

## SEDIMENTARY ENVIRONMENT OF ZAMBIAN COPPER DEPOSITION

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## ABSTRACT

Superseding of the hydrothermal origin by syngeneses subsequent to 1928 is recorded historically. Granites claimed to be intrusive were in 1940 found to be overlain unconformably by Katanga sediments. The bulging intrusive granites became bulging paleo-hills, avoided by copper mineralization. Discovery that ore grade in the deformed and shattered orebeds of a dragfold was no richer than in the unfolded sections, proved that the mineralization was pre-folding. Two decades later dolomitic facies over some granite bulges proved to be algal bioherms. By the syngenetic theory the zonal sequence, from copper-rich to iron-rich sulphide, was interpreted as representing depth zones parallel to shoreline controlled by the activity of anaerobic bacteria.

Recognition of anhydrite explained mysterious cavities in veins, conditions of sedimentation, and the source of the sulphur to form the sulphides and, by its solubility, explained the high porosity of the Katanga sediments to depths of 600 m.

Features of the ore shale deposits such as dissemination instead of selective replacement, mineral zoning, association with basins flanking paleo-hills, barren gaps over bioherms, apply also to mineralization in arenites. Pyritic disseminations in sediments over granite hills and sulphide concretions are confined to orebodies in arenite, explainable by its greater original permeability.

Evidence for syngeneses derives from interpretation of the depositional environment, although many of the processes are still being elucidated. Prior to formation of the major ore deposits, in marine waters, evaporation of playa lakes gave high concentrations of sulphates, borates, and, under anoxic conditions, sulphide precipitation. Drying out of such lakes

exposed mud flats on which efflorescences of gypsum, borates, and iron and cobalt sulphates presumably formed. Wind erosion at Mufulira produced dunes containing high proportions of gypsum later converted to anhydrite.

At Chibuluma floods dissolved iron and cobalt sulphate from desiccated mud flats and on entering the saline lake precipitated hydroxides of these two metals as a heavy red mud with suspended sand grains and pebbles. The hydroxides were then converted to sulphide, whilst copper and iron were precipitated as sulphide in the overlying waters. Borates diffused into the underlying sand and combined with muddy coatings and matrix of the sand grains, to form tourmaline. Copper and cobalt were precipitated in greatest quantity at convergence of currents in the playa.

Sulphide in sediment became sufficiently indurated to be eroded and redeposited as detrital grains, concentrated on foresets and truncation planes with tourmaline, sphene, epidote, and zircon grains.

Compaction folding over Basement hills and even over biohermal and aeolian accumulations were controls for ore deposition.

SHORTCOMINGS OF THE EPIGENETIC  
THEORY OF ORE GENESIS

From 1928 to 1940 the extensive and rich copper deposits of Zambia were considered to be derived from hydrothermal solutions emanating from adjacent intrusive granites. Prof. S c h n e i d e r h ö h n disagreed after examining the deposits during the 1929 International Geological Congress and published an English translation of his revolutionary interpretations in the "Mining Magazine" (1932). However, with very few geologists on the Copperbelt during the world depression his ideas had little general impact,

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although I was worried by his repudiation of the intrusive granite. Having been taught that the Kupferschiefer of Germany was almost undoubtedly an epigenetic deposit, Schneiderhöhn's opinion on ore genesis made little impression.

At Roan Antelope pegmatites were claimed to emanate from the younger intrusive granite, pass through the footwall beds and introduce the copper into the "favourable host" – the ore shale. At Nkana an intrusive contact was believed to have been observed in the 'A' shaft, and 170 m higher an "intrusive granite sill" had been intersected in a drill-hole at the top of the Lower conglomerate. The ore shale in the folded areas was cut by numerous feldspar-bearing veins, which were automatically labelled "pegmatites", but no one had yet mapped the connections through the footwall to the 'A' shaft granite. Major dragfolds in the ore shale were exploited by open stopes up to 40 m high, 50 m across and up to 20 m long between rib pillars. The walls of these "underground cathedrals" contained spectacular veins or "pegmatites" with feldspar, pink dolomite, quartz, and abundant bornite and chalcopyrite, and in the upper part of the ore horizon the exciting rare mineral carrollite.

My first self-imposed task was to map footwall formations, and a series of main level crosscuts from

Central shaft provided a wonderful cross-section. From the basal boulder conglomerate up to the loose sandy formation at the base of the Lower conglomerate were white fine-grained feldspathic quartzites with spectacular large scale crossbedding in high angle tabular planar sets. A few days mapping gave convincing evidence of an aeolian origin. Diagnostic features were angles of up to 34° between foresets and overlying smooth truncation planes, and absence of muddy bottomsets and pebbles (fig. 1). The similarity to the aeolian sandstones underlying the Kupferschiefer of Germany was realized but the significance was missed.

No pegmatites were found traversing these thick aeolian quartzites, nor in the beds between the Footwall and Lower conglomerates, and not a speck of copper mineral was seen in the 150 m thick section. The basal conglomerate rested upon Basement schist and thick pegmatites in the Basement were truncated at the unconformity. A few quartz veins with rectangular bladed cavities after an unknown mineral, but with no feldspar, occupied fissures in the aeolian quartzites. Footwall arkose close to the ore horizon contained veins with the queer assemblage – beautiful rhombs of adularia, blades of specularite, quartz, and the ubiquitous rectangular cavities.

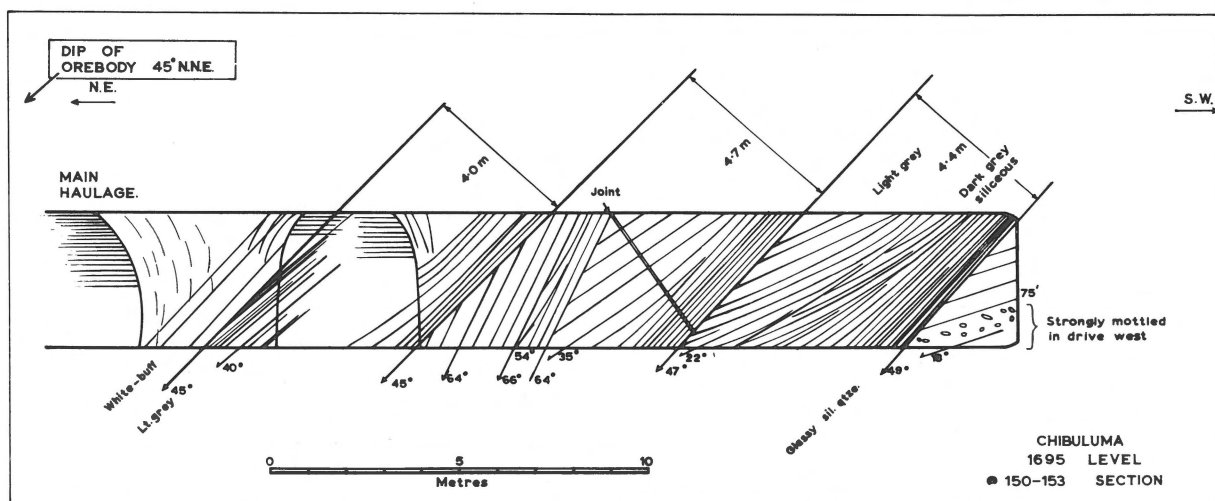


Fig. 1 Structures typical of aeolian beds of Nkana, Chibuluma, Mufulira, and Roan Antelope. Co-sets up to 5 m. thick show parallel truncation planes and dihedral angles of up to 31° between foresets and truncations. Crossbedding from opposite directions makes wedge-shaped co-sets. Some foreset layers show mottling due to leaching of anhydrite cement. The dunes are overlain by parallel laminated buff aqueous arkoses with tiny rosettes of tremolite.

Later mapping of a section under the Mindola stream, 5 km to the north, showed the ore petering out against a protuberance of granite. (fig. 2). The supposedly "intrusive" granite had presumably stopped its way up to the base of the ore shale, but strangely enough the only metamorphic effect in the ore shale was an increase in biotite and development of schistosity. Thick, barren quartz veins occurred along the contact. Garnet, cordierite and andalusite were conspicuously absent and the ore shale graded to a more sandy facies on the flanks of this granite promontory. There could be no doubt that this was an old granite hill projecting to the ore shale horizon and that a sandy shore facies in this horizon flanked the hill.

With one sediment/granite contact proved to be unconformable it was essential to re-examine the contact at 'A' shaft, described by Schneiderhöhn as an unconformity. The contact was thus examined with B.B. Brock: the reddish granite had a gaping fissure filled with feldspathic quartzite and the flaring top of the fissure was blocked by a rounded boulder of red granite — this was undoubtedly an unconformity. The "granite sill" at the top of the Lower conglomerate was found to be recrystallized cross-bedded arkose!

Within a few weeks a visit to Roan Antelope confirmed that the true pegmatites in the Basement were truncated at a Basal conglomerate, and that the so-called pegmatites in the ore shales were small feldspar-dolomite-quartz-sulphide veins and had no

connection through the footwall sediments to the pegmatites and granites of the Basement.

Next a visit was paid to Nchanga where an incline shaft exposed the contact between the Footwall arkoses and the underlying red granite, previously acknowledged to be the youngest looking of the Copperbelt granites. In depressions in the granite surface patches of Basal conglomerate were found and later the geologist at Nchanga found insolation slabs on the old granite surface with the arkose penetrating the intervening space. This insolation slab had previously been interpreted as an intrusive sill of red granite along the bedding of the arkose (fig. 3).

Schneiderhöhn was now completely vindicated regarding the pre-Katanga age of all the granites, but the old ideas of an epigenetic origin for the copper were to die hard.

For some obscure reason, either its carbonate content or its fine lamination, the ore shale was the "favoured host" rock and the only host rock for the Nkana/Mindola orebodies. Hence structural preparation to allow ingress and passage of the mineralizing solutions through the shale should have been very important. It was to be anticipated that, the ore being epigenetic, the tight shales in the straight squeezed limbs of the folds should be barren or low grade, whereas the contorted and veined formations in the big dragfolds should constitute rich ore and major ore shoots. But if the ore were syngenetic, late structural dragfolding should make no difference to copper grade.

