GEOLOGICAL FACTORS AFFECTING TONNAGE-GRADE RELATIONSHIPS IN OREBODIES OF THE ZAMBIAN COPPERBELT

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CONTENTS

<u>NOTE</u> In South Africa, "ton" normally signifies a metric ton and the word "tonne" has no official standing (Coetzee, 1976). The Zambian practice is followed in this text, so that "tonne" means a metric ton of 1000kg while "ton", where quoted from literature, usually signifies a long ton of 2240lbs.

1. INTRODUCTION

Objectives of this study

The occurrence of a major metalliferous province in Zambia and Zaire is a reflection of geological processes operating in a specific environment during a particular period. The size of orebodies, their grade, mineralogy, beneficiation characteristics and therefore the amount of metal produced are all ultimately functions of the geology of the ores. This study is primarily concerned with the effect geology has on tonnage-grade relationships of ore *in situ* on the Zambian Copperbelt.

Five major topics related to ore tonnage and grade are reviewed here :

- behaviour of copper and cobalt in surficial environments.
- geological setting and gross lithostratigraphic relationships of mineralization.
- characteristics of known orebodies.
- geological factors affecting mining and beneficiation of ore
- orebody limits and estimation of tonnage and grade.

In addition, the historical background to the problems discussed here is briefly described, and some general aspects of the evaluation, mining and beneficiation of Copperbelt ores are considered in relation to metal production.

Historical Background

Copper has been mined in central Africa for many hundreds of years, but records of early production and mining methods are scanty. A review of the first fifty years of the modern mining industry in Zambia published in 1978 by Roan Consolidated Mines Limited (R.C.M.) states that the first written reference to copper mining in central Africa was published in 1591. Virtually nothing definite seems to be known of mining activity prior to the middle of the nineteenth centry, but R.C.M.'s publication suggests that the

> "growth of the superior social, economic and political organization of the builders of Zimbabwe in the sixteenth Century . . . . caused the trade in and use of copper to increase greatly."

During the last part of the nineteenth Century, when European explorers first came seeking copper in central Africa,mining and smelting of copper had evidently declined from a previous peak. However, Africans were still mining and smelting small amounts of copper by their traditional methods. Their output was cast into shapes for use as currency, and used in the production of utensils, wire and ribbon, which had a variety of practical and decorative uses. Europeans came to the Copperbelt seeking copper for industrial use, and brought with them new technology for mining ores and extracting the valuable constituents. All their early 'discoveries' were marked by the presence of either ancient workings or characteristic malachite-stained outcrop. Bancroft, in his book published in 1961, stated that all the copper mines operating in Africa in the 1950's, apart from five of the Copperbelt orebodies, were marked by the presence of ancient workings. This must have been written prior to the development of the Kirila Bomwe and Konkola orebodies.

Production of metallic copper from the ores mined from the ancient workings was accomplished by smelting up to about 50kg of malachite ore at one time in a furnace constructed from clay. Wood charcoal was used as the reducing agent. According to Bancroft, only high grade malachite mineralization was regarded as ore because it was the only material amenable to hand sorting and charcoal smelting. The disseminated sulphide ore which is predominant on the Copperbelt is impossible to beneficiate without complex technology, and was unknown due to depth of weathering and inaccessibility to primitive mining.

Oxidised copper orebodies exposed at surface, in the area now known as the Zambian Copperbelt, were exploited at only a few localities. There were fairly extensive ancient workings at Bwana Mkubwa, and also at Kansanshi to the west of the Copperbelt. Minor old workings were found at the Roan Antelope and Chambishi deposits where supergene processes had generated some malachite ore over sulphide bodies. No old workings at all were present at Nchanga, Mufulira, Nkana, Mindola, Chibuluma, Kirila Bomwe or Konkola, although mineralization was exposed in stream sections at the first three localities. In Katanga, the largest ancient working recorded was over 1000m long and between 200m and 300m wide. Ball (1922) is quoted in Bancroft (1961) to have estimated that the old workings of Katanga produced at least 100,000 tons of copper, requiring the mining of over a million tons of ore and waste. Undoubtedly, the lack of mining and beneficiation technology appropriate to the characteristics of much of the Copperbelt mineralization prevented it from being regarded as ore. Today, improved technology enables a much larger proportion of the mineralization to be classified as ore, but mineralization is still left unexploited because of the same kinds of constraints as have operated in the past.

Prain (1975) summarises the growth and development of the copper industry worldwide and places the spectacular twentieth century upsurge of external interest in the copper prospects of Northern Rhodesia in its wider context. He shows that political, economic and medical developments all combined at the right time with new geological knowledge and metallurgical technology to promote interest in the Copperbelt orebodies in the 1920's. They were close to the existing rail link to Katanga, large, of high grade, and exposed at surface. It was relatively easy to define a sufficient tonnage of ore to justify capital investment, and mining appeared to be straightforward. Profitable development and exploitation of the ores was dependent as much on external economic factors as on intrinsic characteristics of the ores.

It is instructive to note the way in which the ore reserves at Roan Antelope (Luanshya) were quoted by Sharpstone in 1929 :

> "Because of the remarkable uniformity of mineralization and remarkable persistency of the ore bearing horizon, Mr T H Field estimated 30,000,000 tons of copper sulphide ore, averaging over 3.25 per cent copper, in the Roan property, as already developed, June 30th 1928. Doctor Otto Sussman, at the same time, estimated a similar tonnage but at a grade of 3.4 per cent copper . . . . Additional tonnage may be expected as other bore-holes cut the ore horizon."

There was thus little concern for the exact grade, and the ore tonnage was seen to be hightly conservative. Development and dewatering were not expected to pose particular problems, and the feasibility of good metallurgical recovery had been established by pilot plant tests.

Luanshya was the first Copperbelt mine to come into production, and still has published reserves (at 31st March 1980) of over 56 million tonnes at 2.49 per cent total copper. With the exception of Bwana Mkubwa, which is now virtually exhausted, ore reserves at all the Copperbelt mines have tended to follow a similar historical pattern. Their present reserves therefore appear adequate for several years of continued production, possibly longer than the original projected lives of the mines. Current grades do, however, tend to be lower than those quoted when mining commenced. Many of the mines, in addition to quoted ore reserves, calculate a more speculative tonnage and grade of material outside published reserves. This mineralization is known by a variety of names, and is kept apart from reserves for different reasons at different mines. These tonnages are either not available for mining with present facilities, or not recoverable at a satisfactory grade, or cannot be economically beneficiated using present technology.

Factors influencing Copper Production

Because the Copperbelt orebodies are large, thick, relatively easy to mine and of high grade, it has in the past been comparatively easy to exploit them profitably. On occasions more efficient mining and beneficiation might have resulted from better assessment, but it has generally not been essential to pay particular attention to tonnage-grade relationships and grade control. However, as the mines have become deeper and production rates have increased. the problems of low recoveries and excessive dilution have become progressively more important. The necessity to make the best economic use of their major natural resource has compelled the mining companies on the Copperbelt to strive for higher recoveries of ore *in situ* at the lowest possible cost. In order to obtain maximum recovery of metal from ore mined, and hence obtain maximum revenue per tonne of ore hoisted, it has become increasingly necessary to understand in detail the occurrence and treatment characteristics of both copper and cobalt. Examination of the current ore reserves and the data concerning past production shows that the amount of metal present in the Copperbelt bodies is enormous. Bowen and Gunatilaka (1977) suggest that the metal content of the Copperbelt in Zambia and Zaire is of the order of 170 million tonnes of copper and 5 million tonnes of cobalt. The basis for this estimate is not stated, but figures of this magnitude show that the quantity of contained metal should not present any problems in maintaining production for a very long time to come.

Mendelsohn, in 1961, wrote that, "The genesis of the Copperbelt ores is not purely an academic question, although much of the discussion regarding it has been academic. A satisfactory theory of ore genesis aids in understanding the general geological environment of the ore deposits; this in turn is of material assistance in the search for new deposits." He could also have added that an understanding of the genetic controls aids in the exploration and evaluation of known orebodies. As there is nothing to suggest that all the orebodies present on the Copperbelt have been found, geological models will unquestionably aid in determining where to look for further ore. Because accurate geological models are necessary in evaluating mineralization, improved knowledge of currently known deposits will also help with future evaluation of these and any new discoveries. Exploration and evaluation must obviously be performed as efficiently as possible in order to ensure maximum benefit to Zambia of an important national resource.

The definition of mineralization as ore reserves presupposes that there exists an economic means of mining and treating the rock to extract the contained metal (Brobst and Pratt, 1973). For technical or economic reasons, considerable resources of material containing copper and cobalt which are known to exist on the Copperbelt are not considered to be ore reserves. This review examines the current state of knowledge of Copperbelt geology as it relates to the tonnage and grade problems being experienced now and anticipated in the future. Increasing capital and energy costs and the necessity to mine deeper or less easily treated mineralization will in all probability act to further reduce the amount of mineralization categorized as ore in future. This will increase the need for new discoveries of sulphide ore at shallow depths. Technical advances in mining and beneficiation, improved recovery and reduced dilution will, conversely, act to reduce the need for new ore discoveries. However, problems in the fields of mining and beneficiation will only be solved using detailed knowledge of the geology of the deposits as a starting point. Thus an integrated understanding of all aspects of Copperbelt orebody geology will be crucial to the success of future mine development. The detailed knowledge of orebody characteristics required to give this understanding was simply not necessary in the early days of exploration and mining on the Copperbelt.

2. GEOCHEMICAL BEHAVIOUR OF COPPER AND COBALT IN SURFICIAL ENVIRONMENTS

This section reviews the geochemical behaviour of copper and cobalt without any specific genetic implications for Copperbelt mineralization, but on the assumption that emplacement of metal in the host rock took place close to, or at, the Earth's surface.

Copper and cobalt grades in stratiform orebodies are a function of the mineralogy and petrology of the ore, these characteristics being determined by the genetic history of the rock. The influence of particular genetic processes may be variable over short distances, and events affecting orebodies or parts of them may be very widely separated in time. The geochemistry of copper, cobalt and any other metals present in the ore is the primary control on their migration and emplacement and hence on the morphology of an orebody prior to any tectonism. The mechanism of metal fixation is the primary control on grade distribution within an orebody, though clearly other factors may operate after initial formation of ore to affect the distribution of metal. Thus the final distribution of grade in a mineralized body reflects three different effects :

- distribution of metal in the host lithology at the time of initial metal emplacement.
- redistribution of metal during diagenesis and metamorphism.
- the operation of supergene or hydrothermal processes after lithification.

The role of the geochemical behaviour of metals in separating them into specific ore fluids is not well understood and it is not proposed to examine this aspect in detail. It is generally accepted that the metal in the Copperbelt ores must have been introduced as a component of an aqueous fluid, although there is still doubt as to exactly how the fluids were related to the mineralized lithologies. Mechanisms of solution and transport of metals in aqueous fluids have a direct bearing on both the initial formation of ore and the behaviour of orebodies exposed to weathering at and near the present land surface. Similarly, the processes by which metal is fixed following aqueous transport also affect both the primary grade distribution within orebodies and the nature of the supergene zone over a weathered orebody.

Historical background to genetic theories

In the early years of the development of the Copperbelt orebodies, geologists who examined them invariably attributed mineralization to hypogene processes. All the early literature implies or specifies that the metal content of the ores must have been introduced subsequent to formation of the host rock. For example, Sharpstone (1929) attributes mineralization at Roan Antelope to a hypogene process, though he does question the observed localization of mineralization within comparatively narrow stratigraphic intervals. In a review concerning the early ore discoveries on the Copperbelt, Bateman (1930) suggests that the occurrence of mineralization in certain beds was controlled by physical rather than chemical features of these beds, and that the mineralizing solutions were relatively hot fluids (over 91°C) of igneous origin. Jackson (1932) suggests a hydrothermal origin for primary ore at Nchanga and even suggests that mineralization was a post-folding phenomenon. He states that both bornite and chalcocite appear to be the result of very extensive supergene effects. To Anton Grey, also writing in 1932, it was "clear that the Mufulira deposit is epigenetic." He proposed that mineralization was post-folding, and attributed the stratigraphic position of the orebodies to the presence of impermeable cap rocks. Douglas (1932) reviewed the occurrence of mineralization in Northern Rhodesia and indicated a hydrothermal origin for all the orebodies of the Copperbelt.

As the great lateral extent of the orebodies, their consistent grade and restriction to certain beds became more evident, various geologists found it increasingly difficult to envisage a hydrothermal mechanism for emplacement of the metals. Mendelsohn (1961) reviewed the evidence relating to the formation of the Copperbelt ore deposits and concluded that the copper was accumulated with the host sediment. Garlick (in Mendelsohn, 1961) proposed a syngenetic theory whereby the copper entered a shallow sea in solution in river water, and was precipitated by a selective process, probably involving biological intervention. Other authors, including McNaughton (1954) and Darnley (1959), examined various characteristics of the Copperbelt ores and were not convinced of the applicability of the syngenetic theory as an explanation of all their characteristics. Amongst others, C F Davidson (1965), Rickard (1973) and Renfro (1974) have contributed further ideas to the discussion of possible genetic mechanism, but controversy remains. It seems unlikely that this will be resolved completely without much further work.

Solubility of copper and cobalt in aqueous solutions

There is no universal agreement as to the sedimentary environment in which the sediments hosting the Copperbelt mineralization were deposited, nor is it entirely clear how the metal was introduced. Nevertheless, it seems certain that metal was transported in an aqueous fluid which permeated the sediment before or during diagenesis. No other mechanism can be applied in any reasonable way when the overall geology of the deposits is considered.

Barnes and Czamanske (1967) state the obvious fact that transport or ore (i.e. metals) in important quantities is limited to aqueous fluids in which ore minerals are appreciably soluble. They also suggest that there is probably a limited spectrum of fluid compositions which are chemically capable of dissolving significant quantities of metallic sulphides at high pressures and temperatures. The approach Barnes and Czamanske take is open to criticism since they consider the solubility of sulphides rather than metals, and there is evidence that at least part of the sulphur in the Copperbelt ores was not introduced with the metal-bearing fluids. Thus the lack of solubility of sulphides may be important in fixation rather than transport of the metal in Copperbelt ores. Barnes and Czamanske,furthermore, do not clearly define the range of temperatures and pressures in which their hydrothermal fluids are considered to exist. Temperature, pressure and fluid composition are the three variables likely to have a significant effect on metal solubility. Discussion in recent literature (for example Annels, 1974 and Eden, 1974) suggests a strong influence of rock characteristics and diagenetic processes in producing the final distribution of metal in Copperbelt ores. Fluid composition may also have an influence on the gangue mineralogy and eventual porosity of ore, with a consequent effect on specific gravity. Normal marine waters contain very small concentrations of copper and other transition metals (Stanton, 1972) and their concentration in seawater is invariably several orders of magnitude less than their abundance in the Earth's crust. Rickard (1973) suggests that any increase in the copper content of seawater would result in the formation of malachite and that other metals would also precipitate before entering the reducing zone, of sulphide precipitation from anoxic water, envisaged in Garlick's syngenetic theory. It is possible that small amounts of metal which would otherwise precipitate as carbonate might remain in seawater solution as complexes. Modern rivers carry only minute amounts of copper (Rickard 1974) and it is, therefore, unlikely that rivers could ever have transported sufficient metal to form the Copperbelt deposits.

Data concerning the solubility and geochemical behaviour of cobalt is much less extensive than that pertaining to copper, and most of the literature dealing with the behaviour of these metals in aqueous fluids is based on work relating specifically to copper. However, since the hydrometallurgical separation of the two metals is complex, it is reasonable to assume that they behave rather similarly in most aqueous solutions. Rose (1976) examined the solubility of copper in various aqueous systems in an attempt to quantify the conditions under which solution and transport of copper might have been achieved in forming red-bed type copper deposits. He acknowledges that the Copperbelt orebodies show certain differences from red-bed deposits, but suggests that in view of their geological similarities and probable low temperature of deposition the same chemical relationships may apply to both types.

The solubility of copper in the system Cu-O-H-S is shown in Figure 2.1, which indicates that the metal is only significantly soluble in an oxidising environment under moderately acid conditions. In less acid oxidising environments, copper oxides are the stable phases, while under

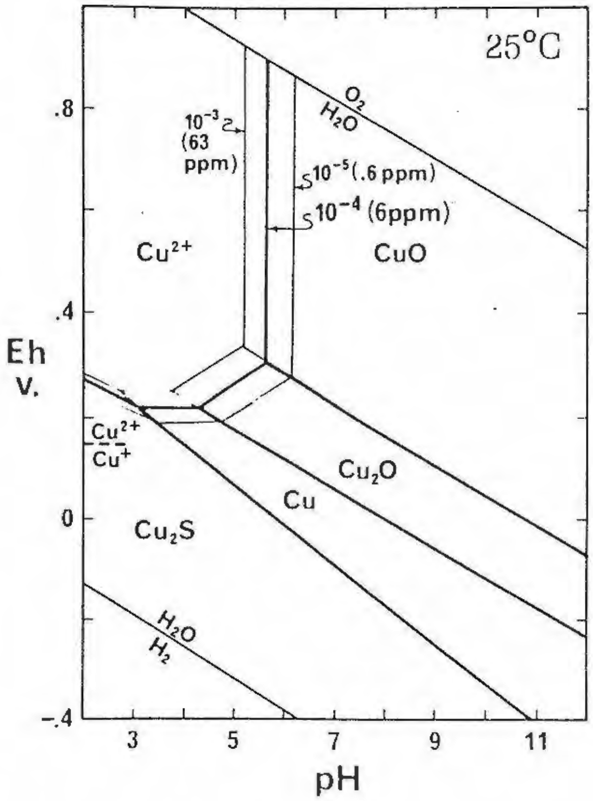


Fig. 2.1. - Eh-pH diagram for system Cu-O-H-S, 25°C, $\Sigma S = 10^{-4}$m (From Rose, 1976)

reducing conditions chalcocite is stable. Within a rather narrow range of Eh - pH conditions, native copper is the stable phase. The diagram shows that copper solubility is about 6ppm in an oxidising environment at pH 5.67, decreasing to 0.6ppm at pH 6.17. Solubility is negligible under reducing conditions. Rose suggests that this system approximates fresh surface waters and dilute groundwaters, and that if 1ppm dissolved copper is taken as significant for ore formation then transport of significant amounts of copper is not possible at pH values of 6.1 or above. Both Rose, and Barnes and Czamanske (1967), propose that mineralogical and chemical features of the environment of many sulphide ore deposits indicate that transport cannot have been in acid solutions. Barnes and Czamanske argue that this precludes chloride complexing as a solution mechanism. They suggest that metals are carried in alkaline solution as sulphide complexes, and some experimental evidence supports this conclusion. Rose shows that by addition of chlorine to the aqueous system already considered, it is possible to extend the stability field of copper in solution very considerably.

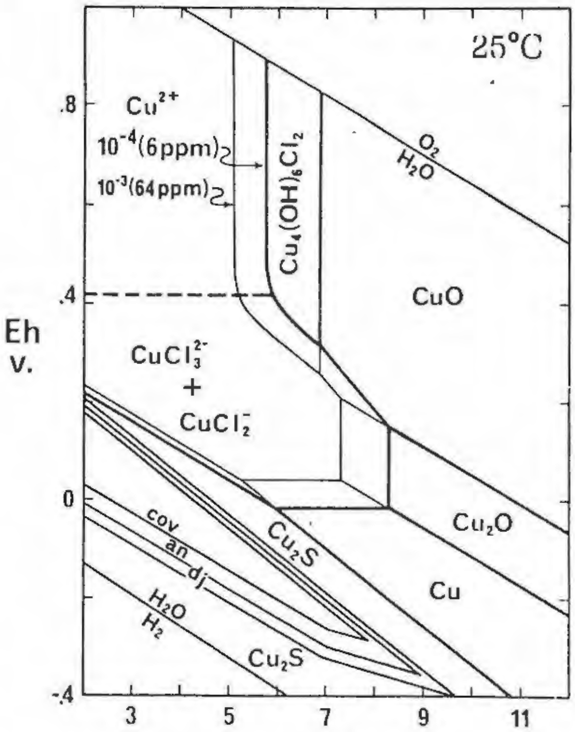


Fig. 2.2.- Eh-pH diagram for system Cu-O-H-S-Cl, 25°C, $\Sigma S = 10^{-4}m$, $Cl^- = 0.5m$ as NaCl. Cov = covellite, an = anilite, dj = djurleite. (from Rose, 1976)

Figure 2.2 shows that chloride complexes with copper may exist in moderately reducing conditions and at substantially higher pH values than those at which copper is stable in simple ionic solutions. The diagram is drawn for $\Sigma S = 10^{-4}m$, but increasing the sulphur molality does not significantly change the diagram. Hence transport of sulphur in the same solution does not seem to present any problem. Figure 2.3 shows how in a neutral solution solubility of copper increases as a function of chloride content in the system Cu-O-H-Cl. Certain of the Copperbelt deposits are characterized by the occurrence of conspicuous amounts of scapolite in close proximity to the ore. This fact and the solubility relationship shown in Figure 2.3 provide strong evidence for the involvement of chloride complexes in solution processes.

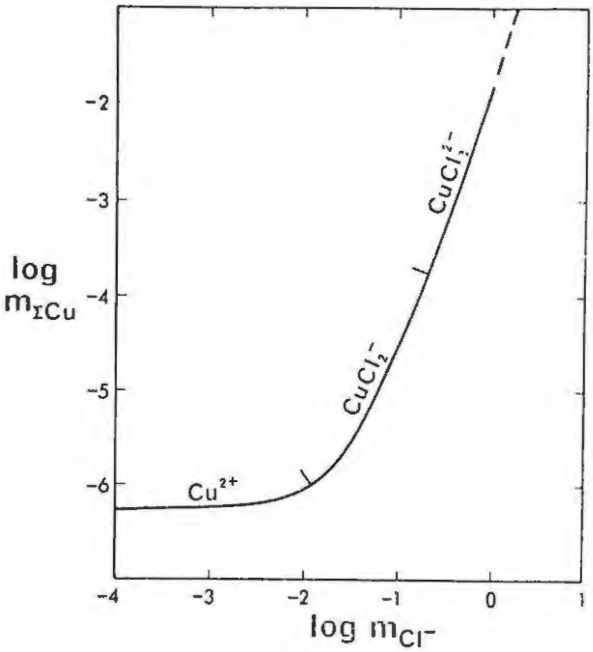


Fig. 2.3.- Maximum solubility of Cu at pH 7 as a function of chloride content in system Cu-O-H-Cl (from Rose, 1976)

In discussing the pH of possible ore solutions, Rose argues that waters of sufficiently high Eh to transport significant amounts of copper should also be in equilibrium with quartz, feldspars and calcite. He suggests that waters of a pH lower than about 8.1 would react at a geologically significant rate to convert feldspar to mica, and that calcite constrains the pH to "relatively alkaline values" unless "very high" carbon dioxide pressures are attained. As already mentioned, Barnes and Czamanske also feel that acid solutions cannot have been the transporting medium on the grounds that the chemistry of the mineralized environment is imcompatible with this. These arguments should be considered in the light of observations by Darnley (1960). He states that for quartzite orebodies on the Copperbelt the host rock is essentially quartz and sericite, while in the argillite bodies biotite is fresh and its presence merely reflects the iron content of the rock. If biotite formation took place after mineralization, as suggested by Darnley, there is no good reason why the silicate mineralogy in the vicinity of any orebody should reflect primary alteration effects due to the passage of an acid mineralizing fluid.

There is no evidence which demonstrates unequivocally the conditions of solution and transport of copper and other metals in natural systems. However, geological and experimental data indicate that substantial concentrations of transition metals may be dissolved and transported as complex ions in natural brines. Skinner et al. (1967) describe pipe scale deposits formed from geothermal brine discharging from a well drilled in the vicinity of the Salton Sea. These pipe scales were formed relatively rapidly without any matrix material and contain an average of 20% copper as sulphide and 6% native silver. Both the Salton Sea brines and those of the Red Sea Deeps contain comparatively low concentrations of copper. Skinner et al. quote 3 to 8 parts per million for Salton Sea brines, while Brewer and Spencer (1969) quote values an order of magnitude smaller for the brines of the Red Sea. Data for cobalt given by Brewer and Spencer suggest that the Red Sea brines also have the potential to transport this metal, but to a lesser extent than copper. The total heavy metal in both brines is, in terms of molality, several times the available dissolved sulphur. Cobalt values in both streams and marine waters are extremely low (Turekian, 1978), despite the solubility of the chloride, nitrate and sulphate of this metal. According to Turekian the role of sulphide-rich reducing environments may be significant in limiting the cobalt concentration in sea water. High cobalt values in streams due to industrial pollution diminish downstream and a significant decrease in cobalt content of normal streams occurs "prior to debouching into an estuary". Turekian states that the distribution of cobalt in sediments and sedimentary rocks most closely follows that of iron, and also suggest that cobalt behaves very similarly to iron during weathering processes.

Transport and fixation of metal

Variations in orebody morphology, metal distribution and mineralogy indicate that the migration and fixation of copper and cobalt did not take place in exactly the same way at all of the Copperbelt orebodies. Even at the scale of the width of an orebody or lesser distances it is likely that different fixation mechanisms operated to produce the heterogeneous grade distributions now commonly observed. Mineralization is present in a variety of host lithologies over a clearly defined stratigraphic range. Where mineralization is preferentially localised at certain stratigraphic levels in one orebody, there is frequently an obvious lithological relationship, but there are also cases where mineralization and host lithology are apparently unrelated. Laterally, on scales ranging from orebody dimensions to the length of the Copperbelt, there is not an obvious relationship between grade of mineralization and host lithology. The deposition of copper at particular sites must therefore have been controlled by the availability of metal in solution at these locations and by some combination of other factors not readily apparent from the nature of the host rocks. Cobalt, where it is present, tends to occur at the fringes of copper orebodies , which suggests that it was slightly more mobile than copper but fixed by very similar mechanisms.

Very large volumes of solution would have been required to transport the metal in the Copperbelt orebodies. White (1971) studied possible models for the formation of the White Pine deposit from cupriferous fluids migrating laterally and vertically in a sequence somewhat resembling that of the Copperbelt. He concluded that a solution containing 50ppm copper, suitably hydrologically constrained,was a feasible copper source. However, no strictly comparable work has been done for the Copperbelt. While the implied mechanism of solution generation in surrounding rocks is difficult to envisage for the Copperbelt, White's work does illustrate that porosity and permeability of compacting sediments would permit substantial post-depositional movement of intrastratal fluids. White's model suggests that hydraulic overpressure was the driving force for the fluid. Renfro (1974) proposed a sabkha model for the origin of stratiform metalliferous deposits, the driving force for fluid movement being provided by evaporation at the sabkha surface, permitting lateral migration of solution. The lack of an adequate metal source is the most obvious deficiency in this model.

The origin of ore-forming solutions is likely to remain speculative. Several possible mechanisms of metal fixation in sedimentary rocks, either contemporaneously with sedimentation or during diagenesis, have been proposed and are examined by Bartholomé (1974). He concludes that there are four possible mechanisms by which sulphide may be incorporated in a sediment.

1 Both metal and sulphur may be brought together by physical or chemical processes acting at the sediment-water interface.
2 Metal may be incorporated as the sediment accumulates while sulphur is subsequently incorporated from a solution by a chemical or biochemical process.

3 Sulphur may be incorporated in the sediment as it accumulates and metal subsequently introduced during diagenesis.

4 Both sulphur and metal may enter a sediment during diagenesis and be fixed as sulphide by some reaction taking place during lithification.

The first mechanism listed above is basically the process envisaged in syngenetic theories. Constraints on synsedimentary sulphide formation are discussed by Rickard (1973), who erects a steady-state model for production of metal sulphide at the sediment-water interface. This is shown in Figure 2.4

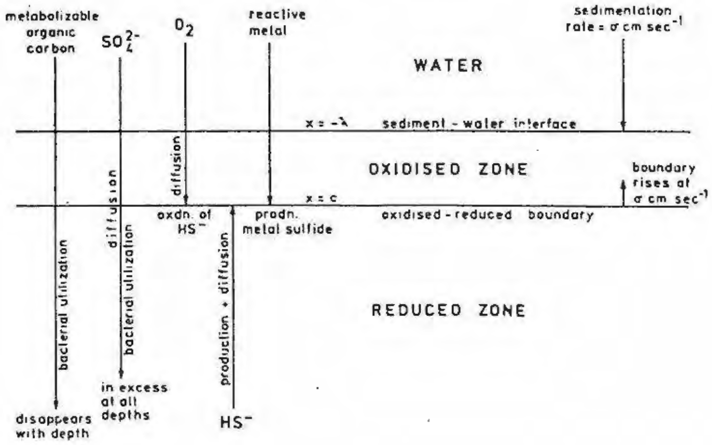


Fig.2.4 - Schematic representation of the model for sedimentary metal sulphide formation,where the oxidised-reduced boundary is within the sediment (from Rickard, 1973)

Rickard concludes that biogenic sulphide production in sediments is sufficient to produce ore-grade sulphide concentrations, but that at least 0.1% (dry weight) of organic carbon is required in the sediment to produce sulphide deposits containing more than 1% metal. Bacterial sulphate reduction is shown by Temple (1964) to be capable of contributing sulphur to both the first and second processes listed. Evidence for reaction of introduced metal with original sulphur is given by Annels (1974) who suggests that sulphur from anydrite was extensively consumed in the formation of sulphides in Copperbelt orebodies. Berner (1969 and 1970) discusses the formation of pyrite in sediments in considerable detail, and indicates that iron and sulphur in organic-rich sediments may migrate by diffusion to form iron sulphide layers. In his 1970 paper, Berner suggests that a series of reactions which take place in anaerobic sediments could liberate elemental sulphur which participates in a reaction that generates framboidal pyrite microspheres. Regardless of exactly how it is generated, pyrite in sediment could react with subsequently introduced cupriferous fluids to form the copper-iron sulphides now present in the ores. Bartholomé's fourth mechanism implies an Eh - pH control on sulphide formation from a fluid containing both metal and sulphur. All of these mechanisms may have operated in various Copperbelt orebodies. Probably different processes operated in different parts of individual orebodies, and examples of evidence for this will be referred to in the sections dealing with individual mines.

Contemporary supergene effects radically alter the character and mineralogy of the Copperbelt orebodies and cause metal migration and fixation in a manner evidently quite different from that which formed the ores. The behaviour of sulphur, iron and copper is such that supergene enrichment effects are rare, and considerable amounts of copper are incorporated into silicates.

3. THE GEOLOGY OF THE ZAMBIAN COPPERBELT

Tectonic and regional setting

The Copperbelt in Zambia is at the south-east end of an arc of folded sediments some 800 kilometres long, known as the Lufilian Arc. The sedimentary rocks of this arc constitute the Katanga sequence, of Upper Proterozoic age. Cahen and Snelling (1966) recognize a Katanga orogenic event beginning at about 1250 m.y. and continuing until 620 m.y. They date the Katanga sequence in Zambia at about 720 to 750 m.y. In a paper concerned with tectonic controls on Proterozoic stratiform copper mineralization in general, Raybould (1978) follows Cahen and Snelling in proposing that the Lufilian Arc continues into Namibia as the Damara (Damaride) Belt. The intervening connection is hidden beneath Kalahari sand cover. Figure 3.1. shows the position of the Lufilian Arc within Africa and its possible relationship to other major structural features.

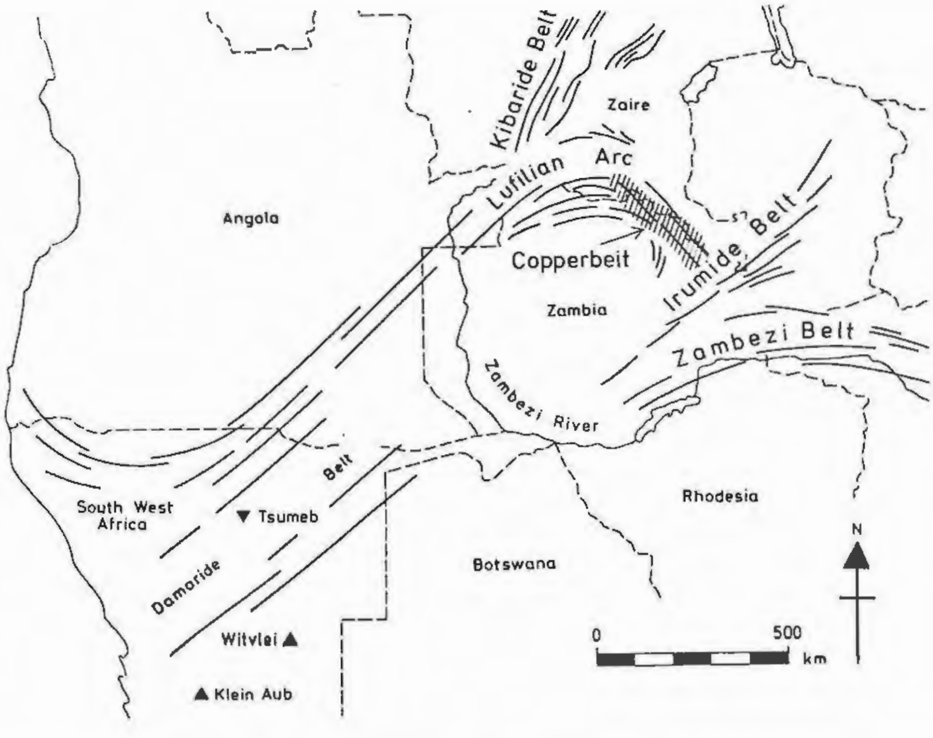


Fig. 3.1. - Location of Copperbelt and South West African deposits in relation to main tectonic lineations of central Africa (from Raybould, 1978).

Garlick, in Mendelsohn (1961), attributes the shape of the Lufilian Arc to movement between the Kibaran massif to the north-west and the Bangweulu Block to the east. Whether the shape of the Arc really reflects movement of this type is debatable, but there has undoubtedly been fairly intense deformation of the rock units which host the ore. Deformation diminishes rapidly away from the axis of the Arc. Figure 3.2 shows the extent and major features of the Lufilian Arc, including the exposures of the pre-Katanga basement.

