A STUDY OF ORE AND ROCK SPECIMENS FROM THE NKANA MINE, NORTHERN RHODESIA

by

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We accept this thesis as conforming to the
standard required from candidates for the
degree of MASTER OF APPLIED SCIENCE.

Members of the Department of Geology.

THE UNIVERSITY OF BRITISH COLUMBIA

May, 1951.

May 15, 1951.

Dr. H. C. Gunning,
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Vancouver, B. C.

Dear Sir:

I take great pleasure in submitting the following thesis, "A Study of Ore and Rock Specimens from the NKana Mine, Northern Rhodesia", in partial fulfilment of the requirements of the course leading to the degree of Master of Applied Science in Geology at the University of British Columbia.

Yours truly,

R. A. BARKER

ABSTRACT

The ore and rock specimens which form the material for this study are a collection sent by Mr. T. D. Guernsey, geologist for the Rhokana Corporation, Northern Rhodesia, to Dr. H. C. Gunning of this University under whose direction the present work was done.

Owing to the lack of previous detailed work a microscopic investigation is undertaken with no particular problem in view, but with the hope that the accumulation of factual evidence may aid in clarifying the geological problems which have led to a diversity of opinion regarding the origin of these deposits.

An historical sketch and a brief description of the geological setting of the Rhodesian copper deposits is given. This information has all been gathered from the available literature on the subject. The character and mineralogy of the ore deposits and relations to their northward extensions in Katanga, Belgian Congo are summarized.

Descriptive notes, with interpretative remarks, of the lithology and ore mineralogy of the NKana 'Ore Horizon' as determined by a study of the 38 specimens and over 30 thin sections, constitute a major portion of the paper.

General theories of ore genesis and supporting geological evidences are summarized for the purpose of clarifying the issues involved and to help in the erection of a theory for the Rhodesian copper deposits. Extant theories regarding these deposits are outlined and an analysis and synthesis of the evidence gathered in this investigation is presented. The framework of an epigenetic theory is constructed but

mention is made that a meta-syngenetic (metamorphic-sedimentary) origin for these deposits is a possibility.

Suggestions for further research both in the field and in the laboratory are given in the hope that they may in some way lend direction to subsequent investigations.

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ILLUSTRATIONS

INTRODUCTION

The ore and rock specimens which form the material for this study were supplied by Mr. T. D. Guernsey, geologist for the Rhokana Corporation, Northern Rhodesia. This collection, comprising representatives of the various lithologic units of the 'Ore Horizon' at NKana Mine, contains 38 individual samples: at least two specimens of each type of ore are present.

It was indicated by Mr. Guernsey that although the NKana Mine had been in operation for a number of years, no detailed studies of the ores had been made. A careful search of the available literature revealed that although much work had been done and much had been written during the first years (ca. 1930) of the development of these deposits, nothing had been published in recent years. It was felt, therefore, that a general study of these specimens might aid in the elucidation of the problem of genesis of the copper ores of one of the most important copper districts in the world.

It was realized that the lack of intimate knowledge of these deposits on the part of the writer and the members of the Department of Geology at this University would provide a serious limitation to the general interpretation of the information gained during the investigation and the correlation of this information with that gained in the field by other writers.

No specific problem was considered as the immediate object of the study at the outset, because in fact no special problem was at once apparent. There had been and still is a diversity of opinion regarding the origin of the copper deposits, but because of their size and continuity there has been no practical necessity for a full understanding of their mode of origin. However, the deposits provide at once both a challenge and a fertile field of investigation to the students of ore genesis.

Because of the disseminated nature of the ore it was felt that thin sections and the petrographic microscope offered the best means of studying both the ores and the host rocks. Consequently, over thirty thin sections and several polished sections were prepared for examination.

The study was conducted under the direction of Dr. H. C. Gunning, to whom the collection of specimens originally had been sent. To him the writer wishes to extend his warmest appreciation for advice and encouragement tendered throughout the course of investigation. Other members of the Department of Geology were extremely helpful both directly and indirectly. To Drs. L. Dolar-Mantuani and K. C. McTaggart particularly the writer extends grateful acknowledgement for many helpful suggestions and sincerely regrets that the limitation of time made it impossible to undertake all the possibilities for investigation. Acknowledgement is also made of the work of Mr. J. A. Donnan who prepared all the thin sections used in the study.

HISTORICAL SKETCH

The Rhodesian Copper Belt parallels the northeastern border of Northern Rhodesia (see Fig. 1) and, together with its northern extensions in the Province of Katanga in the Belgian Congo, forms the most important single copper district in the world.

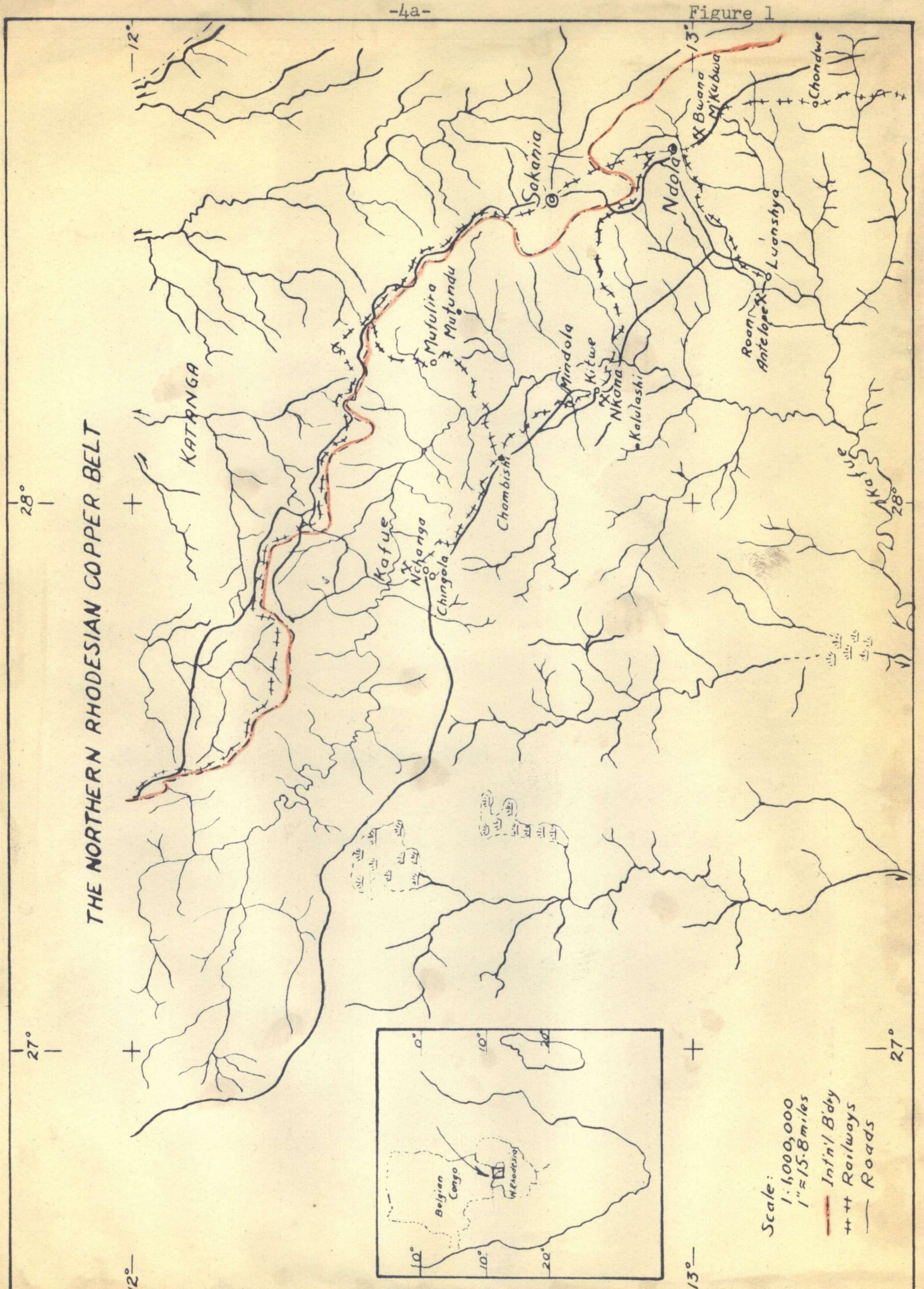
The district has come into such prominence since the turn of the present century. Earliest production came from the deposit at BWana MKubwa which had been known and worked by the natives before the advent of the white man. Production here was sporadic during and after World War I and it was not until the 1920's that British and American interests, provided with prospecting rights over large areas, first realized the magnitude and importance of the Rhodesian deposits.

In an upland country, fairly heavily wooded and with very deep regolith, the surface expression of these enormous deposits was practically non-existant; no great copper stained outcrops or gossans advertised the extent and tenor of the copper-bearing sediments, though it was early noted that straight treeless avenues through the forest ("copper dambos") indicated the presence of hidden copper.

Because of fairly simple structural conditions it was not long before wide-spaced drill holes had, at a number of places, outlined large and rich orebodies, and production commenced in the early 1930's.

Since then the eight proved deposits, consolidated into four operating units, Roan Antelope, Rhokana, NChanga, and Mufilira, have rapidly assumed a position as the greatest single copper district in the world as the following figures of reserves amply illustrate.

Figure 1


THE NORTHERN RHODESIAN COPPER BELT
KATANGA
Kafue
Nchanga
Chingola
Chambishi
Mufulira
Mindola
Kitwe
Nkana
Kalulashi
Sakania
Ndola
Bwana M'Kubwa
Chondwe
Luanshya
Roan Antelope
12°
13°
27°
28°
Belgian Congo
N.Rhodesia
Scale:
1:1,000,000
1"=15.8 miles
Int'n'l B'dy
Railways
Roads

Mine or District	Percent Copper		Reserves (millions of tons)	
Rhokana -				
Nkana North Orebody	3.23		33	
Nkana South Orebody	2.78		20	
Mindola Orebody	3.67		57	
Totals		3.37		110
Roan Antelope	3.26		95	
NChanga	4.66		141	
Mufulira	3.85		148	
Totals		3.86		494

(Note: These figures are taken from the Minerals Yearbook-1948, and estimates have probably increased since then.)

Total annual production of copper from these mines in recent years has been about 350,000 short tons. With the expansion of treatment facilities and improvement in rail and labour conditions this figure will doubtless show a considerable increase within the next few years.

PHYSICAL FEATURES

The copper region lies in a part of the Central African Plateau. This fairly recently uplifted peneplane stands at an elevation of about 4,000 feet and its gently undulatory surface is modified by shallow stream depressions and occasional monadnocks of older crystalline rocks. Relief is nowhere greater than 1000 feet.

Forests cover the land but these consist of fairly widely spaced trees with scanty intervening underbrush. Accordingly, cross-country travel is relatively simple.

