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STROMATOLITES AND OTHER ALGAL STRUCTURES AT MUFULIRA, NORTHERN RHODESIA

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ABSTRACT

Since 1941, stratiform copper-cobalt mineralization in the Katanga has been recognized to be adjacent to algal reefs, but only recently have stromatolites been identified near the western fringe of the 'B' orebody at Mufulira. A study of the well developed and preserved stromatolitic structures here has aided in the recognition, in other localities and at other horizons, of other organic structures, such as algal bedding, algal balls, and the puzzling gray and white dolomitic mottling of the Mufulira ore quartzites.

Reconstruction of the paleoecological conditions indicates that the stromatolitic growths are best developed on a sandy or pebbly bottom at the eastern edge of the Inter B/C dolomite. This dolomite is now interpreted as a shallow-water lagoonal deposit and is thinly laminated, with minor undulations, controlled by algal mats growing initially from a muddy bottom.

Economic and genetic implications are that the 'B' orebody is antipathetic to the Inter B/C dolomite, and also the mottling and carbonate content of the mineralized quartzites is marginal and peripheral to the better ore. The clean dolomite on the margins of biohermal stromatolites is nearly barren, but copper content as chalcopyrite, in the argillaceous beds adjacent to the bioherms, is the same as in the sinuous mud fillings between the stromatolite columns. These data favor a syngenetic origin for the mineralization.

INTRODUCTION

THE Mufulira copper mine lies in latitude 12°32'S, longitude 28°15'E, in Northern Rhodesia, approximately nine miles south of the Northern Rhodesia-Congo border. It is one of seven operating mines comprising the Northern Rhodesian Copperbelt.

In the Congo, the association of stromatolites with the cupriferous beds of the Katanga system has been known since 1941 (8). Recently, these and other algal structures were recognized underground at Mufulira, and were found to be of widespread distribution.

The purpose of this paper is to record briefly the presence and nature of the various algal structures and stromatolites. Observations regarding the distribution of the copper mineralization in relation to these structures are included as they are significant in considerations of ore genesis.

From recent work (2, 6), it appears that stromatolites have been produced not by single organisms, but by colonies, commonly including species of several different families or classes of algae, while the shape of such a colony is dependent on the environmental conditions of growth. Names, such as collenia, cryptozoön, and gymnosolen, therefore, refer to shape rather than the biological genera involved, and have been used in that sense in this paper. To avoid confusion with the binomial system of classification, in which stromatolites are treated as fossil organisms and are assigned generic and specific names, these names are used here in the vernacular sense, without being capitalized or italicized, as suggested by Cloud. The algal deposits and stromatolites at Mufulira are devoid of internal cellular structure, thus defying classification as normally applied to the calcareous algae (10).

GENERAL GEOLOGY

The stratiform copper deposits at Mufulira are situated on the southern limb of a nine mile wide syncline striking northwest-southeast, and have an average dip of 45° to the northeast. The host rocks are the arenaceous Lower Roan beds of the Mine Series, the lowermost subdivision of the late precambrian Katanga system.

A generalized stratigraphic column for Mufulira is given for reference in Table 1, but will not be discussed in detail. The sediments have been metamorphosed to the greenschist facies, biotite and chlorite being the typical minerals of the shaly beds, and talc in some of the cherty dolomite beds.

Structurally, the area under consideration is relatively simple, being only a small portion of the flank of the Mufulira syncline. Small "pod" fold structures, generally associated with hills in the pre-Katanga landscape, are superimposed on the main synclinal structure (11). No faulting of significance has as yet been recorded in the mine area, but local discontinuous dislocations of beds, with displacements ranging from a few inches to a few feet, are mainly of the pre-consolidation slump type.