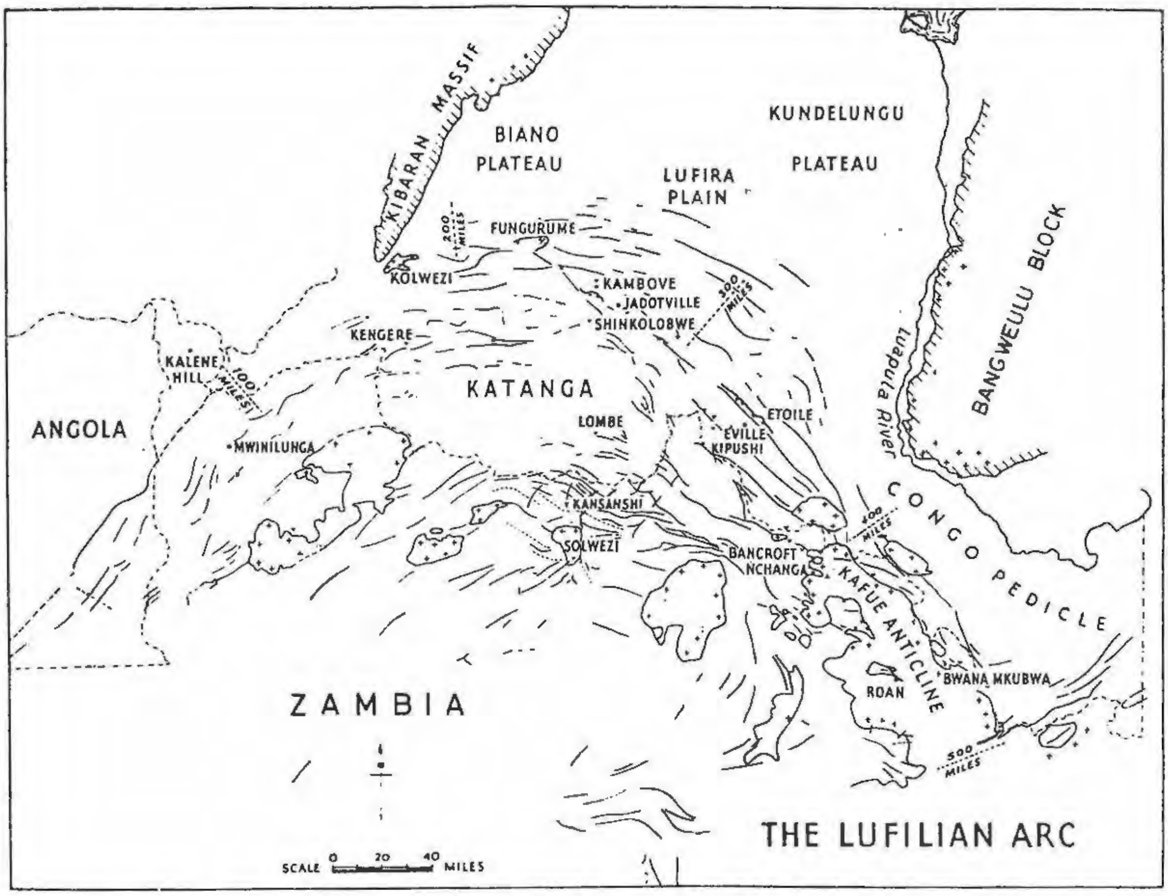


Fig. 3.2. - The Lufilian Arc. (from Mendelsohn, 1961)

Major fold directions are approximately parallel to the trend of the Arc along its entire exposed length, but with a pronounced difference in structural style between the folding in Zaire and that in Zambia. The basement is virtually unknown in Zaire, while in Zambia it forms the core of the Kafue anticline, the principal structural feature. Tight folding and overthrusting of the Katanga in Zaire described by Demesmaeker (in Mendelsohn,1961)contrasts with the generally less intense folding in Zambia. Several domes of basement occur west of the Kafue Anticline and south of the axis of the arc. Pretorius (1973) took a large-scale view of southern Africa and fitted the Lufilian Arc into a context of very major warps in the continental crust. He suggests that these major warps could have influenced Katanga sedimentation, and ascribes the structural trends of the Lufilian Arc to the interference of northwesterly-trending flexures with a set of southwesterly-trending warps parallel to the overall trend of the Katanga 'basin'. Figure 3.3 shows the limits assigned to the Katanga sequence by Pretorius. Brock (1963), in an earlier attempt to analyse the structure and sedimentation of the Katanga

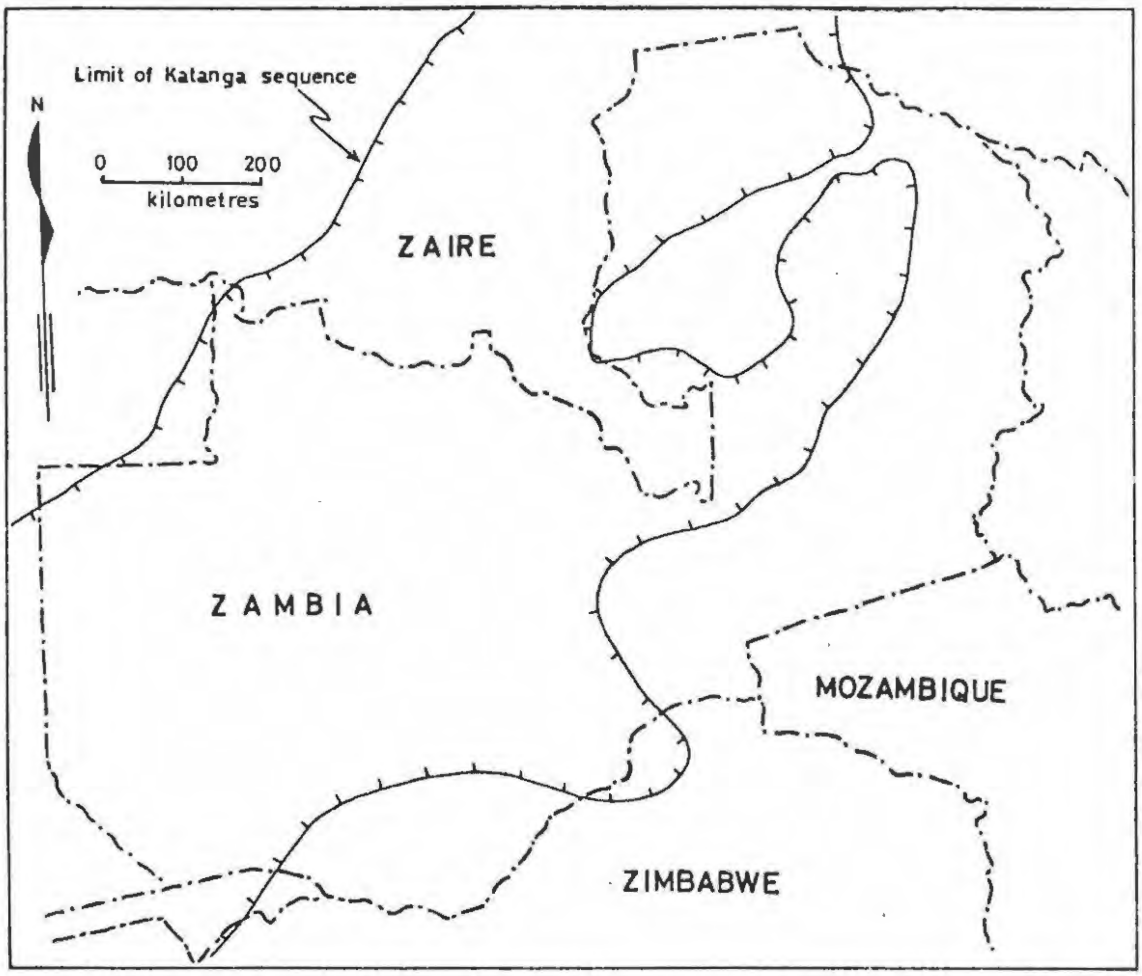


Fig. 3.3 - Extent of the Katanga sequence in Zambia and adjacent territories (after Pretorius, 1979)

basin, defined a number of structural sub-units containing the stratigraphic portion of the Katanga sequence which is mineralized on the Copperbelt. He suggests that a very limited number of structural units expose well-developed sequences which might contain mineralization, and develops a correlation first proposed by MacGregor (1951),who suggested that the Lomagundi sequence in Zimbabwe may be an attenuated correlative of the Katangan onthe Copperbelt. The Lomagundi sequence contains deposits of Copperbelt type but of smaller dimensions.

Raybould's proposal that the Copperbelt orebodies are developed along part of an ancient rift system gains circumstantial support from several lines of evidence. The mineralization so far located is conspicuously aligned along rather straight and narrow zones though there is no conclusive evidence relating to rift patterns. The recent discovery of metalliferous brines associated with contemporary rifting may, however, be signifcant, and Turekian and Imbrie (1966) have shown a striking concentration of cobalt in ocean-bottom sediments close to the Mid-Atlantic Ridge. Degens and Kulbicki (1973) examine the possible hydrothermal origin of metals in sediments in the present-day East African rift system, and show that very substantial amounts of metals are incorporated into the sediments deposited in Lake Kivu over the last 5000 years. They also note the development of relatively thick wedges of sediment in the lakes of the East African rift system, with metal content fluctuations which can be ascribed to hydrothermal activity. Volcanic events occurring during periods of high rainfall are thought by Degens and Kulbicki to be responsible for generating brines enriched in heavy metals by 100 to 10,000 times relative to mean ocean water concentrations.

General stratigraphy

The mineralization exploited on the Copperbelt occurs near the base of the Katanga sequence (accorded the status of a system by Mendelsohn, 1961), which is divided into three major stratigraphic units. These are referred to as the Roan, Mwashia and Kundelungu groups, in ascending stratigraphic order, and the lithologies comprising these groups are described in a later section. In addition to the sedimentary units of which most of the Katanga sequence is composed, gabbroic bodies of an apparently intrusive nature occur in parts of the sequence, and Darnley (1960) recognized a lava within the sequence in the Ndola area. The Katanga sediments rest on an older Proterozoic basement.

The Basement Complex

The basement on which the Katanga rocks were deposited in the Copperbelt area consists of three distinct units, a granite suite and two metasedimentary units referred to as Lufubu and Muva. The Lufubu rocks, assigned the status of a system by Mendelsohn (1961) are the oldest rocks of the Copperbelt, and consist predominantly of schists, quartzites and gneiss with minor carbonate, conglomerate and greywacke. According to Mendelsohn, micaceous schists and gneisses predominate. Granites which extensively intrude the Lufubu system are considered by some authors including Pienaar (in Mendelsohn, 1961) to be part of it. These granites do not cut the younger Muva rocks. Mendelsohn describes several types of granitic rock and discusses their possible origin. His description of gradual change from Lufubu schist through gneiss to granite suggests that at least some of what has been mapped as Lufubu may in fact be schistose rock derived from granite by intense deformation. Whyte and Green (1971) describe schists derived by squeezing of basement rocks in the crests of anticlines at Chibuluma, and similar rocks have been observed at Nkana and other localities on the Copperbelt. The granitic rocks range in composition from alkali biotite granite to tonalite. Rocks assigned to the Muva system by Garlick (in Mendelsohn, 1961) are the youngest component of the basement complex and consist of quartzites and schists resting unconformably on the older basement rocks. The Muva quartzite is massive and forms conspicuous outcrops, but the detailed stratigraphy of the rest of the Muva is not well-known. Garlick assigns several thousand feet of argillaceous, arenaceous and rudaceous sediments to the Muva. Structural and lithological relationships within the basement complex are generally poorly understood except where mine development has exposed the basement rocks and in a few isolated areas which have been investigated for mineralization. Figure 3.4 shows the distributuion of rock units in the basement according to Pienaar (in Mendelsohn, 1961) together with locations of mineralization located within the basement complex. Pienaar describes several minor occurences of

Fig. 3.4. - The distribution of Basement rocks and mineral occurrences. (from Mendelsohn, 1961)

copper sulphides and other mineralization in a variety of basement rocks and Wakefield (1978) gives an account of mineralization in basement schists of a type which he suggests may provide clues to the location of mineralization in the Katanga sequence. However, most basement mineralization is not obviously related to the occurrence of copper-cobalt mineralization in the overlying Katangan rocks, and none of the isolated mineralization within the basement has ever been considered to be ore. Voet and Freeman (1972) suggest that certain orebodies in the Chingola area are the result of weathering of basement mineralization, but fail to explain whether mineralization has been concentrated or dispersed and precisely what mechanisms might have operated.

It is evident that prior to deposition of the Katanga sequence, the basement surface was highly irregular. At most of the mines considerable relief in the basement surface prior to the start of Katanga sedimentation can be deduced. The thickness of basal Roan sediment (a coarse clastic facies) ranges from virtually nothing to hundreds of metres. A chaotic accumulation of angular to rounded blocks is frequently present on the basement surface, and suggests the presence of steep slopes with scree deposits during early Katanga times. At several localities, the thickest development of this basal unit is located at or near the deepest portions of depressions in the basement surface.

Prior to deposition of the lithologies hosting most of the mineralization, the basement surface was sustantially levelled by a combination of deposition in valleys and erosion of hills. Nevertheless, the gross relationships in the ore host and overlying rock units indicate that the original basement topography exerted a controlling influence on the development of ore depositories. Basement configuration probably continued to influence the behaviour of the rock units during deformation and metamorphism and this relationship is examined further in the sections describing individual deposits.

The Katanga sequence

Terminology for stratigraphic units within the Katanga system is not very consistently applied in literature relating to these rocks, so for consistency in this text the usage adopted by Mendelsohn (1961) is followed. He refers to system,series, group and formation in diminishing order of magnitude, but without assigning a formal status to any of these stratigraphic subdivisions. The term "Ore formation" is commonely used to designate the unit which hosts the main mineralization at a particular property, but has no specific lithological connotation and does not imply that exact stratigraphic correlation is possible between different mines. In contrast, the term "ore shale" which also appears frequently in descriptions of Copperbelt mineralization, refers to a specific range of mineralized lithologies present at a comparable stratigraphic level at all the properties where it occurs. The Roan and Mwashia groups together are often considered to constitute the "Mine series". The rocks of the Katanga sequence rest unconformably on the highly irregular surface of the basement complex. The present general relationship of the Katanga sediments to the basement is shown in the map reproduced as Figure 3.5. Three major sub-units recognized within the Katanga sequence are shown in the explanation of figure 3.5, where they are all termed "groups". The Roan group at the base of the Katanga is much better known than the overlying groups because nearly all mine development is within it. The relationship of mineralization to the lithologies present in the Roan group is examined in the next section.

According to Mendelsohn (1961) the overlying Mwashia group is dominantly argillaceous but in places dolomitic near the base and top. The Mwashia is predominantly a carboneous shale unit, particularly west of the Kafue Anticline, and it can contain considerable amount of pyrite. At its base a conglomerate containing fragments of the underlying Katanga rocks is present in places. The total thickness of the Mwashia is given by Mendelsohn as 150m to 600m.

The base of the Kundelungu group is marked by a widespread pebbly unit which is generally interpreted as a tillite and may be 30 m to 150m thick. The persistent Kakontwe formation, up to 1000m thick, overlies the tillite and consists of thick limestone or dolomite beds, and shales, while the remainder of the Kundelungu consists of shales, quartzites, minor limestones and conglomerates, in which detailed stratigraphic relationships are poorly known.

Structure

The principal structural feature of the Copperbelt is folding along two major axial trends. Folding about a set of axes parallel to the axis of the Kafue Anticline has generated anticlines and synclines plunging northwestward. The synclinal structures are preserved in basins apparently resulting from more gentle warping about axes trending NNE-SSW. The only major fault which is known cuts the south end of the Kirila Bomwe South orebody, and appears to continue eastwards to a point north of Mufulira. Major faulting

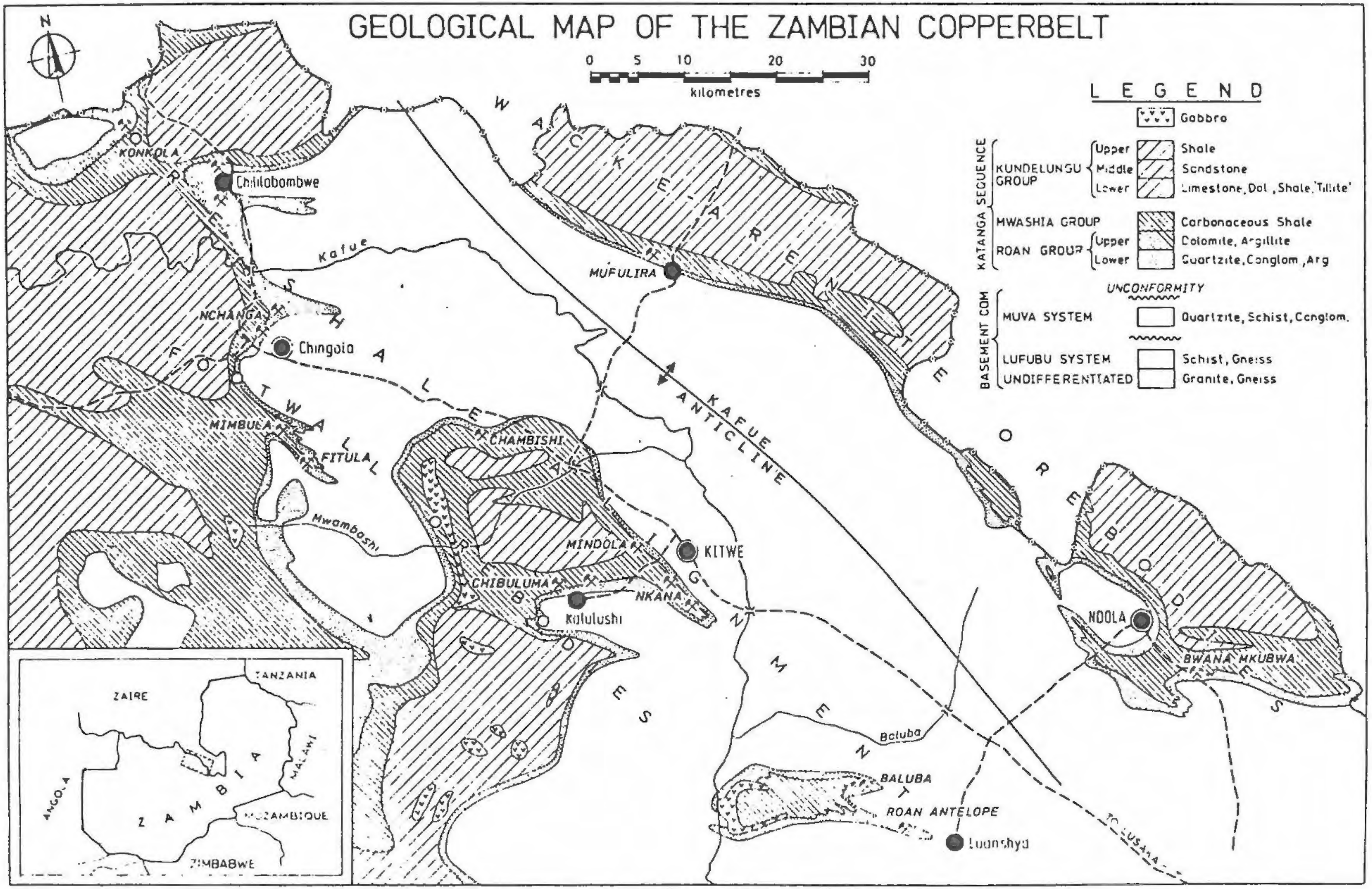


Fig. 3.5 (from Diederix, 1977)

is otherwise notably absent, but faults and shears with small displacements are known in several of the orebodies.

The behaviour of the basement in relation to the overlying Lower Roan sediments during deformation has been determined by competency and ductility differences between the rocks. At some localities basement granites have behaved as extremely competent masses, as for example in the vicinity of 16 shaft Luanshya. In such instances, shearing and deformation has taken place only within the sediments overlying the basement, often preferentially in particular incompetent beds. Elsewhere, for example at Chibuluma West, Chambishi and Chingola, granitic basement is deformed sometimes to an extreme extent with deformation being indicated by intense shearing of the granite. Style of deformation within the Lower Roan is very often completely different from that found in both the basement and the Upper Roan, indicating a strongly disharmonic relationship between folding in the Lower Roan and that in the enclosing rocks. According to Garlick (in Mendelsohn,1961), this is true throughout the Copperbelt. Within the Lower Roan, the ductility contrast between adjacent units causes folds of different styles to develop in close proximity to each other. Examples of this are given in the sections dealing with individual deposits. Dragfolding of the more ductile units is common, even at places where the major folds are of an open style.

Mineral assemblages generated during deformation and metamorphism on the Copperbelt are indicative of greenschist facies metamorphism. Thus the deformation effects seen in the rocks of the Copperbelt are due to dynamic greenschist facies metamorphism. The less competent members of the Lower Roan sequence have deformed by planar shear, with resultant development of cleavage. Fairly extensive remobilization of ore minerals into cleavages is evident in some of the deposits and in some cases considerable redistribution or metal between different parts of orebodies appears to have resulted. Hence the grade distribution within an orebody may not be the same now as at the time of initial fixation of metal in the host rock.

Apart from evaluation problems engendered by metal redistribution, deformation has had two other important effects which complicate the assessment of mineralization for mining purposes.

- The geometry of orebodies or parts of them may be complex and irregular, leading to difficulty in positioning and outlining ore.
- Bad ground conditions may result from shearing and fracturing of the

rocks immediately surrounding ore.

Precise elucidation of the style and shape of folded orebodies is essential when attempting to derive accurate tonnage estimates, and the use of bedding-cleavage relationships in drill core may be very valuable in determining the geometry of drilled structures. Axial plane cleavage will in general bear a constant relationship to fold axes (de Sitter, 1956) and can therefore be used to determine the dip direction of any drilled structure (Laing, 1977). In fold noses, or elsewhere in rock units with appropriate mechanical properties bad ground conditions may result from fracturing, leading to the situation where potential ore cannot be recovered with an acceptable level of dilution.

4. MINERALIZATION IN THE ROAN GROUP

Stratigraphy and sedimentology

The Roan group consists of two major lithological subdivisions of the Katanga sequence, and occurs at the base of the Katanga sequence as shown in the stratigraphic column in figure 3.5. Because it is host to the major mineralization on the Copperbelt, the Roan Group has been investigated more thoroughly than either the overlying sediments or the basement on which it was deposited. The Lower Roan consists of rudaceous and arenaceous basal sediments of undoubted local provenance, overlain by a sequence of arenaceous and argillaceous sediments which differ considerably in composition from much of the basement. The overlying Upper Roan is a dominantly calcareous sequence thought to have been deposited under relatively deep-water marine conditions. At different localities the base of the Upper Roan is established according to local criteria which do not always appear entirely consistent with each other. All the known orebodies occur in the Lower Roan as locally defined. According to Mendelsohn (1961) the thickness of the Lower Roan ranges from nothing to about 1000 m. The individual units of the Lower Roan group are often of rather consistent thickness within each mine area, and several attempts have been made to correlate the stratigraphy of the Lower Roan between the Copperbelt mines.

Many of the names applied to the various sedimentary lithologies present in the Lower Roan group are not petrologically correct, but were employed as field terms in the earliest stages of development and have been retained for consistency of terminology at each property. Where facies differences occur within a mining area the same term has often been used for lithologically distinct rocks either because of rapid lateral facies variations or because a particular unit occurs at a recognizable stratigraphic position. Similar inconsistencies in terminology have arisen between mines, so that many correlations of Lower Roan lithologies are based on similarities which are apparent from local terminology, rather than real and specific relationships. The principal terms in use and the possible compositional range of rocks so described are as follows :

"Conglomerate" - ranges from a basal accumulation of large angular blocks locally derived from the basement and set in a relatively coarse sandy matrix to a pebbly arkose or quartzite.

"Arkose" - normally a coarse feldspathic grit or quartzite but in extreme cases the term may include quartzites and fine-grained micaceous schists.

"Argillite" - can include virtually any dark fine-grained rock whether fissile or massive. May be carbonaceous.

"Quartzite" - normally refers to bedded or massive sandstone and may include rocks containing up to 50% feldspar. The term "feldspathic quartzite" is also used but rocks so termed need not be substantially different from "quartzites". "Argillaceous quartzites" generally contain enough biotite to have acquired a noticeably dark colour or dirty appearance.

Although the use of the terminology outlined above is often inconsistent between mines, certain conspicuous and real similarities in the successions at various widely separated points on the Copperbelt can nevertheless be indentified. The Upper and Lower Roan sequences, first identified at the Roan Antelope mine, were there designated RU and RL respectively, each major stratigraphic unit within the group being distinguished by a number. For comparative purposes this system has frequently been applied at other properties on the Copperbelt. Figures 4.1 and 5.2 show the use of these stratigraphic terms. In this account considerable use is inevitably made of established lithological names which are not necessarily accurate descriptive terms. As far as possible, in the sections describing individual deposits rock units are described according to their actual characteristics rather than by established names which are misleading. Binda and Mulgrew (1974) studied the stratigraphy of the Roan group in some detail and attempted correlations of stratigraphic relationships between the mines. They recognized distinct alignments of particular types of orebody (these are shown in figure 3.5) and saw the most consistent lithostratigraphic relationships as being along the ore shale alignment on the southwest side of the Kafue Anticline. Their correlation of the Lower Roan stratigraphy along this line is shown in figure 4.1. Binda and Mulgrew then generalized the stratigraphy along the one shale alignment, as shown in figure 4.2, and tried to correlate this stratigraphic column with that at Mufulira. It is quite evident that although there are some general similarities in the two columns shown in figure 4.2, individual units do not satisfactorily correspond.

Binda and Mulgrew accept that the depositories between basement hills are of

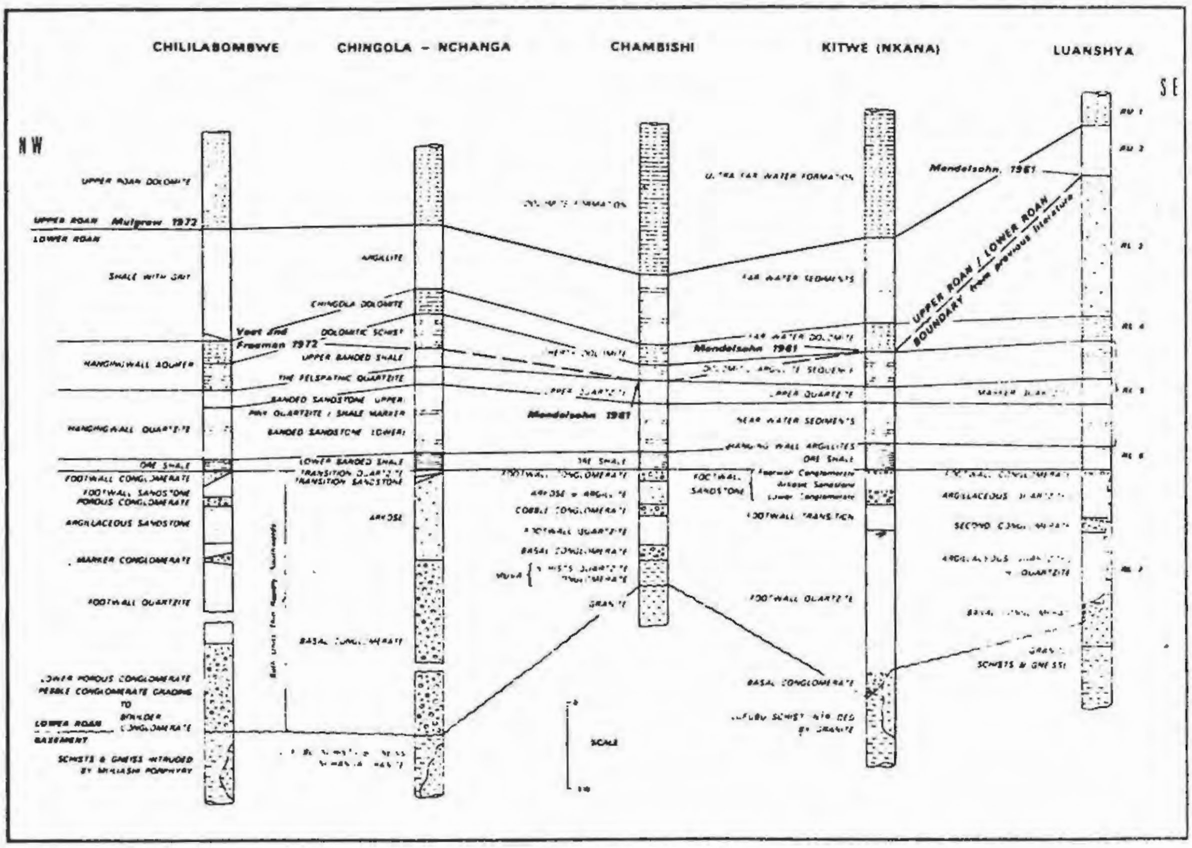
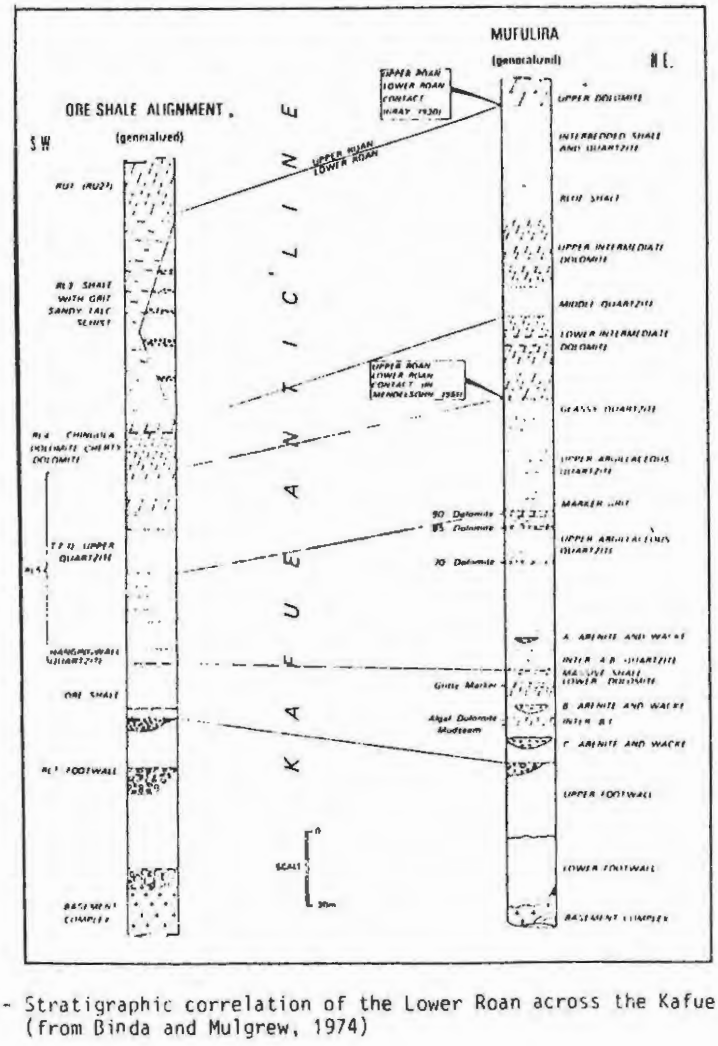


Fig. 4.1. - Stratigraphic correlation of the Lower Roan along the Ore Shale Alignment (from Binda and Mulgrew, 1974)



ig. 4.2. - Stratigraphic correlation of the Lower Roan across the Kafue Anticline (from Binda and Mulgrew, 1974)

such a restricted nature that correlation of individual units between basins is not possible. Good examples of this are known at Nchanga (Diederix, 1977) and at Mufulira (Brandt et al., in Mendelsohn, 1961). The coarse clastic sediments initially deposited on the basement surface are frequently referred to as the Footwall or RL7 formation. These sediments may either just fill the hollows in the basement surface or may cover the tops of basement hills to considerable depths, and many of the features of these sediments are apparently consistent with 'wet fan' deposition of the type discussed by Walker (1976 a and b). Sedimentation of this kind is necessarily of restricted provenance and affected by very localized events, so that there is no reason for any correlation to exist between sedimentary events on different fans. The Lower Roan sediments now occur in tectonically deformed basins and synclinal depressions marginal to the basement exposures of the Kafue Anticline. These basins and synclines probably reflect the existence of basement lows, up to a few tens of kilometres across, during Lower Roan sedimentation. Such depressions, shallow in relation to their lateral extent, at least following deposition of the Footwall formation, would themselves have constituted restricted depositories perhaps considerably different from each other. Thus because of their geographical proximity they would have been in a generally similar environment, but not subject to precisely identical sedimentation. In this sort of situation precise correlation of individual units between basins would not be expected to exist.

Lithostratigraphic relationships of mineralization

Although the Copperbelt orebodies are generally stratiform and locally confined to certain sedimentary units, they do not appear to be invariably stratabound on a large scale. Mineralization of economic grade and thickness is present at comparatively few localaties, but the Lower Roan contains numerous beds with distinctly anomalous concentrations of copper. Figure 4.3. shows the stratigraphic distribution of both major and minor copper occurrences in seven drill holes along the length of the Copperbelt, but does not include any mineralization in the Footwall formation.

Binda and Mulgrew recognize four different groups of orebodies distinguished on the basis of host lithologies. Figure 3.5. indicates the distribution of orebodies and shows the greatest number of deposits lying along a rather straight line from Konkola to Roan Antelope, which is their "ore shale alignment". Southwest of this line lies a parallel set of footwall orebodies, while on the northwest side of the Kafue Anticline the wacke-arenite orebodies are found. A fourth group of hangingwall orebodies is also

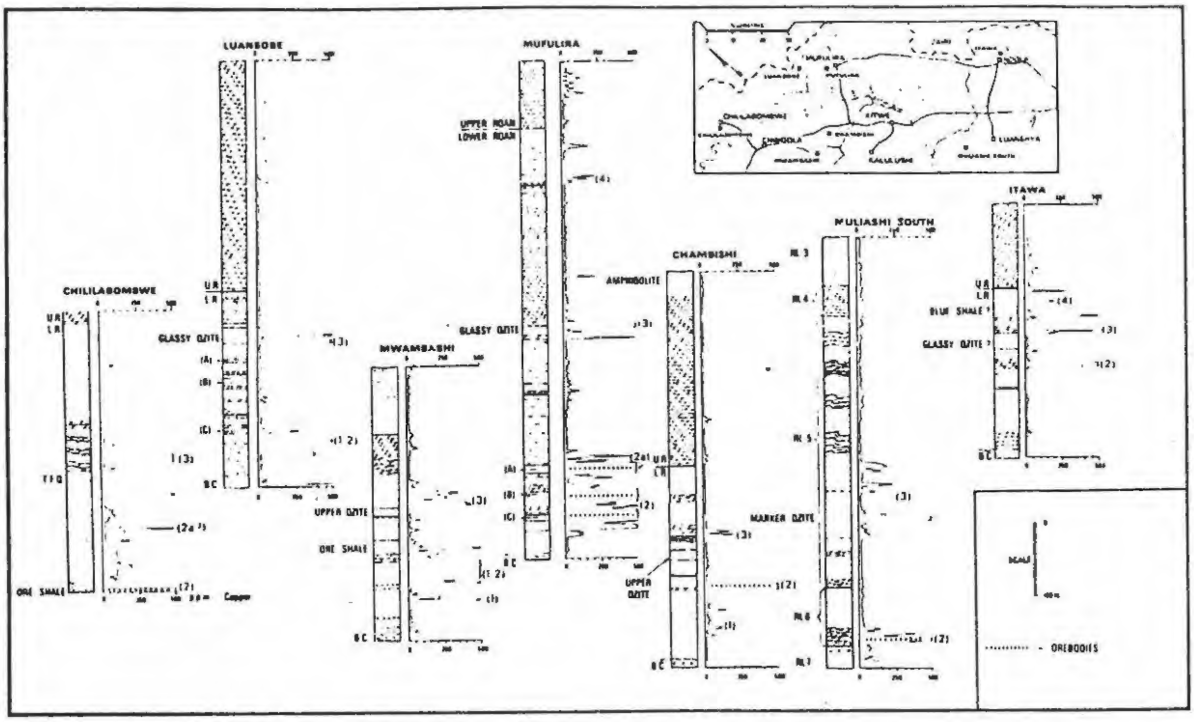


Fig. 4.3. - Stratigraphic distribution of major and minor copper occurrences in seven drillholes from the Zambian Copperbelt (from Binda and Mulgrew, 1974)

suggested by Binda and Mulgrew into which the Upper orebody at Nchanga is categorized. The principal features of their major orebody categories are described below.

<u>Ore shale orebodies</u> are often conspicuously stratabound,mineralization being confined to specific parts of the total thickness of ore shale. There may not be obvious lithological differences between mineralized and unmineralized ore shale. Mineralization may step from one level to another within the ore shale, as at Luanshya where two superimposed bodies occur over part of the mineralized area. These orebodies have notable lateral consistency and tend to fringe out rather gradually. Associated mineralization in the arenaceous footwall rocks is comparatively common but inconsistently developed. Cobalt mineralization, where present, generally corresponds approximately in extent with copper mineralization,but the distribution of grade may differ.

<u>Footwall orebodies</u> are stratiform but of irregular thickness, less regularly mineralized that ore shale bodies, and frequently not stratabound. Where they occur the ore shale is not necessarily present. They show a tendency to be confined against basement hills and at such fringes are frequently thickened considerably. Mineralization may extend through the basal Lower Roan and a short distance (of the order of centimetres to a few metres)

into the basement. Fringes which are not marked by lithological differences may be irregular and rather abrupt. An orebody may split or contain barren patches. Cobaltiferous mineralization shows similar irregular behaviour but where it is present tends to mantle the copper orebody.

Wacke-arenite orebodies are recognised in the literature only on the north-east side of the Kafue Anticline, but the mineralized lithologies at Nchanga shown some affinities with this class of orebodies rather than the ore shale. Mineralization is mostly stratabound but may be found in beds between the major ore horizons. Ore occurs at more than one stratigraphic level and is not developed to the same lateral extent in each horizon. Fringes are frequently abrupt. The mineralized lithologies are mainly arenaceous, but no obvious lithological factor controls the distribution of mineralization and considerable variations in thickness of mineralization over short distances are known.