Outcrop is scarce since the products of decomposition and disintegration have accumulated as a deep regolith; in many places the soil and clay residuum reaches depths of from 25 to 35 feet, grading downwards into badly decomposed rock. Soil cover over easily weathered gabbros and dolomites reaches 100 feet.

Though lying close to the equator the region, because of its elevation, enjoys a very pleasant climate. Rainfall of 40 to 50 inches comes between November and April while in the dry season (winter) sunshine prevails and the nights are cool.

The Rhodesian copper belt is drained by the Kafue River and its tributaries, a part of the Zambesi system. Bateman (1930)[1] states that the Kafue apparently follows its pre-uplift course and crosses the region without regard to hardness or structure of the underlying rocks. As seen in Figure 1 the drainage has developed a dendritic pattern and there are many swamps, particularly at the headwaters of tributary streams.

1. Figures in parentheses refer to the bibliography at the end of this paper.

The boundary between Northern Rhodesia and the province of Katanga in the Belgian Congo follows the very low divide between the Kafue and Congo drainages.

GEOLOGICAL SETTING (Fig.2)

The copper ores are found in a group of sedimentary rocks appearing now as synclines which strike, and plunge slightly, in a northwesterly direction. In Rhodesia the anticlines have been removed during peneplanation, but northwards in Katanga where the folding was more intense, the folds are expressed topographically as successions of nearly parallel strike ridges.

Bateman's interpretation of the region is given below (Bateman, 1930, p.414):

> "The Rhodesian section with its simple open folds and minor faulting represents the eroded foothill region of an ancient mountain structure. The Katanga section lies nearer the axis of this old mountain range, of which only the roots are left. Here the folds are closed and overturned; faults are numerous; and successive nappes of older strata of the Serie des Mines formation are thrust above the younger Kundelungu beds".

Anton Gray (Gray, 1930) correlated the copper-bearing sediments of Katanga and Rhodesia and proposed a nomenclature for the sedimentary Systems of the region. The table below follows that of Gray (1930, p.788) but includes intrusive rocks as given by Bateman (1930), Jackson (1932(2)), and Gray (1932)

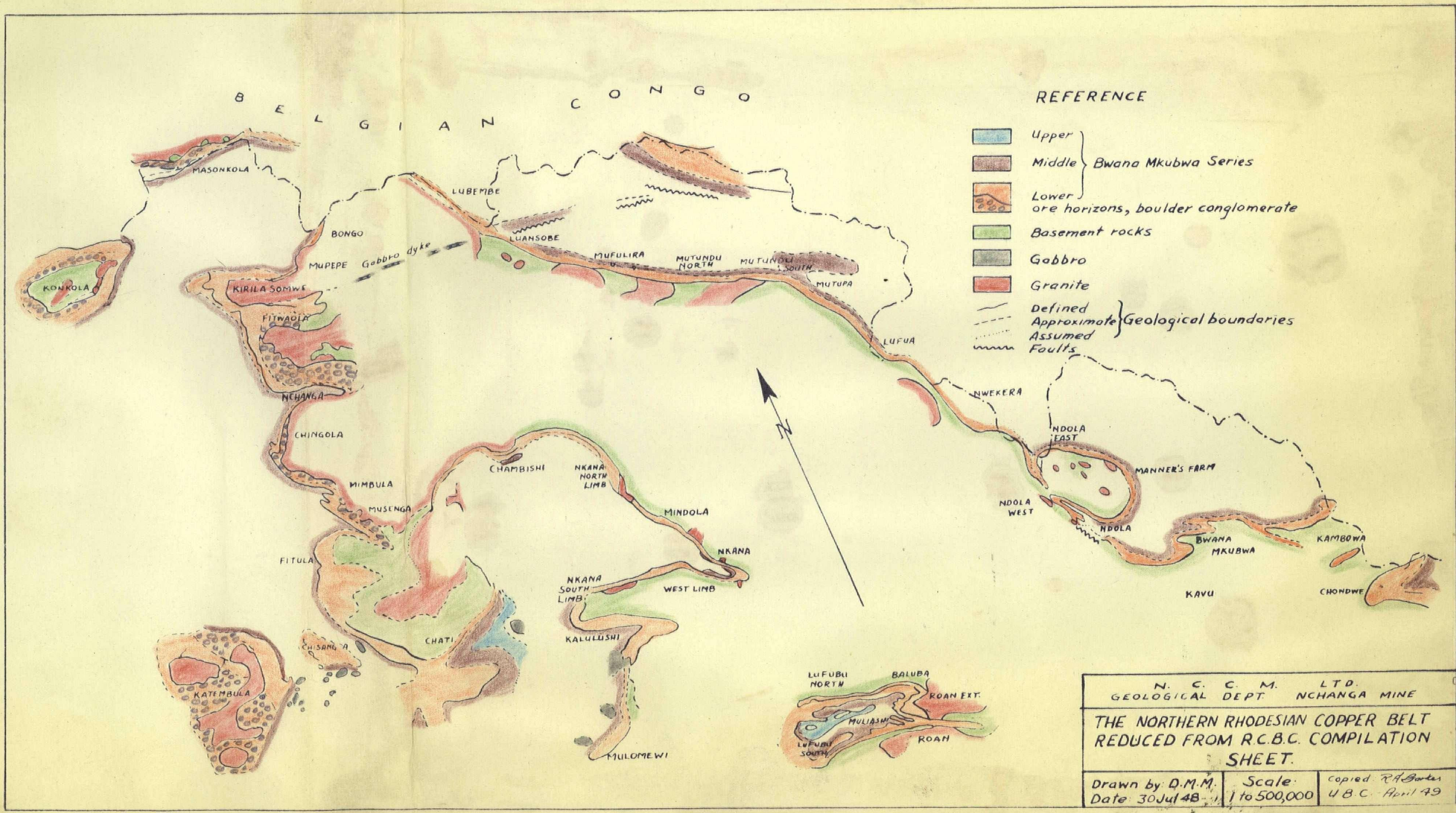

B E L G I A N C O N G O
REFERENCE
Upper
Middle
Bwana Mkubwa Series
Lower
ore horizons, boulder conglomerate
Basement rocks
Gabbro
Granite
Defined
Approximate
Assumed
Faults
Geological boundaries
MASONKOLA
LUBEMBE
BONGO
LUANSOBE
MUPEPE Gabbro dyke
KONKOLA
KIRILA SOMWE
FITWAOLA
MUFULIRA
MUTUNDU NORTH
MUTUNDU SOUTH
MUTUPA
LUFUA
NCHANGA
CHINGOLA
NWEKERA
N
NDOLA EAST
MANNER'S FARM
CHAMBISHI
NKANA NORTH LIMB
MIMBULA
MUSENGA
MINDOLA
NDOLA WEST
NDOLA
NKANA
BWANA MKUBWA
KAMBOWA
FITULA
NKANA SOUTH LIMB
WEST LIMB
KAVU
CHONDWE
CHATI
KALULUSHI
CHISANGA
KATEMBULA
MULOMEWI
LUFUBU NORTH
BALUBA
ROAN EXT.
MULIASHI
LUFUBU SOUTH
ROAN
N. C. C. M. LTD.
GEOLOGICAL DEPT. NCHANGA MINE
THE NORTHERN RHODESIAN COPPER BELT REDUCED FROM R.C.B.C. COMPILATION SHEET.
Drawn by: D.M.M.
Date: 30 Jul 48
Scale: 1 to 500,000
Copied R.A. Barter
U.B.C. April 49

Figure 2

TABLE OF FORMATIONS
Katanga-Rhodesia Copper Belt

Age	System	Series	Formation
Permian-Jurassic			LUBILASH (Karoo)
			Unconformity
?			ACID AND BASIC INTRUSIVES - Gabbro and diabase sills and dykes - Younger Grey Granite - Younger Red Granite (NChanga)
? Probably Pre-Cambrian ?	SYSTEM OF KATANGA	kundelungu	UPPER KUNDELUNGU
			LOWER KUNDELUNGU
		Serie des Mines	MWASHIA
			UPPER ROAN
			LOWER ROAN
Archean to Proterozoic			Unconformity
			GRANITIC INTRUSIVES - Muliashi porphyritic granite and gneiss - Older Grey Granite (MKushi gneissoid granite) (MKushi Granite-Gneiss) - Older Red Granite (NChanga)
			MUVA SYSTEM
			Unconformity
			LUFUBU SYSTEM (BASEMENT SCHISTS)

The following short descriptive notes on the rock units are taken from a number of authors, particularly from Jackson (1932(2)).

LUFUBU SYSTEM (BASEMENT SCHISTS)

These ancient metamorphosed sediments, now micaceous and chloritic schists, are probably Archean in age. Their base is not exposed on the Central African Plateau, but they are doubtless several thousand feet thick.

MUVA SYSTEM

The metamorphic shales and sandstones of this system are several thousand feet thick and lie unconformably above the Lufubu. The upper white quartzites of this series form well exposed ridges.

GRANITIC INTRUSIVES

Older Red Granite

Jackson (1932(2)), pp. 489-94) includes a composite, red granitic stock at NChanga as both older and younger (Younger Red Granite) than the System of the Katanga. (see p.14).

Older Grey Granite

The MKushi gneissoid granite (Bancroft and Pelletier, 1929, p. 6) is identical with Jackson's (1932, p. 454) MKushi Granite Gneiss which consists "characteristically of gneissoid and quartzose adamellites, with porphyritic facies" and is equivalent to Gray and Sharpstone's (1929, pp. 14-15) Older Grey Granite. Jackson (1932(2), p. 455) doubts whether these intrusives are all pre-Katanga in age stating that "There is no essential mineralogical difference between the typical MKushi granite-gneiss and the younger grey granites, and where the latter are locally gneissoid, any difference, either mineralogical or structural practically vanishes". On the other hand Gray (1930, p. 787) states that "Both these Systems (Muva and Lufubu) before the formation of the System of Katanga, were intruded by large masses of granite. From these rocks was derived the material of which the sediments of the System of the Katanga were formed". Jackson notes that typical granitic pebbles of basal BWana MKubwa (Roan) are leucocratic granites, very low in ferro-magnesian minerals for which the provenance is unknown.

Muliashi Porphyritic Granite and Gneiss

This gneissose, strongly porphyritic, biotite-adamellite is of local occurrence along the Muliashi River.

SYSTEM OF THE KATANGA

A synopsis of these sediments is given below in the comparative table drawn up by Gray (1930, p.791). The following points in respect to nomenclature should be noted.

1. The MWashia is locally (NKana) known as the Christmas Series.

2. The Serie des Mines (Katanga); the MWashia-Upper Roan-Lower Roan (Rhodesian Selection Trust, Ltd.); and the Upper-Middle-Lower Bwana Mkubwa (Bancroft and Pelletier) represent equivalent terminologies.

