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THE GENETIC RELEVANCE OF RECENT STUDIES AT MUFULIRA MINE, ZAMBIA

by

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(11 figures and 1 table)

RESUME.- Des études récentes, pétrographiques, minéralogiques et chimiques, des extensions profondes des gisements de MUFULIRA ont mis en lumière certaines relations intéressantes qui peuvent être en rapport avec le mode de mise en place de ce type de minéralisation sulfurée dans des couches à dominance arénacée.

Les résultats acquis paraissent s'expliquer le mieux par la migration de solutions enrichies en métal à partir d'une couche-mère (l'horizon C) vers des bancs de niveau stratigraphique plus élevé situés dans une structure anticlinale résultant de la compaction différentielle des sédiments sur un relief du soubassement. En outre, il semble que les métaux ont été déposés dans des horizons favorables par l'action réductrice de bactéries sur des sulfates au voisinage d'accumulations d'hydrocarbures liquides ou de saumures contenant des hydrocarbures solubles.

ABSTRACT.- Recent petrographic, mineralogical and chemical studies of deep extensions to the Mufulira orebodies have brought to light some interesting relationships which may have relevance to the mode of emplacement of this type of sulphide mineralization in dominantly arenaceous strata. It is suggested that the evidence gained can best be explained in terms of leakage of metal enriched brines from a source bed, the C horizon, into stratigraphically higher horizons within a structural culmination resulting from differential compaction of sediments over a basement hill. Furthermore, it would appear that the metals were fixed within favourable horizons by bacteriogenic reduction of sulphates in the vicinity of liquid hydrocarbon accumulations or brine pools containing soluble hydrocarbons.

INTRODUCTION

The work reported here was undertaken on behalf of RCM Ltd's Mufulira Division and was concentrated in an area under active evaluation which lies in the eastern section of the mine (No 7 Shaft) and below the 810 m Level to depths of 1930 m (ANNELS & STEED, 1977). No development has yet penetrated this portion of the orebody and all of the material studied from here was thus obtained from drill cores. Additional information was derived from drill cores and stopes within the main orebodies above the 810 m Level, the lowest development level. Potentially economic mineralization has been proven in the B and C horizons and a limited area of lower grade Inter BC mineralization has also been outlined. The A and Inter AB horizons, though containing some thin high grade bands, have no economic significance.

Table 1 is a stratigraphic summary of the succession at Mufulira for those who are not familiar with this mine and the reader is referred to papers by MAREE (1962), GARLICK (1967), BRANDT (1962) and van EDEN (1974) for more details of the main orebodies.

GEOLOGICAL RESULTS

SUB 810 m LEVEL GEOLOGY

All the information presented in figs 1 to 7 is the product of a relogging exercise on all the cores still existing from drill holes intersecting the study area east of mining boundary 37/38 m and represents the situation as of June 1978. The maps are based on unrolled plans of drill hole intersections of the Mudseam horizon (immediately above the C horizon) using the 810 m Level as unrolling axis.

BASEMENT PALAEOTOPOGRAPHY

Most of the study area is underlain by Lufubu schist and only in the western section close to the 810 m Level is granite recorded. Isopachs of the thickness of

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Table 1.– Stratigraphy of the Mufulira ore-bearing formations.

Formation	Thickness (metres)	Facies Equivalent	Mineralization
Lower Argillaceous Quartzite	25-30		Barren Hangingwall
A Quartzite	10-11	A Graywacke	Ore Zone
Inter AB Quartzite	10-12		Locally mineralized
Banded Shale and Quartzite (BSQ) Massive Shale	3-5		
Lower Dolomite (+ Gritty Marker)	4-6		Mineralized at base
B Quartzite	5-10	B Graywacke	Ore Zone
Inter BC Quartzite	11-12	Algal Dolomite (stromatolitic)	Locally ore
Banded Shales and Quartzites (BSQ) Banded Shale and Dolomite (BSD) Mudseam (Dolomitic Silt-stone)	2·5-3		
C Quartzite	10-20	C Graywacke	Ore Zone
FW Quartzites	0-150	Grit	Barren Footwall
Basement granite and schist			

the footwall formations drawn on rather sparse data points, suggest that a small basin exists in the west which is separated from a deep trough in the east by a northeasterly trending transverse ridge. This is a spur from the main northwest-southeast ridge which lies close to the 810 m Level and which can be followed from Mufulira West for the entire strike length of the Mufulira orebodies as far as the eastern economic fringe.

The basement palaeotopography at Mufulira is represented in fig. 1 which also includes information on the sulphide zones. The study area is also indicated in this figure.

FOOTWALL FORMATIONS

The basement complex is overlain by a sequence of rocks of highly variable thickness which may include the following :

a) dark grey to black argillaceous quartzites with argillite seams;
b) banded grey-green argillaceous quartzites and pinkish-white dolomitic and/or anhydritic quartzite;
c) gritty or pebbly argillaceous quartzite;
d) buff-white dolomitic quartzite;
e) grits;
f) pale mauve anhydritic quartzites;
g) breccias where the C horizon almost directly overlies the basement.

The transition into the overlying C quartzites is marked by the disappearance of banding and grit and by a deterioration in bedding as the rocks become massive.

C HORIZON

Comparison of fig. 2 with the relevant area of fig. 1 reveals a complete lack of correlation on a regional scale between the C horizon thickness and the basement palaeotopography. However, on a more local scale it appears that this horizon does tend to thicken over the flanks of the transverse basement ridge and thin over the crest. No evidence can be seen of thickening over the valleys. The central zone of the mineralized area of the C horizon (fig. 3) consists of a fine grained light grey dolomitic quartzite but the peripheral areas are dark greenish grey fine grained argillaceous quartzites with dolomitic mottling. A similar charge was noted in the main section of the Mufulira East (No 7 Shaft) orebodies above the 810m L (ANNELS, 1979). Beyond the eastern economic fringe there is a subtle change to rather coarser grained argillaceous quartzite. A small outlier of "greywacke", or carbonaceous arenite, occurs in the upper section of the horizon immediately to the southeast of the transverse ridge and within the area of light grey quartzites. At the base of the C horizon there is a thin pink anhydrite quartzite but this disappears beyond the economic fringe. A very similar situation was recorded by ANNELS (1979) in the main orebody.

The metre-percent map for copper (fig. 3) over the entire thickness of the C horizon bears a close resemblance to the isopachyte map of this horizon; the copper content is greatest in the thickest section. At the same time it appears that a thick footwall is not conducive to good copper concentrations in the overlying C horizon. As the economic fringes are approached the sulphides retreat upwards from the base of the horizon, with only a minor retreat from the hangingwall. Vertically the sulphides become more copper rich as the hangingwall is approached and laterally there is a marked sulphide zonation in a northwesterly direction away from the eastern fringe where chalcocite eventually gives way to bornite, then to chalcopyrite and finally to chalcopyrite plus pyrite beyond the western fringe. No pyrite is developed along the eastern fringe and it is only weakly developed in the west. This situation parallels that in the main orebody where pyrite is a feature of the Mufulira West fringes (fig. 1). The zonation described above could be used to support synsedimentary deposition away from a palaeo-shoreline to the east or precipitation under the influence of redox gradients away from the interface between two groundwater regimes, one of which was a metalliferous brine. The vertical zonation, however, is not compatible with the sedimentological evidence for a deepening of the waters during deposition of the C horizon.

GARLICK (1967, pp. 142-145) states that on the 1200 and 1400 ft Levels dune sands appear at the eastern margin of the C orebody and extend eastwards for many miles. He describes the way in which barren aeolian beds inter-digitate with cupriferous aqueous beds. The implication is that the barren quartzites beyond the fringes are clean and well sorted. The present author unfortunately has not been able to examine the exposures he describes but is familiar with the situation along the same fringe below the 810 m L. All intersections beyond the fringe here are in dark, poorly sorted, very argillaceous quartzites, sometimes with

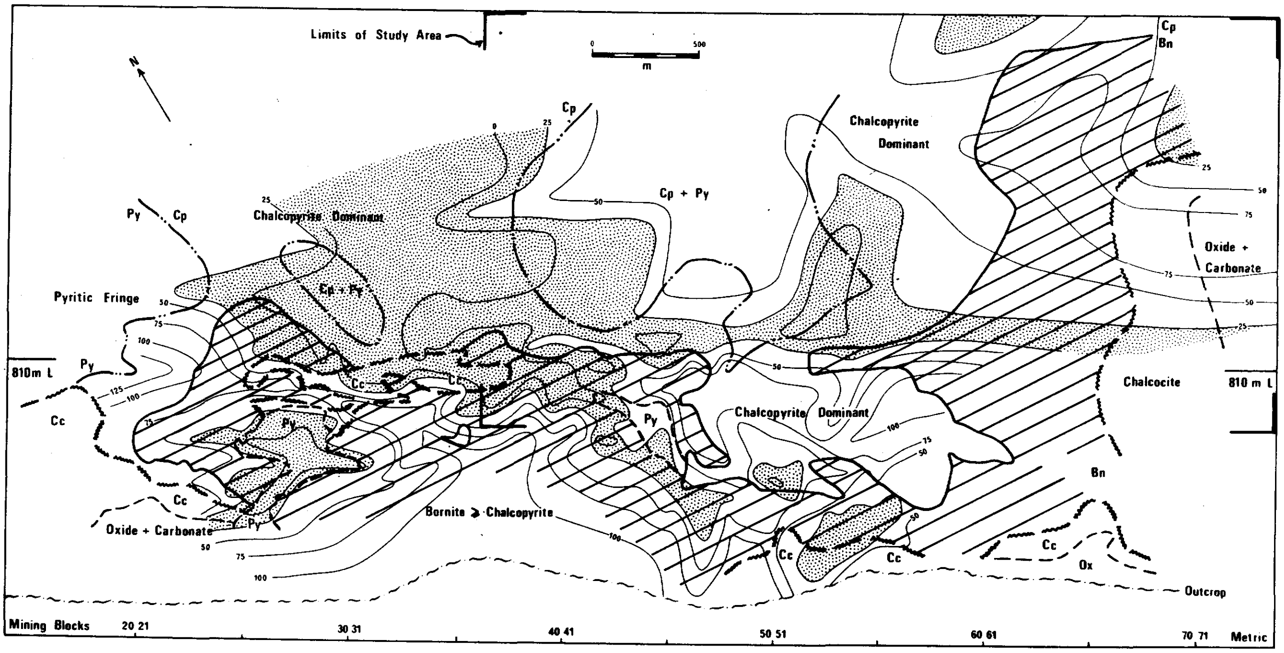

Figure 1.- Sulphide zones superimposed over basement palaeotopography. Isopachs of Footwall Formations at 25 m intervals. Stippling indicates areas where basement is less than 25 metres from the base of the C Horizon.