The fact that Binda and Mulgrew found it necessary to erect a fourth class into which to categorize one orebody is indicative of the artificiality of their classification. Although there are general similarities of type between a number of the orebodies, removal of the confusion caused by use of inaccurate terminology tends to reveal many associations which do not readily fit into the classification above. As has already been indicated, the reasons for the lithological associations of mineralization at different places are far from clear. Examination of the deposits does show that the lithological associations of mineralization are not uniform or consistent either within or between deposits.

Ore Mineralogy

More than thirty minerals containing copper or cobalt have been detected in Copperbelt ores. Of these, relatively few are major constituents of the ores. Nearly all of the metal produced is therefore derived from a small number of species constituting the majority of the mineralization. In addition to copper and cobalt minerals, small amounts of galena, sphalerite, molybdenite and uranium minerals have been identified at various mines (Notebaart and Vink, 1972), but only the uranium has ever been exploited. Pyrite is common in several orebodies, and pyrrhotite is a minor component of the Nkana ore. Table 1 shows the compositions and specific gravities of the important ore minerals found in Copperbelt ores.

Notebaart and Vink discuss the occurrence and relative abundance of the major ore minerals present in Copperbelt ores. Apart from malachite, only sulphide minerals contribute more than 5% of the metal recovered from any of the

MINERAL	FORMULA	SPECIFIC GRAVITY	% OF COPPER AND/ OR COBALT THAT IS ACID SOLUBLE	THEORETICAL ASSAY PERCENT				
				Cu	Co	Fe	S	H_2O
NATIVE COPPER	Cu	8·94	Nil	100·00				
CHALCOCITE	Cu_2S	5·77	1 · 5	79·85			20·15	
DIGENITE	Cu_9S_5	5·63	2	78·10			21·90	
COVELLITE	CuS	4·67	Unknown	66·46			33·54	
BORNITE	Cu_5FeS_4	5·07	2	63·31		11·13	25·56	
CHALCOPYRITE	$CuFeS_2$	4·28	Nil	34·62		40·43	34·95	
CARROLLITE	$CuCo_2S_4$	4·83	..	20·52	38·06		41·42	
LINNAEITE	Co_3S_4	4·85	..		57·96		42·04	
CATTIERITE	CoS_2	4·80	..		47·89		52·11	
CUPRITE	Cu_2O	6·15	50 - 70	88·82				
TENORITE	CuO	6·45	Unknown	79·89				
HETEROGENITE	CoO(OH)	3·44	..		64·10			9·80
MALACHITE	$Cu_2(OH)_2(CO_3)$	4·00	100	57·47				8·15
AZURITE	$Cu_3(OH)_2(CO_3)2$	3·84	..	55·31				5·23
PSEUDOMALACHITE	$Cu_5(PO_4)_2(OH)_4, H_2O$	4·36	..	53·51				9·10
LIBETHENITE	$Cu_2(PO_4)(OH)$	3·93	..	53·16				3·77
CORNETITE	$Cu_3(PO_4)(OH)_3$	4·10	..	56·63				8·03
META-TORBERNITE	$Cu(UO_2)_2(PO_4)_2 8H_2O$	3·76	..	6·78				15·37
CHALCANTHITE	$CuSO_4\ 5H_2O$	2·28	..	25·45			12·84	36·08
BIEBERITE	$CoSO_4 \cdot 7H_2O$	1·83	Unknown		20·97		11·41	44·86
BROCHANTITE	$Cu_4(SO_4)(OH)_6$	4·09	100	56·20			7·09	11·95
ANTLERITE	$Cu_3(SO_4)(OH)_4$	3·93	Unknown	53·74			9·04	10·16
CHRYSOCOLLA (2)	$CuSiO_3 \cdot nHO_2$	2-2·4	100	2·36				
DIOPTASE	$CuSiO_3 \cdot H_2O$	3·35	61·5	40·30				11·43
PLANCHEITE (3)	$3CuSiO_3 \cdot H_2O$	3·30	100	43·63				4·12
SHATTUCKITE	$2CuSiO_3 \cdot H_2O$	3·80	..	42·75				6·06
BISBEEITE	$CuSiO_3 \cdot H_2O$	-	..	40·30				11·43
VERMICULITE (4)	Hydrated Mg, Fe, Al, Silicate	2·70	Variable 18 - 60	0-12				
WAO	Variable Fe, Mn, Cu, Co	2·8-4·4	90 - 100	Trace to 16	Trace to 14			
PYRITE	FeS_2(Co=trace to 8%)	5·01	Nil		Trace to 8	46·55	53·45	
PYRRHOTITE	Fe_7S_8 - FeS	4·69	..			60-64	36-40	
URANINITE	UO_2	6·5-10·0	..					

Table 1 Compositions and specific gravities of Copperbelt ore minerals (after Diederix, 1977)

Copperbelt bodies. Chalcopyrite, bornite and chalcocite are the most important copper sulphides, while carrolite, linnaeite and cobatiferous pyrite contribute virtually all of the cobalt.

Chalcopyrite is the main source of copper in most of the orebodies, and occurs mainly as disseminated grains, the size of which tends to be related to the grain size of the host rock. Where sulphides have been considerably remobilized, veins and irregular masses of chalcopyrite may occur. According to Notebaart and Vink, complex growth twinning which is evident in chalcopyrite of some orebodies is an indication of "relatively high" temperature. They do not specify the time of attainment of high temperature, but if it is during metamorphism, twinning should accompany remobilization of chalcopyrite. In the Nkana South orebody chalcopyrite may occasionally contain exsolution lamellae of cubanite, while at Mindola, Luanshya and Baluba, chalcopyrite has been found as exsolution lamellae in bornite. Chalcopyrite frequently rims or replaces carrolite as thin veins.

Bornite is next in importance to chalcopyrite in Copperbelt ores, and occurs as disseminations and more massive aggregates. Bornite grains often have simple boundaries with chalcopyrite and chalcocite. The colour of bornite varies both macroscopically and in polished sections, in which Notebaart and Vink record a colour range from bright orange to dark pinkish brown. Variation in iron content from 8% to over 11% is also known, but no data appears to exist which correlates colour and iron content of bornite.

Chalcocite is the dominant copper sulphide only in certain orebodies or in some cases in parts of orebodies. It occurs both as disseminated particles and as reaction rims around the copper-iron sulphides. Potter (1976) demonstrated the existence of several phases in the copper-sulphur system, some of which have been known for a considerable period while others are comparatively recent discoveries. The existence of digenite and covellite in Copperbelt ores is definitely established.

Carrolite, according to Notebaart and Vink, is the major source of cobalt in all the cobaltiferous orebodies on the Copperbelt. This mineral occurs as disseminated grains, often associated with chalcopyrite or bornite, and is frequently replaced by chalcopyrite, digenite or bornite. Larger crystals (up to 5cm across) are known from certain localities. The proportions of copper and cobalt in carrolite are invariably close to the stoichiometric values of 20% and 38% respectively, but misidentification of cobalt minerals appears to be a common problem. Winfield (in Mendelsohn, 1961) identifies a cobaltiferous species at Chibuluma as linnaeite, but studies cited by Notebaart and Vink confirm that at Chibuluma the predominant cobalt mineral is carrolite. Richards (1965) describes carrolite from Nkana South orebody, containing between 1.9% and 20.2% copper, which Notebaart and Vink classify as Cu-linnaeite. Nickel may substitute to a small extent (less than one per cent) in carrolite,and at Nkana carrolite is occasionally found as exsolution lamellae in pyrrhotite, associated with cobalt-pentlandite.

Linnaeite has been identified as an intergrown phase in carrolite grains from Chibuluma (Hills, 1968) and at the Nkana South orebody.

Cobaltiferous pyrite appears to be isomorphous with cattierite,but work by Riley (1968) shows that the great majority of Copperbelt cobaltiferous pyrite contains less than 15% cobalt. Notebaart and Vink record a maximum of 8% cobalt in pyrite from Baluba and Nkana. Pyrite occurs mainly as disseminations, but individual crystals may be up to 3 centimetres across. Textural relationships indicate that pyrite is normally the first sulphide to crystallize, before chalcopyrite and pyrite. However, Notebaart and Vink suggest that cobaltiferous pyrite is usually a later phase than cobalt-poor pyrite.

Malachite is the only non-sulphide mineral which contributes substantially to copper production. It occurs principally at Nchanga but is a comparatively common component of ore in the oxidized zone throughout the Copperbelt. At Nchanga it occurs as blebs, disseminations and vein coatings, while in weathered ore it tends to occur as replacements of the minerals from which it is derived.

In addition to the major ore minerals, a variety of oxides, sulphates, phosphates and silicates containing copper are known to occur, and native copper is also found in joints and cavities in certain orebodies. All these minerals are listed in table 1. Certain non-silicate minerals occurring in the Copperbelt ores are important because they contribute undesirable impurities which may be incorporated into the final metallic products. Bismuthinite, Bi_2S_3, and tellurobismuthinite,Bi_2Te_3 , have been recorded from the Nkana and Mindola orebodies, where they occur as inclusions or replacements of copper-iron sulphides. Various tellurides occuring in very small quantities have also been recorded from some of the ores. Silver and gold are recovered from refinery slimes and therefore must be present in such a form that they are recovered via flotation and smelting. However, these metals are present in ore to such a small extent that they are not routinely determined and no published information on their mode of occurrence appears to exist.

The cupriferous mineral assemblages found in the surface zone of weathering differ markedly from those in fresh sulphide ore. Sulphides are generally absent in the weathered zone, which usually extends to a depth of around fifty metres. Oxides, sulphates, phosphates and silicates are all found in the weathered zone, and in some cases in ore at considerable depths.

Cuprite is common and can contain up to 75% of the total copper in the weathered zone of certain orebodies according to Notebaart and Vink. They state that it occurs as earthy masses intergrown with malachite and iron oxides, predominantly towards the base of the weathered zone.

Tenorite normally occurs as a fine-grained earthy material intimately intergrown with cuprite but very much subordinate to cuprite in amount. Tenorite is known as polysynthetically twinned grains encrusting malachite at Nchanga.

Pseudomalachite, libethenite and cornetite are all hydrated copper phosphates which occur to a small extent in the weathered zones of orebodies. Pseudomalachite is the most common, and cornetite is rather rare on the Copperbelt. These minerals tend to occur as coatings on fractures or void surfaces.

Chrysocolla is the only silicate other than the micas commonly found in Copperbelt ores. It is locally abundant, particularly at Nchanga where it occurs as solid masses up to 40 cm across. This mineral is not restricted to the weathered zone.

Cupriferous micas, generally termed vermiculite, are very often present in the weathered zone. Notebaart and Vink express the opinion that the cupriferous micas found on the Copperbelt constitute a mineralogically heterogeneous group including vermiculite, hydrobiotite and cupriferous chlorite. They appear to form very irregularly-shaped caps over weathered orebodies, with copper unevenly dispersed through the stratigraphic units enclosing the primary orebody.

Cupriferous wad occurs as earthy black masses and fissure fillings. It is also frequently intermingled with cupriferous mica. Wad may contain up to 14% cobalt according to Diederix (1977) and 20% copper (Notebaart and Vink). Manganese is also a major constituent of this material, which is amorphous and of very inconsistent composition. The distribution of wad in the weathered zone resembles that of cupriferous micas.

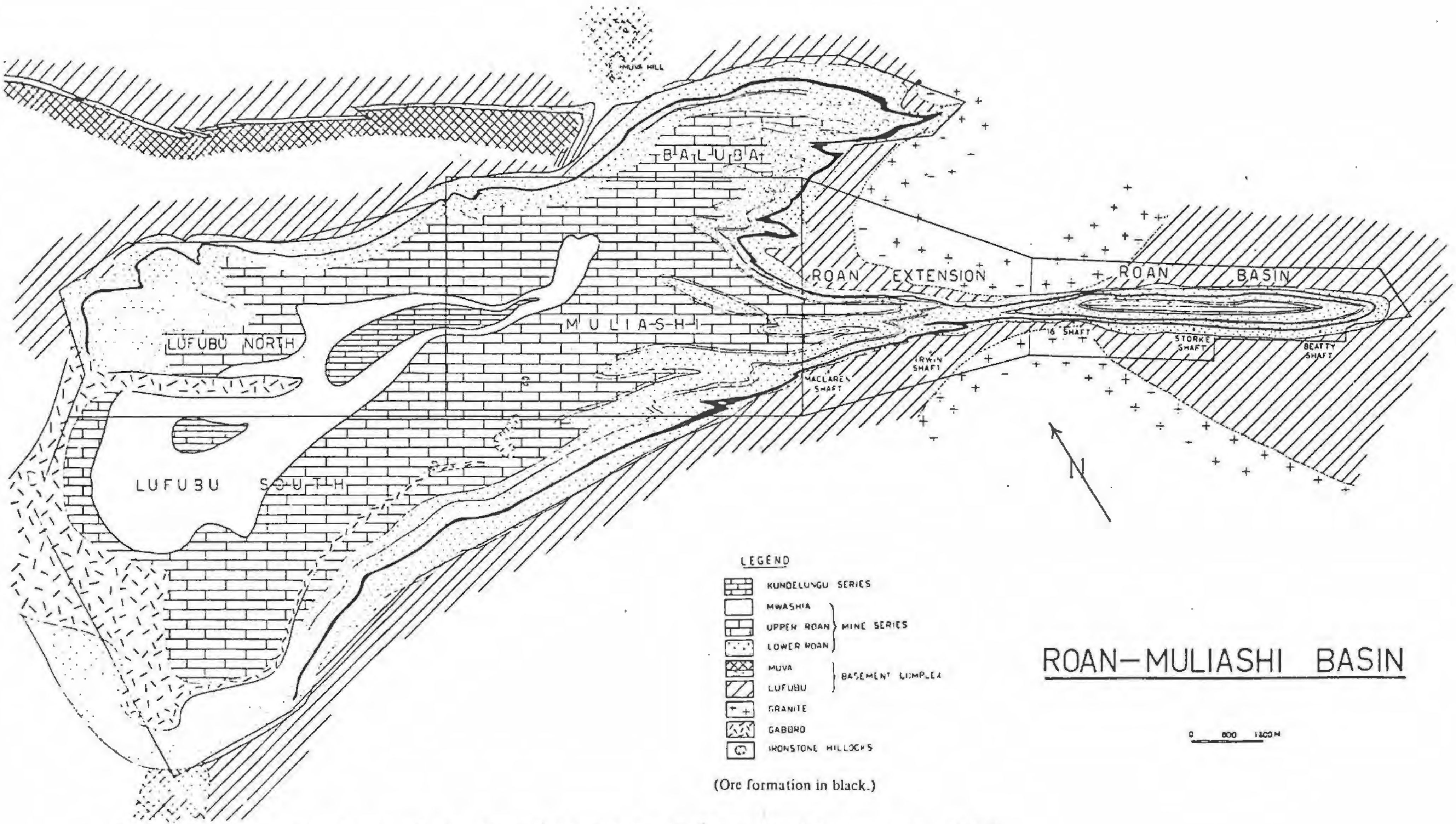
All the non-sulphide minerals found in the surface zone of weathering (and in some orebodies at considerable depths) are loosely referred to as "oxide" copper minerals.

5. THE ROAN - MULIASHI BASIN

Stratigraphy and structure

The Roan-Muliashi basin is an outlier of sediments of the Katanga sequence folded into a syclinorium with basement rocks which entirely surround the younger sediments. The present surface exposure of the basin is predominantly Lower and Upper Roan sediments, but Mwashia and Kundelungu sediments occur in the core of the synclinorium and extensive gabbro bodies are known at its western end. Figure 5.1 shows the extent and surface geology of the basin, which is approximately 20 km long. Within the Roan-Muliashi basin two separate mining operations are conducted, the older of which is the original Roan Antelope mine, now known simply as Luanshya mine. This extends over the three mining areas named Roan Basin, Roan Extension and Muliashi which are shown in figure 5.1. The separate Baluba mine lies within a mining area of the same name to the north of Roan Extension. It is likely that the basin represents a restricted depository, the depth and surface dimensions of which have been considerably altered during subsequent deformation. According to Davis (1954) the major control of subsidiary fold structures in the sediments was the heterogeneous physical nature of the basement rather than the thickness or lithology of the sedimentary units. Although there are local differences in the thickness of particular units within the basin, in general the stratigraphic sequence is fairly uniform. Figure 5.2 shows the principal lithological units. At both Luanshya and Baluba mineralization occurs mainly within the RL6, which is usually considered to constitute the Ore formation at these mines. This unit is present throughout the basin so far as is known but is not uniformly mineralized and shows some variation in lithology.

The structure of the western part of the basin at depth is not well known, but in the mining licence area many of the structures are fairly accurately defined. The wider western part of the synclinorium, approximately six kilometres wide, narrows southwestwards to a single synclinal structure only about one kilometre wide at surface. This relatively simple synclinal structure, the north limb of which is overturned in places, is shown in figure 5.3. In the vicinity of Irwin shaft the structure has been squeezed between two granite bodies giving rise to intense deformation of the sediments (Figure 5.4) Isoclinal folding in this area gives way westwards to more open folding in the wider part of the synclinorium. Most of the fold structures plunge northwest parallel to the axis of the basin. At both Muliashi and Baluba the geometry of the fold structures at depth is poorly known, but



(Ore formation in black.)

Fig. 5.1. - Geological map of the Roan-Muliashi Basin (from Mendelsohn, ed., 1961)

System	Series	Group	Formation	Thickness	Description
Katanga	Kundelungu			?	Tillite
	Mine	Mwashia		300 feet	Black to pink finely banded carbonaceous shale
		Upper Roan	RU1	1700 feet	Mottled dolomite and argillite
			RU2	130–170 feet	Argillite with dolomite and quartzite
		Lower Roan	RL3 Arkose	350–430 feet	Pebbly arkose, felspathic quartzite
			RL4Green shale	40–100 feet	Dolomite and shale
			RL5 Hanging-wall Quartzite	200–430 feet	Argillite, quartzite, dolomite
			RL6 Ore	55–175 feet	Argillite and impure dolomite
			RL7 Footwall Quartzite	0–800 feet	Quartzite, conglomerate, argillite
Muva	Basement Complex				Pure quartzite and mica schist.
Granite					Grey to pink granite.
Lufubu					Biotite quartz schists.

Fig. 5.2. - Stratigraphic column for the Roan-Muliashi Basin (from Mendelsohn, 1961)

near surface relatively open folding predominates. Faulting is virtually absent throughout the basin.

Deformation of the Roan-Muliashi basin has given rise to a variety of fold styles, ranging from the relatively open major anticlines and synclines to isoclinal folds. Figure 5.5 shows fold structures of the isoclinal type as continuous throughout all the stratigraphic units, but comparison with other properties where the succession from footwall to Upper Roan can be observed

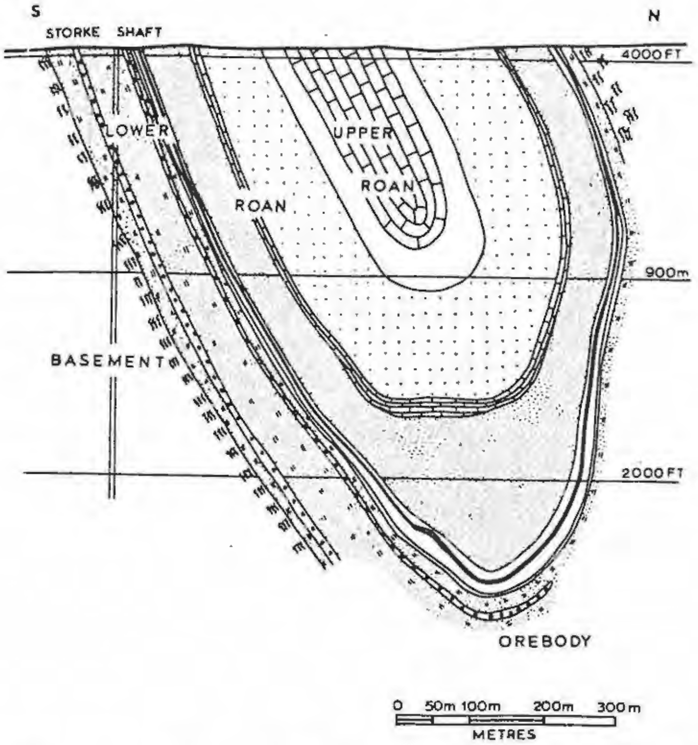


Fig. 5.3. Cross section looking west through Roan Basin (after Mendelsohn, 1961)

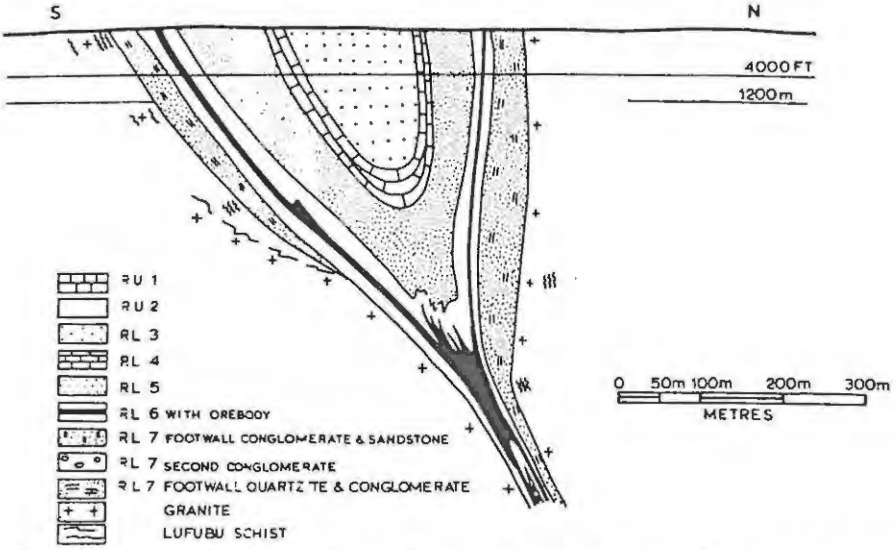


Fig. 5.4. Section through Roan Basin showing the "16 shaft fold", (after Mendelsohn, 1961)

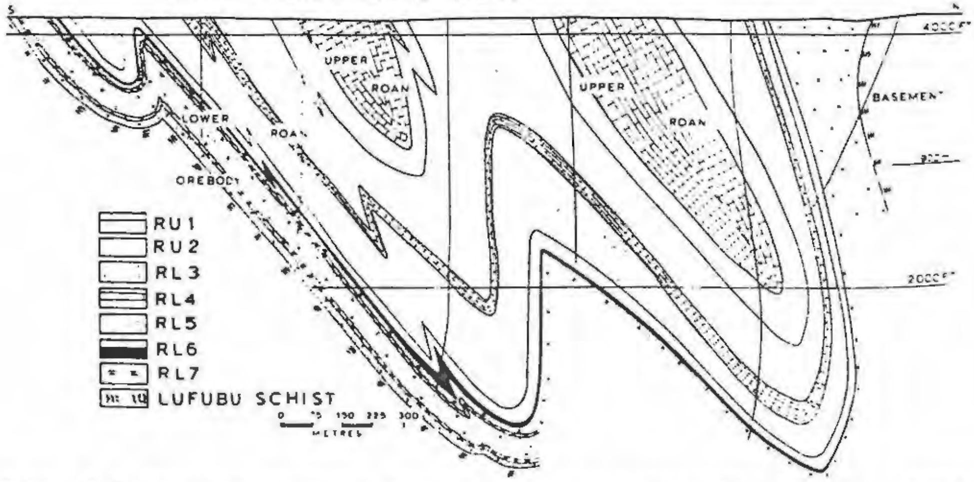


Fig. 5.5 Section through Roan Extension (after Mendelsohn, 1961)

suggests that pronounced disharmony in the folding is likely. Movement often appears to have been confined to particular beds, notably the footwall schist at the base of the ore, and dragfolding on all scales is common. That the basement topography was considerable prior to deposition of the Lower Roan is shown by the extreme variation in thickness of the RL7 basal arenaceous sediments. These are up to 300 m thick at Luanshya and 350 m or more at Baluba. Figure 5.6 shows the more open nature of the deformation at Baluba and gives some impression of the continuity and thickness of the RL7 sediments. At Luanshya, in contrast, the RL7 is in places completely absent and basement hills may protrude a short distance into the overlying RL6.

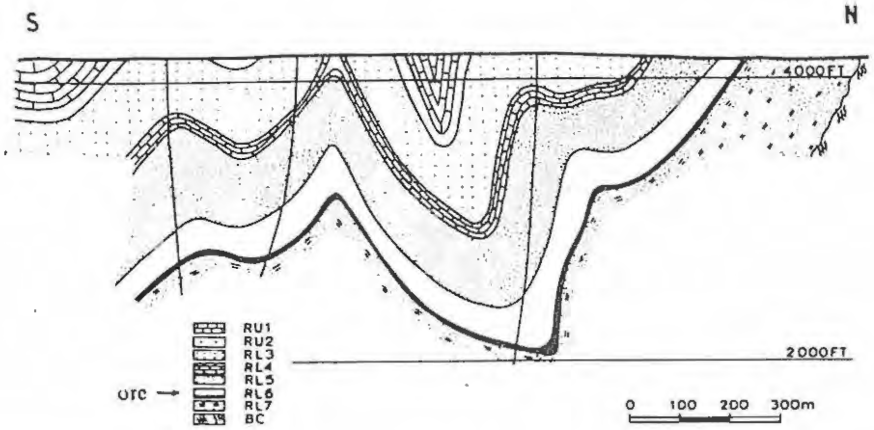


Fig. 5.6. Section through Baluba (after Mendelsohn, 1961)

Luanshya Mine

Two distinct orebodies have been recognized at Luanshya, each characterized by a specific stratigraphic position and somewhat different lithological associations. The Upper orebody extends from the eastern extremity of Roan Basin into Roan Extension where it overlaps and is replaced laterally by the less consistently developed Lower orebody. A separate orebody developed beyond the fringe of the main mineralization at Muliashi is known to be of Lower orebody type. Mineralization is contained largely within the RL6, but extends into the underlying grit or conglomerate unit at the top of the RL7. An impure dolomite bed is present at the base of the Ore formation throughout the length of the mine, and ranges in thickness from one metre at the eastern end to over twelve metres in Muliashi. Because of differences in composition or metamorphism this dolomite bed now ranges from a rather massive micaceous dolomite to a tremolite or tremolite-biotite schist. Overlying the dolomite horizon is the "ore shale", an argillaceous rock which is massive at the eastern end of the mine and becomes more schistose westwards, particularly where folding has been intense. Davis (1954) mentions the presence of a persistent conglomerate over a metre thick at the base of the mineralized beds, and describes the "ore shale" as being too hard and compact to merit this name. In Roan Extension a rather massive and pure dolomite, suggested by Mendelsohn to be a shallow water facies of the Ore formation, replaces an extensive area of argillite. This dolomite does not contain economic sulphide mineralization.

The Upper and Lower orebodies at Luanshya are generally regarded as being separate, and where they are both present the intervening pyrite zone contains little or no copper. It appears that the dolomite schist at the base of the RL6 is mineralized wherever it is present, although it is of low grade or not present at an economic thickness over a considerable portion of the mine. A diagrammatic longitudinal section through the south side of the Roan-Muliashi basin published in Mendelsohn (1962) shows the Upper and Lower orebodies coalescing at the eastern end of the mine and in the vicinity of Irwin shaft. On a very large scale the Upper orebody therefore does not seem to be stratabound, and is in fact partially continuous with the Lower orebody. A distinctly non-stratabound relationship of the orebody to the bedding of the host rock at the eastern end of the mine is described by both Davis (1954) and Mendelsohn (1961). Mendelsohn's longitudinal section indicates also that although the Lower orebody is largely confined to the RL6, in places mineralization extends into the underlying RL7. He shows chalcocite and carrolite mineralization in the RL7 at Muliashi, while work by Holmes (1978) has shown that the Lower orebody in Roan Extension is discontinuous and that significant amounts of copper mineralization occur in the RL7. Mineralization is also known to extend into the basement where the Lower orebody impinges directly onto basement hills. Mendelsohn mentions basement mineralization in Roan Extension but does not elaborate on its continuity or genesis except to say it is "best explained by precipitation of copper during the deposition of the Ore Formation".

The effect of the basement configuration on mineralization is somewhat obscured by deformation effects, but in Roan Extension the Lower orebody tends to correspond with the thickest development of RL7 sediments. However, this relationship is not consistent and ore-grade mineralization may extend over basement highs. At Muliashi the western fringe of mineralization is over a thick sequence of RL7 sediments and shows no obvious relationship to basement topography. Work by Binda (1969) at Muliashi and by Holmes (1978) at Roan Extension suggests that the Lower Orebody mineralization and particularly that in the RL7 is related to palaeochannels of fairly major streams. Basement topography has had no discernible effect on the distribution of the ore shale horizon or the mineralization in the

Upper orebody, and basement hills do not project sufficiently far into the RL6 to interrupt the continuity of the Upper orebody.

Mineralogical zonation both laterally and vertically is pronounced. Mendelsohn (1961) shows lateral zoning in a diagram reproduced as figure 5.7, but does not make a distinction between the Upper and Lower orebodies. Vertical zonation is described by Holmes (1978) for an area of Roan Extension where both Upper and Lower orebodies are present. He states that it is unusual for all zones to be present and well developed, but those present at any particular place invariably conform to the following sequence :

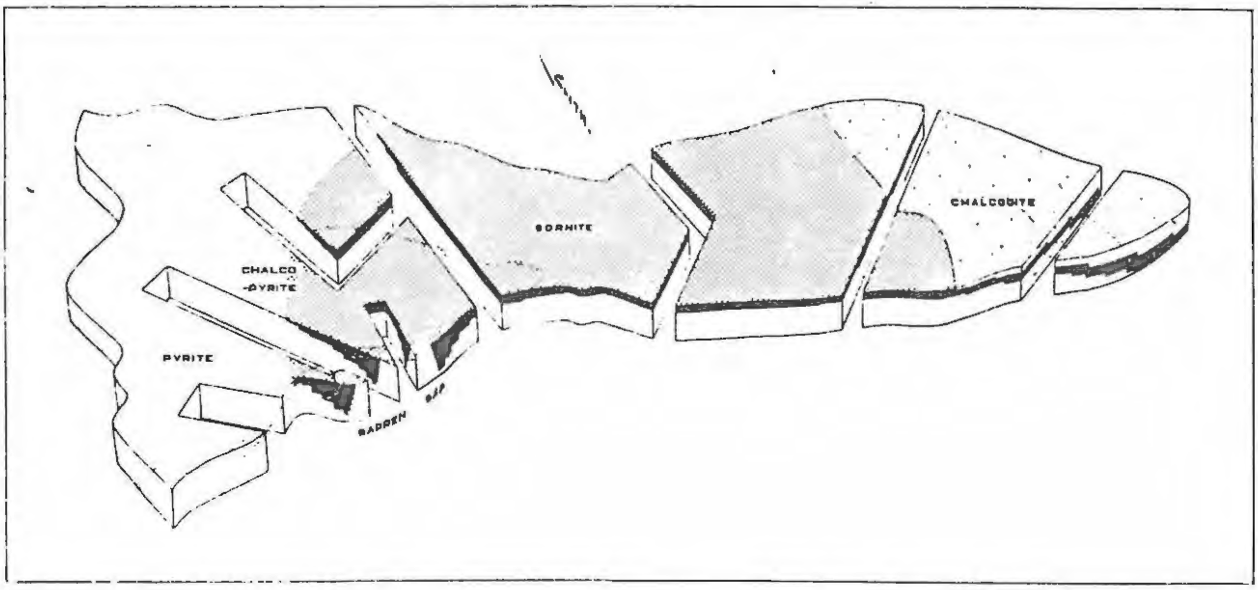


Fig. 5.7. - Sulphide mineral zoning of the Luanshya orebodies. The orebody is shown unrolled and restored as near as possible to its area before folding. Vertical scale much exaggerated. (from Mendelsohn, ed. 1961)

UPPER OREBODY	chalcocite (+ cuprite + native copper)	Argillite
	bornite + chalcocite + chalcopyrite	
	chalcopyrite	
	chalcopyrite + pyrite	
LOWER OREBODY	pyrite	
	pyrite + chalcopyrite	
	chalcopyrite + pyrite	Dolomite schist
	chalcopyrite	
	chalcopyrite + bornite	
	chalcocite	
"FOOTWALL MINERALIZATION"	chalcocite + chrysocolla + cuprite + native copper	Footwall conglomerate and argillaceous quartzite

The sulphides in the Lower orebody occur mainly as irregular blebs and segregations thought to suggest local remobilization, while those in the argillites are finely disseminated or occur as concentrations around calcite, anhydrite or selenite. Holmes describes the footwall mineralization as irregular in lateral distribution and stratigraphic extent.

Lateral variation of grade within the Ore formation is considerable, and reflects the mineralogical zonation to a marked degree. At the eastern end of the mine block grades of between 3 and 4 per cent copper are common. The initial (1929) estimate of grade was based on drilling at this end of the mine. Progressing westwards into Roan Extension, copper grades fall gradually to around 2 per cent to the west of Irwin shaft. Grades in the Lower orebody at the western end of Roan Extension and in Muliashi are somewhat higher, typically between 2.4% and 2.8% copper. At the western fringe of Muliashi and at depth there is a tendency for block grades to show a further slight increase to around 3.0% copper. Mineralization in the Lower orebody is significantly concentrated towards the footwall, and the assay footwall may correspond with the RL6/RL7 contact or may be up to about 4 m below this. Footwall mineralization frequently does not follow lithological boundaries and tends to be thicker in structurally more complex areas. Where footwall mineralization is slight or absent, the highest grades are invariably at the base of the dolomite schist. In Roan Extension the dolomite schist is usually four to five metres thick and overlain by around two metres of argillite containing Lower orebody mineralization. Grades are lower in the argillite than in the dolomite schist, and the hanging wall contact of lower orebody mineralization bears no apparent relationship to any change in lithology. Where two orebodies are present the pyrite zone is lithologically indistinguishable from the mineralized argillite except on the basis of its sulphide content. The upper part of the RL6, which is not mineralized, is a variable thickness of barren argillite, but coarser and less finely bedded than the mineralized argillite. Davis, presumably referring to the eastern orebody, states that the hangingwall contact of the ore is very abrupt, but grades diminish gradually at the footwall leading to the use of an arbitrary cut-off. In Roan Extension the hangingwall cut-off is not sharp. Grades diminish fairly abruptly to less than one percent copper, but tail off gradually into the barren argillite. Figure 5.8. shows the plan extent of the Lower and Upper orebodies at both Luanshya and Baluba. The eastern and southern fringes of the Upper orebody at Luanshya have been eroded, while the fringe at depth lies partially over the Lower orebody. Where it does not overlap the Lower orebody, the Upper orebody fringes by simple diminution of both thickness and grade of

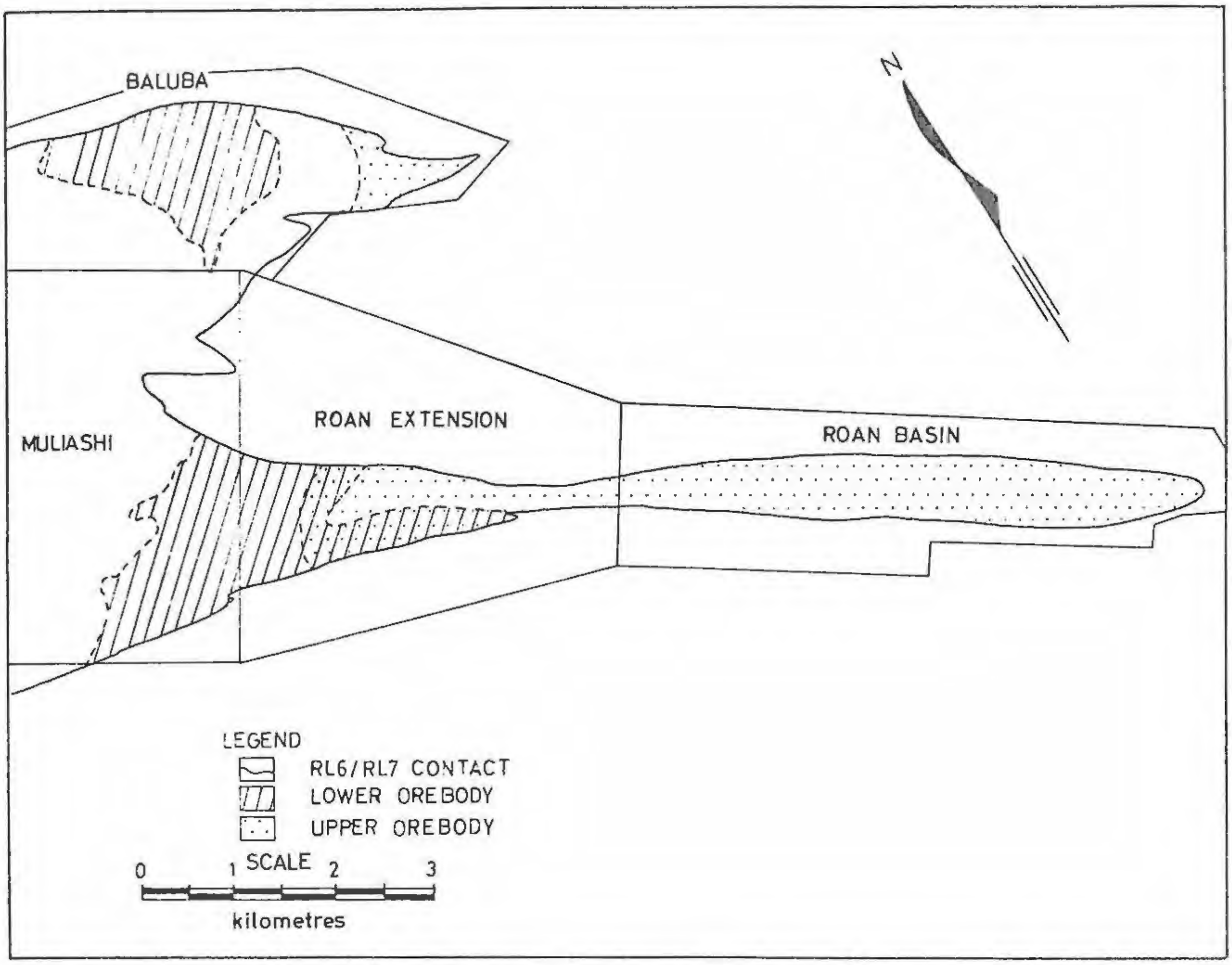


Fig. 5.8. - Extent of the Lower and Upper orebodies at Luanshya and Baluba

mineralization. The same type of fringe appears to occur where a significant pyrite zone separates the Lower and Upper orebodies, but in places the two orebodies tend to merge and are not separated by a significant pyrite zone. This is termed a total orebody. The precise nature of the fringe to the upper part of a total orebody is not clear, but it appears that mineralization may transgress bedding in a manner similar to that observed at the eastern end of the mine. The Lower orebody fringes are irregular in outline and marked by thinning of mineralization and slight diminution of grade.