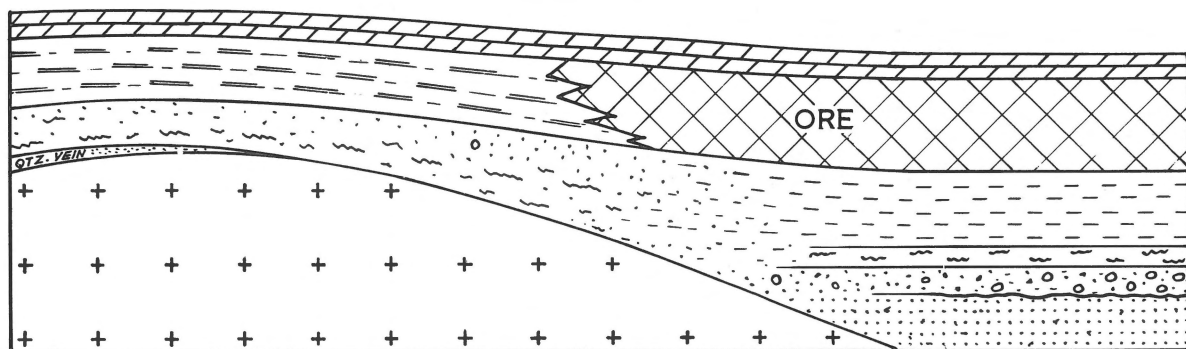


Fig. 2  
Granite protuberance into Lower Roan under Mindola stream. 5 m of ore, consisting of disseminated bornite and chalcopyrite grades laterally into barren argillite with dolomite bands. The lower section of ore horizon is a barren argillite with a thin dolomitic biotite schist at base, overlying Footwall conglomerate. Towards the granite these three formations grade into a pebbly argillaceous arenite, representing unsorted terrestrial debris. A quartz vein is locally developed along the contact with the granite.

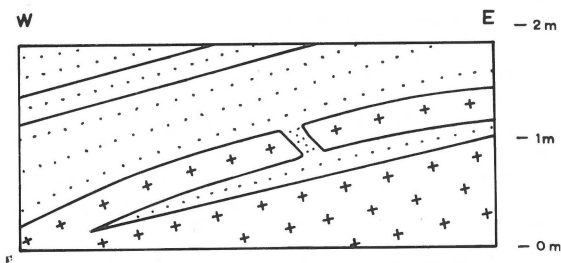


Fig. 3  
Early Katangan exfoliation of Nchanga granite as observed in crosscut, Nchanga West. In 1940, before recognition of the arkose-filled crack in the exfoliated slab, this was interpreted as an intrusive sill.

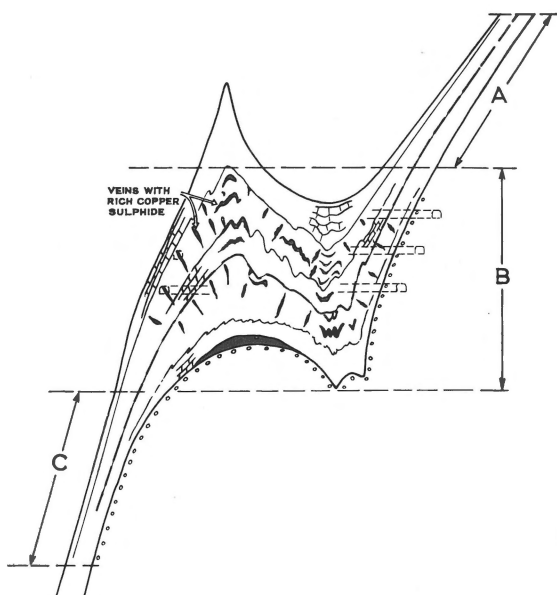


Fig. 4  
Major dragfold at Nkana, north of central shaft. Copper grades in the straight limb 'A' were averaged with those in an equal length of the straight limb 'C' below the fold, and then compared with average grade in the folded section 'B'. Crosscuts through the dragfold area, at 7 m vertical intervals, are indicated to show the big scale.

	High Grade	Low Grade	Combined
Grades A & C	5.62	1.87	3.78
Grade B	5.60	2.06	3.85

In making ore reserve calculations, I had the opportunity to check the grade of the ore in a major

dragfold against that in the squeezed straight limbs above and below. Since there was a slight gradual decrease in tenor with depth in the mine, it was essential to make a comparison with equal lengths of limbs both above and below the dragfold as shown in fig. 4. Therefore on each vertical section the grades for the high grade and low grade section of all the crosscuts were *each* averaged and separated into the following classes:

1. Straight limbs above or below the folded area
2. The dragfold itself, as in fig. 4.

Average grades were calculated over four different vertical sections, from the 450 to the 1400 foot levels. For the upper high grade ore horizon (Banded ore plus Cherty ore) the average value in the thickened and crumpled fold area, in spite of the spectacular veins, was negligibly lower than the average value of the corresponding high grade horizon for the limbs above and below the fold area. For the total ore horizon, from Footwall conglomerate to Hangingwall dolomite, the averages for limbs and fold were the same to the first place of decimals.

This result was incredible, something must have gone wrong somewhere! After checking the results and overcoming 10 years bias in my own thinking, I had to accept that the copper was pre-folding and probably syngenetic with the deposition of the ore shale. Schneiderhöhn, surely one of the world's greatest economic geologists, was correct in all essentials – after only a week on the Copperbelt.

The significance of the aeolian crossbedding and the Footwall conglomerate was now realized, and it became evident that the Lower Roan ore shale was a grandiose version of the Kupferschiefer of Germany, which after reading the literature (Gregory 1930) thereon, I now accepted as syngenetic.

Tectonic folds evidently controlled only the thickness and shape of the orebody, but not the grade. Folding and metamorphism had caused recrystallization and local remobilization of sulphides, but no migration out of the original mineralized beds.

However, compaction folds over buried paleo-hills were to be found to exert a major control over grade and presence or absence of ore. The real ore controls were clearly related to certain facies of the ore formation, and the sedimentary facies were in turn controlled by the topography of the underlying basement.

## DEVELOPMENT OF THE SYNGENETIC THEORY OF ORE GENESIS

### *Paleotopography*

As already described (fig. 2), the Mindola stream crosses a paleo-hill of Basement granite and the ore shale is thinner, sandy, sheared, and barren, whereas rich ore occurs in the basins of thicker sedimentation flanking the ridge.

Between the Nkana and Mindola orebodies is the Kitwe barren gap. At Nkana the ore horizon has economic mineralization in both the 5 m low grade section and the overlying 5 m high grade section, but northwards, nearer the gap, first the low grade section becomes barren and lighter coloured and of a more silty or sandy facies. The ore in the high grade section up to the base of the marker dolomite, persists for 500 m to the edge of the gap, where there is a lateral facies change to massive barren dolomite of twice the normal thickness. In the Mindola section on the north side of the gap only the upper high grade section carries economic mineralization and approaching the gap the same change occurs. Where the ore dies out, underground development stops, but the Kitwe

stream section and drill-holes give useful clues.

The granite of the Kitwe stream bulges through the Lower Roan beds towards the ore shale horizon, and the beds are draped over this paleo-ridge, similarly to that described under the Mindola stream. A similar phenomenon occurs at Irwin shaft, Roan Extension, where on the south limb richly cupriferous ore shales flank a barren cherty dolomitic facies overlying a granite ridge.

Only in 1964 was the problem satisfactorily solved, when under the Mwambashi stream drilling again discovered cupriferous ore shales flanking a dolomitic facies overlying a granite ridge (fig. 5). In this case algal or stromatolite structures are preserved and there is no doubt that it and the barren carbonate over similar granites under the Kitwe stream and at Irwin shaft, Roan Extension, are bioherms formed in shallow agitated clear water where sunlight can penetrate; a rocky shoal or a narrow paleo-peninsula projecting into the sea would provide an ideal environment for such algal growths.

In these examples paleo-hills project through the Footwall formations up to the horizon of the ore shale and are overlain by either a barren sandy facies of the ore shale or a barren dolomitic bioherm.

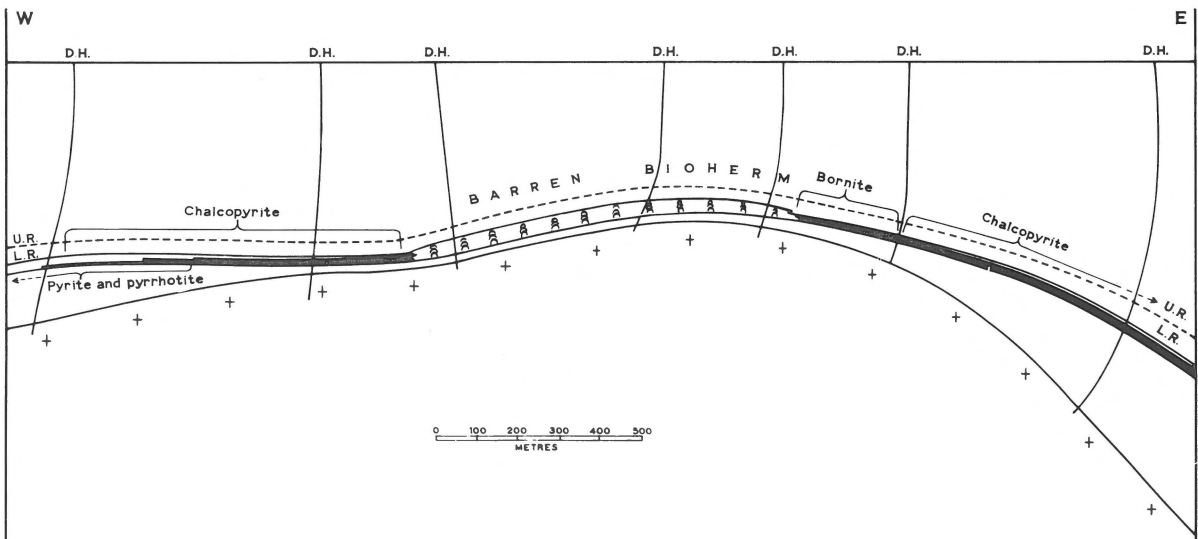


Fig. 5

Barren bioherm in ore shale horizon under Mwambashi stream halfway between Nkana and Chambishi. This barren dolomitic facies was discovered in 1962, but only in 1964 were well preserved stromatolites discovered, proving it to be a bioherm. It is nearly 1 km in diameter, biggest known on the Copperbelt, but small in comparison to the stromatolite reefs in the Katanga province. Note the zoning of the sulphides flanking the bioherm.