Stratigraphy and Ore Distribution.—The Lower Roan sediments at Mufulira were deposited in a large depressed area in the pre-Katanga

TABLE 1

GENERALIZED STRATIGRAPHIC SUCCESSION AT MUFULIRA				
System	Series	Group	Formation	Lithology
Katanga	Kundelungu			Dolomites, shales, quartzites, and tillite.
	Mine	Mwashia	Not subdivided	Shales and dolomites with minor quartzites.
		Upper Roan	Upper Dolomite	Dolomites, argillites and breccias with minor quartzites.
			Interbedded Shale and Quartzite	Quartzites. "Blue Shale" marker bed at base.
			Intermediate Dolomite	Dolomites with minor argillites and quartzites.
		Lower Roan	Hangingwall Formation	Argillites and argillaceous quartzites with minor quartzites and dolomites.
			Ore Formation	Quartzite and carbonaceous quartzites ("graywackes") with minor dolomites and argillites.
			Footwall Formation	Quartzites, grits, and conglomerates.
Unconformity				
Lufubu	Not subdivided			Schists and quartzites with intrusive granite.

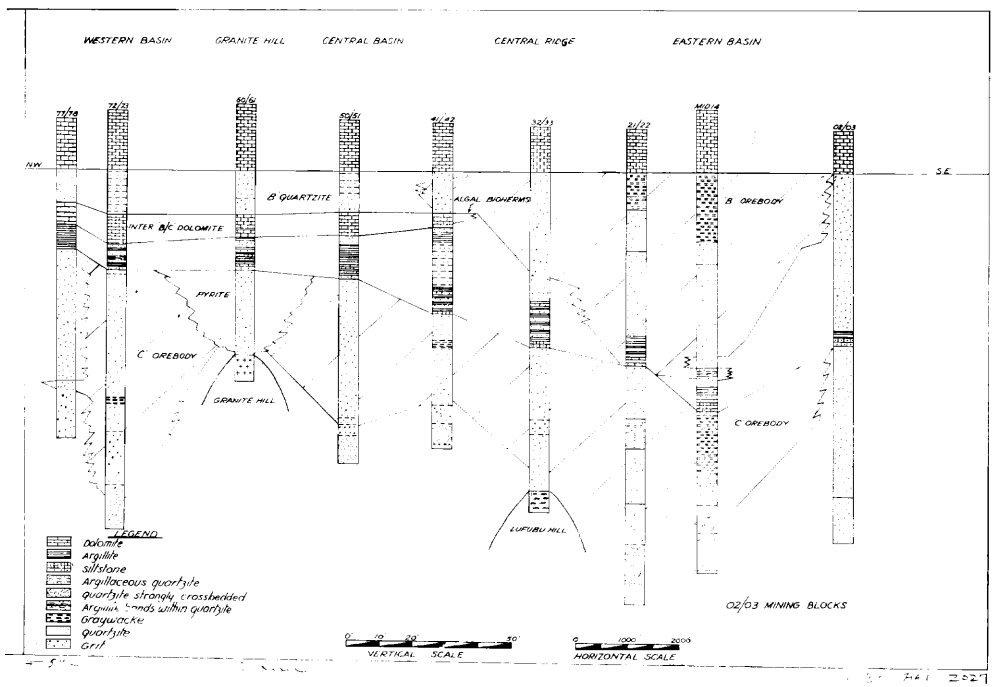


FIG. 1. Generalized strike section showing "B" and "C" orebodies at Mufulira.

topography. This low-lying area, in turn, is subdivided into three embayments or smaller basins by low ridges to give eastern, central, and the western basins. The topographic ridges on the floor of the basin had a pronounced influence, not only on the sedimentary succession, but also on the sulfide mineralization (11).

Three superimposed orebodies, A, B, and C, are present in the eastern basin. The uppermost, or 'A,' orebody is confined to this basin, while the middle, or 'B,' orebody is present in both the eastern and central basins. The lowermost, or 'C,' orebody is present in all three of the basins (Fig. 1).

The stratigraphic succession of the ore formation is given in Table 2.