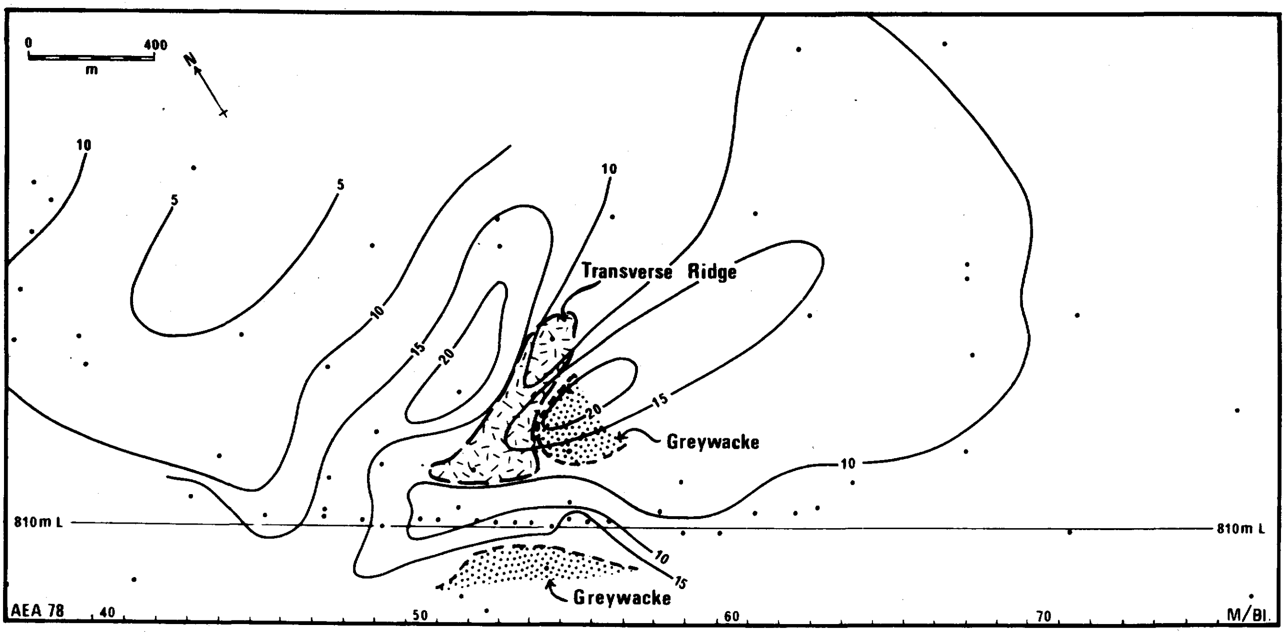

Figure 2.- C Horizon isopachs (in metres) showing location of transverse basement ridge and greywackes.

dolomitic mottling. It is very difficult to envisage these as being aeolian sandstones. They are frequently heavily leached and decomposed and contain small concentrations of chalcocite and malachite along with a certain amount of iron staining. As the economic fringe is approached small patches of chalcopyrite and bornite appear with the chalcocite and it seems possible that at least some of the chalcocite is secondary after these primary sulphides.

INTER BC HORIZON

The C horizon is capped by the Mudseam (dolomitic siltstone), banded shales and quartzites and/or banded shales and dolomites which together total 2 to 3 m in thickness. These are succeeded by 11 to 12 m of hard, recrystallized, clean, pinkish white to buff quartzites which display an upward coarsening in grain size and terminate in a unit characterized by festoon and ripple drift bedding. Less recrystallized interbeds and patches are frequently highly anhydritic imparting a distinct mauve tinge to the rock. Scattered pink feldspar fragments and thin arkosic seams occur throughout the section but become more common to the southeast suggesting a source area in this direction. Small dolomite porphyroblasts occur in the finer grained heavily recrystallized lithologies. No algal dolomite is developed in this horizon comparable with that in the western portion of the main orebody.

The combined thickness of the Inter BC horizon is lower in an easterly striking central area where the average is 13.5 m. It is bounded by areas in excess of 15 m and hence shows a marked resemblance to the C horizon.

The Inter BC is usually barren or low grade (i.e. less than 0.3 o/o Cu) but an east-west corridor (fig. 4) containing more than 5 m o/o copper protrudes from the down dip fringe of the main BC orebody to the limit of exploration. The main area of Inter BC mineralization, which is dominantly bornitic, cuts out very close to the 810 m Level. Below this level the narrow mineralized corridor contains bornite with some chalcopyrite but this passes outward in all directions into chalcopyrite with only minor bornite. A small patch of copper enrichment also occurs in this horizon further to the south east but this is in an area of leaching and oxidation and consists of bornite, chalcopyrite, chalcocite, malachite and some chrysocolla. Beyond the eastern and southeastern fringes of this mineralization the Inter BC horizon is heavily leached and decomposed, often with a pink and green colour mottling. Some intersections are completely barren while others contain patches which are malachite and limonite stained or contain chalcocite, malachite and chrysocolla mineralization. Along the northern fringes, the rocks are fresh and unaltered and are either barren or contain trace amounts of chalcopyrite. Pyrite has not been recorded in this horizon.

B HORIZON

Isopach maps of the B horizon reveal that it too shows a thinning over the transverse ridge and also over the main ridge close to the 810 m Level. Thickenings occur in areas which approximately coincide with depressions in the basement palaeotopography. Lithologically this horizon is a fine to medium grained, dark to medium grey argillaceous quartzite with little evidence of bedding in the upper portion but with the appearance of whispy argillite seams and banded dark grey to white quartzites closer to the base. The latter are best developed in the northwestern area and there is some doubt as to whether they should be considered as parts of the B or Inter BC horizons.

Examination of the B horizon lithologies beyond the eastern economic fringe shows that a transition to aeolian rocks does not exist. All barren intersections are of massive dark grey argillaceous, sometimes mottled quartzites with argillite seams. There is thus no significant sedimentological change to account for the cut-out of sulphides. Two drill holes are recorded as having intersected graywackes in the B horizon but this could not be confirmed by the author; the core from one hole is no longer available and the second hole was completed after the relogging and sampling exercise was finished. If these identifications are correct then they must represent very localized occurrences.

Unlike the C horizon, there is very little correlation between copper content and thickness of the B horizon or between copper content and lithological variations. Dolomitic mottling is variably developed but is most intense where there is good sulphide mineralization and less so in the fringe areas where dolomite is accompanied by anhydrite. Anhydrite only appears in weakly mineralized or barren B intersections. A narrow east-west zone of high copper (fig. 5) directly overlies, but is slightly broader than, that in the underlying Inter BC. There is a weaker correlation with the palaeotopography of the basement than in the C horizon but the north western basement basin does correlate well with an area of very poor mineralization in the B and the western end of the copper rich zone

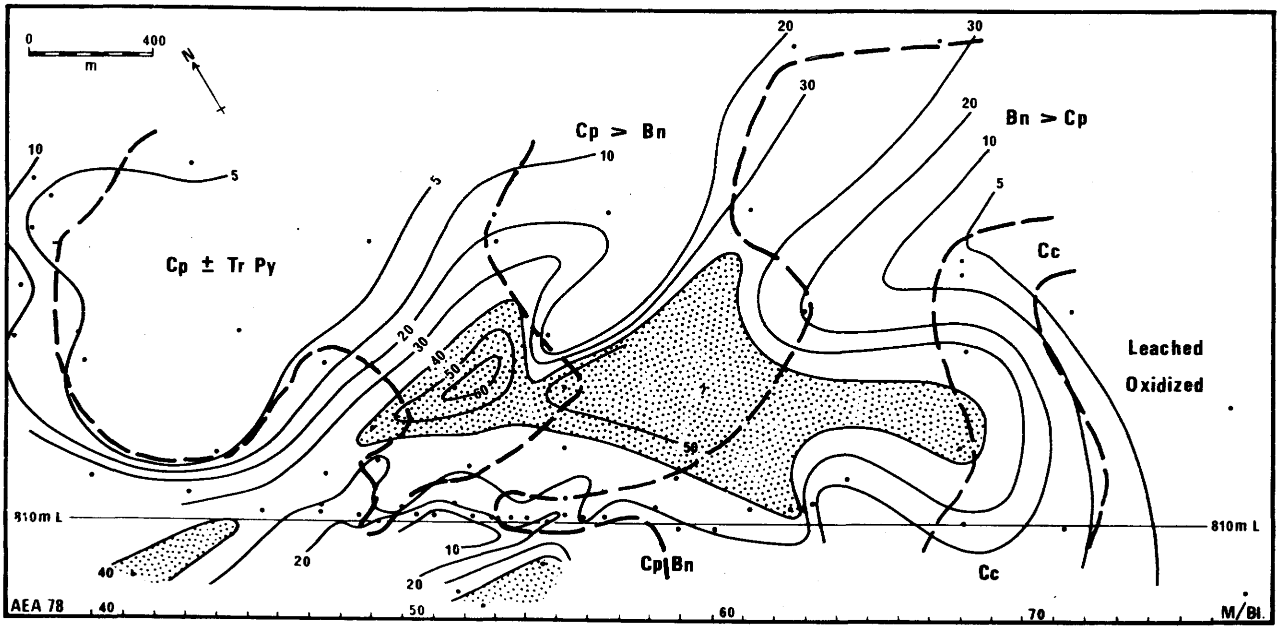

Figure 3.- C Horizon metre-percent copper with sulphide zones superimposed.