*Mineral Zoning*

Early exploratory drilling at Nkana indicated a zonal sequence of sulphides, from chalcocite in the north through bornite to chalcopyrite and eventually to slightly cupriferous pyrite in the south; it is even more conspicuous down the dip of the ore horizon. Jackson (1932) was adamant that both chalcocite and bornite at Nchanga were supergene. Bancroft and Pelletier (1929) were just as certain at Nkana that chalcocite and bornite were both super-

gene. At Roan and Chambishi (Davidson, 1931) bornite was considered to be a primary mineral like chalcopyrite, and Anton Gray (1932) obtained disseminated bornite at 1 000 depth at Mufulira, justifying his assertion that bornite was a primary mineral. Having now worked at both RST and Anglo American mines, I was able to generalize information from all four mines; the downdip sequence of the sulphides at Nkana was the same as the strike sequence, from east to west, at Chambishi (fig. 6) where a progression from disseminated chalcocite,

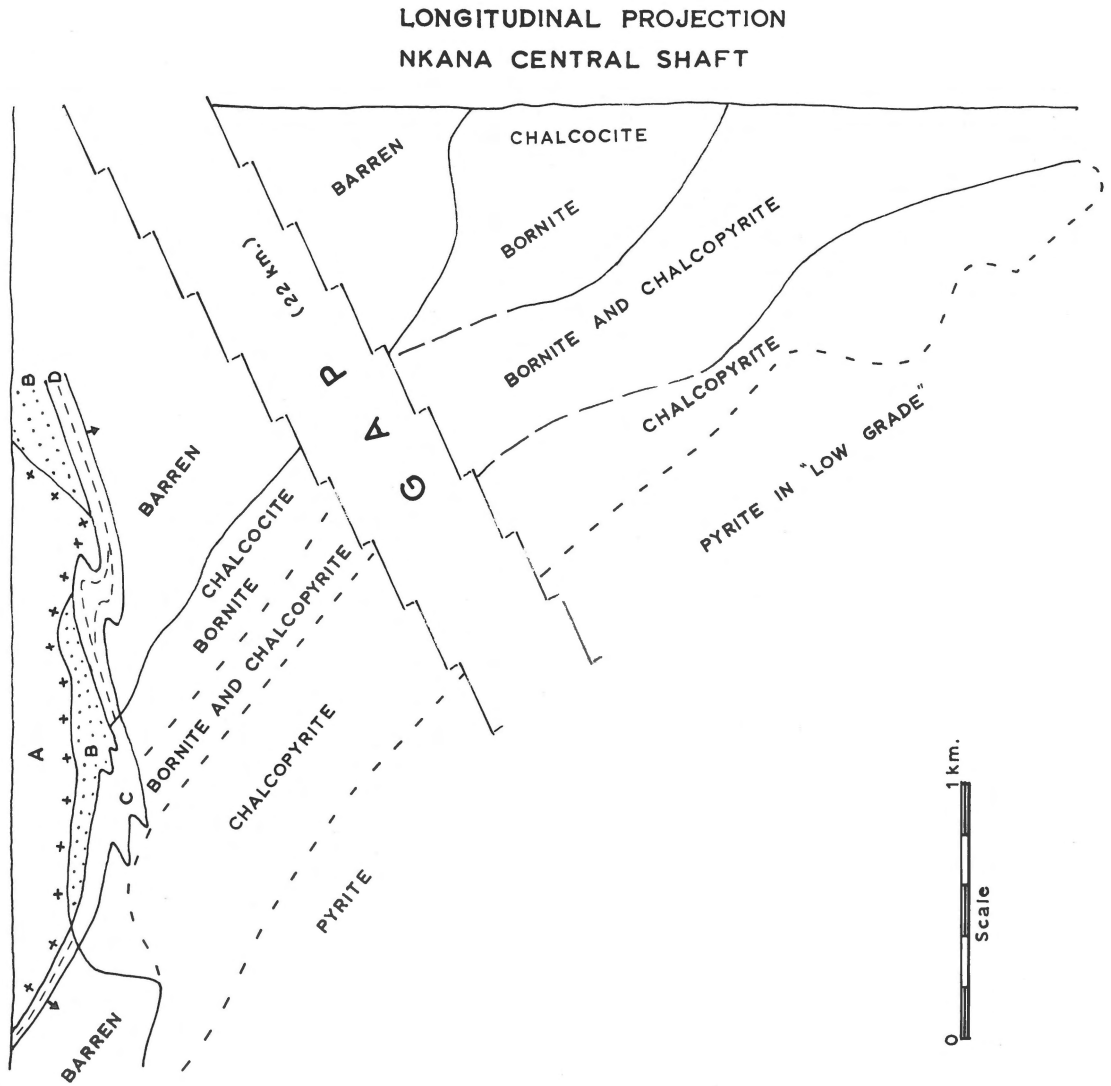


Fig. 6  
Plan of mineral zones at Chambishi compared with those at Nkana 22 km distant, showing similarity in width of zones. The chalcocite, bornite and chalcopyrite zones cover a width of 1, exceptionally 2 km., parallel to a northeastern shore line.

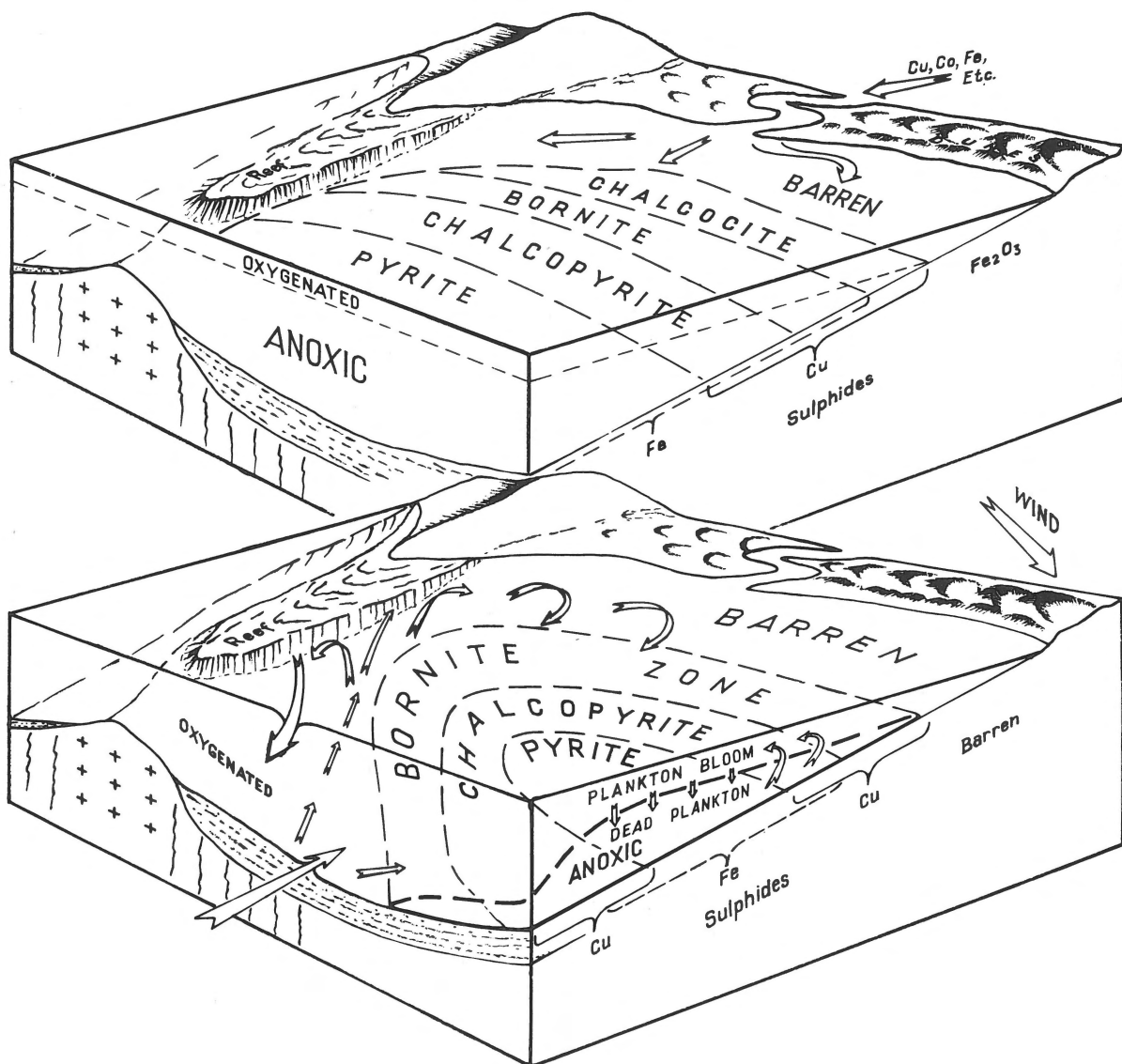


Fig. 7

Above. Block diagram showing diffusion of copper, cobalt, iron, and other metals in solution into a sea, copper only being precipitated in the near shore feather edge of lower layer, with increasing iron precipitation in depth, which after diagenesis or metamorphism gives the sedimentary zoning of the minerals as shown.

Below. Diagram to show arrangement of metal and mineral zones anticipated with an upwelling current bringing metals from ocean depths. The upwelling would be induced by a longshore or offshore wind, forming sand dunes as observed along the eastern shore of the Mufulira 'C' orebody. Plankton bloom and decay, with gradual accumulation of nutrients and metals, eventually leads to oxygen deficiency and development of anoxic zone.

through bornite, to chalcopyrite, and eventually to pyrite west of the orebody was apparent.

Pyritic disseminations in dark shale or especially in carbonaceous shale, as occur west of Chambishi and at Nchanga, are interpreted by sedimentologists as syngenetic deposits by reaction of iron with hydrogen sulphide produced by anaerobic bacteria from dissolved sulphates, usually in salt water. Sulphides of copper and silver, are the most insoluble of all sulphides. Rivers carry small amounts of these metals in solution (and in clay minerals) and where they debouch into the sea, dropping their load of detrital material, the copper and silver should be precipitated before the more soluble zinc, cobalt, and iron sulphide (fig. 7, upper blockdiagram). Transport of the metal ions would be mainly in the upper oxygenated layer and where this layer contacts the shore algal growths would produce carbonate mats or carbonate-rich bioherms, but with no sulphide deposition. At the feather edge of the anoxic zone, hydrogen sulphide would be sufficient only to precipitate copper; with thickening of the anoxic zone in depth hydrogen sulphide would be sufficient to precipitate also iron and cobalt and other metals if present. The gradual seaward change in proportion of copper and iron sulphides would thus form, during diagenesis, the chalcocite, bornite, chalcopyrite zones with, in the deepest waters, only iron sulphide, as all the copper would have been depleted nearer shore. Thus the sulphide zones in the shale deposits of the Copperbelt from Roan Antelope to the Konkola section of Bancroft Mine were simply explained — even if this were not the complete and final answer.

Sedimentologists now state that the heavy metals are discharged into the sea, not in ionic form, but mainly adsorbed on clay minerals and that their release therefrom in the presence of hydrogen sulphide is possibly a much slower and more complicated process and could possibly nullify this explanation. On the other hand Brongersma-Sanders (1967) invokes upwelling currents, notably under the influence of steady trade winds, to bring deep oceanic nutrients and trace elements into the inner shore zone where multicycle plankton bloom and decay can explain development of the anoxic zones and a concentration of metals with little detritus to dilute the deposit of metal sulphides. However, in this case the copper-rich zones should also occur on the deeper or seaward side of the pyritic zone (fig. 7,

lower blockdiagram). Such an original deep cupriferous zone has not yet been identified on the Zambian Copperbelt.

