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SOME ASPECTS OF THE STRATIFORM ORE DEPOSITS OF THE ZAMBIAN COPPERBELT AND THEIR GENETIC SIGNIFICANCE

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ABSTRACT

In recent years the concept of synsedimentary precipitation of copper-iron-(cobalt) sulphides for the stratiform deposits of the Zambian Copperbelt has become widely accepted by many Zambian based mine Geologists and others who have studied these deposits. However, recent work by the author has led him to hold very grave doubts on the ability of this theory to satisfactorily explain the facts.

Though the presence of anhydrite in the potentially mineralized horizons of the Lower Roan Group has long been recognized, and has been used as an environmental indicator, its significance as far as ore genesis is concerned has apparently been missed. Whether the ore bearing host rock be arenite, argillite or siltstone, an antipathetic relationship can be demonstrated between copper and/or iron sulphides on the one hand, and anhydrite on the other. Evidence is presented which indicates that some, if not all, of the sulphides formed at the expense of anhydrite, whether this mineral was originally in nodular form or occurred as an interstitial cement.

A geologic model is proposed to explain the genesis and localization of the Copperbelt mineralization. This model, which bears close similarities with those proposed for Mississippi Valley type deposits, is based on the diagenetic evolution of depositional basins containing both carbonaceous and sabkha facies.

Other factors, such as the distribution of cobalt, and the tectonic evolution of the present structural basins, are examined and their genetic implications discussed.

INTRODUCTION

In very few papers has any reference been made to the presence of anhydrite in the Lower Roan Group of the Katanga System. Garlick (1964 and 1972) and Davis (1954, p. 608) describe lateral secretion veins of metamorphic origin where anhydrite is associated with quartz, felspar, carbonate and either specularite, in

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the footwall formations, or sulphide (mainly chalcopyrite and pyrite), in the mineralized formations. Similar veins containing anhydrite and sulphide are found in the Basement Complex at Mufulira but are generally more quartz rich. Garlick (1972, p. 285) gives the impression that these are also the products of lateral secretion and were derived from the overlying Lower Roan metasediments. However, it seems more likely that they are older hydrothermal veins as the wallrock shows distinct chloritic and epidotitic alteration. At Mufulira such veins are entirely restricted to the Basement and appear truncated at the unconformity.

Darnley (1960, p. 149) records the presence of large anhydrite plates which ophitically enclose detrital grains in the lower part of the Mufulira Section. Garlick (1967, p. 132) mentions that the lower and upper parts of the C orebody at Mufulira contain nodules or lenticles of anhydrite up to 10 cm in diameter and states that, "The anhydrite of the concretions is angular and generally clear of inclusions, but ubiquitously a concentration of sulphide grains, similar in composition to the disseminated sulphides in the adjacent rock coats the nodule." He suggests that they are sedimentary or diagenetic nodules, the evidence being the lack of replacement of the host rock. He goes on to say that, "Similar anhydrite nodules or concretions with peripheral sulphide concentrations are common in certain horizons in the shale deposits, particularly at Roan Extension, Nkana and Chambishi." In a more recent paper (1972, p. 284) Garlick realizes the environmental significance of the presence of anhydrite by stating that "The abundance of anhydrite proves that the shales were deposited in a highly saline environment with local super-saturation of calcium sulphate . . ." Indeed, he came very close to recognizing its genetic significance when he stated that, "On the 1 450 level at

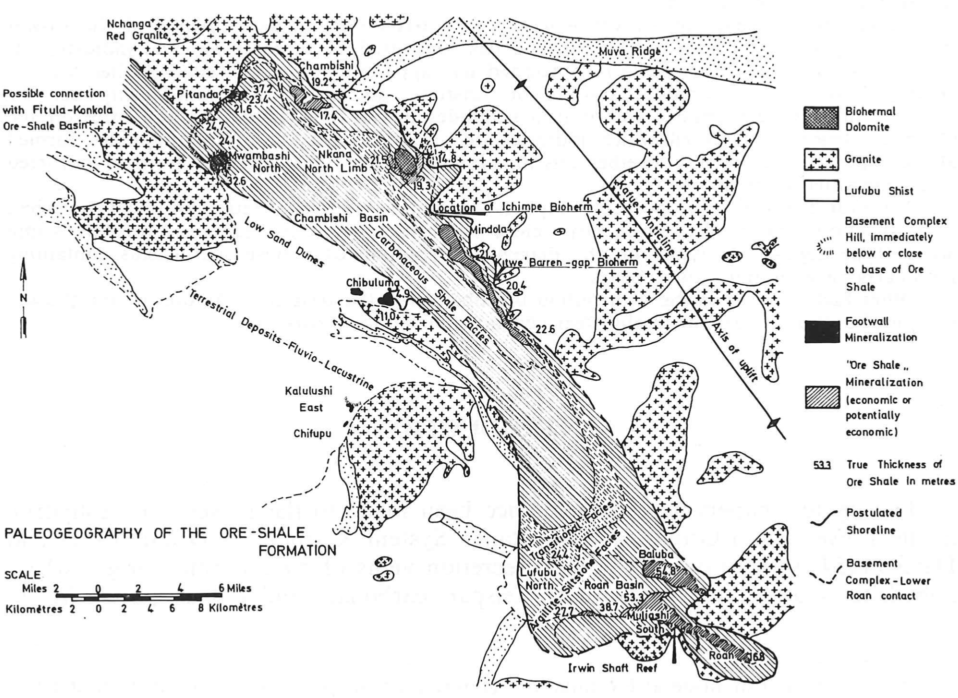


FIG. 1

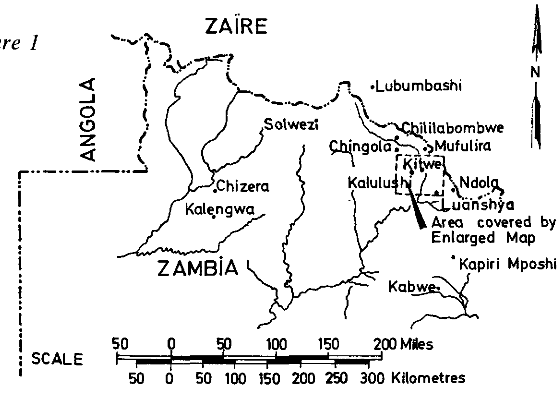
Nkana, the anhydrite occurred as lenses in the *low grade* argillite . . .," and later by pointing out that "It occurs as . . . nodules in the ore horizons in the Lower Roan, whether they be argillite or arenite, mineralized or barren, but *it is generally more common near the margins of the orebody and in the adjacent barren rock.*"

THE ANHYDRITE-CARBONATE-SULPHIDE ASSOCIATION

The possible role of anhydrite in relation to the formation of sulphides was first recognized by the author in 1968 when RST's Prospecting Division was drilling what subsequently proved to be a subeconomic and rather deep copper-cobalt deposit close to the northeastern margin of the Chambishi Basin, between Zam-Anglo's Mindola and RCM's Chambishi orebodies (fig. 1). Because of the low, sub-economic grade of this deposit, referred to as Nkana North Limb, it was possible to examine a process which clearly had not gone to completion as it is believed to have done at the operating mines. Also, as this deposit straddles the transition zone in the ore-shale formation between the carbonaceous argillites of the deeper water facies and the argillite-siltstone facies of the littoral zone (see fig. 1), the effects of lithological changes could be examined.