The Upper orebody shows far less evidence of remobilization of mineralization during metamorphism than does the Lower orebody. Davis (1954), writing before the Lower orebody had been extensively exposed by underground development, was convinced that the sulphides in the ore shale recrystallized during metamorphism, and describes migration of sulphides into veinlets, stringers and cleavages in regions of high strain. He does not suggest wholesale migration of sulphides during metamorphism except in very localised areas. Even where veins are extensively developed, he suggests that the normal disseminated mineralization is unaffected. Localized remobilization of sulphides within the dolomite schist of the Lower orebody is thought by Holmes (1978) to explain the coarse, blebby nature of the sulphides in this horizon. The preservation of mineralogical zones across the width of the orebody suggests that relatively little movement of sulphide took place in a vertical (stratigraphic) sense.

Supergene effects at Luanshya penetrate to variable depths. According to Mendelsohn (1961) the average depth of weathering is between 60m and 90m but alteration extends locally to 240m on the north limb of the Roan Basin syncline. Possible the near vertical attitude of the beds here facilitated the downward migration of surface waters. The amount of leaching of copper from oxidized ore is extremely variable. Near the orebody outcrop in the Luanshya river, finely disseminated malachite was found to occur only 60cm below surface. The rock here assayed 3.5% Cu whereas only 60m away copper was completely leached from the ore shale to a depth of more than 6m. West of the Luanshya River most of the copper is leached from the host rock near surface, the depth of oxidation being greater on the footwall of ore due to the sheared and permeable nature of the rock. Malachite, chrysocolla, cuprite, cupriferous wad and tenorite occur below the zone of complete leaching. Supergene enrichment occurs at the base of the oxidized zone to a small extent. Below the zone of supergene enrichment there is an abrupt transition to almost unaltered primary sulphides. At Muliashi weathering penetrates 60m to 90m, as further east, but much of the copper appears to have been fixed close to the surface in tenorite and micas. Cupriferous green or brown vermiculite was also recorded locally from the weathered zone to the east of Muliashi. Bassett (1958) studied these micas in what appears to have been the first investigation of cupriferous micas from the Copperbelt.

Baluba Mine

At Baluba, copper and cobalt mineralization occurs within a calcareous schist (also referred to as dolomite schist) and the lower part of an overlying argillite unit. Locally mineralization extends into the footwall sediments, designated RL7 as at Luanshya. Both the succession and the mineralization show conspicuous similarities with Muliashi. Mineralization within the area to be exploited by the underground mine is exclusively of Lower orebody type, but a quite separate occurrence of Upper orebody mineralization is known to the east.

Figure 5.8. shows the approximate extent at Baluba of the Lower orebody, which occurs over a strike length close to 2,5 km at surface but narrows at depth. Mineralization of subeconomic grade or thickness is known to extend well beyond the defined fringe. The Ore formation overlies a considerable thickness of RL7 arenaceous sediments, the top of which is marked by an impersistent grit or conglomerate band. This grades upwards over a short distance (less than 30cm) into an incompetent calcareous schist normally four to six metres thick, but which sometimes attains more than double this thickness. At fringes the dolomite schist thins, and extensive areas of thin dolomite schist with mineralization exist outside the economic orebody. The dolomitic argillite above the dolomite schist becomes more sandy upwards, with numerous thin lenses and channels of sand in the barren upper part of the unit. Sedimentation in the Ore formation bears no obvious relationship to basement topography and hence no particular basement effect on mineralization is evident. Lee-Potter (in Mendelsohn 1961) makes only passing reference to the basement complex in his account, which was written prior to the start of mine development. Because development is mostly in the RL7 not much is known about the basement configuration even now.

Up to eight metres of footwall mineralization has been observed in the top of the RL7, but the occurrence of this is very irregular. It may attain a similar grade of both copper and cobalt to the overlying dolomite schist, where high grade mineralization is consistently developed. Copper and cobalt grades in the dolomite schist are invariably higher than in the overlying argillite, but a second peak of cobalt grade may occur towards the hangingwall where copper grades tend to decline further. Vink (1972) sampled some of the first crosscuts through the Baluba orebody and analysed the distribution of copper and cobalt minerals across the width of the body. His results are shown in figure 5.9. A massive sulphide band containing chalcocite is a common feature a the top of the grit or conglomerate band marking the top of the RL7. The calcareous schist contains abundant sulphide in blebs and veins, carrolite being a major component of the sulphide content. In the argillite, carrolite occurs in very small amounts, chalcopyrite being the dominant sulphide. The hangingwall of economic copper mineralization is considered to be where the copper grade drops fairly abruptly from 1% to usually around 0.3%. Pyrite, which becomes the major sulphide around this stratigraphic level, may contain sufficient cobalt to produce a cobalt grade comparable with that in the dolomite schist. This mineralization is usually in the hangingwall of the copper orebody. To the west a large area is known where the dolomite schist is less than three metres thick and

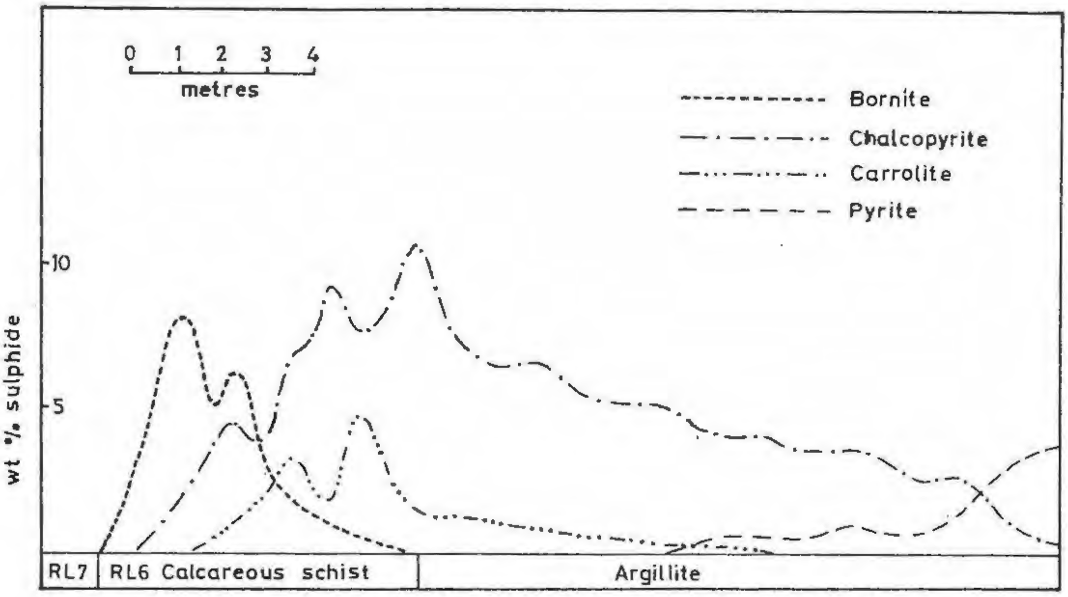


Fig. 5.9. - Sulphide distribution across the width of the Baluba orebody (after Vink, 1972)

contains only about one metre of chalcocite mineralization. The overlying argillite here contains only approximately 0.3% copper and 0.1% cobalt.

Individual borehole grades are quite variable, between about 1.5% and 4.5% copper but on the scale of block sizes the variation is reduced. Grades between 2.5% and 3% copper are common, with a slight tendency for higher grades to occur in blocks centrally placed within the orebody, but in general both grades and thicknesses are relatively constant except at fringes. Extremely rapid reductions in both thickness and grade can occur at the perimeter of the orebody, which is evidently rather irregular in shape in detail . Continuity of mineralization between widely spaced boreholes near the fringes of ore cannot be assumed.

Although the major structure at Baluba is relatively simple, considerable movement has taken place along imcompetent beds. The dolomite schist shows intense dragfolding and may in some places have been tectonically thickened. Deformation has also undoubtedly produced local remobilization of sulphides into blebs and veins, particularly within the dolomite schist.

It appears from Lee-Potter's account (in Mendelsohn, 1961) of the Baluba deposit that mineralization was thought to be continuous from the Upper orebody at Baluba East to the western extremity of the Lower orebody. He quotes a length of 15 000 feet (about 4.7 km) for the orebody and shows the

Upper and Lower orebodies as apparently continuous. The grade of the Upper orebody at Baluba East is somewhat higher (3,9% Cu) than the Baluba main orebody (2.4% Cu) but it does not contain economic concentrations of cobalt. Some of the cobalt in the main orebody occurs in an apparently refractory form within cobaltiferous micas in the dolomite schist. Cobalt in mica is difficult to determine analytically, but seems to constitute up to 30% of the cobalt in the ore. It is not clear whether this is comparable with the supergene cupriferous micas or how it was formed.

The oxidized zone at Baluba extends to about 60m below surface according to Lee-Potter, and is therefore comparable with that at Luanshya. The Baluba East deposit is altered at its western end to depth in excess of 100m, but the base of oxidation is closer to surface than this over most of the area of the deposit.

6. THE CHAMBISHI - NKANA BASIN

Stratigraphy and structure

The Chambishi-Nkana basin, a major structural basin on the southwest side of the Kafue Anticline, is partially closed off to the southwest by an anticlinal exposure of basement, and is approximately 35 km long by 20 km wide. Structures in general dip into the basin, and the surface geology and principal elements of the stratigraphy are shown in figure 6.1. Details of the Roan Group stratigraphy around the basin vary considerably, and will be described for each individual deposit. The entire basin was evidently a major depository for Katanga sediments, within which a number of more restricted basins developed during Lower Roan times. The Lower Roan is completely absent in the northeast of the basin at surface, and its configuration at depth within the basin is poorly known. The maximum depth of the basin is not known, but mining is currently carried out below 1000m depth and mineralization is known at a depth of 2000m.

Within the Chambishi-Nkana basin orebodies are currently exploited at Chibuluma East, Chibuluma West, Chambishi, Nkana and Mindola. In addition, a major unexploited orebody is known within the basin at Chambishi Southeast (formerly Nkana North Limb), and another unexploited body south of Kalulushi is conveniently described here although it is strictly not within the basin.

Chambishi Mine

At Chambishi an "ore shale" type body is exploited, now by underground methods although an open pit has operated in the past and is exhausted. Mineralization occurs in the lower part of an Ore formation similar to that at Luanshya and immediately overlying an arenaceous footwall sequence comparable to the RL7 at Luanshya. The basal part of the ore host, frequently referred to as orebody schist, is an incompetent sandy and micaceous rock. It is frequently brecciated and has obviously behaved as a very incompetent unit, being squeezed and dragfolded during deformation. This schist is generally about 1m thick, and usually rests on an argillaceous sandstone though in places a band of arkose or conglomerate up to a metre thick intervenes. A dark argillite generally more than 15 m thick in straight limbs overlies the orebody schist, and passes upwards into a sequence of sandstones, quartzites and sandy argillites. Towards the top of the "ore shale" unit thin bands and lenses of sand begin to appear. These are normally less than one centimetre thick and their presence is invariably

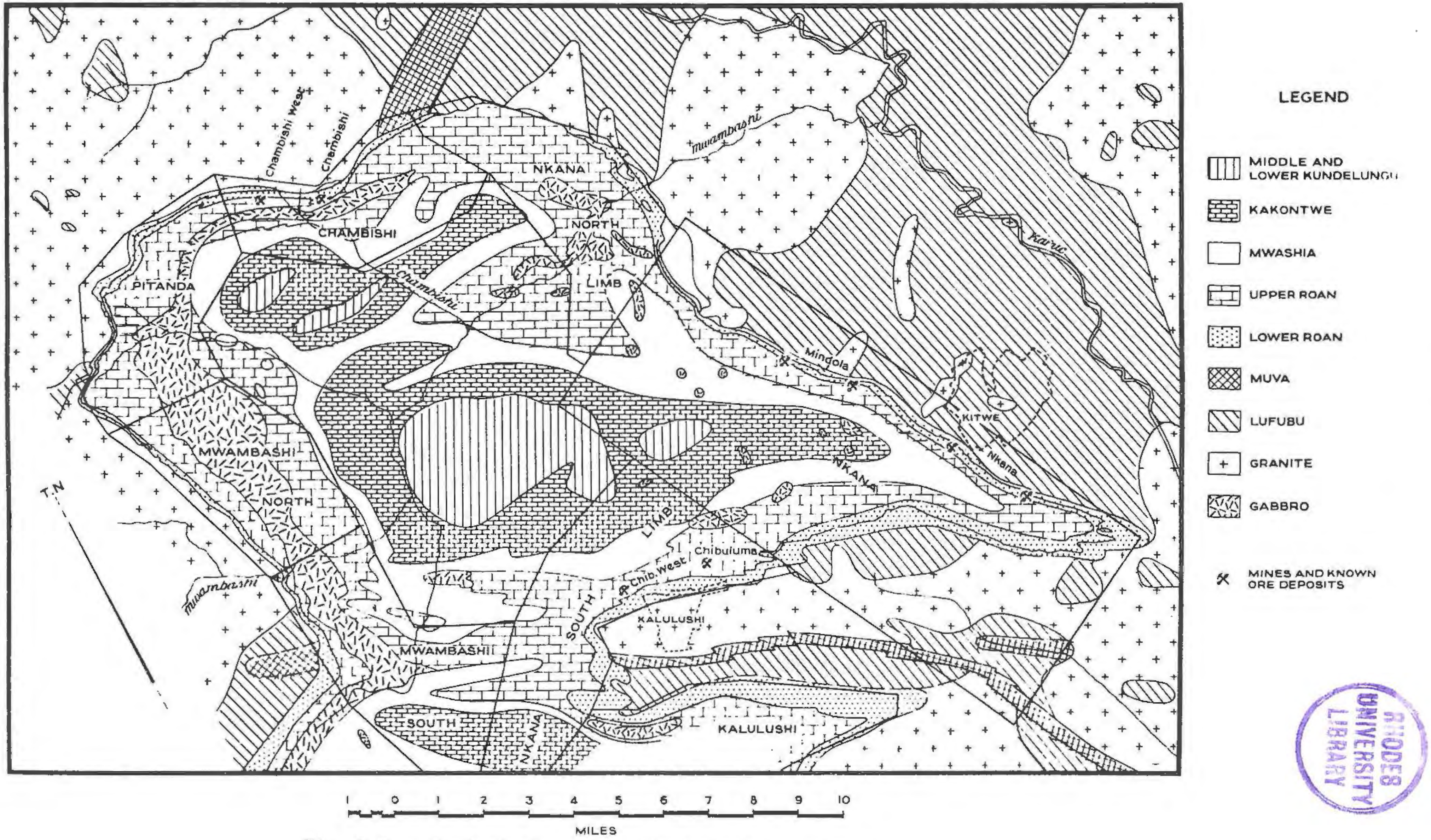


Fig. 6.1. - Geological map of Chambishi-Nkana basin

accompanied by an abrupt reduction in grade of mineralization. Barren hangingwall usually grades less than 0.1% Cu.

Only copper is so far known to be present in economic amounts in the Chambishi orebody, although minor quantities of cobalt have recently been detected near the centre of the orebody (J.Tinkler, pers. com.). The vertical distribution of copper grades within the ore is extremely heterogeneous, with a marked concentration of mineralization in the orebody schist. Grades of up to 15% total copper occur at the base of the orebody. Higher in the "ore shale" grades of less than 2% copper are common. Overall intersection grades are generally between 2% and 3% Cu, with up to 50% of the contained copper in the orebody in the bottom three metres. The total thickness of ore in underformed limbs is usually between 10m and 15m.

The part of the Chambishi orebody close to surface (now mined out) straddles a palaeovalley filled with arenaceous sediments attaining a maximum thickness of more than 100m. Figure 6.2 shows the configuration of the orebody and its enclosing rocks in plan. Although the ore shale is shown lapping directly onto the basement, in actuality a thin veneer of arenaceous sediments lies directly on the basement. The relationship of basement topography to mineralization is not well known at depth where the basement has been exposed at only a few places. It is however evident that the basement has been deformed with the cover rocks as shown in figure 6.3, though in places to a considerably greater extent. Figure 6.4. shows the basement configuration on 200m level where a tongue of basement has been caught

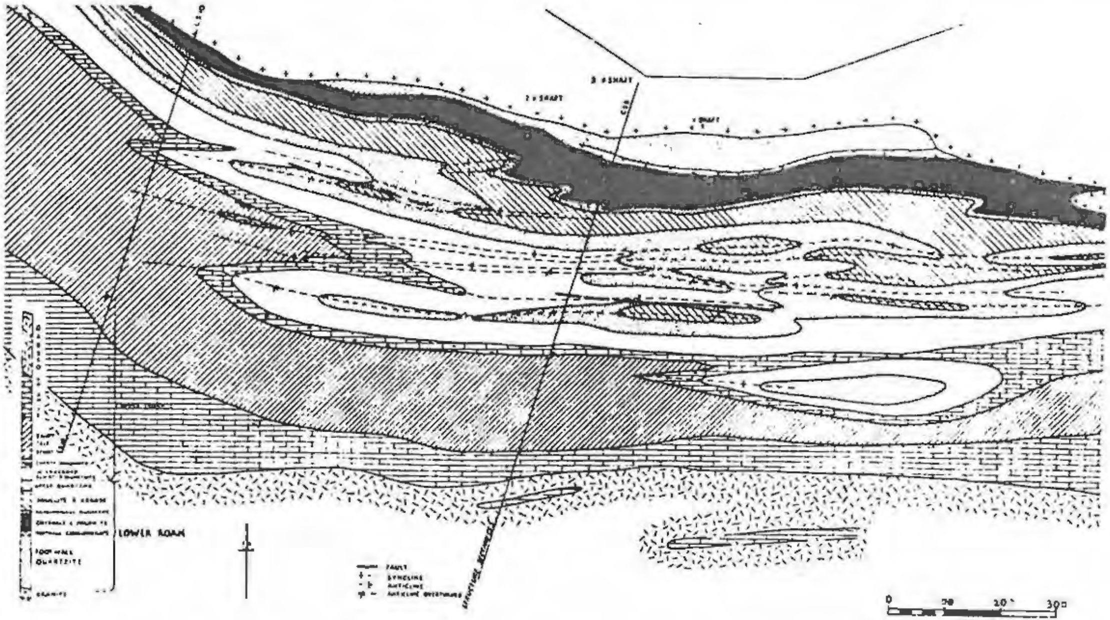


Fig. 6.2. - Surface plan of Chambishi (from Mendelsohn, 1961)

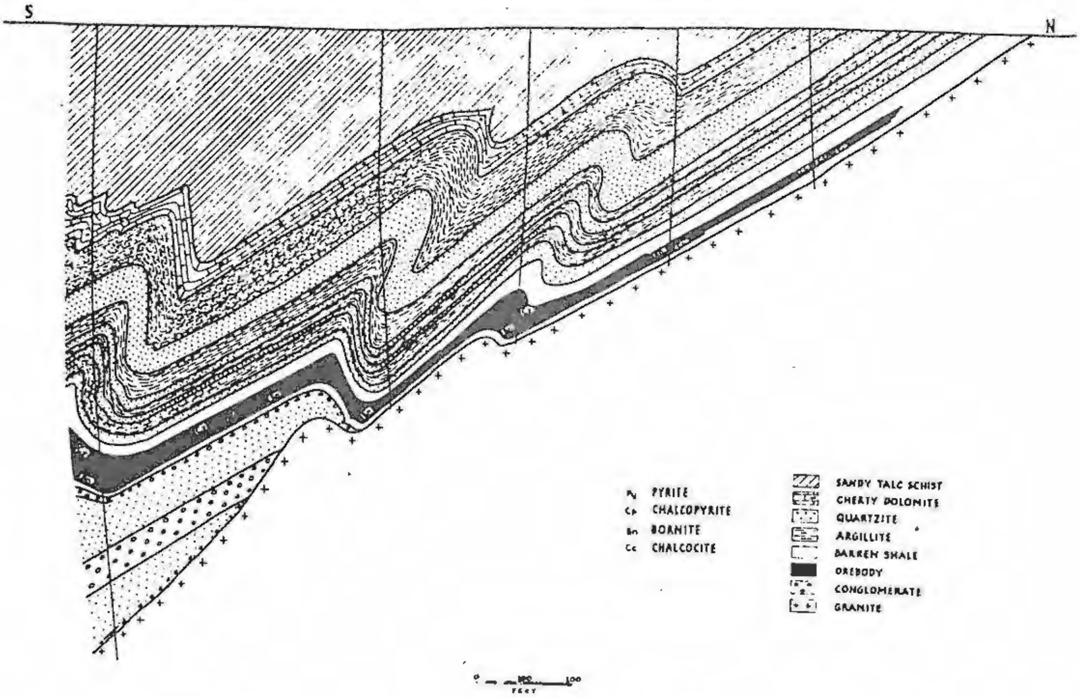


Fig. 6.3. - Section through the west end of the Chambishi orebody (from Mendelsohn, ed. 1961)

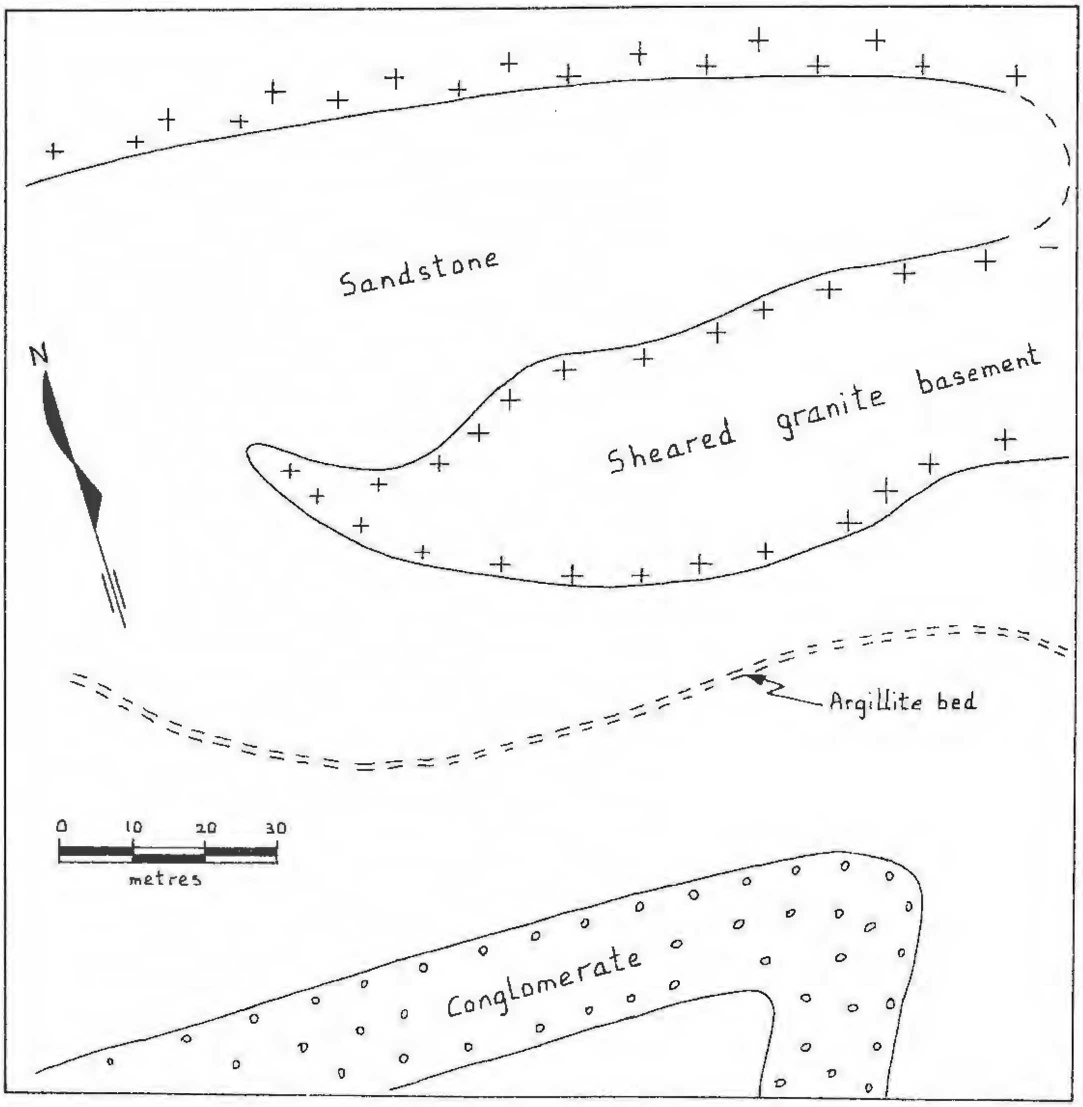


Fig. 6.4. - Basement configuration on the 200m level, Chambishi

up with basal Roan sediments and intensely deformed. Chalcopyrite and bornite are the only copper minerals present to a significant extent in the unoxidized part of the Chambishi orebody. Data for the upper levels of the mine shows a pronounced increase in the ratio of chalcopyrite to bornite from the eastern edge of the orebody towards the centre. The available data does not indicate the trend of this ratio towards the western fringe and down-dip. In individual intersections, the disseminated mineralization in the ore shale tends to consist mainly of chalcopyrite, with a much large proportion of bornite in the basal mineralization. Disseminated pyrite is common in the barren ore shale immediately above the orebody.

Lateral variation in grade is conspicuous but not very regular. At the eastern fringe of the orebody overall grades of 3.5 to 4.0% copper are common. The fringe of the orebody becomes thin but of high grade. Westwards, grades drop to below 2.5% copper in places, but grade contours are of irregular shape with a slight tendency to parallel the major structures. At the western fringe of the orebody both grade and thickness diminish gradually. The basal schist dies out over a basement hill capped by a thin sequence of porous sandstone underlying the ore shale. The ore shale is sparsely mineralized, and mineralization shows little tendency to be localized at its base. Figure 6.3. shows the character of the fringe against the basement. West from this fringe the ore shale is barren for at least 500m before mineralization which forms the Chambishi West deposit starts to appear. The western fringe of the Chambishi orebody plunges south-west to a depth of at least 300m, while the eastern fringe plunges eastwards near surface. Both fringes are not defined at depth and there are no geological initeria from which their geometry can be estimated at present. A thin mineralized intersection has been obtained at a depth of 2000m, centrally situated with respect to surface outcrop.

The major structural feature at Chambishi is considered by Garlick (in Mendelsohn, 1961) to be a monocline which is expressed as a granite salient projecting into the Chambishi-Nkana basin between the east and west forks of the Chambishi stream (figure 6.1). This major structure plunges southeast parallel to the Kafue anticline. Developed on it are a number of relatively major folds which Garlick describes as dragfolds. Over most of the strike length of mineralization these plunge very gently west. Figures 6.3 and 6.5 represent approximately the geometry of the folding of the upper part of the Chambishi orebody. Mining operations have revealed that these interpretations are inaccurate in detail, primarily because plastic deformation of

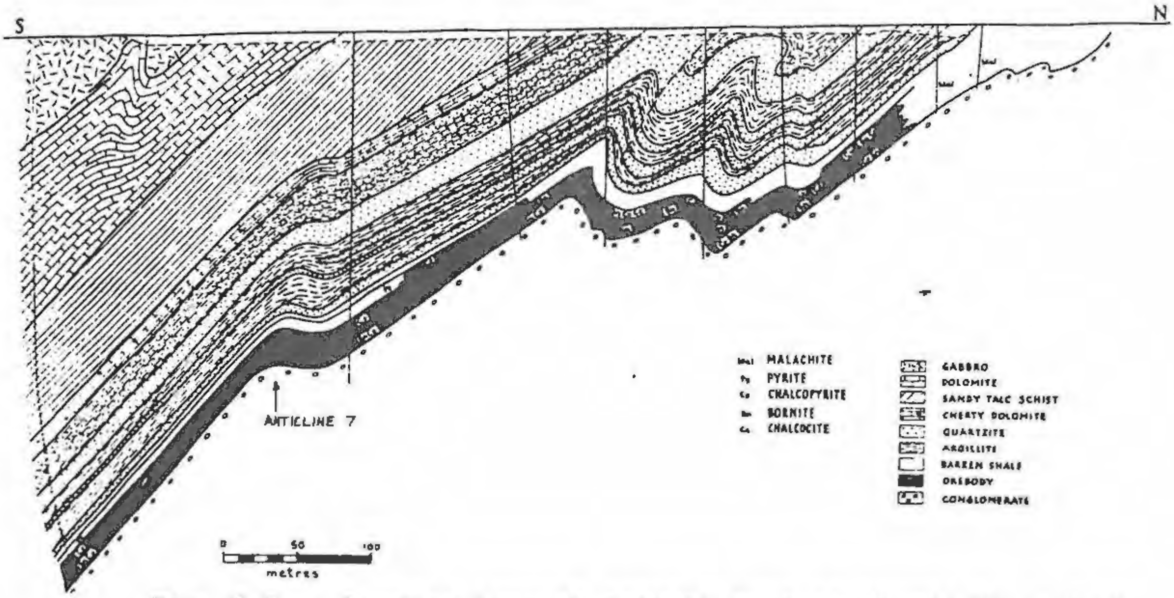


Fig. 6.5. - Section through central part of Chambishi orebody (from Mendelsohn, 1961)

incompetent beds has allowed the development of isoclinal folding in the hangingwall beds. Considerably more thickening of the orebody around fold axes than is evident from these sections has also been demonstrated. Where the orebody plunges south below the open pit only one major fold (Anticline 7) is known, but there are indications from drill cores that further folding exists. Dragfolding of the footwall schist has been observed in the vicinity of Anticline 7, leading to local squeezing and thickening of this unit.

Remobilization of mineralization during metamorphism has had only local effects. Quartz veins within the footwall schist, and particularly concentrated in fold axes, contain bornite and chalcopyrite segregations, but there is no evidence that mineralization has moved more than a few metres. Jolly (1972) describes a barren shear zone exposed by mining in Chambishi open pit, which she attributes to the passage of hydrothermal fluid through a structure caused by differential subsidence. Only one such shear has so far been encountered.

Supergene effects at Chambishi have totally altered the character of the orebody within 50m of the surface. Most of the copper within this zone has been leached from its original site in the primary ore, and effects attributable to supergene alteration have been observed at more than 200m below surface. According to Davidson (1931) the copper in the weathered zone within 30m of surface occurs as invisible finely disseminated malachite. It is likely that much of this copper was in fact incorporated into cupriferous micas. Copper carbonates, wad and presumably cupriferous mica formed a zone of rather refractory mineralization considerably wider than the primary orebody and below the zone of complete leaching. Some of this material was never treated and remains on stockpiles.

Nkana Mining Area

Two major ore occurrences are mined at Nkana. The Nkana North and Nkana South orebodies are contiguous and separated from the Mindola orebody by the Kitwe Barren Gap. The orebodies occupy a strike length of some 14km, along the east limb of a northwest plunging syclinorium, at the southeast of the Chambishi-Nkana basin. Open pit operations are conducted at the northwest extremities of the Mindola and Nkana North orebodies. but the majority of production comes from underground stoping. The lithology of the ore host rock varies somewhat along the mineralized strike length. A stratigraphic correlation from the north end of the Mindola orebody to the south of South orebody is shown in figure 6.6, while figure 6.7 shows the distribution of copper in the various lithologies. There are distinct lithological differences between the host rocks of these orebodies, and considerable variations in the distribution of metal.

In the Mindola orebody mineralization occurs in several distinct lithologies which together make up the Ore formation. Maximum grades usually occur towards the top of the Cherty Ore, a strongly banded siliceous argillite or siltstone which can contain considerable amounts of anhydrite. Chalcopyrite mineralization is concentrated at the base and top of thin sand bodies within the Cherty Ore, and finely disseminated in the sands. The sand bodies appear to have been deposited in very shallow channels and exhibit fine-scale cross-bedding. The Cherty Ore becomes more dolomitic and less siliceous towards its top, passing upwards into the Porous Sandstone unit, which is a calc-arenite. This unit is also banded, with alternating sandy and silty layers cemented with dolomite and anhydrite. Leaching of the cementing minerals produces a friable porous rock near surface. Mineralization consists of disseminated chalcopyrite and bornite, and the grade diminishes gradually to near zero towards the top of the Porous Sandstone. Below the Cherty Ore is a banded carbonate rock known as Banded Ore, a striped rock which becomes more massive upwards. This unit contains mainly chalcopyrite mineralization plus a small amount of carrolite. The base of the Banded Ore is frequently also the footwall of mineralization, with the grade dropping to near zero across the bottom contact. The underlying Low Grade Argillite is usually poorly mineralized but is in places of ore grade. At the base of the Ore formation is Schistose Ore, similar to the basal lithology at Luanshya, Baluba and Chambishi, but rarely containing much mineralization. The grade of the Schistose Ore and Low Grade Argillite taken together is usually between 0.5% and 1% Cu. Variations in the thickness of the units making up the Ore formation are shown in figure 6.7.