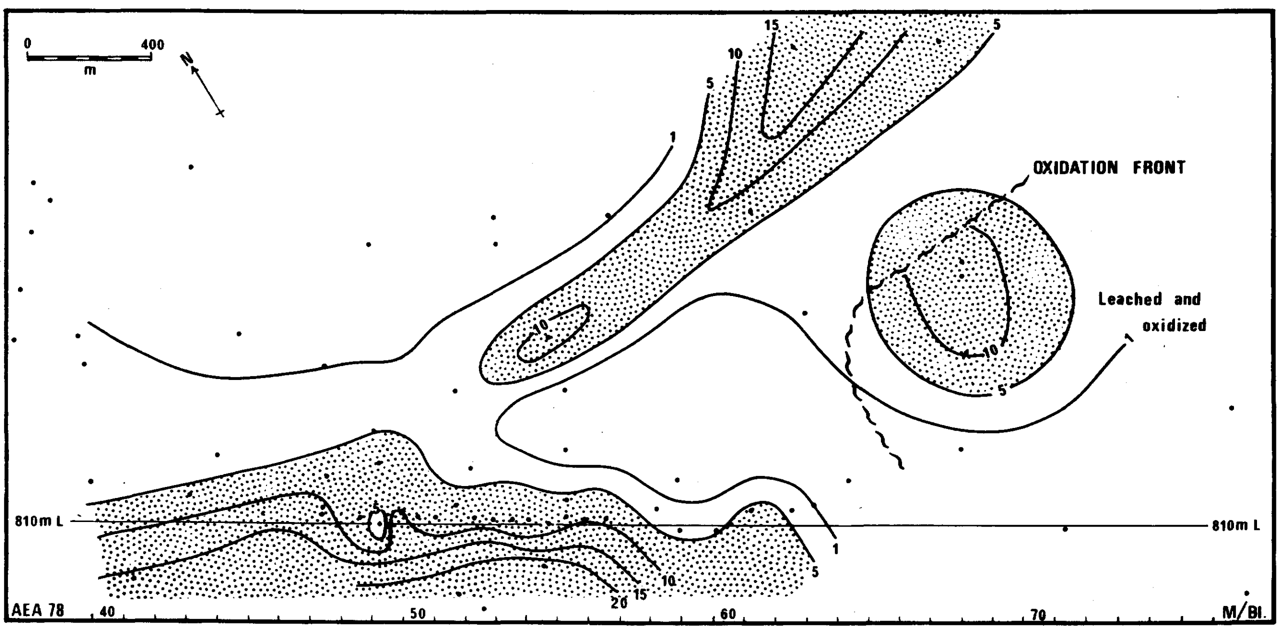

Figure 4.- Metre-percent copper in entire Inter BC Horizon.

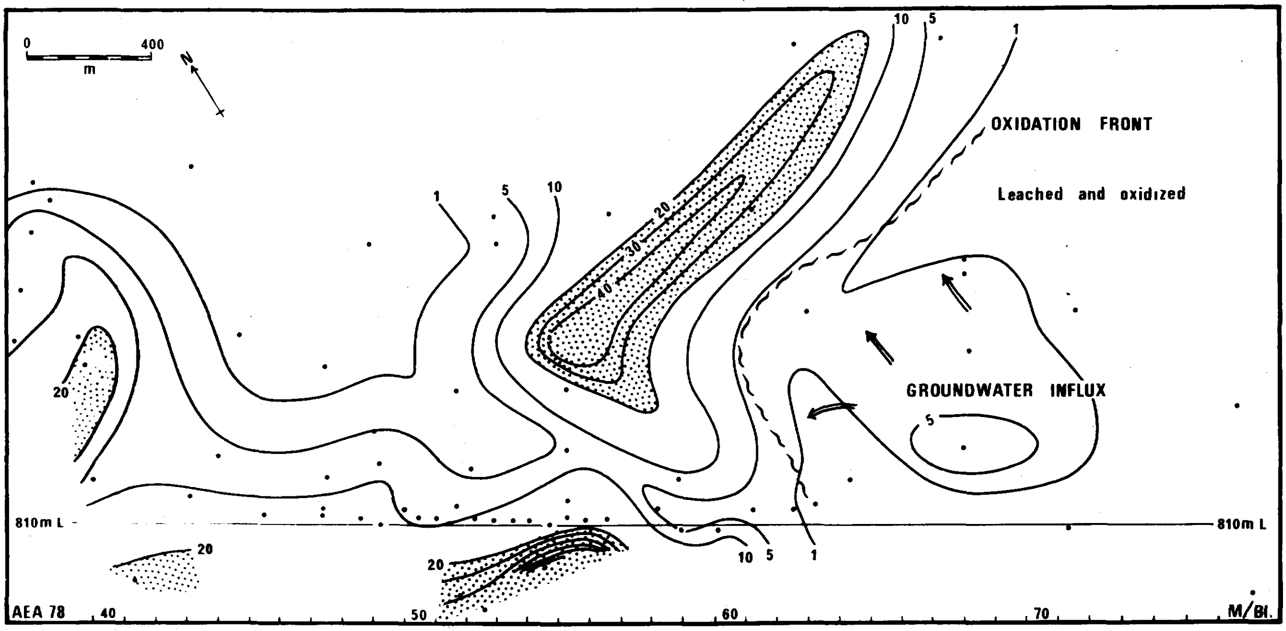

Figure 5.- Metre-percent copper in entire B Horizon.

does overlie the transverse ridge. It is perhaps of greater significance that the richest portions of both the Inter BC and B orebodies lie directly above a zone of apparent depletion in the C orebody (fig. 3).

The B copper zone contains bornite and chalcopyrite with a chalcopyrite rich fringe. Pyrite is very rare in the horizon. To the southeast of this sulphide zone the B horizon is intensely leached, oxidized and friable resulting in very poor core recovery. Malachite and chalcocite are patchily developed in these iron stained rocks. The "oxidation" front coincides with the southeastern edge of the copper sulphide zone (fig. 5) and parallels the metre percent copper contours suggesting that in some way there is a relationship between these features.

INTER AB DOLOMITES AND SHALES

Immediately above the B horizon there are approximately 8.5 m of dolomites, shales and quartzites (Lower Dolomite, Gritty Marker, Banded Shale and Dolomite, Massive shale and Banded Shales and Quartzites) which would have created a major barrier to upward migration of interstitial brines or groundwaters. Isopachs of the basal massive portion of the Lower Dolomite indicate that it could be a biohermal structure situated directly above the transverse basement hill. The Lower Dolomite is normally barren and forms a very sharp assay hangingwall to the B orebody. There is some evidence that locally this contact is erosional and in some areas there is a thin sandy seam at the top of the B which represents a reworked sediment. Much of the clay content has been winnowed away and the quartz grains are often well rounded and have a higher degree of sorting. Over the richest portions of the B horizon the basal 0.5-1.5 m of the Lower Dolomite is brecciated or fractured, limonite stained and may contain economic chalcocite, cuprite, bornite and chalcopyrite mineralization.

INTER AB AND A QUARTZITES

Within the sub 810 m Level area the Inter AB quartzites are, or were, light greenish-grey, fine to medium grained, quartzites with generally indistinct bedding though occasional intervals do have better developed bedding or even cross-bedding. Towards the base interbeds of dark grey argillaceous quartzite or silty argillite appear. The grey-green quartzites are characterized by occasional scattered feldspar grains, both white and pink, and by tiny flecks of chlorite. Small dolomite porphyroblasts occur, some of which may be surrounded by a narrow chloritic halo. In many intersections these rocks have been invaded by anhydrite. These anhydrite rich patches and bands have a pink colouration and have, in certain sections, largely

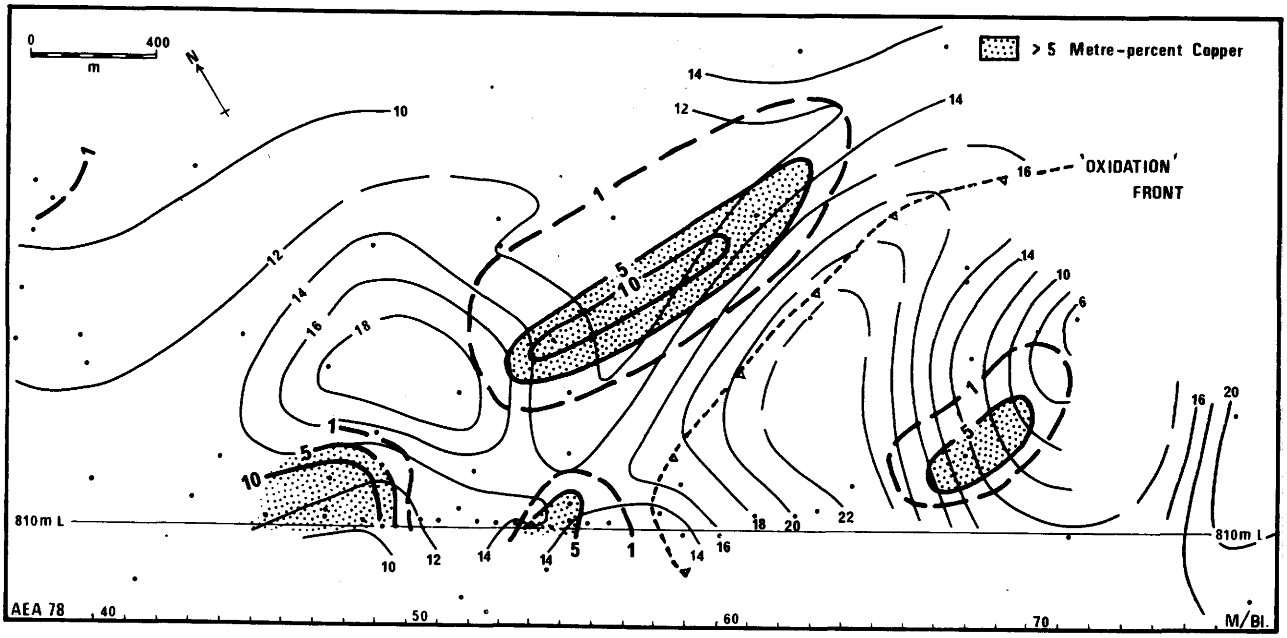

Figure 6.- Metre-percent copper in A and Inter AB Horizons superimposed on isopachs of arenites above the Massive Shale and below Lower Argillaceous Quartzites.