COMPARISON OF THE SYSTEM OF THE KATANGA IN KATANGA AND RHODESIA

Vicinity of Elizabethville - Du Bois		Vicinity of Mufulira - Gray	
System Lubilash	not present	System Lubilash	not present
unconformity		unconformity	
System Katanga		System Katanga	
Upper Kundelungu	2000 m.	Upper Kundelungu	2000 m.
Shales, sandy	--	Arkose, "purple" Quartzite, Shales	--
Calcaire Rose	5-10	Calcaire Rose	
Shales	0-10	Shales	
Petit Conglomerat	10-30	Petit Conglomerat	
Lower Kundelungu	1500 m.	Lower Kundelungu	2000 m.
Feldspathic Sandstone	0-30	Feldspathic Sandstone	--
Shales	--	Calc. sandy Shale	--
Calcareous Sandstone	--	Shales	--
Calcaire de Kakontwe	50-100	Kakontwe Limestone	100
Shales	0-50	Shales)	
Grand Conglomerate	100-400	Basal Conglomerate)	150
MWashia	300-500	MWashia	400-600
Feldspathic Quartzite	10-50	Feldspathic Quartzite	15
Black Shale)		Black and Var.	
Green Dol. Shale)	200-4000	banded Shale, Ss.	--
Chert and Jasper	1-2		
Siliceous Oolites	1-2	Chert and Oolites	5
Dolomites of the Serie des Mines	200-400	Upper Roan Dolomite and dol. Shale with int'b'd. Sandstone	--
(Base unknown)			
		Lower Roan	350
		Int'b'd. Shale, Ss.	
		Dolomite	175
		Feldspathic Sandstone grit, conglomerate	175
		unconformity	
		MUVA SYSTEM	

The beds of the System of the Katanga are unfossiliferous, hence no faunal dating has been possible. Radioactivity determinations (Bateman, 1930, p. 375) on the radium deposits of Chinkolobwe, Katanga (occurring in beds of the Serie des Mines) give 610 million years, or pre-Cambrian, as the age of the ores. Bateman feels that the uranium and copper mineralization in Katanga are of one age, and also that the copper of Northern Rhodesia is the same age and therefore pre-Cambrian.

Serie des Mines.

Since this series will be discussed in more detail on subsequent pages, only brief notes will be given here.

The lower beds of the series, not exposed in Katanga, are separated by a marked unconformity from the underlying Muva and Lufubu Systems. The copper deposits of Katanga are found in the basal MWashia and Upper Roan, while those of Rhodesia are found in the Lower Roan.

Kundelungu Series

The basal member, lying conformably above the Serie des Mines, is composed of fluvio-glacial shales and conglomerates and is called the "tillite of the Katanga". Bancroft (Gray, 1930, p. 789) found these beds over a greater area than the Serie des Mines, the basal conglomerate at places lying directly on the ancient schists and Gray states that "these beds represent, therefore, a transgressive overlap in the sedimentation of the original basin in which the System of the Katanga was laid down".

ACID AND BASIC INTRUSIVES

NChanga Red Granites

Under this heading Jackson (1932 (2), p. 489) describes a large composite granite stock at NChanga composed of red biotite-adamellite-granite to red microcline-alaskite, which he believes represents two ages, the Older Red Granite and the Younger Red Granite, older and younger respectively than the BWana MKubwa (Serie des Mines). Jackson also believes that the copper ores of NChanga are genetically related to the Younger Red Granite.

Younger Grey Granite

This includes a widespread group of grey biotite-adamellites, with quartz-diorite and granite facies which are intrusive into the basal members of the Lower Roan Series, and these together with the NChanga younger red granite, are believed to have been the source of copper mineralization of Northern Rhodesia and of the Katanga. Pegmatite and aplite dykes of the younger grey granite cut the Basement Schists, and the granite has, in places, a garnetiferous contact aureole where it intrudes the Basement Schists.

Basic Intrusive Group

The gabbros and norites of this group occur chiefly as sills of over a thousand feet in thickness and are apparently the youngest intrusives. The sills on the whole conform to the structure of the sediments, but in places form irregular transgressive bodies. They certainly cut upper Serie des Mines beds and are probably younger than Kundelungu. Bancroft and Pelletier (Jackson, 1932 (2), pp. 504-505) suggest that the Basic Intrusives may correspond broadly to the Keweenawan basic intrusives of the Canadian Shield.

LUBILASH SYSTEM

This system consists of a basal glacial or fluvo-glacial conglomerate which is overlain by sandstones, coal measures, variegated argillites and shales, and upper friable sandstones and lenticular con- clomerates. It lies unconformably and almost horizontally upon the Kundelungu and has been almost entirely removed from the area of the copper belt. The system is said to be Permian to Jurassic in age and is correlated with the Karoo System of South Africa.

SEQUENCE OF EVENTS

The sediments of the Katanga System were laid down on an erosional surface formed of a basement complex of ancient schists and gneisses intruded by older granites. Subsequently, and possibly accompanied by intrusions of younger granites, the Katanga System was highly folded and faulted to the north in Katanga but fairly gently folded in Northern Rhodesia. This latter folding produced a system of rather open synclines and anticlines with a regional northwesterly trend. Those writers who conceive of an epigenetic origin for the copper deposits relate the mineralization to the intrusions of the Younger Granites, but state that since the shape of some of the deposits was controlled by it, the folding preceded the mineralization.

The relation between the rather gentle folding in Northern Rhodesia and the stronger overthrusts of Katanga is aptly described by Douglas (1930, p. 337) who says:

> "An European parallel may be drawn between the African structures and those of the Alps and Jura. The anticlines and synclines of the Jura can be likened to the similar folds in Northern Rhodesia, while the nappes and thrust blocks of the Alps find their equivalent in the Belgian Congo".

Following the intrusion of the Younger Granites, which in places domed the sediments, gabbroic and diabasic sills and dykes were intruded, and are often found, according to Jackson, as the cores of synclines.

The region was then base-leveled and the Permian to Jurassic beds of the Lubilash, or Karoo System were deposited. These rocks have subsequently been removed during further uplift and peneplanation which has continued until recent times.

Bateman suggests (1930, p. 381-384) that there is evidence that just before or since the latest uplift, very arid climatic conditions prevailed in the region. The water table must have been very deep since oxidation is found to depths of 2000 feet (Gray, 1932, p. 323), and it is suggested that only during the very latest uplift, to the present 4000 feet elevation, has the water table risen to within several tens of feet of the surface.

A new cycle of erosion has commenced; the upland region is in the stage of extreme youth and many streams are beginning to entrench themselves in their old courses.

THE ORE DEPOSITS

Since many details of the ore deposits, especially at NKana, will be brought out in a later section of this paper, a brief and general description will be given here and a short comparison with the Katanga ores will be made.

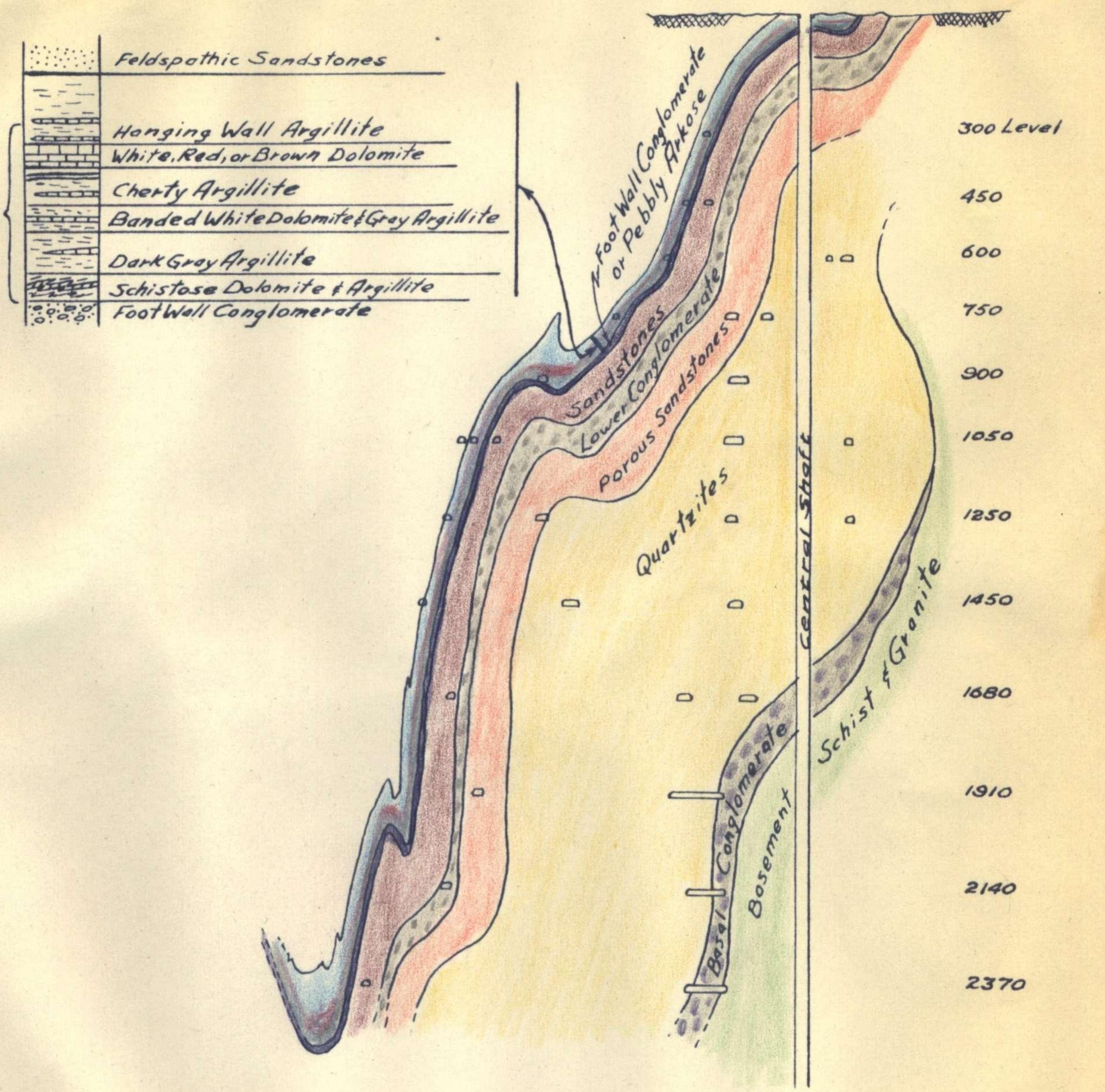
As already indicated, the ores in Northern Rhodesia usually occur in the basal beds of the Lower Roan. The more common host beds are feldspathic, quartzites, shales, and dolomitic shales, though locally talc-tremolite schists and schistose limestones may carry ore. At most mines the tabular orebodies extend through a very short stratigraphic interval; however, at Mufulira for example, three distinct and stratigraphically separated orebodies are present.