The Nkana North and South orebodies are hosted mainly in a black to grey carbonaceous shale called the South Orebody shale. According to Clemmey (1974) this comprises an upper more massive unit and a lower banded unit which is underlain by the Contact Shale. This unit consists of interlaminated dolomites and argillites which Clemmey regards as the lateral equivalent of the Schistose Ore at Mindola. Jordaan (in Mendelsohn,1961) describes

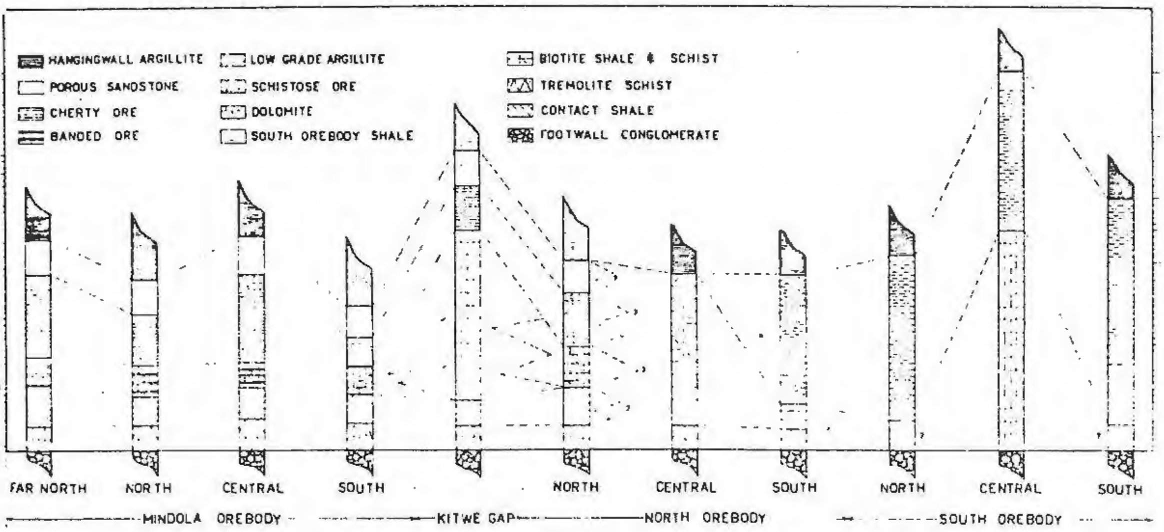


Fig. 6.6. - Correlation diagram of the Ore formation at Nkana and Mindola, showing changes in lithology along the East Limb of the syncline. (from Mendelsohn, 1961)

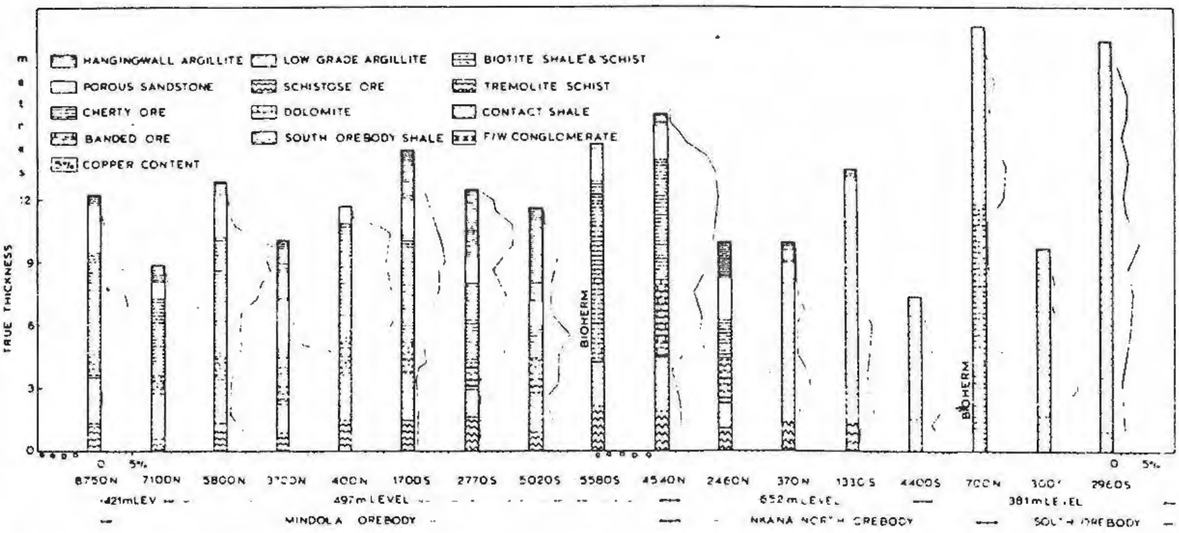


Fig. 6.7. - Lithology and copper grades along the east limb of the syncline in the Nkana area. (From Jordaan, in Mendelsohn 1961 - modified by Fleischer et.al.)

how the Contact Shale gives way northwards to a dolomite bed 10 m thick. He also says that in the central area of Nkana North orebody all the beds of the Ore formation grade into transitional beds including a tremolite schist which is the equivalent of the Schistose Ore. Folding and metamorphism are said to have masked the transition so that, as indicated on figure 6.6, it is not clear how the Mindola and Nkana successions correlate.

In the South orebody area mineralization is present both in the Ore formation and in the underlying Footwall Sandstone, as shown in figure 6.8. Richards (1965) investigated the primary distribution of mineralization in the South orebody area and the redistribution of grades as a result of folding

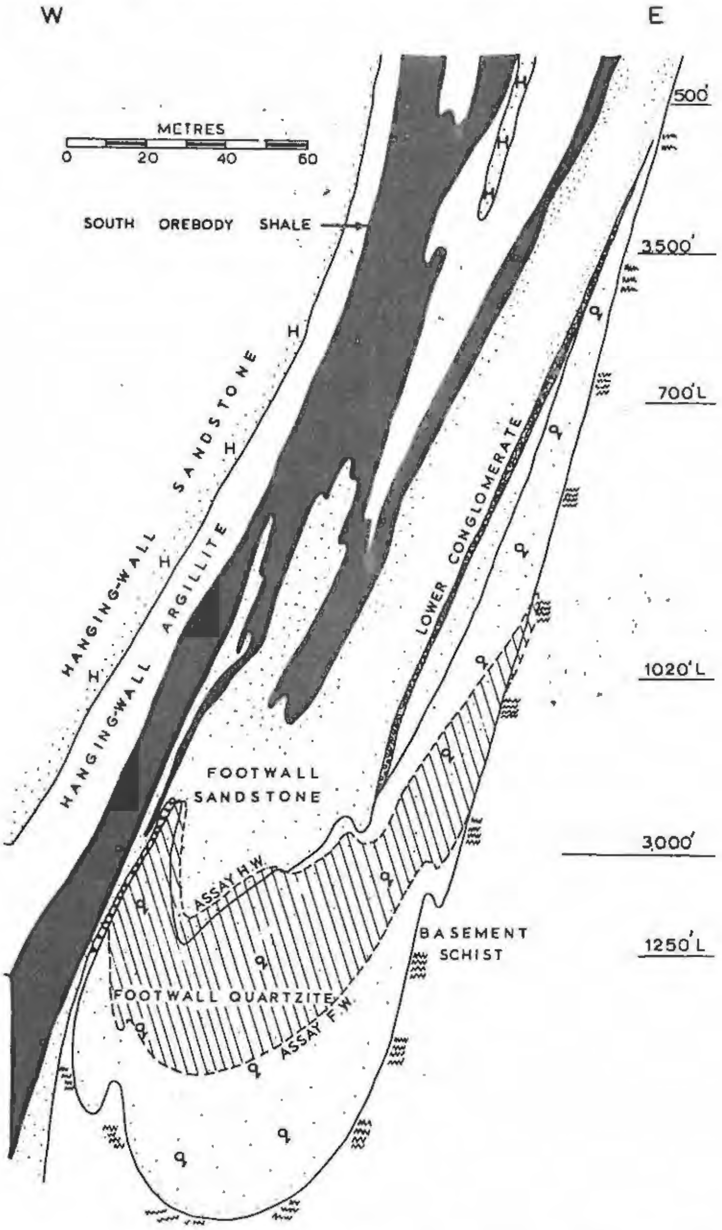


Fig. 6.8. - Cross-section of the South Orebody, Nkana. The footwall orebody is shown hatched. (from Fleischer <u>et al.</u> 1976)

and metamorphism. He states that six to eight metres of black carbonaceous shale is mineralized with grades of approximately 2.6% Cu and 0.20% Co, the copper grade diminishing gradually stratigraphically upwards. Three to five metres of lithologically indistinguishable carbonaceous shale carried copper grades of 0.2% to 0.8%, an arbitrary hangingwall cutoff of 1.4% Cu is being used. According to Jordaan (in Mendelsohn, 1961) mineralization at South orebody is limited to the highly contorted, fissile and veined portions of the carbonaceous shales with copper sulphides mainly in the veins. This is evidently not a reflection of the primary distribution of mineralization. The footwall orebody shown in figure 6.8 occurs in an arkose, locally termed quartzite and containing some mica and a little anydrite. In places the full thickness of the quartzite is mineralized but the mineralization is not conspicuously stratigraphically controlled. Mineralization extends into basement rocks where these abut against the Lower Roan mineralization. Sulphides are rather irregularly distributed in the quartzite as fairly coarse disseminations, and also as streaks or lenses in cleavages unrelated to bedding. This orebody appears to be closely similar to the Chibuluma West and Kululushi East orebodies, but rather more deformed. A basement hill on the west side of this orebody has squeezed into a narrow tongue of schist similar to those described at Chibuluma West by Whyte and Green (1971).

At Nkana and Mindola the original basement configuration has had a significant effect on the distribution of mineralization, primarily through its control on the development of the depositories. Facies differences between Nkana and Mindola and in the barren gaps suggest that two distinct basins existed at the time of deposition of the Ore formation. The barren gaps appear to be controlled by the presence of hills in the basement surface which have affected the facies deposited over them. Clemmey (1974) explains the Kitwe Barren Gap as being due to a fringing reef of dolomite around a "palaeoisland", and other barren gaps as being the result of deposition of arkosic sediments instead of Ore formation over granite "highs". Mineralogical zonation through the width of the ore is not a conspicuous feature of the Nkana and Mindola orebodies. Jordaan (in Mendelsohn,1961) suggests zonation from hangingwall to footwall of pyrite, chalcopyrite - carrolite, bornite - chalcopyrite - carrolite and chalcopyrite - carrolite, but lateral zonation of mineral type is far more pronounced. Jordaan indicates that the change from the bornite chalcopyrite - corrolite regime to chalcopyrite - carrolite in the Nkana North and South orebodies is associated with a facies change from argillites and dolomites to black carbonaceous shale. Grade and thickness in all the orebodies tend to

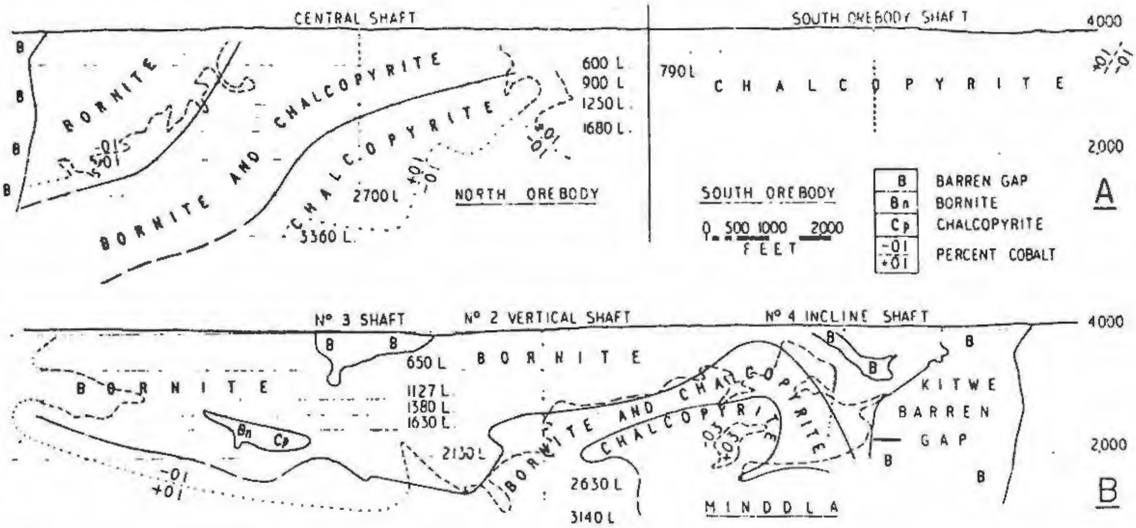


Fig. 6.9 - Longitudinal projection showing the mineral zoning at Nkana North and South orebodies Nkana (A), Mindola (B) (from Mendelsohn, Ed. 1961)

increase towards the basement highs. Cobalt tends to occur in pyritic lateral fringes of the orebodies and in hangingwall pyrite mineralization, and uranium-molybdenum mineralization is known at the south edge of the Kitwe barren gap.

Both copper and cobalt grades are erratic on the scale of the thickness of the orebody. At Mindola the Hangingwall Argillite is pyritic and contains around 0.1% Co while carrolite in the Cherty Ore gives rise to overall grades of 0.1% to 0.2% Co. This metal is usually concentrated in the upper part of the orebody. Copper grades are extremely variable through the vertical thickness of the Ore formation and also laterally. Sections 20m apart can vary in grade from 1.4% to 2.2% Cu, while cobalt grades are even more erratic. Variation from 0.1% Co to 0.4% Co between sections 20m apart has been observed. Some of the grade variation may well be due to remobilization of sulphides during metamorphism. At Mindola disseminated ore tends to carry better grades than deformed areas where mineralization is in coarse grains and stringers, suggesting that copper has been moved out of deformed zones.

Deformation at Mindola is comparatively slight, whereas the Nkana orebodies have undergone extreme deformation, as indicated by the configuration of stratigraphic units in figures 6.8 and 6.10. Folds near the nose of the Nkana sycline are tight and isoclinal in and near the orebody. Folding of the basement is usually much more gentle, but with localized rather extreme deformation of basement hills. The Nkana sycline plunges northwest at between 20 and 30 degrees. Garlick (1976) describes the fold structures on both limbs of the sycline as parasitic dragfolds, the plunge of which is usually about 20 degrees northwest. Plunges of individual folds may be steeper, flatter or reversed. Progressing north along the mineralized limb folds become more open. At crests and troughs of folds the ore formation tends to be drag-folded whereas the underlying arenaceous beds are more concentrically deformed. (Figure 6.10). At Mindola movement is considered by

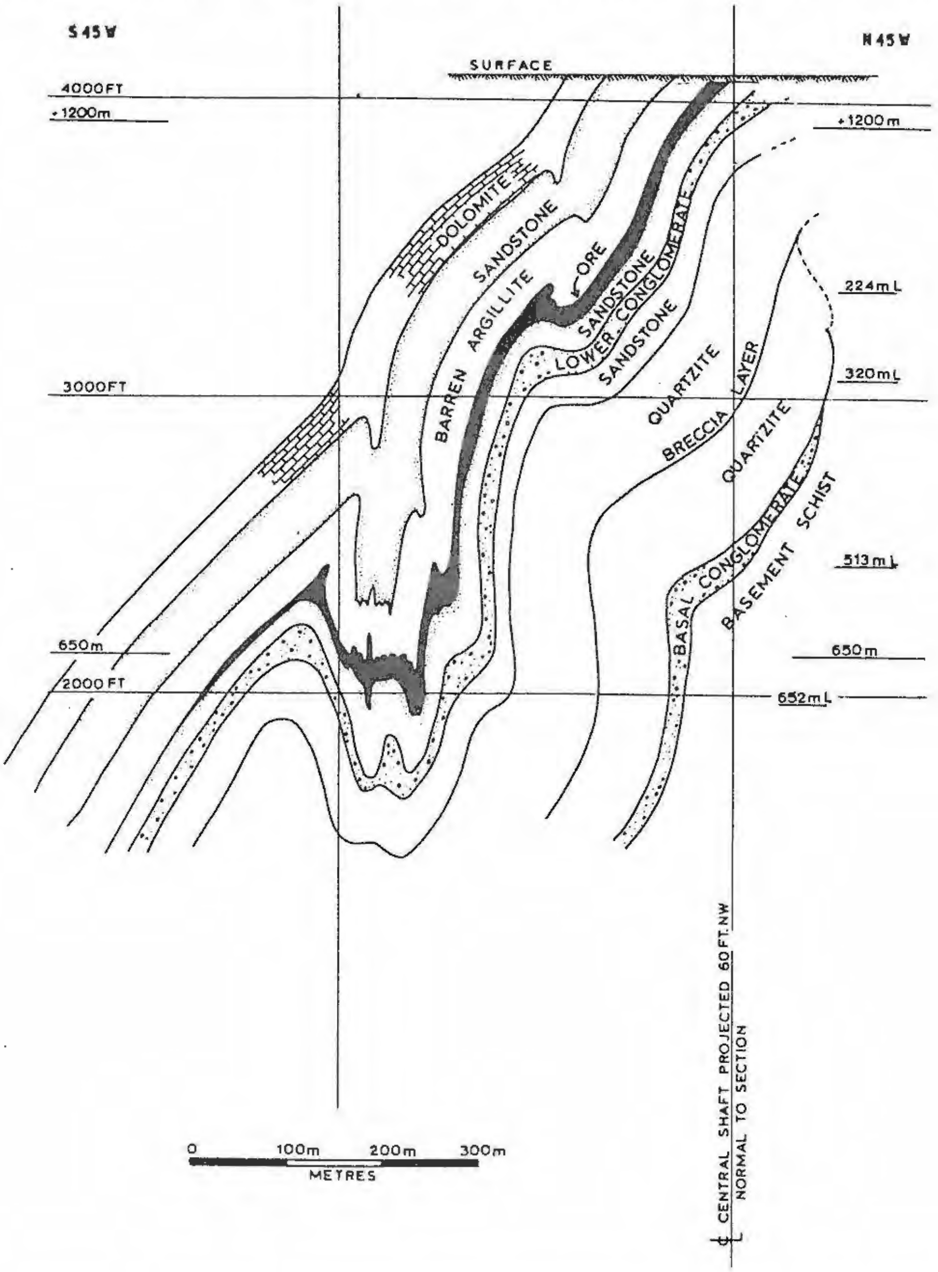


Fig. 6.10. - Section showing configuration of Lower Roan sediments near Central Shaft, Nkana. (from Fleischer et al. 1976, modified after Mendelsohn, ed. 1961)

Jordaan (in Mendelsohn, 1961) to have taken place only on bedding planes without deformation of the beds. Minor rolls in the footwall are evident, and some movement has been taken up by faulting. Jordaan describes faults at the north end of Mindola which trend along strike for short distances before veering off into the hangingwall. Some of the rolls in the Mindola orebody are considered to be caused by sets of parallel faults, which are approximately at right-angles to the strike of the orebody and displace it in a series of small amplitude steps (R.Ashton pers. comm). Faulting has no significant effect on grade and does not contribute to the problems of ore reserve estimation.

The intensely deformed nature of the Nkana orebodies causes severe difficulties in both tonnage and grade estimation. As the shape of the mineralized body is so irregular it is necessary to decide what can be mined and define its morphology before attempting to estimate grade. The grade distribution is extremely erratic and unpredictable, apparently because of pronounced metamorphic redistribution. Copper tends to be concentrated in synclinal culminations, and grades of complete orebody intersections can vary from 1.3 to 4% Cu over short distances.

At the South orebody, supergene effects described by Richards (1965) extend between 25m and 75m below surface, the depth of oxidation showing no relationship with surface topography except that the shallowest oxidation occurs in the valley of a stream crossing the orebody. Jordaan (in Mendelsohn, 1961) writing about the Nkana area in general, describes the presence of a leached zone extending to a depth of as much as 30m, below which oxidation effect extend to 120m. Cupriferous minerals present in the oxidized zone are malachite, chrysocolla, cuprite, tenorite and minor amounts of azurite and libethenite.

Chibuluma and Chibuluma West

These orebodies are situated on the south side of the Chambishi-Nkana basin west of Kitwe, and appear to be separated from each other by a barren gap of about 3km. Both orebodies are on the north flank of an anticline of basement which plunges westwards beneath a saddle of Katanga sediments connecting the Chambishi-Nkana basin with the main Katanga depository. There are conspicuous difference in basement configuration and structural style between the two orebodies, but the Lower Roan lithologies are rather similar at both localities. Winfield (in Mendelsohn, 1961) described the Chibuluma East deposit (referred to then and in most subsequent literature simply as Chibuluma) principally with reference to stratigraphy, making only passing reference to palaeogeography. The geology and palaeogeography of Chibuluma West, described by Whyte and Green in 1971, were little known at the time of publication of Mendelsohn's book.

At both deposits scree and boulder deposits on an irregular and weathered basement surface form a basal conglomerate. The maximum thickness of this at Chibuluma West is about six metres, marginally more than at Chibuluma East. This probably reflects the greater basement relief at Chibuluma West. The conglomerate consists of angular to sub-angular boulders and pebbles derived locally from the basement and set in a sandy matrix. The conglomerate is thinnest on the crests and flanks of basement ridges, and thickest in "lows" on the basement surface. Overlying the basal conglomerate is a banded feldspathic quartzite, composed mainly of quartz and plagioclase cemented by quartz or locally carbonate and anhydrite. At Chibuluma West this lithology is up to 100m thick, thickening at Chibuluma East to 130 metres maximum thickness. This lithology contains large-scale cross-bedding and is referred to as aeolian quartzite, although there is no reason to suppose it was not laid down by water. At both localities the top of the aeolian quartzite has an eroded and potholed surface on which rests an arkosic grit unit. This is referred to as aqueous quartzite and attains a maximum thickness of 15m at Chibuluma East. Here it is slightly more consistently developed than at Chibuluma West where it ranges in thickness from zero to 12m. Whyte and Green (1971) describe the aqueous quartzite as consisting mainly of quartz and microcline with some biotite and carbonate, and also mention the presence of large sub-angular boulders of argillite and quartzite along the basal contact. At Chibuluma East, Winfield (in Mendelsohn, 1961) mentions gravel lenses, pebbles and minor shale interbeds in the aqueous quartzite, and also higher contents of argillaceous and calcareous material. At both localities, pyrite occurs in the aqueous quartzite and this unit is immediately overlain by a similar but sericite-rich lithology which constitutes the Ore formation. Up to 20m of Ore formation is overlain by a hangingwall formation considered to be the topmost unit of the Lower Roan. At Chibuluma East up to ten metres of massive feldspathic quartzite is separated from the Ore formation by a thin layer of clay. An overlying conglomerate ranges from ten metres of rounded pebbles in a gritty matrix over the centre of the deposit, to an impersistent grit or pebble bed at the fringes. No such systematic thickness variation is evident at Chibuluma West, where the hangingwall rocks are predominantly red-brown arkoses with argillaceous and sandy interbeds.

The Upper Roan at both localities is a carbonate-rich sequence separated from the Ore formation by not more than 30m of hangingwall formation assigned to the Lower Roan. A calcareous arenite at the base of the Upper

Roan passes upwards into a sequence of talc schists, dolomites and carbonaceous pyritic shales. Sills and irregularly shaped bodies of gabbroic composition occur in the Upper Roan, sometimes as close as 3m above the base of the Upper Roan.

Garlick (in Fleischer et al. 1975) implies that a granite greiss hill underlies the Chibuluma East orebody, but goes on to explain that it occupies a channel eroded in the aqueous quartzite. It seems reasonable to suspect that the position of a major valley in the basement surface would have had some effect on the subsequent configuration of a river channel in overlying sediment. The ore host sequence fills a broad depression, shallow in relation to its width, in the basement surface. This channel-like feature is approximately one kilometre wide and up to 150m deep. The Ore formation at Chibuluma East is a lensoid sericitic sandstone body to which mineralization is confined so that it nowhere approaches the basement. Both cobalt and copper are present as sulphides generally evenly disseminated through the rock. Winfield (in Mendelsohn, 1961) describes marked contrasts in the abundance of mineralization between adjacent beds, and the occurrence of rounded clots of pyrite up to 7.5cm in diameter. Pyrite is a widely distributed component of the ore, mainly as a fine dissemination. Chalcopyrite is the principal copper mineral, but Winfield describes disseminated bornite zones at the east and west fringes of the orebody. Veins within the orebody contain quartz and blebs or masses of chalcopyrite, pyrite and linnaeite, according to Winfield. He also recognizes concentrations of linnaeite in the lower part of the orebody at the eastern fringe, and a sulphide-rich layer containing up to 19% cobalt at the base of the orebody over a wide area. There is a distinct correlation between chalcopyrite mineralization and the most micaceous parts of the Ore formation. The most striking aspect of mineralogical and grade zonation in the Chibuluma orebody is the occurrence of cobalt mineralization fringing the copper orebody. Mineralization is mainly cobaltiferous pyrite occurring in the same lithological unit as the copper mineralization and partially overlapping it both laterally and vertically. Figure 6.11 shows a typical orebody fringe at Chibuluma East and the way in which cobalt mineralization mantles copper. The orebody fringes range from very abrupt to very gradutional. Copper mineralization of mineable grade and thickness may terminate over an irregular front only 20m wide, with mantling cobalt mineralization extending as little as 30m further. Cobalt grades at such fringes may be markedly irregularly distributed through the thickness of the orebody. Basement geometry has had no apparent direct effect on the mineralization at Chibuluma East, but evidently exerted some control over the development of

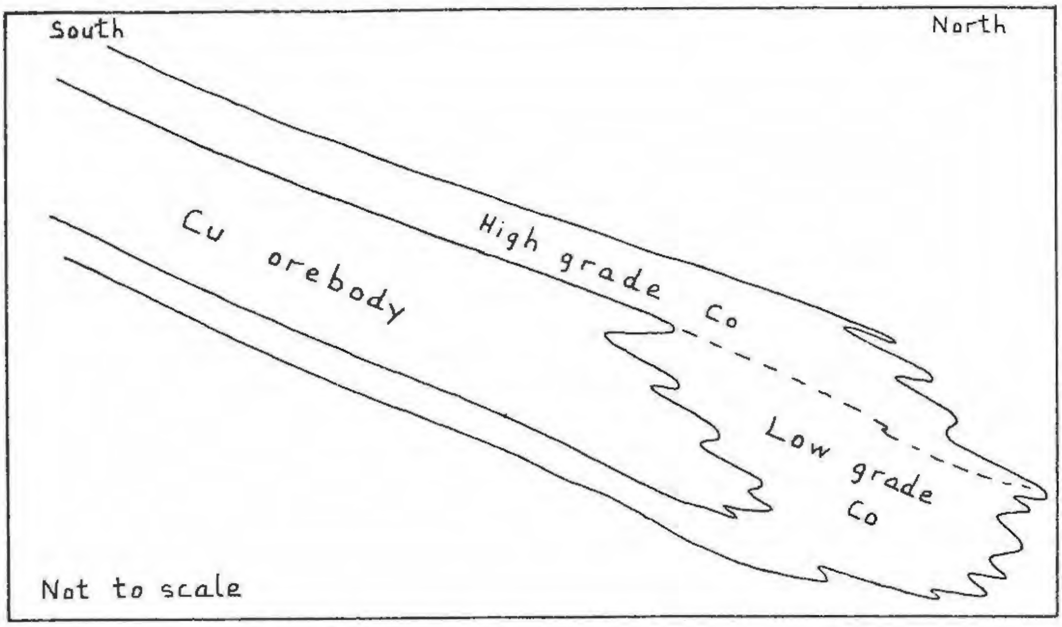


Fig. 6.11. - Schematic cross-section showing relationship of mineral zones at fringe of Chibuluma East orebody.

the ore-bearing facies.

The Chibuluma West ore, in contrast, abuts directly against basement at certain of its boundaries, and mineralization may penetrate up to several metres into the basement. Mineralization is predominantly within a sericitic or biotitic quartzite unit. Where this rests directly on basal conglomerate or basement these lithologies may be mineralized, but the "aeolian" quartzites are never mineralized. Although the orebody is broadly stratiform it shows marked thickness variations and is rather irregularly mineralized with both copper and cobalt. Figure 6.12 shows how the orebody thickens against the basement where its continuity is interrupted by a basement hill. Where mineralization is continuous over basement ridges, as shown in figure 6.13, little or no thickening is evident. The tectonism to which the Chibuluma West deposit has been subjected obscures the precise pre-folding relationship of mineralization to the basement, but it appears that where basement ridges projected to the level of the Ore formation prior to its deposition, the orebody became thickened and the surface of the basement was mineralized. Where basement ridges were eroded to such a level that the Ore formation was deposited as a continuous sheet, it became mineralized to a uniform width over the ridges. Subsequent deformation has evidently considerably altered the shape of both the basement surface and the orebody, though not in exactly the same way. At Chibuluma West the amplitude of the basement relief almost equals the thickness of the Lower Roan as locally defined, a situation not known elsewhere on the Copperbelt.

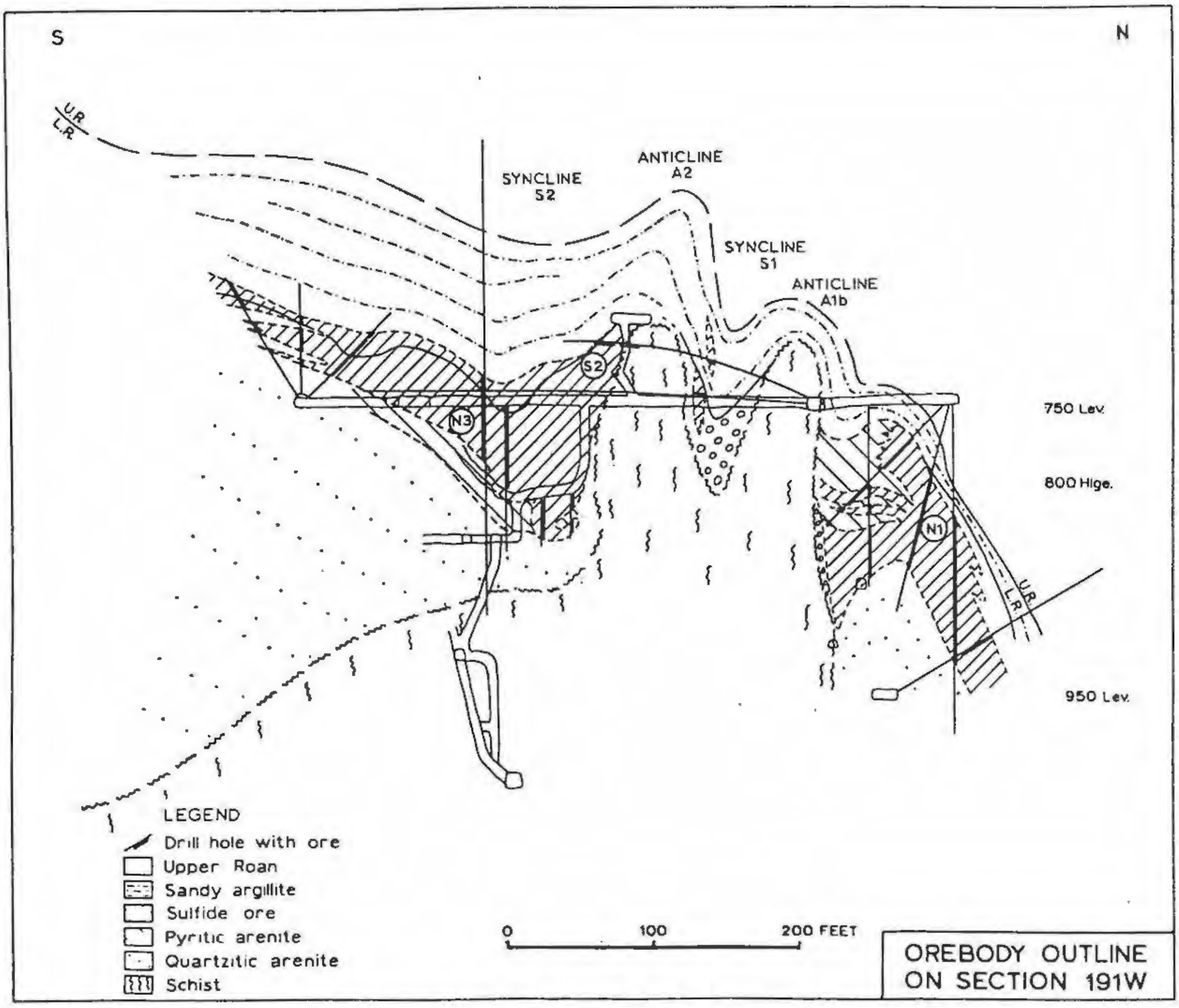


Fig. 6.12. - Section through Chibuluma West orebody showing mineralization terminated against a basement high (from Whyte and Green 1971)

Copper minerals at Chibuluma West are principally disseminated bornite and chalcopyrite, which generally appear to have crystallized together though occasionally bornite is seen to replace chalcopyrite. Chalcocite replaces both minerals in shears and veins, some of this sulphide apparently being secondary. Carrolite occurs as disseminations associated with the copper-iron sulphides and often as segregations along joints and fractures. Its relationship with the host lithologies suggests that it remobilized readily during metamorphism, reflecting the intensity of shearing at Chibuluma West. Although the Chibuluma East host sequence reached a sufficient grade of metamorphism to recrystallize, mineralization was not remobilized to the same extent. The intensity of shearing at Chibuluma West is shown by both the structural style and the deformation evident in basement topography and the rock fragments in the basal conglomerate.

At fringes away from basement hills the Chibuluma West ore diminishes rather rapidly in thickness, but cobalt mineralization may form irregular lenses

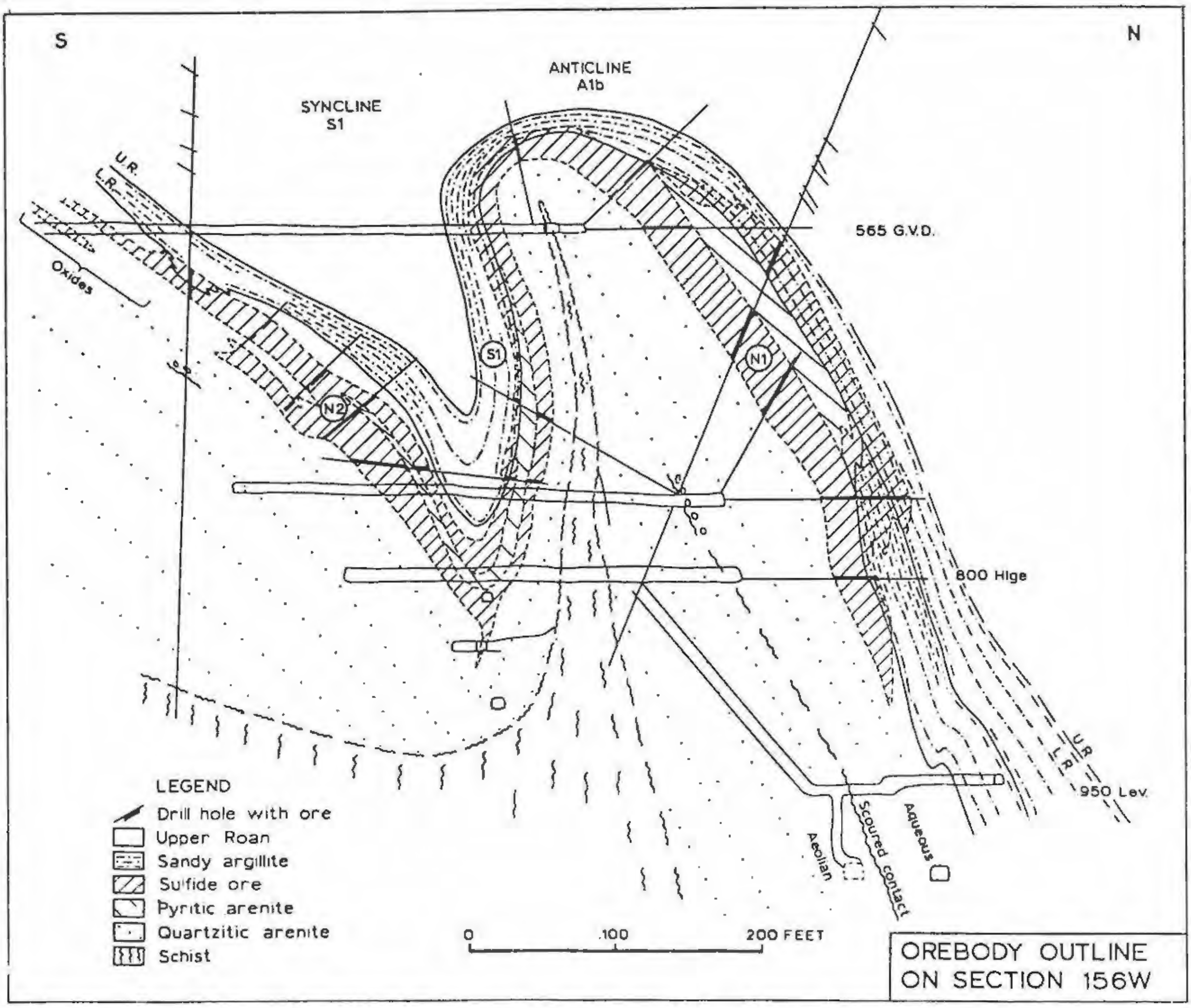


Fig. 6.13. - Section through Chibuluma West orebody showing mineralization over a basement ridge (from Whyte and Green, 1971)

outside the copper orebody. Mineralization is patchy in places and the orebody may bifurcate. Lateral mineralogical zonation is not marked but there is a tendency for bornite to predominate to the west. At fringes pyrite becomes the predominant sulphide, and lenses of chalcopyrite occur in pyritic quartzite outside the orebody. The amount of pyrite gradually decreases away from fringes to a sparse dissemination, and the quartzite eventually becomes completely barren without any other obvious lithological change. At some extremities of the orebody a band of disseminated chalcocite occurs in the hangingwall above barren or pyriticOre formation quartzite.

