones of higher grade. In addition there is a less noticeable tendency for potash to vary sympathetically with the copper. Thin sections show that the soda in the low-grade middle zones of these examples is in oligoclase, which, in the absence of any evaporite minerals, or abnormal alumina content, must be either metasomatic or detrital.

In the initial study of the data from the remainder of the composite samples a quick comparison between copper and the alkalies is presented in the following table.

Number of assays	Percent Copper	Percent Soda	Percent Potash
4	< 0.5	2.71	4.07
8	0.5-1.0	0.89	4.64
13	1.0-1.5	0.51	4.43
12	1.5-2.0	0.59	4.73
16	> 2.0	0.51	4.45
41	> 1.0	0.53	4.53

From the above table and the data on the preceding pages it is concluded that where copper exceeds 1% soda feldspar is uncommon, but where copper is less than 1% soda feldspar may be abundant. In addition there is a slight tendency for the potash content to be lower

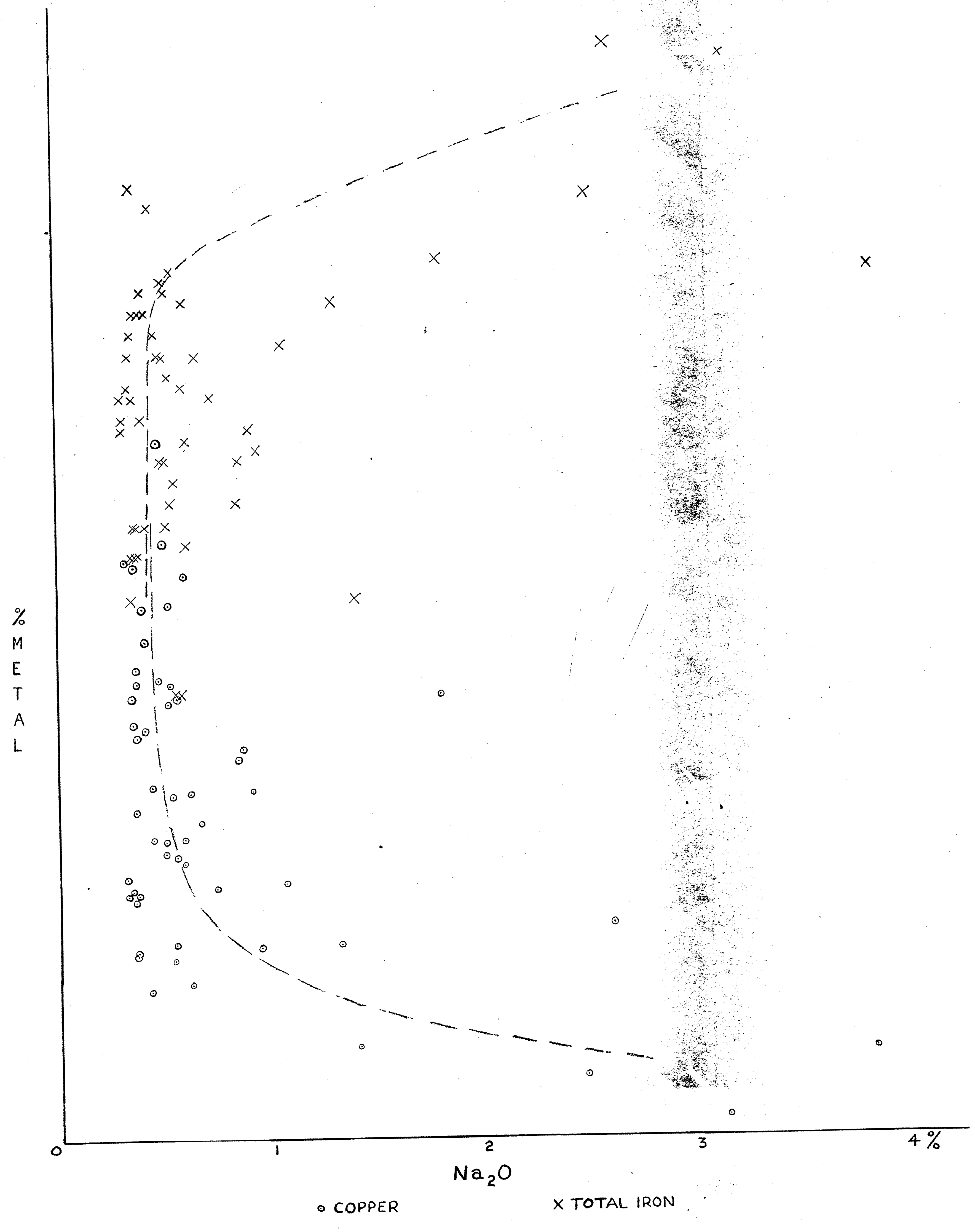


FIGURE 30

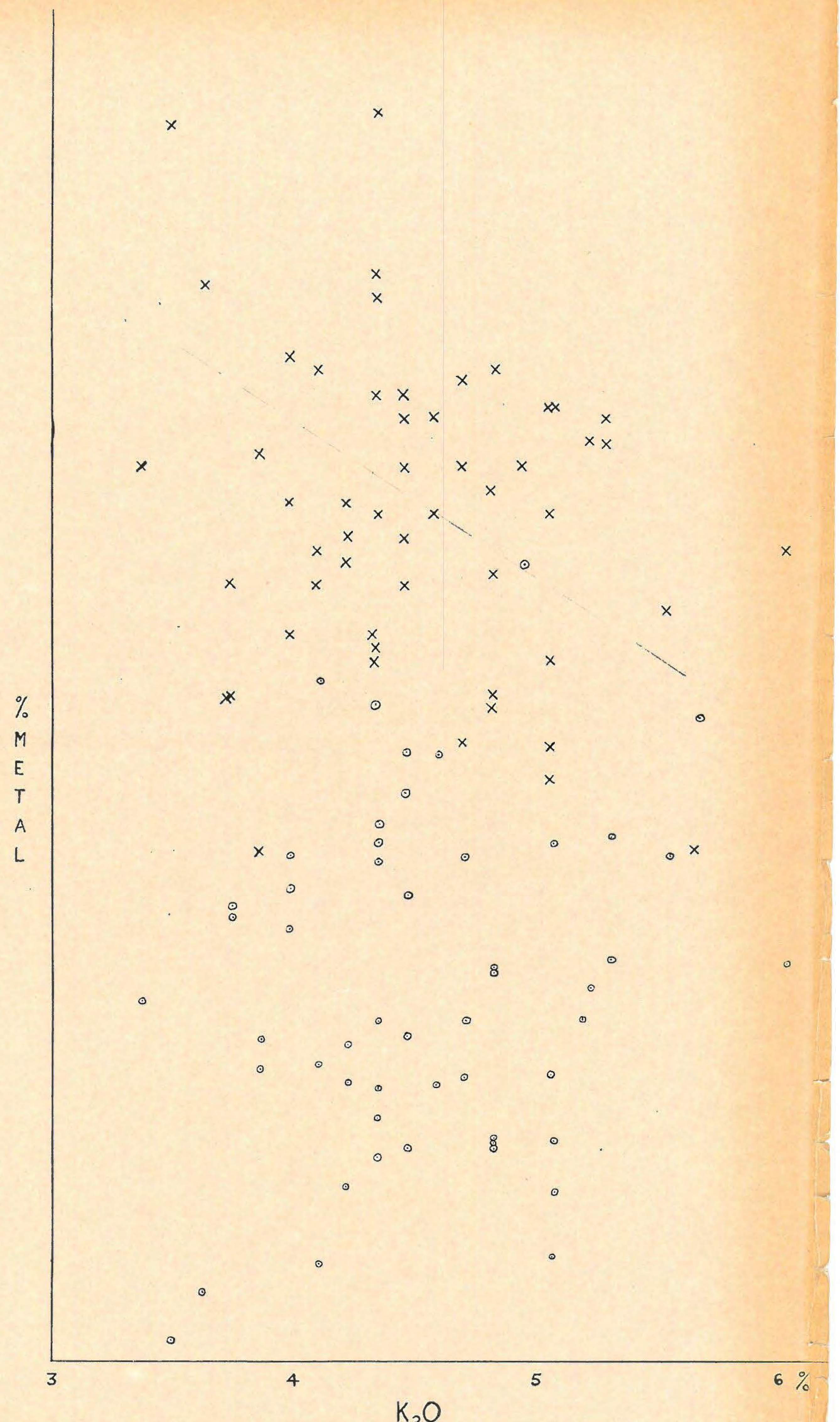


FIGURE 31

than normal where copper is also low and soda is high.

A metasomatic origin for the high soda in the low grade zones is unlikely because of the limited distribution, and the writer prefers a detrital origin for the following reasons.

(1) The lower barren arkosic schists and the barren schists which occur between orebodies are essentially similar, and are therefore likely to have been formed in a similar manner.

(2) The barren schists in (1) grade vertically and laterally into ore. This gradation takes place in such a manner that where soda feldspar is abundant copper mineralization is sparse, and copper grades reach 1% or more where soda feldspar in turn is rare.

(3) There is slight inverse variation between potash and soda in these samples. This variation is expected if the sediments were derived from the Basement; the breakdown of soda feldspar and soda loss into solution would result in relative enrichment of each of the remaining constituents.

(4) Other considerations lead to the conclusion that the copper mineralization is syngenetic and any systematic variation between soda and copper implies a similar origin.

(5) Any exceptions from the normal can be explained logically on sedimentological grounds.

In Figures 30 and 31 copper from the composite samples is plotted against soda in the one case and potash in the other. These samples include those with low copper and soda in addition to the particular cases described where low copper is associated with high soda content, but nevertheless a trend is apparent wherein the soda content is high where copper is low. In two cases both copper and soda are sufficiently high to constitute exceptions (see (5) above) for which explanations can be found either in local rapid transportation of soda feldspar to the environment of copper deposition, perhaps due to greater relief in certain localities; or alternatively in local reworking of separate sodic and cupriferous sediments with redeposition close to the original site of deposition.

In contrast to the graph of soda versus copper which shows a definite relationship between the two in the ore-schists, the plot of potash versus copper is haphazard.

Moore (1963) and Hirst (1962) have established that copper (and cobalt) vary according to clay content where they are present in minor amounts, and that metals such as these are attached to the clay minerals, and furthermore are largely transported as such. It has been shown that potassium in modern sediments varies sympathetically with sodium, and that both are present in greatest quantity in arkoses and clay-rich rocks, it follows therefore that in deeper water modern sediments where copper is only present in small amounts it varies sympathetically with both soda and potash.

The copper-bearing sediments at Lumwana bear no analagy to these sediments, that is, soda and potash do not vary sympathetically, copper and soda are antipathetic and copper and potash are unrelated. The reasons for the lack of analogy can be a combination of:

(1) copper is too abundant ,

(2) the clay content is too low , or

(3) conditions prevailing at the time of deposition have no present-day analógy.

It is concluded therefore that deposition of the best copper mineralization at Lumwana occurred in fairly shallow-water conditions where detrital soda feldspar was rare, but where potash in the sediments originated from detrital feldspar and mica as well as from clay minerals.

From the table showing the variation in content of soda, potash and copper, and Figure 31, there is a tendency for potash to vary sympathetically with copper where copper is low and soda high. The slight increase in potash as copper increases is attributed to impoverishment in soda, the variation occurring only over the lower ranges of copper content because of complete loss of soda before the higher ranges of copper content are reached. Since there is no overall relationship between copper and potash, and since it has been concluded that potash is present largely as detrital feldspar and mica, the copper cannot have a detrital origin except under unusual local circumstances.

The distribution of the alkalies enables certain conclusions to be drawn regarding the environment of copper deposition; these conclusions with respect of the Lumwana orebody are:

(1) that copper was deposited sufficiently far from the source of the rock-forming minerals that soda feldspar was destroyed,

(2) that copper was deposited sufficiently close to the source that potash feldspar or mica was deposited detritally, while clay minerals were not abundant.

(3) From (1) and (2) it can be inferred that on a uniform submarine slope copper deposition would be found at an optimum depth in fairly shallow water.

If the conclusions cited above are valid, it is to be expected that systematic variations would be found between iron or sulphur and soda or potash.

In Figure 30 it can be seen that like copper the iron content is variable where soda remains less than 1%. However, unlike copper which tends to be low, the total iron tends to be high when soda exceeds 1%, so that the low grade arkosic parts of the orebody are iron-rich. Since these parts of the orebody are made up mainly of detritus it can be assumed that detrital iron silicates or oxides are the main source of iron. Where detrital soda feldspar is absent, detrital iron minerals are less common or absent.

It has been shown that detrital potash minerals occur within the ore-bearing schists, and it is likely that detrital iron was present to a larger degree than is visible now as a result of metamorphism.

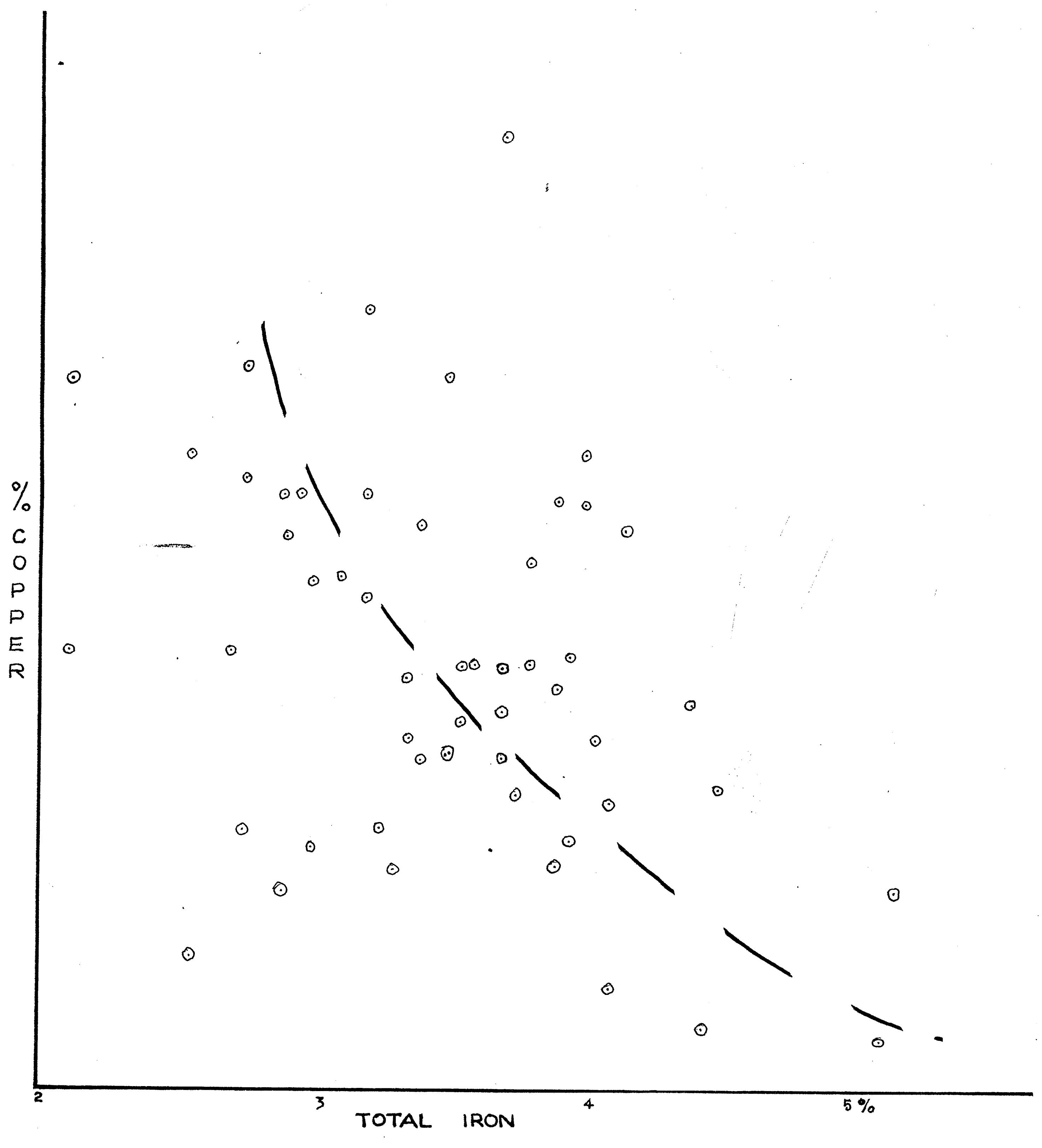


FIGURE 32

Samples were of sufficiently large widths to include some of the thin barren amphibolites in some cases; these samples were abnormally high in iron but neither copper nor potash was particularly low.

Some samples contained pyrite in quantities sufficient to result in abnormally high iron assays. Normally it would be expected that such samples would be from deep water sediments in which detrital potash minerals would be uncommon, and the potash content low. This, however, need not be true as the deeper water sediments would be richer in clay minerals, which would fix potash from solution, and potash would be low only if it was deficient in the waters at the site of deposition. Such samples are therefore likely to be high in iron and low in copper, but potash need not be low.

The reason for postulating a detrital origin for part of the iron in the orebody is apparent in Figure 31. Where potash is low total iron is high, and there is a slight tendency for copper to be low; where potash is high total iron is low while copper tends to be high. The relationship between iron and potash is sufficiently distinct to indicate some degree of similarity of origin. Since potash is largely detrital some of the iron is likely to be detrital in origin and the inverse relationship could be the result of mechanical separation.

Total iron content displays a tendency to increase at the expense of copper (see Figure 32) in the quartzitic ore-schists at the Lumwana Prospect, but copper and iron are variable through the range of potash content. (Fig. 31) Low copper and high iron in a rock of normal intermediate potash content may indicate conditions under which pyrite was deposited (usually deep water.) Low copper and high iron in a rock poor in potash indicates shallow water oxidizing conditions in which detrital iron minerals were separated mechanically from detrital potash minerals. Low copper and high iron in a rock rich in potash may be the result of poor mechanical separation of detrital minerals in the sample selected, hence shallow water conditions; or good

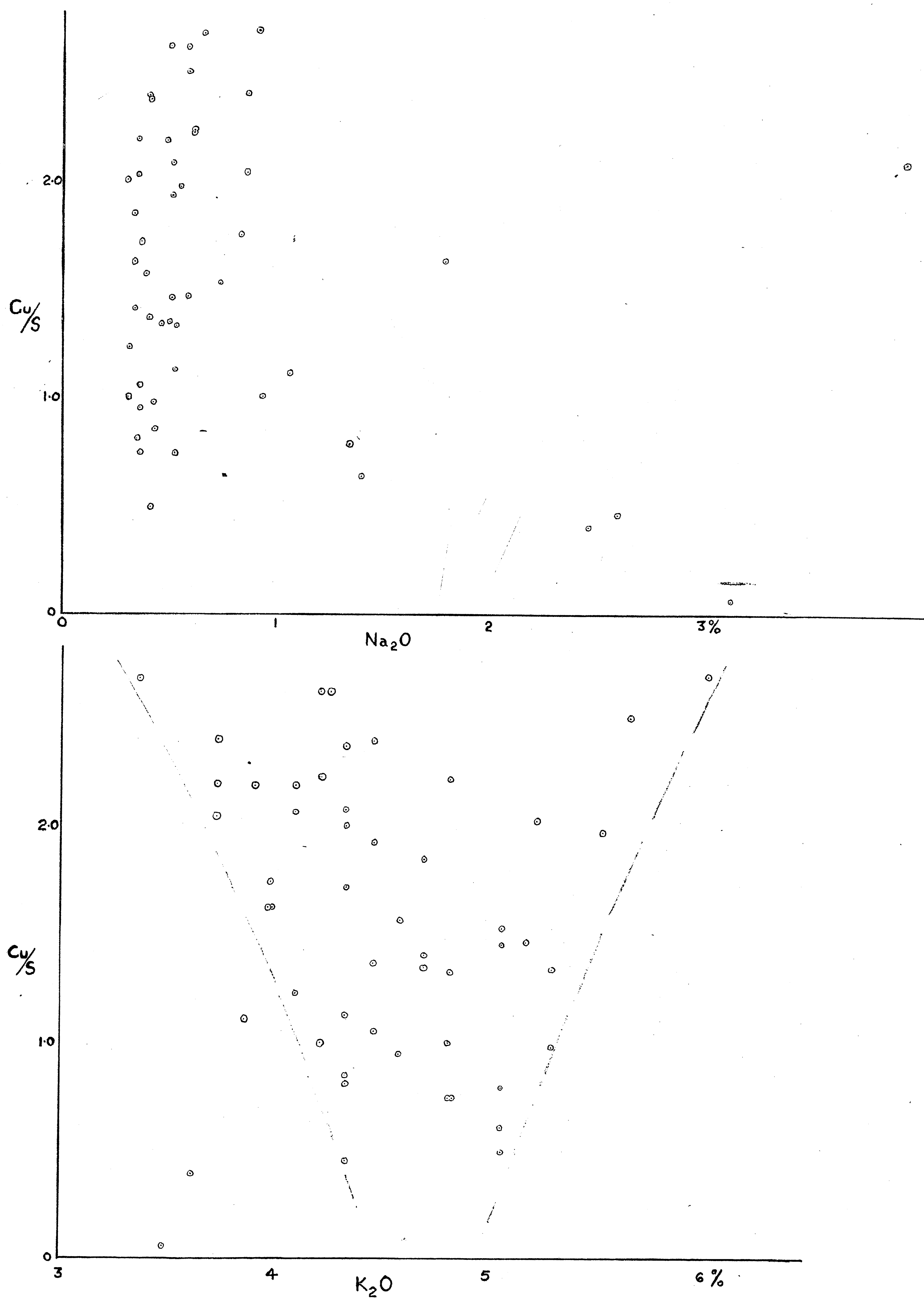


FIGURE 33

separation of the detrital iron minerals but local abundance of diagenetic pyrite; or local abundance of pyrite deposited in shallow water from intermingling of currents, or any particular reason prohibiting the precipitation of copper minerals, or resulting in impoverishment of copper in solution.

The constancy of potash through sediments deposited at intermediate depths to sediments deposited at depth, and the variability of potash content in shallow water sediments is illustrated further when the sulphur assay data are examined. It is established in a later chapter that chalcocite and bornite are found in shallow water sediments, while pyrite and chalcopyrite are found in deeper water sediments. In Figure 33 the alkalies are plotted against Cu/S, and since the ratio of Cu:S in bornite is 2.47 and in chalcopyrite is 0.99, between these two figures it can be assumed that the sulphides are bornite and chalcopyrite, while below 0.99 the sulphides are chalcopyrite and pyrite, and above 2.47 they are bornite and chalcocite.

Soda remains fairly constant over the complete range of Cu:S ratios with exceptionally high soda mainly where the Cu:S ratio is low or fairly high. These high soda assays therefore come both from ore which is characterized by pyrite and bornite. In Figure 34 sulphur is shown to range from less than ½% to nearly 2% where soda is less than 1%. Where soda exceeds 1% the distribution is sufficiently scattered to show that the soda-rich samples may have a considerable sulphur content in both the ferruginous and cupriferous cases. The association of high soda with copper-rich sulphides is not unexpected as the shallow water arkosic sediments containing soda feldspar are likely to contain chalcocite or bornite. The association of high soda with moderate to fair pyrite mineralization is less easily explained as these pyritic samples are not from deep water sediments but from shallow water arkosic sediments. Such pyritic sediments have been described over granite hills in the Copperbelt

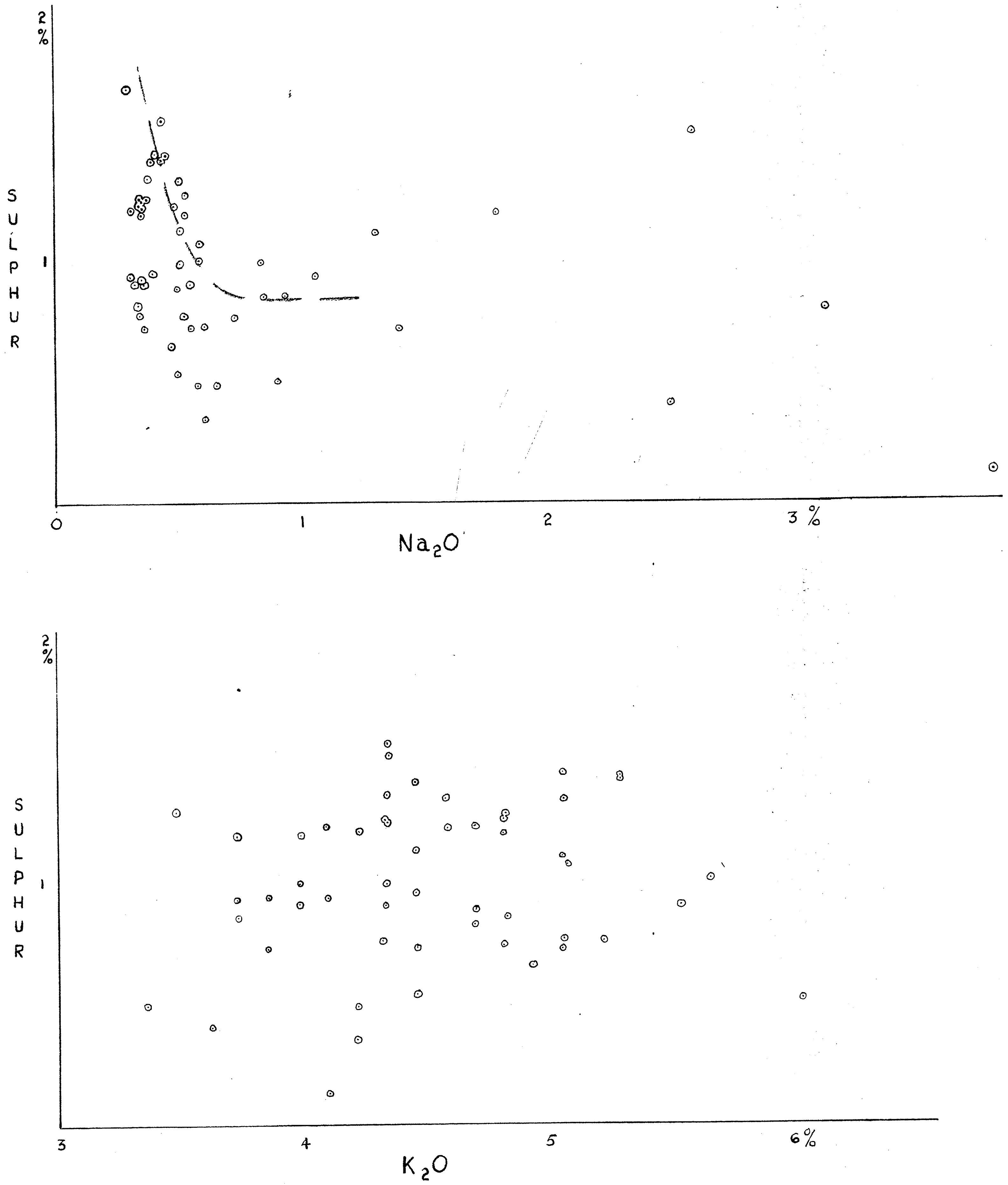


FIGURE 34

mines, and similar circumstances may be operative at Lumwana. Other explanations are that the pyrite is detrital or diagenetic, or alternatively the abundance of soda feldspar may represent a climatic change to extremely arid conditions in which wind blown feldspar fragments were deposited well away from the shore.