In many of the deposits ore is concentrated at drags or thickenings (Fig. 3) on the synclinal limbs. Thus both tabular and roughly pipe-like orebodies are present, the former being by far the most important. At Roan and NChanga the ore forms part of both limbs of narrow pitching synclines and hence has a horizontal V-shape in plan and a rough U-shape in section. At Mufulira and Nkana (Fig. 3) where the deposits are on one synclinal limb only, they have the form of tabular bodies.

From the epigenetic viewpoint several features seem to be responsible for ore localization: the proximity of granitic intrusions that supplied the metallizing solutions has been cited by a number of writers (Bateman, 1930, p. 411; Davidson, 1931, p. 148; Jackson, 1932 (1), p. 256; Gray, 1932, p. 335).

The position of the ores within the sediments is apparently

Figure 3



TYPICAL SECTION - NORTH OREBODY

Rhokana Corporation - Nkana Mine

Scale: 1" = 416' (approx.)

Copy: R. A. Barker. April 1951
From: Guernsey & Silva-Jones Aug. 1945

the result of physical rather than chemical control since the ores occur in beds of diverse chemical and mineralogical character. Thus permeability favoured the lateral progression of mineralization and Jackson (1932(1), p. 256) suggests that bending and fracturing of otherwise impermeable beds along the axes of minor folds rendered them especially favourable to entry by solutions.

Another factor noted by several authors is the control of solutions by overlying impervious beds. Gray, especially, points this out in his description of the Mufulira Mine (Gray, 1932, pp. 335-336). Each of the three orebodies is overlain by an impervious horizon and Gray states that "the stratigraphic position of the orebodies is clearly due to the damming action of the dense and unfractured overlying beds".

No large, cross-cutting, "feeder" faults or fracture zones are mentioned by any of the writers though Gray (1932, p. 335) states that "the solutions reached the sediments most probably through tension cracks in the cooled granite margin, joint cracks in the Muva schist and joints in the basal Mine series quartzites in all of which they formed sulphide bearing veins".

Davidson (1931, p. 151) introduces the possibility of chemical or mineralogical control when he mentions that the ore replaces the original calcareous cement of the shaley host rock at Chambishi.

As Lindgren (1933, p. 629) puts it, "The persistance of the ore-bearing beds is amazing". For example, along 42,000 feet of the north limb of the NKana syncline ore is developed, with two interruptions, for something over 35,000 feet and extends to a depth of about 2400 feet. This ore has a stratigraphic thickness averaging 30 to 40 feet which is the order of magnitude for the whole district. Batemen 1942, p. 517) says, "At Roan Antelope the metallized bed laps around the nose of a plunging syncline and extends along both limbs for a total proven length of 5 miles and an indicated length of another 4 miles".

The Ores.

A feature of these copper ores is their fairly simple mineralogy. Chalcopyrite, bornite, chalcocite, and carrollite or linnaeite are the major sulphides which are, for the most part, finely scattered through the sediments. The sulphides are sometimes so minutely disseminated that a cursory examination does not detect their presence in rock that is classed as ore.

Minor amounts of pyrite, hematite, and native copper make up the remainer of the metallic minerals but these have not the uniform distribution of the first named group.

Oxidation products (excluding bornite and chalcocite) are numerous but are generally considered to be of minor importance though McKinnon (1943) writes: "One-third, or more, of the copper mineralization in these (NChanga) orebodies occurs in the form of carbonates and oxides, ...". Cuprite, native copper, malachite, azurite, chrysocolla, tenorite, bieberite ($CoSO_4.7H_2O$), limonite, goethite, jarosite, cornetite ($Cu_3P_2O_8.3Cu(OH)_2$), libethnite ($Cu_3P_2O_8.Cu(OH)_2$), and manganese wad have been reported from the district.

The problem of hypogene versus supergene bornite and chalcocite has received much attention from the early workers.

In the case of bornite, Gray, Bateman, and Davidson advocate an hypogene origin for the major part of the bornite, while Bancroft and Jackson hold the supergene viewpoint. A brief analysis of the arguments presented leads the writer to believe that in most instances bornite is primary but that in some cases much bornite may be supergene.

The chalcocite problem has been very thoroughly dealt with by Bateman (1930, pp. 393-405) who concludes, contrary to the opinion of the resident geologists of the time, that "part, and perhaps the major part, of the Rhodesian chalcocite is of hypogene origin and was formed at a temperature above 91°C. or possibly above 200°C".

Gray, Bancroft, and Jackson hold that the majority of the chalcocite is supergene.

Bateman's extensive treatment of the chalcocite problem is very impressive and, as with the bornite, the writer feels, after a perusal of the literature, that though in some places most of the chalcocite now appears supergene much of it throughout the district was originally introduced.

It should be pointed out that since the relative amounts of copper sulphides differ somewhat from mine to mine it is difficult to generalize for the district. For example at Chambishi (Davidson, 1931, p. 149) bornite is the predominant sulphide, and "Bornite and chalcopyrite make up fully 98 percent of the primary copper minerals so far exposed", while at NChanga (Jackson, 1930, p. 261 "chalcocite is the most abundant sulphide copper ore-mineral", with bornite second in importance and chalcopyrite occurring sparingly. In this latter case Jackson believes that the chalcocite is predominantly supergene.

It does not appear, upon consideration of the whole district, that secondary sulphide enrichment has played a major role in the formation of the copper deposits of Northern Rhodesia.

Not all copper mineralization is found in the sediments. At Chambishi (Davidson, 1931, p. 151) the "granite itself carries traces of copper, and pegmatites and quartz veins that come from it also carry copper sulphides". This statement may be applied to a number of mines in the district.

Comparison of the Rhodesia and Katanga Deposits. (Gray, 1930, p. 801)

In the first place the ores of Rhodesia and Katanga occur at different stratigraphic levels: the former in the argillites, shales, and arkoses of the Lower Roan while the latter are found in the dolomitic beds of the Upper Roan and MWashia.

Secondly the Katanga deposits are all oxidized bodies lying close to the surface, while those of Rhodesia, with the exception of the old BWana Mkubwa Mine, are sulphide deposits that go to depth.

The reasons for the difference in stratigraphic position are not perfectly clear but no doubt local structural conditions exerted a primary control.

DESCRIPTIONS OF SPECIMENS FROM THE 'ORE HORIZON' AT NKANA MINE.

The following is a generalized but fairly typical section of the Lower BWana MKubwa (Roan) Series as found at NKana Mine (after Guernsey, 1947).

Top	Feldspathic Sandstones, quartzites, and argillites		150 feet
	Grey, well bedded, quartzose (Hanging Wall) argillite		25-35
	"Ore Horizon"		30-40
	Foot Wall Conglomerate		0-30
	Feldspathic sandstones and thin sandy argillites		50
	"Lower" Conglomerate		40-50
	Grey-brown, muddy, dolomitic sandstones		60-70
	Hard, light, cross-bedded, feldspathic quartzites	up to	600
	Basal conglomerate	up to	80

The following divisions of the "Ore Horizon" are also taken from Guernsey. Although the horizon changes to some extent both along the strike and with depth this is a typical sequence at the North and Mindola Orebodies.

Top	1. Hanging Wall Argillite	
	2. 'Porous Sandstone' -banded, impure dolomite	5 feet
	3. 'Cherty Ore' -hard, fine grained argillite	9

4.	'Banded Ore' -interbedded grey argillite and white dolomite	6 feet
5.	'Low Grade Argillite' -grey, fairly massive dolomitic argillite	12
6.	'Schistose Ore' -schisted dolomite and dolomitic argillite	5
7.	Foot Wall Conglomerate	
8.	Arkoses and Argillites -feldspathic sandstones and thin sandy argillites	

In the following descriptions "N" refers to the North Orebody, "M" refers to the Mindola Orebody, and the numbers refer to the above beds of the Ore Horizon.

1. Hanging Wall Argillite

Megascopic -

The five specimens of this bed show fairly similar general features. The rock is dense, soft to rather hard, grey in colour, and has a slight to marked clay odour. Two of the specimens exhibit a lamellar structure manifested by dark and light colouring. The lamenae have thicknesses measuring about 1 mm. and they are doubtless parallel to, or represent, bedding. One specimen (M1-C) differs somewhat from the others in that it exhibits no laminations, is harder, and is speckled with very small flecks and blobs of carrollite and a little bornite, which minerals also line numerous cavities averaging 3 or 4 mm. in size. Guernsey states that this last is not a typical specimen.

Microscopic -

Typically the rock consists of a mosaic or mat of quartz, feldspar, and sericite grains that average 0.02 mm. in size. Very roughly these minerals are in equal proportions though it is difficult to make quantitative estimates of the quartz and feldspar. The latter is usually in small irregular grains that have a negative relief but no polysynthetic twinning. Some of the slightly larger feldspar grains are twinned and these are albitic in composition.

Minor constituents are biotite, carbonate, and tourmaline. Biotite is pleochroic, pale tan to colourless; carbonate is ragged in outline and staining (Copper nitrate) shows that it is virtually all dolomite; rare tourmaline grains are very small, greenish in colour, and often have thin colourless rims which are interpreted as authigenic outgrowths. Variable, small amounts of carrollite, bornite, chalcopyrite, and pyrite are present in one or two of the specimens. The details of ore mineral occurrences will be dealt with in a later section.

"Argillite" is possibly not a very precise name for this rock because it contains practically no clay minerals, but the writer can suggest no better one that is in common usage. Most probably the sericite has developed through diagenetic or low grade metamorphic processes subsequent to the deposition of an originally siliceous argillite.

2. White, Red, or Brown Dolomite (misnamed "Porous Sandstone").

Three specimens of this member present a medium grained crystalline carbonate aspect with scattered grains of quartz, feldspar, and biotite. The red colouration of the rocks is imparted by feldspar, native copper, and hematite in varying proportions. An ill-defined colour banding, which may be equivalent to bedding, is derived from a layering of silicate and carbonate minerals.

Staining shows that in one case (N2-B) all the carbonate is calcite but in another case (M2-A) approximately equal amounts of calcite and dolomite are present.

The fourth specimen (M2-B) of this group bears not the slightest resemblance to the other three and the writer feels that it should be grouped with the "Cherty Ore" specimens. Consequently it will be considered a part of that horizon for descriptive purposes.

Microscopic -

Under the microscope the rock presents a mosaic of closely interlocking grains which average about 0.5 mm. in size.

The carbonate is variable in character. Small subhedral to euhedral grains are dolomite and larger irregular grains are calcite. Feldspar which is referable to orthoclase and microcline forms irregular and cloudy grains replaced by calcite and sericite. Some twinned feldspar grains, albitic in composition, are quite clear and may therefore be authigenic.