At Nkana North Limb the mineralization lies within siltstones, argillites, dolomitic argillites, and argillaceous dolomites, which surround a large mass of talcose dolomite. This dolomite is capped by a colony of oncolite stromatolites and is believed to be a biohermal structure (Annels, 1972). Immediately to the west of this bioherm a dolomitic carbonaceous argillite appears just above the more dolomitic basal portion of the ore-shale (fig. 2). The upper half of the ore-shale consists of argillite and siltstones which may show well defined banding or even lamination. Within the mineralized lower portion of this unit there occur numerous lenses of carbonate and quartz which contain, or are surrounded by, sulphides. These lenses, which are most abundant to the southeast of the bioherm, are between 1 and 3 cm long and 0.5 and 1.5 cm high. As the economic hangingwall of the mineralization is approached, cores of sulphide-free, granular anhydrite appear. Initially these are only in the larger lenticles but eventually they also appear in the smaller ones. Above the zone of visible sulphide mineralization the entire lenticle consists of anhydrite. These anhydrite lenticles are identical in size to the carbonate lenses of the main ore zone, except that they have undergone more compaction.

Index map for figure 1



This probably reflects the low competence of the anhydrite relative to carbonate and quartz indeed, as the proportion of the former mineral in the lenticle decreases, so does the degree of elongation parallel to the bedding. The host rock shows deformation of the bedding traces around both the anhydrite and carbonate-quartz lenticles which is suggestive of growth in a relatively soft sediment prior to complete compaction.

Perhaps one of the most significant occurrences in the uppermost portions of the ore-shale is the simultaneous appearance of carbonate and sulphide, usually pyrite, at the margins of anhydrite nodules. Only when the peripheral rim of pyrite is well developed and there is a wide continuous zone of carbonate replacement around the nodules do significant quantities of pyrite appear in the host sediment. Plate 4 shows a lenticle that is completely replaced by carbonate and has a continuous pyrite rim. Similarly the first chalcopyrite to appear is found at the lenticle margins as an encrustation, and locally a replacement of, the rim-pyrite. Within the main mineralized zone the lenticle may be completely replaced and the central cavity infilled with chalcopyrite and pyrrhotite. It seems fairly clear that the first formed sulphide was pyrite but later, as competition for the available sulphur increased with the precipitation of copper sulphides, pyrrhotite was formed. Both chalcopyrite and pyrrhotite show mutual contacts and enclose and replace the early subhedral or euhedral pyrite grains.

Within the bornite zone of the deposit the lenticles do not possess a pyrite rim, indeed pyrite and bornite appear incompatible. This antipathetic relationship also appears to hold true for all Copperbelt orebodies. The bornite and chalcopyrite are dispersed through the entire nodule or within the marginal replacement zone, if an anhydrite core still exists (see plate 1).

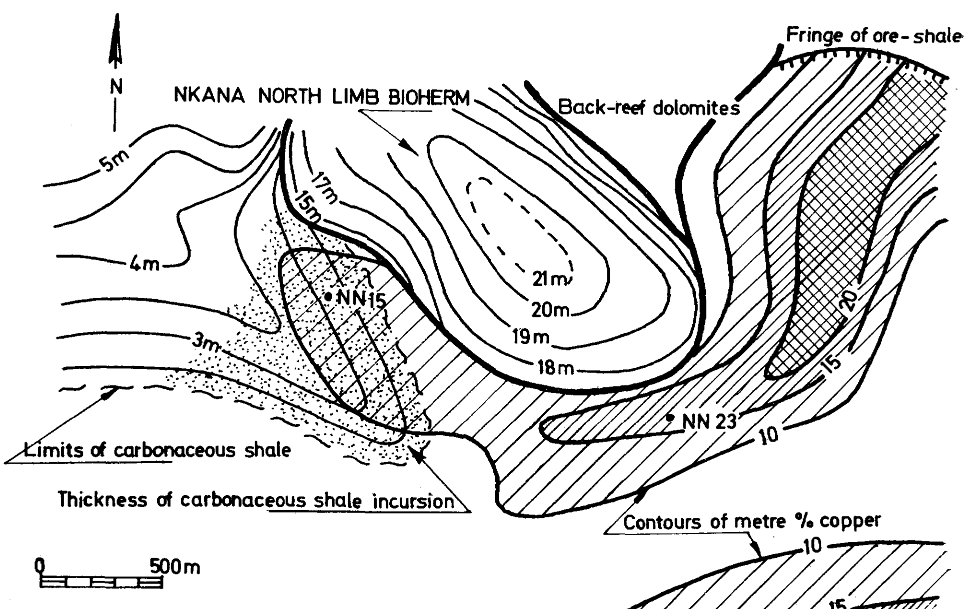


FIG. 2. — *Copper distribution relative to bioherm and carbonaceous argillite.*

At Nkana North Limb the evidence suggests that a large proportion of the iron sulphides were formed during the replacement of anhydrite by carbonate. Estimation of the relative amounts of the two minerals was made by counting grid intersections superimposed on cut core. The results from this study for all the drill holes in the area were contoured as in figure 3. This diagram shows that the pyrite rich areas of the ore-shale coincide with a zone of high replacement (i.e. >60 %) while the pyrite-pyrrhotite rich area, to the northwest, roughly corresponds to an area in which replacement is between 80 and 100 % complete. There is thus a correlation between the amount of replacement which has taken place and the amount of iron sulphide present. Drillhole NN 15 (fig. 4), also reveals a close relationship between pyrite-rich zones and the abundance of lenticle carbonate vertically through the ore-shale.

Figure 3 also shows that the zone of high copper metal content (>15 metre percent) east of the bioherm, approximately corresponds with a zone of high lenticle replacement. Where iron sulphides occur in quantity the copper sulphides show a less obvious correlation with the presence of lenticle carbonate. However, where they are absent, or sparsely developed, as in drillhole NN 23 (fig. 5), the correlation between copper sulphides and lenticle carbonate is good.