destroyed the original sedimentary fabric of the rock giving it a mottled appearance. Veins containing one or more of the minerals quartz, dolomite and anhydrite are common. In many drill holes, especially in the northwest, these grey-green quartzites constitute the entire section up to the Lower Argillaceous Quartzite, the usual hangingwall formation above the A horizon/ orebody. In these holes there is frequently evidence of an erosional break between the two formations in the form of truncated and disturbed bedding or a layer of rubble derived from the Inter AB horizon. Further to the southeast many holes have a thin horizon of medium to coarse grained, pinkish white, anhydritic and felds-pathic arenite containing abundant scattered quartz, feldspar and granite fragments and also thin arkosic grit bands. Bedding in this unit many be weak to moderate and cross bedding is not uncommon. It is possible that this gritty feldspathic horizon is either the attenuated equivalent of the A horizon which, above the 810 m Level, averages 10 to 11 metres in thickness or that it is part of the Inter AB in which case the A horizon is missing. It appears that there is no equivalent of the A graywacke or the associated massive medium grey quartzite in the study area.

Fig. 6 is an isopachyte map of the arenaceous A and Inter AB formations above the Massive Shale which shows that there are remarkable thickness variations (6 to in excess of 22 metres) due, it is believed, partly to non deposition and erosion but largely to differential compaction and subsidence of the underlying sedi-ments. On this map is superimposed the copper content of the two horizons which reveals, once again, a narrow corridor of mineralization and an isolated patch to the southeast, which directly overlie similar mineralized areas in the B and Inter BC horizons. It is interesting to note that this mineralization, which is dominantly bornite with minor chalcopyrite, is concentrated in areas where the combined thickness of the A and Inter AB is low, a feature not anticipated for synsedimen-tary sulphides.

The southeastern area of the A + Inter AB ho-rizons, in common with all the other horizons con-sidered, is heavily leached and altered. The only sul-phide present is chalcocite which is usually patchily distributed and associated with malachite, chrysocolla, cuprite and limonite staining. GARLICK (1967) be-lieves that these red stained arkoses reflect a return to terrestrial conditions but this is not accepted here. An influx of more oxygenated acid groundwater from the southeast seems a better explanation for this second-ary staining and alteration.

GEOLOGICAL CONTROL OF THE MINERALIZATION

The distribution of the C horizon isopachs (fig. 2) around the flanks of the underlying transverse basement ridge would suggest that shoal conditons were maintain-

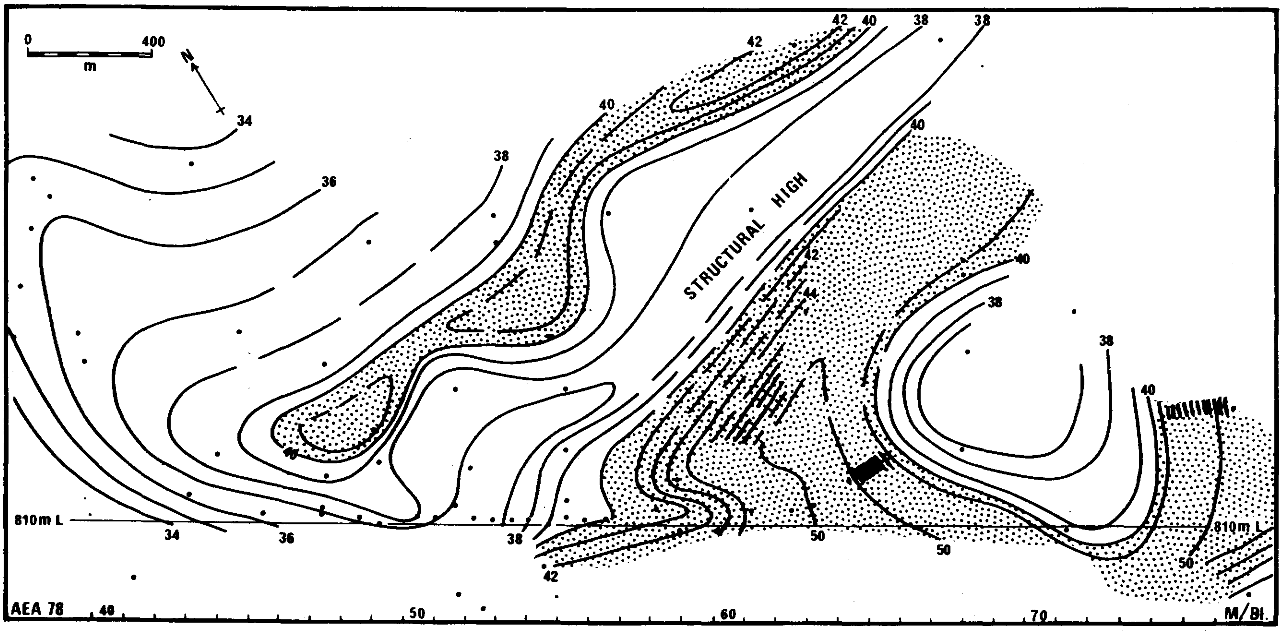

Figure 7.- Structural culmination on Mudseam (Isopachs H/W "A" to F/W Mudseam in metres).

ed immediately above the crest of this ridge and that subsidence and sedimentation continued on either side. This could be due to rejuvenation of the ridge during basal Lower Roan times along marginal faults of the type proposed by ANNELS (1979). The marked similarity between these isopachs and the metre percent copper map in fig. 3 suggests that the metal content of this horizon was of sedimentary origin.

The sulphide zones of the C horizon, however, are completely unrelated to metal content or sedimentary facies changes; they are transgressive and are thus considered to be a post depositional phenomena. The zones are crudely concentric to the eastern economic fringe and show an increase in the iron-copper ratio to the west. The change in mineralogy from an eastern oxide-carbonate assemblage through a fringe chalcocite zone, into a bornite-chalcopyrite zone and finally to a chalcopyrite ± pyrite zone is believed to reflect systematic changes in the Eh-pH conditions of the interstitial groundwaters with distance from the interface between highly alkaline reducing groundwaters and more acid oxygenated waters invading the area from the southeast. There is some evidence that early formed copper-iron sulphides were redissolved and replaced during the gradual westwards encroachment of the oxygenated waters.

There is very little evidence of a sedimentological control on the distribution of metal in the overlying horizons and the sulphide zonations that can be detected are centred on the Inter BC, B and Inter AB + A copper enriched zones. The vertical superimposition of all these narrow belts of copper enrichment above a thin and copper depleted zone in the C horizon is strongly suggestive of some structural control.

In order to test this hypothesis, an isopach map was drawn (fig. 7) of the units from the hangingwall of the A Horizon down to the footwall of the Mudseam. This would then represent the amount of flexuring superimposed on this latter horizon by differential subsidence by the time the mine hangingwall formations were deposited (assuming a flat depositional surface). The resemblance of the fold pattern produced to that of the mineralization in each of the horizons above the C is striking. The western end of this flexure overlies the transverse basement ridge but there is no direct correlation between the shape and orientation of the flexure and the basement morphology. Fig. 7 would indicate an amplitude of 12 to 14 metres, quite a remarkable flexure in a sedimentary pile whose post compactional thickness attains a maximum of only 50 metres. Such a culmination in a sequence containing both aquifers and aquacludes must have had considerable influence on the hydrographic system existing at the time. The vertical superimposition of the belts of copper mineralization may indicate that leakage of brines took place along the crest of the flexure so the contained metals were allowed to escape from their source in the C horizon into the overlying beds. Reactivation of basement faults and their upward transmission into the overlying clastics may have assisted this upward migration. Basal Lower Roan fractures, containing minor sulphide mineralization, have been observed at Mufulira (ANNELS, 1979). Small areas of carbonaceous arenite (greywacke) are believed to have been small accumulations of liquid hydrocarbons trapped in structural irregularities in the main culmination.

PETROGRAPHY AND LITHOGEOCHEMISTRY

The petrographic and chemical studies described in the following sections were made in order to investigate post sedimentary mineralogical changes in the mineralized and unmineralized strata below the 810 m Level and to make comparisons with the changes that have taken place above this level in the main orebody. The object was to determine whether these changes are compatible with those expected in, and around, oil reservoirs in sandstones.