A small amount of quartz in irregular interlocking grains is present in all the rocks. Several of these grains have clearly defined secondary outgrowths in optical continuity.

Other minerals present in minor amounts are tan to green biotite, yellowish chlorite, muscovite and sericite, and clay minerals which are alteration products of the feldspars. Metallic minerals are native copper, hematite, and bornite all in fairly small amount.

The rock varies from an impure limestone to an impure dolomitic limestone. Some authigenic feldspars may be present but it is most probable that the cloudy, irregular grains of orthoclase and microcline are original detrital constituents.

3. Cherty Argillite or "Cherty Ore"

Megascopic -

Megascopically the nine specimens of this ore bed present varied aspects. Colours are predominantly shades of grey but two specimens are brown and one is black. Most of the specimens show light and dark laminations, these often containing ore minerals.

The rocks are all very fine grained, dense in fact, and in most cases are quite hard, hence their "cherty" description. One of the dense brown specimens contains a one-half inch white lens parallel to the laminations and also thin lacey veinlets or stringers cutting across the rock.

The black specimen (N3-D) previously referred to is unique in the collection. It is a dense black fissile rock cut by a number of quartz-carbonate veinlets and lenses about 2 mm. in width containing fair amounts of chalcopyrite. Most of these veinlets follow the fissility but several cut it at high angles and some are irregular and curved.

Varying amounts of carrollite, bornite, pyrite, and chalcopyrite are present in all the specimens and are mainly distributed along the laminations but some sulphides appear as blobs and disseminations throughout the rocks.

Microscopic -

The specimens, though differing in outward appearance, are quite similar mineralogically. Very fine grained quartz, feldspar, and sericite are the major constituents together with varying amounts of carbonate.

Quantitative estimates of quartz and feldspar are very difficult to make but in general the feldspar is at least equal in amount to the quartz.

Quartz, feldspar, and sericite grains average about 0.02 mm. in size but the ragged carbonate grains are usually about 0.1 mm. in diameter.

The very fine grained untwinned feldspar is of indeterminate composition but because it has negative relief it is probably either a potash feldspar or albite. Some larger poysynthetically twinned grains are usually present and these are albite. Several altered and irregular grains of orthoclase and microcline are also present.

Much of the quartz exhibits strain shadows. The sericite and other micas have a fairly good preferred orientation parallel to the megascopic lamellar structure.

Minor though recurring constituents are biotite, tourmaline, and a few grains of zircon, chlorite, and epidote. Biotite and tourmaline are both apparently allogenic though the latter, which is normally green in colour, is often narrowly rimmed with colourless secondary outgrowths.

The black fissile rock has slightly different mineralogical features. It is almost wholly composed of white mica grains 0.02 to 0.03 mm. in length and having an extremely good preferred orientation. Some very fine grained quartz occurs interstitially with the mica. The veinlets are composed of interlocking quartz and carbonate grains with interstitial chalcopyrite. The black colouration is produced by a good deal of very finely divided black, opaque, carbonaceous material.

It is rather difficult to apply a rock name to this group of specimens. Their present quartz, feldspar, sericite composition is no doubt due in some degree to the impress of conditions differing from those existing at the time of deposition though it is not likely that there has been much, if any, material introduced. Some of the feldspar could possibly be authigenic (Gruner and Thiel, 1937), though here it exhibits no diagnostic features. An originally siliceous or feldspathic shale could have given rise to this rock under conditions of fairly low grade regional metamorphism. For want of a better name and because of its outward appearance it may be termed "argillite".

One or two of the specimens have a large content of carbonate. This is assumed to be original calcareous material the grains of which having acquired an irregular shape through recrystallization.

The black rock with the marked fissility, though very different megascopically from the other specimens is, nevertheless, minerallogically quite similar. It is probably best called a black fissile shale.

4. 'Banded Ore' - banded white dolomite and grey argillite.

Megascopic -

This is typically a grey to white, finely crystalline to dense, rather soft laminated rock. The laminations vary from paper-thin to several millimeters in thickness, the grey laminae being thicker and denser and the white ones thinner and finely crystalline. The lighter crystalline material is carbonate, staining indicating that it is mostly dolomite.

Ore minerals, bornite, chalcopyrite, a very little carrollite, and possibly some chalcocite, are distributed in thin layers paralleling the lamellar structure. Some sulphides are disseminated through the rock, and in specimen N4-A much bornite occurs in thicker lenticular masses and in irregular blobs associated with coarse quartz and calcite.

Microscopic -

Irregular and anhedral grains of dolomite, averaging about 0.1 mm. in size, comprise the major portion of these specimens. Varying amounts of irregular feldspar and quartz grains and in some cases a little sericite are the other important constituents.

The carbonate is doubtless an original constituent; the grains may possibly have assumed their present irregular outlines through some recrystallization. In one specimen (N4-B) they are somewhat elongate owing presumably to deformation. Specimen M4-A contains anhedral to subhedral dolomite crystalls enclosed in irregular and cloudy calcite grains.

Many of the thin sections contain much (up to 30 or 40 percent) feldspar. This occurs in irregular interlocking grains of which some are potash in composition but many of which are polysynthetically twinned plagioclase. It is believed that most of this last is albite but that is by no means proven. Inclusions of carbonate are very common but the feldspar grains are otherwise quite clear. Other evidence is not apparent, consequently it cannot be said whether the feldspar is allogenic or authigenic. Quartz has much the same occurrence as the feldspar but there is much less of it.

The micas, biotite, muscovite, and sericite, are on the whole of quite minor amount. In one case small elongate biotite flakes make up 15 or 20 percent of the thin section and in several cases a good deal of sericite is present. The biotite for the most part has a detrital aspect but in one specimen (M4-A) very irregular and roughly equidimensional biotite scales have every appearance of being endogenic.

Very small amounts of detrital tourmaline and apatite occur in one or two of the specimens.

This rock appears to be a very dolomitic phase of the previous "Cherty Argillite". Dolomite grains usually forming 50 percent or more of the rocks permits the use of the rock name "dolomite". The darker laminations are feldspar, quartz, and minor sericite so it can possibly be said the rock consists of argillaceous and dolomitic layers. Actually the mineralogic segregation is not as clear as this last statement might imply so that a laminated argillaceous, or quartzo-feldspathic, fine grained dolomite might present a clearer description of this rock.

5. 'Low Grade Argillite'

Megascopic -

The specimens of this bed are fairly uniform in colour, texture, and all outward appearances. They are shaley or argillaceous appearing rocks, uniformly dark grey in colour, fairly soft but compact, and have parting or bedding planes one or two inches apart. These last are defined in one or two cases by thin (1 mm.) layers of gypsum or anhydrite and in another case by a similarly thin layer of fine white calcite very finely speckled with biotite.

Very close scrutiny reveals the presence of rare small blobs and lenses of chalcopyrite and bornite, the latter often having a little fine grained quartz in association.

Microscopic -

The major minerals of this rock, quartz, feldspar, biotite and muscovite form a rather uniform interlocking mosaic with no special textural features. The quartz and feldspar together, in grains averaging slightly less than 0.1 mm. in size, make up about 50 percent of the rock and the remainder is mostly biotite and muscovite or sericite, with additional small amounts of carbonate (3 or 4 percent), chlorite, and anhydrite.

The quartz and feldspar form a background of small irregular and interlocking grains which are difficult to distinguish for quantitative estimations. Some feldspar grains are twinned and those grains measured are albite; many grains are untwinned and because they appear to have negative relief may be either albite or a potash feldspar. A few small and rather rounded grains of bornite are scattered in the rock section.

Argillite seems to be a fair name for this rock. At places it may be dolomitic but the specimens available to the writer do not contain dolomite as a major constituent.

One of the specimens of this group (M5-C) is cut, at an angle of about 40 degrees to the bedding (?), by an one-half inch wide quartz vein, which has bleached the rock for distances up to one inch from the vein. A little calcite coats the quartz centrally in the vein and a very little chalcopyrite and bornite occur in the drusy parts of the vein.

6. 'Schistose Ore'

Megascopic -

The specimens of this bed are characterized by grey to greyish white and white banding. In the two specimens which are "schistose" the bands, one-quarter to one inch in width, are for the most part not sharply defined. The grey bands are dense and derive their colour mainly from very fine grained biotite. These layers grade into others in which the texture is sugary and the biotite is scarcer but of larger grain. Other layers are quite white and in the Mindola specimens they are composed of violet tinted anhydrite, quartz, and white dolomite. In places the banding gives way to a mottled or patchy appearance. Specimen M6-B contains a two-inch white layer composed of fine to medium grained purplish anhydrite, whitish dolomite, a little quartz, and irregular strings of biotite. It is bounded on either side by dark to light grey fine grained rock.

A little scattered bornite and chalcocite occur in the North Orebody specimen.

Microscopic -

Dolomite and varying amounts of biotite are the major constituents of the "schistose" specimens. Small amounts of quartz, chlorite, and feldspar are the minor constituents.

The dolomite has subhedral and anhedral outlines in a "close-packed" textural arrangement of grains averaging about 0.3 mm. in diameter. Staining indicates that all the carbonate is dolomite and it appears to be of primary origin. Yellowish biotite scales and shreds, slightly smaller in size, are scattered among the dolomite grains and also concentrated in bands where it has good preferred orientation. These narrow bands are often irregular and discontinuous and are sometimes composed of biotite and dolomite grains about one-half the average grain size. The evidence for the origin of the biotite is not clear and though it occurs "interstitially" and with no good replacement features it may not be an original constituent.

Feldspar grains vary both in size and composition. Large irregular orthoclase grains are crammed with inclusions of carbonate and biotite. Smaller irregular twinned and untwinned grains of albite are fairly clear. Quartz grains are usually fairly small and irregular.

The fine grained portion of one of the specimens is composed of quartz, carbonate, and biotite in roughly equal proportions.

Small irregular grains of bornite and chalcocite occur sparingly.

The evidences for deformation are not apparent and there is some doubt as to whether the rock has been "schisted" to any great extent.

7. Foot Wall Conglomerate.

The specimens of this bed are divisible into three groups each exhibiting distinctive petrological characters.

One group, including specimens N7-C, and M7-A, C, and D, is grey-white in colour and though typically conglomeratic in aspect has a "welded" appearance. Larger rounded and subrounded pebbles, of one inch or so in size and consisting mostly of quartz and chert, are quite scarce. Most of the rock consists of small (averaging about 1 cm.) angular fragments of quartz and white plagioclase feldspar in a grey siliceous matrix. Femic minerals, which together with fine grain size impart the dark colour, include biotite and muscovite.

One specimen, M7-A, contains some violet tinted grains of anhydrite. Another, N7-C, is speckled with small masses of pyrite.

Microscopic characters were only observed on specimen N7-C. The thin section contains feldspar of several varieties - orthoclase, microcline, and albite - totalling about 50 or 60 percent, and quartz comprising 25 or 30 percent of the section. The remainder is made up of biotite (ca. 5%) and minor amounts of chlorite, carbonate, zircon, apatite, and pyrite.