The richest mineralization to the west of the reef is at the base of the carbonaceous argillite horizon and in the upper part of the basal dolomites of the ore-shale (see NN 15, fig. 4). This mineralization is in concordant and transgressive veins rather than as disseminations. To the southeast, the carbon content of the argillite decreases and this horizon becomes a dolomitic argillite or calc-biotite

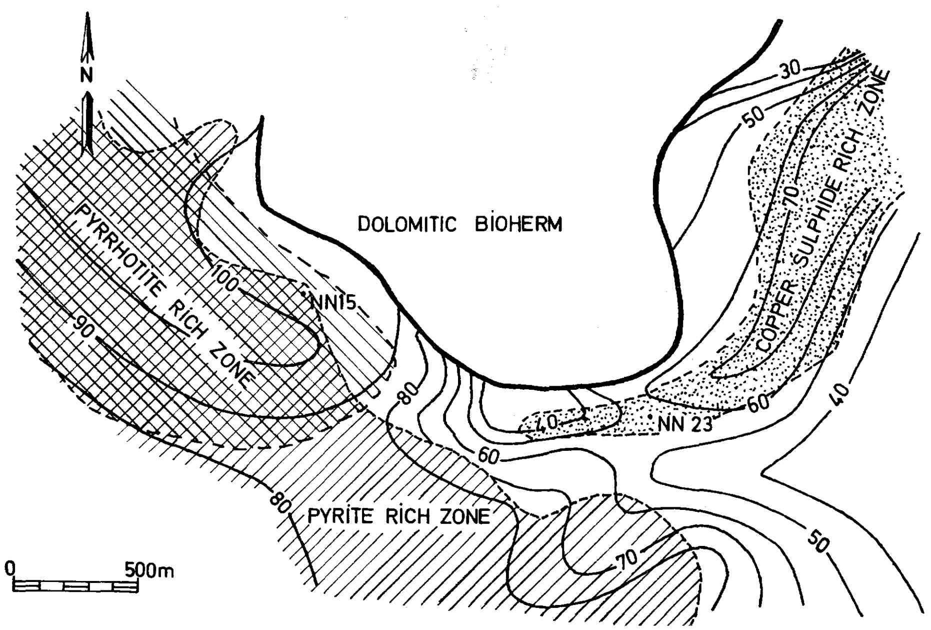


FIG. 3. — *Sulphide zones relative to % carbonate replacement of nodules.*

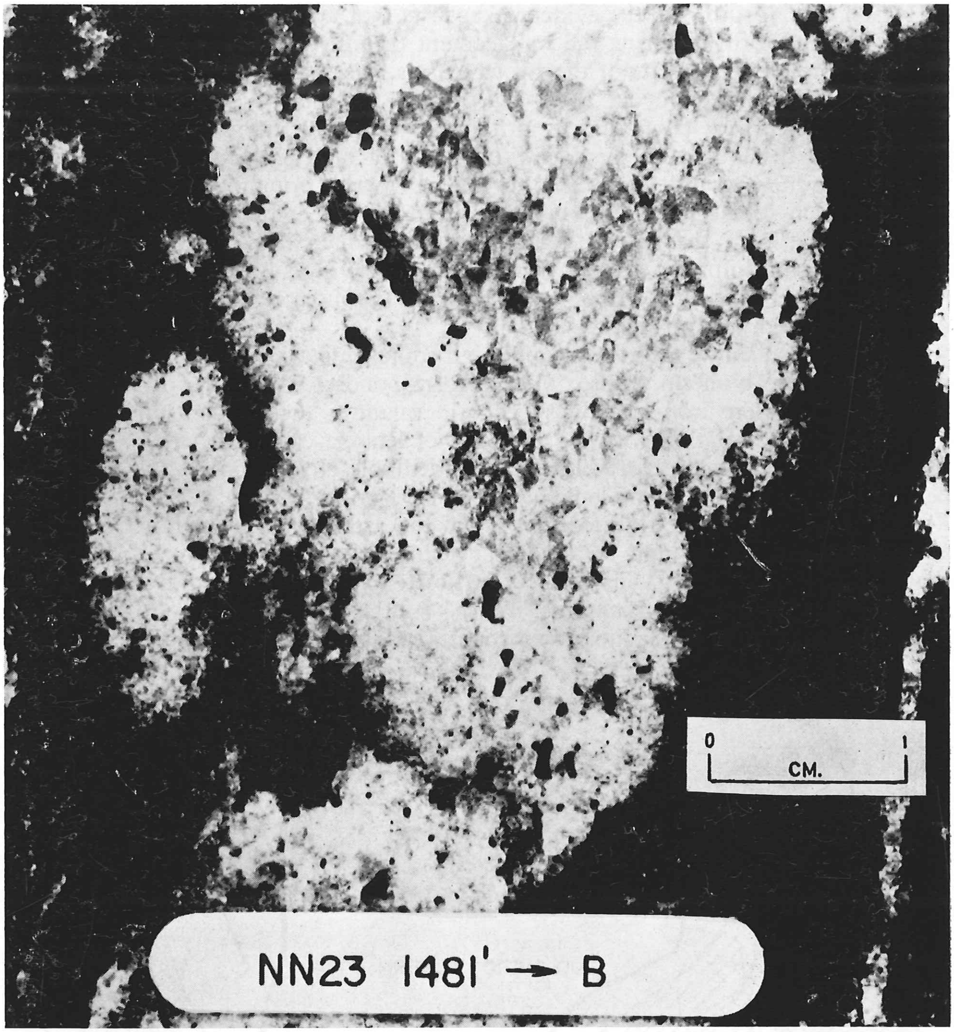


PLATE 1. — *Anhydrite nodule with peripheral replacement zone consisting of calcite-bornite and chalcopyrite. Sulphides disseminated throughout calcite zone but absent from anhydrite core.*

schist. At the same time, abundant nodules and almost enterolithic masses of anhydrite appear which are extensively replaced and heavily mineralized (see NN 23, fig. 5), as are the enclosing meta-sediments. There is thus an inter-relationship between the appearance of a carbonaceous argillite interbed, the decrease in the quantity of nodular anhydrite or carbonate, and the decrease in the amount of copper (see fig. 2).