LITHOGEOCHEMICAL AND X-RAY DIFFRACTOMETRIC ANALYSES

Preliminary analytical and petrographic studies had indicated that rocks rich in detrital microcline and orthoclase had high Ba contents and that the converse was true in those rocks in which feldspar was absent. Similarly high Sr values seemed to reflect rocks with high anhydrite contents. It was thus decided to investigate the use of trace element geochemistry for the detection of mineralogical changes in the transition from mineralized to unmineralized rocks. This investigation was combined with a study of the use of X-Ray Diffractometer analyses for the same purpose. As a basis for this work, electron microprobe and X-Ray Fluorescence analyses were made to determine the levels of Ba and Sr in feldspar, dolomite and anhydrite from Mufulira rocks. This study, reported in ANNELS & STEED, 1977, confirmed the belief that potash feldspar was the main source of the Ba, averaging 0.42 o/o, whereas the other phases contained levels below the detection limit of the electron microprobe (600 ppm Ba). Similarly, Sr was found to be enriched in the anhydrites analysed and had a limited composition range around a mean of 1900 ppm; all the other phases were below detection for this element. X-Ray Fluorescence analyses of monomineralic concentrates of anhydrite, potash feldspar and dolomite gave values of 1600, 100 and 150 ppm Sr respectively.

X-Ray Diffractometer analyses for anhydrite were then made on 56 samples using both the (210) and

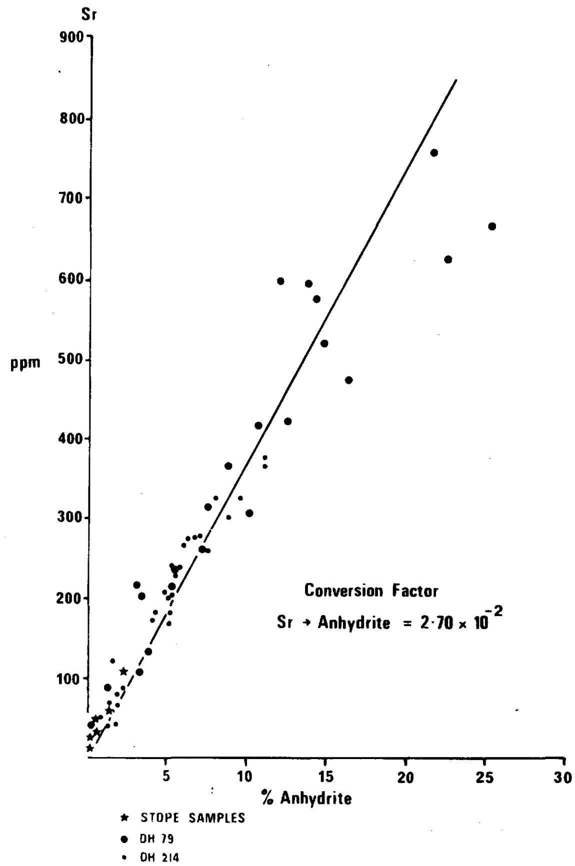

Figure 8.- Linear regression strontium versus anhydrite (as determined by XRD).

(002, 020) peaks. The results were then plotted against the Sr content of those samples obtained by X-Ray Fluorescence techniques. In both cases, an excellent positive linear regression was obtained (fig. 8 and ANNELS & STEED, 1977). The implication was that the compositional range of Sr in anhydrite was sufficiently small to be able to use this trace element as a good indicator of the content of anhydrite in the Mufulira rocks. Ba has a rather wider compositional variation within the potash feldspars but its use as a semi quantitative indicator of the changes in the content of these feldspars seems justified. Na_2O, determined by AAS techniques, was used to monitor changes in the albite content of the rocks as this is the only sodium bearing mineral and its composition is remarkably constant (An_{6-8}). These three lithogeochemical indicators were thus used to back up and extend the petrographic investigations described in the following sections.

PETROGRAPHY OF THE INTER-OREBODY HORIZONS

The Inter AB and Inter BC horizons have many petrographic similarities and can be described conjointly. Both contain dominantly fine grained rocks in which the sorting, when still discernible, deteriorates upwards from moderately good to poor as the rock becomes coarser grained towards the footwall of the overlying ore horizon. This coarsening in grain size is accompanied by the appearance of festoon, cross, ripple drift and graded bedding. The grain size distribution throughout both horizons is unimodal. Both horizons, and in particular the Inter AB, are, or were originally, relatively highly feldspathic. These detrital feldspars occur as elongate to subrounded grains, generally larger in diameter than the associated quartz, and are frequently poorly twinned and turbid. Cobaltinitrate staining reveals that it is all potash feldspar - orthoclase and microcline - and that it constitutes between 10 and 25 o/o of the rock when unaffected by the alteration to be described later. The detrital feldspars have, in most cases, resisted the effects of recrystallization which is moderate to intense and which has virtually destroyed the detrital character of the quartz grains.

Secondary plagioclase in an important characteristic of these horizons but its abundance is highly variable in individual intersections and between drill holes. On the basis of the thin sections studied, it is considerably less abundant in the Inter AB than in the Inter BC as it rarely exceeds 3 o/o. Some intersections of the Inter BC contain very little albite but have 10 - 20 o/o potash feldspar while others have undergone intense albitization and potash feldspar is absent. In this latter case the Ba content is very low and often below the analytical detection limit. This antipathetic relationship suggests that the detrital feldspars have been destroyed or replaced during the albitization process. Only in the BSQ horizon at the base of the Inter BC is detrital feldspar universally preserved, a situation reflected in the high K_2O and Ba and low Na_2O obtained at this level. Above this horizon there is a rapid, almost exponential decline in the Ba content. The presence of argillaceous interbeds in the BSQ would have markedly reduced the vertical permeability of this horizon and impeded the influx of sodium rich brines.

The plagioclase referred to above may occur as direct replacements of detrital potash feldspar, in which case it shows poorly developed twinning and an abundance of inclusions and may possess a core of corroded potash feldspar. In other cases the plagioclase forms small fresh looking authigenic crystals in the matrix to the quartz or is enclosed in grains of anhydrite or carbonate or is intergrown with quartz and sulphides in what are probably metamorphic remobilization veinlets and concretions. The plagioclase may display hazy and discontinuous twinning but more commonly is well twinned on the albite or combined albite-carlsbad laws. Stepped and chequer-board twins are relatively common. Compositionally the plagioclase is albite (An_{6-8}) and it is evident that there is no significant change from horizon to horizon throughout the entire mine section.

Significant variations in feldspar content of individual samples are apparent which can be related to the presence of mineralized, recrystallized or anhydritic patches. Anhydritic patches, for example, may contain 5 o/o secondary albite and 5 o/o detrital potash feldspar, while the adjacent more strongly recrystallized rocks contain 12 to 15 o/o detrital feldspar and less than 1/2 o/o albite. Such changes must reflect localized diagenetic processes and cannot be synsedimentary.

Both inter-orebody horizons are clean quartzites in that they lack the fine grained sericitic matrix, developed from detrital clays, found in the ore horizons. Scattered large flakes of muscovite do occur and are particularly abundant in the heavily mineralized Inter BC quartzites above the 810 m Level. There is, however, little evidence of sericitization of feldspars and sericite clots after feldspar are only rarely recorded. Pale brown biotites appear in the BSQ horizons where argillaceous quartzites and argillite interbeds occur. Occasional sheafs of almost colourless chlorite may be found, often in association with anhydrite, and are particularly abundant in the Inter AB quartzites.

Detrital "heavy" minerals are a feature of both horizons. Green, brown or blue grey tourmaline grains may show overgrowths of pale green to yellow tourmaline. Rutile is perhaps the commonest of these minerals and may be randomly scattered through the rock or concentrated along bedding planes. It has, however, undergone considerable post depositional change and now occurs as small clots with tiny prismatic outgrowths. Apatite and zircon grains have also been identified, the latter being characteristic of the Inter AB where it forms bedding plane concentrations clearly visible in hand specimen.

The distribution of anhydrite in the inter-orebody horizons is very variable and it may occur as poikiloblastic plates, an interstitial cement to coarser less recrystallized rocks or in patches within otherwise anhydrite poor, fine grained quartzites. A common lithology of the Inter AB horizon is a fine grained greyish green quartzite containing pink anhydrite rich patches. The greyish green rock is heavily recrystallized and generally lacking in anhydrite while the anhydritic areas are poorly recrystallized and often contain abundant authigenic albite. The normal range for anhydrite is 0 to 15 °/o though locally patches may contain as much as 30 °/o. Similar wide variations occur between drill holes. In those areas above the 810 m Level where the B, Inter BC and C horizons are all sufficiently mineralized to constitute a single BC orebody, X-Ray diffractometer analyses of Inter BC samples reveal a range of anhydrite contents of 0.3 to 2.5 °/o with the majority lying below 0.5 °/o. Similar analyses of drill cores from below the 810 m Level, however, show values in the range 2 to 25 °/o. Mineralized patches within anhydritic quartzites rarely possess more than to 2 to 3 °/o anhydrite. This antipathetic relationship between sulphides and sulphates is demonstrated by the plot of copper vs strontium in fig. 9.

PETROGRAPHY OF THE ORE HORIZONS

As with the inter ore-body horizons, the ore horizons can be dealt with simultaneously. Studies of the grain size distributions, degree of rounding and sorting of both the carbonaceous and argillaceous facies of both the B and C horizons reveal that they are basically very similar. At the base, these horizons are moderately well sorted and have unimodal grain size populations. Upwards, however, the rock becomes finer grained but has suffered from the admixture of coarser detritus so that sorting deteriorates and a distinct bimodality appears in the grain size distribution. This coarser detritus consists of well rounded grains of quartz and potash feldspar which contrasts sharply with the finer, more angular, quartz detritus in the matrix. Approximately 20 to 25 °/o of the rock consists of fine grained sericite though a pale yellowish brown biotite appears towards the base. This micaceous matrix, representing the initial clay content, may be due to a combination of infiltrated, detrital and authigenic material. It, together with early diagenetic carbonate, has been responsible for the lack of recrystallization in these horizons in that they have prevented grain impaction, pressure solution, grain overgrowths and recrystallization of quartz.