Supergene effects on the ore at Chibuluma West are negligible because mineralization does not outcrop.

Kalulushi East

The Kalulushi East deposit is ten kilometres south of Chibuluma West, in a northwest dipping Lower Roan sequence on the flank of a fairly major synclinal structure. This syncline is separated from the Chambishi-Nkana basin by the anticline of basement on which the Chibuluma deposits are located. The deposit therefore lies outside the Chambishi-Nkana basin, but shows similiarities with Chibuluma West and is most conveniently considered here.

The deposit is undeveloped and therefore known only from drill core and surface mapping. Mineralization is stratiform and contained within an arenaceous sequence resting on a basement of granitic composition. Considerable topography in the pre-Roan surface is evident, with a coarse basal conglomerate of up to 15m thick filling hollows in the basement surface. Conglomerate occurs principally along a steep-sided sinuous palaeovalley now trending roughly north-south, and contains gneiss, schist and granite pebbles. A description of the Kalulushi East deposit by Hancock (1977) makes no attempt to correlate the stratigraphy with that of the Chibuluma deposits, but there are clear similarities. There is no suggestion of an aeolian unit, but Hancock recognizes five predominantly arenaceous units below the Ore formation. Some of these units are of restricted areal extent, and their maximum combined thickness is about 100m. An Argillite-Grit unit forms a distinctive marker at the top of the footwall formations over part of the deposit, and consists of a micaceous grit with abundant argillite interbeds. The overlying orebody formation is divided into four micaceous and arenaceous units, only one of which is generally well mineralized. The thickness of the Ore formation as locally defined is up to 40m, but the thickness of mineralization is usually considerably less than this. Above the orebody formation occur up to 50m of argillaceous sandstones and grit, frequently very calcareous. This unit rests directly on the basement to the north and west of the deposit, and is overlain by the Upper Roan which is conspicuously calcareous as elsewhere. However, the detailed stratigraphy of the Upper Roan is not clearly defined because of the presence of large thicknesses of gabbro.

To the northeast, north and northwest mineralization terminates with its host quartzite against the basement, while at other fringes mineralization thins, often to be replace by pyrite. In the hangingwall and footwall of the orebody pyrite is common. Most of the copper occurs in bornite, the highest concentration of which relative to other sulphides coincides with the central portions of the orebody. Chalcopyrite increases in abundance around the fringes of the orebody, particularly adjacent to the basement ridges, while chalcocite is irregularly distributed and at least partly due to supergene effects. Chalcocite is apparently concentrated towards the hangingwall and footwall of the orebody, but the other copper sulphides show only slight vertical zonation. Both bornite and chalcopyrite occur as fine disseminations and blebs up to one centimetre across. Both tend to be slightly more abundant in the lower part of the orebody. To the southwest, mineralization bifurcates before fringing out, and the orebody has a barren central zone over a fairly substantial area. Cobalt is very sporadically distributed, and occurs mainly as carrolite disseminations associated with zones containing chalcopyrite and pyrite. Sporadic concentrations of up to 0.7% Co have been found, but orebody intersections never exceed 0.3% Co overall. Most of the orebody contains less than 0.01% Co, whereas the sulphide copper grade is around 4.0%. Ore thickness ranges up to ten metres, increasing above this figure in places close to the basement where mineralization abuts directly against this.

Supergene effects extend to a depth of between 50m and 70m, copper having been almost completely leached from the top 10 - 15m of the orebody. Malachite, native copper, cuprite, chrysocolla and wad occur in the weathered orebody. In addition, irregularly distributed cupriferous mica occurs in the hangingwall sandstone, apparently as a result of lateral migration of copper in groundwater solutions. Grades of between 1% and 2% Cu are common for micaceous mineralization, but the distribution of copper is extremely unpredictable.

7. THE CHINGOLA REGION

The orebodies of the Chingola region occur on the indented west flank of the Kafue Anticline in a number of synclinal basins plunging west to northwest at rather shallow angles. All the deposits considered in this section lie within a single Mining Licence area known as Nchanga and embracing both the Nchanga Syncline and the Mimbula Syncline to the south. Figure 7.1 shows the principal features of the surface geology and occurrence of mineralization in the Nchanga Mining Licence, in which, according to Diederix (1977) there are 14 "conventional" orebodies and three containing refractory copper in micas. All mineralization which can be successfully treated by flotation or leaching or a combination of these methods is referred to at Chingola as "conventional" ore, while the copper in micas is called Chingola Refractory Ore (C R O). Diederix (1977) records the presence of over 20 million tonnes of copper and "significant quantities" of cobalt in the 17 known deposits.

Stratigraphy and Structure

The Lower Roan at Nchanga lies on a basement surface with considerable relief, but the shape of the basement surface appears to have been altered by subsequent deformation also affecting the Lower Roan sediments. As well as Lufubu schists, McKinnon and Smit (in Mendelsohn, 1961) recognize three different granites within the Nchanga Mining Licence area, and rocks assigned to the Muva system have also been recognized at Mimbula.

At the base of the Lower Roan is a basal conglomerate overlain by a well bedded arkose derived mainly from weathering of the granites. It is not clear from the available accounts exactly what the maximum thickness of these units is, but there is certainly wide variation in the thickness of these units as a result of basement topography. McKinnon and Smit suggest that the total thickness of these basal units exceeds 1200m in places, whereas Diederix appears to suggest that not more than about 350m of basal clastics are present. The Arkose formation filled all the basins between basement hills, so that by the close of deposition of the Arkose formation the surface on which subsequent Lower Roan sedimentation took place had very low relief. A number of orebodies occur within the Arkose formation, which in the Mimbula syncline is subdivided into several distinct lithological units.

Although the stratigraphic units of the Lower Roan can be correlated between the Nchanga and Mimbula synclines, in the intervening Chabwanyama region

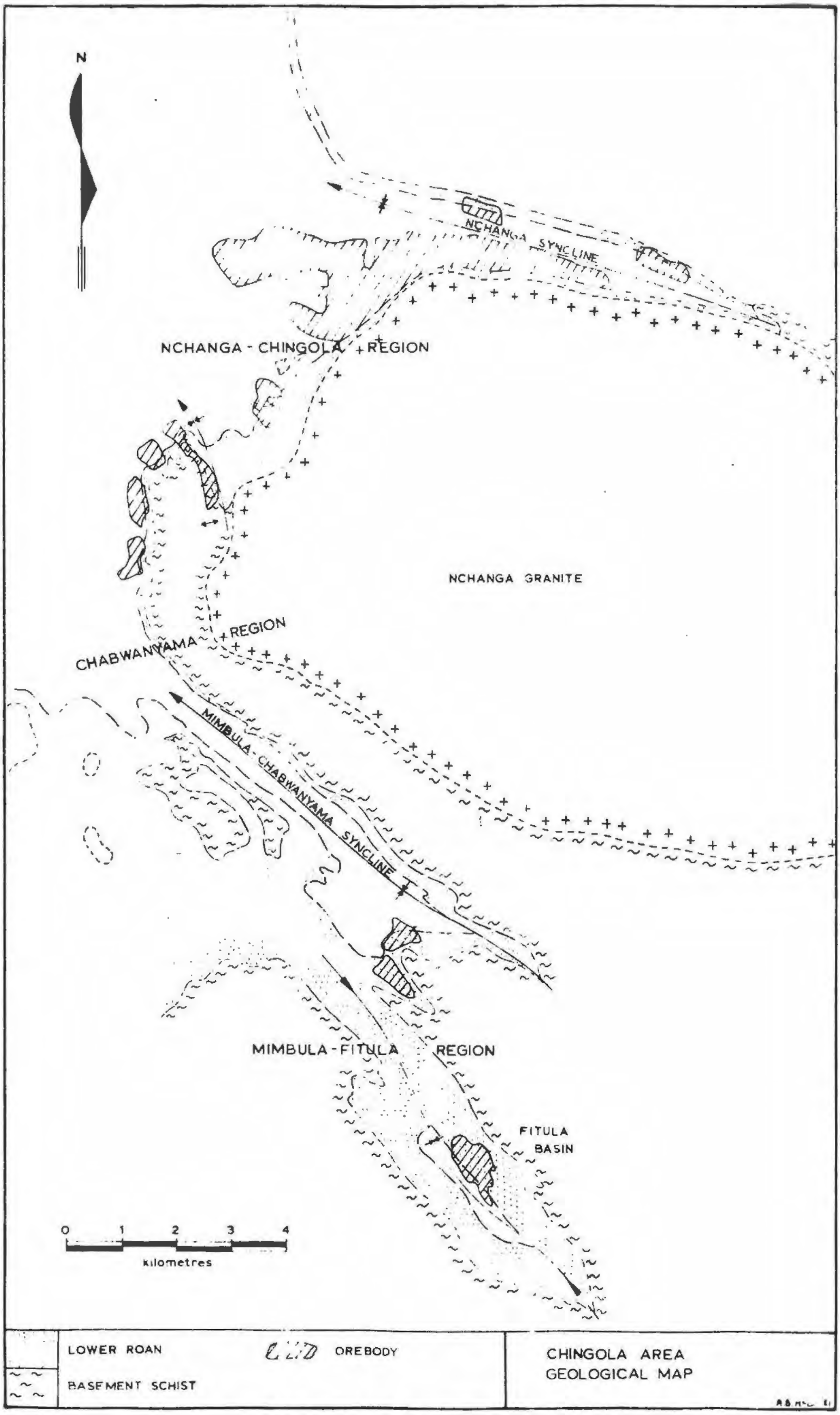


Fig. 7.1. - Geological map of the Nchanga area.

thickness and facies differences make some correlations doubtful. The type succession is considered to be that derived from the Nchanga open pit and underground mining operations, reproduced as figure 7.2. Mineralization in this area (shown in black on figure 7.2) extends over a vertical stratigraphic interval of more than 150 m in several different host lithologies.

Overlying the Arkose formation is a unit referred to as the Transition, now divided into two subunits. The lower Transitional Arkose is an incoherent limonitic and micaceous kaolinized arenite,overlain by a bleached and silicified sandstone - shale unit known as the Transitional Lower Banded Shale. The Transitional Arkose is regarded by Diederix as an "evaporite collapse breccia" formed by leaching of evaporite minerals from a calcareous sandy or silty unit. Together, the Transition units have a maximum thickness of 18m.

The Transitional Lower Banded Shale grades upwards into the Lower Banded Shale, a dark indistinctly laminated argillaceous rock of rather variable composition. It consists principally of varying proportions of quartz and sericite and may also contain substantial amounts of carbon. Although the formation is widespread over the area of the Mining Licence and can attain a thickness of 35m, it is locally completely absent or replaced by a thin band of dolomitic quartz-mica schist. McKinnon and Smit describe the presence of leached zones at the top and bottom of the Lower Banded Shale, apparently only where it is mineralized. They also mention siliceous "geode" cavities in both the Transition and at the top of mineralized Lower Banded Shale, and these geodes may contain malachite or pyrite. The Lower Banded Shale is regarded as the equivalent of the "ore shale" horizons in the Chambishi-Nkana and Roan-Muliashi basins, but does not everywhere have typical "ore shale" characteristics. Over basement ridges the unit appears to become thinner and more quartzitic.

Above the Lower Banded Shale is a discontinuous layer, up to six metres thick, of porous, microcrystalline quartz with muscovite flakes and hydrous iron oxides. This is known as the Brown Chert or Chert Marker, and is regarded as a siliceous residue or a silicification product of a carbonate unit.

The Banded Sandstone unit overlying the Chert Marker is up to 50m thick and is subdivided into four distinct lithologies. The Banded Sandstone (Lower) consists of thinly bedded feldspathic sandstones and siltstones,

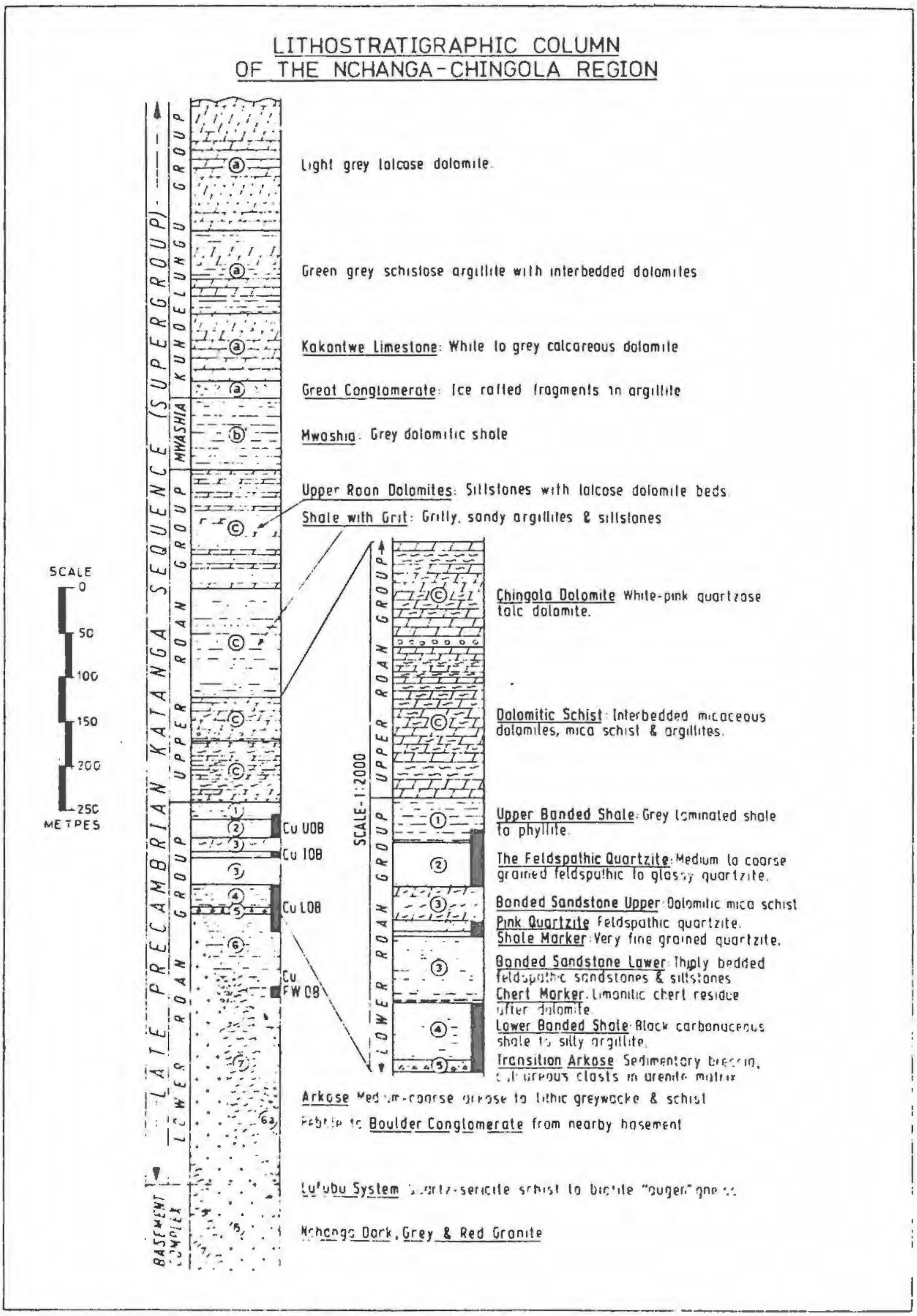


Fig. 7.2. - Lithostratigraphic column of the Nchanga-Chingola Region (from Diederix, 1977)

cemented by carbonate and anhydrite. Alteration of this rock to an incoherent mass, through leaching of the cementing minerals, extends to at least 600 m vertically below surface. The Shale Marker, which occurs at the top of this unit, is petrologically a fine-grained micaceous quartzite with distinct bedding, and is overlain by the Pink Quartzite, a well sorted feldspathic quartzite. Both these units are fairly persistent throughout the Nchanga Mining Licence. Over them lies the Banded Sandstone (Upper) which is generally similar to the Lower unit but contains more vermiculite and may also contain a substantial concentration of scapolite. The Banded Sandstone can be quite schistose in places whereas the Pink Quartzite has developed many joints during deformation. Both the Banded Sandstone units and the Pink Quartzite show cross-bedding and channel sand deposits indicative of lacustrine and low-energy stream deposits.

The overlying Feldspathic Quartzite unit from 8 to 40 m thick, is a well-sorted sediment containing up to 50% feldspar. It has a gradational lower contact and may in places be seen to consist of three distinct units, according to Diederix (1977). The Black Marker is a hard, massive, silty, dolomitic quartzite up to 4.5 m thick but only locally developed. Ripple marking is common on this unit, which pass up into the Feldspathic Quartzite Transitional, a brown to grey feldspathic quartzite with argillaceous bands. From 4 to 8m of this occur beneath the Feldspathic Quartzite sensu stricto, which is a medium to coarse grained, sometimes feldspathic, sandstone or quartzite. It has pronounced bedding and also contains large scale cross-bedding and major channel deposits.

The Upper Banded Shale, 15 to 40m thick, is the uppermost unit assigned to the Lower Roan at Nchanga, and is a grey, laminated, thinly bedded shale consisting of quartz, microcline, muscovite and vermiculite. Towards the top, interbedded dolomite layers start to develop, and this rock unit grades very gradually into the Upper Roan group, which is a predominantly dolomitic unit as elsewhere on the Copperbelt.
From 250m to 400m or more of Upper Roan dolomitic sediments separate the Lower Roan from the Mwashia, which is known only from one borehole at Nchanga.

Gabbro bodies are known in Upper Roan sediments to the west and southwest of Nchanga. Diederix (1977) describes these as sills and considers that they are younger than folding. According to Garrard (1972) these rocks are more or less altered to a rock consisting of hornblende, scapolite and epidote. In the Nchanga Syncline, dykes of basic composition, referred to as lamprophyre although not of this composition, are known to occur. At least one of these cuts the Lower Roan and according to Diederix is of post-folding age.

South of the Nchanga Sycline, the principal differences in stratigraphy of the Lower Roan group are as follows :

- in the Chabwanyama region the Lower Banded Shale and Banded Sandstone formations are represented by a thin (2 - 10m) dolomitic quartz-mica schist. The Feldspathic Quartzite also thins to an average of only eight metres thickness.

- in the Mimbula Syncline the Arkose formation is subdivided into several recognizable and fairly continuous lithological units, while the overlying Lower Roan sequence is somewhat thinner than its typical development in the Nchanga Syncline.

- the Upper Banded Shale is either absent or represented by a somewhat different facies in the Chabwanyama area.

Figure 7.3 shows schematically the principal structural features of the Chingola region and the locations of orebodies.

Three major synclinal structures are recognized, called the Mimbula, Chingola and Nchanga synclines. Each has developed in the same location as a sedimentary basin active during Lower Roan times. Thus it is evident that basement topography has exerted an important control both on Roan sedimentation and on the configuration of the structures generated during deformation. Garrard (1972) suggests that basement topography may have had important effects on sedimentation which are now reflected in the distribution of copper minerals. Basement highs not only defined the sedimentary basins, but also may have controlled the flow of water from open sea and hence the salinity of each basin. Segregation of brines could have produced various slightly different chemical environments at different times and places. Precipitation of metals could be related to specific evaporite chemistry, and the resultant rock composition might also have affected mineral zonation.

Basement topography has clearly had an effect on the folding which resulted from deformation, but other factors including sediment compaction and competency contrasts have also affected fold shapes. As at Luanshya, the basement appears to have in places behaved in a highly competent manner, whereas at other localities it has been sheared and deformed with frequently

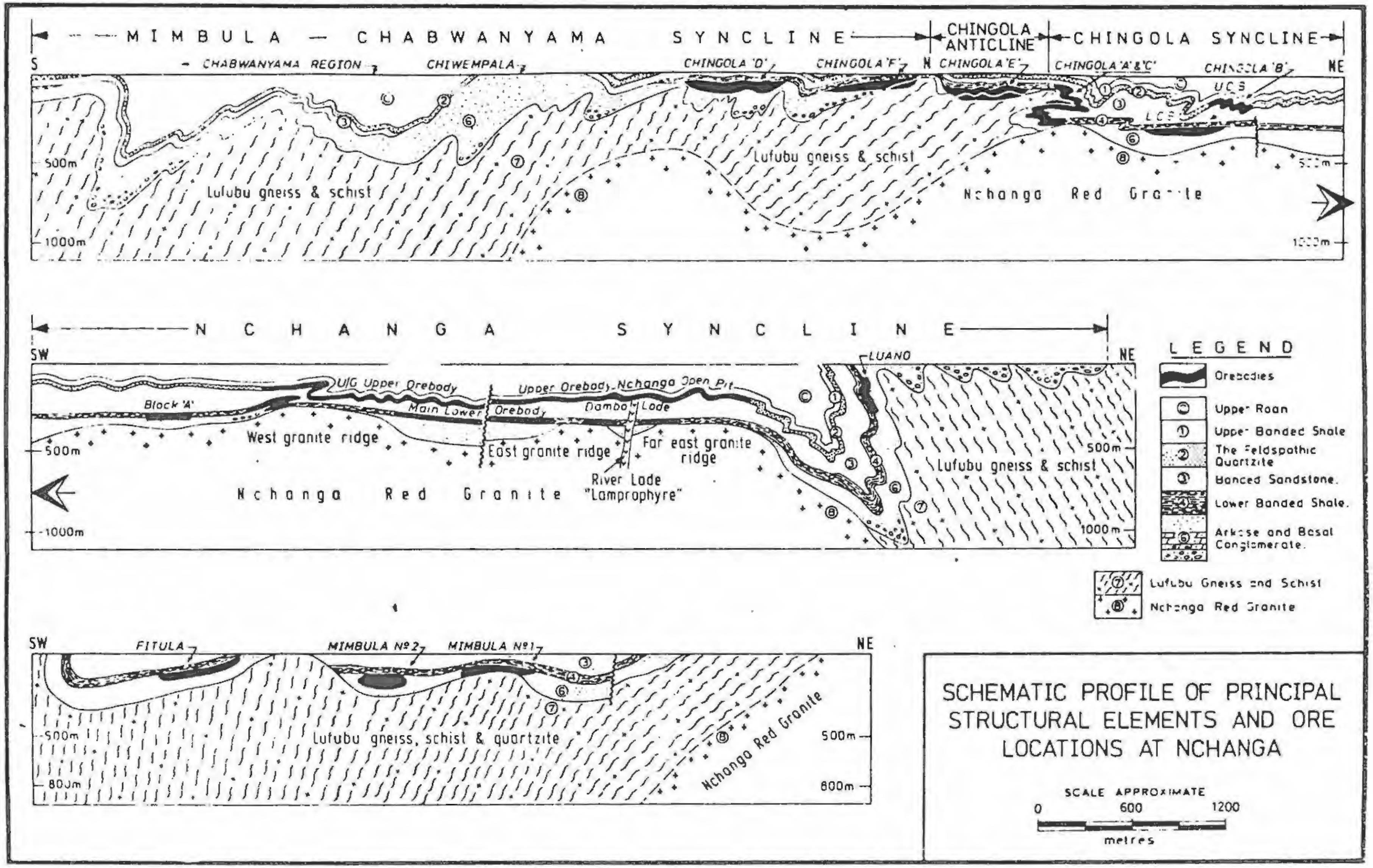


Fig. 7.3. - (From Diederix, 1977)

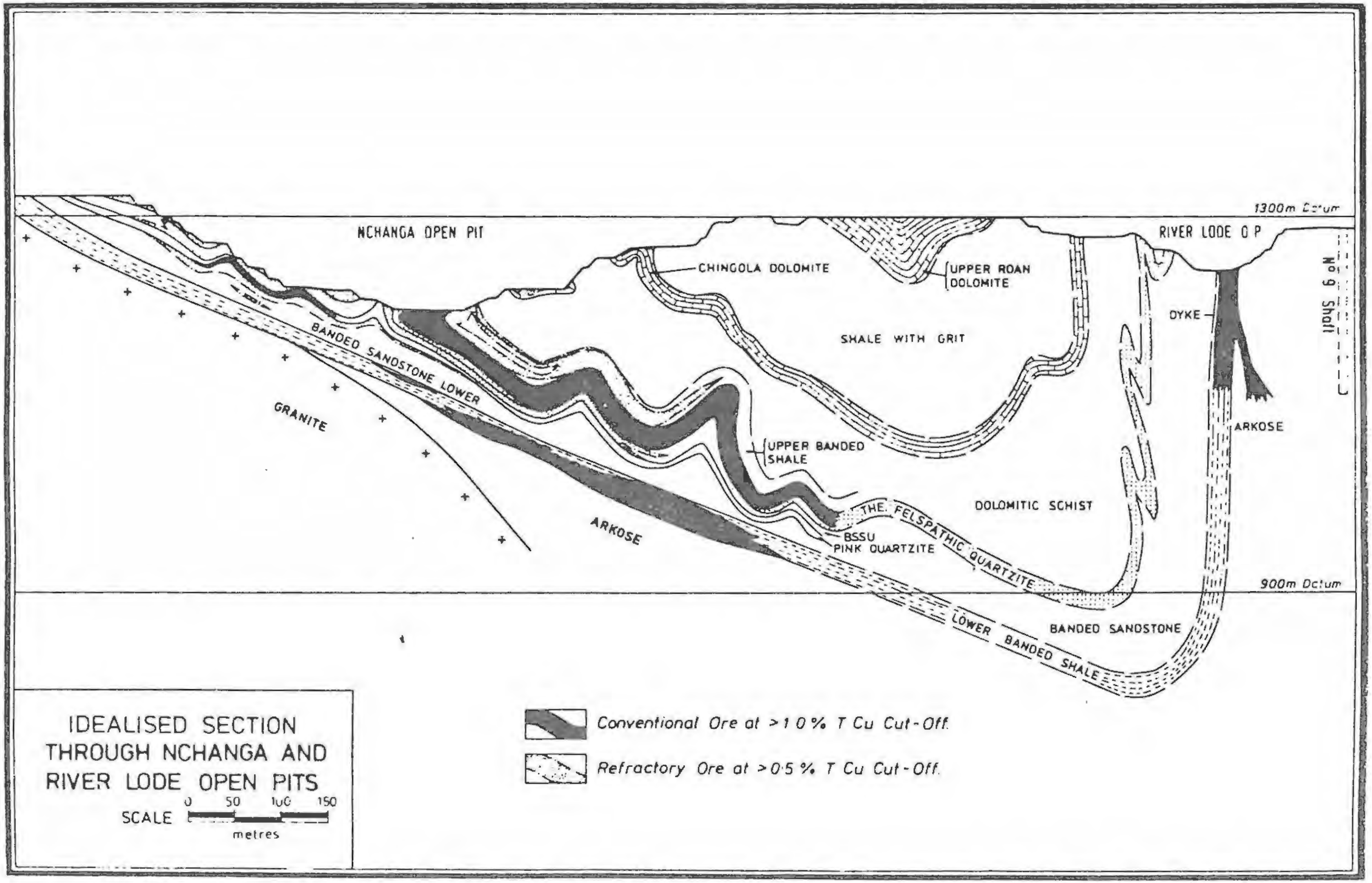


Fig. 7.4. - (From Diederix, 1977)

little effect on overlying ore.

Only one significant fault zone is known, towards the west end of the Nchanga sycline. It is approximately parallel to the axis of the syncline.

Nature and Distribution of Mineralization

The Nchanga Syncline is the largest and most extensively mineralized structure in the Chingola region. Three major orebodies have been mined, and a fourth is known which is so far unexploited. Figure 7.4 shows the exploited orebodies in the Nchanga syncline and also the occurrence of refractory mineralization which is at present stockpiled.

The Lower orebody consists of mineralization in the Arkose, Transitional Arkose and Lower Banded Shale, and is exploited both undergroundand in the Nchanga Open Pit. Because caving of the Lower orebody can be very readily induced, it is possible to employ a caving method of mining which does not involve developing through the orebody. For this reason the Lower orebody underground is known almost exclusively from drillholes and the distribution of mineralization is therefore less well known than in other orebodies. According to Diederix (1977) approximately 55% of the contained copper is in the Lower Banded Shale, 15 per cent in the Transition and 30 per cent in the Arkose. The orebody extends along more than four kilometres of strike and at least 2.3km down dip, with a thickness which ranges from 0.5m to 45m. Extremely large variations in thickness are known over short distances, but the orebody is relatively underformed as shown in the diagram. To the west this orebody terminates against a granite hill, but to the east, although a granite ridge forms part of the fringe, patchy mineralization continues beyond the ridge.

The orebody mined from underground is divisible into two distinct areas, west and east of the Main Nchanga Fault zone. West of the fault mineralization in the Arkose thins over basement ridges and wedges out entirely against a granite ridge at its extremity, whereas east of the fault no palaeogeographical control on mineralization is evident and mineralization in the arkose is more consistent in thickness. West of the fault, Arkose mineralization ranges from zero to 20m in thickness and thins towards the fault. Mineralization is described by Diederix as "disseminated chalcopyrite and cupriferous pyrite blebs with subsidiary bornite and chalcocite in a well sorted arkose orfeldspathic quartzite". East of the fault, mineralization in the arkose is principally chalcocite with subsidiary malachite, bornite and azurite in a micaceous and feldspathic lithology. Mineralization in the Lower Banded Shale is less well known in detail, and takes the form of fine disseminations and veinlets of chalcocite, except where the host rock is bleached and silicified. In these areas blebs of bornite plus chalcocite, or malachite plus cuprite are found. Chalcopyrite is found at both lateral and vertical fringes of the Lower Banded Shale ore, which characteristically becomes pyritic outside the copper mineralization. Eastwards, the Lower orebody mineralization becomes patchy and is evidently controlled by basement topography. Mineralization occurs in the same lithologies as further west, and also within a dike of "lamprophyre" which carries "oxide" copper minerals and native copper for at least 80 m below the lower orebody. The best development of mineralization in the sediments occurs around this intrusive body, which has also apparently introduced copper for tens of metres laterally into the adjacent arkose below the Lower orebody. Minor faulting of the Lower orebody is known in this area. Cobalt mineralization, principally in the form of carrolite, occurs in substantial amounts at the fringes of the Lower orebody, with grades of up to 2% Co being known.

Nchanga Open Pit exploits principally the Upper orebody shown in figure 7.4, which consists of malachite, chalcocite and bornite mineralization, with some "oxide" copper minerals, in the Feldspathic Quartzite. Mineralization at this stratigraphic level is extremely extensive, occuring over a strike length of 7000m in the Nchanga Syncline and to a minor extent in the Chingola Syncline. Supergene alteration of mineralization is commonly suggested to explain the leached and oxidised nature of this orebody,and lateral zoning of mineralization has been observed at depth. Towards the margins of the orebody, chalcopyrite becomes the predominant copper sulphide, while significant cobalt mineralization also occurs predominantly on the down dip fringe, as carrolite. Tight and sometimes overturned folds are a characteristic feature of this orebody, which is separated from the Lower orebody by a zone of decollement. The Upper orebody extends into the area exploited by underground mining, where the highest grades tend to occur in the top three metres of the Feldspathic Quartzite and the bottom three metres of the Upper Banded Shale. Mineralization which does not attain the present ore cutoff grade of 1.5% total copper is present over a very wide area, and occurs near the base of the Feldspathic Quartzite. Throughout the orebody, bornite and chalcopyrite occur disseminated through the rock, but with "oxide" minerals developed on joints and bedding planes.