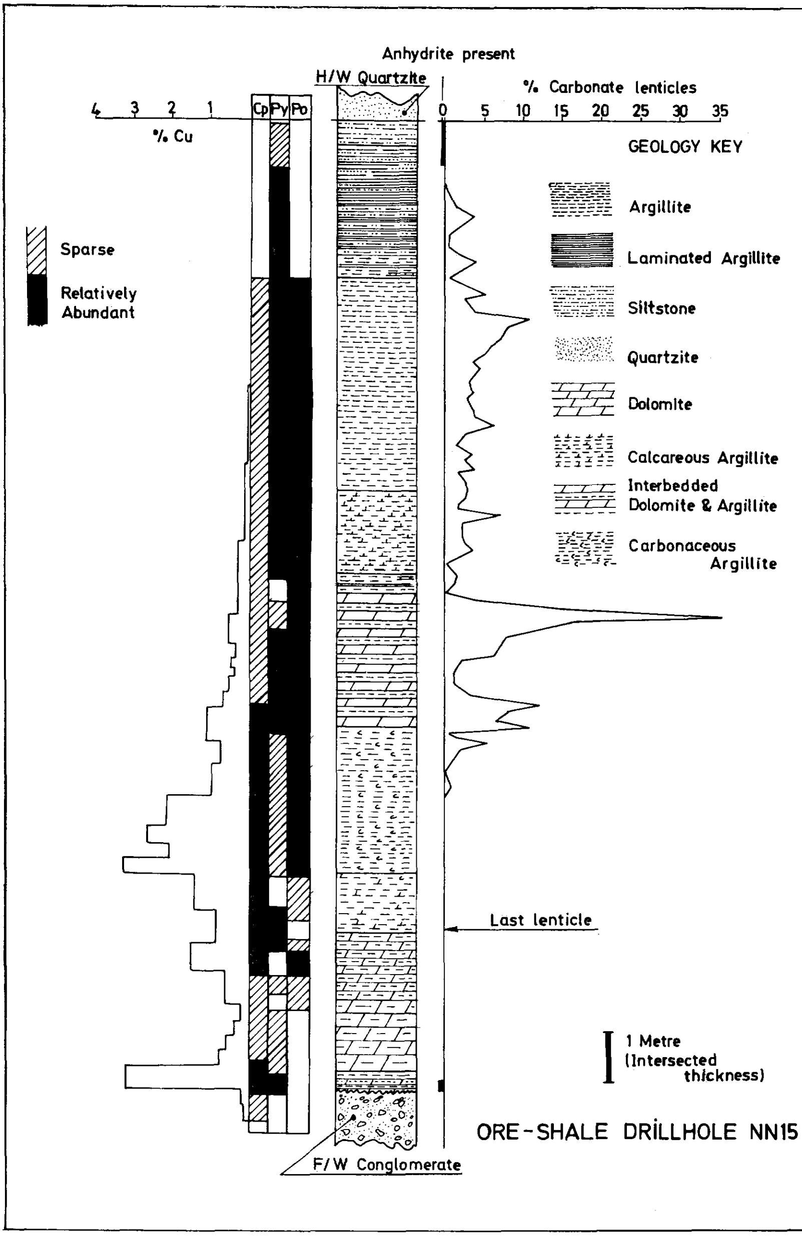


FIG. 4

Carrollite shows an extremely close affinity with carbonate in general, but in particular with lenticle carbonate. The area in which carrollite has been identified corresponds with that in which lenticles are most abundant, i.e. to the southeast of the bioherm.

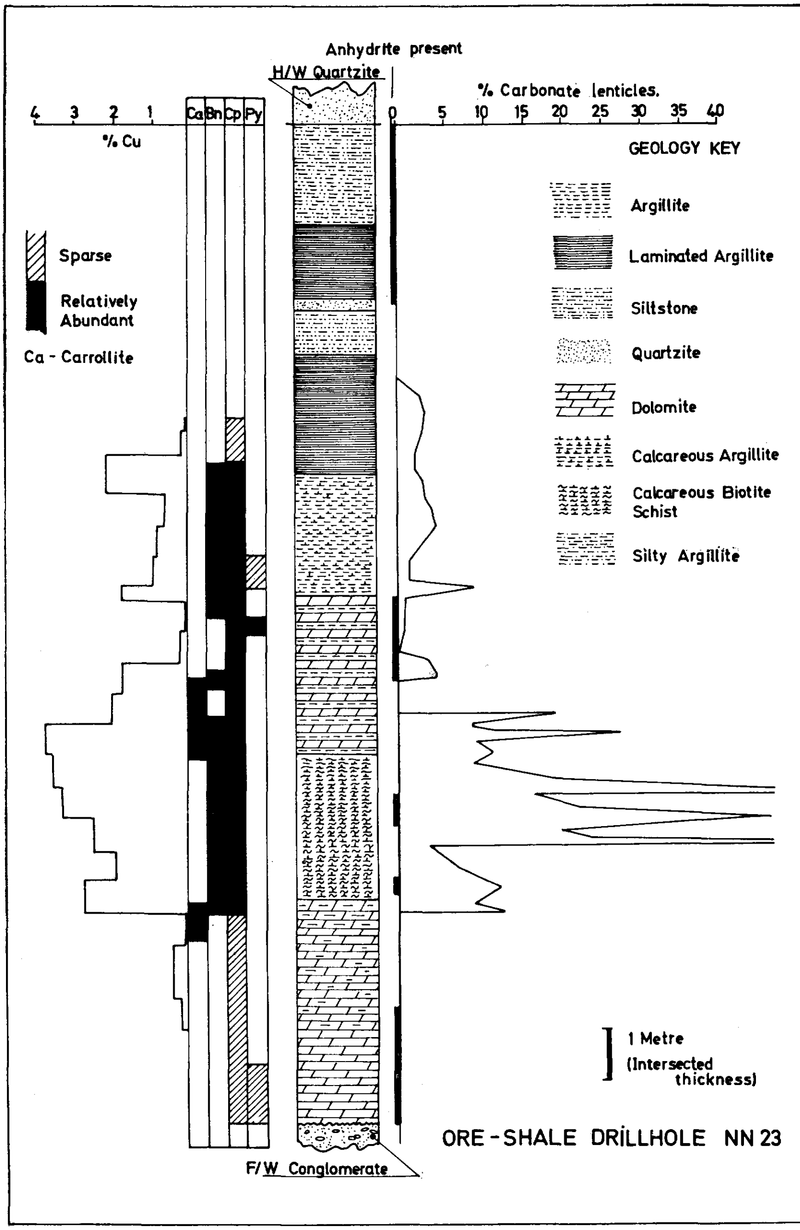


FIG. 5

Microscopic studies show that the contact between anhydrite and carbonate phases in a lenticle is a replacive one. Rounded and corroded residual grains of anhydrite occur enclosed in the carbonate, which also penetrates the anhydrite along cleavages and intergrain boundaries.

THE LENTICLE CARBONATE

There is reason to believe that at Nkana North Limb the carbonate which formed initially at the expense of the anhydrite was dolomitic in composition. However, as the reef margin is approached, replacive calcite appears at the margins of the lenticles, particularly at their apices (see plate 4). Calcite may occur also at the centre of dolomite lenticles where it displays the characteristics of a cavity infilling. Close to the reef calcite is the dominant constituent and around the southeastern margin of this mass it is the sole constituent. The change from 100 % calcite to 100 % dolomite takes place in as short a distance as 200 m. The replacive or late stage character of the calcite suggests that it may be metamorphic in origin. The association of calcite with phlogopitic mica and the replacement of K felspar by calcite near the reef, suggests that calcite and the mica were