Perhaps the most significant graph in the understanding of the distribution of the alkalies at Lumwana is that in the lower half of Figure 33, where the spread of potash content is greatest where the copper sulphur ratio is greatest; as the ratio decreases the spread decreases. Since the high copper sulphur ratio is thought to indicate shallow water conditions of chalcocite-bornite deposition, the large potash spread will be the result of poor sorting of detrital minerals. In deeper water corresponding to the lower copper:sulphur ratios sorting of detrital minerals will be more complete and clay minerals with adsorbed potassium will be more abundant. In the case of the Lumwana orebody, sediments in progressively deeper water were such that as potash from detrital sources decreased, potash adsorbed on clay minerals increased so that the total tends to increase to about 4.75% potash (average 4.53%).

The two exceptions in Figure 33, where low potash is associated with pyritic sediments, contain the lowest copper of all the samples analysed. They confirm that in addition to the normal deep water deposition, pyritic sediments are deposited in shallow water.

In the lower part of Figure 34 the distribution of sulphur is shown to be completely unrelated to potash. The factors which control the distribution of potash do not therefore control the distribution of sulphur.

The salient conclusions concerning the petrology of the Lumwana ore-bearing schists are:

(1) There are three main ore-bearing horizons which may be contiguous or separated by low-grade mineralization or barren rock.

(2) Barren rock occurs between the orebodies, as thin bands within them and stratigraphically above the ore. The composition is similar to the gangue within the orebodies except for:

(a) feldspathic rocks regarded as arkoses,

(b) magnetite-bearing rocks regarded as having detrital iron concentration,

(c) amphibolites, regarded as having an igneous origin.

(3) Barren rocks between the Basement and the orebodies are regarded as arkoses or arkosic conglomerates.

(4) The richest copper mineralization occurs in light coloured micaceous rocks. In contrast, copper mineralization is poor in dark ferruginous formations, and in bands rich in soda which grade into barren arkose.

(5) The average soda content where copper exceeds 1% is 0.53%, and potash is 4.53%. The soda content is much lower than that of the Basement, while the potash content is approximately the same as that of the Basement.

(6) The high potash content of the mineralized schists is regarded as resulting from weathering and deposition of the constituent minerals of the Basement alkali granite, gneisses and schists. These constituents in the newly deposited sediments included detrital potash feldspar and mica, and clay minerals with adsorbed potassium, subsequently altered to mica.

(7) The soda content is not regarded as abnormal, and is thought to have been controlled mainly by clay content and amount of connate water present at the start of metamorphism, and to a much lesser extent by detrital feldspar.

(8) Lack of relationships between copper and potash preclude a detrital origin for any large amount of the copper.

(9) Relationships between copper, sulphur and soda indicate a tie between them which should be reflected in the postulated origin of the copper and sulphur. Since there is no evidence for a

metasomatic origin of soda, it is unlikely that the copper and sulphur are metasomatic.

(10) The origin of the copper is syngenetic, sedimentary and non-detrital. The environment of deposition was such that potash feldspar and mica were abundant, whereas soda feldspar was rare. This corresponds to shallow water conditions with an optimum depth for copper deposition.

(11) Low-grade copper, marginal to the better mineralization was deposited in:

(a) shallower water with detrital soda feldspar as well as potash feldspar, and detrital iron oxides and silicates.

(b) deeper water with more homogeneous potash content due to decrease of detrital potash feldspar and increased potash fixation on clay minerals, and pyrite.

(12) Pyritic sediments were deposited in shallow as well as deep water.

(b) Minor Constituents and Trace Elements.

In addition to alkali determinations and ore examination of samples from the various Lumwana drill-holes, spectrographic analyses were conducted for trace elements. The results were reported in six categories as follows:

0	N.D.	Not detected.
1	B.V.	Barely visible.
2	T	Trace.
3	F.T.	Faint.
4	F.S.	Fairly strong.
5	S	Strong.

Of the elements which were sought As, Be, Bi, Ge, Li, Sb, Ta, Tl, V, Zr, Pt, and Pd were not detected, and Zn was barely visible throughout. The remainder which were present in significant quantity were Ag, Cr, Mn, Mo, Pb, Sn and Ti, and of these Cr was fairly strong throughout.

In order to present the data on trace elements in relation to Cu, Cu/S and K_2O, the reported categories were assigned values from 0 to 5 respectively, and all results over a particular range were meaned and plotted accordingly. Potash was selected for comparison to indicate possible detrital relationships, while the relationships to actual copper sulphides and hence the environment of deposition is shown up by the Cu/S ratio.

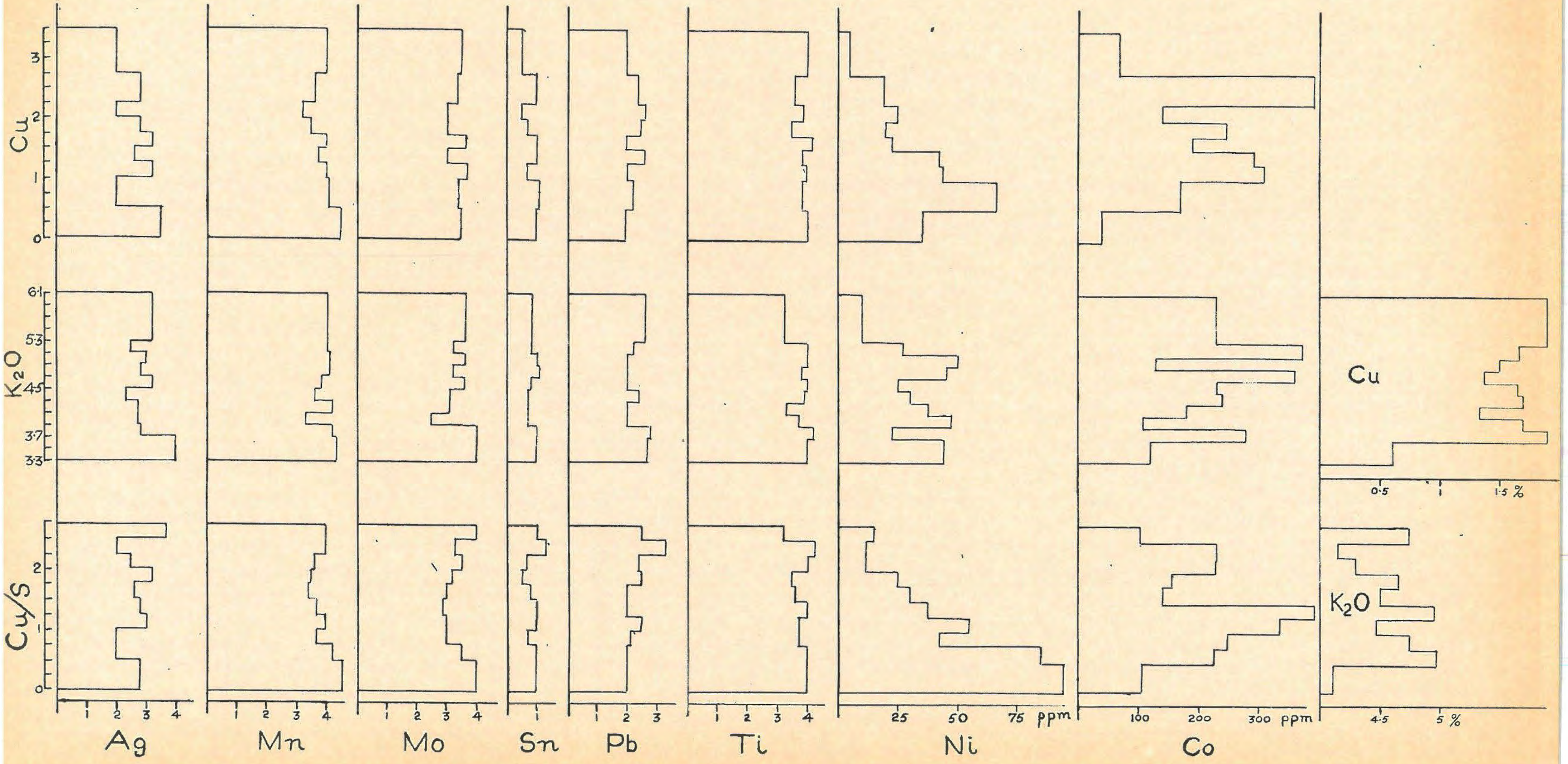
Cobalt and nickel are present in greater amounts than any of the other elements listed. The average cobalt content is in the order of 250 parts per million, with several samples containing more than 0.05% and two exceeding 0.1%. The content was sufficiently high to warrant chemical assay and the data for this discussion are these results. Nickel, determined chromatographically, is always much less abundant than cobalt, and averages out at less than 50 parts per million.

Uranium is also present in the orebodies but analyses were confined to those cores in which uranium was shown to be of economic significance with a scintillation counter. Its occurrence is sporadic, and this is discussed separately at the end of this section.

With the exception of nickel and cobalt it is shown in Figure 35 that there is little variation in trace element distribution through the orebodies. What variations appear to exist could possibly be established with detailed quantitative spectrographic work, an expense not thought warranted in this thesis.

The Lumwana orebody is very much richer in total iron than either the Copperbelt or the Katanga orebodies, and much of the iron, like potash, is present in detrital minerals. This is an important observation as there is likely to be overlap between trace elements deposited in an oxidizing environment, and those found in association with sulphides, presumably formed in a reducing environment.

The elements of the oxidizing environment are usually those forming stable oxides or dioxides such as Ti, Mn, and Sn, and the insoluble oxides of the trivalent metals especially Fe^{+++}, Cr^{+++}



DISTRIBUTION OF TRACE ELEMENTS

FIGURE 35

and Co^{+++}.

The elements found in a reducing environment are usually those with strong affinity for sulphur such as Mo, Cu^{++}, Ni^{++}, Co^{++} and to a lesser extent Ag.

The statements made above are, however, generalizations which apply to simple conditions, and most metals can be deposited in part under oxidizing or reducing conditions. Numerous factors control the type and amount of precipitation, the most important being the supply of the metal and sulphur (H_2S), pH and fluctuations thereof as a result of chemical reactions which cause precipitation, and ocean currents which can cause deposition of the precipitates in apparently inhospitable environments.

At the Lumwana Prospect, it is likely that the tin and titanium were deposited detritally, or, together with Cr^{+++} and Co^{+++} actually precipitated in the environment of oxidation. Such precipitates may have been sufficiently fine to have been carried directly into the environment of sulphide precipitation or may have been distributed by reworking of the gangue material in the orebodies.

The distribution of manganese may be accounted for in the same way as that of titanium or tin, but there is remarkable similarity between the graphs of manganese and molybdenum in Figure 35. This is especially noticeable in the graphs against Cu/S so that both Mn and Mo are richest in the bornite-chalcocite and chalcopyrite-pyrite parts of the orebodies. Molybdenum may form insoluble molybdates in the zone of oxidation but is more commonly dissolved in alkaline waters which, on mingling with more acid H_2S-bearing waters, precipitate the molybdenum as sulphide. Manganese, like molybdenum, has a great affinity for sulphur according to Rankama and Sahama (1950), but unlike the insoluble molybdenum sulphide, manganese sulphide is highly soluble and precipitation is unlikely. Attention has been drawn to the association of manganese and molybdenum by Hauptmann and Balconi (quoted by Rankama and Sahama, 1950), but no satisfactory explanation for their sympathetic behaviour has yet come forth. At the Lumwana Prospect the manganese and molybdenum are enriched on the margins of the orebody, thus the waters from which copper was precipitated were impoverished in these metals. It is more likely therefore that the common molybdenum sulphide was accompanied by the rare manganese sulphide, than that manganese oxides were accompanied by the formation of rare molybdates, and that both manganese and molybdenum combined with sulphur at the margins of the environment of sulphur availability.

The sulphide constituents may have been deposited according to Schürmann's Law (quoted by Garlick, see Mendelsohn 1961), in which the elements at the Lumwana Prospect would be arranged in approximate order of sulphide solubility as follows: Ag, Cu, Pb, Zn, Ni, Co, Fe, Mn, so that a solution of a salt of any of these metals will be decomposed by the sulphide of any succeeding metal and the first metal will be precipitated as a sulphide. This explains why silver, which itself has a low affinity for sulphur, is evenly distributed through the orebody, but tends to be richest where copper is low. It also explains the distribution of manganese on the margins of the orebody.

Lead and zinc are distributed evenly through the ore. They are present in such small amounts that they were probably locked up in other sulphides in such a way that Shürmann's Law would not be applicable. Alternatively they may have been bound to clay minerals and deposited as such without ever forming sulphides.

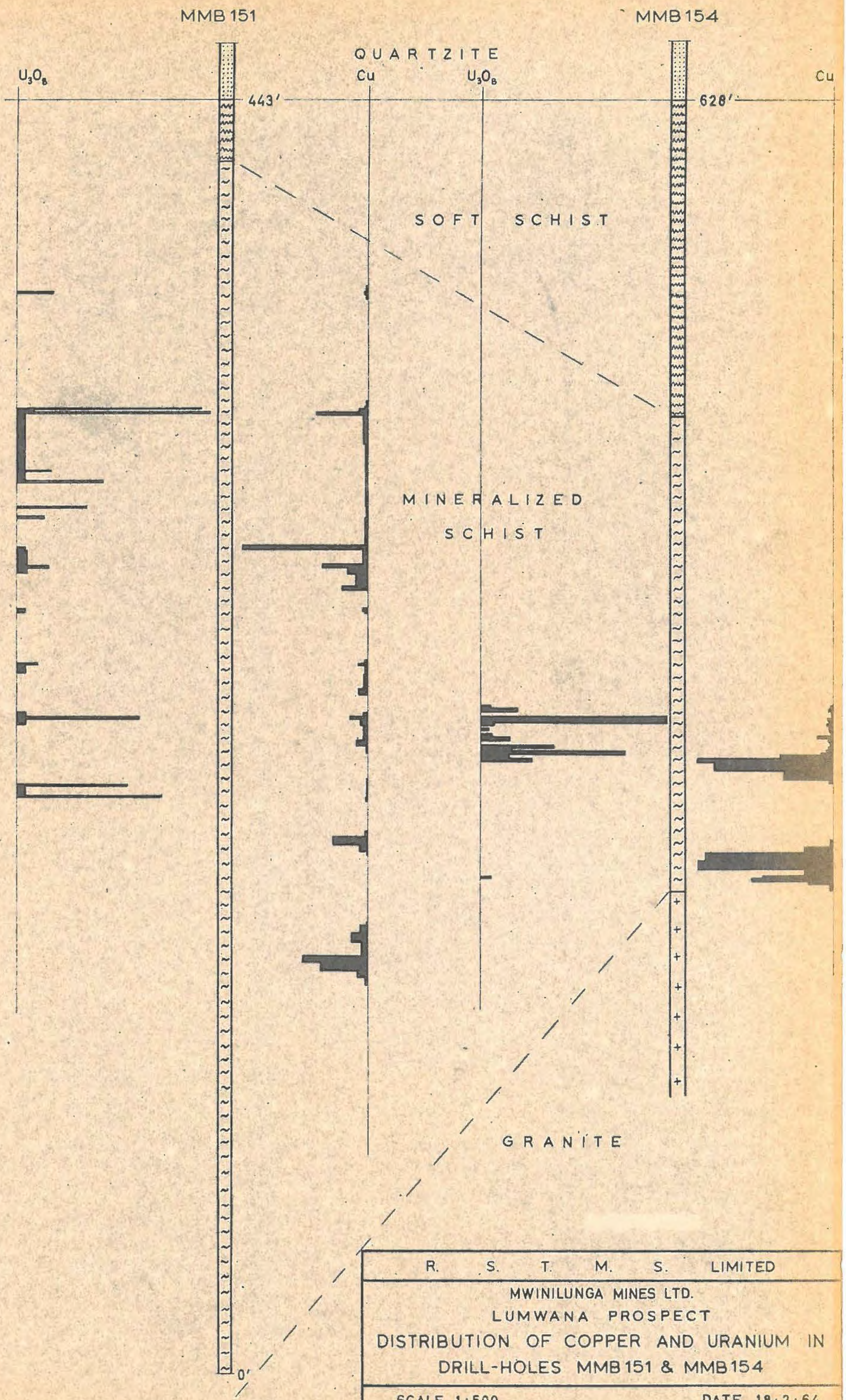
The antipathy between nickel and copper is striking as is the concentration of nickel in the pyritic parts of the orebody. This appears to be an excellent illustration of Schürmann's Law so that nickel was deposited only from solutions that had been impoverished in copper. Thus as the waters flowed down-slope copper was deposited first in the shallower waters, and deposition of nickel and iron followed in the deeper parts.

The graphs of cobalt against Cu/S has two peaks, one in the bornite-chalcocite zone and one in the chalcopyrite-pyrite zone. The shallow-water peak is presumed to be due to Co^{+++} deposition in the zone of oxidation, whereas the second peak corresponds to Co^{++} deposition which reaches a maximum after most of the copper has been deposited. The graph of cobalt against copper shows similar relationships, so that a Co^{++} maximum corresponds to a copper content of a little over 1%, whereas the Co^{+++} maximum occurs with copper at about 2.5%. The copper-cobalt relationships appear to fit in with Schürmann's Law but the cobalt-nickel relationships do not. It is clear from a comparison of the graphs that the Co^{++} maximum occurs with a greater copper content than does the nickel maximum, furthermore the Co^{++} maximum occurs opposite a higher Cu/S figure than the nickel maximum. It appears therefore that cobalt is deposited before nickel. Cobalt sulphide is only slightly more soluble than nickel sulphide, and in view of the affinity suggested by the common cobalt-copper sulphide, carrollite, it is unlikely that Lumwana is the only exception to the general rule that nickel precedes cobalt sulphide precipitation.

(c) Uranium.

The discovery of uraninite at the Lumwana Prospect is significant in that uranium is associated with the stratiform deposits of the Copperbelt. Examples on the Copperbelt are the barren gaps in the NKana orebody and the uraniferous footwall of the Chibuluma orebody. In syngenesis, according to Garlick (see Mendelsohn 1961), uranium is sensitive to reducing conditions and is deposited as oxide prior to deposition of copper sulphides. Its position in the sequence of zoning is in shallower waters than any of the copper sulphides, being associated rather with molybdenum and tungsten sulphides than copper.

Krasnikov and Sharkov (1962) state that secondary uranium deposits are found only in dry or semi-arid conditions, while Gruner (1956)



R. S. T. M. S. LIMITED

MWINILUNGA MINES LTD.
LUMWANA PROSPECT
DISTRIBUTION OF COPPER AND URANIUM IN
DRILL-HOLES MMB 151 & MMB 154

SCALE 1:500
DATE 18·2·64
DRAWN BY : D. PARRY
FIGURE 36

believes that any accumulation of uranium may be the result of several cycles of deposition, oxidation, migration, reprecipitation and probably enrichment. Swanson (1961) believes that the sedimentary origin is unrelated to living organisms, but precipitation is accomplished by acids and phosphates of biogenic origin, while Rankama and Sahama (1950) on the other hand set great importance on detrital concentration.

There is doubt as to the actual method of deposition of uranium minerals, but there is no doubt that concentration of uranium oxides has occurred in the footwall to the Chibuluma orebody - copper following uranium in normal transgression, and that uranium in the barren gaps at Nkana occurs in shallow water or littoral deposits.

At the Lumwana Prospect the distribution of uranium is not at first glance analogous to that of the Copperbelt, as its occurrence is characteristically stratigraphically above the orebodies. It is also very sporadic in occurrence so that uranium found over several feet in one drill-hole is absent in the stratigraphically equivalent beds in all the surrounding drill-holes.

The vertical distribution of uranium at Lumwana is illustrated by two drill-holes in Figure 36. In MMB 154 the uranium zone is stratigraphically above the second orebody, but is very close to it and approaches economic grades. MMB 151, on the other hand, intersected a thick succession in which uranium occurs sporadically with copper stratigraphically above the lower orebody, which itself contains poor copper mineralization.

The Lumwana copper-ore occurs in three main and several minor horizons which may be contiguous or separated by barren rock. The orebody, considered as a whole, is zoned vertically so that copper-rich sulphides are separated by copper-lean sulphides (see later chapter on sulphide zoning). It is interpreted that copper deposition was initiated during transgression and halted during regression, and intercalated barren arkosic or conglomeratic schists indicate that minor transgressive and regressive phases were included in the main sequence.

In considering the factors controlling uranium deposition the importance of environment is paramount. In transgression from oxidizing (shallow water) to reducing (deep water) conditions, detrital uranium concentrations will be preserved as well as any precipitates trapped by rapidly accumulating sediment. Thus some uranium may be present at the base of the copper orebodies as on the Copperbelt, and at Lumwana this type of deposit is represented by small amounts of uranium minerals beneath the ore in MMB 154, (see Figure 36). Precipitated uranium need not be preserved, however, as the uranium minerals are likely to return to solution in oxidizing conditions following upon reducing conditions in which deposition took place. Such uranium may be redeposited and redissolved during subsequent regressive and transgressive phases until it is either transported elsewhere, or in a final stage of regression followed by transgression it is concentrated in solution, deposited and preserved. Such conditions are likely to have developed very locally, and to have resulted in pockets of good uranium mineralization of limited size.

Such an origin is postulated for the uranium mineralization in drill-hole MMB 154 so that the mineralization in the drill-hole is of limited extent and represents local ideal conditions for precipitation and concentration of uranium in the manner described by Swanson (1961).

In MMB 151 the stratigraphically lowest orebody is followed by numerous minor zones of copper mineralization, in which the copper sulphides are almost entirely restricted to bornite, and pyrite is uncommon. These vary from less than an inch to several feet in thickness and are separated by barren rock. The uranium occurs in beds often an eighth of an inch or less in thickness. The formation of these mineralized bands is essentially similar to that of the orebodies, i.e. deposition of copper took place in successive periods of transgression separated by short periods of regression. It is likely that the waters were depleted in copper during deposition of these beds and consequently the deposits do not reach economic proportions. The uranium on the other hand would be concentrated in these waters and would be deposited in greatest concentration when reducing transgressive conditions immediately followed an oxidizing regressive stage.

In addition to the bedded disseminations of uranium which have been described, uranium minerals are frequently found in veinlets cutting, or in close proximity to, the disseminated concentrations. These veinlets are regarded as having derived their uranium from the rock during metamorphism, though the extent of metamorphic redistribution (regarded as important for concentration by Getseva, 1958) cannot be estimated from the limited observations possible in drill-cores.

LOWER ROAN EPIDOTE AND KYANITE SCHIST (SOFT SCHISTS).

The epidote and kyanite schists which occur stratigraphically immediately above the mineralized schists are distinctive in appearance as they are characterized by excessive development of either epidote or kyanite. They have been referred to also as the "soft schists", as, compared with the over- and under-lying strata they have low rock strength. The formations have not been found in outcrops, and at surface they are always the sites of development of thick laterite. In drill-cores the formation is always broken, and in some holes "core" was confined to an epidote rich sand.

The schists appear to consist of distinct epidote and kyanite-rich facies, though there is gradation between them. Thus a drill-hole may pass through both kyanite and epidote-rich members, either one may be present alone, or the formation may be uniformly intermediate in composition between the two end-members. This is illustrated in the centre of the prospect where in drill-holes MM 123 and 124 the sequence is:

<u>Plate 32</u>. Porphyroblast of kyanite containing inclusions of quartz and altered marginally to sericite. Soft schists, MMB 234, 279'.

Photomicrograph, x 23.

<u>Plate 33</u>. Phlogopite-kyanite-quartz schist containing specularite. Soft schists, MM 115, 399'.

Photomicrograph, x 23.

	MM 123	MM 124
mineralized schist		
kyanite schist	40'	30'
epidote schist	75'	90'
quartzite		

Immediately to the south of these holes the composition is variable, and further south in drill-hole MM 117 the sequence is:

	MM 117
mineralized schist	
barren quartz-mica schist	30'
epidote schist	40'
kyanite schist	33'
quartzite.	

The soft schists have been found in every drill-hole put through the mineralized schists to the quartzite. The true thickness varies from 20 feet to 130 feet, and the average is approximately 75 feet. The contacts between the two members (where present) are gradational, as are the contacts between the soft schists and the over- and underlying formations.

The epidote schists are finer grained than the adjacent mineralized schists and have an average grain size of less than 0.5 mm. The texture is granular and core chips are sufficiently friable to be fragmented between the fingers.

Megascopically the kyanite and epidote schists differ in that the epidote schists contain only rare large porphyroblasts of kyanite, while in the kyanite schists porphyroblasts from 3 to 4 cm. abound. Under the microscope there is less difference in composition than appears to be the case in hand specimens. In the epidote schists epidote may comprise as much as 15% of the rock, and kyanite is present as small bladed crystals about ½ mm. in length making up less than 5% of the rock. The kyanite schists on the other hand contain up to 30% kyanite while epidote varies from 2 to about 10%. Whereas the kyanite occurs as distinct bladed crystals which are often altered on their rims to sericite, the epidote has a poorly crystalline or granular habit, and has been observed in fibrous form only in veins.

There is little difference in the rest of the mineralogy. Quartz and sericite make up most of the rock, pale brown biotite and specularite are significant, and in addition small amounts of orthoclase, apatite, zircon, magnetite and tourmaline have been observed. Kaolin occurs in patches of what appears to be rock more weathered than usual, and in fractures.

The microscopic examination of the soft schists has been somewhat cursory as their leached and granular characteristics make section preparation difficult. The rocks are thought originally to have been quartzitic and variously aluminous and calcareous. Specularite, zircon, apatite and some of the tourmaline were probably detrital, and deposition is therefore likely to have occurred in a neritic environment.

Conjecture on the history of the soft schists is hampered by alteration of the rock. This alteration includes metamorphic formation of epidote from primary calcite, and kyanite from clay minerals. Three samples from drill-hole MM 115 had an average soda content of 0.44% and an average potash content of 4.56%. These figures are very similar to those from the mineralized schist, but whereas the alkalies can be related at least partly to feldspar in the mineralized schist, little feldspar has been observed in this formation. The alkalies are therefore thought to be contained in the micas, which may have a partly detrital origin, but are equally likely to have developed from alteration of feldspar or clay minerals.