The development of the biotite is interesting for it is absent in the area of potentially economic B mineralization below the 810 m Level where sericite occurs alone. It increases, however, in a northwesterly direction away from this narrow belt until it becomes the dominant mica. In one drill hole on the flanks of this belt biotite represents 30 °/o of the upper section of the B horizon decreasing to 5 °/o towards the base as sericite increases to its normal levels of close to 20 °/o. Biotite is never developed in the carbonaceous facies of the ore horizons. Sheafs of very pale green to colourless chlorite are often found in mineralized rocks, often partially enclosed within sulphides. There is some indication that it is mainly developed within the sericitic quartzites.

Detrital potash feldspar, usually untwinned orthoclase and poorly twinned microcline, may represent 5 to 10 °/o of the ore horizons. However, in many cases it is turbid and sericitized or shows marginal replacement by carbonate, anhydrite and sulphide. In some samples it is completely absent but there is evidence of its previous existence in that clots of sericite are present whose shape and dimensions are compatible with their being pseudomorphs after feldspar. Into the footwall rocks the detrital feldspar content increases again to 10 to 20 °/o. The replacement of feldspar is most intense in the carbonaceous facies of the two ore horizons where it is accompanied by a dramatic fall in Ba content. Detrital feldspars may be preserved in these rocks where the carbon content is low and the carbonate cement high. This is particularly true of the B quartzites immediately below the Lower Dolomite. In carbonate rich bands and patches sericite clots are absent and the feldspars unaltered except for marginal replacement by the carbonate itself. This situation strongly suggests that the destruction of detrital feldspar was a diagenetic effect post-dating the emplacement of an earlier carbonate cement.

Secondary plagioclase is only weakly developed in the ore horizons (1/2 to 1°/o) and is only rarely found in greywackes and their immediate facies equivalents but it increases downwards into the underlying quartzites. There is some evidence to indicate that plagioclase increases away from the B ore zone and values as high as 10 °/o have been recorded. The plagioclase may occur as direct replacements of potash feldspar, as tiny crystals enclosed in sulphides or as larger plates enclosed within, and replaced by, carbonate.

Anhydrite and carbonate may be moderately abundant in the ore horizons but are highly variable and patchy in their development. Light grey mottling of the argillaceous facies is due to a localized dolomite cementation. Dolomite may thus vary between 0 and 15 °/o of the rock but can reach higher values immediately beneath the Mudseam or Lower Dolomite. Where the rock is heavily mineralized these light patches may contain dolomite alone (35 o/o); where the mineralization is weak or absent these patches may contain 1-10 o/o anhydrite giving them a distinct pink or mauve tinge. Anhydrite is virtually absent from the carbonaceous greywackes (very low Sr values) and the light grey, carbon poor, patches contain dolomite alone. The C greywackes contain less carbonate than the seritic quartzite facies equivalents and also less than the B greywaches above. Into the underlying clean quartzites there is a decrease in carbonate and an increase in anhydrite.

The carbon in the greywackes is also patchy in its distribution and occurs as an impregnation of the quartz-sericite groundmass or as rims to, and fracture fillings in, quartz grains. B greywackes samples taken from the 20P2 cross cut, 610 m Level, showed a systematic increase in carbon content towards the base of the Lower Dolomite.

DIAGENESIS IN THE MUFULIRA ARENITES

Having considered the petrography of each of the potentially mineralized horizons below the 810 m Level at Mufulira we are now in the position to trace the events leading to the formation of sulphide in these rocks.

The presence of stromatolite (cryptozoan) patch reefs in the upper portion of the Inter BC and of anhydritic dolomites in the Lower Dolomite horizon strongly suggest that the waters in which the Mufulira arenites were deposited were warm and saline. Evaporation and sediment-brine reactions are thus likely to have resulted in the production of alkaline intrastratal brines enriched in Na, Al, Cl, K, Si and SO_4. Such brines would then be the medium for considerable diagenesis within these sediments.

Albite is closely associated with, partially or wholly surrounded by, and marginally replaced by, both anhydrite and carbonate and thus seems to have been one of the earliest diagenetic phases to be formed, especially in the more porous inter-orebody horizons. Anhydrite and dolomite usually show sharp linear or curved mutual contacts and would thus appear to be simultaneous in formation, however, cases do exist in which ragged anhydrite grains occur within dolomite. It would appear that calcium sulphate deposition, probably as gypsum, began soon after the initiation of albitization and the growth of authigenic albite. At the same time calcium bicarbonate percolated downwards from overlying carbonate rich horizons so that carbonate was able to form in the more argillaceous ore horizons to a greater degree than in the inter-orebody arenites. Some of the carbonate formed is, as indicated above, of later origin than the anhydrite and this is probably bacteriogenic, the by product of bacterial reduction of interstitial calcium sulphate. This early cementation and replacement was very patchy in its development.

Diagenesis of the detrital clays in the ore horizons released considerable amounts of Si and K into the increasingly alkaline groundwaters so that illitization of detrital feldspars began along with the formation of authigenic illite. Illite was later converted to sericite under conditions of higher temperature and deeper burial. As detrital feldspars enclosed within carbonate cemented bands and patches are relatively unaltered compared to those in the adjacent sediments, the implication is that illitization post dates the formation of much of the albite, anhydrite and dolomite. At Mufulira feldspar alteration within the greywackes consists of sericitization alone but beneath these rocks there is evidence of much more severe diagenesis in the form of advanced albitization and the continued development of an anhydrite cement. This situation is best explained in terms of illitization during hydrocarbon influx which eventually resulted in the termination of diagenesis in the oil saturated zones (the greywackes). Beneath these zones diagenesis was able to continue and the enrichment of sodium in these brines resulted in advanced albitization of the feldspathic detritus. This association of illitization with hydrocarbon influx and the cessation of diagenesis in oil saturated zones is a well documented feature of oil fields. HANCOCK & TAYLOR (1978) consider that illitization of feldspars and oil influx are synchronous events in the Middle Jurassic Brent Sand Formation of the North Sea and they state that the oil rich section is now devoid of feldspar. Similarly SOMMER (1978) believes that most illitization of feldspar occurs during the migration of oil and not after progressive downward oil saturation so that illitized feldspars are incorporated in the oil zone. Below the oil-water interface diagenesis is allowed to continue and, in most cases, results in the formation of a pure orthoclase feldspar. Plagioclase feldspar is, however, recorded from the Rotliegende sandstone of northern Germany (HANCOCK, 1978).

The inter-orebody horizons would, by this time, have become fairly well cemented and the quartz grains would have begun to recrystallize under the effects of

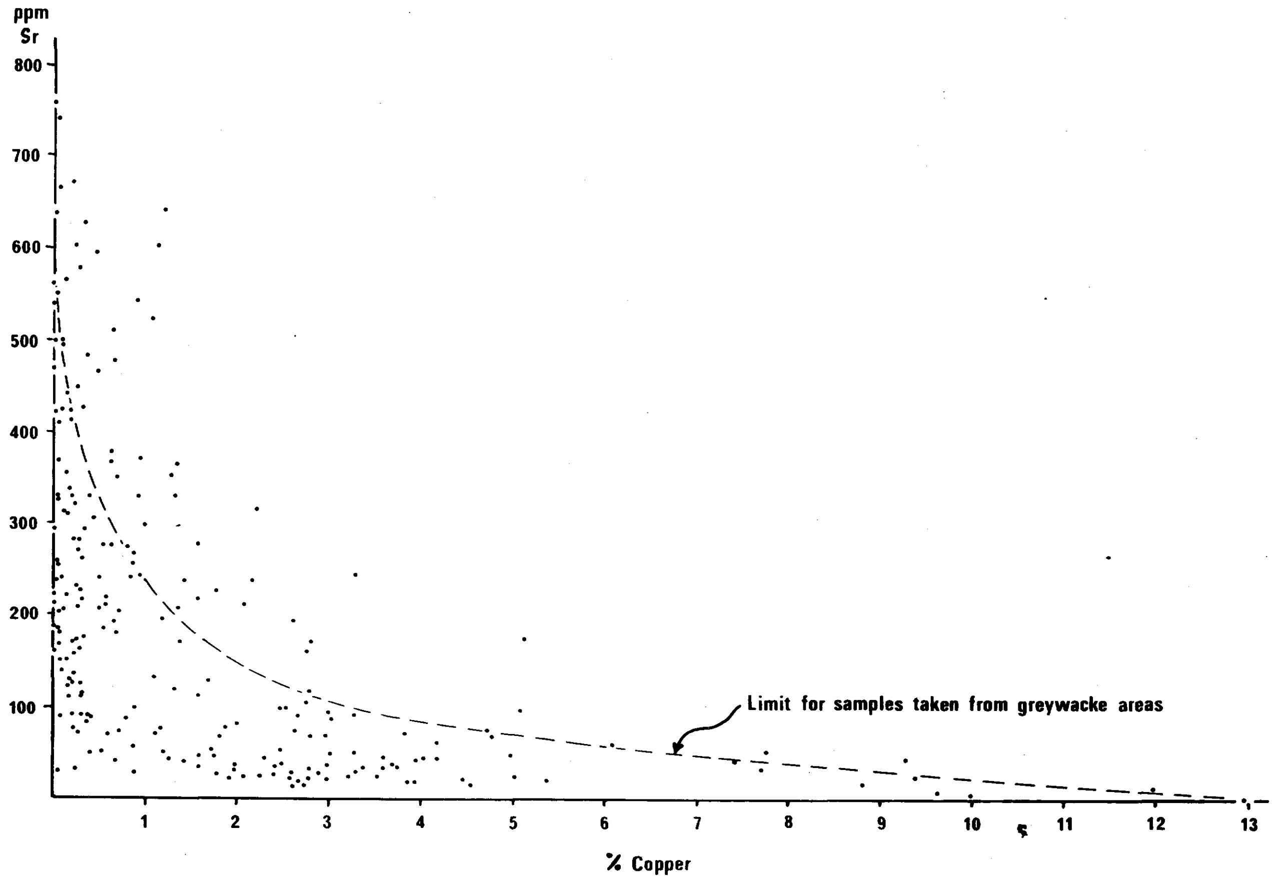

Figure 9.– Plot of strontium versus copper.