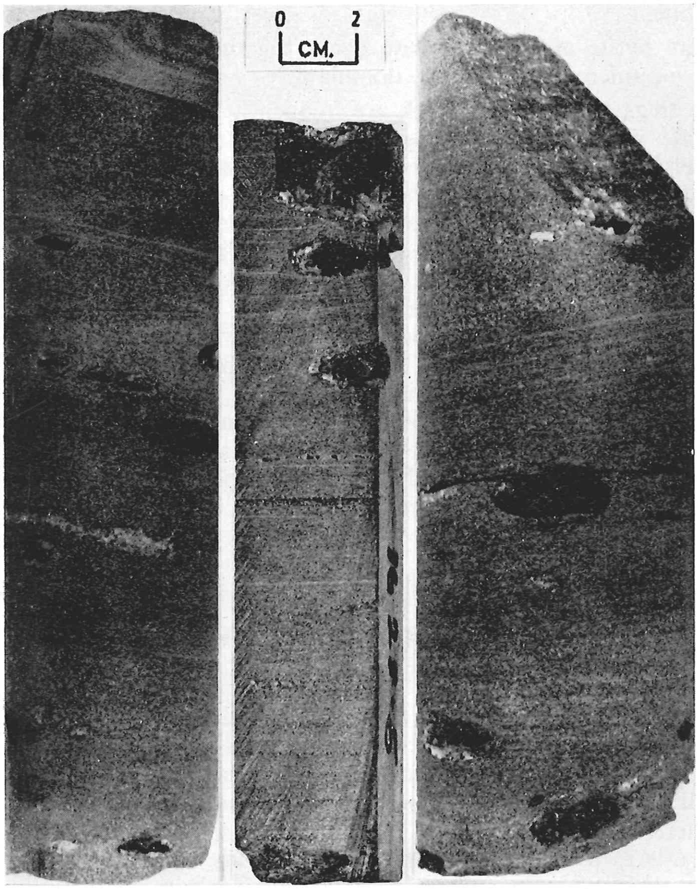


PLATE 2. — *Ellipsoidal Cavities — Chambishi Ore-Shale.*

formed at the expense of dolomite and K felspar. Such a de-dolomitization process, however, only took place in the vicinity of the reef margin.

SECONDARY FELSPAR

The following conclusions concerning the secondary felspars associated with sulphides and carbonate lenticles are based on thin section studies of material from both Chambishi and Nkana North Limb. These felspars may be enclosed in the outer carbonate rim or, together with quartz, form a halo around the lenticle.

(*a*) The amount and type of felspar in the lenticles can differ markedly from that in the surrounding host rock. Microcline can be the dominant secondary felspar in the host rock, while albite (An_{7-9}) is dominant in the lenticle or *vice versa.*

(*b*) Where lenticles contain pyrite alone the associated felspar is microcline.

(*c*) Where lenticles contain chalcopyrite (or bornite) alone then the associated felspar is albite.

(*d*) Where pyrite and chalcopyrite occur together both albite and microcline may coexist but microcline is usually dominant.

Pyrite aggregates in the host rock are frequently surrounded by microcline and quartz. Albite may accompany the microcline but is never found as the sole secondary felspar around pyrite. It is also closely associated with lenses and bands of coarsely crystalline calcite in the host rock.

Though there is an apparent relationship between the appearance of copper sulphides and the appearance of secondary albite, there is no quantitative linear correlation. Maps of metre-percent copper for the entire ore-shale around the Nkana North Limb reef and for the distribution of secondary albite are, however, remarkably similar. Analyses for sodium within the ore-zone show increases from 0.05 % to >1.0 % (weight %) as the reef is approached and in the vicinity of the 10 metre percent copper contour. Similarly the sparsely mineralized hanging-wall argillites show a two- to threefold increase in sodium content in the same direction. These observations cannot be readily explained if the ores are considered to be of syngenetic origin. It should, however, be pointed out here that a similar relationship between sodium and copper has not been described for the larger deposits of the Copperbelt.

LENTICULAR CARBONATE IN OTHER DEPOSITS

Though anhydrite nodules and carbonate-sulphide lenticles were both recognized in the ore-shale in the past, it seems that even though they show remarkably similar shapes, they were never associated. This may be because the transitional stage so well displayed at Nkana North Limb was not exposed by mining development elsewhere.

Garlick (1967, p. 132) states that "Concretions of dolomite ... occur only rarely in the shale type ore, where these nodules contain small biotite flakes and aggregates of chalcopyrite or other sulphide." This is not the case in the carbon-

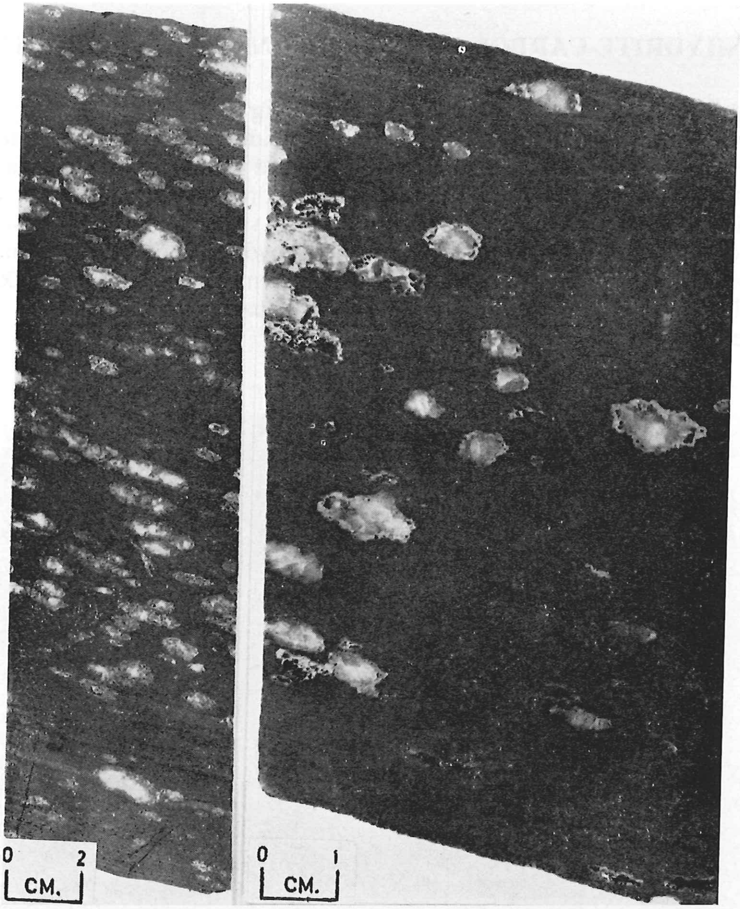


PLATE 3. — *Lenticles in carbonaceous argillite — Mwambashi Ore-Shale.*

aceous argillite facies which, as can be seen in plate 3, is heavily charged with small carbonate-quartz nodules rimmed with pyrite. The majority of drillholes intersecting this facies in the Chambishi Basin revealed an abundance of such nodules. The author has collected examples of carbonate-quartz lenticles rimmed with, and including, chalcopyrite and pyrite from drillholes in the deeper intersections of the Chambishi orebody itself, which like Nkana North Limb, is in the argillite-siltstone facies of the ore-shale. Such lenticles may not have been recognized at Chambishi, because, as is shown in plate 2, they have been completely leached out at shallow depths leaving an ellipsoidal cavity lined with grains of sulphide and quartz. Similar lenticles occur at Roan Extension in the Luanshya Basin.

ANHYDRITE-CARBONATE RELATIONSHIPS IN ARENITES

Anhydrite has been recorded as constituting a cement to the Footwall Quartzites at Mufulira. Garlick (1972, p. 292) considers that it formed interstitially, or as concretions, during exposure of muddy sand flats or from detrital gypsum accumulated with wind blown dune sands. He records as much as 35 % anhydrite in some laminae of the "aeolian" sandstones. In the same paper he states that, "Deposition of sandy muds with considerable anhydrite or gypsum terminated the 'A' graywacke deposition." Darnley (1960, p. 149) mentions that the poikiloblastic interstitial habit of anhydrite in the Footwall Quartzites, "... closely resembles that of the interstitial carbonates. ..."