In addition to metamorphic alteration, the soft schists are leached and porous, and carry artesian water which flows under considerable pressure from holes such as MM 117, collared at relatively low altitudes and drilled near the centre of the main synform. This secondary alteration may have occurred with complete solution of remnant calcite, and assisted in the destruction of feldspar, which accounts for the patchy and joint development of fine kaolin.

The soft schists occur between the mineralized schists and the ridge-forming quartzite. They represent transition between the predominantly reducing conditions in which the mineralized schists were deposited and the markedly oxidizing conditions of deposition of the quartzite. It is thought possible that these schists were deposited under conditions climatically different from those in which the over- and under-lying formations were deposited, rather than that they represent any major change in tectonic behaviour. Such climatic conditions may have been cold so that lime precipitation could have occurred with falling temperature, while the abundance of alumina suggests that the surface conditions were moist enough to have resulted in advanced weathering of feldspar.

The epidote and kyanite schists are therefore likely to have been derived from sediments deposited in a cool wet climate, in a neritic environment with gradual transgression, so that the sediment included aluminous, calcareous, quartzitic and detrital fractions.

LOWER ROAN QUARTZITE.

The Lower Roan or ridge-forming quartzite is the marker horizon on which litho-stratigraphic correlation between the Mombezhi Dome and the Copperbelt is based. This quartzite occurs at the base of the Katanga System on the Copperbelt, where it lies unconformably on Basement schists and granite. On the margins of the domes west of the Copperbelt the outward dipping quartzite is overlain by Katanga sediments, but as at Lumwana, it may have additional conformable facies between it and the Basement.

In addition to the similarity of stratigraphic position the Lower Roan quartzite has characteristics which prevail through various grades of metamorphism in all major exposures from the

Plate 34. Bent kyanite. Coarse kyanite-quartz schist, Lower Roan outcrop, sheet 194, line 3, near peg 43.

Photomicrograph, x 23.

Plate 35. Fine kyanite-quartz schist. The kyanite contains fine inclusions at the centres of crystals which may indicate that they are pseudomorphs after andalusite, the opaque mineral is specularite. Sheet 194, line 2, near peg 46.

Photomicrograph, x 23.

TABLE 4

MMB 226

Sheet 216, line 10, peg 48½.

Basement at least	130'						
Mineralized schists	80'						
Soft schists	35'						
Quartzite	150'						125'
Dolomitic limestone	18'	FAULT	16'				8'
Dolomitic schist	8'		50'				16'
Dolomitic hybrid	50'		(Breccia) 6'		34'	FAULT	-
Dolomite, impure	55'				(Breccia) 28'		36'
Dolomitic hybrid	20'				(Dol. Impure) 120'		42'
Gabbro	15'			FAULT	(Amphibole Breccia) 15'		-
							Magnesite 5'
							Dolomite and dolomitic schist with gypsum and anhydrite 320'
							FAULT. (?)
							Quartzite 20'
							FAULT. (?)
							Dolomite and dolomitic schist with gypsum and anhydrite 70'
							Quartzite, (normal ?) at least 80'

	MM 115.	MM 122.	MMB 234.
	194/4/72.	194/8/72.	194/0/70½.
Basement	at least 210'	at least 200'	at least 155'
Mineralized schists	85'	105'	105'
Soft schists	110'	55'	48'
Quartzite	280'	320'	120'
Dolomitic limestone	8'	-	-
Dolomitic schist and impure dolomite	188'	70'	at least 24'
Gabbro	6'	-	
Impure dolomite	8'	-	
Gabbro	at least 120'	at least 150'	

Copperbelt westwards to the Kabompo Dome.

Deposition of the Lower Roan took place on a rugged Basement topography and the formations thus have a variable thickness between 0 and 3000 feet both on the Copperbelt (Mendelsohn 1961) and on the Kabompo Dome (McGregor 1960). On the Mombezhi Dome similar thicknesses are encountered where the quartzite rests directly on Basement, but at Lumwana it has a less variable thickness which is thought to be due to smoothing of the topography by deposition of the earlier conformable formations.

The full thickness of the quartzite was intersected in drill-holes MM 115, MM 122, MMB 234 and MMB 226, the lithology of which is summarized in Table 4 . It can be seen that the thickness varies from as little as 120 feet to as much as 320 feet in these holes. The quartzite is regarded as having been deposited on a fairly flat surface as the soft argillo-calcareous schists occur consistently beneath the quartzite, and are likely to have been absent if Basement hills had projected through this formation. The thicknesses are as near true as can be ascertained by making allowance for folding, but the effect of faulting, especially near the Lower Roan-Upper Roan contact cannot be assessed. The variation in thickness may be due to compaction of this and the underlying formations alone, but it is likely that the minimum thickness is somewhat low due to faulting.

There is considerable lithologic variation in the Lower Roan formation from mine to mine on the Copperbelt, but usually it consists of aeolian quartzites overlain by cross-bedded aqueous quartzites, argillites and dolomites, though often the first dolomite is regarded as the base of the Upper Roan. The characteristic cross-bedding occurs in exposures west of the Copperbelt, but at Lumwana the quartzite has been subjected to metamorphism and shearing such that sedimentary structures are obscured in all but the most quartzitic beds, and only rarely has cross-bedding been observed. It is likely that the aeolian facies is absent as the prevalence of sericite and talc is suggestive of subaqueous rather than terrestrial conditions of deposition.

At Lumwana the quartzite consists of the same essential minerals throughout its width. There are no distinctive horizons or trends of variation in composition. Where intersected in drill-holes there is no footwall conglomerate, but west of the prospect, on the northwest flank of the dome a footwall conglomerate has been mapped in some localities. Various thin conglomerates, pebble beds and isolated pebbles occur in the quartzite but are not consistently present along strike. All the pebbles found are composed of quartz or quartzite, and are usually deformed into augen or lenses parallel to the first schistosity.

In addition to quartz pebbles there are abundant quartz veins in the rock which vary in size from stringers to veins up to six feet in thickness. The quartz in these veins is often fractured, and while some of the thinner veins are folded, others exhibit boudinage, and still others cut across folds, and are themselves neither folded nor fractured. It is clear therefore that some veins were present prior to folding while others were emplaced after folding.

The term "quartzite" has been widely used to describe this formation in order to differentiate it from the Basement and the other older schists, but more correctly it should be called variously quartz-sericite, quartz-talc or quartz schist. The rock always consists of a high proportion of quartz with varying amounts of sericite, muscovite, chlorite, serpentine, talc and biotite. Iron and titanium oxides are always present, mainly specularite with subordinate magnetite and ilmenite, while rutile and sphene appear to be of metamorphic origin. There is often separation into bands rich in specularite and those rich in light coloured minerals. These bands are useful in determination of attitude of bedding in outcrops with cross-cutting cleavage or schistosity, as the bands are usually differentially weathered. Other minor constituents are orthoclase and oligoclase, and apatite, zircon and tourmaline which may be of detrital origin.

Local variations in original composition have, after metamorphism, resulted in various mineral assemblages. The development of metamorphic minerals and the degree of deformation have in turn exercised control over the preservation of bedding. These variations include combinations of the following.

(1) Hard well-cemented quartzite with well-preserved bedding, except where originally massive.

(2) Sericitic and specularitic quartzites with well-preserved banding, and bedding sometimes visible.

(3) Sericite-kyanite quartzites,

(a) with large (two to three cm.) kyanite porphyroblasts, usually massive, and especially present at the base of the quartzite as a whole, or,

(b) with abundant small acicular kyanite porphyroblasts, occurring usually interbedded with specularitic quartzite.

(4) Talc-chlorite schists with no trace of original bedding, considered to be the sites of thrusting.

In addition to these variations the quartzite sometimes contains anthophyllite and becomes distinctly talcose, chloritic or even dolomitic towards the top where it grades into the Upper Roan formation, and this is likely to be a major zone of thrusting or shearing.

The average alkali content of three samples taken at 50 feet intervals across the quartzite in drill-hole MM 115 was soda 0.51%, and potash 1.16%. Neither is abnormal for a quartzite, as the average of 253 sandstones quoted by Shand (1952) includes 0.45% soda and 1.32% potash. It is thought therefore to be highly unlikely that alkalies have been introduced into the quartzite by any method other than normal shallow water deposition in what was probably a temperate climate.

The soda is present in oligoclase which is quite fresh and well twinned. It is present as interstitial grains in the general quartz-mica mosaic and is almost certainly metamorphic in origin. It is possible that original detrital feldspar was simply recrystallized during metamorphism, but it is more probable that such detrital feldspar was first altered to secondary minerals and the oligoclase was subsequently reformed during metamorphism. The potash minerals are the micas and orthoclase, and only rarely has detrital highly altered microcline been observed.

The Lower Roan quartzite, although singularly uninteresting from an economic, or even a petrological point of view, has been a most useful horizon in mapping and structural interpretation. It is the only formation that is consistently well exposed and even where outcrops were absent it was mapped without pitting by panning for specularite and the fine acicular kyanite. Examples of the structures found in cores were also found in the outcrops of the quartzite, though sometimes only after diligent searching, and although pitting provided a wealth of data for statistical analysis, it is doubtful whether any solution to the complex structural problems would have been reached without continued examination of the quartzite outcrops over a period of several years.

UPPER ROAN AND MWASHIA.

The formations stratigraphically above the Lower Roan quartzite were explored in four drill-holes. The first two, MM 115 and MM 122, were halted in gabbro after cutting short sections of dolomitic rocks. The third hole, MMB 226, was drilled 1700 feet through successive Lower and Upper Roan formations variously repeated by faulting. There is considerable doubt in this hole whether the formations were inverted or normal after the first repetition, as there is distinct lithologic difference between cores from the lower and upper parts of the hole. These differences may be due to their being different parts of the vertical succession, or simply to change of facies round what is now the nose of the recumbent syncline. (See Table 4). A fourth hole, MMB 234, was drilled into Upper Roan rocks and halted.

The maximum true thickness of the Upper Roan-Mwashia, (excluding gabbro) investigated by drilling is probably of the order of 320 feet, but may be considerably less as there is constant doubt as to the amount of repetition of these formations by thrusting, especially in drill-hole MMB 226. There are no marker horizons, and the rocks in the succession vary widely in dolomite content so that they have behaved variously during orogenesis and metamorphism. In general the more dolomitic rocks have become wholly or partly recrystallized while the cherty parts of the succession are less deformed and retain banding which may represent original bedding. In addition these rocks have been intruded by gabbro and various dolomite-amphibole-biotite-scapolite(hybrid rocks) may be related rather to gabbro intrusion than to regional metamorphism. Since all the knowledge of the Upper Roan has been obtained from widely spaced drill-holes, and the lateral distance at any depth to the nearest gabbro mass is unknown, little can be done to determine the true relationships of these hybrid rocks to the normal rocks in the succession. There is however some indication that the hybrid rocks are related to gabbro as, whereas the dolomite and impure dolomite are conspicuously schistose, the hybrid rocks contain coarse clusters of unorientated mica and amphibole and an impression is present that any schistosity inherited from folding has been destroyed. This can be most easily explained by hydrothermal alteration of impure dolomitic rocks during post-orogenic igneous activity.

The Upper Roan-Mwashia of the Copperbelt is from 1700 to over 4000 feet thick (Mendelsohn 1962),and a similar thickness may be present north of Lumwana on the northwest flank of the Mombezhi Dome. On the north and east flanks of the dome however, the width of the Upper Roan-Mwashia is thought to be less than 1000 feet, and this is

Plate 36. Upper Roan dolomite containing euhedral scapolite. MM 115, 912'.

Photomicrograph, crossed nicols x 23.

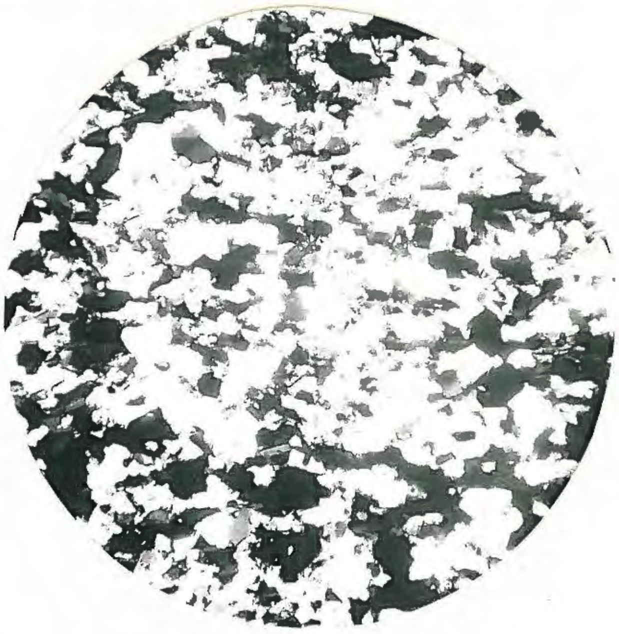


Plate 37. Cherty Upper Roan schist - typical hornfelsic texture. MM 115, 760'.

Photomicrograph, x 23.

probably more similar to the thickness at the Lumwana Prospect.

On the Copperbelt the Upper Roan and more particularly the Mwashia, are largely argillaceous, but west of the Copperbelt the succession is more consistently dolomitic. The Upper Roan beds intersected in the Lumwana drill-holes are broadly similar to those intersected in a number of holes drilled in normally dipping Upper Roan formations on the Solwezi, Mombezhi and Kabompo Domes. Both at Lumwana and in these other areas of investigation there is little basis for detailed correlation in the dolomitic succession from hole to hole. The only band which has been correlated at Lumwana is a thin fairly pure dolomitic limestone at the base of the Upper Roan in two drill-holes, yet absent in the other two.

About twenty five thin sections were cut from the Upper Roan-Mwashia formations interesected in drill-holes. This collection was made with a view to examining the different rock types and establishing some of the variations in petrology, but drill-cores from the Upper Roan-Mwashia were insufficient to endeavour to find systematic variations between the different rock types.

Examination of the thin sections reveals variations based on the original constituents. These include normal variations in the ratio of lime and magnesian carbonate, quartz (chert) and the ferro-magnesian minerals, as well as special cases of concentration of any of these constituents or anhydrite-gypsum. Other variations, which have resulted from metamorphism, are in grain size and mineralogy, and still others have arisen from soda metasomatism and hybridization with the gabbro. The normal carbonate is dolomite and a broad classification of the Upper Roan-Mwashia rock types into carbonate rocks, cherty dolomites, impure dolomites and hybrid rocks is possible, but it must be borne in mind that there is gradation between them and variations of metamorphism within them.

The purest carbonate rocks are thin (about twelve feet thick) pink dolomites or dolomitic limestones, one of which occurs at the base of the Upper Roan in two drill-holes. They are coarsely crystalline with an average grain size of about 5 mm., and crystals have one cleavage orientated parallel to the schistosity. Coarse pyrite, pyrrhotite and magnetite are often associated with these dolomites, and quartz is usually present occurring both interstitially and as somewhat rounded grains. Scapolite and oligoclase sometimes occur in the dolomites; grains of these minerals contain very much fewer inclusions and have a much better crystal form than where they occur in the cherty and impure dolomites.

In the lower part of drill-hole MMB 226 and also in MM 115 gypsum and anhydrite beds occur in association with the dolomites. They are exceptionally coarsely crystalline so that individual crystals often exceed the core size which is approximately 5.5. cm. in diameter. One such crystal of gypsum was moulded on projecting dog tooth spar dolomite crystals which are clearly visible through the transparent gypsum crystal. In these beds the anhydrite is usually twinned and has altered to gypsum which always appears to be secondary in origin. Also present in MMB 226 at a depth of 1161 feet is a thin talcose magnesite, which like many of the rocks described below, contains a little oligoclase. The sulphate horizons and the magnesite are regarded as sedimentary deposits, probably evaporites in the dolomitic succession.

The cherty dolomites are common in the succession. Quartz occurs in a mosaic with other constituents and also as rounded aggregates which presumably were concretions originally. Much of the quartz is fine grained (0.03 mm. average), but locally recrystallization has resulted in grains over 0.5 mm. in size. The carbonate material is invariably dolomite which in the course of recrystallization has become moulded on the other constituents. Biotite is characteristically present and is orientated parallel to the schistosity. The normal brown biotite and a pale green variety ($Z = 1.604$) have been observed. and phlogopite ($Z = 1.598$) is not uncommon. In drill-hole MMB 226 at a depth of 1604 feet, pale brown phlogopite crystals have cores of the pale green biotite suggesting little difference in chemical composition. The biotite may be fine grained and scattered through the rock giving some sections a hornfelsic texture, but where recrystallization is at all advanced larger porphyroblasts reaching 1.5 mm. in size are common. Amphibole is not particularly common but a little actinolite or hornblende may occur. Muscovite, chlorite, apatite, orthoclase, oligoclase, scapolite, garnet, sphene, magnetite, pyrite and pyrrhotite are usual accessories. Tourmaline is quite abundant in some sections, and zircon has been observed.

The impure dolomites and the hybrid rocks are separated on textural grounds. The former display a schistosity, which is usually well developed, while the latter are massive and more coarsely grained rocks.

The impure dolomites are rich in biotite and amphibole. The common biotite is dark brown but once again some sections are found to contain the green variety. The amphibole is usually green hornblende of variable composition as attested by variation in colour and pleochroism. It is medium to fine grained and has a granular habit in most sections, but wherever the rocks are recrystallized and more coarsely-grained,larger and larger subhedral to euhedral crystals are found. Pink almandine garnet is frequently present with crystals as large as 2 cm. across. The micas wrap around the garnets which contain the usual inclusions of other constituents. Quartz, oligoclase, orthoclase and scapolite are other major constituents, and chlorite, sphene, apatite, magnetite, pyrite and pyrrhotite are accessories. The most common colourless mineral is oligoclase which is seldom twinned. It occurs in the mosaic of other constituents and may have inclusions of the other minerals present in the slides. Where scapolite occurs plagioclase is usually absent, and where they do coexist scapolite is in the form of large widely spaced porphyroblasts while the intervening mosaic is made up of oligoclase and the other constituents. Apatite is present in crystals which for this mineral

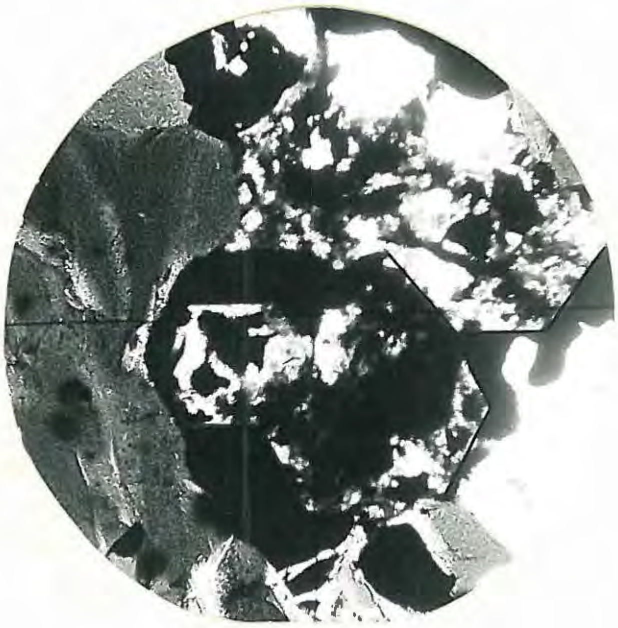
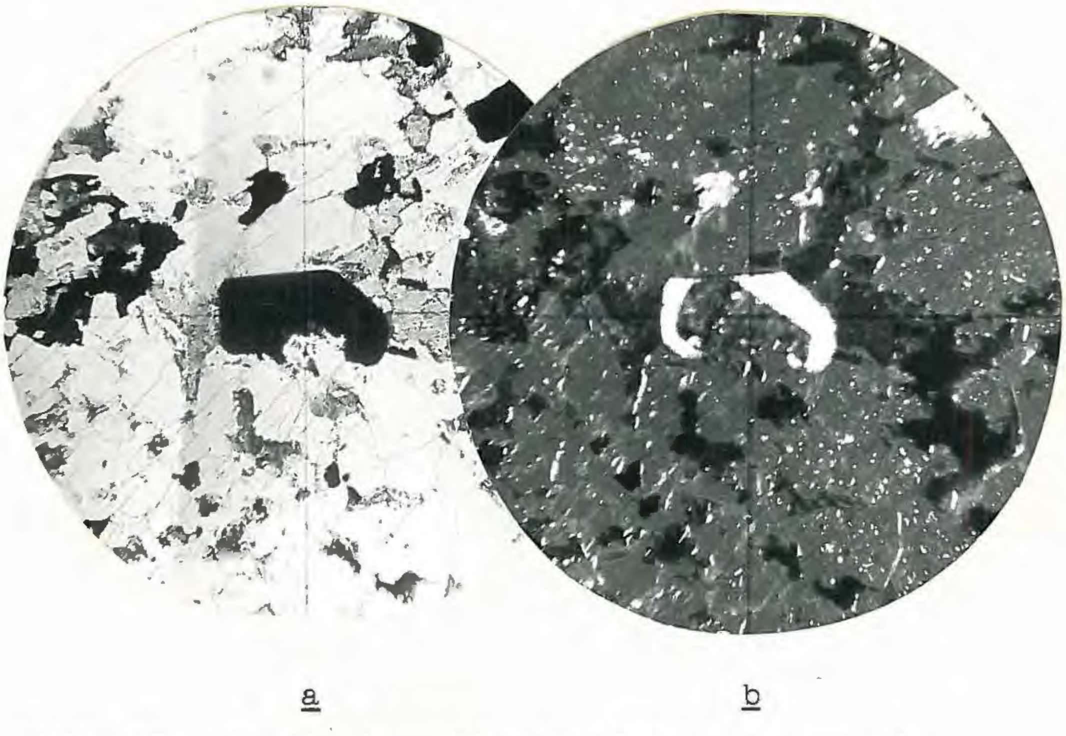


Plate 38. Pyrite moulded on hexagonal dolomite. Other minerals are biotite and quartz. Upper Roan dolomitic schist, MM 115, 753'.

Photomicrograph, x 60.



a b

Plate 39. Euhedral pyrite moulded on a crystal of magnetite and contained together with biotite in a large porphyroblast of scapolite. Upper Roan schist, MM 115, 850'.

Photomicrographs, a polarized light x 60
b reflected light.

are perhaps unusually large, reaching 0.5 mm. in cross section.

The opaque minerals in both the cherty and impure dolomites are of interest as both magnetite and pyrite are usually euhedral. The pyrite crystallization in many cases appears to have occurred after that of the other constituents and pyrite is moulded on the earlier crystals which may be transparent (dolomite) or opaque (magnetite). In addition pyrrhotite and chalcopyrite occur in small amounts.

In two sections from MMB 226 at depths of 437 and 904 feet respectively sheared impure dolomites were examined. In both sections the rock is seen to be composed of coarse pale-green biotite with subordinate colourless anthophyllite ($Z = 1.645$ and $X = 1.627$). The presence of anthophyllite in place of hornblende in these rocks suggests that it has formed as a result of local metamorphic upgrading due to dynamic metamorphism.

The hybrid rocks in the Upper Roan-Mwashia succession are those which have been recrystallized and metasomatized into coarse grained massive rocks which resemble the gabbros more than the schistose sediments in composition. They consist mainly of hornblende, brown biotite, oligoclase and scapolite, and have only minor amounts of quartz and dolomite. The major constituents occur in grains several millimetres in size, all with characteristic sieve texture. As in the impure dolomites scapolite and oligoclase do not normally occur together in the same rock section, and the feldspar is seldom twinned.

The scapolite is richer in lime than in the gabbro and in a sample from drill-hole MM 115 at a depth of 911 feet, near the contact with gabbro, the scapolite is zoned with less birefringent sodic material surrounding cores of more birefringent calcic scapolite. This is in contrast to a sample from within the gabbro two feet lower in this drill-hole where scapolite is zoned in the reverse order. The plagioclase in all samples except one was found to be oligoclase. The exception occurred in drill-hole MMB 226 at a depth of 619 feet; this rock is rich in albite (An_5) which contains small inclusions of

Plate 40. Anthophyllite-biotite schist from a sheared amphibolite. The biotite is a light green variety. MMB 226, 904'.

Photomicrograph, x 60.

Plate 41. Dolomite-amphibole hybrid containing radiating hornblende. MMB 234, 441'.

Photomicrograph, x 23.

carbonate and it is remarkable that the plagioclase is not more calcic.

Though actinolite has been found.the amphibole is usually a lime-rich variety of hornblende. Crystals are usually well formed and as in MMB 234 at a depth of 411 feet the habit may be radiating. The biotite occurs as porphyroblasts up to 1.5 cm. in size, and is always particularly well developed close to gabbro intrusions. The accessory minerals in addition to quartz and dolomite are orthoclase, muscovite, chlorite, sphene, magnetite, ilmenite, pyrite, pyrrhotite, apatite and occasionally epidote. The apatite includes both the normal weakly-birefringent variety and an apparently isotropic type which is described later in the account of the gabbro.

The average alkali content of four samples of the Upper Roan-Mwashia from drill-hole MM 115 is soda 4.08% and potash 2.62%. The potash in these rocks is contained mainly in the micas while the soda occurs mainly in scapolite and feldspar. The potash content is not regarded as abnormal, and it is probable that its presence in the rock is related simply to deposition of mica and clay minerals. The soda content, on the other hand, is high, and in the opinion of the writer is largely metasomatic in origin, being related to intrusion of the gabbro. There is particularly strong evidence for a metasomatic origin in zoning of the scapolite crystals and the absence of twinning in the feldspar.

The Upper Roan-Mwashia is always characterized by disseminated pyrite and very sparse chalcopyrite, with pyrrhotite often present west of the Copperbelt. At Lumwana in addition to the sulphides magnetite is common and often abundant. It is possible that much of the magnetite originated from hydrothermal oxidation of sulphides during intrusion of the gabbro, but it is just as likely that some of the pyrite in the Upper Roan-Mwashia sediments was introduced hydrothermally after the main period of metamorphism, probably during emplacement of the gabbro.

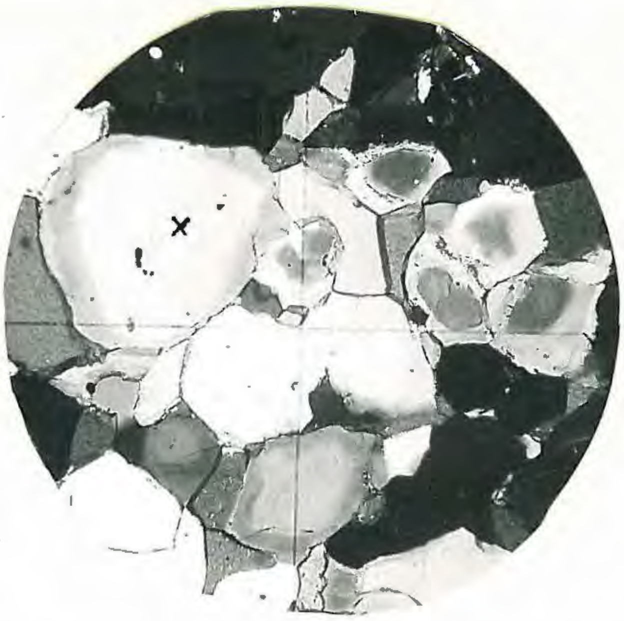


Plate 42. Zoned scapolite with low-birefringent sodic material on calcic cores. Grain (x) has similar birefringence to that in Plate 43. MM 115, 911'. Photomicrograph, crossed nicols x 60.