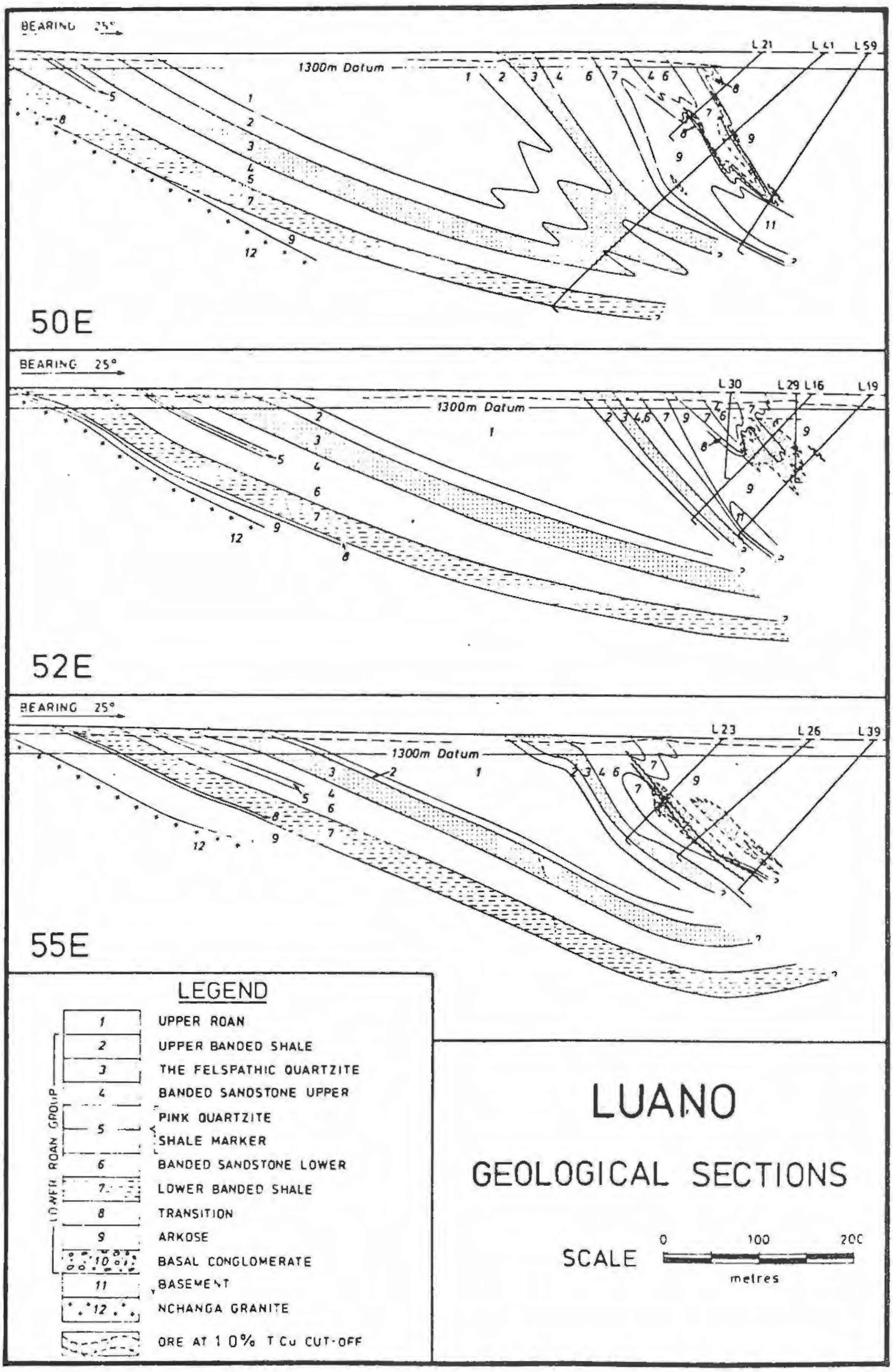


Fig. 7.5. - (From Diederix, 1977)

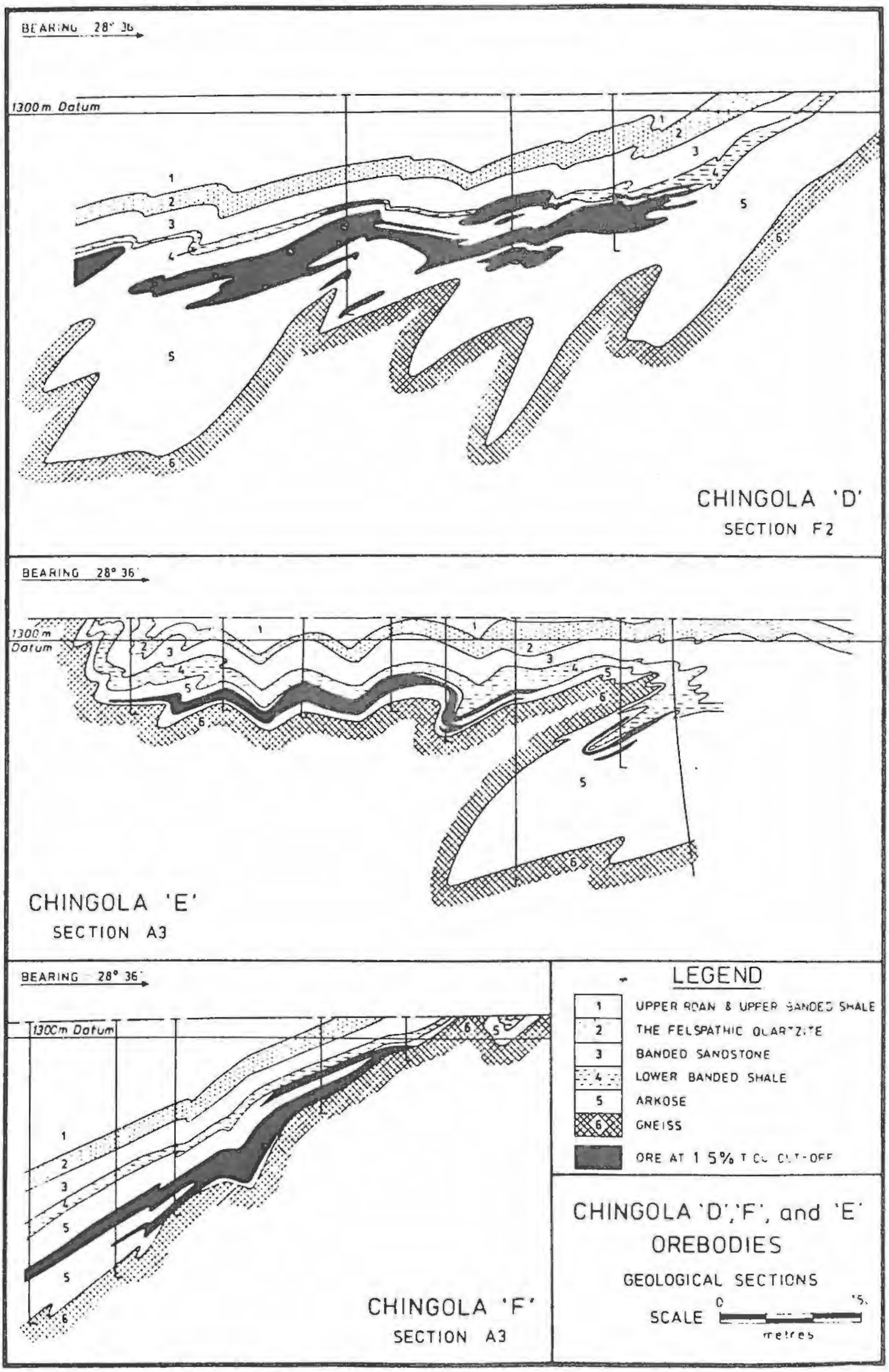


Fig. 7.6. - (From Diederix, 1977)

The Intermediate orebody which is present in part of the Nchanga Open Pit is also highly folded. Mineralization is hosted in the Shale Marker and Pink Quartzite lithologies, and is in fact very widespread. However, it attains ore grade only on the south limb of Nchanga Syncline and in isolated patches on the north limb and east of the main occurrence. Malachite and chalcocite are the principal ore minerals, but some chrysocolla and other "oxide" minerals occur, and cobalt mineralization is also known.

On the north limb of the Nchanga Syncline mineralization is known at River Lode (shown on figure 7.4) and at Luano, some 3 km east of the River Lode Open Pit. The ore at River Lode is hosted mainly in Lower Banded Shale and to a lesser extent in the Transitional Arkose, and some mineralization is also known in a "lamprophyre" body which intrudes the Lower Roan. In the sediments, ore minerals are malachite and chalcocite within about 60m of surface, but bornite and chalcopyrite predominate below this depth. The ore has an average thickness of 17m, thinning at depth and to west and east. Lenses of high grade chalcocite ore of varying thickness occur within the arkose, and the intrusive body carries malachite, cuprite and chrysocolla near surface, but bornite,chalcocite, malachite and traces of chalcopyrite occur at depth. The mineralization at Luano occurs in a similar stratigraphic position to that at River Lode but is hosted in a strongly folded and partially overturned succession and has a rather irregular outline. Figure 7.5 shows a typical section through the Luano orebody, the mineralization of which is in the form of "oxide" copper minerals with chalcocite plus minor chalcopyrite and bornite.

In the Chingola Syncline several comparatively small orebodies have been found, most of the mineralization being hosted in the Arkose. These orebodies are all stratiform but tend to be of irregular thickness and may split or degenerate into isolated lenses of mineralization at their fringes. Figure 7.6 shows typical sections of the Chingola "D","E" and "F" orebodies. Chingola "E" orebody is the only one of these currently mined, with "oxide" minerals near surface and chalcocite plus chalcopyrite with some bornite appearing at depth predominantly in Arkose. At its fringes this orebody generally diminishes in grade and thickness, except that where mineralization extends to the basement it may continue for a short distance into basement rocks immediately below the Arkose. Copper mineralization locally extends into the Lower Banded Shale, and carrolite has been found at fringes in the basement. A significant part of the copper content outside the Arkose occurs in the form of mica mineralization. The Chingola "D" and "F" orebodies are similar in lithological association of mineralization, with variable proportions of the total copper present in micas. Leaching occurs to a depth of at least 40m, bornite and chalcopyrite being the principal sulphide minerals below this depth. All these orebodies have been deformed to some extent but appear to be of an irregular original shape, clearly related to basement-controlled depositories in some cases.

The Mimbula I, Mimbula II and Fitula orebodies occur in the Arkose formation in the Mimbula syncline, but each is distinctly different from the others in both lithological associations and mineralogy. Fitula orebody is confined exclusively to a single unit in the Arkose, as shown in figure 7.7 The mineralized unit is a massive, medium grained sericitic and feldspathic sandstone, of which about 5m thickness contains chalcopyrite, bornite and some chalcocite. Massive chalcopyrite - bornite ore occurs towards the base of mineralization, particularly in small synclinal depressions, while higher up sulphides are disseminated through the rock. The ore is pyritic and becomes cobaltiferous at the fringes, where mineralization thins and rises above the base of the host unit. Disseminated mineralization tends to be erratically distributed, but both footwall and hangingwall cutoffs are sharp. Immediately above the mineralized horizon is a dark grey micaceous argillite which is in appearance very much like the shale horizon elsewhere. A minor amount of refractory ore is known at the east side of the pit where mineralization approaches the surface.

Mimbula I and II orebodies both consist of several superimposed irregular lenses of mineralization, in the case of Mimbula I lying over a basement ridge whereas Mimbula II lies in a syncline. At Mimbula I, shown in figure 7.7, the Arkose formation is draped over the basement ridge and slightly downwarped on either side of the ridge, over which mineralization is continuous. Three distinct mineralogical zones are recognized in this orebody :

- vermiculite "ore", not containing macroscopically detectable copper minerals.
- "oxide ore", containing mainly malachite
- sulphide ore consisting of disseminated bornite and chalcopyrite.

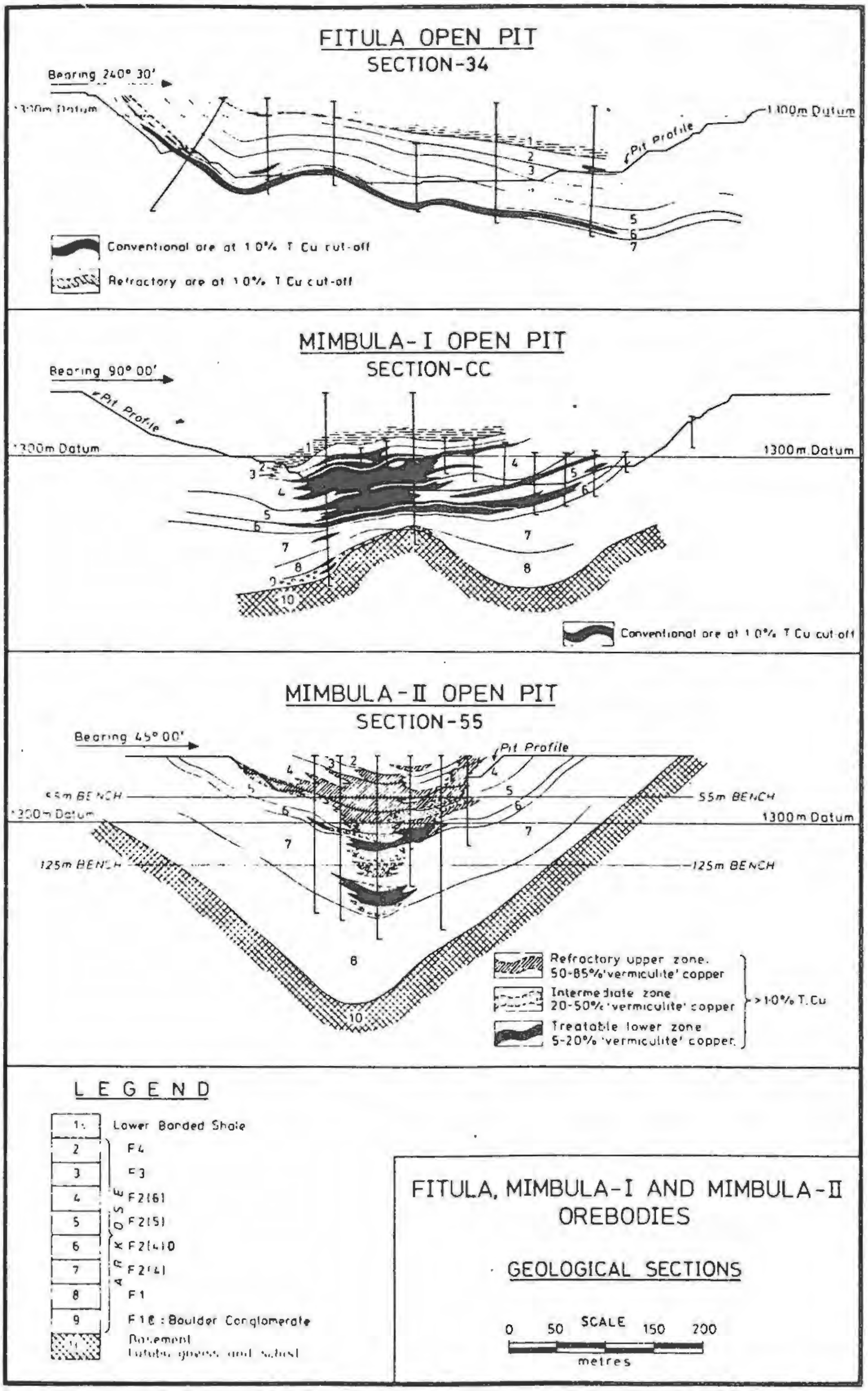


Fig. 7.7. - (from Diederix, 1977)

Mineralization at Mimbula I is extensively developed in the same formation as that at Fitula, and in the overlying argillites and schists. As the section shows, ore is irregular in outline and only locally stratiform. The Mimubula II orebody occurs over a similar stratigraphic interval, as indicated in figure 7.7, but is symmetrically disposed about a synclinal fold axis and forms rod-like shoots parallel to the plunge. Mineralization is of similar type to that at Mimbula I, with a fairly substantial proportion of the copper in vermiculite. The beneficiation properties of the ore are such that it is not at present economic to treat, only about one third of the contained copper being readily recoverable.

8. CHILILABOMBWE - KONKOLA REGION

The orebodies of the Chililabombwe-Konkola region are draped around the northwestern extremity of the main basement exposure in the Kafue Anticline and on the eastern side of the Konkola Dome. Mineralization may be continuous across the base of the intervening saddle of Katanga sediments. More than 1000 million tonnes of ore-grade mineralization are thought to exist in this area at a grade of around 3% copper, but very considerable groundwater problems will make extraction difficult or impossible.

Stratigraphy and Structure

The footwall sequence of pebbly conglomerate, arkosic grit and feldspathic quartzite is more than 600m thick, and the basement is known only from one borehole. Mineralization is thus not obviously associated with any feature of basement topography. A feldspathic quartzite, usually banded and sometimes calcareous, is the principal component of the footwall sequence. Schwellnus (in Mendelsohn, 1961) distinguished a basal conglomerate separated by a disconformity from the arenaceous sequence above, but included a variety of lithologies interbedded with conglomerates. It seems unlikely that he was

System	Series	Group	Formation
KATANGA	Kundelungu	Lower	*Basal Conglomerate* and locally, shales.
	Mine	Mwashia	Not recognized except for some lenticular, finely bedded quartzites in a series of Mwashia or Kundelungu laminated shales.
		Upper Roan	Dolomitic shales, sandstones, and impure crystalline dolomites.
		Lower Roan	*Banded Shale and Sandstone:* Closely bedded silt and sandstone of Ore horizon at the base and dolomitic sandstone to dolomite at the top. (((((((((DISCONFORMITY (((((((((*Footwall Conglomerate/Sandstone:* Footwall conglomerate Footwall sandstone Porous conglomerate. *Footwall Quartzite:* Cross-bedded quartzites, argillaceous sandstones and arkoses with occasional boulder beds. (((((((((DISCONFORMITY? (((((((((
		Basal Conglomerate	*Basal Conglomerate:* Alternating grits, micaceous sandstones, arkoses, and conglomerates with granite, schist and argillite pebbles and boulders.
			UNCONFORMITY
BASEMENT COMPLEX			Granitoid Gneiss and Schist Intruded by Granite and Muliashi porphyry.

Fig. 8.1.- Stratigraphic column for Chililabombwe-Konkola Region (from Mendelsohn, 1961)

discussing a true basal conglomerate, but rather a part of the footwall quartzite succession which includes arkose units and boulder beds. Figure 8.1 shows the principal features of the stratigraphy at Chililabombwe. The Porous Conglomerate is a pebble or boulder conglomerate up to 25m thick, which dies out southwards, whereas the overlying Footwall Sandstone thickens to the south. The Footwall Sandstone unit is a feldspathic quartzite, unconformably overlain by the pebbly Footwall Conglomerate, which is sporadically developed and not present at all in the south.

According to Schwellnus (in Mendelsohn, 1961), the underlying Banded Shale and Sandstone formation, which is about 60m thick, contains traces of copper throughout its thickness.Only the lowest ten metres are economically mineralized, in five distinct lithological units which can be recognized at both Kirila Bomwe and Konkola, Schwellnus describes the Banded Shale and Sandstone formation as cyclic, and it is overlain by a succession of calcareous sediments assigned to the Upper Roan. Anhydrite is common in the footwall sediments, but less so in the mineralized lithologies.

At Chililabombwe the mineralized horizon rests with an erosional contact on Footwall Sandstone or Footwall Conglomerate. It has been subdivided into five units as follows :

- Unit A, the basal unit, is normally a finely laminated bed of calcareous sandstone and siltstone which shows no sign of deformation, but, where it rests directly on the Footwall Conglomerate, is decomposed to a soft brown laminated sandy clay.
- Unit B is a massive banded quart-feldspar-mica siltstone, two to three metres thick and with lateral variations in sand content.
- Unit C consists of grey siltstone and pink calcareous sandstone in alternating bands around 10 cms thick, and grades upwards into Unit D.
- Unit D is a thinly bedded light to dark grey siltstone containing layers and lenses of pink calcareous sandstone. It can be rather compact and massive but in places is extensively leached.
- Unit E is a siliceous siltstone with interbedded dolomitic sandstone. It becomes more sandy towards the hangingwall and grades into the Hangingwall Quartzite.

Mineralization may persist into the Hangingwall Quartzite, which is a laminated or banded rock consisting of sandstone and siltstone layers. It may be leached and kaolinised, and becomes massive feldspathic sandstone towards the top.

Three orebodies have been mined in the Chililabombwe-Konkola region, all of which occur at the same stratigraphic level. Figure 8.2. shows the disposition of known ore around the Kirila Bomwe anticline and on the east flank of the Konkola Dome. Continuity of mineralization across the Lubengele Syncline between the Kirila Bomwe North and Konkola orebodies seems likely, but has not been conclusively demonstrated. The South Orebody dips west or south-west at around 50 degrees and is a rather straight virtually undeformed limb except at the extreme south where it is affected by the western extension of the Luansobe Fault. A typical section through the main part of the South

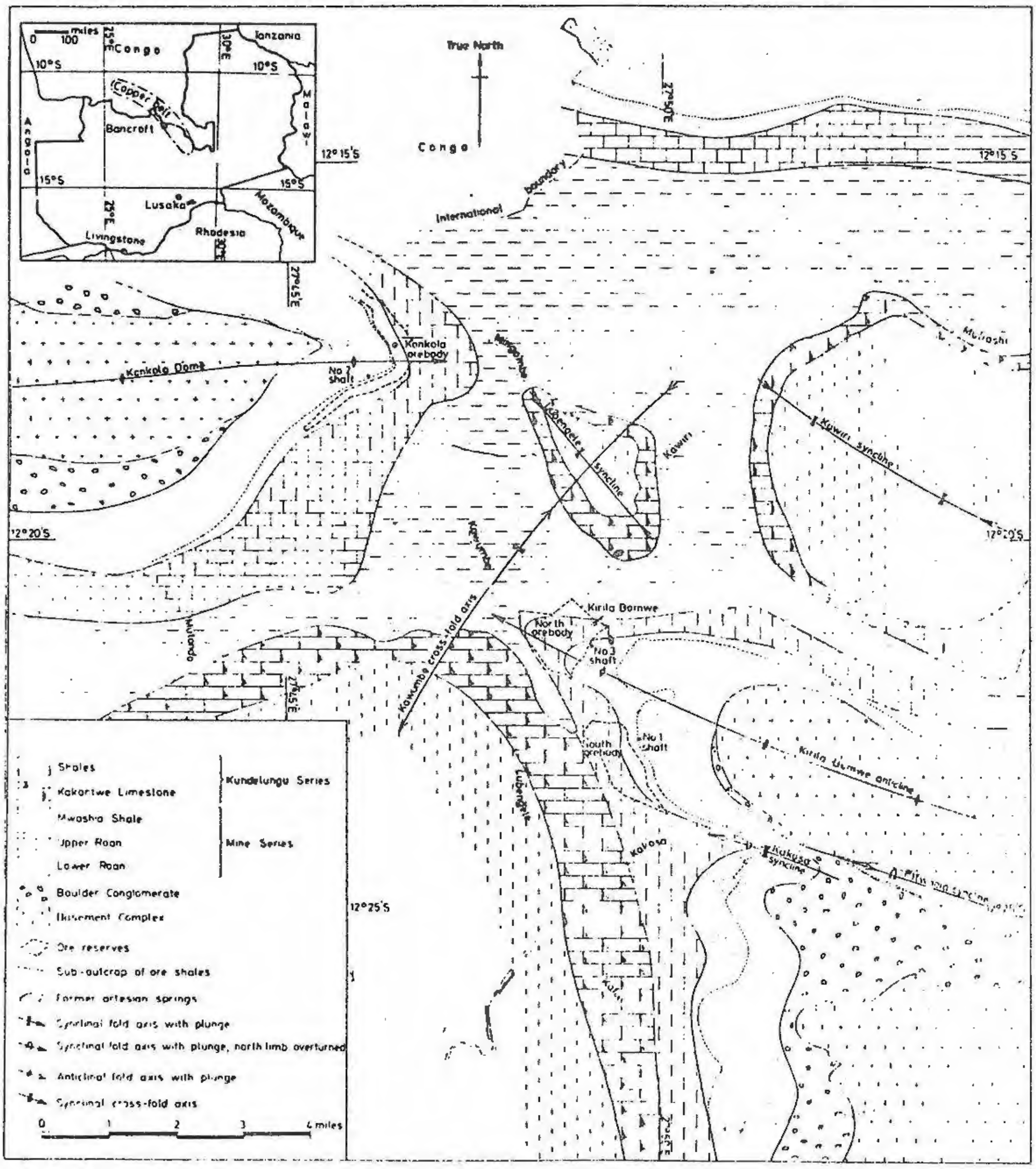


Fig. 8.2. - Geological map of Kirila Bomwe mine area (from Whyte and Lyall, 1969)

Orebody is reproduced in figure 8.3. At its southern extremity this orebody is folded and cut by a number of en echelon faults causing lateral repetition of the mineralized horizon. Figure 8.4 shows the general form of the folding and displacement. The North Orebody is folded around the axis of the Kirila Bomwe anticline and dips at an angle of around 35 degrees near surface. To the west the dip flattens to only ten degrees at depth, but eastwards the dip steepens to as much as 80 degrees in places. The Konkola orebody dips at about 50 degrees into the Lubengele syncline. All three orebodies are in general very little deformed and show no signs of dragfolding. However, complex folding is evident in the hangingwall sequences and the structures here bear no obvious relationship to any folding in the vicinity of the ore. Large thickness variations are evident from boreholes passing through the Upper Roan dolomites, and strongly disharmonic folding is evidently present throughout the Chililabombwe-Konkola region.

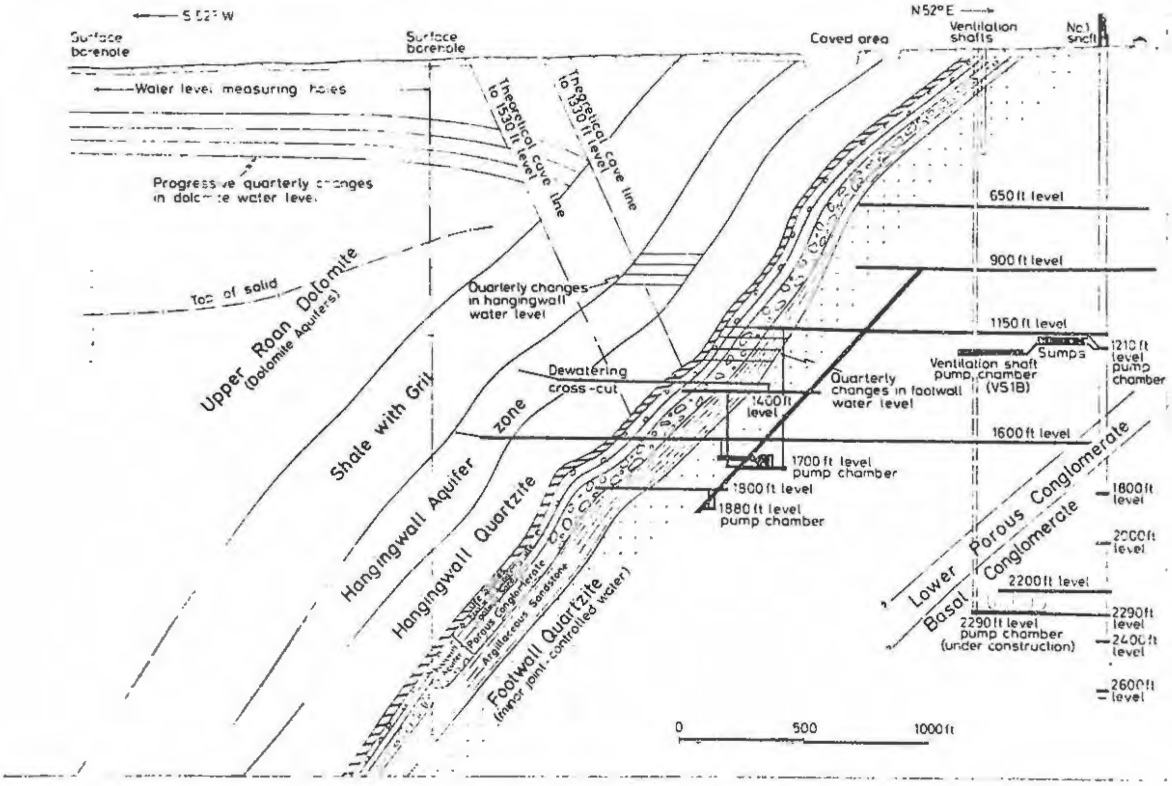


Fig. 8.3. - Geological section (looking N 38° W) through Kirila Bomwe South orebody (from Whyte and Lyall, 1969)

Nature and distribution of mineralization

Copper is not evenly distributed through the five units of the ore horizon. Table 2 shows the distribution of copper mineralization between the various lithological units. The top and bottom units of the ore horizon are

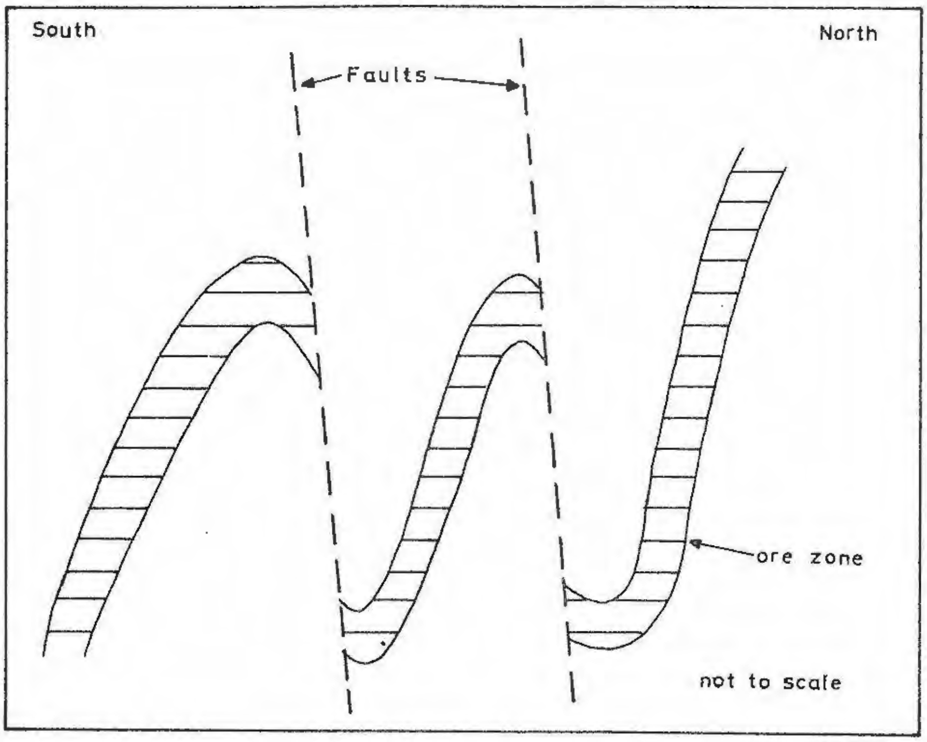


Fig. 8.4. - Schematic section showing repetition of the ore zone by faulting at the south end of Kirila Bomwe South Orebody

Stratigraphic Unit	A	B	C	D	E
Thickness, metres	0.6 - 1.2	1.5 - 3.0	1.5 - 2.2	1.0 - 2.0	0.6 - 1.5
Average total Cu%	1.4	5.6	5.6	2.4	1.3
% total Cu which is acid soluble	90	10 - 20	20	50 - 70	90
Uniformity of mineralization	Highly erratic	Fairly uniform	Fairly uniform	Erratic	Highly erratic

Table 2 - Distribution of copper in the Ore formation at Kirila Bomwe South Orebody (after Schwellnus, in Mendelsohn, 1961)

least consistently mineralized and generally contain less than 2% total copper. In Unit A mineralization is usually in the form of chalcocite disseminations in sandy laminae. Unit B is the most consistently cupriferous horizon and contains disseminated sulphides, predominantly bornite and chalcopyrite. Unit C is also usually mineralized, but sulphides tend to be concentrated on bedding planes, and thin sulphidite layers have been observed. Unit D tends to contain copper carbonates and oxides which are also concentrated on bedding planes and occur as small lenses. However,mineralization is rather erratic and becomes highly inconsistent in Unit E, which also has a low sulphide content. Where only units C and D are mineralized, units A and B are thin and poorly mineralized, but where the A and B units are well developed the whole section contains copper at ore grade. Mineralization is laterally very extensive on a broad scale, but localized barren gaps are known within the South Orebody. These are characterized by the presence of sandy facies of the ore horizon units, and do not appear to have a consistent or predictable pattern. The major barren gap separating the North and South Orebodies at Kirila Bomwe is thought to close off at depth, but approaching the barren gap, mineralization thins and diminishes in grade until it eventually becomes completely uneconomic. The Ore formation is very dolomitic in the barren gap, as it often is in barren areas adjacent to mineralization at other properties on the Copperbelt. Sporadic footwall mineralization is known to occur in the footwall sandstone and conglomerate both in the barren gap and in the South Orebody, but not elsewhere in the Chililabombwe-Konkola Region. The conglomerates become thicker and coarser in the barren gap and at the fringes of the orebody.

Both grade and thickness of the Kirila Bomwe orebodies show a wide range and with the present drillhole spacing in undeveloped areas no clear pattern of variation can be discerned. The mineralized zone attains a thickness of almost 20 m in places, and there is a slight tendency for thicker intersections to have higher copper grades. Individual intersections range in grade from about 2.5% to 4.5% Cu, with somewhat lower grades at the fringes. Cobalt mineralization is significant only in the North Orebody, where bands of cobaltiferous ore occur on either side of the axis of the Kirila Bomwe anticline. Mineralization is sporadic and grades are generally only around 0.1% Co overall, but may exceed 0.2% occasionally. Schwellnus states that cobalt is concentrated in the A and D stratigraphic units.

Metamorphism and oxidation

Metamorphism and deformation appear to have had negligible effects on the distribution of copper. Some remobilization of sulphides into cleavages may have taken place in Unit C, but the distribution of metal is probably altered very little. Schwellnus suggests that more remobilization of copper sulphides may have taken place at the north end of North Orebody leading to development of coarse chalcopyrite and bornite in cleavages. Apart from the faulting at the south end of the South Orebody, the effect of deformation is limited to the development of very gentle rolls in the orebodies.

Supergene effects on the ore in the Chililabombwe-Konkola region are considered by Schwellnus (in Mendelsohn, 1961) to be very considerable giving rise to enrichment along bedding planes and bleaching of the gangue. He does not indicate the depth to which obvious weathering effects extend, but according to Whyte and Lyall (1969) alteration is evident to depths of around 300m in the Upper Roan. Secondary alteration due to normal weathering processes extending to this depth seems unlikely, but alteration by large quantities of circulating ground water is a distinct possibility. Whyte and Lyall in fact record that weathering has extended to depths of 60m or more and suggest that lateral movement of water in this zone may be important in promoting recharge of aquifers, but they do not fully explain the magnitude of the groundwater problem encountered at Chililabombwe.

9. MUFULIRA

The Mufulira deposit is on the southwest side of the Mufulira Syncline, a large asymmetric structure on the northeast side of the Kafue Anticline. The principal features of the surface geology in the Mufulira area are shown in Figure 9.1. Mufulira mine exploits mineralization extending along more than five kilometres of strike, by way of two separate sets of shafts in areas known as Mufulira East and Mufulira West. The Lower Roan on the flank of the Kafue Anticline dips northwest into the Mufulira Syncline at an average angle of 45 degrees in the mine area. Copper mineralization is also known at Mokambo, some 15 km from Mufulira on the northwest side of the syncline. There the Lower Roan sequence dips steeply to vertically and appears to be cut by a northerly-dipping fault. The depth of the Mufulira syncline is not known with any certainty, but mineralization is known to extend to at least 1500m below surface. Brandt et al. (in Mendelsohn,1961) suggest that the trough of the syncline lies over ten kilometres below surface, but there is no sound basis for this estimate.

Stratigraphy and structure

At Mufulira the basal Lower Roan sediments rest on basement consisting mainly of micaceous and chloritic quartz schists assigned to the Lufubu system, but at both the east and west ends of the mine, granitic basement, having an apparently intrusive relationship to the schists, is known. Prior to deposition of the Lower Roan the basement surface had considerable relief. Brandt et al. (in Mendelsohn, 1961) indicate relief of over 100m, with hills dividing the mine area into three distinct depositional basins in which lithologically distinguishable Lower Roan sediments were deposited. A basal conglomerate rests on the flanks of basement hills and occupies hollows in the basement surface, but in places the overlying quartzites rest directly on the basement surface and can be difficult to distinguish from the basement rocks where both units are massive. A sequence of quartzites, argillaceous quartzites and grits which fills the basins between basement hills can be subdivided into three major lithological units in all three of the basins, but individual beds cannot generally be correlated between basins. The basement hills are commonly truncated at the level of the top of the arenaceous sequence filling the basins, and rarely extend more than one or two metres into the overlying sediments of the Ore formation. Figure 9.2 shows schematically the occurrence of the footwall arenaceous sediments and the lateral facies variations between basins.