increasing depth of burial. Pressure solution effects leading to recrystallization are expected to occur at burial depths of approximately 1500 m (NAGTEGAAL, 1978) which, under normal geothermal gradients, would experience temperatures in the range 40 to 65^{o}C. The lack of a clay matrix in these inter-orebody horizons means that these quartz grains quickly impinged and under-went contact pressure solution. Those areas which contained a calcium sulphate cement, however, resisted recrystallization and retained their detrital characteristics. A certain amount of residual porosity would still remain and this would be augmented by the 38 o/o volume reduction caused by the dehydration of gypsum to anhydrite at approximately 50^{o}C. It is interesting to note that at this same temperature kerogens derived from degraded organic matter in marine shales begin to release liquid hydrocarbons. This release becomes significant at 60-65^{o}C. It is thus very probable that brines penetrating the mine strata at this time would contain traces of hydrocarbons in solution or as emulsoids.

The influx of hydrocarbons is bound to lead to enhanced bacterial activity so that increasingly large amounts of dissolved SO_4 or intersitial anhydrite are used up producing larger amounts of reduced sulphur. This process would be brought to an end by the demise of bacteria above 80^{o}C. Below this temperature then, any metals previously in the C horizon or brought in by lateral migration of chloride rich brines, would be fixed as sulphides. Other metal from this source horizon would be carried upwards along fractures associated with structural culminations and would be precipitated in the overlying formation by hydrocarbon enhanced bacterial activity.

Above the 810 m Level extensive zones of hydrocarbon impregnation developed, in and around which metal sulphides were precipitated (ANNELS, 1979). The frequent occurrence of very high grade assay intervals close to the base of the carbonaceous greywackes at Mufulira can thus be explained by intense bacterial activity at the oil-water interface. Hydrocarbon influx, sericitization (illitization) and sulphidization of the ore horizons are considered to be a contemporaneous event. This is supported by the fact that sulphides are commonly found within sericite clots after detrital feldspar and within the replacement rims of feldspars which have avoided complete destruction.

The above theory requires the presence of abundant sulphate to precipitate the metals present and also that a depletion of anhydrite should be demonstrable within the ore zone. Both are well documented by thin section and lithogeochemical studies, the results of which can be summarized as follows :

a) well mineralized greywacke horizons contain only trace amounts of anhydrite ($\ll 1$ o/o);
b) well mineralized non carbonaceous ore horizons contain less than 5 o/o anhydrite;
c) weakly mineralized or barren ore horizons contain more than 5 o/o anhydrite and up to 30 o/o;
d) well mineralized Inter BC quartzites, especially in BC orebody areas, are depleted in anhydrite relative to those which are less well mineralized and lie below the 810 m Level outside the BC orebody limits;
e) well mineralized rocks do seem to contain enhanced carbonate contents compared to barren or low grade equivalents.

A plot of Sr vs Cu (fig. 9) shows a wide range of Sr values at low copper grades reflecting the variable distribution of anhydrite in the original rocks. As the copper content increases, the Sr values drop almost exponentially responding to a decrease in anhydrite. The antipathetic relationship between diagenetic sulphates and the sulphides also supports the contention that the latter are also diagenetic. Areas of rock heavily cemented with early diagenetic carbonate and anhydrite tend to be sulphide poor; the pore spaces necessary for precipitation of later sulphides were limited in these areas.

If the sulphide mineralization is related to entrapment of brines and associated hydrocarbons in a structural culmination, it should also be possible to demonstrate that the effects of diagenesis in the host rocks are most severe in the vicinity of this culmination. It has already been suggested that the mineralization below the 810 m Level has been localized by such a structure. At the same time, if anhydrite is the source of the sulphur then a coincident depletion of anhydrite (and hence Sr) should be detectable. Composite samples representing the C, IBC and B horizons in selected drill holes were thus analysed for Sr and Ba or weighted averages calculated from existing assay sample data. As the most important diagenetic effect seen in these rocks involves the replacement of K feldspar, depletion of Ba should be evident.

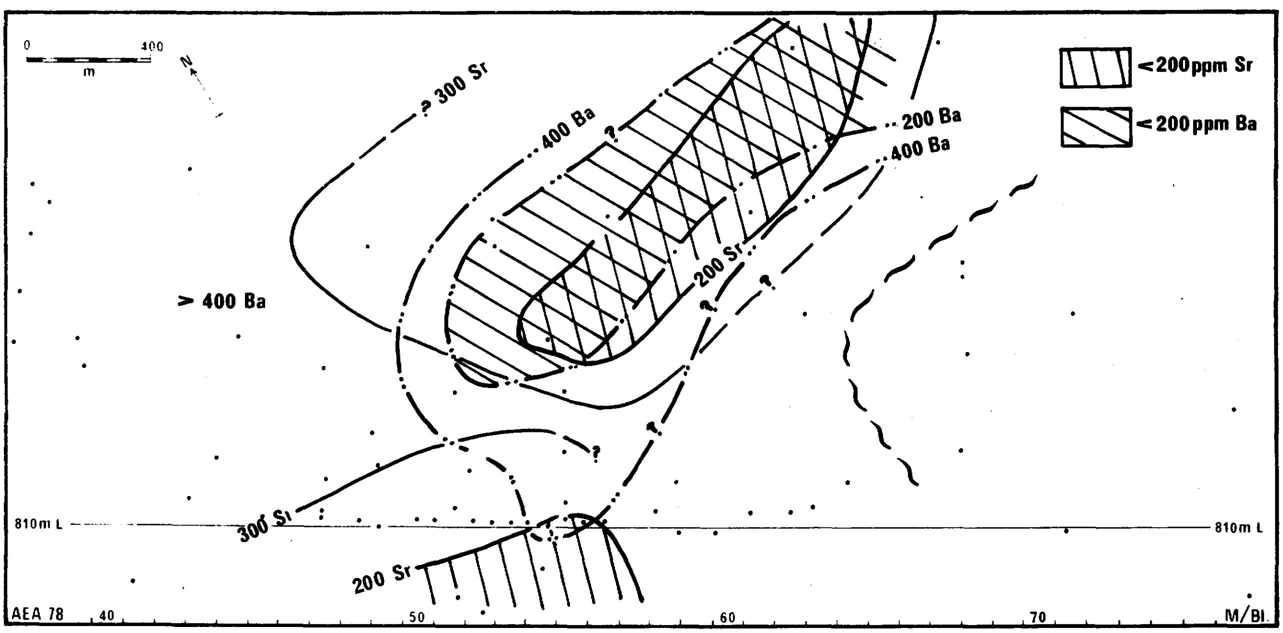

Figure 10.- Strontium and Barium depletion in Inter BC Horizon.

Insufficient data exists for the B and C horizons to interpret the results satisfactorily but the carbonaceous greywackes of these horizons do contain very low Ba values reflecting the complete destruction of feldspar. The strontium values showed the expected sharp decrease in the mineralized zones. In the B horizons Sr dropped to less than 100 ppm at approximately the 15 m o/o copper contour with several values below 40 ppm. Outside this contour, values are in excess of 200 ppm attaining 354 ppm in one hole.

Much more information was wavailable for the IBC horizon and the data coverage is sufficient to allow the production of a map here produced as fig. 10. This map outlines coincident areas of both Ba and Sr depletion directly corresponding to the narrow corridor of IBC mineralization, further evidence that sulphide formation was a diagenetic event closely associated with sericitization and albitization and the consumption of early diagenetic anhydrite. No samples from holes in the southeastern sector were analysed because here the core is leached and friable due to the influx of more acid, possibly meteoric, groundwaters.

The sulphide zonation in the C horizon described earlier is best explained in terms of a hydrographic model in which the strata to the southeast of the economic fringe below the 810 m Level contains a more acid, oxygenated groundwater regime. These waters mixed with more reducing and alkaline waters further to the west causing a gradual change in pH-Eh conditions in this direction. This situation resulted in a change in the type of sulphide formed from chalcocite to bornite to chalcopyrite to pyrite. Metals were leached from the acid zone only to be precipitated near the groundwater interface as oxides, carbonates and eventually chalcocite. A westward encroachment of this oxidation front caused replacement of earlier sulphides by secondary sulphides, oxides and carbonates.

Metal enriched brines leaking vertically through the Inter BC into the B horizon were dammed up beneath the Lower Dolomite. Migration was then laterally outwards influencing both the concentration of metal and the sulphide zonation. Though oxidizing and acid ground waters did penetrate both these horizons from the east, they did not control the distribution of their sulphides zones. Progressive recrystallization and cementation of the Inter BC horizon would eventually have sealed the lower horizons preventing further escape of metal and brines. As the culmination on the base of the Lower Dolomite developed so the process described above was repeated; brines and their contained hycrocarbons then leaked up into the Inter AB arenites and precipitated their metal load as sulphides. By this stage, however, very little metal remained in solution in the form of chlorides and hence no economic mineralization was formed.