#### *Significance of Anhydrite*

For many years the mauve coloured anhydrite of the Copperbelt had been misidentified either as fluorite, in hand specimen, or as muscovite in thin section. I first became aware of the presence of anhydrite when, visiting the 1450 level at Nkana, I noticed that the mineral was hydrating to gypsum with explosive decrepitation.

On the 1450 level at Nkana the anhydrite occurred as lenses in the low grade argillite which was barren near the Kitwe gap. Subsequently in the arkose below the Footwall conglomerate I found veins with specularite, feldspar, quartz, and the mauve mineral with its typical rectangular bladed shape, which identified it as the leached core of the numerous rectangular moulds recorded before.

Previously it had been considered that the ore shales of the Copperbelt were marine deposits with a Footwall conglomerate representing a transgressive pebbly beach deposit. The abundance of anhydrite proved that the shales were deposited in a highly saline environment with local supersaturation of calcium sulphate such as occurs on the shores of the Persian Gulf.

The importance of this easily soluble mineral in the geological history of the Copperbelt cannot be over-estimated. It occurs as evaporite deposits up to 2 m thick in the Upper Roan dolomites, and as nodules in the ore horizons in the Lower Roan, whether they be argillite or arenite, mineralized or barren, but it is generally more common near the margins of the orebody and in the adjacent barren rock. It forms the cement of many arkose and sandstone beds and its solution to depths of 600 m, renders the formations highly permeable. Thus the Copperbelt has the wettest mines in the world, and at Nchanga this permeability has allowed deep supergene oxidation.

#### *Metamorphism*

To identify the Katanga sediments and recognise the sedimentary processes involved it is essential to visualize the sediments prior to metamorphism.

Regional metamorphism in the eastern part of the

Copperbelt attains the chlorite-biotite grade of the lower greenschist facies, but westwards the grade increases to the higher greenschist facies and biotite is the dominant mineral in argillaceous beds. At Nkana south, the western part of Roan and in Muliashi, tremolite, actinolite, and epidote are developed, but garnet does not appear in the Katanga metasediments until 30 km west of Chingola (see inset fig. 1, paper D r y s d a l l et al., this issue). Biotite, microcline, and albite are the typical metamorphic minerals in the argillites, whilst detrital quartz and feldspar in arkoses and feldspathic quartzites have recrystallized, achieving conspicuous overgrowths. Detrital tourmaline has ubiquitous paler green or blue overgrowths.

This low rank regional metamorphism resulted from the Lufilian orogeny, which caused severe folding, dragfolding, and minor rupturing of the beds, and in the breaks and joints so formed metamorphic veins developed by lateral secretion; these are short and commonly confined to one bed, dying out against less competent beds above and below. At Mufulira they contain specularite, anhydrite, dolomite, and quartz, but in the ore horizons sulphides take the place of specularite – albite occurs rarely. In the western mines the same minerals occur in the veins, but are accompanied at Nkana by adularia, mostly inverted to microcline, which also occurs at Bancroft and Roan. With the higher grade of metamorphism at Roan, microcline is more abundant and is accompanied by muscovite and rare tourmaline. The latter increases in importance westward into Muliashi.

Amongst these vein minerals anhydrite and quartz are probably the most mobile during metamorphism. After specularite, anhydrite is generally the first mineral to crystallize in the veins, and at Roan it occurs in post-Katanga fissures in the Basement for 300 m below the unconformity. Even at Mufulira, anhydrite-quartz veins penetrate for 10 to 30 m into the basement. At greater distances below the unconformity no anhydrite nor the characteristic rectangular bladed cavities are found in quartz veins.

Recognition of metamorphic or lateral secretion veins adds another criterion for identifying syngenetic metal deposits – and pre-metamorphic deposits. The wallrock is usually impoverished by the movement of metallic sulphide into the vein, commonly producing a light coloured barren or low grade halo (fig. 8).

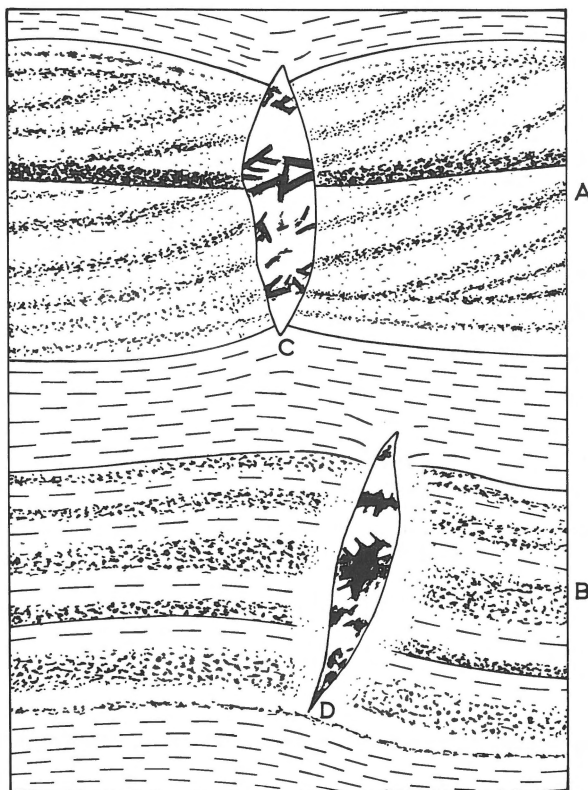


Fig. 8

Metamorphic veins in host rocks of different composition.

The usually short lenticular type vein 'C' occurs between boudins of crossbedded arkose (with strong concentrations of detrital iron on foresets and truncations) and consists of pink microcline, white quartz, minor dolomite, and conspicuous irregular blades of specularite, bunched near iron-rich portions of the wallrock. Anhydrite may occur. The Vein 'D' occurs in deformed argillites containing disseminations of sulphides along the bedding. In the vein are microcline, anhydrite, dolomite, and quartz, and the opaque minerals almost invariably consist of the same sulphides as occur in the adjacent wallrock. Sulphides are often crystallized opposite those parts of the wallrock richest in sulphide, and there is commonly a halo of impoverishment in sulphide up to 25 mm – rarely 50 mm wide.

#### *Stratigraphic Mineral Zoning*

The mineral zoning previously described is lateral, but in most of the mines there is in addition a marked zonal arrangement of the same minerals perpendicular to the bedding. At Chambishi and Nkana a bornite zone at the base grades up through mixed bornite-

chalcopyrite, to chalcopyrite and commonly pyrite in the hangingwall. At Roan Antelope, specifically in the Roan Basin, the zonal sequence is reversed, with pyrite close to the base, grading up to chalcopyrite, then bornite and into disseminated chalcocite, very fine-grained and hard to see even when the rock assays over 5% copper. The chalcocite dissemination gives way abruptly (in less than 1 cm) to barren argillite containing less than 0.1% copper. Assuming that these mineral zones represent very roughly depth zones in the sea (other factors, such as copper supply remaining constant) it is evident that at the Roan the deposition of the Footwall conglomerate was followed by rapid subsidence to give a pyritic zone and then a gradual shallowing up to the barren argillite. Near the top of the bornite zone and in the overlying barren argillite there is commonly a zone of anhydrite lentils formed as evaporites. This shallowing of the water during ore shale deposition is further confirmed first by thin silty sandy beds, and later lenses of coarse arkose in the barren hangingwall argillites. The crossbedded arkose of the hangingwall quartzite represents the eventual burial of the marine muds by deltaic formations, advancing from the north-east.

#### *Geochemical Analyses*

If the ore be epigenetic, then the ore solutions have been extremely selective in choice of host rock and this should be reflected in selective replacement of some mineral and hence of its constituent elements, as may be revealed by complete rock analyses. If the ore be syngenetic, then the copper sulphide should show no selectivity against any of the minerals or constituent elements. Thus with increasing copper sulphide content of the ore all gangue minerals should be reduced proportionally; therefore by omitting copper sulphide and recalculating the other components to 100%, the recalculated composition should remain constant for all copper grades and the same as for the barren rock. Stanton (1962) first demonstrated a similar test on the Mt. Isa orebodies.

*Chambishi.* — As the sedimentary facies and chemical constitution change over any considerable lateral distance, geochemical tests have been made

over as short a strike length as possible and sampling was restricted to the same stratigraphic interval. J.L.W. Jolly of the Geological Research Department is presently investigating the folded ore shale on the east wall of the Chambishi open pit. In this section the ore shale is involved in two major folds and the 61 cm thick horizon was followed exactly and sampled at 1.5 to 3.0 m intervals through various benches, through the folds, and into the barren ore shale updip.

I have interpreted some preliminary results of J.L.W. Jolly's investigation as follows:

Silica, alumina, soda, and potash are practically identical in the barren and in the recalculated mineralized shale, omitting the 4.22% copper sulphide. Lime and CO<sub>2</sub> are appreciably higher in the mineralized shale, which indicates that copper sulphide has not replaced the most easily replaceable mineral in the rock. Neither is there indication of chalcocite replacing silica, or the aluminous feldspars, or micas. By contrast, in the vein deposits within the orebodies, it is evident that sulphides preferentially replace carbonate and corrode previously crystallized quartz.

Variations in the minor elements are of considerable interest. Iron decreases, manganese is doubled, but phosphate is almost halved in the cupriferous rock. Association of manganese with copper mineralization had been noted at Roan and at Nkana. The higher phosphate in the barren ore shale may indicate more abundant planktonic activity in shallower water with fixation of the phosphates therein, whereas in the anoxic zones anaerobic bacteria may destroy organic material, releasing phosphate back into solution.<sup>1</sup>

The sampling of the 61 cm thick horizon was extended into the bornite zone and just into the chalcopyrite zone on the south wall of the open pit. Recalculation to 100% of 6 analyses for bornite mineralization and 4 for the chalcopyrite mineralization show very little change in silica, alumina, soda, and potash. Iron, which decreases from the barren shale into the chalcocite zone, increases again through the bornite zone to the chalcopyrite zone, which may be ascribed to increased biotite or to bacterial precipitation of iron in the deeper waters of the chalcopyrite zone. Soda increases significantly by one half to 0.33%. Potash increases by about one twentieth into the bornite and chalcopyrite zone,

<sup>1</sup>) This accords with Dr. Brongersma-Sanders' hypothesis of upwelling currents, plankton bloom and decay, and enrichment of near shore waters with nutrients.

attaining 10.5 and 10.4% respectively, but carbonate, according to the CO<sub>2</sub> content, decreases to the same value as it does in the barren shale. However, phosphate continues to decrease and reaches its lowest value in the chalcopyrite zone.

*Mufulira.* — Unfortunately very few complete analyses are available and titania and manganese oxide were never assayed. The available analyses refer to different stratigraphic horizons, which vary appreciably in carbonate content. However, they are all essentially arkosic arenites. There is no analysis of barren ore formation, but the Inter 'B/C' glassy quartzite contains only 1.07% copper, contrasting with the 10.79% copper in the 'A' quartzite. Such great variation in copper grade should reveal any selective replacement of minerals by considerable variations in SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, or CO<sub>2</sub> in the recalculated analyses.