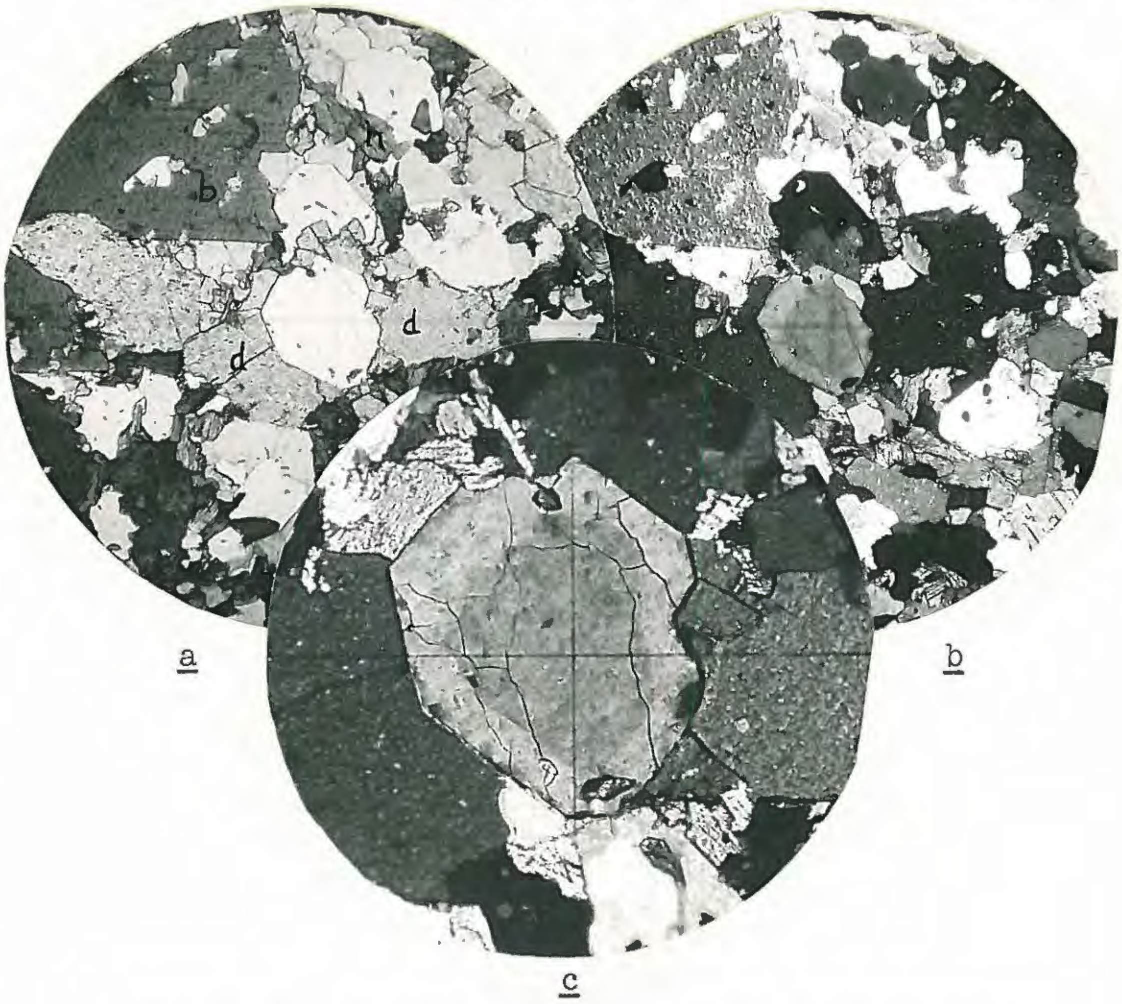


Plate 43. Zoning of scapolite in contaminated gabbro in the reverse order to that in Plate 42. Note that the grain is surrounded by dolomite (d); other minerals are biotite (b) and hornblende (h). MM 115,913'. Photomicrographs, a polarized light x 23,

b crossed nicols,

c crossed nicols x 60.

THE GABBRO.

The gabbros of Zambia have long been a source of interest to Copperbelt geologists and discussions as to age, origin and relationships to ore genesis are common in the literature.

At the Lumwana Prospect the evidence favours late or post-orogenic emplacement of the gabbros as they have not been folded, and appear to be related to post-orogenic faulting. The ore minerals were present before folding and metamorphism occurred, and therefore no relationships exist between ore genesis and gabbro emplacement in the manner ascribed by Sales (1962).

Mendelsohn (1961) regards the gabbros as magmatic and intrusive but suggests that they may be a product of metamorphism of sediments. The writer believes that there is truth in both views but although metamorphosed Upper Roan impure dolomites may resemble the gabbro in chemical and mineralogical composition, such rocks differ from the intrusive gabbros in texture. The gabbros vary greatly in grain size and composition, and there is evidence for considerable contamination of the gabbro by lime and possibly magnesia, with accompanying scapolitization, albitization and possibly ferruginization of country rock. It is likely therefore that a variation exists which may permit rocks of gabbroic chemical composition to be classified as follows.

(1) Gabbroic rocks with typical interlocking texture.
(2) Contaminated gabbroic rocks which exhibit interlocking texture.
(3) Hybridized sediments in which sedimentary or tectonic foliation is destroyed by recrystallization, but which contain coarse clusters of metamorphic minerals not typical of the intrusive rocks.
(4) Metasomatized sediments which exhibit foliation and possible mimetic recrystallization in the foliation planes.

Discussion in this chapter is confined mainly to those rocks which are classified in (1) and (2) above, as those classified in (3) and (4) have been discussed in the previous section. They are typically dark in colour due to abundant amphibole, have a grain size which varies from 0.3 to 5 mm. and in general are massive. A few feet of core in drill-hole MMB 226 contain brecciated fine-grained gabbro enclosed in later unbrecciated material.

Before describing the petrology of the Lumwana gabbro, it is worth quoting the main features of the Copperbelt gabbros which are referred to as such by custom, though amphibolite would be a more suitable term. Referring to the Chibuluma and Chambishi gabbros in particular, Mendelsohn (1961) states that while pyroxene and olivine are absent, amphibole, oligoclase, quartz and scapolite are common, and accessory minerals are chlor-apatite, epidote, zoisite and clinozoisite, sphene, biotite, chlorite and iron ores. Pyrite, chalcopyrite and carbonate occur locally and a little orthoclase is common. Labradorite, olivine and augite have been described from other intrusive bodies.

The gabbros at Lumwana are similar to those of the Copperbelt in many respects. Amphibole is abundant, usually between 45% and 65% and oligoclase, scapolite and augite make up most of the remainder of the rock. Accessory minerals are ilmenite, sphene, orthoclase, pyrite and apatite. Unlike the Copperbelt gabbros quartz has not been identified, epidote occurs in place of clinozoisite, and a little pink garnet is sometimes present. Magnetite, brown biotite and chlorite occur in small amounts within the gabbro but are well developed only near contacts between gabbro and sediment.

There is considerable variation in the mode of occurrence of the major constituents. Hornblende occurs as anhedral or subhedral crystals containing relict augite and inclusions of the other constituents. Grains are often rather small and sometimes form granular aggregates. Augite is common only in the large intrusion northwest of the Lumwana Prospect but has been observed in specimens of the gabbro in MM 122. Where found it is largely replaced by hornblende and scapolite and only rarely are subhedral crystals seen.

Plate 44. Large fleecy scapolite grains enclosed by hornblende. From gabbro outcrop northwest of Lumwana.

Photomicrograph, x 60.

Plate 45. Augite grains (a) altered to scapolite (s) and hornblende (h). Note scapolite occurs as clear grains and also as fleecy grains crowded with inclusions at their centres. From gabbro outcrop northwest of Lumwana.

Photomicrograph, x 60.

Oligoclase is the more abundant of the colourless minerals. It occurs sometimes as equant porphyroblasts as large as a centimetre across which are characteristically crowded with inclusions of amphibole, but more commonly as anhedral grains with relatively few inclusions in the rock mosaic. The oligoclase is rarely twinned and in a normal section containing 25% oligoclase only about half-a-dozen grains will be found twinned. Scapolite occurs in the mosaic of other constituents, often in clear euhedral crystals, but unlike oligoclase is more common in porphyroblasts averaging about 5 mm. in size. These porphyroblasts are sometimes crowded with inclusions and the mineral appears to have replaced country rock regardless of composition, others have inclusions concentrated in the centre with clear fleecy margins. Although no original lime-feldspar has been identified ghost poikilitic structures are not uncommon, and occasionally, as in MMB 226 at a depth of 603 feet, phenocrysts of the original feldspar now replaced by a mosaic of scapolite and some hornblende reach over a centimetre in size.

An accessory mineral found in all rock sections of the gabbro, and frequently in the Upper Roan hybrid rocks as well, has not been identified but received careful examination. It occurs in distict grains usually less than 0.3 mm. in size, which often have a hexagonal or distorted hexagonal outline, but also in elongated habit apparently as doubly-terminated prisms. The remarkable feature of the mineral is that it is apparently isotropic in all sections. It occurs sometimes surrounding cores of apatite which are weakly anisotropic and uniaxial negative, but in no case was an interference figure obtained from the isotropic mineral. The refractive index was determined as 1.668. There is no common mineral with these properties and two X-ray powder photographs were taken to aid identification. The line spacing on these photographs shows that the mineral is not cubic, though a strong doublet may mean that two minerals of the same isomorphous series were present in the powder. The X-ray data is as follows.

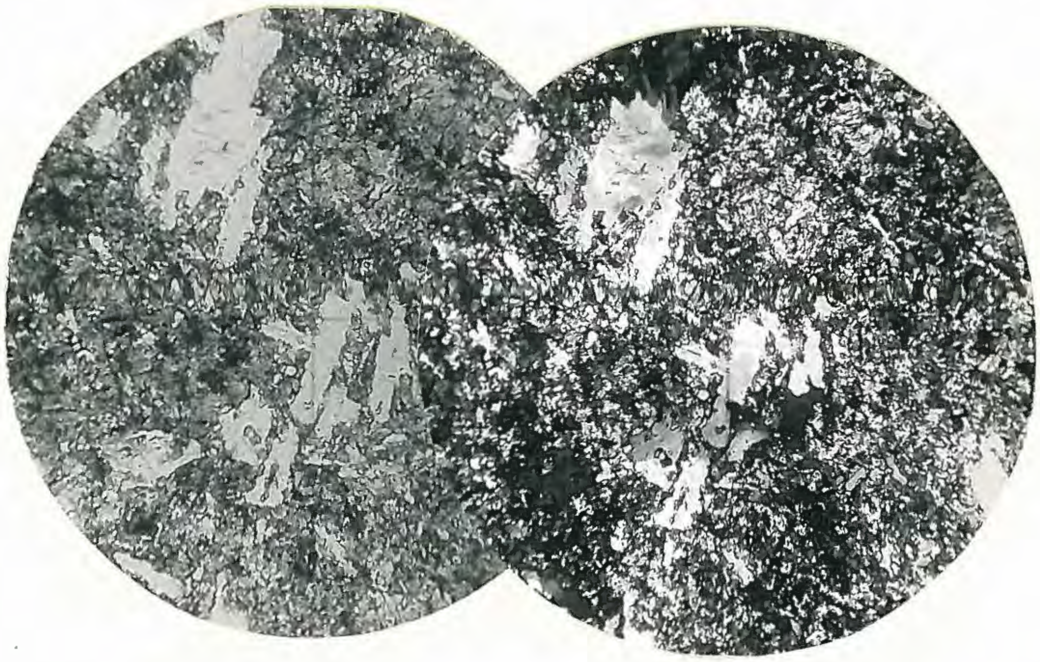
	Picture 1		Picture 2			
	s in mm.	Strength.	s in mm.	Strength.	θ°	d
1.			27.5	faint	13.13	3.393
2.	32.4	2	32.3	2	15.471	2.892
3.	33.5	1	33.4	1	15.996	2.798
4.			36.0	4	17.19	2.608
5.	40.5	4	40.3	6	19.339	2.329
6.			47.4	5	22.63	2.004
7.	48.1	5			22.968	1.976
8.	51.6	3	51.5	3	24.639	1.849
9.	56.8	faint	56.6	v. weak	27.122	1.692
10.	59.5	faint	59.5	8	28.411	1.620
11.			62.0	7	29.61	1.561
12.	64.4	faint			30.751	1.509
13.	66.5	faint	66.3	v. weak	31.754	1.466
14.			76.1	v. weak	36.34	1.302
15.	79.7	6	79.6	9	38.057	1.240

Radius of camera 30.0 mm.

λ Cu 1.542 Å

The occurrence of this mineral with apatite and the general similarity of its properties to those of apatite suggests that it is a member of the apatite group of minerals. Mr. A. Erlank of Cape Town University who kindly attempted an identification from the X-ray data, states that it has all the properties of an apatite type mineral but does not fit the data that they have on minerals of that type. Although suspecting that it was related to apatite this could not positively be confirmed.

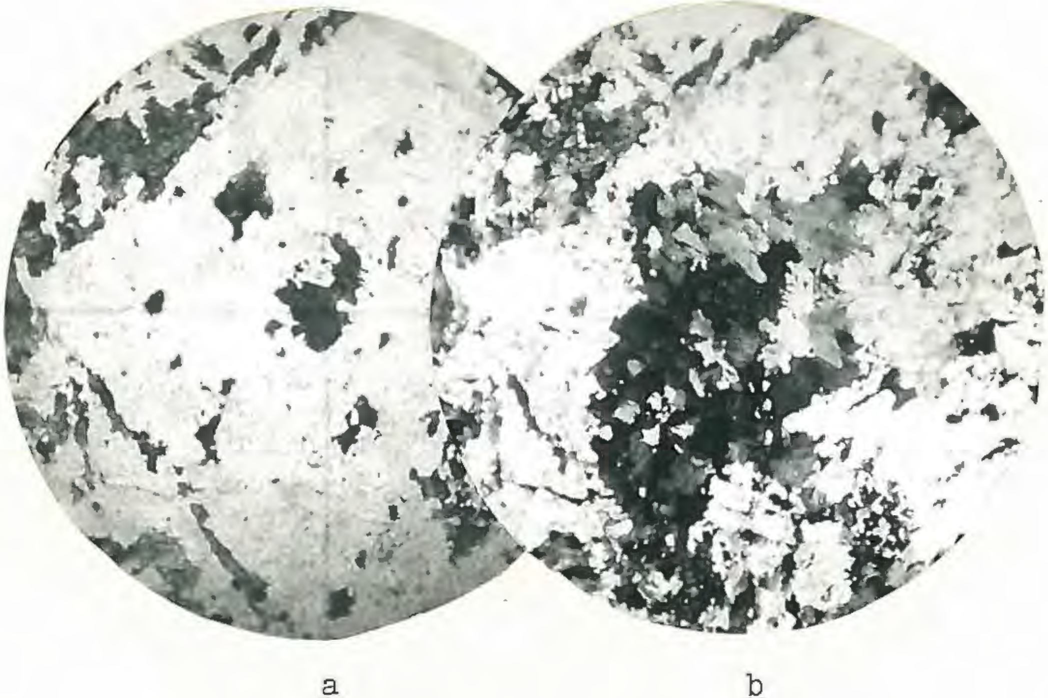
A sample of the gabbro from an outcrop in sheet 238, line 34, 100 feet east of peg 40, was selected for chemical analysis. Megascopically it did not appear to differ in any way from the normal intrusive gabbro, but the analysis reveals that unwittingly a contaminated gabbro was chosen. The analysis is a contribution to the



a b

Plate 46. Relict ophitic texture in gabbro now composed of scapolite and hornblende. From outcrop northwest of Lumwana.

Photomicrographs, a polarized light x 60,
b crossed nicols.



a b

Plate 47. Porphyroblast of feldspar in gabbro replaced by a mosaic of scapolite with a few grains of hornblende. MMB 226, 603'.

Photomicrographs, a polarized light x 23,
b crossed nicols.

TABLE 5

ROCK ANALYSES

	Lumwana Contaminated gabbro.	Chambishi Amphibolite. (Mendelsohn 1961, av of 3).	Scapolite metagabbro. (Weiss 1947).	World plateau basalt. (Daly 1933).
SiO_2	46.75%	47.64%	43.55%	49.70%
Al_2O_3	14.87	14.98	16.01	14.24
TiO_2	1.24	ND	2.32	2.23
FeO	10.62	7.88	9.16	9.96
Fe_2O_3	1.22	3.99	2.22	3.66
CaO	13.16	7.47	13.53	9.55
MgO	6.51	7.13	7.26	6.82
MnO	0.16	0.13	0.10	0.17
Na_2O	3.25	3.62	2.83	2.64
K_2O	0.62	1.82	1.59	0.70
CO_2	0.18	ND	0.11	
P_2O_5	0.06	0.23		0.33
Cl	0.33	ND	0.27	
FeS_2	0.24	0.22		
H_2O	0.41	2.17	0.70	
H_2O^-	0.06	0.14	0.10	
SO_3	tr			
Cr	Absent			
	99.68%	97.42%	99.69%	100.00%

MODE

Amphibole	63%
Scapolite and oligoclase	34%
Sphene	0.5%
Ilmenite	2%
Apatite and related mineral	0.3%
Pyrite	0.2%
Magnetite	
Chlorite	

NORM

Orthoclase		3.89%
Albite		13.62
Anorthite		25.58
Sodalite		4.85
Nepheline		1.70
Diopside	Wo	16.12
	En	7.80
	Fs	8.05
Olivine	Fo	5.95
	Fa	6.63
Magnetite		1.86
Ilmenite		2.43
Calcite		0.40
Pyrite		0.24
Unallocated		0.53
		99.65%

C.I.P.W. Classification. Class III, Subclass 1, Order 6, Rang 3, Subrang 5.

knowledge of the Zambian gabbros, but should not be regarded as typical of the Lumwana gabbros.

The analysis is presented in Table 5 together with an average of three analyses of the Chambishi gabbro (Mendelsohn 1961), the average world Plateau Basalt (Daly 1933), and a scapolite metagabbro from Bucks County, Pennsylvania (Weiss 1947). The C.I.P.W., Norm of the Lumwana contaminated gabbro was calculated in order that the C.I.P.W. classification be used to draw comparison with other analyses. Only six rocks of the same classification are listed by Washington (1917) including four gabbros and diabases, a camptonite and an ijolite.

The analysis was carried out following the method prescribed by Washington (1919) with the exception of CO_2 which was determined volumetrically using the apparatus described by Fahey (1942-5). The total of the analysed constituents is a little low and it was checked by analysis of separate portions for CO_2, H_2O, Cl and SO_3, without significant modification of the results.

The Copperbelt amphibolite is strikingly similar in chemical composition to the world Plateau Basalt, and it is conceivable therefore that they originated from a similar magma type. Daly (1933) regards the parent magma as a late-crystallization alkali-enriched type, but the widespread occurrence in Zambia of gabbros of similar composition is suggestive of an actual alkali-rich parent magma. This view is held by Lehmann (1930) on the origin of the Malawi alkali basalts, which may be genetically related to the Zambian gabbros, and in this connection it is interesting to record Jackson's (1933) view that the gabbro intrusions are related to the Great Dike of Southern Rhodesia, and Eales' (1965) observations on albitization at the Empress Nickel Mine in Southern Rhodesia.

The Lumwana gabbro resembles the Copperbelt gabbro both megascopically and microscopically. Chemically the average results of three alkali analyses were soda 4.77% and potash 1.14%, which

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Note. The Great Dike, dated at 1,900 million years, is very much older than the Zambian gabbros.

indicates that the true gabbro of Lumwana is richer in soda even than the Copperbelt gabbros, a feature which may be strictly local, but which may indicate progressive increase in soda in the gabbros westwards from the Copperbelt. The sample analysed contains considerably less soda and potash than that of the indicated normal for the Lumwana area, and in addition is greatly enriched in lime relative to the Copperbelt amphibolites. This suggests that alkalies have been removed from the gabbro and that lime has been added.

The concepts of contamination by lime and alkali metasomatism of surrounding sediment are applicable only where, (1) the gabbro is alkali-rich and, (2) the sediment in which the gabbro is emplaced is lime-rich. Since the gabbros of Zambia are characteristically emplaced in impure dolomites and limestones of the Upper Roan and later rocks of the Katanga succession, contamination is likely to occur within the gabbro while alkali metasomatism is possible within the sediments.

In order to understand the processes which have given rise to the mineralogical composition of the gabbros, much detailed work on a regional basis would be required, but explanation of certain aspects of these processes can be suggested by mineralogical examination of the gabbroic rocks at Lumwana.

The contaminated gabbro analysed is very similar in chemical composition to that described by Weiss (1947), the analysis of which is presented in Table 5. This gabbro is intrusive into Precambrian limestone and is composed chiefly of andesine and hornblende. Oligoclase occurs in lighter coloured bands, and some interbands are composed mainly of diopside and scapolite. Weiss regards scapolitization as having occurred long after intrusion, during dynamic metamorphism, and aided by introduction of small amounts of hydrothermal solutions. The high lime in this rock is, in the opinion of the writer, suggestive of contamination from the limestone in which the intrusive body is emplaced, and it is regrettably unknown if the limestone is enriched in alkalies adjacent to the gabbro.

The modal analysis of the Lumwana contaminated gabbro is presented in Table 5. Under the microscope the colourless minerals scapolite and oligoclase resemble each other closely. The oligoclase is seldom twinned and although the scapolite can be recognized by a slight difference of colour, and slightly higher refractive indices when adjacent to oligoclase, in general they are indistinguishable in modal analysis. The hornblende is usually crowded with inclusions of the colourless minerals and the modal method of analysis is thus somewhat inaccurate.

According to Shaw (1960) the scapolites form an isomorphous series between two end-members marialite and meionite, and have a general formula $W_4 \ (Al_{3-0}Si_{9-6})O_{24}R_{1-2}$ where W includes mainly Ca and Na with some substitution of K and lesser substitution of Mg, Fe, Mn and possibly Ti; R is primarily CO_3 for meionite with lesser SO_4, OH, Cl and F, and primarily Cl in marialite with lesser HCO_3, HSO_4, OH and F. In some scapolites the sulphate radicles may have a high proportion relative to Cl and CO_3, and the water content is highly variable. For most general purposes the end-members are regarded as chloride marialite with a chemical composition $(Ab)_3NaCl$, and carbonate meionite of composition $(An)_3CaCO_3$.

To determine the composition of the scapolite the refractive indices are meaned to give a value n_m, this figure and the birefringence (called n_d) increase linearly with increase of calcium content, and are presented by Shaw in a diagram for easy reference. In the contaminated gabbro at Lumwana the scapolite refractive indices were determined to be ϵ 1.542 and ω 1.552. n_m is 1.547, and n_d is 0.010. Using Shaw's data the scapolite is found to have a composition of Me_{23}, falling within the dipyre range (Me_{20-50}).

The oligoclase in the few twinned crystals observed has a maximum symmetrical extinction angle of 7^o, is optically negative and cleavage flakes give refractive indices of X 1.539 and Z 1.547. Using Dana's (1958) tables the composition of the plagioclase is found to be An_{20}. The identification of this plagioclase was made specifically on the plagioclase in the material analysed, and it should be mentioned that in other sections cut of the gabbro, the plagioclase, still identified as oligoclase, is more sodic with maximum symmetrical extinction angles of up to 12°.

Finally, the amphibole was observed to resemble hornblende, being moderately pleochroic from greyish green (Z) to pale yellowish green (X). The refractive indices were found to be X 1.646 and Z 1.675, with a rather unusually high birefringence of 0.029, and also a rather high maximum extinction angle of c-Z 32°.

Exact determination of the proportion of scapolite to oligoclase, and the determination of the composition of the amphibole is not possible from the single analysis made, as both the scapolite and the amphibole have too many variables in their chemical composition. To obtain these data analyses of the amphibole and the scapolite would have to be made. This task was contemplated by the writer and a heavy liquid separation into four fractions was made with a view to exploring the possibility of preparation of pure samples of each mineral. The finely intergrown character of the rock coupled with the similarity in appearance of the scapolite and the feldspar makes separation of the scapolite virtually impossible. The amphibole likewise is crowded with inclusions and short of hand sorting minute grains of pure amphibole from the heavy concentrate, preparation of a pure sample is impossible. Hand sorting was not thought to be warranted by the information to be gained, but portions of the heavy concentrate were checked by the flame photometer method for Ca, K and Na. The concentrate was also analysed for TiO_2 (9.90%) and the equivalent ilmenite content calculated as 18.8%. By making allowance for ilmenite but neglecting other impurities the amphibole contains approximately 11% CaO, 0.6% K_2O and probably more soda than potash.

Considering the actual analysis, a rough idea of the proportion of scapolite to plagioclase can be obtained by the following method.

1. CO_2 is allocated to meionite assuming a formula of $(An)_3CaCO_3$ for meionite.
2. Marialite is calculated assuming a composition $(Ab)_3Na(Cl,OH)$ for marialite, and the scapolite composition Me_{23}, the deficiency of Cl after allocation to chlor-apatite being made up by OH.
3. All the remaining soda is allocated to albite.
4. Anorthite (An_1) is calculated on the basis that the plagioclase composition is An_{20}.
5. The potash is assigned to orthoclase, but assuming that it exists entirely in solid solution with the plagioclase, it is allocated an equivalent amount of the anorthite molecule (An_2).

The results of these calculations considered as percentages of the whole rock are:

	Me	Ma	Ab	An_1	Or	An_2
SiO_2	1.47	7.39	9.00	1.50	2.37	0.40
Al_2O_3	1.25	2.09	2.55	1.28	0.67	0.34
CaO	0.92			0.70		0.19
Na_2O		1.29	1.55			
K_2O					0.62	
CO_2	0.18					
Cl		0.32				
OH		0.07				
Na		0.31				
	3.82	11.47	13.10	3.48	3.66	0.93
	15.29			21.07		

Manipulation of the chemical data in this way gives statistically valueless figures, but attention is quickly drawn to major discrepancies in the original assumptions, which the check analysis of the amphibole-rich concentrate emphasizes. Firstly the alkalies are not confined to scapolite and oligoclase but are present in significant amounts in the amphibole. Secondly the lime left after allocation to scapolite and oligoclase is far in excess of that present in the amphibole. If the mode analysis is to be relied upon, approximately 3% of the material included in the light minerals is actually present in the amphibole and thus the presence of alkalies in the amphibole is explained.