EOMETAMORPHISM AND METAMORPHISM

Sulphides trapped in the strongly recrystallized Inter BC quartzites are generally in the form of very fine equidimensional grains while those in the more argillaceous ore horizons are often highly irregular grains which surround, and marginally replace, other rock forming constituents especially detrital K feldspar. Larger sulphide masses contain numerous inclusions of both detrital and authigenic minerals. The implication of this is that the early recrystallization of the Inter BC quartzites protected the sulphides from the degree of remobilization which affected the sulphides in the argillaceous horizons. Large amoeboid patches of sulphides do occur within the Inter BC horizon which are believed to be the product of metamorphism and these are associated with considerable remobilization and enrichment of albite and carbonate. Similarly, metamorphic lateral secretion veins of quartz, carbonate, sulphide and anhydrite are common features of the ore bearing strata.

Because of the intense recrystallization in the Inter BC horizon, stress relief during tectonism was brought about by the development of minute hair fractures which caused comminution of adjacent rock forming grains and allowed a localized late stage sericitization to take place. These cut across mineralized patches and, though they contain quartz and dolomite, they are barren of sulphide.

Any hycrocarbons present undergo eometamorphism at temperatures of approximately 175°C (BAILEY, 1977) during which hydrocarbon cracking takes place producing methane gas and liberating organically bound sulphur. The destruction of liquid hydrocarbons leads to the formation of pyrobitumens, the forerunner of the graphite found today. Though the porosity of rocks subjected to these high temperatures would be low because of their depth of burial, it is conceivable that the sulphur liberated could be transported in gaseous form and eventually used in the production of vein sulphides. At the same time methane produced may react directly with anhydrite and so produce inorganically reduced sulphur. It is possible that recently discovered Upper Roan mineralization in brecciated zones may be the product of escaping hydrocarbon gases.

GENETIC MODEL FOR MUFULIRA

That the Mufulira orebodies could perhaps be explained in terms of a brine plus hydrocarbon leakage mechanism operating at a structural culmination was originally proposed in an earlier paper (ANNELS, 1979). It is suggested that the information presented here for the sub 810 m Level area does indeed fit such a model and that it can be used to explain some of the features of the orebodies above this level. These features are as follows :

a) the vertical superimposition of the carbon impregnated greywackes;

b) the occurrence of economic Inter BC mineralization only in the area where B and C greywackes are superimposed;

c) the upward decrease in lateral extent of the three orebodies;

d) the upward increase in the copper/iron ratio in the sulphides constituting each of the three orebodies which is reflected by an upward increase in copper grade.

It is suggested that the metals were originally deposited, by hydrothermal exhalation, with the sediments of the C Horizon and that they were then further concentrated, by subsurface groundwater movements initially confined beneath the Mudseam horizon. Much of this metal was then fixed as sulphide by the generation of sulphur by the bacterial reduction of interstitial anhydrite or dissolved sulphate. There is little relationship between sulphide zones in the C Horizon and basement palaeo-topography (fig. 1) with the exception of the two internal pyritic areas. The sulphide zones, on the over hand, do not seem to be compatible with a palaeo-shoreline control, whether or not a shoreline to the east or southeast (GARLICK, 1967) or to the north or northeast (Van EDEN, 1974), is accepted. Fig. 11 presents an alternative explanation in which the sulphide zonation in the C Horizon is partly controlled by distance from the interface between two groundwater regimes, one acid and oxygenated and the other more alkaline and reducing. Additional factors are the presence of hydrocarbon saturated zones (the greywackes) and the content of dissolved or suspended hydrocarbons in the migrating brines.

Chalcocite found in the up-dip portions of the C orebody has, in the past, been ascribed to near surface supergene effects and has thus not been included in the zonal scheme (e.g. BRANDT *et al.*, 1961). A similar conclusion was reached by Van EDEN (1974) but he considered the deeper occurrences of this mine-

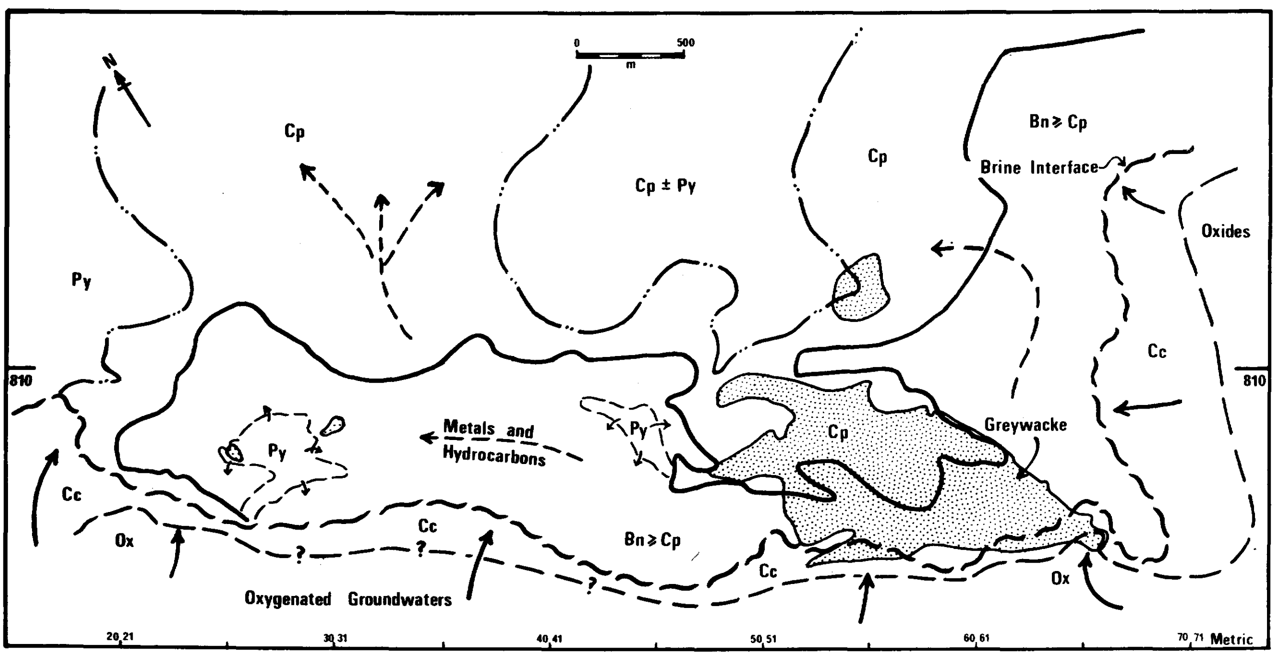

Figure 11.- A possible interpretation of the sulphide zones at Mufulira.

ral to be due to the presence of porous conglomeratic sandstones. Though this may explain the internal chalcocite zone close to the 810 m Level at Mufulira West, it cannot be used to account for the very deep (1600 m) occurrence of chalcocite along the eastern orebody fringe. The present author thus suggests that the areas of chalcocite, together with leached oxide and carbonate zones, are remnants of originally continuous mineral zones around the up-dip and eastern fringes of the orebody (fig. 11). Obviously the former fringes would also have suffered supergene effects related to the present level of erosion. This model thus envisages an area dominated by alkaline groundwaters, in which liquid hydrocarbons were accumulating, being invaded by more oxygenated and acid terrestrial (meteoric) waters. The latter may have caused leaching of metals from the rocks through which they passed and possibly kaolinization of feldspars. Towards the interface with the alkaline groundwaters, intermingling caused the pH to increase and the Eh to drop so that the stability fields of cuprite, native copper and heamatite were reached and eventually of chalcocite and malachite also. Beyond the interface a further drop of Eh resulted in the formation of bornite. However, the presence of abnormally acid and reducing conditions in the area of hydrocarbon impregnation gave rise to a further shift towards the stability field of chalcopyrite (GARRELS & CHRIST, 1965) thus explaining the coincidence of this mineral with a large proportion of the greywacke area in fig. 11. The gradual increase in alkalinity of the groundwaters, together with a slight decrease in Eh, away from the groundwater interface led to a change from bornite to chalcopyrite and eventually to chalcopyrite and pyrite beyond the orebody fringe.

The vertical zonation seen in the C Horizon, in which there is a downward change from bornite to chalcopyrite ± pyrite, is again believed to be due to the presence of alkaline brines beneath rocks in which bacterial activity and the presence of hydrocarbons has depressed the pH.

The 810 m Level chalcocite zone at Mufulira West (fig. 1) may be due to the northwards or eastwards penetration of the terrestrial groundwaters through arkosic grits and conglomerates of the Footwall Formation which infill basement valleys. These valleys would funnel this water towards the convergence of the basement contact and the footwall of the C Horizon. At this point it penetrated the orebody replacing the primary sulphides, bornite and chalcopyrite, by chalcocite over much of the mineralized section.

As Van EDEN (1974) remarked, the internal pyritic zones are less easy to interpret but it is possible that they may be due to the expulsion of brines from sediments being compacted over rigid basement hills. Only early pyrite was able to form here together with small amounts of chalcopyrite precipitated from those brines which were able to penetrate these overcompacted sediments. The main problem is that not all hills possess a pyritic halo in the overlying sediments.

Rupture of the Mudseam and BSQ Horizons overlying the C Horizon allowed escape of metal enriched brines into the overlying strata where they migrated upwards and outwards beneath impermeable caprock horizons. The formation of chalcopyrite in the C greywackes, rather than bornite, led to a general copper enrichment of these escaping brines relative to iron. The overlying orebodies thus contain more copper rich sulphide phases. The total metal load of the brines, however, was considerably reduced and hence the lateral extent of each orebody with respect to that beneath was reduced. Whether the main hydrocarbon accumulations were the result of upward migration or lateral flow parallel to the stratigraphy is uncertain.

It is hoped that the data presented, and the theories proposed in this paper, will lead to a reappraisal of the mode of formation of basemetal deposits in arenitic host rocks and will perhaps lead to a more satisfactory explanation of how sulphides can form in such rocks. The classical synsedimentary theories certainly do not, in the author's opinion, explain enough of the facts to be acceptable.

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