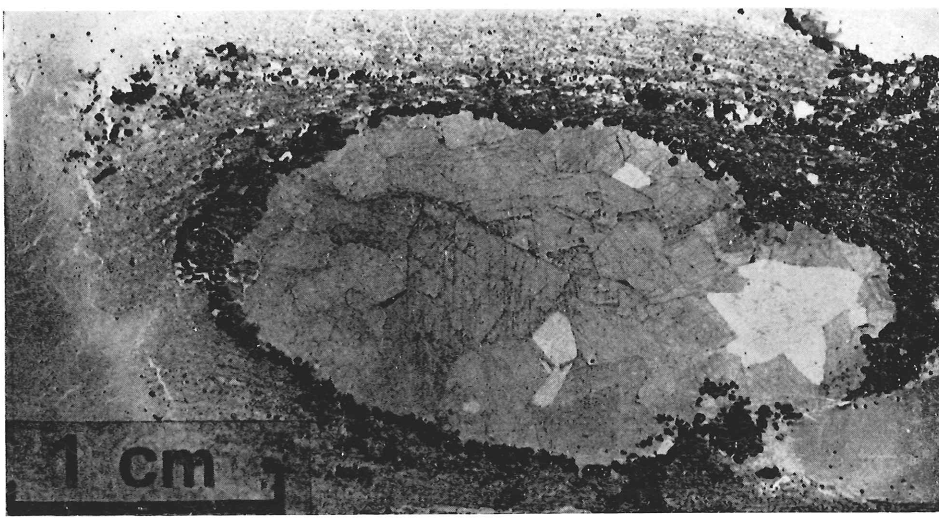


PLATE 4. — *A dolomite-quartz lenticle with rim of pyrite. Some dolomite crystals show clouded cores (carbon?). Alizarin-red staining has revealed the presence of secondary calcite as darker areas at the apices of the lenticle. Specimen from drillhole NN 15, Nkana North Limb.*

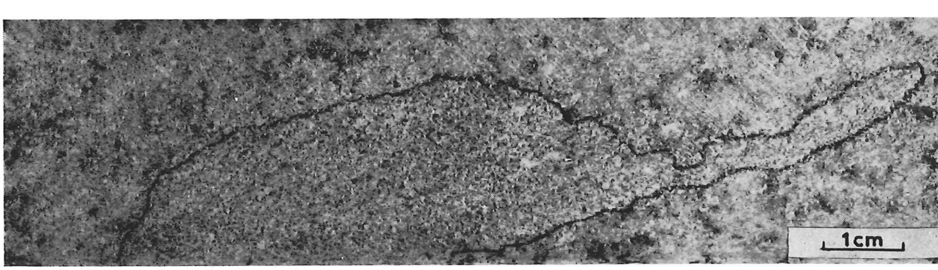


PLATE 5. — *Unmineralized anhydritic arenite patch within mineralized dolomitic arenite. Sharp contact between the two is emphasized by a pencil line. The sulphide is chalcopyrite. Specimen from the footwall of the B orebody, Mufulira.*

At Mufulira there is a very marked antipathetic relationship between interstitial anhydrite and copper mineralization (Annels, 1973). The orebodies themselves contain variable but often relatively large quantities of interstitial dolomite, anhydrite being conspicuously absent, except as late veinlets or pods. However, towards the economic footwalls of the "B" and "C" orebodies, and possibly also of the "A" orebody (stratigraphically the youngest), there are irregular patches or bands of sparsely to un-mineralized arenite within the lower grade, often chalcopyritic, basal zones of the orebodies (see plate 5). These patches are characterized by a lower carbonate content and show a mauve to pink colouration due to the presence of anhydrite. Similarly in the barren anhydritic footwall rocks there are light grey transgressive patches of mineralized arenite. Careful sampling and analysis of some of these coexisting mineralized and "barren" arenites produced the following results:

	Cu %	Anhydrite %	Dolomite %
Mineralized arenite	1.7-3.0	0-5.0	8-13
"Barren" arenite	< 0.3	19-25	2-7

The margins of the above mentioned light grey mineralized transgressive patches are very sharply defined, as can be seen in plate 5, and are unrelated to changes in the original sediment type. These patchy rocks do not represent slump breccias as traces of bedding pass uninterrupted through both the light-grey and pink arenites. The very sudden disappearance of anhydrite is marked by the equally sudden appearance of copper sulphides.

Work on the anhydrite-carbonate-sulphide relationships at Mufulira is still at an early stage, but recent drilling across the fringes of the combined B/C orebody has revealed that the barren or sparsely mineralized portions of the "Inter B/C Quartzite" including the "Banded Shales and Quartzites" immediately above the "Mudseam," are often highly anhydritic. Similarly, recent intersections of the "A" horizon, which were un-mineralized, proved to be highly anhydritic.

Returning to the Nkana North Limb deposit in the Chambishi Basin we find that the "Footwall Conglomerate" beneath the ore-shale and the coarse, gritty feldspathic arenites in the hangingwall, both contain interstitial anhydrite where unaffected by recent groundwater movements. However, as the biohermal mass is approached, the upper and lower limits of visible copper mineralization in the ore-shale rise and drop respectively, so that close to this body they are within the arenite and conglomerate respectively. Where this has occurred petrographic studies show that the original interstitial anhydrite is almost entirely replaced by calcite.

SIGNIFICANCE OF ANHYDRITE-CARBONATE RELATIONSHIPS

It is envisaged that the original nodular anhydrite formed during early diagenesis under conditions of supersaturation of $CaSO_4$. These may have existed in either a supratidal sabkha environment or in sediment at the centre of a basin in which dense, $CaSO_4$ saturated bottom waters were accumulating. During advancing diagenesis, still under relatively low temperature conditions, the anhydrite was replaced by carbonate thus liberating sulphur which was then utilized in the precipitation of diagenetic sulphides, initially pyrite. However, the presence of coexisting anhydrite and calcite in metamorphic secretion veins without evidence of replacement of one by the other, indicates that at more elevated temperatures the two phases were stable. Cross-cutting masses of quartz-carbonate-chalcopyrite-anhydrite do occur in the basal dolomites of the Nkana North Limb ore-shale. Here the sulphides and anhydrite co-exist without an intermediate carbonate phase. These masses are similarly interpreted as being of metamorphic origin.

At Roan Extension diagenetic nodules of anhydrite or gypsum after anhydrite (a post-mining phenomena) are found near the hangingwall of the orebody. These, however, are surrounded by a discontinuous rim of chalcopyrite without intermediate carbonate. This at first presented a problem until it was noted that sulphide concentrations at the rims lay adjacent to depleted areas within the very finely disseminated chalcopyrite mineralization of the host rock. This is strongly suggestive of a metamorphic secretion phenomena.

A drillhole intersection of the ore-shale close to the Nkana North Limb bioherm also showed unaltered anhydrite lenticles surrounded by well developed rims of sulphide close to the economic hangingwall. However, careful search failed to reveal sulphide depletion around the lenticles.