It appears that there has been extensive reconstitution and possibly metasomatism active in the formation of this rock. The larger potash feldspars, as well as containing sericite and clay alterations, have been replaced by quartz of the fine grained variety. Two types of plagioclase are present: larger twinned grains of albite (An. 5), and small (less than 0.1 mm.) clear untwinned grains with negative relief. This latter type may be of authigenic origin. The larger grains of albite exhibit "chessboard" or "schachbrett" texture which is taken by some (Gilluly, 1933, pp. 68, 73; Goldschmidt, 1916, pp. 68, 71, 78, 86; Becke, 1913, pp. 124-25; Grubenmann and Niggli, 1924, pp. 435-36) to be evidence of replacement origin. Biotite may replace other minerals but the evidence is not clear.

It might be suggested that this grey conglomerate has been derived from the Older Gray Granites, but because no specimens of this latter rock are available to him this is pure conjecture on the part of the writer.

The second group of Foot Wall Conglomerate specimens includes N7-A and B which are more typically sedimentary than those of the first group. These are thoroughly indurated rocks but they do not at all have the welded appearance of the first group. Larger (1 to 2 cm.) rounded quartz and chert pebbles and smaller (less than 1 mm.), angular, reddish potash feldspar fragments are embedded in a sandy and clayey cement which is slightly calcareous. Microscopically the specimens are fairly similar. Feldspar, including microcline, orthoclase, and albite, and quartz are the major minerals with small amounts of biotite, chlorite, muscovite and carbonate. A few detrial tourmaline grains are also present. The boundaries of the strained quartz grains are minutely scalloped by narrow bands of authigenic (?) albite (?). The larger feldspars contain much sericite and clay alteration.

Obviously the grey conglomerates have been subjected to an higher grade of metamorphism than the buff or pink rocks whose characters may have been derived from purely diagenetic processes.

The final group of the foot Wall Conglomerate types is represented by one specimen, M7-B. This rock is a fairly porous polymictic conglomerate. Rounded to sub-angular pebbles are one-half to one inch in size and range in composition from dense chert and clear quartz, to red, medium grained "granite", and to finely crystalline, calcareous, biotitic, and chloritic (possibly serpentinous) dark fragments. The cementing or matrix material consists of medium to fine grained quartz, pink potash feldspar, and biotite at least partly held together in a rather porous mass by powdery calcite. A 2mm. quartz veinlet cuts through the specimen.

No suggestion can be given by the writer for the provenance of this rock but it is obviously quite different from that of the other representatives of the Foot Wall Conglomerate.

It is suspected that although this Foot Wall Conglomerate may, as a conglomerate facies, be persistent over large areas, the details of its lithologic character, with respect to both components and induration or metamorphosm, vary considerably in a local sense.

8. "Feldspathic Sandstones and thin sandy Argillites" or

Arkoses and Argillites

Megascopic -

The three specimens of this bed differ somewhat in outward appearance but are apparently quite similar in overall mineralogic composition. All are reddish or pinkish in colour and of medium or fine grain.

Specimen N8-A is a fairly fine grained compact rock consisting predominantly of pink feldspar and quartz and containing several wavy, very thin dark bands which consist of specular hematite. Specimen N8-B though mineralogically similar, is banded with pinkish quartzo-feldspathic layers alternating with dark fine grained siliceous bands up to 5 mm. in width. The layers tend to have rather irregular surfaces and the dark colour is apparently the result of a lack of pink feldspar and a slightly smaller grain size rather than an increase in dark mineral content. Specimen M8-A has a rather porous texture and is composed predominantly of angular pink feldspar grains about 1 mm. in size. Angular and rounded quartz and chert fragments occur here and there as do dark biotitic and chloritic masses. The rock also contains a very thin dark lens of fine grained specular hematite.

Microscopic -

The rock sections are composed almost wholly of quartz and feldspars in about equal proportions and averaging about 1 mm. in size.

The quartz has rounded to sub-rounded outlines which are scalloped in detail. Most of the quartz grains exhibit strain shadows. The larger grains of feldspar are mostly orthoclase and microcline usually containing a good deal of clay alteration. The matrix material consists of an intimate mixture of very small (o.05 mm. or less) grains of quartz and feldspar. The latter shows negative relief but only rarely polysynthetic twinning, and is quite clear. Varying but small amounts of carbonate, biotite, muscovite, chlorite, tourmaline, and anhydrite are also present. As noted previously minor amounts of specular hematite produce thin darkish layers in parts of the rocks.

Feldspathic sandstones, or arkoses are appropriate names for these rocks. Textures are apparently due to diagenesis and no obvious metamorphic effects are apparent. The fine grained quartz-feldspar cementing material may have derived its present character from some compaction and possible reconstitution subsequent to deposition. Microcline has clear secondary outgrowths which may be termed "pressure microcline" and fine grained feldspar produces, by replacement, the scalloped borders on quartz grains and may therefore be authigenic. The other minerals, including tourmaline, exhibit no features that would class them as other than detrital fragments.

Specimen M8-A can possibly best be described as a "recomposed" granite, i.e. a sedimentary rock formed of the products of a rapidly weathered granite, which products have undergone little or no transportation and have formed a rock little different from the parent.

DETAILS OF ORE MINERALOGY AT NKANA MINE

General Statement -

Copper mineralization, according to Guernsey (1947), has been found in the 'Ore Horizon' and to a minor extent in the Hanging Wall strata, along both limbs of the syncline but, to date, mining has been done only along a part of the East limb where the South, North, and Mindola Orebodies are located. The 'Ore Horizon' is continuous between them but is poorly mineralized at two or more localities along the outcrop.

Guernsey makes the following statements concerning the ore minerals and their occurrences.

> "The dominant ore minerals are chalcopyrite, bornite, chalcocite, and carrollite. Pyrite is present at some localities where chalcopyrite is the principal ore mineral. Bornite and chalcocite are important below the zone of oxidation but tend to decrease down the dip. The decrease is not uniform throughout and is evidently conditioned, to some extent, by the structure and porosity of individual members of the 'Ore Horizon'. Chalcocite and native copper extend to a depth of at least 2370 feet at the north end of the North Orebody. The latter, in thin sheets and small irregular aggregates, is generally restricted to the 'Porous Sandstone' but has been noted near the foot wall. Minor malachite staining has been observed at a depth of 1810 feet in this section.
>
> The sulphides occur principally as disseminations throughout the 'Ore Horizon' strata and, to a lesser extent, as clots, aggregates and vein-like aggregates with carbonates and quartz. Throughout the North and Mindola Orebodies the so called 'Cherty Ore' is generally richest in copper, while the 'Low Grade Argillite' is the poorest. The cobalt-copper sulphide Carrollite is most often concentrated in the copper members of the 'Ore Horizon', - the 'Cherty Ore' and the 'Porous Sandstone'".

Because of the disseminated character of the ore minerals, thin sections and the petrographic microscope offered the best means of studying mineralogic relationships and consequently very little polished section work was undertaken.

Details of ore mineral occurrences will be discussed under the various members of the 'Ore Horizon'.

1. Hanging Wall Argillite.

Carrollite, bornite, chalcopyrite, and pyrite are found in small amounts in this bed. Carrollite (in specimen M1-C) is present both as disseminations and in cavities from 1 to 5 or 6 mm. in diameter. Euhedral, subhedral, and irregular grains from 0.2 to 0.4 mm. in diameter, and larger masses up to 3 mm. in size are found throughout the specimen. Bornite forms thin rims on the carrollite and is disseminated as individual grains from 0.1 to 0.2 mm. in size. The small amount of chalcopyrite is associated with, and replaces to some extent, the carrollite and is itself partially replaced by bornite. Pyrite, in grains from 0.01 to 0.05 mm. in size and also in cubes and irregular masses averaging 0.3 mm. in size, is thoroughly disseminated throughout some of the specimens.

The grain size of the pyrite bears a direct relation to the grain size of the rock minerals with which it occurs: coarser grains of pyrite are found in coarser portions of the rock and finer grained pyrite with finer grained rock minerals. It is fairly certain that pyrite replaces rock minerals because the larger masses of pyrite contain inclusions of both biotite and feldspar though no preference for any one mineral species is apparent. There is some tendency for small pyrite grains to be oriented in "strings" parallel to the laminations in the rock but microscopically no structural or mineralogical control can be discerned.

Carrollite, bornite, and chalcopyrite have features similar to those of the pyrite, with the difference that the grain size of the rock does not control the size of the sulphides. The sizes of the carrollite grains and masses are much larger than those of the surrounding rock minerals. Irregular carrollite masses, rimmed by bornite and partially replaced by chalcopyrite, contain inclusions of carbonate, feldspar, and white mica, and apparently replace rock minerals although, as with the pyrite, no metamorphic or hydrothermal effects connected with sulphide emplacement can be recognized. It is suggested that the sulphides may have replaced carbonate preferentially but this is merely an impression and conclusive proof is lacking.

2. 'Porous Sandstone'

Native copper and hematite are the metallic minerals found in this bed and although they can be discerned with the naked eye nothing concerning their relationships to other minerals can be determined. The this sections reveal that the native copper, which occurs as dusty fragments and shapeless masses often a millimeter or so in size, has a very marked affinity for feldspar grains. The latter are so thoroughly crammed with copper that relict polysynthetic twinning is barely perceptible. Although it is sometimes found between carbonate grains the copper practically never is included in them. Powdery red hematite, sometimes impossible to distinguish from the copper, appears to line minute fractures and cleavage cracks as well as outline the carbonate grains.

Why the copper has such preference for the feldspar and at the same time such disdain for the carbonate is rather inexplicable in the writer's opinion. The copper is probably of secondary origin and its reduction may have been brought about by the hematite. If such is the case then the present position of the copper has been controlled by the position of the hematite. Thus the copper followed the hematite and now appears as coatings on the rock minerals and fills the interstices between them.

3. 'Cherty Ore'

The sulphides, carrollite, bornite, chalcopyrite, and pyrite, are found in varying quantities, never more than several percent of the total rock mass, in the specimens of this ore bed.

In general the sulphides are oriented along laminations or bedding (?) planes but this is by no means always so. In many instances small blobs and masses are scattered through the rock seemingly without regard to structure. There are rare cases in which the ore minerals are located along cross-cutting fractures but because these structures are very infrequent that type of occurrence is similarly uncommon.

No obvious mineralogic controls of ore emplacement are apparent in the thin sections with the exception that the size of the sulphide grains is clearly a direct function of the size of the rock minerals. The sulphides all occur as irregular masses that doubtless replace rock minerals, as evidenced by inclusions of feldspars, carbonate, tourmaline, quartz, and even rock fragments.