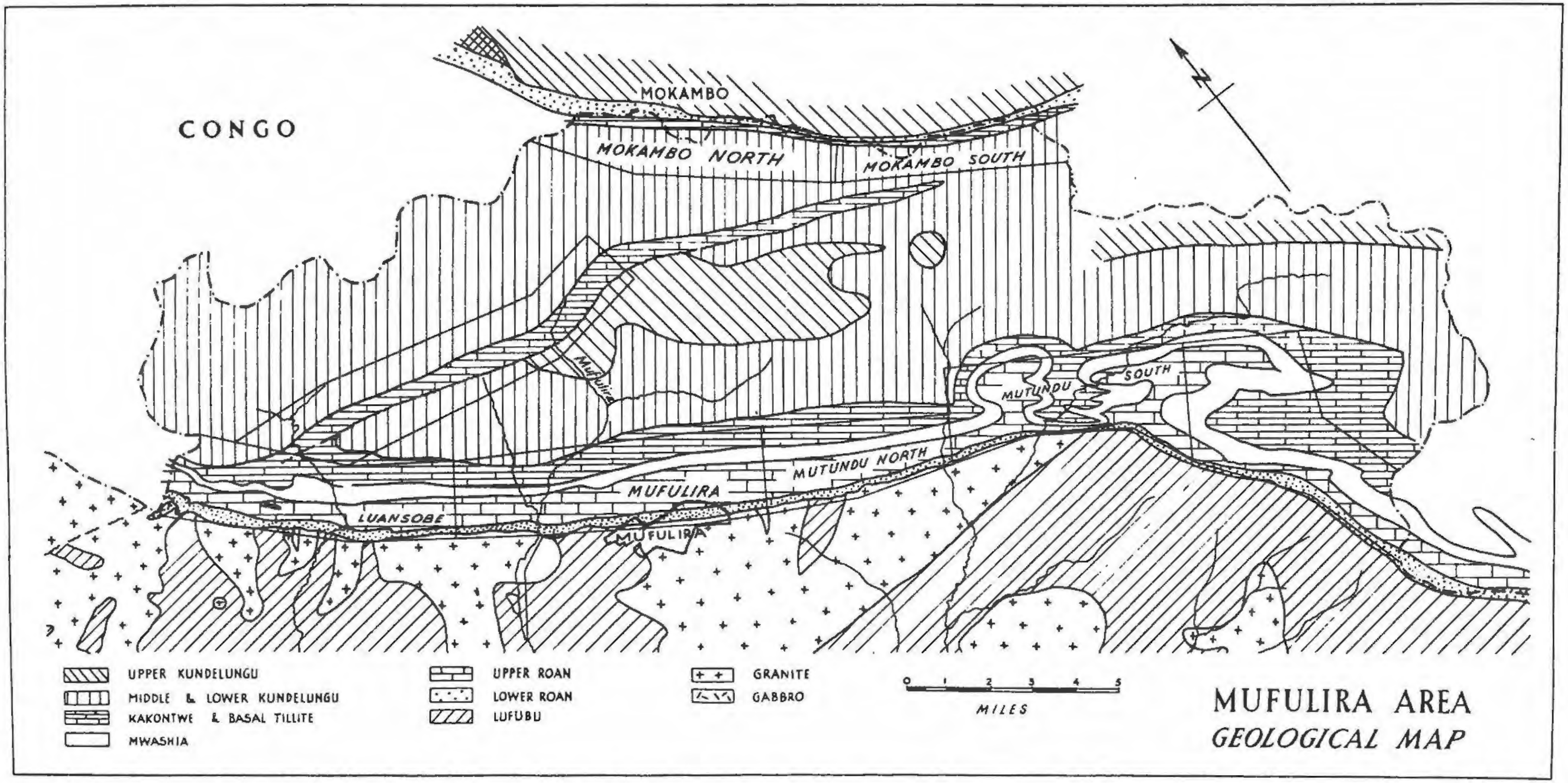


Fig. 9.1. - Geological map of Mufulira area (from Mendelsohn, ed. 1961)

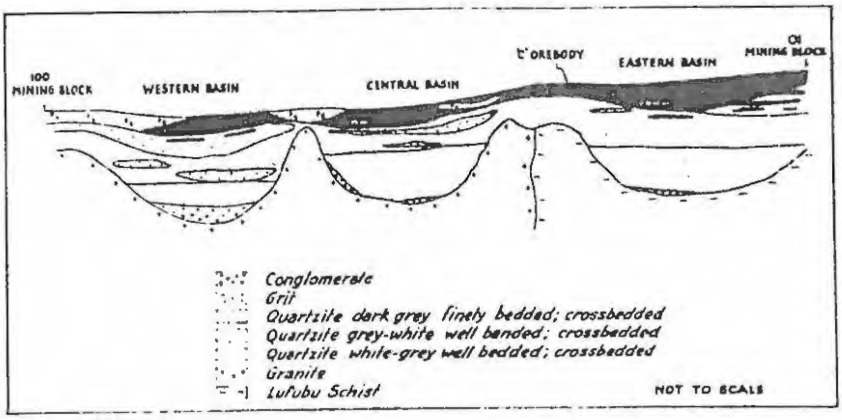


Fig. 9.2. - Lateral facies changes in the Footwall formation at Mufulira (from Mendelsohn, 1961)

The Ore formation at Mufulira consists of a sequence of feldspathic and sericitic quartzites, dolomitic and argillaceous units, and occasional pebbly or gritty horizons. At the top of the Ore formation a transition takes place over a few metres into a more argillaceous sequence which, however, includes several quartzite and dolomite bands. The top of the Lower Roan at Mufulira is marked by a massive grey to white quartzite, on which the dolomitic Upper Roan sequence rests, usually with a rather sharp contact. The typical stratigraphy of the Ore formation and the sequence within which it occurs is shown in figure 9.3.

The C orebody is laterally most extensive, and according to Maree (1962) consists of mineralization in five different lithologies. The Pink Quartzite is only developed in the central basin (figure 9.2). It is a pink feldspathic quartzite characterized by the presence of large scale cross-beds, often with concentrations of sulphides on bedding planes. The "C" Grit is also developed in the central basin over the Pink Quartzite and occurs over a strike length of about 1000m thinning westwards against a basement hill. Its maximum thickness is about two metres, and it consists of rounded to angular quartz and feldspar fragments with occasional fragments of siltstones or shale.

The "C" Grey Quartzite, the most extensive mineralized lithology of the "C" orebody, is a mostly massive grey feldspathic and sericitic quartzite, often cemented by carbonate. Anydrite and gypsum occur in this horizon, particularly where the grade of mineralization is low. This quartzite is the most extensively and uniformly developed horizon hosting "C" orebody

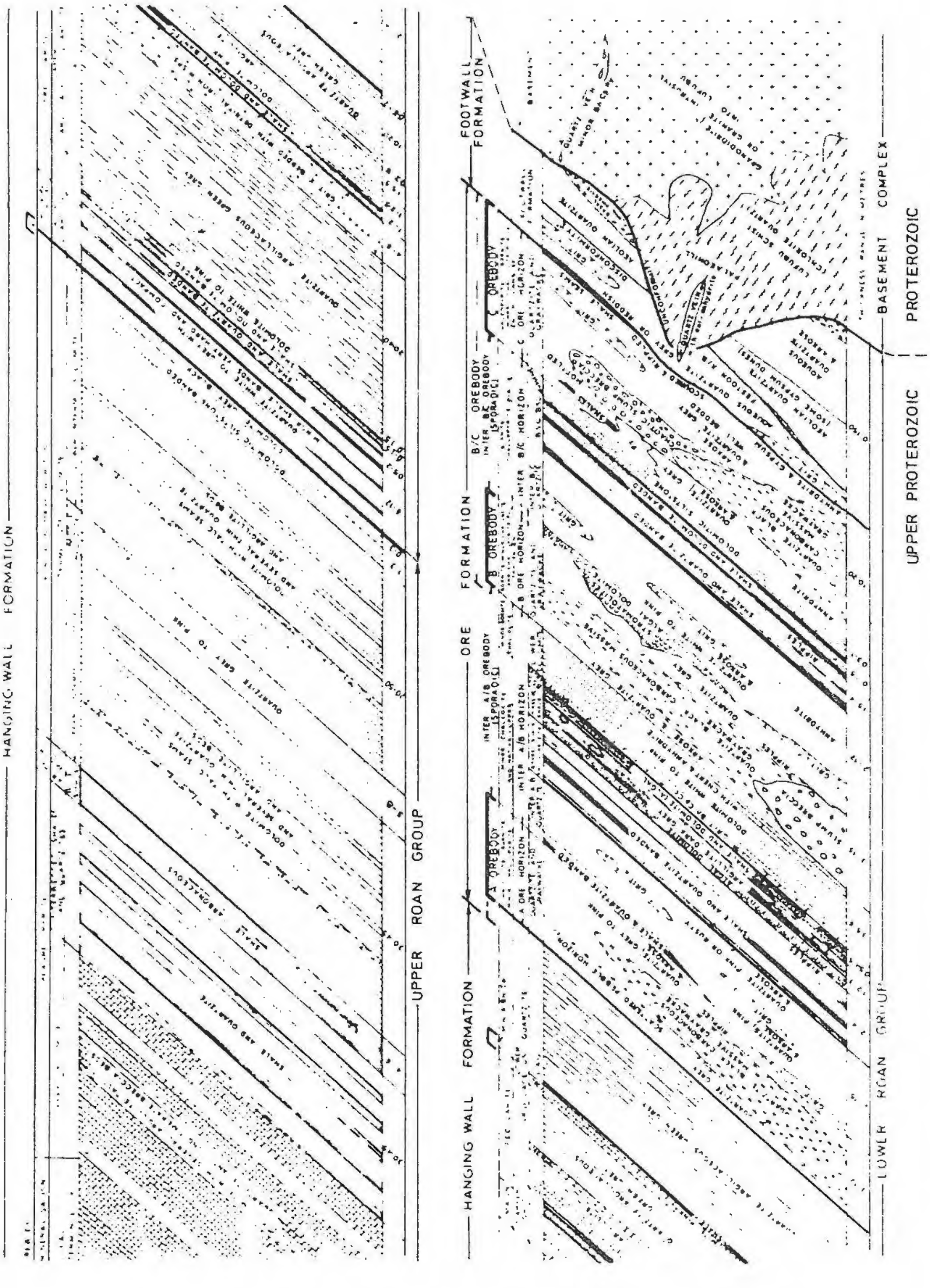


Fig. 9.3. - Generalized stratigraphy at Mufulira mine (modified from Fleischer _et al._, 1976 and Maree, 1962)

mineralization, and extends well beyond the limits of ore. The "C" Greywacke is a black, carbonaceous and argillaceous feldspathic quartzite, often rather massive. Bedding is rarely seen in this unit, which is irregular in its distribution and best developed over the central and eastern basins. The Footwall Grit is an apparently extensive horizon developed somewhat irregularly at the base of the "C" Grey Quartzite, and composed of quartz and feldspar fragments set in a red-brown sandy matrix. It is altered to a variable extent, a phenomenon which Maree (1962) suggests may be due to weathering.

The "B" orebody consists of mineralization in certain stratigraphic units overlying the "C" Grey Quartzite. The bulk of the mineralization is in sericitic quartzite and greywacke units similar to those in the "C" horizon.

The Mudseam is a predominantly dolomitic horizon up to 1.2 m thick overlying the detrital sediments of the "C" horizon. It is a persistent and conspicuous band of dolomitic siltstone, containing chert bands in the east but becoming argillaceous westwards. The bed is decomposed and therefore actually a mud layer in the upper levelsof the mine according to Brandt et al. (in Mendelsohn, 1961). Above the Mudseam in the eastern basin is a horizon called the Inter "B/C" quartzite, which however changes laterally into a shaly dolomitic facies towards the west end of the mine. The "B" Grey Quartzite is a bedded feldspathic quartzite with a slightly calcareous matrix, developed mainly over the eastern basin. It extends over the central basin but thins considerably in this area.

The "B" Greywacke is a black carbonaceous rock similar to the "C" Greywacke, often with a slightly calcareous matrix. This unit is present only in the eastern basin and coincides with the maximum development of the "B" orebody.

Overlying the "B" horizon is a dolomite, referred to as the Lower Dolomite, which is in turn overlain by a shale and dolomite sequence. These units together are known as the Inter "A/B" horizon. Maree (1962) describes thin lenses of mineralized quartzite in the upper part of this formation, particularly towards the centre of the basin. The "A" Grey Quartzite is a compact pink to grey feldspathic quartzite which overlies the Inter "A/B" horizon. It becomes coarser grained, pink and more feldspathic towards the fringes of mineralization,whereas the well mineralized zone is grey and sericitic. The lower part of this unit is well-bedded, calcareous and contains persistent grit bands, but the upper part is massive and contains lenses of greywacke.

The "A" Graywacke may contain a higher concentration of carbon than the "B" and "C" graywackes but is otherwise similar to these in texture and colour. It contains pebbles and boulders, mostly of quartz but granite fragments are also found.

Studies of the sequence hosting the "C" orebody at Mufulira West by Paverd (1965) and Hodgson (1969) indicate some differences in stratigraphy between the eastern and western basins. The fact that the "B" and "A" horizons are absent or of a different facies at Mufulira West was recognized prior to work by the above authors.

The structure at Mululira is relatively simple, as shown by figure 9.4. Folding has involved both the sediments of the Katanga sequence and the basement on which they rest, and is predominantly of concentric type. Brandt et al. (in Mendelsohn, 1961) describe folds plunging northeast at an angle

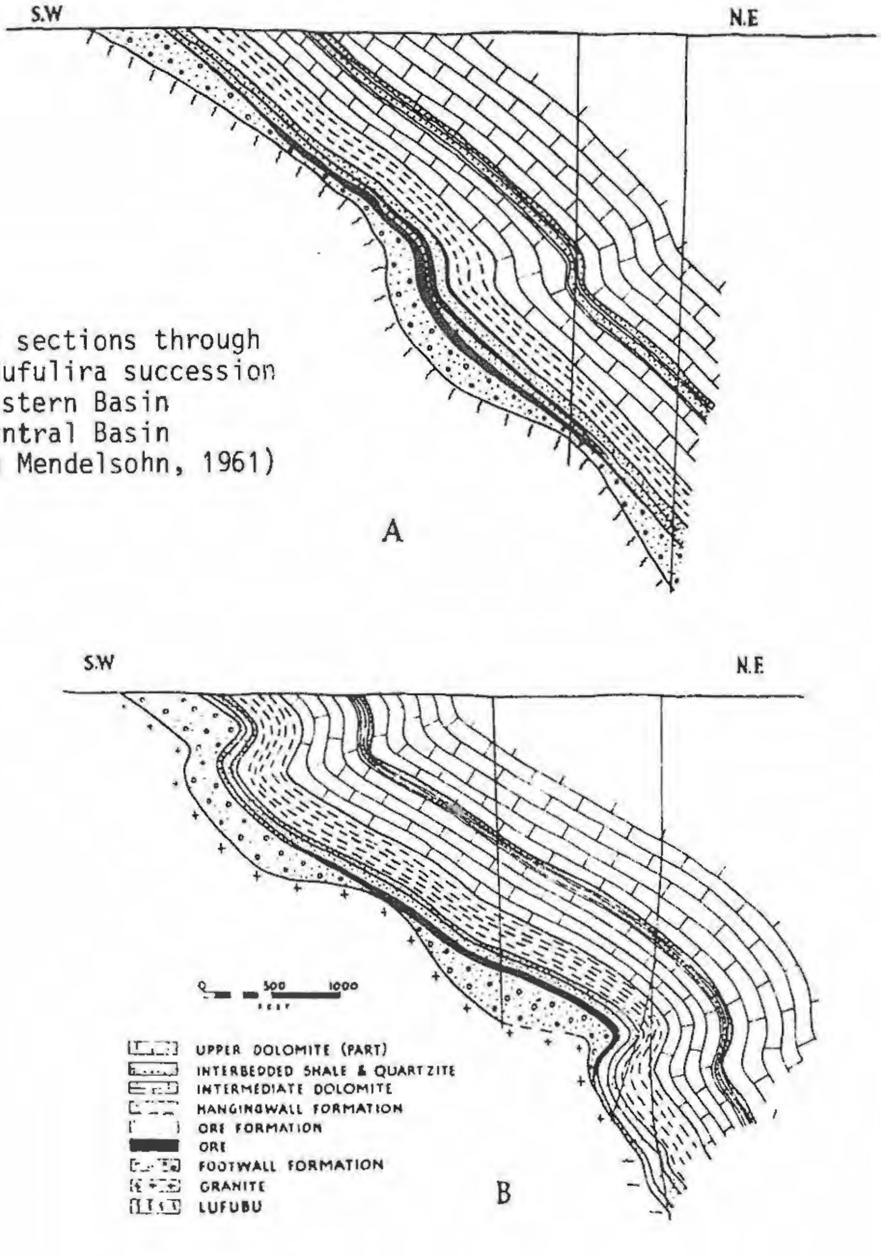


Fig. 9.4. - Cross sections through the Mufulira succession
A. Eastern Basin
B. Central Basin
(from Mendelsohn, 1961)

of ten degrees, but show these folds as of limited strike extent. They suggest that compaction of sediments in the valleys of the pre-Katanga basement surface may have influenced the development of folds. The configuration of basement and the footwall sediments in figure 9.4B suggests, however, that deformation of the basement was not influenced by the positions of basement hills to the same extent as in the Chambishi-Nkana basin.

Nature and distribution of mineralization

The occurrence of mineralization at Mufulira in relation to the basement palaeogeography and host sediments is shown schematically in figure 9.5, which shows that the three orebodies do not have the same lateral extent and that mineralization is not entirely stratabound.

The "C" orebody extends over all three basins and in certain cases also over basement hills. Mineralization pervades joints and fissures in underlying schist and granite where the "C" orebody rests directly on the basement surface. Although both the "C" quartzite and the "C" orebody are of fairly uniform thickness over basement highs and lows, it is nevertheless evident that basement topography has exerted a pronounced control on mineralization. This control is even more striking in relation to the "B" and "A" orebodies, which are developed only over the eastern basin where their host lithologies are also thickest. There is thus a very vague correspondence between the lateral extent of the orebodies and their host units, and a rather more definite association of mineralization with carbonaceous graywacke.

Mineralization at Mufulira shows a marked preference for medium-to fine-grained quartzite horizons as well as conspicuous association with the carbonaceous graywackes identified in all three orebodies. Although ore-grade mineralization shows a strong tendency to be concentrated in three specific horizons, mineralization of sub-economic grade is widely distributed through the stratigraphy. Figure 9.3 indicates some of the more important occurrence of minor mineralization. Fleischer et al. (1976) mention the discovery of mineralization in the Upper Roan hosted by a talcose dolomite and with a grade of over 2% Cu.

Mineralogical zonation is evident both laterally and vertically in all three orebodies, but the most pronounced vertical zonation is between the orebodies. The "A" orebody contains dominantly chalocite, while in the "B" and "C" orebodies bornite and chalcopyrite are the principal ore minerals. Paverd (1965) identified a vertical zonation in the "C" orebody at Mufulira

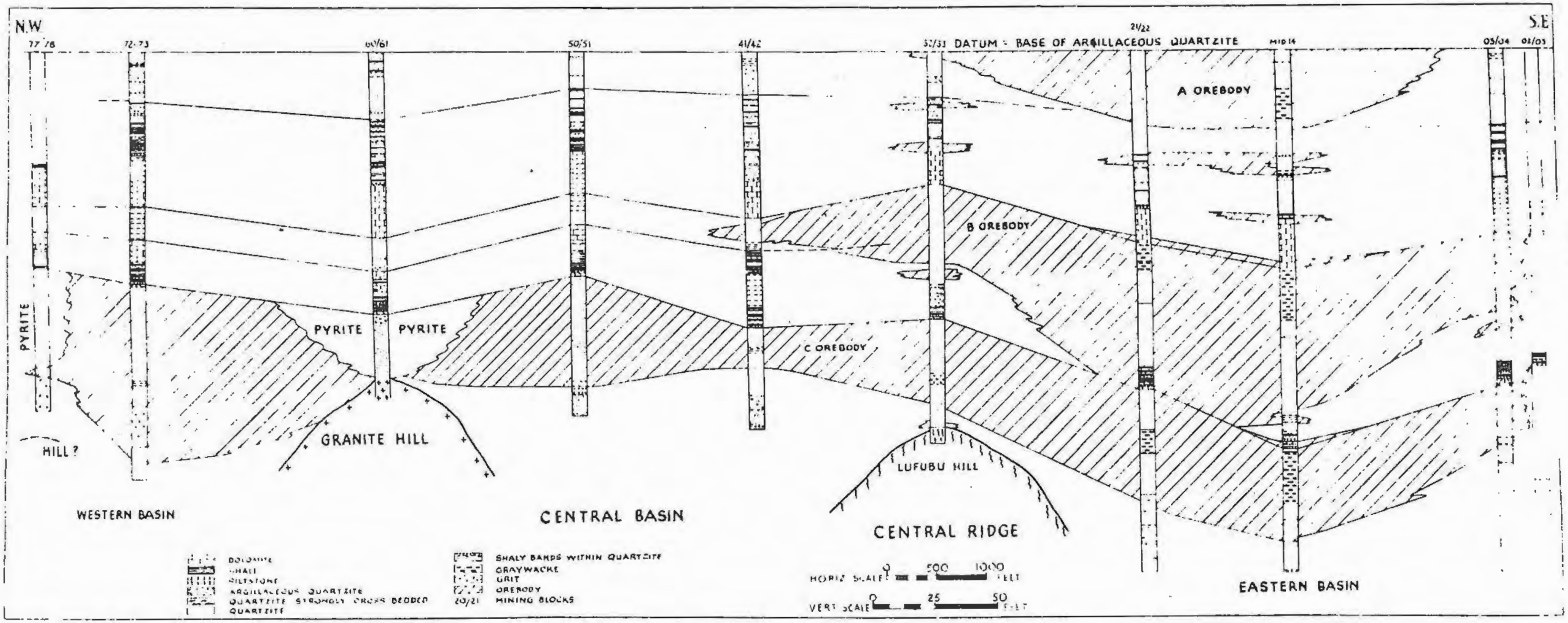


Fig. 9.5. - Relationship of mineralization to the lithologies of the Ore formation at Mufulira, 1 400 feet level (from Mendelsohn, 1961.)

West from footwall to hangingwall of chalcopyrite ore followed by bornite-chalcopyrite then bornite at the top of the orebody. In the central basin a fourth zone of bornite-digenite ore overlies the bornite zone. All three orebodies tend to be of lower grade towards their footwalls, though the "A" orebody also has a conspicuously low grade central zone.

In the "C" orebody, as the basement highs are approached chalcopyrite becomes dominant, while over the basement and at the western fringe chalcopyrite is replaced by pyrite. Figure 9.6 shows the sulphide zonation in the "C" orebody. The mineralogy of the ore is the major control on grade, which in the "C" orebody ranges from 2.0% to 5.0% Cu approximately. Grades show comparatively little tendency to diminish towards the fringes of this orebody.

The "B" orebody occurs in three areas isolated from each other in the eastern and central basins, and in only one of these areas is mineralization of ore grade present between the "B" and "C" orebodies as depicted in figure 9.4. Grades are usually between 2.0% and 4.0% Cu in this orebody, with a tendency for grades to diminish towards the fringes. The "B" orebody in the central basin, known only from drillholes, appears to be of lower grade than mineralization in the "B" horizon over the eastern basin. Bornite is the dominant sulphide in the eastern basin, and the percentage of chalcopyrite increases to the west.

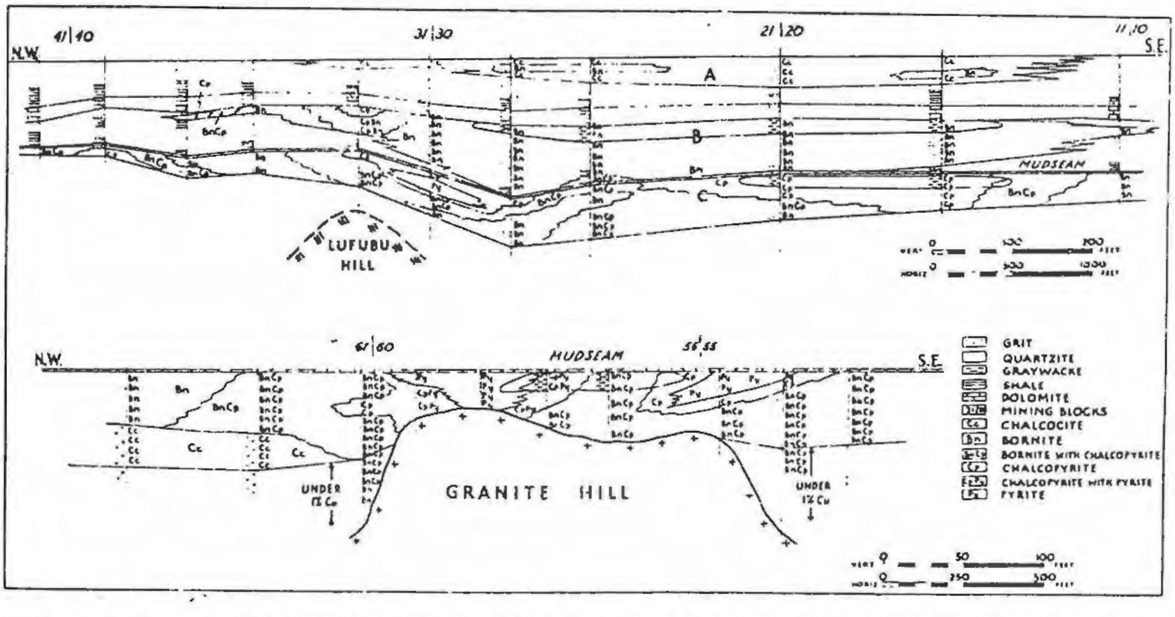


Fig. 9.6. Stratigraphic and lateral sulphide zoning in the C orebody (from Mendelsohn, 1961)

The "A" orebody is least extensive and occurs in a number of isolated areas as well as over the eastern basin in the higher levels of the mine. Chalcopyrite may occur towards the bottom of this orebody but chalcocite predominates higher up,frequently also with some bornite. Grade is variable from 2% to 6% Cu, with high grades frequently occurring towards the fringes. However, mineralization may die out very rapidly and completely at fringes within distances of less than 50 m.

Metamorphism and oxidation

Metamorphism has caused recrystallization of the sediments and the formation of numerous veins and segregations. Quartz, carbonate, anhydrite and sulphides all appear to have been mobilized into veins of generally irregular distribution and attitude. However, all the veins contain the same minerals as the enclosing rocks, and sulphides are generally present only in veins traversing mineralized rock. Movement during metamorphism therefore was over small distances only, and probably did not significantly affect the gross distribution of metal.

Oxidation effects extend to about 60 m depth. In the oxidized zone chalcocite, cuprite,malachite and native copper occur, but the depth to which complete leaching extends does not appear to be recorded anywhere in the literature. According to Bateman (1930) supergene enrichment is more extensive at Mufulira than in other Copperbelt mines, but there is no obvious reason why this should be so. Brandt *et al*. (in Mendelsohn, 1961)state that oxidation effects are evident in the footwall sediments more than 600 m below surface but that the orebodies are fresh and unaltered at this depth. The extent to which chalcocite is a supergene enrichment product is unknown, but it appears that almost all of it may well be primary.

10. GEOLOGICAL FACTORS AFFECTING MINING

In all mines, the geology of the ore and its surrounding rocks is a major constraint on mining methods and their effectiveness. This section examines the general nature of geological constraints on mining of Copperbelt ores.

Orebody morphology and attitude

Many of the Copperbelt orebodies are tabular, but folding has produced major difference in shape and attitude of different orebodies or parts of them. Folding may make mining easier, as at Chambishi and Nchanga where folds within the depth limits of open pit mining have increased the tonnage of ore available to open pit mines. In most underground situations,folding makes mining more difficult, because if a caving system is employed then mining must follow a sequence designed to ensure that caving effects do not interfere with future stoping. Folding may also be beneficial in underground mining, however, if tectonic thickening of mineralization renders it economic. Because the detailed morphology of a folded orebody is less predictable than that of a straight orebody the accurate delineation of folded orebodies is often a problem, and this may affect both underground operations and open pit design, as at Nchanga (Dalgleish and Diederix, 1979).

The attitude of a tabular orebody may render it suitable for open pit mining independently of any folding, provided it extends close to surface. The stripping ratio for a tabular orebody which outcrops is a function of its dip. However, underground mining of a flat-dipping orebody is generally difficult and inefficient, as shown by experience in Roan Basin, Muliashi and several other Copperbelt localities. Effective open stoping of steep dipping tabular orebodies is generally easy to achieve. The principal disadvantage of mining a vertical tabular orebody is the fact that for a given strike length and thickness of ore, the tonnage per unit depth of the mine is a minimum. Depth is a major constraint on underground and open pit mining for a variety of reasons which are beyond the scope of this study.

Orebodies which are not confined to particular horizons present significant mining problems which arise from the difficulty inherent in defining the shape and extent of mineralization. The Chibuluma West, Chingola D and Mimbula II orebodies are examples of orebodies where this kind of problem arises. In open pit mining there is less need than in underground mining to know the precise outline of ore prior to extraction, but a reasonably accurate ore volume must be established prior to any development, in order to estimate tonnage.

Ground Conditions

The mechanical behaviour of rock in a mine is determined primarily by the number and type of discontinuities in the rock mass and the load due to gravity (Jaeger and Cook, 1968). Any given rock type will therefore behave in a manner determined by several factors including composition, deformation history, alteration and depth from surface. Ground conditions substantially affect both cost and efficiency of mining in most situations.

In open pit mining the effect of ground conditions is apparent in two principal areas :

1. The final pit slope, and hence the size of excavation needed to extract a given orebody, is determined by the characteristics of the rocks overlying and surrounding the ore. Dalgleish and Diederix (1979) show the importance of assessment of ground conditions in the design of the Nchanga open pit.

2. Cost of mining is affected by the amount of blasting required and the rate of wear of in-pit machinery, both of which are controlled by the nature of the rock mined.

Underground, the cost and ease of access to an orebody is determined by the mechanical properties of the rock in which tunnels and shafts must be excavated. Although some access problems have arisen in Copperbelt mines, a far more widespread problem is that of dilution due to caving of stopes.

Distribution of metal

Recovery and dilution of ore are affected in many underground situations by the distribution of metal in ore, but invariably other factors are involved. If the defined orebody is all extracted without dilution then the distribution of metal within the orebody is of no consequence, but there are inherent losses in most underground mining methods. In mining of an orebody with a concentration of metal towards the base it is important that the mining methods used should achieve the recovery of the basal ore. Where low grade mineralization exists adjacent to an orebody and enters the stope, dilution will be accompanied by a recovery which is apparently slightly better than the true figure.

Drainage

In all the underground mines of the Copperbelt it is necessary to drain the hangingwall strata in order to avoid the possibility of a sudden inrush of water as a result of stope caving. This problem becomes rapidly more severe as a mine increase in depth, because of the relationship between the required cone of dewatering and the depth of the mine. In the Chililabombwe-Konkola region the rate of recharge of aquifers and their permeability are such that water may be a serious constraint to mining, but this is not such a severe problem elsewhere on the Copperbelt under normal circumstances.

11. GEOLOGICAL FACTORS AFFECTING METALLURGICAL TREATMENT OF ORES

The extractive properties of copper and cobalt minerals found in Copperbelt ores greatly affect the amount of metal which can be recovered. Gangue mineralogy and the relationship of the gangue and ore minerals also affect metal recovery and the choice of treatment routes for particular ores. A total copper or cobalt assay is therefore not necessarily indicative of the amount of metal ultimately extractable from an ore.

Sulphides are normally recovered from the Copperbelt ores by a relatively cheap and simple route requiring grinding of the ore and flotation to recover sulphides. Ores containing both copper and cobalt sulphides may be successfully treated using a differential flotation process to recover two separate concentrates, but most non-sulphide minerals cannot normally be recovered by flotation. The usual extraction procedure for non-sulphide copper involves leaching with sulphuric acid, but gravitational methods of recovery could also be employed.

Copperbelt mineralization has traditionally been classified as "sulphide" or "oxide" according to the suitability of the ore for beneficiation by flotation. Determination of "sulphide" and "oxide" copper is normally carried out by means of assays for total copper and acid soluble copper using cold dilute sulphuric acid saturated with sulphur dioxide for the acid soluble copper determination. The difference between these values is taken to be the amount of copper present in sulphides. However, values for sulphide and oxide copper obtained by this method can be misleading. O'Meara (1961) discussed the relationship between the mineralogy and metallurgical properties of Copperbelt ores and noted several problems inherent in extrapolation from assay values to mineralogy :

1. A small percentage of the copper present in chalcocite and bornite reports as acid-soluble or oxide copper, but would be recoverable by flotation.
2. Native copper is not soluble in cold sulphuric acid and therefore reports by assay as sulphide copper. However, massive native copper can cause problems because it will not grind, and coarse grains of native copper will not float. Thus coarse grained disseminated native copper may be liberated by grinding but nevertheless is lost to tailings during flotation. Fine-grained native copper appears to float readily with sulphides and thus presents no metallurgical problem.

3. Chrysocolla, malachite and pseudomalachite, plus various minor cupriferous phases, none of which are really oxide minerals, are all completely soluble in cold sulphuric acid. Cuprite is the only true oxide present in Copperbelt ores to a significant extent, but is not completely soluble when leached by sulphuric acid, and the copper present in micas and wad is soluble only to a limited and inconsistent extent. A proportion of malachite may be induced to float by the use of sulphidizing reagents.

The treatment routes followed in individual plants differ from one another, often substantially, because of inherent differences in the orebodies. Three primary extraction processes may be considered to exist :

- flotation of a single concentrate, nomally containing only cupriferous sulphides.
- differential flotation to recover two different concentrates, the minerals of which float under different conditions.
- acid leaching of ore, either in situ or after mining.

In flotation processes designed to recover only one concentrate a limited range of problems is encountered. Recovery of sulphide may be reduced if the grains of sulphide are very small or locked to gangue, and the concentrate grade may be reduced if gangue minerals float with the sulphides. O'Meara (1961) examines the problems of gangue flotation encountered at some of the Copperbelt mines and shows that they may generally be overcome by the use of appropriate reagents. The problem of locked grains is less readily overcome, and these account for a large proportion of metal losses in tailings.

Differential flotation processes may be employed both to separate different sulphides and to separate sulphide from flotable "oxides". At Nchanga and Chililabombwe a differential flotation process, described by O'Meara (1961) is used to produce two concentrates. The intention is that these concentrates should contain respectively only sulphides and only acid soluble minerals, for subsequent treatment via smelting in the first case and by leaching in the second. The principal problem with this process is flotation of chalcocite with the acid soluble minerals, while considerable losses to tailings are due to locked grains of malachite which will not float. Differential flotation to obtain copper-rich and cobalt-rich concentrates from Chibuluma ore is described by Harper (1961), but he does not examine the effect of mineralogy on the process used. O'Meara describes two problems encountered at Rokana in separating copper from cobalt.

- Where carrolite occurs as fine veinlets traversing chalcopyrite and bornite grains, much of the carrolite floats with the sulphides to which it is attached. O'Meara suggests that finer grinding would not increase the proportion of free grains of carrolite owing to the extremely small size of the attached particles.
- Where carrolite is mantled by chalcopyrite or bornite, these grains float in conditions designed to produce a copper-rich concentrate despite being mainly composed of carrolite. The effect is again to produce a loss of cobalt to the copper concentrate.

Extraction of non-sulphide mineralization which cannot be floated has been achieved by various routes, most of which eventually produce a solution containing copper or both copper and cobalt. Treatment routes exist for all known forms of refractory mineralization, but technical complexity, high cost and large energy requirements are constraints on their use, and therefore only certain of the refractory ores can be treated economically at present. Fisher and Notebaart (1976) examined possible treatment routes for cupriferous mica mineralization from Nchanga and concluded that availability of suphuric acid would be a major problem in treating this ore by a leaching process. Pyrometallurgical treatment routes for copper mineralization also depend on the availability of a concentrate containing sufficient sulphur, so that the availability of sulphur on the Copperbelt is an important aspect of copper production.

12. TONNAGE AND GRADE ESTIMATION

Estimates of tonnage and grade ("reserves") are made to determine :

- extent of exploration and development
- distribution of metal values
- annual output of a mine
- probable and possible productive life of a mine
- methods of extraction and plant design
- requirements for capital, equipment, labour, power and materials (Popoff, 1966)

The principal factor affecting the reliability of reserve calculations, according to Popoff (1966), is the reliability and completeness of knowledge of the mineral deposit considered. He lists the assumptions accepted for interpreting variables, the boundaries of mineral bodies, accuracy of averages and mathematical formulae used as further factors affecting reliability.

On the Copperbelt,as elsewhere, the definition of boundaries of an orebody is affected by the interaction of geology, economics and the practicalities of mining and beneficiation. Without accurate and complete geological models of orebodies and a detailed knowledge of interacting factors it is not possible to compute reserve tonnages and grades which have real meaning. The evaluation of orebody limits, both laterally and vertically, is a particularly complex problem. The lateral fringes of Copperbelt orebodies are usually only approximately known from surface exploration drilling,and very often their precise nature is neither clear nor consistent. Hangingwall and footwall positions are often difficult to define because they do not conform exactly with lithological boundaries, or are not clearly defined by a sharp grade change, or do not correspond for both copper and cobalt. Once an orebody is defined, the selection of a method for reserve computation depends on the geology of the deposit, the exploration method, the availability and reliability of factual data, purpose of computations, and the degree of accuracy required (Popoff, 1966).

The accuracy of reserve calculations for Copperbelt orebodies is not known, nor has accurate estimation of ore been vitally necessary in the past because of the unusually high grade of the orebodies. Elsewhere in the world, orebodies with grades that would be considered uneconomic in Zambia are successfully mined by methods comparable with those used on the Copperbelt. The White Pine deposit, Michigan, the Klein Aub and Oamites deposits in Namibia, and the Roxby Downs deposit, South Australia, all have in situ copper grades considerably less than any orebody currently mined on the Copperbelt. In the case of Oamites, silver was quantitatively evaluated as a co-product of copper for economic assessment, and uranium will be a major co-product at Roxby Downs. Zambia produces cobalt as a co-product of copper, but its assessment in reserve calculations has been difficult because of incomplete understanding of its occurrence and treatment characteristics.

Individual stopes in Copperbelt mines have sometimes been shown to be overvalued or undervalued, but situations in which grade estimation bias at this scale can be conclusively demonstrated are rare. Taylor (1966) gives an example from Chililabombwe, and examples of similar evaluation bias in other mines are known. Taylor concludes his paper with a comment to the effect that although basic principles of orebody evaluation are universally valid, practical application of these principles varies with the nature of the orebody being evaluated. Each Copperbelt ore occurrence is unique in some respect, so that accurate evaluation of every orebody is a unique problem.

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