The excess of lime in these calculations indicates that there is actually more of the anorthite molecule present than the other considerations lead one to expect. If this is true then some of the scapolite or plagioclase must be richer in lime than is indicated by the optical properties of the large colourless grains, and it is concluded that many of the small grains included in the amphibole are richer in lime than the larger grains. This conclusion refers particularly to the rock analysed, and it should be mentioned that in other samples of the gabbro, particularly close to contacts with lime-rich sediments, large scapolite crystals are sometimes zoned with lime-rich scapolite zones on soda-rich cores.

Another consideration which cannot be assessed is the substitution of aluminium for silicon which occurs in scapolite (Shaw 1960) and in the calciferous amphiboles (Hallimond 1943).

A further point of interest is the low water content of the analysis, and hence of the amphibole. Hallimond explains that water can be lost or gained without loss of structure, though not usually exceeding $\frac{1}{2}H_2O$. This is not particularly unusual as approximately ten percent of the amphibole analyses quoted by Deer, Howie and Zussman (1963) contain less water than expected from the general formulae, with an extreme $H_2O=0.28\%$ in hornblende from a hornblende eucrite in Sweden.

Although the actual composition of the amphibole has not been determined, the analytical data which have been presented show that it contains ferrous iron, calcium, magnesium and aluminium in order of abundance, with minor sodium, potassium and ferric iron. The amphibole is thus a hornblende which trends somewhat in composition towards actinolite.

The postulate was made early in this chapter that the analysed gabbro and others are igneous rocks contaminated with lime from the hosts in which they are emplaced, and the Lumwana contaminated gabbro was shown to be much richer in lime than the Copperbelt gabbros. This lime assimilation appears to have occurred in the gabbro firstly with substitution of Ca for Na (and possibly other elements) in the amphibole without causing the amphibole to become unstable or to convert to actinolite; and secondly with substitution of the Na in scapolite and possibly the plagioclase as well.

It has been mentioned that unlike those of the Copperbelt, the Lumwana gabbro contains pyroxene, largely replaced by hornblende. It is a pale greenish augite with c-Z 45° and 2V 61°. It occurs as remnants enclosed in and replaced by amphibole, and there is little doubt that it is original pyroxene and is not metamorphic in origin. It is not common in gabbros intersected in drill-holes or in the outcrops in the southwestern part of the Lumwana Prospect, but is found in most sections of the extensive gabbro emplaced in the normally dipping Upper Roan strata northwest of the Lumwana Prospect. This gabbro appears to be a particularly large intrusion which displays certain features less marked in the smaller intrusions, one such feature being the presence of pyroxene.

Another feature of the large gabbro mentioned is banding which may have resulted from flow or differentiation within the intrusion. The bands are seldom more than one or two centimetres in width and consist of alternate concentrations of dark and light material. They are not distinctly planar and frequently bifurcate, but have not been folded during orogenesis.

An interesting feature of the gabbro in MM 115 at a depth of 930' is bending of the amphibole crystals. Bending is common, often

Plate 48. Gabbro containing a large grain of the apatite-type mineral (a), hornblende, scapolite and reticulated ilmenite. MM 115, 1001'.
Photomicrograph, x 60.

Plate 49. Bent hornblende in gabbro. MM 115, 930'.
Photomicrograph, x 60.

of stubby crystals, and in extreme cases has occurred through 180°. Bending of metamorphic minerals such as kyanite, biotite and chlorite occurs frequently at Lumwana, and is explained simply by stresses present during crystallization, or actually set up by the force of crystallization, but such minerals are seldom bent through more than a few degrees. The essential difference between bending of the amphibole and the other metamorphic minerals was the medium in which bending took place. Whereas the metamorphic minerals grew in a solid medium under stresses which restricted directions of growth, the amphibole could hardly have grown in any but a fluid medium in which growth could take place in any direction, and stress relief was by flow. Bending of the amphibole is likely to have occurred comparatively early during crystallization of the gabbro, as, if the original narrow limbs of a crystal were bent in some way as they first grew, the subsequent deposition would bring about the curved thicker limbs. The distortion due to curvature would be spread out in a molecular way, and the bending of a narrow crystal limb in this way is easier to imagine than that of a thicker crystal. (Buckley 1951).

Finally, a late vein from the large intrusion, 5 mm. thick, was examined in thin section and found to consist of coarse clear scapolite and fine crystals of andalusite. The needles of andalusite occur in parallel bundles which are orientated preferably parallel to the c axes of the scapolite crystals so that both minerals extinguish at the same time. This occurrence suggests that andalusite actually unmixed from scapolite during crystallization and cooling.

Contact effects are not readily discernible within the regionally metamorphosed Upper Roan formations, and no chilled margins in the gabbro have been observed. Contact effects postulated include soda fixation in the sediments surrounding the gabbro, and evidence is found in zoning of scapolite in these sediments with sodic material outside calcic cores. Another contact effect of importance is the presence of biotite, both in the gabbros and adjacent sediments.

Plate 50. Scapolite-andalusite vein from gabbro outcrop northwest of Lumwana.

Photomicrograph, x 60.

It may be that the biotite is formed indirectly as a result of contamination, or it may be the outcome of thermal metamorphism. Finally a common contact effect is oxidation of pyrite to magnetite immediately adjacent to the gabbros, an effect which often gives what may be a false impression of ferruginization of the sediments by the gabbro.

The present investigations have led the writer to adopt certain views relating to emplacement of the gabbro. These views are not always substantiated by indisputable evidence but may provide future research workers with suggestions towards fields of exploration, and are summarized as follows.

1. The gabbro was intruded after the Lufilian Orogeny.
2. Emplacement occurred preferentially in the Upper Roan, but also in other carbonate-bearing rocks higher in the succession.
3. The gabbro is often associated with normal faults of post-Lufilian age, the association being a feature of a period of tension.
4. Mineralogically the gabbro probably consisted initially of labradorite and augite, but alteration to oligoclase and hornblende was started during crystallization probably while the gabbro was being emplaced. The last stages of crystallization were accompanied by soda scapolitization.
5. During emplacement the gabbro was often contaminated with host rock material of which lime was the chief constituent, and extensive albitization and scapolitization affected the surrounding sediments.
6. At contacts between sediment and gabbro small-scale exchange of calcium from the sediment and sodium from the gabbro occurred towards the end of scapolitization, so that scapolite in the gabbro is zoned with lime-rich material on sodic cores while scapolite in the sediment has the reverse order of zoning.

METAMORPHISM

Perhaps the most difficult task of the field geologist studying an area which has been regionally metamorphosed, is to equate various mineral assemblages with the observed fabric of rocks and metamorphic facies.

In purely thermal or contact metamorphism a simple zonal relationship between metamorphic minerals and temperature gradient can readily be established. Regional metamorphism, however, is dynamothermal, and although the temperature relationships can often be assessed by estimation of depth of burial, stress has seldom been uniform and where stress has been particularly active the facies can be recognized only on a very general regional basis.

The concept of metamorphic facies assumes that equilibrium has been attained, but since the application of stress is seldom, if ever, uniform, the question arises whether equilibrium is in fact ever attained. Fortunately the facies concept can be applied regionally even where equilibrium has been reached only locally though it is not always clear how best to achieve this purpose. For instance, is one to assume that the highest grades observed in some highly deformed rocks would have been reached in other less-deformed rocks if they had been subjected to the same stress, or should one assume that if stresses had been more evenly distributed the local high grades would never have been reached? Examples which illustrate this type of problem include some breccias in which the rock fragments exhibit lower metamorphic grade than the matrix, and on a larger scale, competent beds which exhibit a lower metamorphic grade than incompetent beds.

In introducing the subject of metamorphism of the formations at Lumwana it is important to note that rocks of certain chemical composition are suited to the development of some of the recognized facies index minerals while other rocks may be suited to others, and yet other formations such as the purer quartzites and dolomites are devoid of metamorphic minerals in the grades encountered. In addition, the Upper Roan intrusive rocks contain minerals unrelated or only partly related to regional metamorphism, while sediments adjacent to intrusions may have been thermally metamorphosed at temperatures greater than those prevailing in regional metamorphism.

Although detailed description of the minerals in the various formations can be found in the appropriate sections in the previous chapter, a summary of the main mineral assemblages, with less common minerals included in brackets, is presented here for convenience of reference.

Granite. Quartz-microcline-oligoclase-biotite-muscovite.

Basement schist and gneiss. Quartz-orthoclase-oligoclase-biotite-muscovite-epidote-clinozoisite-sphene, (microcline).

Lower Roan Mineralized schist (a) Barren footwall. Quartz-orthoclase-oligoclase-biotite-muscovite-epidote-sphene, (rutile).

(b) Mineralized facies. Quartz-orthoclase-oligoclase-phlogopite-muscovite-kyanite-almandine-sulphides, (anthophyllite.)

(c) Barren hangingwall. Quartz-orthoclase-oligoclase-biotite-muscovite-kyanite-almandine-epidote-clinozoisite, (hornblende).

(d) Basic intrusions. Hornblende-oligoclase-biotite-almandine, (tremolite, anthophyllite, quartz.)

(e) Ultrabasic intrusions. (1) Hornblende, (calcite, oligoclase, biotite).

(2) Olivine-bronzite-talc-serpentine-chlorite-tremolite-magnetite.

Lower Roan Soft schists. Quartz-kyanite-epidote-orthoclase-biotite-sericite-specularite, (phlogopite, chlorite.)

Lower Roan Quartzite. Quartz-kyanite-talc-sericite-specularite-sphene-rutile, (orthoclase, oligoclase, chlorite, biotite, anthophyllite.)

Upper Roan (a) Dolomites. Dolomite-quartz, (scapolite, oligoclase, magnetite, pyrite, pyrrhotite.)

(b) Cherty dolomites. Dolomite-quartz-biotite (phlogopite)-muscovite-oligoclase-scapolite-orthoclase-sphene-pyrite-pyrrhotite, (almandine, hornblende.)

(c) Impure dolomites. Biotite-hornblende-quartz-oligoclase- scapolite-dolomite-orthoclase-almandine-sphene-pyrite-pyrrhotite, (biotite-anthophyllite in sheared specimens.)

(d) Hybrid rocks. Hornblende-biotite-oligoclase-scapolite-almandine-magnetite-sphene-pyrite-pyrrhotite, (albite, orthoclase, muscovite, chlorite, quartz, epidote.)

Gabbro. Hornblende-augite-oligoclase-scapolite-ilmenite-sphene-pyrite, (orthoclase, epidote, almandine.)

The metamorphic history of the Basement formations includes periods of metamorphism prior to deposition of the Katanga System. The highest grades of metamorphism in the early epochs probably arose in association with the intrusion of granite and granitization of Basement sediments. The occurrence of microcline in the granite at Lumwana is evidence of post-intrusion metamorphism, but the granite could have been one of a number of early intrusions and conclusions regarding metamorphism are of little value. The coexistence of microcline and orthoclase in Basement schists and also in the lower members of the Katanga System is of interest as higher in the succession the potash feldspar is almost entirely orthoclase. It is likely that the metamorphic development of microcline occurred in the granite prior to deposition of the orthoclase-bearing Basement schists, and that any microcline in these schists and later formations was derived by detrital deposition after weathering of the older formations such as the granite.

The main problem is not so much the coexistence of microcline and orthoclase, but why orthoclase is present at all. According to Harker (1932) either microcline or orthoclase is formed at grades right up to the granulite facies. Other writers such as Turner and Verhoogen (1951) and Ramberg (1952) stress the importance of microcline rather than orthoclase from the greenschist facies upwards. Heier (1961) states that orthoclase is stable in the granulite facies and microcline in the amphibolite facies. Microcline, according to Ramberg, is actually characteristic of the epidote-amphibolite facies, and considering the other metamorphic minerals present it is surprising that the potash feldspar at Lumwana is so consistently represented by orthoclase. There is little in the literature to suggest why orthoclase should form in place of microcline at moderate to low grade of metamorphism, and presumably special circumstances are required for its formation. Since microcline is the normal potash feldspar of the Copperbelt (Mendelsohn, 1961), it can be inferred that the conditions operative at Lumwana were different from those at the Copperbelt, and that orthoclase has displaced microcline in the higher grade of metamorphism encountered at Lumwana. If this is true in its simplest form, then orthoclase would have to be regarded as stable in grades as low as the epidote-amphibolite facies - well below the granulite facies. There are however other factors which may exercise control on the development of potash feldspar, one of which is the quantity of soda present in the rock. W.S. MacKenzie (1954) believes that the development of orthoclase or microcline is chemically controlled, and depends on the degree of exsolution of soda feldspar, so that microcline formed during metamorphism is almost pure $KAlSi_3O_8$, and orthoclase contains dissolved soda feldspar impurity. If MacKenzie's view is correct it is possible that under moderate grade of metamorphism, rocks rich in soda such as those at Lumwana, will recrystallize with development of orthoclase, while under lower grade, such as that encountered on the Copperbelt, microcline will be formed.

Coexistence of microcline and orthoclase is not confined to the Basement schists but occurs also in the lower parts of the Katanga System. The microcline in such cases is regarded as detrital as is some of the orthoclase. The remainder of the orthoclase is considered to have formed by metamorphic alteration of micas. It is perhaps remarkable that the homogenization of the Katanga rocks, for which process there is considerable evidence, has not resulted in the inversion of either one of the feldspars to form the other.

The Lower Roan sediments contain different mineral assemblages in the various horizons which can be related to both chemical composition and metamorphism. They are characteristically quartzitic, and in addition to orthoclase, oligoclase and the uncommon detrital microcline, kyanite and micas are usually present.

The kyanite in the epidote and kyanite schists and in the mineralized horizon occurs as porphyroblasts several centimetres in size, which are full of inclusions of the other constituents, and which may be altered peripherally to sericite. In the quartzites kyanite occurs in small acicular crystals which form a felt in the plane of schistosity. Unlike the large porphyroblasts of the lower beds the crystals are euhedral or subhedral and have a completely different pattern of inclusions. These inclusions are not definite fragments of the other constituents, but a fine black dust which is confined to elliptical zones in the centres of the crystals. It is considered likely that these congregated inclusions indicate that the kyanite has replaced andalusite, although no relict chiastolite crosses have been found at Lumwana and the assumption that the inclusions were redistributed during stress cannot be substantiated. In this connection it is interesting to note the large pseudomorphs of kyanite after andalusite from the Lomagundi (Workman and Cowperthwaite, 1962), and Piriwiri (Wiles 1961) in Southern Rhodesia; these are identical to andalusite in crystal form and in many cases the chiastolite cross is preserved. On the basis of experimental work which is summarized by Green (1963), andalusite is the low-temperature, low-pressure polymorph while kyanite is the high-pressure member. The inversion from andalusite to kyanite, which can take place without an intervening sillimanite stage only at temperatures below 280° C, occurs at between 6 and 7.5 kilobars, the pressure rising with temperature from zero.

The micaceous minerals are always well represented in the Lower Roan quartzose rocks. Muscovite or sericite is usually present, biotite is associated particularly with the more ferruginous rocks, and phlogopite and talc with the more magnesian strata. The occurrence of phlogopite may be an indication of high stress: Turner and Verhoogen (1951) record phlogopite in the high pressure almandine-diopside-hornblende subfacies of the amphibolite facies. Ramberg (1952) regards biotite, phlogopite and talc as stable minerals of the amphibolite facies, but in addition states that most chlorites are unstable. In the normal Lower Roan strata chlorite is uncommon, although in sheared beds and near to faults it is sometimes a major constituent of the rock.

Epidote and clinozoisite have formed in Lower Roan rocks which, presumably, were calcareous. Almandine is common in the more ferruginous parts, and forms crystals a centimetre or more in diameter, and in addition a little hornblende is sometimes present. Anthophyllite is sometimes present in the Lower Roan sediments but is more common in association with sheared intrusive rocks and is discussed fully later in this chapter. Sphene is the normal titanium mineral, but rutile occurs in the quartzites. Sphene is the normal titanium mineral of the epidote-amphibolite and amphibolite facies and though rutile sometimes displaces sphene in the almandine-diopside-hornblende subfacies (Turner and Verhoogen 1951), according to Ramberg (1952) it is typical of the granulite facies. Magnetite or specularite is present and is probably related to conditions of sedimentation rather than to metamorphism, as Harker (1932) states that haematite transforms to magnetite in advanced grades of metamorphism. The sulphide minerals occur as large grains which are homogeneous except in the cases of low-temperature supergene intergrowths of chalcocite, digenite and covellite, and of chalcopyrite-cubanite intergrowths which indicate temperatures greater than 235°C and probably greater than 255°C (Edwards 1947). Despite the widely held view that pyrrhotite is a high-temperature mineral, its occurrence at Lumwana seems to have been controlled by availability of sulphur during sedimentation, and by temperature of formation or subsequent metamorphism.

The ultrabasic rocks intrusive into the Lower Roan succession are characterized by alteration of both olivine and pyroxene to serpentine (bastite) and talc. Since serpentine is stable up to 500°C irrespective of pressure, (Bowen and Tuttle, 1949), the maximum upper limit of thermal metamorphism at Lumwana can be set at 500°C. Tremolite in these ultrabasic rocks occurs as euhedral or subhedral crystals which have clearly not been formed directly from alteration of olivine and pyroxene. This mineral, and chlorite which occurs as occasional large porphyroblasts, appear to have formed by alteration of serpentine or talc, so that there are two distinct stages in the development of the metamorphic minerals in these rocks: (1) the olivine and bronzite degraded with addition of silica and water to form talc and serpentine, and (2) serpentine and talc upgraded to form tremolite and chlorite. The stage of tremolite formation according to Ramberg (1952) corresponds to the upper part of the epidote-amphibolite facies, and according to Barth (1952) the temperatures would be less than 250°C otherwise forsterite would have started to form as well. (Note that this figure may be low as Bowen and Tuttle (1949) quote 500°C for the equation: serpentine→ forsterite, talc and water vapour.)

The basic intrusive rocks are characterized by hornblende, but where sheared, anthophyllite is conspicuous. Anthophyllite is also found in talc schists adjacent to ultrabasic intrusions and occasionally in the Lower Roan sediments as well. It occurs both as small well-formed crystals and as larger grains without distinct form. A feature of the occurrence of anthophyllite is fine powdery magnetite enclosed by and surrounding the crystals. An analogy may be drawn in examining its formation with the characteristic alteration of olivine to serpentine and magnetite, where the serpentine lattice is incapable of retaining the iron derived from the olivine. Similarly anthophyllite, formed from what was probably a relatively unstable calcareous hornblende, is expurgated by removal of iron which goes to form magnetite. This reaction is considered to indicate local high stress resulting in increase of grade, and evidence is usually found in shearing of these rocks. Since Ramberg (1952) states that anthophyllite is characteristic of the amphibolite facies, it can be concluded that the highest grades attained were within the amphibolite facies.

Although sometimes conflicting, the bulk of the evidence from the Lower Roan favours assignment of the metamorphic grade to the upper part of the epidote-amphibolite facies, with grades entering the amphibolite facies under local conditions of high stress. Temperatures were likely to have been between 250° and 280°C, with pressures well in excess of 6 kilobars and subject to variation. There is evidence which suggests more than one stage of metamorphism, with the ultimate stage of the main epoch of regional metamorphism being one of slightly higher grade than the penultimate one. The writer considers that it is likely that each of the periods of folding was accompanied by development of metamorphic minerals, and that the two stages cited correspond to second and third folding respectively. A final stage of pure dynamic metamorphism probably occurred after orogenesis when normal faulting took place, the grade of metamorphism falls within the greenschist facies, and the metamorphic minerals are confined to the chlorite developed in the vicinity of fault planes.

The petrology of the Upper Roan altered sediments is closely related to that of the gabbro which is emplaced in them, and care must be exercised in differentiating minerals developed during regional metamorphism from those of metasomatic origin. The typical assemblage is dolomite-oligoclase-scapolite-quartz-biotite-hornblende-almandine-sphene-pyrite-pyrrhotite, and in this dolomite is the main original constituent; scapolite and most of the oligoclase appear to be metasomatic and the remainder are largely metamorphic.

In the fairly pure dolomites, dolomite is recrystallized, quartz is largely interstitial, and no combination of the two minerals to form tremolite-actinolite has been observed. This is surprising in view of the amount of hornblende in the impure dolomites and in view of the preliminary allocation of grade to the epidote-amphibolite facies, seeing that Ramberg (1952) and Turner and Verhoogen (1951) actually regard the formation of actinolite as the border between the greenschist and epidote-amphibolite facies. Either there was little silica in the original sediment, and the quartz found today is secondary, having been introduced after metamorphism, or metamorphism of the dolomites examined did not reach the epidote-amphibolite facies.

The cherty dolomites on the whole present a picture similar to that given by the dolomites. Dolomite and quartz are recrystallized, but have not combined to form tremolite or actinolite; the micas are well developed, and hornblende and almandine are rare. There is little doubt that the quartz is a primary constituent in this case, and the evidence favours allocation of these beds to the greenschist facies rather than to the epidote-amphibolite facies of metamorphism. It must, however, be borne in mind that the cherty dolomites were competent relative to the impure dolomites, and that stress exercised less control on metamorphism in the cherty dolomites than in the impure dolomites.

The impure dolomites appear to have been more susceptible to metamorphism than the cherty dolomites. In addition to the micas, hornblende is characteristically present and almandine is common. There appears to have been some decarbonatization of the rock as dolomite is often present only in minor amounts, particularly where hornblende is abundant. The mineral assemblage is typical of the epidote-amphibolite facies.

The hybrid rocks differ from the impure dolomites mainly in texture. The chief difference in mineralogy is that dolomite is usually absent and hornblende abundant, and it is thought that decarbonatization was advanced. Since the hybrid rocks are closely related to the gabbros, it is likely that the process of decarbonatization is not one of regional metamorphism, but a thermal reaction or contact phenomenon related to intrusion of gabbro.

The gabbro, apart from including relict augite and ilmenite, is essentially similar in mineral composition to the hybrid rocks. Among the constituents common to both are scapolite and oligoclase, the genesis of which is a problem which hinges on the following syllogism.

(1) The grade of regional metamorphism was determined primarily by stress, and the highest grades of regional metamorphism occurred during orogenesis at stages corresponding to first, second and third folding respectively.

(2) The gabbro was intruded after folding.

(3) The presence of oligoclase and scapolite in both Upper Roan sediments and gabbro suggests co-genetic relationships of the minerals in both rock types. If this is the case, then from the premises cited, genesis of scapolite and oligoclase occurred during or after emplacement of gabbro, which in turn occurred after orogenesis and the main stages of regional metamorphism.

It was mentioned in the previous chapter that of the two processes feldspathization preceded scapolitization since where the two minerals coexist scapolite replaces oligoclase. The two processes are discussed in chronological order.

The normal feldspar in both gabbro and sediment is oligoclase. In the gabbro ghosts of a more calcic feldspar have been observed, but replacement by oligoclase has not been crystallographically controlled. The oligoclase in both gabbro and sediment is rarely twinned, and although it is recognized that metamorphic plagioclase is often untwinned, the lack of twinning suggests that since recrystallization it has not been subjected to advanced stress. Although oligoclase is the common feldspar, it has been suggested by the writer that inclusions in amphibole in the gabbro are of a more calcic variety, and in the sediments albite is sometimes present in place of oligoclase. It can be concluded therefore that homogenization of the feldspar has not occurred. In this connection it is interesting to note that coexisting plagioclase feldspars may be more common than is generally realized, as Evans (1964) has identified coexisting albite and oligoclase in some New Zealand schists using an electron probe microanalyser. The significance of the coexistence of albite and oligoclase is that albite is characteristic of the greenschist facies of metamorphism, while inversion to oligoclase occurs in the epidote-amphibolite facies, (Turner and Verhoogen, 1951). In the Upper Roan sediments at Lumwana, therefore, it can be concluded that some of the plagioclase has recrystallized in the epidote-amphibolite facies, while the remainder was subjected to grades corresponding to only the greenschist facies of metamorphism.

Scapolite occurs widely in the Upper Roan formations in Zambia. On the Copperbelt it has been recognized by Mendelsohn (1961) to be of metasomatic origin and to be associated with gabbro. At Lumwana zoning of the scapolite in the gabbro and adjacent sediment has shown the intimate nature of this association, as, in at least one case, exchange of sodium and calcium has occurred across the contact between gabbro and sediment. There is little doubt therefore that late crystallization of scapolite in the already emplaced gabbro was accompanied by widespread development of this mineral in the surrounding sediments.

Scapolite is not a common mineral yet it occurs so widely in the Upper Roan of Zambia that understanding of its chemistry and mode of occurrence is essential in any discussion on metamorphism. Prior to 1960 little was published on the overall characteristics of scapolite. Shaw, however, in that year published a very thorough examination of the literature which includes a general discussion on the mode of occurrence which is summarized below.

"The main modes of occurrence (are) 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 ground-water action...),

(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....

"It is evident from the literature that scapolite can coexist with a wide variety of common minerals, and there are few rock types in which it has not been found: however, it seems unable to form in sedimentary environments. It is typically metamorphic and is not a product of primary magmatic crystallization.

"There is a general tendency for scapolite and plagioclase to be mutually exclusive and many authors have described progressive replacement of feldspar by scapolite. However, the two minerals are not always antipathetic and there are numerous examples of metamorphic rocks in which scapolite and feldspar appear to be in equilibrium.

".... it is evident that it (scapolite) is most prevalent in rocks which recrystallized in the upper amphibolite facies ... (eg.) the Precambrian Grenville province of Quebec and Ontario....

"It is evident that scapolite is by no means confined to a narrow range in metamorphic conditions, but can occur in almost any grade of metamorphism. This is partially obscured by the fact that plagioclase, which plays such an important role in estimating metamorphic grade, is often absent from scapolitic assemblages.

"Examples... (occur) however, from the epidote-amphibolite facies... (eg.) Kiruna, Sweden, where scapolite-biotite-hornblende-epidote-plagioclase assemblages are found.... Kiruna also provides examples of the greenschist facies, with similar assemblages including chlorite and sericite....

"Veins cutting a diabase at French Creek, Pennsylvania, contain scapolite associated with prehnite and heulandite.... which indicates the zeolite facies.

".....scapolite....in the Shai Hills, Ghana, has been taken as evidence of recrystallization in the granulite-eclogite facies....

"The ejected blocks of the Laacher See.... contain scapolite associated with sanidine, and indicate the sanidinite facies. The occurrences in the Oslo district of Norway.... are in contact rocks of the pyroxene hornfels facies.