If there is any preferential replacement it is of carbonate; but the writer doubts whether this could be proven statistically or otherwise. Carrollite is invariably confined to coarser layers within the rocks. Chalcopyrite, bornite, and pyrite although often concentrated in layers are also very thoroughly disseminated.

The range of grain size is quite large. Carrollite averages about 1 mm. in size; bornite, chalcopyrite, and pyrite range from less than 0.05 mm. to over o.1 mm. in diameter.

Very noticeable are the lack of hydrothermal type alterations or the association with the sulphides of "gangue" minerals. It is possible that some of the coarser grained feldspars and carbonates may have originated with the ore solutions but no evidence can be put forth to substantiate such a proposition.

4. 'Banded Ore'

The occurrences of the ore minerals in this bed are much the same as in preceding horizons. Bornite and chalcopyrite and a rare grain of carrollite are the sulphides. For the most part these minerals, as strings of grains and elongate irregular masses, are situated along lamination or bedding planes. Some smaller grains are disseminated. In one specimen (N4-A), in which the lamellar structure is not as clearly defined, larger and more irregular masses of bornite with a little chalcopyrite are present, in one place as interstitial masses associated with quite coarse and interlocking quartz and carbonate grains.

Microscopic similarities to other occurrences are also noticeable. Some of the larger masses of bornite and chalcopyrite (from 0,1 to 2 mm. in size) contain inclusions of carbonate, biotite, white mica, and feldspar. Thus the sulphides assuredly replace rock minerals but at the same time the sulphides are moulded to some extent around the rock mineral grains in which manner they have acquired quite irregular outlines.

Again, as before, the ore minerals are larger and more numerous in coarser portions of the rock and smaller in finer portions as evidenced by scattered specks of bornite 0.05 mm. in size in rock of similar grain size. No alterations or gangue mineral introduction can be attributed to the sulphide emplacement.

5. 'Low Grade Argillite'

Ore minerals are practically imperceptible in this bed. A 1 mm. lens of chalcopyrite occurs in one of the specimens but nothing else can be seen with the naked eye.

Two thin sections reveal the presence of small (0.1 to 0.3 mm.), rather roundish grains of bornite very sparsely scattered through the rocks. These grains are somewhat larger than the enclosing rock minerals and have no apparent replacement relations with them. In fact the method of emplacement of the sulphide grains is rather puzzling.

6. 'Schistose Ore'

The two Mindola specimens contain no sulphides whatsoever. The North Orebody specimen contains bornite and possibly some chalcocite in very small irregular masses scattered through the coarser portions of the rock.

In thin section the metallic minerals are no different from those already described. Some larger (1 mm. or so) irregular aggregates are found in the coarser portions of the rock and a very few smaller grains are scattered through the finer portions. In places red powdery hematite outlines the rock minerals.

7. Foot Wall Conglomerate.

Only one of the specimens of this member contains any sulphide mineralization. The matrix of specimen N7-C, one of the "welded" appearing rocks, contains about 1 percent of pyrite as small (1 mm. or less) scattered irregular blobs. The thin section shows that the pyrite encloses small grains of biotite, white mica and feldspar. No structural controls, preferential replacement, or alteration effects are apparent.

8. Arkoses and Argillites

The specimens of the member contain no sulphides. The only metallic mineral present is a small amount of specular hematite which, in two arkosic specimens forms very thin, wavy, and discontinuous layers. This iron mineral is very fine grained and its identification is based on its appearance both in hand specimens and in thin sections and on the fact that chemical tests detected only iron and no other metallic element. In the thin section the hematite appears as small fragments and irregular masses (less than 0.5 mm. in size) scattered through the fine matrix material of the rock.

How this hematite came to its present position is a perplexing problem. The grains are most certainly arranged in a linear or planar pattern but the continuation of a controlling structure is not to be seen in the hand specimens, which are, in one case at least, apparently quite structureless. Nor can any structure be seen in the thin section. Large grains of kaolinized feldspar cut across the band formed by the metallic grains and certainly no structure crosses the feldspar. There does not seem, therefore, any reason for supposing that this material has been introduced; in fact it is more probable that it was deposited contemporaneously with the other detrital mineral fragments.

ORIGIN OF THE ORES

This section of the paper will be devoted to: a brief review of general theories of ore genesis; a recapitulation of prevalent theories concerning the Northern Rhodesian copper ores; a summation and interpretation of evidence gathered in this study; and suggestions for further work which may help in the elucidation of the genesis of the copper ores.

General theories of ore emplacement.

It is not the object of the following remarks to present a critical review of the details of various theoretical concepts respecting the origin of ore deposits. It is hoped that a brief summary of theories will aid in the direction of thought: the case for any theory must be built upon a foundation of numerous pieces of factual evidence which have been put together in such a way that the strongest possible structure results. Facts may be related one to another in many ways but there is assuredly only one way which is right: this then is the ultimate truth.

The first step towards the attainment of the truth is the accumulation and analysis of the factual evidence; the second is the synthesis of this evidence. It is therefore necessary to know what evidence to accumulate and what the synthesis is likely to produce.

Theories of ore genesis may be broadly cast into three groups:

1. Epigenetic - ore deposits of later origin than the rocks among which they occur.
2. Syngenetic - ore deposits formed contemporaneously with

the enclosing rocks; for the present purpose two subdivisions may be made:

i. Deposits in sedimentary rocks.

ii. Deposits in plutonic rocks.

In the following discussion the term syngenetic will be restricted to deposits in sedimentary rocks.

3. Meta-syngenetic - ore deposits resulting from the metamorphism of pre-existing deposits.

These theories have three essential factors in common: a source of material; a means of transport of material; a site and a means of deposition of material.

Epigenetic theories of ore genesis presuppose a previous accumulation of materials at depth in a reservoir of some sort. These materials must now rise to the scene of deposition and obviously two factors are essential. Firstly there must be some means of access to the site of deposition and secondly the materials must be in a condition of 'potential mobility'. There must of course be a suitable site for the re-accumulation of the upward migrating material and a means of deposition (a physical or chemical process).

Pre-existing rocks provide the source of materials for syngenetic (sedimentary) theories of ore genesis. These materials are transported to the site of accumulation or deposition by surface agencies: water, wind, and ice. The site is obviously a sedimentary channel or basin and the means of deposition may be physical or chemical or both.

Meta-syngenetic theories of ore genesis include the middle ground between epigenetic and syngenetic theories. The elucidation of meta-syngenetic ores is fraught with complexities, as is that of their counterparts in petrology, the metamorphic rocks.

Geologic evidence.

The support of any theory will be based upon geologic evidence. Where will this evidence be found and what will be its nature?

Epigenetic deposits -

Because a source at depth has been postulated some evidence of this magmatic source may be discovered or possibly induced. These questions must be answered: Are possible source rocks close at hand? Can these rocks be identified as source rocks? Evidence will be provided by ore-bearing plutonic rocks, or by plutonic rocks which are obviously the parents of ore-bearing veins.

Closely related to the source is the means of access. Along which paths were the materials brought to their present resting place? Such features as major faults or shear zones, secondary or subsidiary faults and fractures, and small to very small scale openings will be looked for to answer this question.

As a corollary of the preceding question comes the next question: If pathways are present do they bear the imprint of the materials which used them? Ore minerals themselves, or exotic minerals, or transformations of pre-existing minerals will provide an answer to this query.

Finally: What is the site of deposition and what were the means of deposition? The growth of minerals in open spaces, the filling of cracks, the replacement of pre-existing minerals and similar features which point to the ore minerals as 'late-comers' will help to elucidate the problem posed by this question.

A lack of evidence for epigenesis leads naturally to a syngenetic conception. If no plutonic source, no tectonic structural controls, and no alterations or mineralogical replacements can be discerned then obviously the foundation has been laid for the erection of a syngenetic theory. Upon this foundation evidence relating the ores to purely sedimentary phenomena may be built. Such facts as stratigraphic layering of ore, detrital characteristics of ore minerals, and the presence, either actual or inferred, of precipitating agents may be used.

The middle ground provided by the meta-syngenetic theory is very difficult to map, depending on the extent to which the processes responsible for transformation have been effective. At one extreme the over-print of metamorphic effects will be very light and relict sedimentary features will still be apparent. At the other extreme the sedimentary deposit will be so thoroughly transformed that no original features remain and the deposit is now indistinguishable from an epigenetic one.

The reader is referred to a recent paper by Backlund (1950) for a more extensive treatment of this last extreme viewpoint.

A brief recapitulation of theories of origin of the Northern Rhodesian Copper Deposits.

Some reference to theories of origin has already been made in an early part of this paper. (p. 18).

Both syngenetic and epigenetic theories have been proposed for these copper ores but only the latter is dealt with to any extent in the literature. In fact the only literature available to the writer proposes and cites evidences for epigenetic theories. Schneiderhohn (1931) is the only author known to this writer who has upheld the syngenetic concept. His work was done very early in the history of the development of the deposits and forms a part of a larger part of a work on South Africa. Schneiderhohn's theory was doubtless based upon the large extent and bedded nature of the deposits and also upon the apparent lack of hydrothermal alterations.

Much evidence has been put forward by proponents of epigenetic theories. Some of this may be open to question but the following tabulation gives an indication of the type and extent of evidence that has been cited.

1. Proximity of Younger Granites (source rocks) and ore bearing strata. In places these granitic rocks are said to cut the ore horizons.
2. Copper is found in the granite, in fissures in the Basement Schists, in joints in the basal Mine series quartzites, and in veins in the ore horizon itself (Gray, 1932, p. 329).
3. Ore is found in beds of diverse mineralogical and chemical composition: a physical control is indicated.
4. The ores are confined to beds which are, or have been quite permeable. Permeability of beds has been increased by folding and consequent re-arrangement.
5. The ores have been localized by the damming action of impermeable sedimentary horizons.
6. The ore has migrated from one horizon to another through openings in impermeable beds.

7. The ore minerals replace rock minerals. Ore replaces the original calcareous cement of the ore horizon (Davidson, 1931, p. 151).
8. Presence of the high temperature mineral, tourmaline, and other minerals such as white mica, colourless chlorite, and secondary feldspars which have been introduced by the ore solutions. The introduction of quartz and carbonate minerals and the association of ore minerals with this 'gangue'.
9. Sulphides oriented along schistosity show no elongation.
10. The majority of the chalcocite was formed above 91°C. or possibly above 200°C.
11. The shape of the deposits is partly controlled by the folding: the ore mineralization is later than the folding.

Some remarks concerning these evidences and their interpretation will be made after the ensuing presentation of evidences gathered during the study of the specimens.

Evidence gathered in this study.

It is certainly not possible to base a completely detailed theory of genesis upon the evidence accumulated in an investigation such as this. Nevertheless if answers to certain questions are forthcoming the erection of a theory may be facilitated or at least the search of evidence may be given direction.

Logically the first question is: In what beds are the ore minerals concentrated and what reasons can be given for the occurrence of ore in these beds?