Combined copper and sulphur at 13.55% in the high grade 'A' quartzite, however, results in little variation in the proportions of the elements. Silica and alumina are practically the same; there is a slight decrease in lime and in CO<sub>2</sub>. However, with only 1.39% lime in the low grade rock, its complete replacement could not account for 13.55% copper sulphide in the 'A' quartzite.

The low grade 'A' quartzite with 4.4% copper sulphide and the 'C' quartzite with 5.92% copper sulphide also show very little variation of any of the major rock forming elements or oxides.

The composition of a graywacke containing 7.65% copper sulphide is similar to that of the quartzites, except that alumina has increased from about 5.5 to over 9%, which with potash at 3.8% as in the other rocks, explains the high sericite content of the graywacke and the dearth of microcline. Combined water also increases with the mica content and free carbon assays 0.47%.

Although there are insufficient total analyses of the arenite type of orebody, the available data indicate a complete lack of evidence for selective replacements. Hence on this test the Mufulira arenite orebodies appear to be of syngenetic origin.

## APPLICATION OF SYNGENETIC CRITERIA TO THE COPPER DEPOSITS IN ARENITES

The following criteria characteristic of syngenetic ore deposits can be applied to the Mufulira arenites.

1. Sulphides are disseminated evenly along the bedding, richly in some horizons, poorly in others. This even dissemination persists for up to thousands of metres and is interrupted only by mineralized veins.
2. Metamorphic veinlets consisting of quartz, dolomite, and sulphides, or of quartz, anhydrite and sulphides in both the 'C' and 'B' horizons, especially where the dissemination is lean, exhibit the best examples of barren or low grade haloes observable on the Copperbelt. The mineralization is evidently pre-metamorphism.
3. In both the 'C' and 'B' orebodies there is a lateral zoning especially on the eastern margins of the deposits from barren arenite westwards to a bornite zone and then into a chalcopyrite zone, and stratigraphic zoning of the copper and iron sulphides is prominent in all three orebodies. Northwest of the mine, pyrite persists in the 'B' and 'C' horizons for up to 12 km.
4. In the development of the Mufulira West deposit it was found that the ore horizon over the crest of a buried granite hill is pyritic (fig. 9) whereas ore shales in a similar environment are generally barren. Malan (1964) discovered a stromatolite reef forming a biohermal barrier on the western margin of the lagoon in which the 'B' orebody formed. The presence of rich copper deposits in sands flanking this barren dolomitic bioherm with pyritic laminated carbonate sediments on the seaward side of the bioherm was the final vindication of the syngenetic origin for this and other orebodies at Mufulira.
5. The carbonaceous so-called graywacke of the 'A', 'B', and 'C' orebodies, with its muddy or sericitic matrix, is obviously the equivalent of the favoured host of the ore shale deposits.
6. The three graywackes occur only in the central parts of the depositional basins relatively further from shore, and the presence of free carbon is confirmation of anoxic conditions.
7. No continuous blanket of conglomerate forms the footwall of any of the orebodies, but near the base

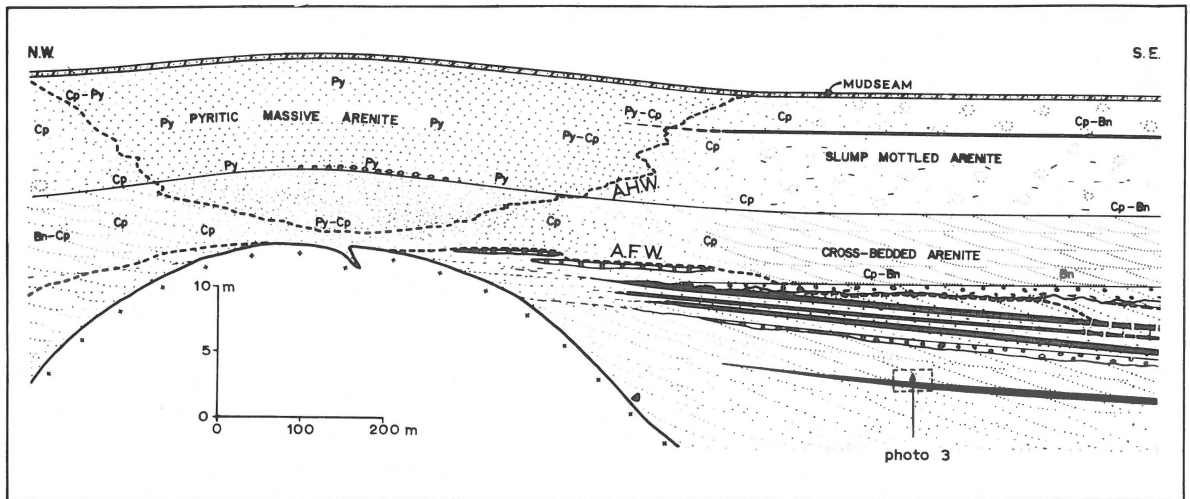


Fig. 9

Mufulira West. Hill of granite projects into base of 'C' orebody and fissure in granite is filled with chalcopyrite-rich arkose. Aeolian beds flank east side of hill and are overlain by pebbly grit, arkoses, and argillites with desiccation cracks. A coarse pebbly arkose transgresses these beds and incorporates fragments of the barren argillite into the cupriferous sediments. In compaction fold over hill chalcopyrite disseminations grades into pyritic dissemination. The pyritic cap is narrow close to the granite surface, but widens out upwards, reaching a maximum width of the "Mudseam". Location of photo 3 is shown.

of all three orebodies there is commonly a thick arkosic pebbly grit, locally mineralized.

8. Aeolian dune bedding was early recognized in the footwall of the 'C' orebody and also laterally equivalent to the 'C' orebody at its eastern fringe. The aeolian sands are devoid of sulphide mineralization.

Disseminated copper iron-sulphides, distributed similarly to the syngenetic deposits in graywacke and the ore shale deposits, but occurring here in conspicuously crossbedded arkose and even in pebbly arkose posed a problem as these sediments are deposited by high energy currents inimical to anoxic conditions. However, over the last 20 years evidence has accumulated that strong currents can occur under anaerobic conditions especially under an atmosphere lower in oxygen content than the present. The Mufulira ore deposits reveal a picture of slumping and generation of spasmodic turbidity currents feeding sediments into the centre of lagoons, at the same time that delta building modified by longshore currents deposited fine to coarse sands with rich precipitates of copper sulphides in an anoxic zone which must have extended close to the shore. Locally, concentrations of sulphides along foresets and truncation

planes, accompanied by abundant detrital heavy minerals are probably detrital.

At Chibuluma there is no carbonaceous graywacke and the presence of layers of nearly massive sulphide in an orebody averaging 5.25% copper and 0.25% cobalt made a replacement hypothesis attractive. However, the orebody occupies a basin in aqueous sediments overlying aeolian, and rich ore shoots of both copper and cobalt coincide with convergence of paleo-currents. Study of this deposit has thus provided convincing evidence that anoxic conditions are not confined to stagnant water, but that currents capable of carrying sand and pebbles up to 10 cm diameter occur in waters replete with hydrogen sulphide. Spasmodic floods bringing in iron and cobalt to give hydroxide precipitates, with subaqueous erosion of earlier disseminated sulphides provides evidence of the processes leading to syngenetic sulphide deposits – as described later.

#### EROSIONAL FEATURES IN COPPERBELT DEPOSITS

Sub-aerial exposure and local erosion is evident at the margins of the Zambian Copperbelt deposits.

Study of conspicuous erosion surfaces at Chibuluma and Mufulira has revealed rewarding evidence of depositional conditions of both sediments and sulphides.

#### *Chibuluma Scour Surfaces with Sulphidite<sup>1)</sup>*

In the western part of the mine (174 section) crossbedding in the lower third of the orebody is due to currents from northeast – that is updip. Bottomsets and truncation planes, marked by layers of rich sulphide mineralization, dip at 42° north, whereas underlying foresets dip at 20° north, a dihedral angle of 22°, typical of aqueous sand deposits. At the base of the upper third of the orebody a scoured surface overlies disseminated chalcopyrite and pyrite in grey albitized arkose, whilst immediately above the scour a 45 cm thick sulphidite layer consists of cobaltiferous pyrite with detrital sand grains (photo 1). Overlying the sulphidite is a layer of scattered quartz pebbles up to 30 mm diameter, which give the impression that they are “floating” on the sulphidite. Above the sulphidite layer two or three bands of arenite alternate with sulphidite; both are rich in chalcopyrite, and form a transition into the overlying quartzitic arenite with rich dissemination of chalcopyrite and minor cobaltiferous pyrite. This quartzitic arenite is an albitized arkose, with detrital tourmaline grains. Immediately beneath the knife-edge sharp scoured surface is a 22 mm band of darker quartzitic arenite and the top 10-15 mm is impoverished in sulphides. Thin sections (photo 2) show detrital sand grains in a felty matrix of tiny tourmaline needles which represent originally a muddy cement, tourmalinized by borates carried in by the current, which deposited the iron and cobalt of the overlying sulphidite. The surge of water must have been strong enough to transport large pebbles of quartz and quartzite and to scour and erode the underlying sediment.

A scoured surface in the upper third of the Chibuluma orebody at 120 section has potholes nearly 10 cm deep. The scour is covered by a layer of about 30 cm of sulphidite consisting of 80% cobaltiferous pyrite and 20% detrital quartz. Similar

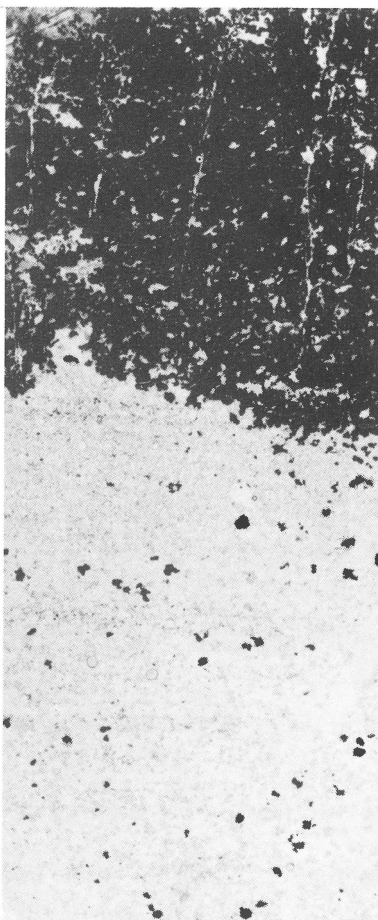


Photo 1

Ordinary light, x 2.5. Opaque (black) cobaltiferous pyrite, with few detrital quartz and albite grains overlying sharp irregular contact with detrital quartz and feldspar and few grains of pyrite and chalcopyrite.

material fills the potholes in which are conspicuous pebbles and cobbles of both quartz and arkose. The sulphidite is a massive rock in which detrital quartz and feldspar grains are streaked out in roughly parallel layers. At the top surface it grades abruptly into arenite in which detrital quartz and feldspar are dominant in sericitic matrix with 10% sulphides and crossbedding reappears in this horizon. Below the scoured surface is a crossbedded unit of feldspathic arenite with disseminated chalcopyrite and pyrite and rare concretions of pyrite up to 3 cm long. The quartz and feldspar pebbles and cobbles are not resting on the scoured surface of the pothole but are

<sup>1)</sup> Sulphidite is a term of convenience for any rock containing more than 33% sulphide of any metal. It does not imply any genetic significances.