"..... (there is) abundant evidence that scapolite can form (stably or metastably) in all facies from zeolite to granulite to sanidinite. This is roughly equivalent to a temperature and pressure range of 200-1,100°C and 0-10,000 kg/cm^2..... One might therefore expect scapolite to be much more widespread than in fact it is. In point of fact its complex consitution limits its field of occurrence to conditions where not only temperature and pressure, but also composition is suitable.

> "Until adequate synthesis studies have been carried out it is only possible to speculate on the necessary conditions.... All the components of scapolite are.... present to some degree in a variety of geological environments. The problems of supply mostly centre on the question of how much comes from the parent rock and how much is introduced from elsewhere."

Considering scapolitization at Lumwana, the Upper Roan dolomitic rocks are thought to have contained all the necessary constituents for the formation of scapolite, with the possible exception of sufficient sodium. Sodium was introduced at least in the immediate vicinity of the gabbro intrusions, but further from these intrusions, however, a source of sodium from intercalations of evaporite minerals, largely destroyed during metamorphism, is very likely. Indeed Shaw states that it is possible that regional scapolitization occurs only where the sedimentary sequences include such evaporite intercalations. Although possibly the genesis of scapolite in gabbro and sediment occurred under slightly different conditions, these conditions appear to have been those of low grade regional metamorphism.

The typical Upper Roan mineral assemblage includes sphene, though ilmenite occurs sometimes immediately adjacent to gabbro intrusions. Both pyrite and pyrrhotite occur, and as in the Lower Roan the pyrrhotite is not regarded as indicative of high temperature crystallization. The chief control exercised on crystallization of sulphides is thought to have been availability of sulphur, though the occurrence of pyrrhotite may indicate slightly higher temperatures than would have been the case if pyrite had occurred alone.

Considering the Upper Roan as a whole, the formations are less competent than those of the Lower Roan, so that whereas the normal metamorphic grade of the Lower Roan is that of the competent strata, the normal grade of the Upper Roan is that of the incompetent strata. The grade here corresponds to the epidote-amphibolite facies, but more competent strata have recrystallized in the greenschist facies. The relationships between grade and formation can thus be summarized as follows.

Upper Roan competent strata - Greenschist facies

Upper Roan incompetent strata and Lower Roan competent strata - Epidote-amphibolite facies

Lower Roan incompetent strata - Amphibolite facies

-the general picture is one of increasing metamorphic grade downwards in the succession.

The metamorphic history at Lumwana can be summarized as follows:

(1) Orogenic phase: regional metamorphism in stages corresponding to the three major periods of Lufilian Orogeny, with the average grade that of the epidote-amphibolite facies.

(2) Post-orogenic tensional phase:

(a) feldspathization (oligoclase) of Upper Roan sediments and probably autometamorphism of the gabbro with early intrusion (declining epidote-amphibolite facies),

(b) albitization of Upper Roan sediments, chloritization along faults, and completion of gabbro intrusion, (greenschist facies),.

(c) scapolitization of Upper Roan sediments accompanied by final crystallization of gabbro.

In conclusion, the grade of metamorphism at Lumwana may be said to fit in with the general statement by Garlick (1954) that grade increases southwards from the Katanga. The Copperbelt sediments have recrystallized in the greenschist facies according to Mendelsohn (1961), and although now thought to be of **somewhat** lower grade than estimated at that time, the Kalaba sediments (McGregor 1960) display higher grades of metamorphism than those at Lumwana. The grade in sediments surrounding the Solwezi Dome appears to be comparable with that at Lumwana, but may be slightly higher.

THE OPAQUE MINERALS

In the chapter on petrology, opaque minerals in the various horizons were mentioned briefly. These include iron and titanium oxides which are found in all rock types, minor occurrences of sulphides in the Upper Roan-Mwashia and the gabbro, and the major occurrences of sulphides in the Lower Roan mineralized horizon. Throughout this thesis the investigations have been centred around the mineralized horizon, and examination of the other formations has been made only to ensure that factors concerning the history of the mineralized horizon have not been overlooked. In the examination of the opaque minerals the same approach was adopted, so that, whereas the sulphides of the mineralized horizon have been examined in detail, only one polished section of Upper Roan sulphide mineralization was prepared.

Fifty-four samples from the various drill-holes were concentrated by flotation after crushing in a laboratory ball-mill, mounted and polished, and examined under the microscope. Dr. H. Meyer of R.S.T. Mine Services conducted a grain-count analysis of these samples, and head, concentrate and tail samples were assayed for copper, cobalt, total iron and sulphur, partly because the method of flotation included suppression of pyrite. The preparation and analyses of these samples were done by the R.S.T. Mine Services Research Laboratory as part of the investigation of the Lumwana Prospect. The writer examined the polished specimens of the sulphide concentrates, and in addition prepared polished sections of rock specimens in order to study textures.

The description of the sulphide minerals falls into two parts: (1) the description of the minerals themselves, their mutual relationships, and their relationships to metamorphism, and, (2) the description of the distribution of the sulphides within the area of the Lumwana Prospect, and their relationships within the stratigraphic succession. Following the descriptive sections a discussion (3) is presented on the genesis of the sulphide minerals.

MINERALOGY.

The most characteristic feature of the sulphides at Lumwana is the coarse grain of most minerals, with single crystals of uniform composition reaching two centimetres in size. The minerals identified include pyrite, chalcopyrite, cubanite, valleriite, bornite, chalcocite, digenite, covellite and carrollite; in addition, native copper, various copper oxides, magnetite, haematite, limonite and graphite have been observed in the polished sections. Pyrrhotite although common in the Upper Roan, is of very local occurrence in the Lower Roan. It has been observed in one band of sulphide mineralization stratigraphically above the main sulphide zone in drill-hole MMB 168, and in the drill-holes northeast of the Lumwana Prospect.

The sulphides are directly associated with silicates of metamorphic origin such as kyanite and phlogopite. With the exception of pyrite which is often euhedral, the sulphides occur interstitially, but in addition sometimes occur as thin films along cleavage planes of the silicate minerals, especially micas. The coarseness of grain and the association with metamorphic minerals leaves little doubt that the sulphides have been affected by metamorphism, and in general terms the sulphide body is similar to the metamorphosed Bodenmais sulphide deposit described by Schreyer, Kullerud and Ramdohr (1964).

Megascopic examination of drill-cores shows that the mineralized horizon can be subdivided into four ore types on the basis of mineral composition as follows:

(a) oxidized ore - rock containing chalcocite, other sulphides and oxides,

(b) chalcocite - bornite ore - rock containing mainly chalcocite and bornite,

(c) chalcopyrite - pyrite ore - rock containing mainly chalcopyrite, cubanite and pyrite.

This subdivision is used in the following paragraphs to classify the microtextures and also in the subsequent sections on the distribution and genesis of the sulphides.

(a) Oxidized Ore.

The distribution of oxide minerals and related chalcocite is controlled at Lumwana by the water-table. This ranges from approximately forty feet beneath the surface on high ground to zero at some places along the Lumwana River. The water-table is estimated to rise and fall at least ten feet between wet and dry seasons in a single year, and may also vary from year to year depending on the amount of rain in the wet season. Where the mineralized horizon projects above the water-table a thin zone of chalcocite mineralization is found to be overlain by a leached zone.

The zone of leaching is one in which sulphides are very uncommon, and indeed copper mineralization often appears to be absent except for the occasional speck of malachite or chalcanthite. Chemical assays however reveal that weathered rock in this zone commonly contains 0.5 to 1% copper, and since black earthy material is present it is assumed that much of the copper is in the form of melaconite.

The zone of chalcocite mineralization is thin at Lumwana, varying from 0 to a few feet in width, and as far as is known there is no lateral spreading of this zone into barren formations at the water-table. The poor development of this zone has resulted from the impervious character of the mineralized horizon, which is illustrated by the artesian water contained between it and the quartzite, and also by the fresh occurrence of bornite and chalcopyrite in exposures from just below the water-table in the bed of the Lumwana River. The supergene process at Lumwana is thus thought to have been one in which downward percolating water leached out sulphides, but instead of depositing them, has largely removed them by lateral flow at the top of the impervious unweathered rock, causing secondary enrichment to be absent or insignificant.

Plate 51. Supergene rim alteration of bornite and chalcopyrite (pitted) to chalcocite. The grains are surrounded by successive bands of limonite. From outcrop near the Lumwana River.

Photomicrograph, reflected light x 23.

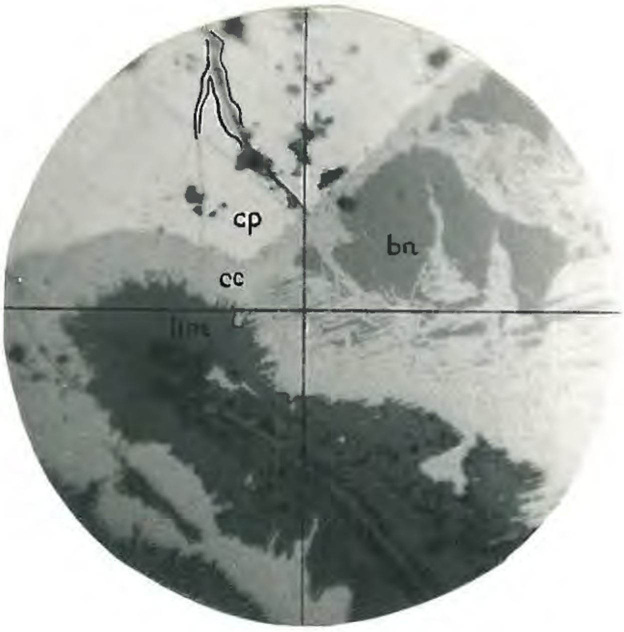


Plate 52. Rim and lattice replacement of bornite by chalcocite which in turn is replaced by limonite. Note that chalcopyrite is also replaced by chalcocite but only along cracks and at the margin of the grain. From outcrop near the Lumwana River.

Photomicrograph, reflected light x 300.

Interpretation of textures in this zone is made difficult by uncertainty whether the observed textures are related to pure supergene processes, or to modification by low grade metamorphism. The main criteria for pure supergene action are the weathering of host rock and the occurrence of limonite and copper oxides. Some features of sulphides occurring in the absence of oxides however, appear more likely to be related to supergene action than to metamorphism, but there is always doubt in interpretation where oxides are absent.

The characteristic mineral of the supergene zone is chalcocite. It occurs in rims around bornite and chalcopyrite which in turn are surrounded firstly by banded limonite and then by malachite. No digenite or covellite has been obserbed in direct contact with oxides in this way, but native copper sometimes occurs as separate grains or films with chalcocite. The occurrence of chalcocite with native copper indicates that under these conditions sulphide ion was in short supply, and chalcopyrite and bornite were altered to the richest copper sulphide without passing through intervening stages of digenite and covellite formation. This is probably simply evidence of reducing conditions operative in this zone.

Where rim alteration of chalcopyrite and bornite to chalcocite occurs in the presence of oxides, as outlined above, bornite has wider rims of chalcocite than has chalcopyrite. Bornite, though altered primarily on the margins of grains, also exhibits marginal lattice replacement by chalcocite, but chalcopyrite shows only rim alteration.

Where supergene conditions are thought to have prevailed, even although oxides are not found, more sulphide sulphur was available and chalcocite is accompanied by digenite and sometimes covellite. In such cases chalcopyrite and bornite are once again altered peripherally, but the rim of chalcocite is always separated from the primary sulphide by a distinct rim of digenite. Once again alteration of bornite includes some minor lattice replacement, but this feature is absent in chalcopyrite. Covellite does not fit into the zonal sequence of

Plate 53. Chalcopyrite replaced in two parallel bands by successive rims of digenite and finely intergrown chalcocite and digenite. MMB 163, concentrate.

Photomicrograph, reflected light x 300.

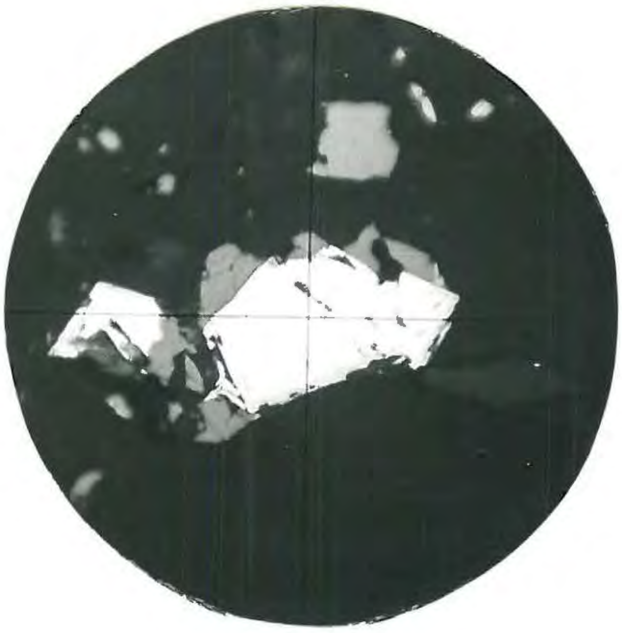


Plate 54. Subhedral pyrite replaced by digenite. MMB 184, concentrate.

Photomicrograph, reflected light x 300.

replacement, but occurs as patches enclosed in bornite, chalcopyrite or digenite. These patches are composed of grains which are usually orientated in crystallographic directions of the host mineral, and it is possible that covellite is not in fact supergene at all, but entirely metamorphic in origin.

An additional mineral association which is found with apparent supergene action in the absence of oxides, is fine subgraphic intergrowth of bornite and digenite. Such textures, according to Lindgren (1933), are common in the supergene zone, but have been regarded as indicative of higher temperature by Bateman (1942). Since they are absent in the typical chalcocite-bearing metamorphic ore, it appears that Lindgren's view is the more likely. Of particular interest is a similar fine subgraphic texture in which chalcopyrite, bornite and digenite are intergrown, and the possibility that some bornite is supergene cannot be ruled out. Yet another type of subgraphic intergrowth was observed in a vein which may have been formed late in metamorphism. In this vein chalcopyrite encloses coarse subgraphic bornite grains nearly ½ mm. in size.

In addition to the copper sulphides, pyrite and carrollite are also replaced by digenite and chalcocite in the supergene zone. Replacement is seldom advanced and there is no zonal relationship of digenite and chalcocite about these minerals. The mode of occurrence is that of remnants in the digenite and chalcocite surrounding chalcopyrite (and sometimes bornite) and it is assumed that these are partly replaced grains which were originally enclosed in chalcopyrite.

Supergene action at Lumwana may be summed up as follows. It occurred at normal temperatures under the action of normal weathering processes and downward percolating water. The effects on the mineralized horizon were the development of (1) a zone in which sulphides were leached above the water-table, and in which melaconite is the main copper mineral; on the basis of data presented by Garrels (1960) conditions of high pH would have been necessary for the

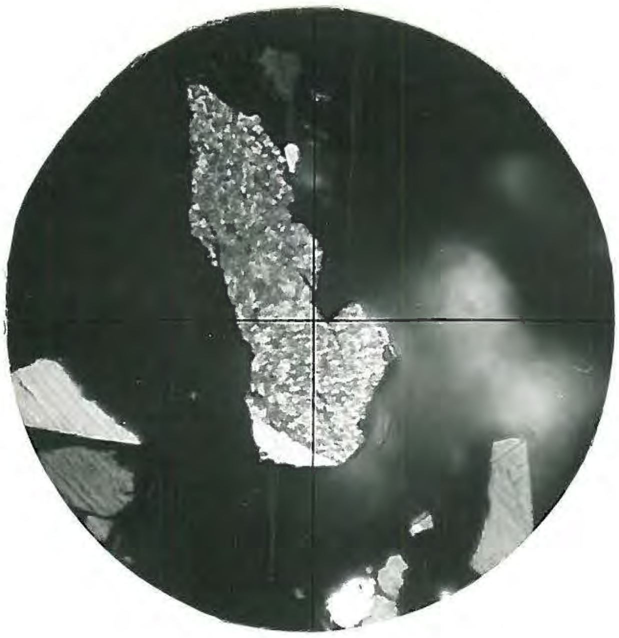


Plate 55. Fine subgraphic intergrowth of chalcopyrite and bornite. The very dark spots and lamellae are covellite. MMB 167, concentrate. Photomicrograph, reflected light x 600.

Plate 56. Coarse subgraphic intergrowth of chalcopyrite and bornite from a vein. MM 129, 131'. Photomicrograph, reflected light x 23.

development of this zone; (2) chalcocite and oxide enrichment in joints and at the top of unweathered rock; native copper occurs with chalcocite and according to Garrels the downward percolating acid waters are neutralized in this zone; and (3) minor chalcocite-digenite enrichment for a restricted depth (30 feet in drill-hole MMB 184) in unweathered rock beneath the water-table.

Finally, mention must be made of oxidation of magnetite to haematite in the supergene zone. A small amount of magnetite, which is probably detrital in origin, occurs in the mineralized horizon, and under supergene conditions margin and lattice replacement by haematite occurs (martitization).

(b) Chalcocite-bornite ore.

The chalcocite-bornite ore is characterized by bornite, chalcocite, digenite, covellite and chalcopyrite. Bornite grains reach two centimetres in size as do composite grains of chalcocite and digenite, and even individual grains of covellite are uncommonly large exceeding 0.2 mm. in size. Although there is a strong tendency for the minerals to occur as individual grains, lattice intergrowths are characteristic of this part of the ore and are of great interest. These intergrowths include both unmixing and replacement phenomena, and before proceeding with the description it is considered necessary to outline the process of development of copper and copper-iron sulphide intergrowths as a result of metamorphism.

Consider a sediment containing finely divided copper, iron and sulphur combined perhaps in some rudimentary form, which is subjected to metamorphism. The first stage of metamorphism, and in fact one which proceeds throughout metamorphism, is that of metamorphic diffusion. This does not imply diffusion giving rise to rock homogeneity, but diffusion through the rock of elements with affinity for one another so that grains become progressively larger in size and individual minerals tend to become homogeneous. In the case of copper

Plate 57. Carrollite (white) and bornite replaced by digenite. The bright lamella in the northwest quadrant of the photograph is chalcopyrite. MMB 184, concentrate.

Photomicrograph, reflected light x 300.

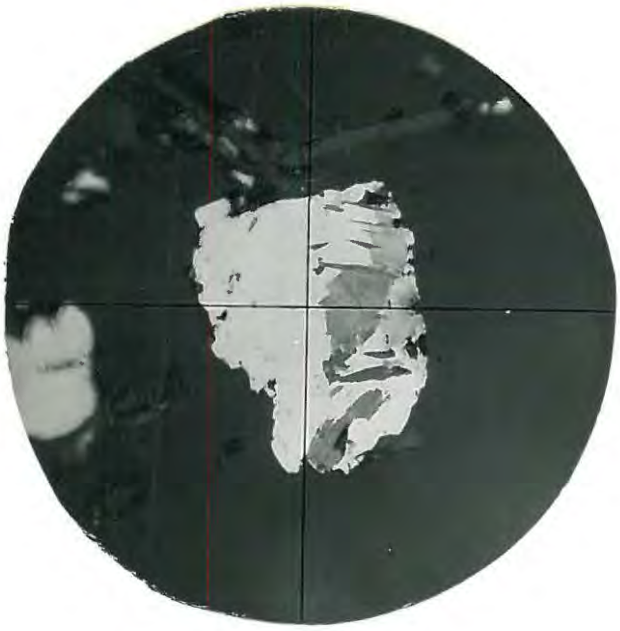


Plate 58. Coarse lamellae and patches of covellite in digenite. The variable dark colour of the covellite is due to pleochroism. MMB 157, concentrate.

Photomicrograph, reflected light x 300.

and iron sulphides the minerals formed will depend upon the proportions of the three constituent elements and the metamorphic conditions attained. Although the effects of stress are largely unknown, the significant steps in thermal metamorphism can be anticipated from data presented by Edwards (1954) and Buerger (1941), and are as follows.

Above 75° digenite and covellite are in solid solution with each other.
At 105° digenite is exsolved from chalcocite on heating. If formed below this temperature much of the digenite is retained in solution in chalcocite.
Above 225° bornite and chalcocite solid solution is complete.
Above 225°C chalcopyrite and valleriite are in solid solution.
Above 235°C chalcopyrite and cubanite are in solid solution.
Above 475°C chalcopyrite and bornite solid solution is complete.

Assuming that the rock under consideration is subjected to temperatures above 105° and less than 225°, in a copper-rich part of the ore growth will occur of separate grains of chalcopyrite, bornite and a mineral of composition between chalcocite and covellite. On cooling chalcocite-digenite or digenite-covellite intergrowths will result according to Buerger's simple phase diagram. In more iron-rich ore chalcopyrite and pyrite or possibly pyrrhotite will be formed as separate grains.

Cooling following temperatures in excess of 235° will result in intergrowths of bornite and chalcocite as well as those of chalcocite-digenite and digenite-covellite in copper-rich ore. In iron-rich ore cubanite and valleriite will be found intergrown with chalcopyrite provided that there is insufficient copper to form bornite. Where bornite is present with chalcopyrite some exsolution of chalcopyrite in bornite or vice versa may occur, but although unmixing occurs at temperatures as low as 220°, the unmixed material is generally dispersed to the grain boundaries according to Edwards (1954).

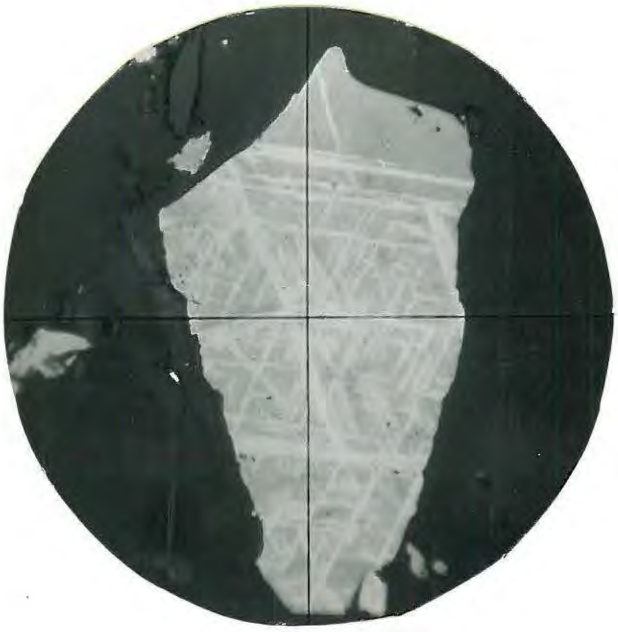


Plate 59. Exsolution lamellae of chalcocite in digenite. MMB 184, concentrate.

Photomicrograph, reflected light x 300.

Plate 60. Grain showing complex replacement. The suggested order of events is (i) chalcopyrite replaced by bornite, (ii) chalcopyrite and bornite replaced by digenite with preferred replacement of bornite, and (iii) supergene rim and lattice replacement of digenite by chalcocite with oxidation to limonite on the edge of the grain. MMB 157, concentrate.

Photomicrograph, reflected light x 300.

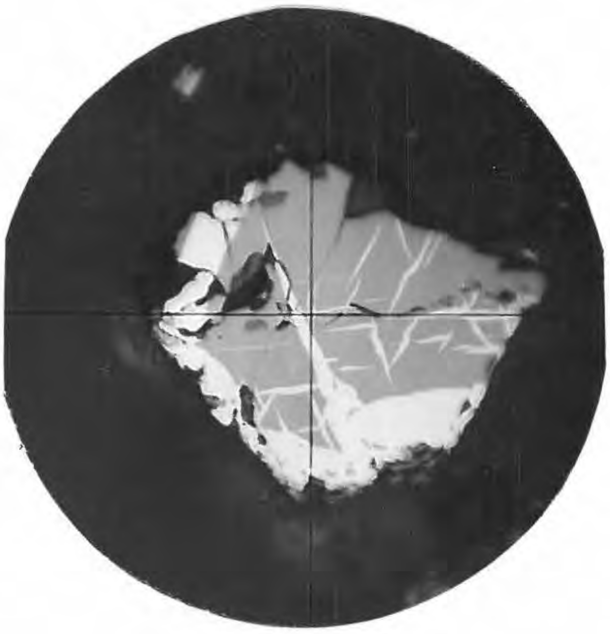


Plate 63. Rim and lattice replacement of bornite by chalcopyrite. MM 120, concentrate.

Photomicrograph, reflected light x 300.

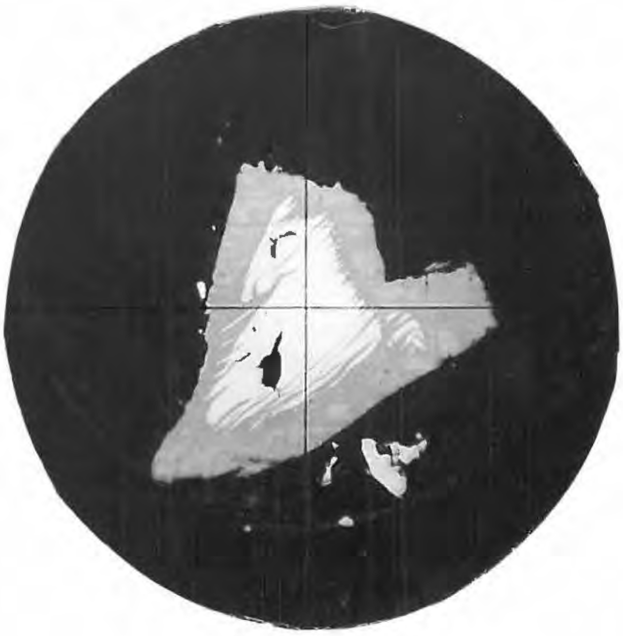


Plate 64. Rim and lattice replacement of chalcopyrite by digenite which is finely intergrown with chalcocite. MMB 167, concentrate.

Photomicrograph, reflected light x 300.

The relationships cited above depend on homogeneity of composition being reached in the grains prior to cooling, and because complete homogeneity is often not attained in metamorphism, replacement textures are common. Consider the coalescence of two grains of different composition. If the conditions of metamorphism are sustained, a single grain of uniform composition will result, but if these conditions are not sustained, residuals of the original grains may be found enclosed in a grain of composition between that of the two original grains. The result is that combinations of exsolution and replacement textures are sometimes found in the same grain, and since replacement textures are variable and complex, copper-rich material may appear to replace and envelop copper-poor material as often as the reverse. Finally, in regions of polymetamorphism such as Lumwana, textures of early phases of metamorphism are usually destroyed by subsequent phases, but they are preserved in some grains, especially where the later phase is of lower grade than the preceding one.

In the chalcocite-bornite ore at Lumwana lattice intergrowths of chalcocite-digenite and digenite-covellite are normal, though occasionally grains of the pure minerals are found. Bladed triangular lattices of digenite in bornite are uncommon, and similar enclosures of bornite in digenite are of rare occurrence. Although common as large uniform grains, bornite is normally found enclosing wide tapering laths of chalcopyrite, and in some cases fine lattice intergrowths of chalcopyrite. These textures include examples of exsolution and indicate that the temperature of metamorphism exceeded 225°C.