It thus appears that, on the evidence from both Roan and Nkana North Limb, it was possible for some nodules to escape replacement during diagenesis and hence take no part in the mineralization process, even though the surrounding sediment was enriched in sulphides. During diagenesis or metamorphism these nodules merely provided a surface on which sulphides could accumulate. It is suggested that the cause of replacement was not a metamorphic process but one which was patchily operative at the lower temperatures existing during diagenesis. As temperatures increased and rock porosity decreased under increasing depth of burial, reaction between interstitial brines and anhydrite slowed down and eventually ceased. Either portions of the ore-shale (i.e. towards the hangingwall) were not penetrated by these brines or the reactive constituent was completely depleted by reaction with anhydrite elsewhere (e.g. lower in the ore-shale).

Perhaps the main implication of the above observations is that at least some of the metals must have been in a mobile non-sulphide form during diagenesis. We have the evidence of upward and downward migration of metals as the Nkana North Limb bioherm is approached together with the replacement of early diagenetic anhydrite by carbonate. One begins to wonder as a result, whether any of the sulphide, with the possible exception of some of the pyrite in the carbonaceous argillites, was synsedimentary as proposed by Garlick (1961).

NATURE OF THE REPLACEMENT PROCESS

There are two possible processes which could explain the replacement of anhydrite by carbonate and the resulting liberation of sulphide ions.

(1) Bacterial Reduction

Anaerobic bacteria, such as *Desulfovibrio -desulfotomaculum* and *desulfuricans,* break down SO_4 during their metabolic process to retrieve oxygen and in the process release H_2S and CO_2. Such bacteria need not only a plentiful supply of SO_4 but also decomposing organic matter, both of which would be available in the carbonaceous argillite facies of the Chambishi Basin. This process would not, of course, take place at high temperatures.

(2) INORGANIC REDUCTION

In the literature hydrocarbons have been recorded in association with ore deposits either as a coating of ores or wallrock or as immiscible droplets in fluid inclusions (e.g. Barton, 1967). Davis and Kirkland (1970) have postulated that the native sulphur in the laminated anhydrite-calcite rocks of the Castile Formation is the product of a reaction between hydrocarbons and anhydrite, the initial phase of which can be represented by:

$$CaSO_4 + (C + 4\,H) \rightarrow H_2S + CaCO_3 + H_2O$$

A similar reaction is proposed by Schnellmann (1959) to explain the Ras Gemsa sulphur deposit in Egypt. At low temperatures it is possible for methane and SO_4 to coexist metastably in a brine, or to react only sluggishly but above 90 °C a more rapid a reaction takes place.

It is very likely that both mechanisms operated, but that the latter became the more effective of the two as temperatures and pressures rose with increasing depth of burial.

PROPOSED GEOLOGICAL MODEL

In recent years there have been numerous papers describing the possible role of intrastratal brines, particularly those derived from carbonaceous oil shales in evaporite basins, as a medium for the collection and transport of metals during diagenetic compaction of a basinal sedimentary pile. This discussion was initiated by the conflict between Davidson and Dunham over the association of evaporites with mineralization. Davidson (1966) pointed out the spatial relationships between ore deposits and basin margin sabkha facies. Bush (1970) and Llewellyn and Stabbins (1968) have recently written on the same subject. A common theme has been the existence of potentially hydrocarbon bearing shales in the basin centre and the presence of sabkha type facies and reef complexes on the basin periphery. Reef complexes, back reef evaporites and supratidal mudflats containing nodular anhydrite all appear potential locations of ore deposition. Dozy (1970) quotes several examples of producing oil fields with base metal mineralization at the basin margins including those around the Kankakee Arch and the Ozark Uplift in the Mississippi valley. The Pine Point Pb-Zn mineralization in Canada occurs on the flanks of the Elk Point Evaporite Basin known to contain hydrocarbons (e.g. in the Keg River Reefs).

Returning to the Zambian Copperbelt once again we see an analogous situation for the central portion of the Chambishi Basin contains carbonaceous shale which is pyritic but generally lacking in copper sulphides. This passes up-dip into a typical sabkha facies in which nodular anhydrite, or carbonate after anhydrite, occurs and in which there are several recorded biohermal structures (see fig. 1).

All known ore deposits of ore-shale type are within this littoral zone. It is thus suggested that the geological situation on the Copperbelt bears some resemblance to that existing in present day oilfield basins. The carbonaceous argillite of the Chambishi and Konkola basins could thus be considered as equivalent to the oil-shale and the rather problematical carbonaceous arenites or "graywackes" of Mufulira the oil-sands of this postulated Pre-Cambrian oilfield. Hydrocarbons may have migrated with the metal enriched chloride brines towards the basin edge where they reacted with anhydrite, or escaped into the arenites on the opposite side of the Kafue anticline. This hypothesis would account for the occurrence of graphitic carbon in relatively coarse arenites at Mufulira. It should also be noted that each carbonaceous arenite body here is overlain by what would have been fairly impermeable "cap rocks" e.g. the dolomitic "Mudseam" plus the "Banded Shales and Quartzites" over the C horizon, the "Lower Dolomite" plus "Massive Shale" over the B horizon and the "Lower Argillaceous Quartzite" containing silty argillites, over the A horizon. A summary of the Mufulira stratigraphy is tabulated below.

Simplified Stratigraphy of the Mufulira ore-bearing Formations

Formation	Facies equivalent	
Lower argillaceous quartzite		
A Quartzite Inter A/B quartzite Banded shales and quartzites Massive shale Lower dolomite	A Graywacke	Ore zone
B Quartzite Inter B/C quartzite Banded shale and quartzite Banded shale and dolomite Mudseam (dolomitic siltstone)	B Graywacke	Ore zone
	Algal dolomite (stromatolite horizon)	
C Quartzite FW Quartzite	C Graywacke	Ore zone
	FW Grit	
Basement granite and schist		

We can thus summarize the events which are envisaged to have led to the formation of the stratiform orebodies of the Zambian Copperbelt in the following way:

(1) Metals brought into the depositional basins either by rivers or by metal enriched hot brines emanating from springs along the possibly fault controlled basin edge, were dispersed throughout the accumulating sediment. Such metals may have been adsorbed onto particles of clay or organic material or may have occurred as hydroxides, carbonates or other complexes.

(2) The basin became restricted from the open sea and the waters became increasingly saline. A marked brine density layering developed in the centre as described by Schmalz (1969). Sabkha type mudflats appeared along the littoral zone in which reef masses were inundated with muddy sediments.

(3) Nodular anhydrite was formed in both the basin centre and peripheral sedimentary facies by supersaturation of interstitial waters.

(4) Bacterial action in the carbonaceous argillites at the basin centre quickly converted the small nodules of anhydrite (or gypsum) to carbonate and allowed the formation of abundant early diagenetic pyrite. Similar replacement may also have begun in the littoral facies. The potash rich nature of the interstitial fluids allowed the formation of abundant sericite and/or secondary microcline.