Guernsey (1947) states that the 'Cherty Ore' is richest in copper while the 'Low Grade Argillite' is the poorest, and also that carrollite is most often concentrated in the 'Cherty Ore' and the 'Porous Sandstone'. These statements are borne out by the collection of specimens. The 'Cherty Ore' member carries the largest quantity of sulphides and the 'Porous Sandstone' and 'Banded Ore' carry less, but nevertheless important, quantities. Other beds contain very minor amounts of sulphide minerals: the Hanging Wall Argillite contains a little carrollite, bornite, chalcopyrite, and pyrite; the 'Low Grade Argillite' has a few scattered grains of bornite and chalcopyrite; the 'Schistose Ore' contains a little bornite; the Foot Wall Conglomerate contains a little pyrite; the Arkoses and Argillites contain no sulphides.

What are the features of the major ore beds? Marked differences in mineralogical composition are at once apparent. The 'Cherty Ore' horizon is a dense, fairly hard argillite, in places containing small amounts of carbonate. The 'Banded Ore' is an argillaceous dolomite and the 'Porous Sandstone' is an impure limestone or an impure dolomitic limestone. Obviously the presence of sulphides is not a direct function of the composition of the rocks.

Presumably then the presence of ore in these beds may in some way be connected with their physical characteristics. What physical characters these beds might have in common is not readily imagined.

If it is believed that ore minerals are deposited from hydrothermal solutions then permeability is a factor to be considered. The writer cannot imagine that the primary or secondary (product of deformation) permeability of what is now a very dense argillite can ever have been greater than that of the other beds of the 'Ore Horizon'. Possibly Mackay's (1946) 'principle of impedance' (essentially the 'hypo-filtration' or obstruction of 'ore radicles' but not of the 'carrier' solution: an osmotic process) may account for the preponderance of ore in this dense horizon. It must be pointed out however that even if this principle is applicable here it does not apply to other mines in the district whose major ore horizons differ, both chemically and physically, from this 'Cherty Argillite'. Also inexplicable is why the lower 'Low Grade Argillite' of similar physical and mineralogical character did not 'impede' the rising solutions before they progressed to the 'Cherty Argillite'. The writer can produce no satisfactory explanation, following epigenetic theory and based on the chemical and physical character of the rocks, for the preponderance of ore in this horizon.

Perhaps the stratigraphic position of the ores may be attributed to features which are not a direct function of the character of the host rock. This introduces the possibility of 'damming' action. Rising solutions upon reaching an impervious horizon may be obstructed in their vertical progression and thereupon spread laterally along more permeable horizons. This appears to be a possibility at NKana. The hanging wall of the ore deposit is formed by a fairly massive argillite which has been mineralized to some extent near its base. The 'Low Grade Argillite', near the foot wall of the 'Ore Horizon', may also have acted as a barrier because, though very sparsely mineralized itself, it overlies the 'Schistose Ore' which in places contains appreciable copper mineralization.

Because only those evidences observable in the collection of specimens are being considered, the effect of faults and like structures as possible 'localizers' of ore will not be considered here.

The position of the ore minerals within the beds of the 'Ore Horizon' should be reviewed. The sulphides, though disseminated to a greater or lesser extent, are noticeably oriented along lamination planes. Presumably this might be an effect of hydrothermal processes. It is possible that microstructures were formed along the lamination (bedding) planes during deformation and prior to or accompanying mineralization. These openings would provide pathways for the mineralizing solutions. Such openings may have been very small indeed but it is only necessary that they were larger than the pore spaces of the rock. Cross-cutting fractures are not at all common in the ore beds but where they do occur they are found to be mineralized.

The black fissile shale requires special comment. Conformable (with fissility) and cross-cutting chalcopyrite bearing quartz-carbonate veins are a unique feature of this rock. The origin of these veins most assuredly conforms with epigenetic theory. The cross-cutting veins exhibit an interesting form. They are sinuous, a shape which is interpreted by the writer as the result of nonaffine deformation along the fissility surfaces. If such is the case then they were obviously emplaced before or during the deformation which produced the fissility.

What microscopic characters may be used as evidence? The size of sulphides is goverened by the size of the enclosing rock minerals. This morphological correspondence suggests replacement of the rock minerals by the ore minerals. In the writer's opinion this has definitely occurred. Inclusions of silicate and carbonate minerals in the sulphides is evidence of this but it must be admitted that a specific example in which sulphides could be 'seen' to replace other minerals would be hard to find.

At some places there is doubtless an association of the ore minerals with quartz and carbonate, as witnessed by the veins in the fissile shale. A similar association is found along some of the lamination planes. But this is by no means always the case. Many instances of sulphide occurrence without the association of these 'gangue' minerals have been noted and the writer would be loath to generalize that the ore minerals are always associated with quartz and carbonate, introduced or otherwise.

Tourmaline occurs in small quantity throughout the rocks of the 'Ore Horizon' but every grain examined by the writer showed detrital characteristics, though some grains did have colourless rims which are interpreted as authigenic outgrowths. Other minerals such as biotite, sericite, chlorite, and feldspars may or may not be original sedimentary constituents but they certainly show no special relations to the ore minerals and are probably best attributed to diagenetic or low grade regional metamorphic processes.

Summation and suggestions for further research.

Enough data have been accumulated to form a basis for a theory of origin of these ores but it is clear that much of these data require re-examination and substantiation. In the writer's opinion the evidence most markedly points to an epigenetic theory. There are certainly too many criteria for epigenesis to warrant an attempt to construct a syngenetic (sedimentary) theory. It is not proposed that any one fact or piece of evidence alone must support the theory: numerous relatable facts must be used.

Considering as factual all evidence that has been cited up to this point the case for epigenesis may be stated in the following manner.

There is a source for the ore minerals in the younger granites and these rocks exhibit evidence in the form of copper mineralization that they were indeed source rocks. Channelways bearing the imprint of metallizing solutions lead from the source rocks to the sites of deposition. The sites of deposition are provided by rocks more permeable than their neighbours and mineralogical relationships show that replacement of these rocks by the ore minerals did take place. Barriers to rising solutions were present and were effective in concentrating the mineralization.

The strength of a theory depends upon the strength of the evidence with which it is built. How strong is this evidence? The writer submits that his evidence is strong enough to preclude a purely syngenetic (sedimentary) theory.

Because of his unfamiliarity with the district the writer can scarcely critically review the evidence of other writers but doubt apparently exists (Brock, 1951) concerning the validity of some of the evidence and certainly much of it is not clear to the writer.

There seems to be some doubt extant concerning both the proximity of granite rocks to ore deposits and their authenticity as source rocks. Though the problem is not quite clear to the writer the distinction between 'older' and 'younger' granites is apparently sometimes difficult. Jackson considers that the 'younger' granites are indeed the source rocks but nevertheless admits (1932(2)), p. 455) that:

> "There is no essential mineralogical difference between the typical MKushi granite-gneiss(Older Grey Granite) and the younger grey granites, and where the latter are locally gneissoid, any difference, either mineralogical or structural

practically vanishes".

Here then is one field for further work: detailed field mapping and especially detailed petrographic work would doubtless aid in the elucidation of the problem of the granites.

It should be interjected here that the writer realizes full well the difficulties of detailed field mapping in a region such as this where outcrops are scarce and where much information is derived from exploratory 'pot-holing' through deep overburden. Nevertheless a complete awareness of the type of evidence being sought will lead to a more thorough and critical analysis of all available information and it is with this thought in mind that these remarks are made.

Doubtless a result of the lack of outcrop is the paucity of knowledge of faulting in the district. Jackson (1932(2)) remarks that faulting is undoubtedly present to a considerable extent in the NChanga area but few outcrops render the discovery and solution of the results of tectonism a most difficult task. It is most probable that in an area which is a part of a region of the world in which enormous vertical displacements are commonplace and in which tectonic doming of sediments is known to exist, some large scale faulting is present. Faults have apparently presented no problem to mining operations but a knowledge of them is certainly necessary for the understanding of 'why the ore is where it is'.

Crests of large and small drag folds have been cited as loci of ore accumulation thus inferring that folding preceded mineralization. The writer does not doubt the probability of this but it is apparent that concentrations of ore in such places may have been produced mechanically. A close examination might substantiate one or other of these possibilities.

A more thorough examination of what has been termed the 'sites of deposition' is obviously necessary and in this respect the writer suggests that with this an examination of 'sites of non-deposition' would be especially fruitful. It is noted that along the east limb of the NKana syncline for example that the 'Ore Horizon' is "poorly mineralized at two or more localities along the outcrop" (Guernsey, 1947). Surely an investigation to determine the reasons for this 'poor' mineralization would answer some of the problems of 'rich' mineralization. There are also places in the copper district where lower members of the Mine Series have been explored and found unmineralized. A detailed petrographic study of these beds, along the lines of the present investigation, and comparison of findings with those resulting from the study of mineralized beds would yield much information. Perhaps the problem of whether certain minerals - tourmaline, biotite, white mica, chlorite, and feldspars - are the products of metamorphic (including diagenetic) or 'hydrothermal' processes could be answered. Comparative chemical analyses of certain rocks in which mineral grains are too small for optical identification is a suggested approach.

The possibility of these deposits being of meta-syngenetic origin has been omitted purposely from the preceding discussions. The writer feels that owing to the complexities involved the best approach to the formulation of a theory of origin for these deposits lies in an attempt to construct an epigenetic theory using the information now available. At the same time the possibility of meta-syngenesis must be kept in mind in order that no piece of useful evidence is overlooked. If metamorphic processes acting on an originally sedimentary deposit have proceeded to the extent that some 'migration' of ore minerals or reconstitution of the whole mineral aggregate has occurred then criteria for either epigenesis or meta-syngenesis would in general be similar or indistinguishable. Theory would diverge however when the problems of source and of access of material to sites of deposition were considered. Thus if no rocks could be found and proven to be source rocks and if no pathways were found to lead from these sources to the ore deposits then the origin of a deposit exhibiting 'replacement' features might be explained in terms of meta-syngenetic theory. The writer is quite aware that such is a possibility in the Rhodesian Copper Deposits.

Concluding remarks.

The writer lays no claim that the results of his study have clearly indicated the processes which formed the NKana copper deposit. Nor does he claim that, using the material available, the possibilities for investigation have been exhausted. Many more facts can doubtless be gleaned from the specimens. Both sulphide and silicate mineral identifications and relations leave much room for further work. Statistical methods could be employed, with a good chance of success, to determine whether or not ore minerals have replaced any rock mineral species preferentially or whether there is any special association of non-sulphides with the ore minerals.

However, the writer feels that because no previous laboratory type work had been done (or at least has been published) on Nkana deposits a coverage of the whole problem at a more general level has been more valuable than if an attempt had been made to treat exhaustively a specific problem at a more detailed level.

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