Covellite is of interest as in addition to its normal occurrence as exsolution lamellae in digenite, it is quite often found as small intersecting plates with parallel orientation in chalcopyrite and bornite. It is likely that these plates have unmixed from the host minerals which, at the temperature of metamorphism, were probably able to contain a little more copper than normal.

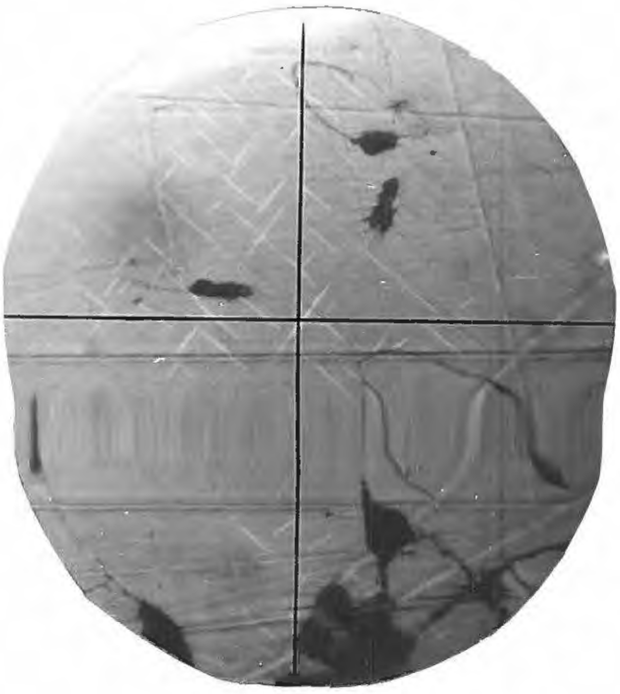


Plate 61. Exsolution lamellae of chalcopyrite in bornite. Note the small proportion of the grain occupied by chalcopyrite. MMB 167, concentrate.

Photomicrograph, reflected light x 830.

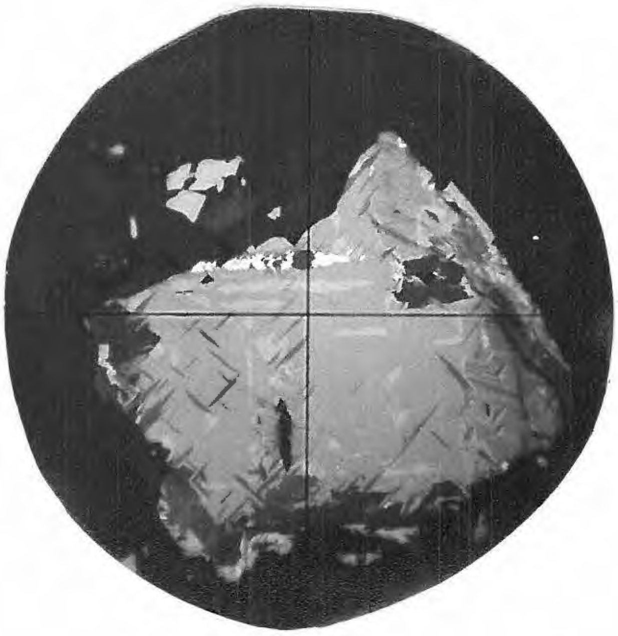


Plate 62. Bornite containing lamellae of digenite and a single plate of chalcopyrite in parallel orientation. Exsolved covellite occurs as plates which are oriented differently from the chalcopyrite and digenite, and which cut across all three other minerals. MMB 154, concentrate.

Photomicrograph, reflected light x 300.

As expected, a variety of replacement textures are found in the chalcocite-bornite ore. In general the sulphides which contain the most copper replace those with lesser copper content, and chalcocite-digenite replaces bornite more readily than chalcopyrite. Examples of chalcopyrite replacing bornite are quite common however, and in rare occurrences digenite-chalcocite can be seen to be replaced by bornite. Where chalcopyrite is replaced by digenite-chalcocite, rim replacement similar to that of supergene action occurs, but in addition lattice replacement is common.

Endogenetic pyrite has not been seenin the chalcocite-bornite ore, and carrollite is uncommon. Carrollite is **usually** associated with chalcopyrite, and occurs as small grains which are usually enveloped by chalcopyrite. Where chalcocite has replaced chalcopyrite it is not uncommon to find small white inclusions in the chalcocite. These inclusions, measuring only one or two microns across defy identification by conventional methods, but appear to be carrollite which has been expelled from the chalcocite. It is thought that chalcopyrite probably has a little cobalt impurity even at normal temperatures, and when it is replaced by chalcocite under metamorphic conditions the cobalt is expelled from the chalcocite. It is unlikely that the white mineral is pyrite, but the possibility cannot be overlooked.

(c) Chalcopyrite-bornite ore.

The chalcopyrite-bornite ore is mineralogically and texturally similar to the chalcocite-bornite ore. Both bornite and chalcopyrite occur commonly as large uniform grains,but enclosures of laths of one mineral in the other are equally common. Fine exsolution lamellae of bornite in chalcopyrite or vice versa have been observed but are not common. A little chalcocite, digenite and covellite are usually present and relationships with chalcopyrite and bornite are identical to those found in the chalcocite-bornite ore.

Carrollite is not uncommon. It occurs in the form of small grains

Plate 65. Chalcopyrite replaced by digenite which is intergrown with chalcocite and which contains fine exsolved (?) grains of a white mineral thought to be carrollite. MMB 184, concentrate.

Photomicrograph, reflected light x 600.

Plate 66. Bornite in the same grain as euhedral pyrite. The two minerals are separated by quartz. MMB 154, concentrate.

Photomicrograph, reflected light x 300.

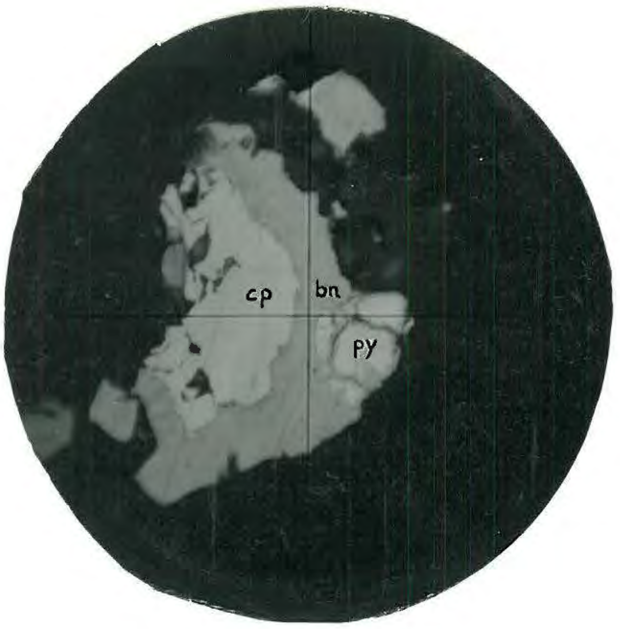


Plate 67. Pyrite and chalcopyrite replaced by bornite. Note that pyrite is replaced along cracks and at the edge of the grain. MMB 166, concentrate.

Photomicrograph, reflected light x 300.

Plate 68. Relict grain of bornite intergrown with chalcopyrite (northwest quadrant of photograph) and enclosed by later chalcopyrite containing only a few lamellae of bornite. MMB 166, concentrate.

Photomicrograph, reflected light x 300.

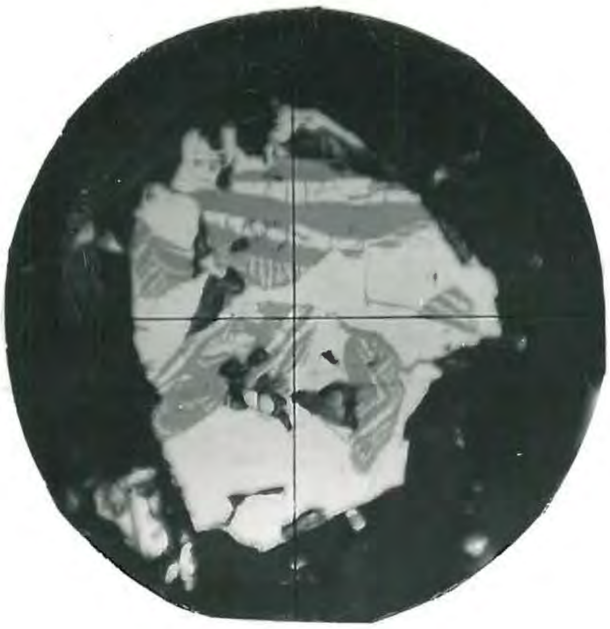


Plate 69. Relict grains of bornite intergrown with chalcopyrite, replaced by later chalcopyrite. MMB 167, concentrate.

Photomicrograph, reflected light x 300.

less than 0.1 mm. across, enclosed by chalcopyrite and sometimes bornite. Pyrite and bornite tend to be mutually exclusive, but occasionally a little pyrite is found, either as separate euhedral grains or partly replaced by bornite and chalcopyrite. The pyrite is probably diagenetic in origin, and with advanced metamorphism it would probably be completely replaced by the other sulphides.

The exsolution textures of chalcocite, digenite and bornite confirm that temperatures during metamorphism exceeded 225°C, and the occasional occurrence of fine lattice intergrowths of chalcopyrite and bornite suggests that incomplete chalcopyrite-bornite solid solution occurred during the last phase of metamorphism. "Fossil" textures preserved in relict grains formed during the previous phase of metamorphism have similar textures to those of the last phase, and it is likely that the grades of the last two phases of metamorphism were similar.

(d) Chalcopyrite-pyrite ore.

The chalcopyrite-pyrite ore includes all rock in which bornite is absent and the copper content is sufficiently high to warrant the use of the term ore. It thus embraces rock with large and small amounts of pyrite, and although the relative abundance of copper sulphides and pyrite varies, similar textures are found throughout the chalcopyrite-pyrite ore.

This part of the ore is characterized by chalcopyrite, cubanite, pyrite and valleriite. Composite grains consisting mainly of chalcopyrite and cubanite often exceed two centimetres in size, and the individual lamellae which make up the grains are clearly visible to the naked eye. Although homogeneous grains of chalcopyrite and cubanite have been observed, coarse lattice intergrowths of the two minerals are characteristic of this part of the ore. When examined under the microscope small separate grains of valleriite are also found to be present in chalcopyrite. These grains occur in chalcopyrite lamellae which are intergrown with cubanite, and are

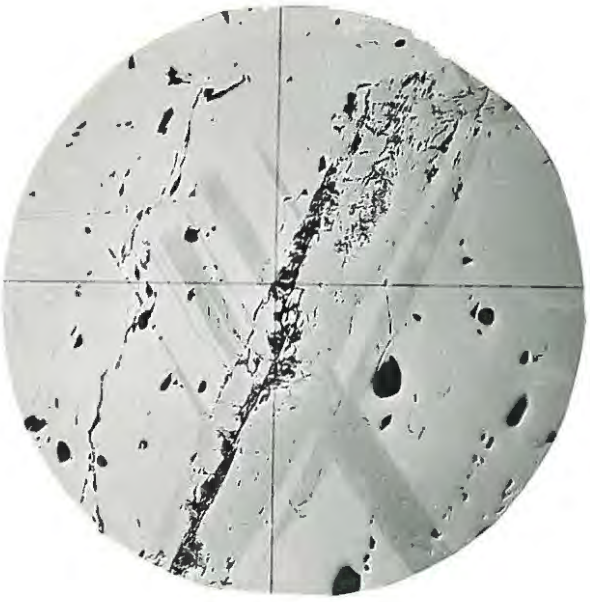


Plate 70. Very coarse exsolved lamellae of cubanite in chalcopyrite. Lightly etched with dilute HCl/CrO_3. MM 128, 213'.

Photomicrograph, reflected light x 23.

Plate 71. Pyrite replacing biotite and apparently forcing cleavage flakes apart. MM 128, 213'.

Photomicrograph, reflected light x 23.

usually most frequent near the contact of the chalcopyrite with silicate. Occasionally valleriite is found as small twinned grains completely enclosed by silicate. (Cubanite and valleriite are never found in the presence of bornite.)

Pyrite occurs as separate grains and is also found enclosed and replaced by chalcopyrite and cubanite. In addition to the more normal occurrence, small slender plates are found in parallel orientation in both chalcopyrite and cubanite. They are particularly common on the margins of larger composite grains, and sometimes coalesce along the boundary of chalcopyrite and cubanite with silicate. It is possible that the pyrite in this case is supergene in origin, but in view of the numerous other metamorphic textures, a metamorphic origin seems more likely. Since cubanite is part of a high temperature isomorphous series with chalcopyrite and pyrrhotite (Edwards 1954), it might be expected that pyrrhotite would be formed during unmixing, but pyrite is apparently formed instead, and two possible explanations for the phenomenon are offered by the writer.

Assume firstly that cubanite is formed from a mixture of chalcopyrite and pyrrhotite, and that the composition of pyrrhotite is $Fe_{10}S_{11}$. The small excess of sulphur in pyrrhotite may result in the formation of pyrite, a process which is summed up in the following equation:

$$9CuFeS_2 + Fe_{10}S_{11} = 9CuFe_2S_3 + FeS_2$$

The second possibility is that cubanite can be formed by reaction between chalcopyrite and pyrite as well as between chalcopyrite and pyrrhotite, and in the following equations the sulphur liberated on reaction with pyrite may combine with excess pyrrhotite to form pyrite:

$$CuFeS_2 + FeS_2 = CuFe_2S_3 + S$$

$$FeS + S = FeS_2$$

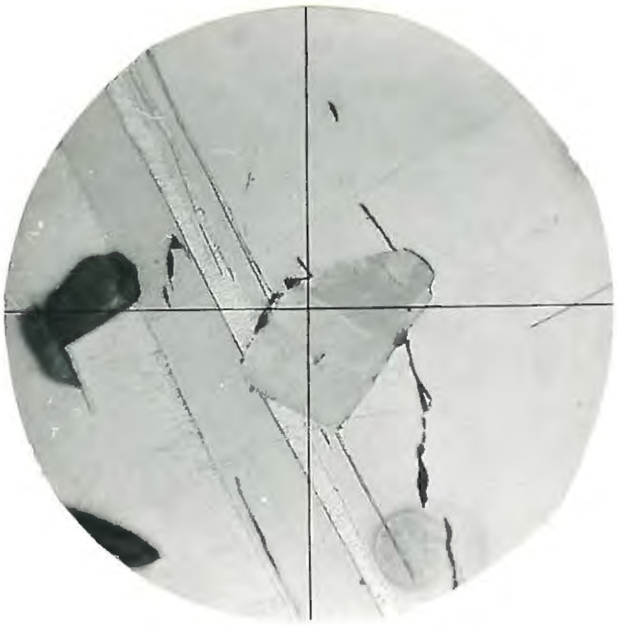


Plate 72. Subhedral valleriite grain at the transition between chalcopyrite (light) and cubanite. Lightly etched with HCl/CrO_3. MM 128, 213'. Photomicrograph, reflected light x 300.

Plate 73. Valeriite grain in silicate. The slender laths are composed of fractured chalcopyrite. MM 128, 213'.

Photomicrograph, reflected light x 300.

Plate 74. Exsolved pyrite lamellae in chalcopyrite. Note that the pyrite is most abundant at the boundary of the grain. MM 128, 213'.

Photomicrograph, reflected light x 300.

Plate 75. Hackly cubanite with interdigitated chalcopyrite in one orientation and thin exsolved lamellae of pyrite in two different planes. Note that the hackly edge of the cubanite is separated from silicate by chalcopyrite - a common feature of the Lumwana chalcopyrite-cubanite intergrowths, and that the chalcopyrite also contains exsolved pyrite which is concentrated at the boundaries of the chalcopyrite. MM 128, 213'.

Photomicrograph, reflected light x300.

The characteristic lattice intergrowths of cubanite and chalcopyrite in the chalcopyrite-pyrite ore indicate that temperatures of metamorphism exceeded 235°C. As these intergrowths are extremely coarse and well developed, it is suggested that temperatures were somewhat higher than 235°.

Considering the textural evidence as a whole, intergrowths of chalcocite-digenite and digenite-covellite indicate temperatures of metamorphism of at least 105°C. Those of bornite and digenite, and chalcopyrite-valleriite indicates temperatures of at least 225°C, and intergrowths of cubanite and chalcopyrite suggest temperatures in excess of 235°C. Unmixing textures of chalcopyrite in bornite and vice versa are always such that the unmixed material is a small proportion of the whole grain, and only limited solid solution of bornite and chalcopyrite is likely to have occurred. Since solid solution is complete between chalcopyrite and bornite at 475°C, this temperature has not been reached and the writer suggests that the temperature of metamorphism was in the order of 250°C.

DISTRIBUTION.

As on the mines of the Copperbelt, the sulphides at the Lumwana Prospect are distributed in a zonal pattern in the orebody. Since the explanation of sulphide zoning is fundamental to any hypothesis which attempts to explain the genesis of the ore, care must be exercised to ensure that the data used to establish the distribution of sulphides are as accurate as possible. In this respect the geologist working only with drill-cores is at a great disadvantage compared to the geologist with underground exposures to examine, as correlation of mineral zones from one drill-hole to another can seldom be made with certainty.

The sulphide minerals at the Lumwana Prospect occur in layers within the quartz-mica schist between the granite and the quartzite. As in the case of Mufulira Mine on the Copperbelt, these horizons may be separated by barren rock or lean mineralization, or may run together to become indistinguishable from one another, but unlike those of Mufulira, the sediments have a well-developed schistosity which has obscured most sedimentary features such as bedding and minor facies changes.

Considering the orebody as a whole, the ore can be classified into:

ore containing supergene minerals,

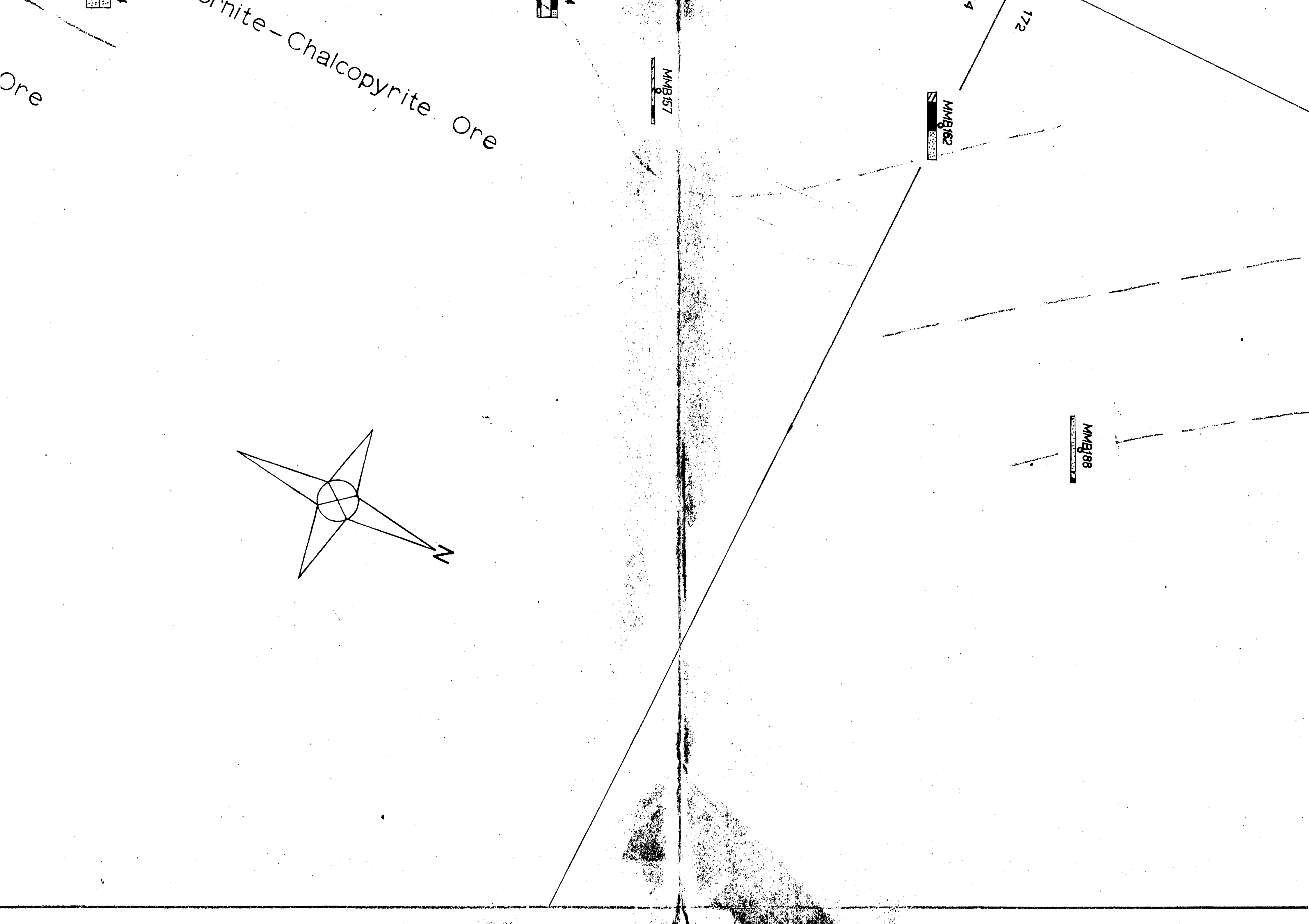
chalcocite-bornite ore, (also containing digenite and covellite),

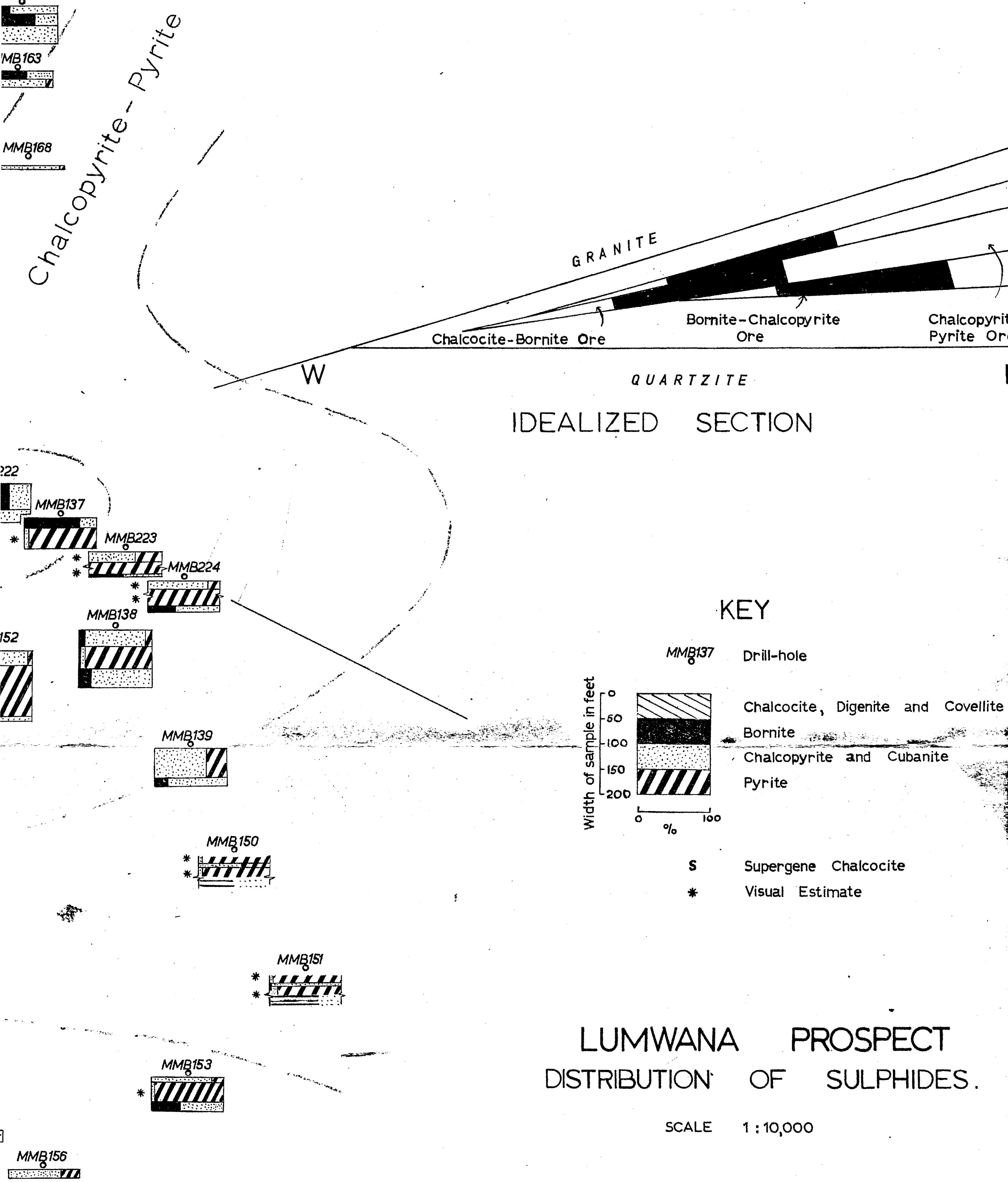
bornite-chalcopyrite ore, and

chalcopyrite-pyrite ore, (also containing cubanite.)

The distribution of ore containing supergene minerals has already been discussed, and the remaining three types constitute the three zones which occur in the orebody, so that chalcocite-bornite ore is separated from chalcopyrite-pyrite ore by bornite-chalcopyrite ore. At one end of the zonal sequence the ore may become yet richer in copper relative to iron and sulphur, with development of more and more chalcocite and even primary native copper, (these conditions are approached in drill-hole MMB 157 where chalcocite, digenite and covellite total 71% of the sulphides.) At the other end of the sequence copper ceases to be present in economic quantities, but pyrite persists.

In the assessment of the relative abundance of each sulphide, the grain-count analyses of samples of concentrates prepared from cores by Dr. H. Meyer were used where possible. In the method of concentration (flotation) pyrite was suppressed, however, and in pyritic samples the amount of pyrite was calculated by assuming only pyrite and chalcopyrite to be present, and using the copper, sulphur and total iron analyses of the head samples. Some drill-holes were completed after the analytical work was undertaken, and in these holes visual estimates of the sulphide mineral proportions in cores were the only data used. These


rnite – Chalcopyrite Ore
Ore
MMB157
MMB162
MMB188
172
N



LUMWANA PROSPECT

DISTRIBUTION OF SULPHIDES.

SCALE 1 : 10,000

FIGURE 37

data are presented in Figure 37.