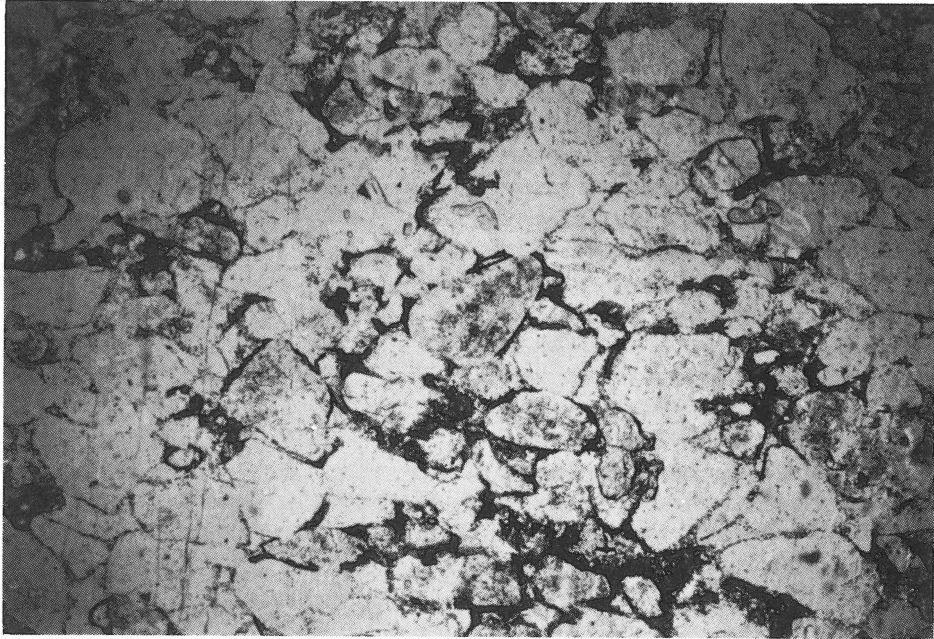


Photo 2  
Plane polarized light, x 40. The original detrital outlines of the quartz and feldspar grains are outlined by dusting of tourmaline.

apparently “floating” in the massive sulphidite (fig. 10).

An exposure at 154 section in the middle of the orebody shows a scoured surface overlain by 2 cm of massive cobaltiferous pyrite and above that by another 5 cm of sulphidite with numerous coarse detrital grains of quartz and feldspar and scattered pebbles of quartz and quartzite up to 2 cm across. This rock then grades up into the normal sericitic feldspathic arenite with less than 15% disseminated sulphide, mostly chalcopyrite. The pyritic arenite below the scoured surface has 3 cm of darker rock immediately below the contact, grading to nearly black in the upper 1 cm. Under the microscope the original detrital grains of quartz and feldspar are seen perfectly outlined by a coating of fine tourmaline crystals – few of which are 10 microns – growing out into the pore spaces filled by new growths of quartz and albite. The rounding of some sand grains is conspicuous, suggestive of aeolian transport.

Another scoured surface 10 m below the orebody separates the aqueous arkoses from the underlying aeolian feldspathic arenites. This surface, with spectacular potholes, rises eastwards resulting in thinning of

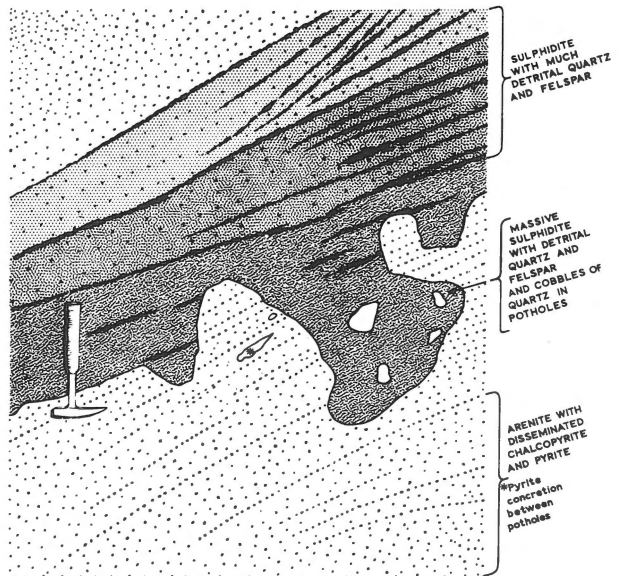


Fig. 10  
Chibuluma 1340' level, 120 section.  
Sulphidite layer is 80% cobaltiferous pyrite and carrollite with only a little chalcopyrite and, with cobbles of quartz, fills potholes eroded in crossbedded arenite with disseminated chalcopyrite and pyrite assaying 2% copper. Crossbedded sericitic arenite, assaying 6% copper and 0.2% cobalt, overlies sulphidite.

the ore horizon arkoses between the aeolian beds and the Hangingwall conglomerate. On this scoured surface pebbles of quartz and quartzite rest immediately on the bottom or against the sides of the potholes, in contrast to the "floating" pebbles in sulphidite filled potholes in the orebody.

### Interpretation of Environment

A detrital origin for these cobaltiferous pyrite layers is unlikely as no natural mechanical methods of separation would separate chalcopyrite and bornite from cobaltiferous pyrite with similar specific gravities. Tourmalinization of the underlying surface indicates that waters rich in boron must have flowed over the scoured surfaces. The complete conversion of detrital microcline and orthoclase grains to albite indicates that the lake waters were saline. Unlike Mufulira, there is little carbonate or anhydrite in the Chibuluma orebody.

The orebody occurs in pebbly arkoses and pebbly sericitic arenites resting on an eroded surface of desert sands. It thus appears that the aqueous beds containing the sulphides were deposited in a highly saline lake or lagoon rich in sodium chloride, and possibly calcium sulphate, fed by ephemeral floods enriched in borates and cobalt and iron carrying gravel, sand, and mud.

The scoured surfaces overlain by sulphidite form natural marker horizons in the orebody and do not appear to have been exposed to the atmosphere. High cobalt and copper grades overlying the scoured surface can be traced from east to west right through the Chibuluma orebody. Thus these surfaces can be extrapolated to, and beyond, the orebody fringes where commonly a thinning of the aqueous sediments between hangingwall conglomerate and underlying aeolian occurs (fig. 11). Here sun-cracked mud layers, more prominent crossbedding, and pebbly layers occur, some of which may be extensions of the scoured surfaces in the orebody. Thus outside the orebody these "scour horizons" were probably subject to desiccation for varying periods. Such exposed playa lake sediments would contain disseminated pyrite with a little cobalt and copper as sulphides which, when exposed to the air, would decompose and effloresce<sup>1)</sup> on the surface. Likewise other soluble salts would form efflorescences and encrustations including sodium carbonates and borates. At rare intervals this surface was swept by floods originating in rain storms in the adjacent hills or by

<sup>1)</sup> In these efflorescences cobalt increases in concentration over nickel, which tends to remain below, locked up in clay silicates. Laboratory experiments are being made and show doubling of the cobalt/nickel ratio in the efflorescences.

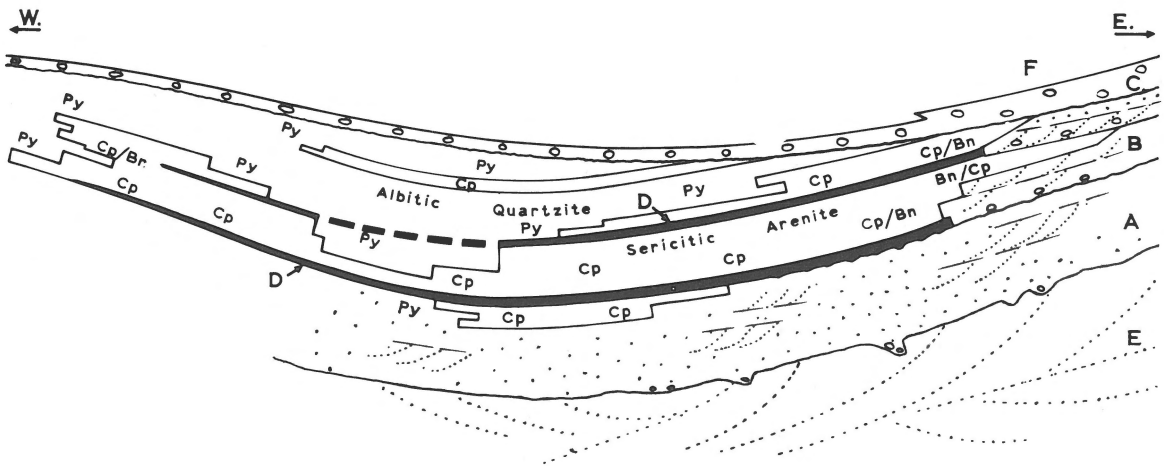


Fig. 11  
Diagrammatic cross-section of Chibuluma orebody, showing principal sulphidite marker horizons. Vertical scale grossly exaggerated.

E. aeolian arenites; A. arkoses; B. pebbly arkoses grading westward into sericitic arenite; C. hangingwall conglomerate; F. dolomitic sandstones, shales and dolomites of Upper Roan.

D. sulphidite marker horizons traceable for long distances through orebody, locally with scours and potholes at base.

marine incursions. The rush of waters over the flat dried out surface would pick up sand and mud and dissolve the efflorescences of sodium carbonate, borate, and iron and cobalt sulphates. These waters would be somewhat acid and would flow to the low lying basin in which the orebody was being deposited. Here they merged into a standing body of water with high pH. Immediately iron with cobalt would be precipitated as a red hydroxide. This red mud, with an admixture of sand and pebbles, displaced the bottom waters causing local scours and potholes, and the red hydroxide mud with its included pebbles carpeted the scoured surface. Borates diffusing into underlying sand would be absorbed by interstitial clay and sodium salts would convert microcline to albite. Anaerobic bacteria generating hydrogen sulphide would gradually convert the red hydroxide mud to sulphide, to form the layer of richly cobaltiferous pyrite. In the overlying clear waters copper and iron in solution would be precipitated by  $H_2S$ ; thus is explained the gradation from cobaltiferous pyrite into the overlying chalcopyrite dissemination.