(5) As diagenesis proceeded and compactional effects became more pronounced, intrastratal brines, plus hydrocarbons generated by the decay of the organic material, began to move towards the basin margins. Under elevated temperatures these brines desorbed metal ions, and carried them into the littoral zone where anhydrite was abundant as a cement or as nodules.

(6) Reaction between the hydrocarbons in the brines and the anhydrite resulted in the rapid precipitation of sulphides. Initially iron sulphides dominated, but with advancing diagenesis copper, hitherto strongly bonded to organic material, was desorbed in increasing amounts and carried into the sabkha facies by the brines and then precipitated in the form of chalcopyrite or bornite. The gradual depletion of potash in the brine by the formation of potassium silicates produced a relative increase in soda concentrations and the appearance of secondary albite along with the copper sulphides.

(7) The magnesium rich nature of the brines is indicated by the dominance of dolomite in the lenticles and by the dolomitization of the bioherms. Chlorites intergrown with the sulphides are magnesium rich varieties such as clinochlore and sheridanite.

Thus, during diagenesis we have a reconcentration of metals towards the shoreline from which they were originally dispersed during sedimentation. The rate of supply of sulphur (or H_2S) from the anhydrite was sufficient to balance the rate of influx of metals though at times competition for sulphur was great enough for pyrrhotite to form instead of pyrite, especially in those areas where the lenticle concentration was lowest, i.e. to the northwest of the Nkana North Limb bioherm. The small quantity of mineralization in the bioherm is explained by the fact that its porosity was restricted by compaction and cementation, by the lack of a precipitant there, or by the fact that all the metals had been precipitated from the brines before the brines entered this dolomite mass. In the latter case the reef masses are envisaged as having acted as a plumbing system for the basin allowing the upward and outward escape of the brines.

THE COBALT PROBLEM

It is not intended to deal with this subject in detail. Some of the problems which face the proponents of the syngenetic synsedimentary origin for both the copper and cobalt mineralization should, however, be pointed out.

If the metals are derived from weathering of the Basement Complex and then deposited in the various basins flanking land masses, then:

(1) Why is cobalt only found on the southwest side of the Kafue Anticline (see map, fig. 1)? On the Luanshya-Mufulira-Ndola side cobalt is only at background levels.

(2) Why are all known occurrences of cobaltiferous pyrite and cupriferous linnaeite and carrollite found along a narrow belt which passes through Baluba, Nkana, Chibuluma, Nkana North Limb, Mwambashi and Bancroft?

Is it fortuitous that virtually all the sills (extrusions?) of amphibolite in the Upper Roan are found on the southwest side of the Kafue anticline and that their thickest development coincides with the central portion of this cobalt lineation?

Why is it that analyses of pyrites extracted from late stage veinlets in the Upper Roan amphibolites show an enrichment in cobalt only when the Lower Roan orebody beneath contains cobalt? Up to 2.5 % cobalt has been recorded in these pyrites.

Why is it that all analyses of Basement mineralization and Basement rocks known to the author fail to reveal the presence of cobalt?

The majority of occurrences of cobalt throughout the world are associated with basic magma, why should Zambia (and for that matter, Zaire) be an exception to the rule? Perhaps both the amphibolites and the cobalt mineralization are related to the same magma body at depth.

SULPHIDE ZONATION

The picture of sulphide zones parallel to shorelines as presented by Garlick (1961), Davis (1954) and others, is in the author's opinion an over simplification. In reality such clearly defined zones are extremely difficult to recognize. Vertical and lateral sulphide zonation is often explained in terms of transgressions and regressions of the shore line which are incompatible with changes in water depth as indicated by sedimentological evidence. At Nkana North Limb a gradual deepening of the ore-shale basin was accompanied by the deposition of carbonaceous argillites. This event was then followed by a gradual shallowing so that the sediments became increasingly silty and sandy and eventually gave way to coarse grained quartzites. These lithological changes coincide with a change from Cp + Py at the base of the ore-shale to Cp + Bn to Py + Cp and then to Py close to the top. Syngenetic theories (Garlick, 1961) indicate that a shallowing of the water should not be accompanied by a change to pyrite, or deepening by a change to bornite. A similar reversed profile is found at Baluba, Chambishi and Muliashi South. The opposite zonation, in which the changes are Py $\rightarrow$ Cp $\rightarrow$ Bn $\rightarrow$ Cc in an upward direction, is found at Roan and Roan Extension. It should be borne in mind that both the Roan and Chambishi Basins (see fig. 1) were probably part of one large depositional basin and should show the same sedimentary trends, which they do. We should thus find, after taking into account diachronous contacts, identical pictures in the mineral zoning which should correspond to lithological zones. This is not the case.

STRUCTURAL CONTROLS

Brock (1962) first postulated the theory that sections of the crust may have collapsed in the Katangan geosyncline thus accounting for the distribution of the present sedimentary basins. While his conclusions should be treated with reserve, there is certainly some evidence which tends to support his ideas.

Firstly, it is remarkable that pinchouts of the ore-shale in the Chambishi Basin tend to coincide with the present margins of this structural basin. The extremely sudden pinchout of the carbonaceous shale to the southwest between Mwambashi North and Chibuluma (fig. 1) is, in the author's opinion, too rapid to be explained in terms of facies changes. What is more remarkable is that this line also marks the sudden disappearance of the upper portion of the Lower Roan above the ore-shale and possibly even the basal Upper Roan. At the same time the Upper Roan amphibolite "sills" lie almost directly on arenites which are believed to represent the Footwall Quartzites. In the area where the ore-shale is present, all the amphibolites are separated from the Footwall Formations by more than a 100 m of arenites, argillites and dolomites. Though it is realized that such "sills" could be transgressive, the above facts appear to the author to be too much of a coincidence. They could, however, be explained by block subsidence during the deposition of the Lower Roan.

Secondly, large sections of the margin of the Chambishi Basin are followed by monoclinal fold limbs some of which are subvertical or even overturned. A major monocline strikes eastwards from Pitanda, in the northwest of the Basin, passing immediately to the south of the Chambishi Open Pit, while a second runs approximately north-south to the east of Nkana North Limb and links up with another in the Nkana syncline. The base of this fold is followed by a thick sedimentary trough.

If block faulting did take place during sedimentation of the Lower Roan, then this may have allowed the influx of metal enriched, possibly magmatically derived, solutions into the basin from a series of springs around the margins.

CONCLUSIONS

In recent years many geologists have accepted that the syngenetic deposition of sulphides in the Copperbelt is a proven fact and have based their studies on this assumption. The main aim of this paper is to point out that such a theory by no means explains all the facts, and indeed has certain serious limitations. While it is attractive in many ways, it is still difficult to accept that sulphides could be precipitated from waters beneath which, coarse, often cross bedded, arenites were being deposited and in which cryptozoon stromatolites were able to establish themselves. Similarly, bioherms, oncolitic stromatolites, and possibly also collenoid stromatolites, are also found in the ore-shale surrounded by mineralized sediment.

The theory that at least some of the sulphide mineralization in the Copperbelt was formed by the combined bacterial and inorganic reduction of anhydrite in the diagenetic environment is presented for critical examination by those familiar with such deposits.

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