Bearing in mind that the composite samples frequently include widths of lean mineralization or barren rock, the general features of sulphide zoning from Figure 37 can be tabulated as follows.

(1) The orebody, considered as a whole, thickens from west to east. Note: the flags at drill-holes MMB 223, 224, 150 and 151 have been shortened, and MMB 168 is close to the outcrop of the mineralized horizon and does not contain the full width of the sulphide-bearing horizon.

(2) The orebody is richest in chalcocite in the west and becomes pyritic towards the east.

(3) The thickening of the orebody and the decrease in copper content towards the east corresponds to thickening of the whole mineralized horizon. (See Figure 10.)

(4) Considering the vertical distribution of the sulphides, three main zones can be recognized. The middle zone is probably the best-developed and appears to be present in most drill-holes; the upper zone (actual, not stratigraphic,) is usually present, but the lower zone is apparently not present north of MM 115.

(5) The three zones overlap upon each other in such a way that the full width of the orebody contains sulphides leaner in copper in the centre than those at the top or bottom.

The theory of sulphide zoning in hydrothermal deposits is outlined by White (1941) and is summarized as follows. At the centre of hypogene copper mineralization one may find chalcocite, bornite or chalcopyrite, and varying amounts of the non-copper-bearing sulphides. Chalcopyrite persists outwards from the centre of mineralization, and at its outer limits it gradually diminishes and finally stops, whereas pyrite persists far out towards the limits of hypogene rock alteration. Darnley (1960) likens vertical zoning to the separation which takes place in chromatographic partition and says that it may be accounted for by upward diffusion. This does not explain reverse order zoning (chalcocite at the top), as it would imply upward and downward diffusion in the same orebody if zoning is of the Lumwana type. Furthermore, diffusion in this manner does not seem adequate to account for the small vertical dimension in contrast to the large horizontal dimensions of the stratiform orebodies. From the hydrothermal viewpoint it seems to the writer that zoning in the stratiform orebodies can be explained only by horizontal dispersion. This would imply diffusion in pulses or fronts taking place within very narrow vertical limits and over very considerable distances. Furthermore, these fronts would have had to travel different distances within these narrow limits in order to account for vertical zoning. Finally the chalcocite zone is close to the source of the mineralizing fluids, and neither on the Copperbelt nor at Lumwana has any source, whether it be an intrusion or a zone of weakness, been discovered adjacent to the chalcocite zone or indeed anywhere else in these orebodies.

An alternative to the hydrothermal hypothesis is that metals were emplaced by vapour transfer as suggested by Brown (1950). This hypothesis is attractive as it does not require a nearby mineralizing source, and although the writer recognizes the value of the theory in regional metasomatism, it does not satisfactorily explain sulphide zoning or the dimensional relationships of the orebodies. According to Brown mineral vapours could originate at great depth and rise upwards using microscopic and sub-microscopic fractures to become concentrated in areas of greatest fracturing. This theory may be carried even further if one realizes that the volume of voids is astonishingly large in many minerals. (The extreme cases quoted by Brajnikoŕ (1945) are kyanite 33.58% and sodalite 68.27%.) This suggests that such minerals must be relatively permeable to many of the smaller ions, and that diffusion through rock is structurally possible. Such diffusion would normally be increased by deformation of the crystalline network in consequence of stress or of rise in temperature. Although structurally possible, diffusion apparently is not a process which occurs normally in non-porous rock as is shown by the concentration of helium in the Panhandle Gas Field. According to Pierce, Gott and Mytton (1964), helium, derived by decay of radioactive minerals, does not dissipate and only passes through the more porous rocks, becoming concentrated in cracks and fissures, and thence to the gas bodies. If helium does not diffuse through non-porous rocks, how much less likely it is that large metal irons would pass through apparently solid rock.

In recent years Croxford in Australia (no specific reference available) and Darnley (1960) have broken away from the classical hydrothermal views, and combine syngenetic deposition with epigenetic mineralization in what Darnley calls "Hydrothermal Syngenesis". Darnley summed up the problem from his viewpoint in 1961 saying, "I fail to see how any syngenetic process dealing solely with the metals dissolved in rain water run off could produce in a geologically brief time the grade and tonnage of copper that exists." In his paper of 1960 he proposes that copper was introduced into the basin of deposition by volcanic or juvenile waters, and he explains sulphide zoning in terms of control of precipitation by natural variations of the Eh and pH of the depositional environment.

The syngenetic viewpoint is summarized by Garlick (1958) who relates zoning to shorelines as follows.

> "In the shallow waters bordering basins, the sediments are commonly barren of sulphides. Further from the shoreline, towards deeper water, sulphides come in usually abruptly, and are characterized by a high copper and low iron content. Still further out towards the centres of the basins, the copper content diminishes and at the same time iron increases until it is the dominant sulphide in the centres of the basins.
>
> "This distribution of the metallic sulphides is explained on elementary chemical principles. River waters containing metals in solution would enter the basins at the shoreline and mixing with the lake or sea waters migrate towards the centres, probably mainly in

the upper oxygenated layers. Intermixing would take place with underlying layers of stagnant water with high sulphuretted hydrogen content due to the action of anaerobic bacteria. Near shore in the absence of the stagnant layer, the metal-bearing waters passed over the barren zone without deposition of copper, and the sediments dropped in this zone commonly contain less than 0.05% copper. On reaching the underlying wedge of stagnant water, selective precipitation of copper took place, and precipitation of iron occurred only where there was excess hydrogen sulphide or after most of the copper had already been precipitated ..... During diagenesis these mixtures of copper and iron sulphides would be converted to the appropriate copper-iron sulphides.....according to the proportions of iron and copper present.

"With transgressive advance of the shoreline, and usually an advance of the stagnant water conditions from the centre of the basin outwards towards the enlarging margins, so the zones in the succeeding beds of the deposit overlapped each other......Less commonly, with regressive conditions......bornite-bearing layers may overlie chalcopyrite or pyrite."

There can be no doubt that the syngenetic view supplies the most logical explanation for sulphide zoning, and hence most logically explains the genesis of the ore. At Lumwana the thickness of the quartz-mica schist is thought to have been determined by the topography prior to its deposition, and since the mineral zoning is related to thickness of the quartz-mica schist it appears to be related to the pre-Roan topography. Following this hypothesis it appears that in the deepest parts of the basin of deposition the ore is pyritic and thick, and in the shallowest parts the orebody is thin and generally contains chalcocite. The best ore is found in parts of the section with intermediate elevation, that is, where thickness is fair and bornite and chalcopyrite are the dominant ore minerals.

The vertical distribution of sulphides at Lumwana suggests that, in general, deposition of the sulphides occurred under transgressive conditions followed by those of regression, but, as outlined in the chapter on petrology, additional minor transgressive and regressive periods occurred within the main sequence. These minor fluctuations resulted in intercalation of barren strata in the orebody, and, after the main orebody was deposited, in local preservation of uranium minerals.

In conclusion, while it is believed by the writer that syngenesis followed by metamorphism supplies the only satisfactory explanation of the features of the Lumwana orebody, the processes resulting in certain of these features are not yet understood. One of the unsolved problems is the occurrence of pyrite in shallow water sediments, contrary to the general zonal pattern, (see earlier chapter on petrology). Another problem is the occurrence of pyrrhotite. Although generally absent, pyrrhotite does occur with pyrite and sparse chalcopyrite in a band below the main mineralized zone in MMB 164, and also in other drill-holes surrounding the prospect (e.g. MM 197 to the northeast.) It is possible that pyrrhotite is formed in place of pyrite during diagenesis or metamorphism in sediments with a high iron - low sulphur content.

ORE GENESIS.

The Lumwana orebody is but one of a number of orebodies in the great copper province of Zambia-Katanga. The bulk of the evidence from detailed examination of the stratiform deposits in this province is overwhelmingly in favour of sygenetic deposition of the copper, and over the years, by far the majority of geologists working on the copper mines have come to accept that a syngenetic origin for the copper is the most likely. Garlick, (see Mendelsohn 1961), on the basis of diligently collected evidence, has developed a plausible theory for the introduction and precipitation of copper, which, although containing minor anomalies, explains the general features of the stratiform deposits.

As mentioned in the previous section, Garlick believes that copper is introduced to the basins of deposition in solution in river waters, and deposition occurs where these waters mingle with deeper stagnant waters rich in hydrogen sulphide. The possibility was also mentioned that copper was introduced to the basins of deposition by methods other than simply solution in runoff waters, and volcanic action or juvenile waters were suggested as possible sources of copper.

Although Garlick has made it clear that the sparse copper mineralization of the Basement is quantitatively capable of supplying all the copper necessary to form orebodies of the Copperbelt type, doubt must be expressed whether selective precipitation from dilute solutions, as envisaged by Garlick, would occur sufficiently rapidly in conjunction with accumulating detritus to give rise to as much as 7 or 8% copper, as is found in some Copperbelt deposits. Consider how much more likely such a process would be if the solutions instead of being dilute, were saturated, as could be the case if copper were introduced to the basin of deposition from some hydrothermal source as envisaged by Darnley (1960).

The Zambia-Katanga province of syngenetic copper considered in comparison with other copper provinces on a global scale is unique, and the proposal that it was formed entirely as a result of normal processes leads to the question: why are stratiform copper deposits of Copperbelt grade not more widespread? The answer to this question is thought by the writer to be that at some stage, either the sediments containing copper today, the waters from which they were deposited, or some earlier sediment or basin of sedimentation was enriched in copper. This enrichment could have occurred as a result of any of volcanic, fumarole or hydrothermal action. Since zonal distribution of sulphides is characteristic of the economic deposits, and is explained satisfactorily only by derivation of copper from a land source, it is likely that enrichment occurred prior to deposition of the bodies mined today.

Copper occurs in different stratigraphic positions in the Katanga System, and in different host rocks. Thus in Katanga the ore is found in Upper Roan dolomites; on the Copperbelt ore occurs mainly in shale or quartzite near the top of the Lower Roan, but is also found in conglomerate and dolomitic rocks; at Lumwana ore occurs in what are regarded as sediments at the base of the Lower Roan. The Lower Roan - Upper Roan is regarded generally as a conformable series, but in actual fact this is far from the case. The writer has seen numerous examples of disconformities within the Mine Series on the Copperbelt; sometimes these actually form the contact between ore and barren rock, but may even occur within the orebodies. The disconformities sometimes exist simply as truncations of cross-bedded strata extending for a thousand feet or more, but there is also evidence of lithification of sediment underlying the disconformities in the form of potholes, and intra-formational breccias or conglomerates containing fragments of the underlying rocks. This evidence leads the writer to believe that much of the Lower Roan part of the succession was not derived directly from Basement rocks but was deposited in a number of sedimentary cycles interspersed with periods of erosion, i.e. the sediments have been reworked.

Considering the premises (1) that copper enrichment occurred at an early stage in sedimentation, and (2) that reworking of the Lower Roan strata has occurred, the earliest formed copper deposits in the province become important, as it is these that would have been the source of the copper found in the later deposits.

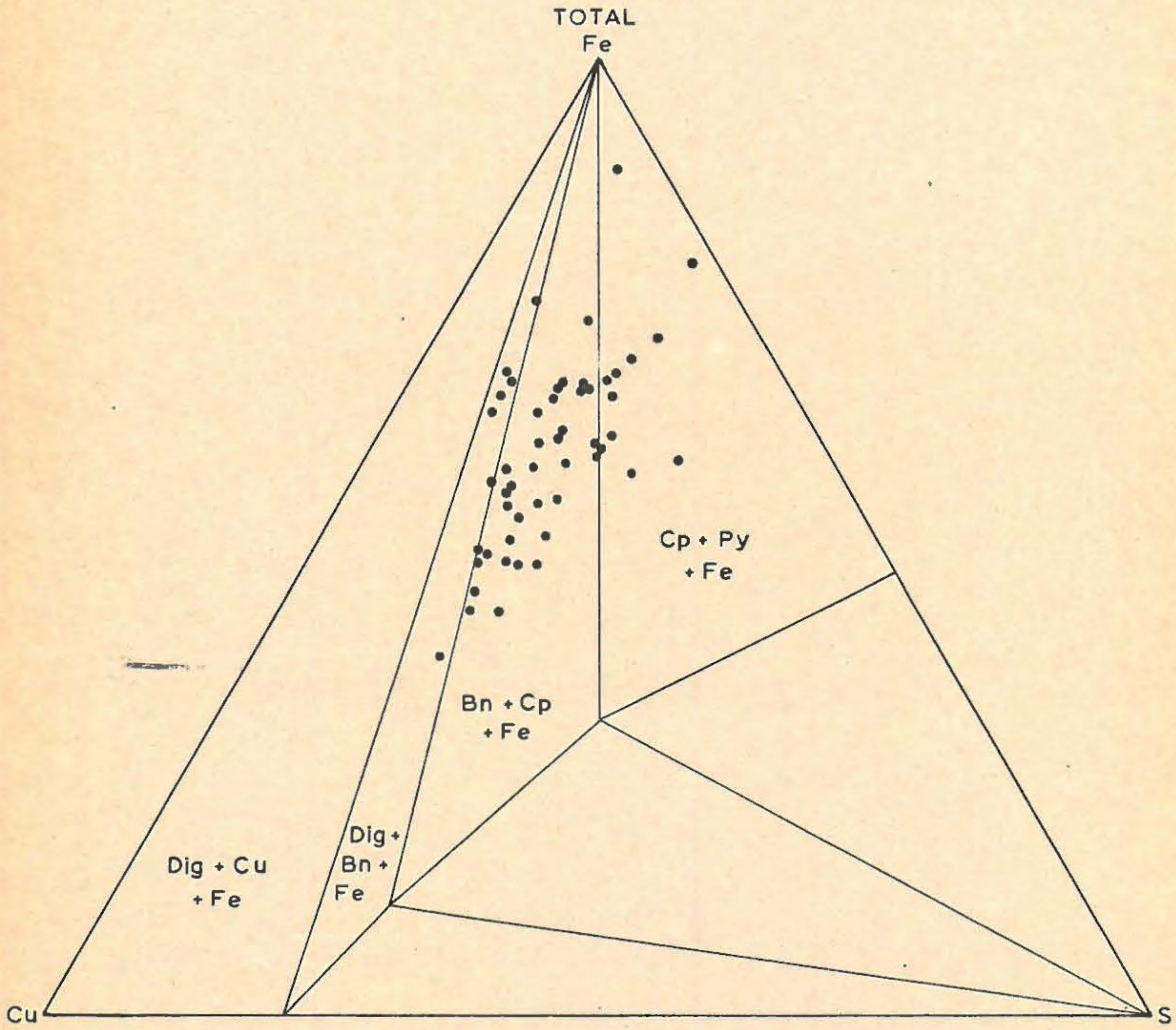
Drilling of copper deposits in the presumed early-Roan sediments has been extensive on the Mombezhi Dome, where, in addition to the Lumwana orebody, other mineralized bodies have been discovered. In one of these to the east of the Lumwana Prospect, copper mineralization, estimated at approximately 0.2% copper, occurs in nearly 2000 feet of quartz-mica schists similar to those at Lumwana. If this drill-hole is representative of the original copper-enrichment sediments, and such sediments were wide spread, the problems of supply of copper in the Zambia-Katanga province fall away.

If one assumes that such a deposit was eroded and redeposited in a restricted basin, it is probable that copper would enter solution until such time as saturation was approached, while at the same time detritus would be deposited free of copper. Copper deposition would thus occur at the close of sedimentation, and all the copper spread over say 2000 feet in the original sediment would be confined to say the upper 200 feet of the new deposit. If the original sediment contained 0.2% copper, and no copper was lost, the new deposit would contain 2% copper.

If reworking has caused concentration, it is also possible that some early formed deposits of comparatively high grade were themselves eroded and redeposited, and a detrital source for some of the copper is possible. This view is held by Fleischer (1961) who has shown the writer interesting occurrences of probable detrital concentration. These include "buckshot pyrite", and copper concentration in pebble-hollow margins at Chibuluma Mine, and most convincing of all, a pebble of azurite from well down in the sulphide zone at Nchanga Mine. While not of significance at Lumwana, detrital concentration may play a part in the final constitution of some Copperbelt orebodies, and indeed may be the only source of copper in the oxidate sediments such as conglomerate.

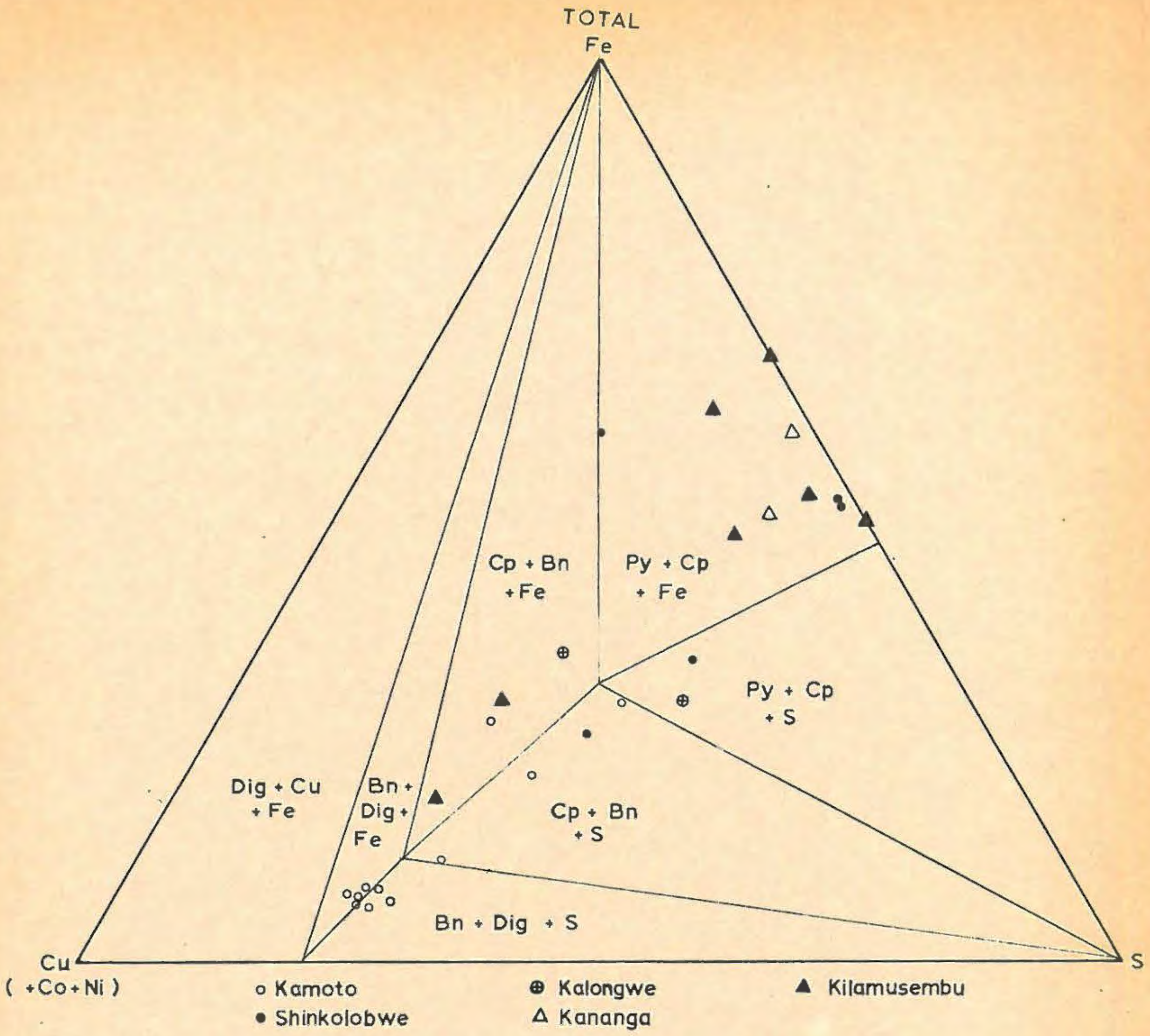
Neglecting local effects of mechanical concentration, the deposits of copper in the Zambia-Katanga province are thought to have occurred in the manner propounded by Garlick, with the exception that the writer regards the copper-bearing solutions as having been rich in dissolved copper due to reworking of earlier cupriferous sediments. If the processes of precipitation causing the zonal distribution of sulphides are considered in conjunction with reworking, it would be expected that certain chemical differences would differentiate the early-formed copper deposits from those formed by reworking of the early deposits. Unfortunately there are insufficient published data on the chemistry of most deposits to attempt to establish these chemical differences on any but the most rudimentary grounds. Such an attempt has been made by the writer in respect of copper, sulphur and total iron as outlined in the following paragraphs.

The proportions based on weight percentages of copper, sulphur and total iron in the Lumwana cores have been plotted on a triangular

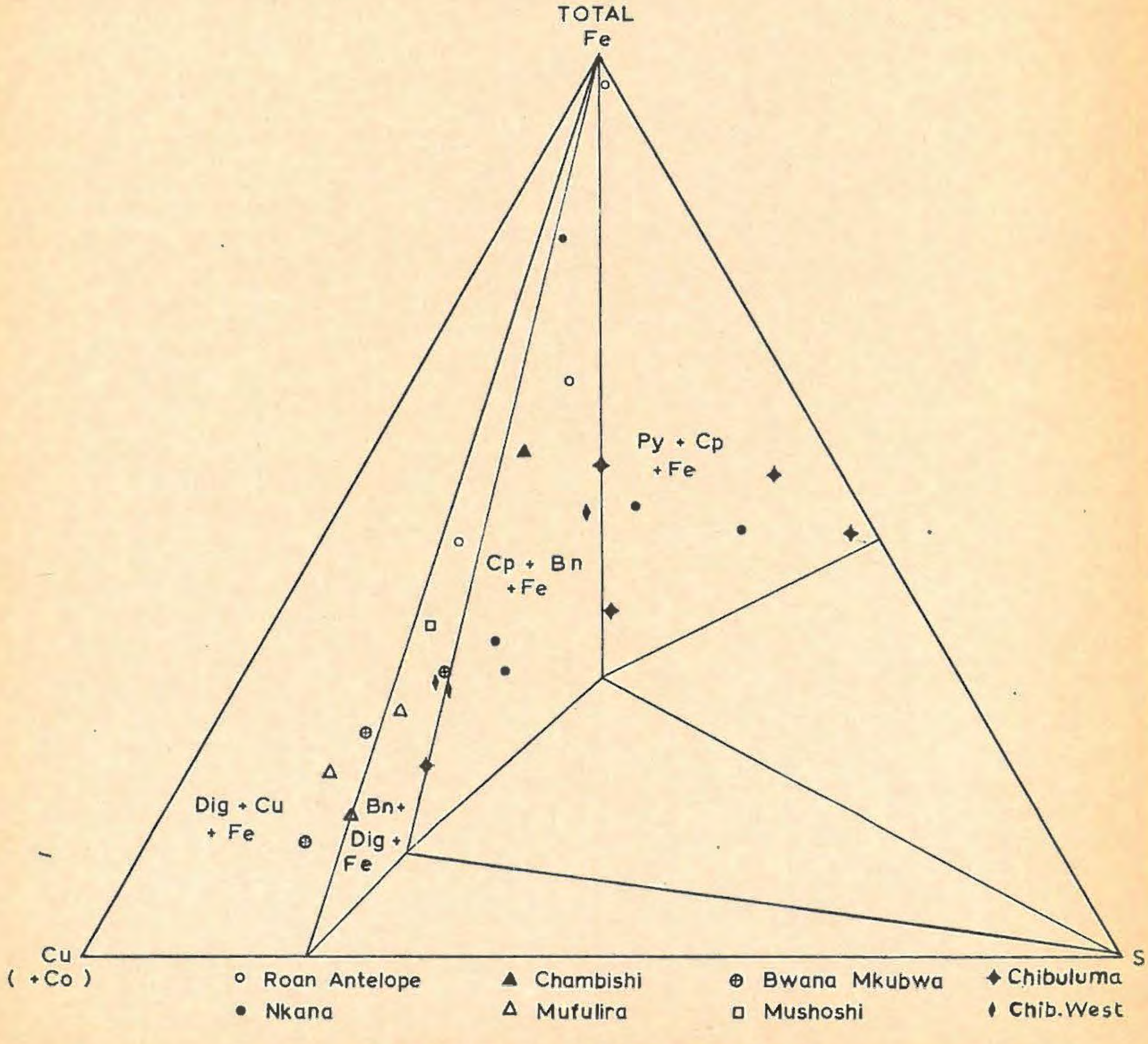


LUMWANA PROSPECT

FIGURE 38



KATANGA MINE SERIES



RHODESIA MINE SERIES

FIGURE 39

diagram, Figure 38. Similar diagrams (Figure 39) from the Katanga orebodies have been prepared from data presented by Oosterbosch (1962), and from the Copperbelt Mines from data published by Mendelsohn (1961). In addition, samples from Chibuluma and Chibuluma-West orebodies were collected by Mr. I. Thomson and kindly analysed by the R.S.T. Mine Services Research Laboratory.

Comparison of Figures 38 and 39 shows that total iron is richest in the Lumwana orebody, and poorest in the Katanga orebodies. In the process of deposition which gives rise to the zoned stratiform copper deposits, iron being deposited from solution is separated from copper. With reworking it can be anticipated that successive cycles of weathering and deposition would result in improvement of this separation. Thus it is considered that the decrease in total iron relative to copper and sulphur in the orebodies occurring successively higher in the succession may be evidence of reworking.

In the Lumwana orebody there is an abundance of iron and copper relative to sulphur, so that even where the sulphides contain little or no iron, iron is present in the form of oxides and silicates. In the Copperbelt mines, once again there is never an excess of sulphur, and in the case of the Mufulira "A" orebody sulphur is so deficient that native copper is likely to be a primary mineral. It is unknown to what extent the mineralization in the Mufulira "A" orebody is supergene or oxidized, particularly as the two samples from Bwana Mkubwa which also fall in the digenite + copper + iron field almost certainly include oxidized ore.

Figure 39 shows that in Katanga it is apparently quite common to find sulphur in excess of that present in the sulphides. This is an unexplained and interesting problem as, so far as is known, these orebodies do not contain any large amounts of sulphate, nor is the writer aware of any reference in the literature to the occurrence of native sulphur.

In conclusion the stages in the genesis of the Zambia-Katanga stratiform orebodies can be summarized as follows.

(1) Deposition of sediment containing sparse copper sulphides, which were probably introduced into the sediments or the basins of deposition epigenetically.

(2) Reworking of those early-formed cupriferous sediments resulting in concentration of copper, sometimes mechanically, but more commonly during precipitation from solution by hydrogen sulphide generated in stagnant water by anaerobic bacteria.

(3) Metamorphism of the deposits causing coarsening of grain-size, and possibly redistribution of sulphides in some deposits.

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