#### PALEOGEOGRAPHY OF MUFULIRA DEPOSITS

(This section is submitted jointly by V.D. Fleischer and W.G. Garlick)

##### *Footwall and 'C' Orebody*

Prior to deposition of the 'C' orebody sediments, the landscape consisted of sand dunes drifted by a wind from northwest with numerous inselbergs of Basement schist and granite projecting through the sand blanket. The dunes were bevelled by water and wind cutting down to a rising water table. The dune field was locally inundated by saline waters in playa lakes in which sand and mud accumulated to give horizontal and parallel lamination. As the lakes dried out, mud flats, especially on the east flank of the Mufulira west granite ridge, were exposed and desiccated. Gypsum, later to form anhydrite concretions, was precipitated in the emerged muddy sands and crystallized on sun-cracked surfaces. With the change of wind to north, dunes again spread over the thin aqueous deposits and detrital gypsum contributed to these new dunes, laminae of which assay as much as

35%  $CaSO_4$ . This later dune field was again bevelled to an essentially flat surface and inundated, thus repeating the playa lake formation and development of gypsum or anhydrite concretions in the sandy muds. Local anaerobic conditions developed and deposited either siderite or small amounts of copper-iron sulphide now represented by chalcopyrite or bornite. Dune sands from the north overwhelmed these second playa deposits, the wind-blown foresets of light grey sand, often with considerable gypsum, advancing over the wet surface of flat lying dark muddy beds (photo 3).

The subsequent major aqueous invasion, probably a *marine* transgression, resulted in deposition of one or more thick pebbly arkosic grits in the lower parts of the basins, overlain by deltaic deposition of tabular co-sets of markedly crossbedded arkose. Towards the granite ridge the pebbly grit thins, but contains more and more barren mud flakes from the shores of the original playa lakes, now transformed to a marine lagoon.

The marine transgression terminated the alternate playa and aeolian conditions and the basins were filled gradually with an increasing thickness of muddy sand containing copper-iron sulphide precipitate. On the flanks of the ridges these sediments, lubricated by slimy sulphide precipitates, slumped to give a chaotic slump breccia and periodically generated minor turbidity currents which carried sand, mud, and sulphides with organic carbon, into the central parts of the basins to form the so-called graywacke.

During deposition of the 'C' orebody the Basement ridges were truncated and buried under sediment, but evidently the waters over these ridges remained shallow. Thus over the crests of the ridges sedimentation of cleaner sand occurred in wave swept shallows; anhydrite formed as concretions but no copper sulphide was precipitated. After burial anaerobic conditions spread through the sub-aqueous sediment, and  $H_2S$  precipitated iron only, since copper ions were insignificant in the pore waters. Calcite and anhydrite filled the remaining pore spaces.

A slump breccia occurring within the 'C' horizon is usually interrupted by several continuous layers of argillite representing layers of mud settled from the water during long quiescent periods between episodes of slump and turbidity flow. On the east flank of the granite several scour channels or "washouts" prove

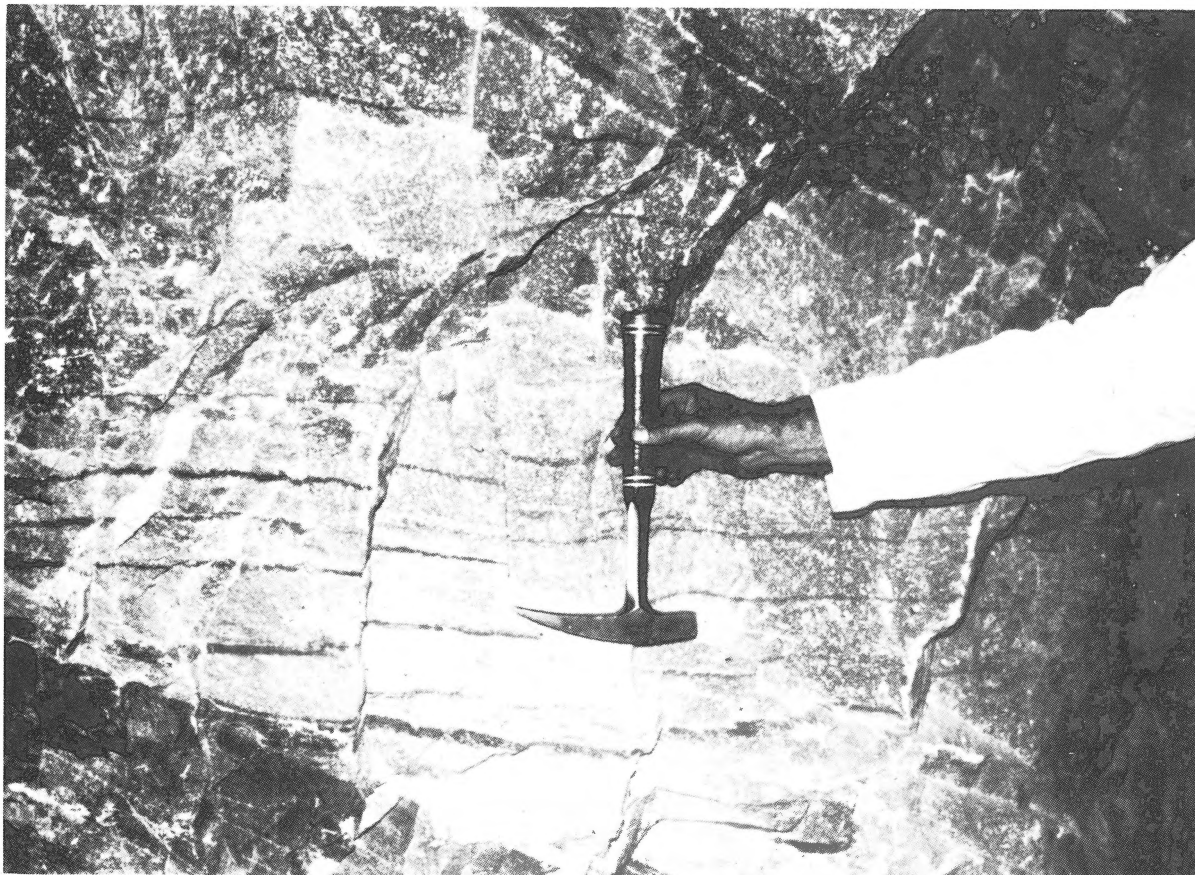


Photo 3  
Mufulira West 2150' level, 45 section.

Aeolian crossbedding with thick white laminae consisting of up to 35% anhydrite show abrupt inflexion into dark grey to black aqueous graywacke type sediment with mauve lenses and nodules of anhydrite. Foresets make angle of  $33^\circ$  with truncation plane which dips northeast.

the syngenetic age of the slumping and brecciation. The channels are filled with barren clean white, fairly well bedded arkose, and in some channels a thin chalcocite layer occurs along the footwall scoured contact, probably representing a *detrital* concentration of copper sulphide (G a r l i c k 1967).

#### 'B' Orebody

The clean feldspathic sands of the Inter 'B/C' beds indicate a marine regression. The formations of the 'B' orebody are nearly identical with those of the 'C', and reveal a second marine transgression again advancing eastwards.

Differential compaction of the thicker sediments

in the central parts of the basin caused continued sagging and preservation of similar basin conditions to form the 'B' orebody superimposed over the eastern basin of the 'C' orebody. Anaerobic conditions again developed, first in the centre of the basin and then spreading outwards up the flanks of gentle swells, draped over ridges of Basement schist in the west and over thick aeolian beds in the east (fig. 12).

Over the western swell wave action broke up weakly cemented sands to form a sedimentary breccia on which a stromatolite reef developed (M a l a n 1964). This forms the western barrier of a lagoon in which chaotic slump breccias, and graywacke of the 'B' orebody were deposited with even richer mineralization than in the underlying 'C' orebody. West of

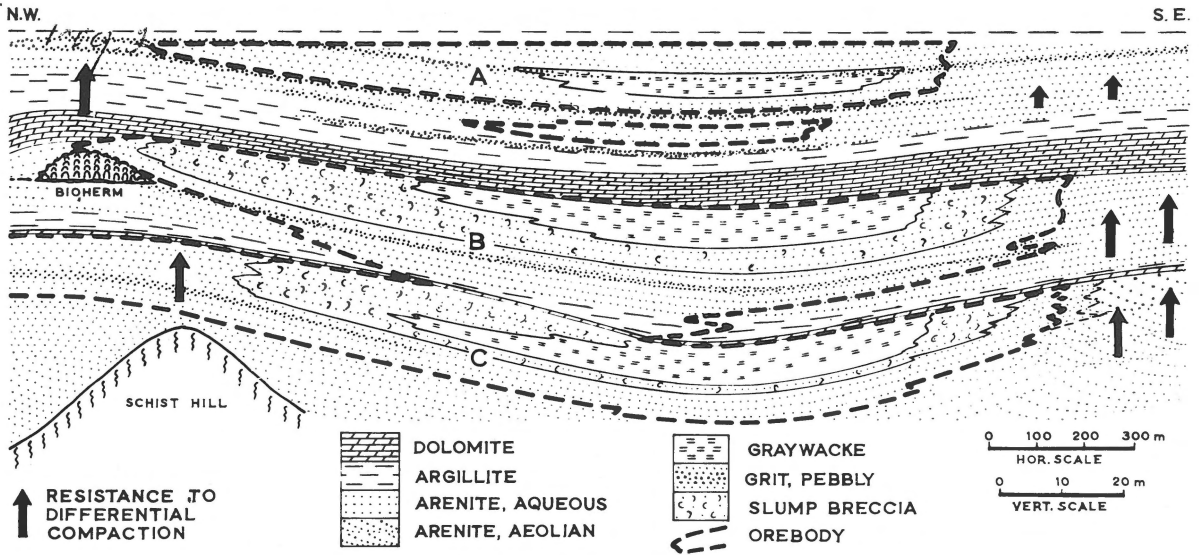


Fig. 12 Super-imposition of Mufulira 'A', 'B', and eastern part of 'C' orebodies by compaction folding. Note development of algal bioherm on west flank of compaction fold over schist hill, thus enclosing lagoon in which 'B' orebody developed.

the reef pyritic disseminations occur in a thinner seaward facies of the 'B' horizon.

A 6 m thick dolomite terminated copper deposition but compaction of the underlying muddy sediments continued and the basin shape was preserved.

Regression followed, marked by thick barren muds, followed by sands with magnificent load casts into the black muds.

#### 'A' Orebody

Coarse red arkosic sediments marking the third marine transgression were poured into the basin and copper precipitation was renewed in the centre. The sediments became finer upwards and copper deposition (now represented by chalcocite) was initiated in the centre and then spread up the flanks of the basin. Eventually, carbonaceous graywacke was again deposited. This 'A' graywacke is characterized by rich chalcocite mineralization, graded bedding, and a layer of glassy quartz pebbles near the top; chalcopyrite and local pyrite are restricted to a central area of the graywacke.

Deposition of sandy muds with considerable anhydrite or gypsum terminated the 'A' graywacke deposition, but copper occurs for 1 or 2 m into this stratum

in the central part of the basin. The formation is poorly bedded with small sandy lenses and much gypsum or anhydrite. It is interrupted by two thick beds of crossbedded arkose and several layers of pink dolomite to give a total thickness of 100 m. It possibly formed on an extensive tidal flat. It is overlain by the Upper Roan dolomites, marking a fourth major marine transgression.

#### Detrital Sulphides

Concentration of sulphide grains along foreset laminae and truncation planes of crossbedded strata is a conspicuous feature of all the orebodies in arenites. Ubiquitous examples at Chibuluma and Chibuluma West were interpreted by one of us (V.D.F.) in 1955 as primary detrital concentrations of sulphides derived from the erosion of nearby sulphide bodies.

However, especially in arenites, there is the problem of movement and recrystallization of the sulphides by diagenesis to form concretions and, during metamorphism, sulphides migrated into porous zones and into fissures. Detrital deposition of sulphides fails to explain sulphide mineral zoning. Proof for a detrital origin has therefore remained elusive until recently.

Concentrations of sulphides on laminae of cross-bedded sandstones of the 'C' Orebody, and in the hollows of ripples of the 'B' Orebody have been described by G a r l i c k (1967). On the 665 m level — 65 section, a magnificent exposure of festoon crossbedded arkose contains conspicuous concentrations of chalcocite and bornite grains along dark laminae separated by white laminae with practically no sulphide. The foresets have a maximum dihedral angle of  $25^\circ$  and inflect into truncation planes also carrying sulphide concentration, as seen in photo 4. Examination of thin sections reveals that the white layers contain few minute specks of sulphide and abundance of quartz, feldspar, anhydrite, and carbonate, but that the dark laminae with less of the above minerals contain coarse blebs of sulphide, invariably accompanied by detrital grains of tour-

maline, with overgrowths, and by zircon.

P.L. Binda of the Geological Research Department, examining one of these occurrences, found that the sulphide-rich dark laminae have a much higher content of detrital zircons than the barren light laminae. Since zircon and copper sulphide share a higher specific gravity than the main constituents of the arenite, this can be taken as an indication of detrital concentration of the sulphide.

## CONCLUSIONS

The geology of the Zambian Copperbelt provides a plethora of facts and theories from which it is difficult to choose special features for emphasis. Recognition of aeolian dunes and paleo-hills buried

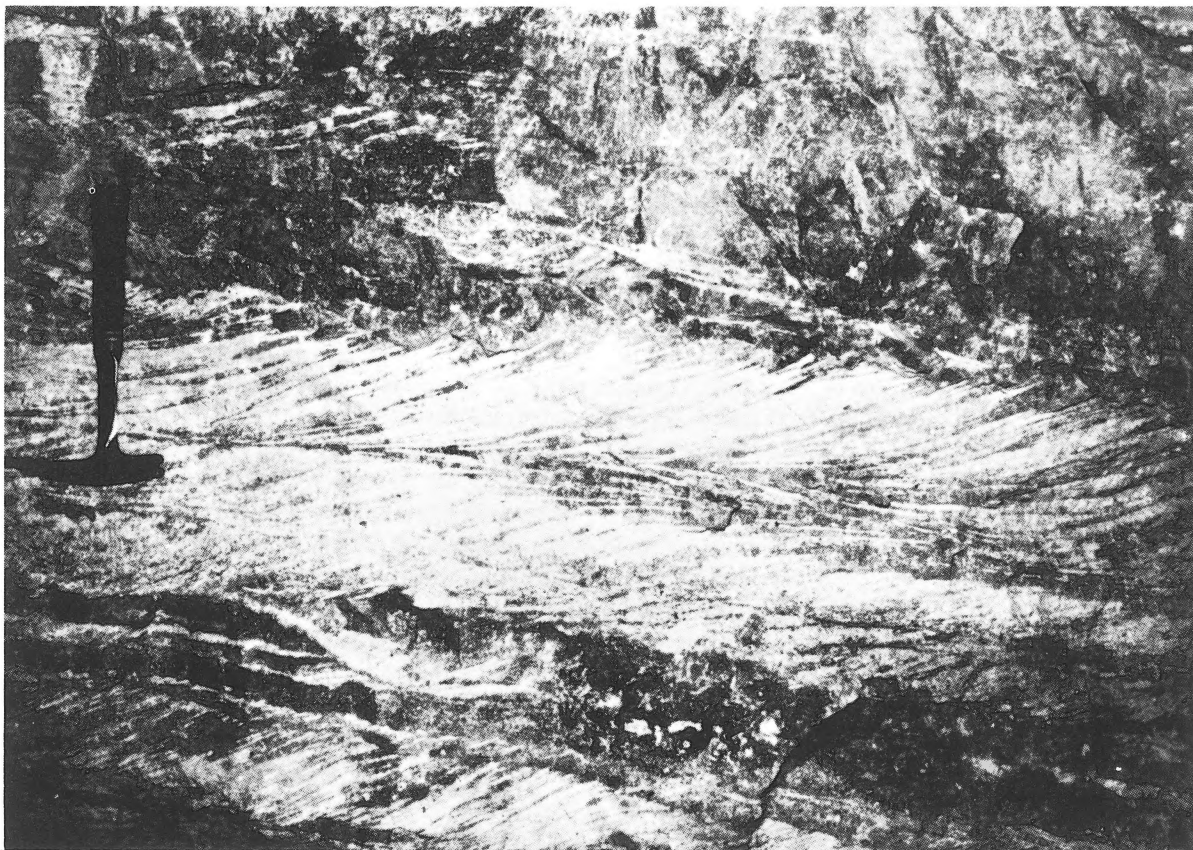


Photo 4  
Mufulira West 2150' (655 m) level, 65 crosscut.

Festoon crossbedding at base of 'C' orebody showing dark layers due to bornite-chalcocite concentrations along foresets and truncation planes. Foresets make angles of  $25^\circ$  with truncation planes, which dip to northeast.

under thick layers of metasediments would appear purely academic yet these features have an important control on the distribution and grade of orebodies and even present day streams.

The critical reader will have noted the mention of streams of the present landscape superimposed over paleo-hills of Basement, usually granite, projecting into the Katanga system. This is due to the more resistant Lower Roan arenites forming minor watersheds, broken through by the drainage where the Lower Roan is thinner and arched in compaction folds over Basement ridges. Over these paleo-hills the ore formations are commonly barren; hence prospecting of the streams in the 20's of this century gave a misleading picture of mineralization in these sediments. An exception was the Luanshya stream, which, failing to find thinner Lower Roan over a paleo-hill, cuts across the tight syncline and by stripping the usual tropical overburden from the ore shale revealed the latter with moderate grades of oxide copper mineralization. Another exception was the Nchanga stream over the River Lode of Nchanga where the footwall formations were thicker than 650 m. Due to the interplay of many geological processes – some obscure and apt to be overlooked – a stream section does not necessarily give a reliable picture of the geology nor of stratiform mineralization.

In the early days of the Copperbelt the epigeneticists claimed that most of the orebodies should have some outcrop because of the silicification associated with hydrothermal mineralization. However, this surmise was wrong, the orebodies are syngenetic; there is no silicification of the ore, and subsequently many orebodies have been found on the Copperbelt with no outcropping copper stains.

Compaction folding over Basement ridges is an important factor controlling barren, or pyritic, gaps over the ridges with basins on either side containing copper deposits. This is neatly exemplified at Mufulira where in the eastern basin thick muddy sediments in the slump breccia and 'C' graywacke suffered greater compaction than the thin cleaner sediments over the Basement schist ridge to the west. Thus the basin of sedimentation containing the 'C' orebody survived to receive the lagoonal 'B' orebody sediments, which was flanked by an algal reef growing on the seaward side of the compaction fold over the same buried Basement ridge. Aeolian dunes forming

the eastern margin of the 'C' orebody basin also suffered less compaction and thus exerted remote but precise control of this other margin of the 'B' orebody. The same controls – deeply buried aeolian beds of 'C' horizon in the east and the buried schist ridge in the west, with a thick column of argillaceous sediments of both 'B' and 'C' orebody between – allowed perpetuation of a basin in the same geographic position for reception of the superimposed rich 'A' orebody, as shown in fig. 12.

Other small orebodies, commonly in the footwall of the ore shale, are even more closely associated with hills and ridges of Basement. Some of these deposits are extremely rich; one drill-hole section of the Chibuluma West orebody grades 13% copper over a true thickness of 21 m and occupies the lowest aqueous beds above aeolian, flanking a schist ridge. This orebody appears to occupy a "moat" in the aeolian beds surrounding a Basement schist ridge. (White and Green, 1971). A daylight flight over the Sahara revealed that the sand dunes were commonly separated from isolated rocky hills by such a moat, evidently due to greater wind turbulence over these projections inhibiting adjacent sand deposition.

The Copperbelt orebodies provide a never ending and fascinating study of special conditions of sedimentation followed by folding, metamorphism, erosion, and weathering.

Sedimentation under anoxic conditions, localized both in place and time, controlled the stratiform shape, the disseminated nature, the metal zoning, and the grade of the ore.

Diagenesis resulted in formation of sulphide concretions in arenite orebodies and was presumably the main process in development of pyrite over the paleo-hills, which commonly cause interruption in the continuous stratiform nature of the orebody.

Compaction folding over paleo-hills and other resistant bodies controlled the margins of the stratiform orebodies.

Later tectonic folding modified the shape of the orebodies and the enclosing sediments, but had little or no effect on grade.

Regional metamorphism caused complete recrystallization of most minerals of the sediments including the sulphides, and resulted in lateral movement of solutions into fractures with development of appropriate minerals in the veins.

At least 600 m.y. of erosion has resulted in peneplanation and exposure of the upper edges of the folded orebodies. Weathering has allowed leaching and local supergene enrichment in the upper 70 m of all the orebodies and locally, minor leaching, oxidation, and supergene enrichment has extended to that depth.

A part of the picture is still missing — the source of the metals of these vast, rich orebodies. The copper, cobalt, and iron may be derived from either:

1. Erosion of a vast hinterland with perhaps only normal concentrations of the metals, with perhaps local rich concentrations.
2. Supply by upwelling oceanic currents.
3. Volcanic exhalations, which in view of the lack of recognizable volcanic debris in the Lower Roan, were probably distant from the Copperbelt.

The high potash contents of the ore shales and the boron content of certain strata at Chibuluma and Chibuluma West orebodies were first noted by Darnley (1958 and 1960) and ascribed to igneous emanations at, or immediately after, sedimentation. Study of the orebodies during the last decade has indicated however, that the potash and boron concentrations are ascribable to unusual sedimentary processes although the boron may be ultimately of igneous origin.

It is evident that study of these orebodies is still far from complete and promises to be even more rewarding.

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