TABLE 2

DETAILED STRATIGRAPHIC SUCCESSION OF THE ORE FORMATION			
Formation	Member	Bed	Av. Thickness
Ore Formation	'A' Horizon	Grey quartzite and graywacke. Pink quartzite.	35'
	Inter A/B Beds	Pink quartzite. Interbedded shale and quartzite. Massive shale. Interbedded shale and dolomite. Lower Dolomite.	60'
	'B' Horizon	Grey quartzite and graywacke. Banded quartzite.	40'
	Inter B/C Beds	White quartzite. Dolomite. Interbedded shale and quartzite. Interbedded shale, siltstone & dolomite. Mudseam (dolomitic siltstone).	30'
	'C' Horizon	Grey quartzite and graywacke. Quartzites and grits.	50'

(NOTE: Nomenclature as used on Mufulira mine and is not always strictly correct in a petrological sense).

Detailed Stratigraphy Between B and C Ore Horizons.—The first collenias recognized at Mufulira were in the Inter B/C dolomite, and most of the following discussion is related to the lithology of the beds between the B and C orebodies.

The lowermost bed in the Inter B/C succession is a dolomitic siltstone called the Mudseam, which forms the hangingwall of the 'C' ore horizon. It is a conspicuous and persistent bed up to 4 feet thick (average 2 feet), containing thin cherty layers in the east, but in the western basin the thickness is greatly decreased and the Mudseam is more argillaceous. In the eastern basin, the Mudseam is overlain by up to 10 feet of felspathic quartzites, with minor silty, argillaceous, and dolomitic bands and partings, especially towards the base. This, in turn, is overlain by a white glassy felspathic quartzite, mostly massive and sporadically mineralized.

In the central basin, an interbedded shale and siltstone succession, with minor quartzite bands, rests directly on the Mudseam with a comparatively thin felspathic quartzite at the top of the Inter B/C succession. These beds are generally unmineralized, except locally, where thin lenticular beds of richly cupriferous quartzite may occur.

In the central and western basins, the Inter B/C succession shows a great

decrease in thickness, and consists of a thin sequence of interbedded argillite, dolomitic argillite, and quartzite, immediately above the Mudseam. Above this interbedded sequence is the Inter B/C dolomite of the central and western basins. This bed is a silty dolomitic argillite along the eastern margin of the central basin, but towards the centre of the basin it is a dolomite with lesser silt content and is characterized by structures indicating that this dolomite is mainly of biogenic origin.

ALGAL STRUCTURES IN THE DOLOMITIC BEDS OF THE MINE SERIES

General.—Collenias and other structures indicative of biogenic origin have been described from various horizons and locations in the Series des Mines of the Congo (8), and similar structures have been recognized re-

FIG. 2. Plan view of an algal bioherm showing elongation of the stromatolites.

cently at a number of horizons in the Mufulira vicinity. Investigations of the structures have been concentrated on the Inter B/C dolomites because of the coincidence of well preserved stromatolitic structures and of good underground exposures for three dimensional studies in this formation.

Although all the algal structures are inter-related, they have been subdivided, for convenience of description, into the following groups: (1) Stromatolites with associated reef structures; (2) Algal bedding (weedia); (3) Algal balls (girvanella or pycnostroma); (4) "Dolomitic mottling" in quartzites.

Stromatolites with Associated Reef Structures.—As used here, the term "Stromatolite" includes all those well defined laminated structures classified by Pia (13) under the sub-family Stromatolithi (i.e., attached forms). Form designations such as cryptozoön, collenia, and gymnosolen are used in the way advocated by Pettijohn (12) and Cloud (2).

Stromatolites were first recognized early in 1963 on the eastern margin of the Inter B/C dolomite, and subsequent underground mapping has shown these structures to have their most spectacular development here. Little is known about the western margin, as it has as yet not been exposed by mining operations, and only drill-hole information is available.

Along the eastern margin, the composition of the Inter B/C dolomite is that of a dolomitic argillite, rather than a true dolomite. Westwards, this

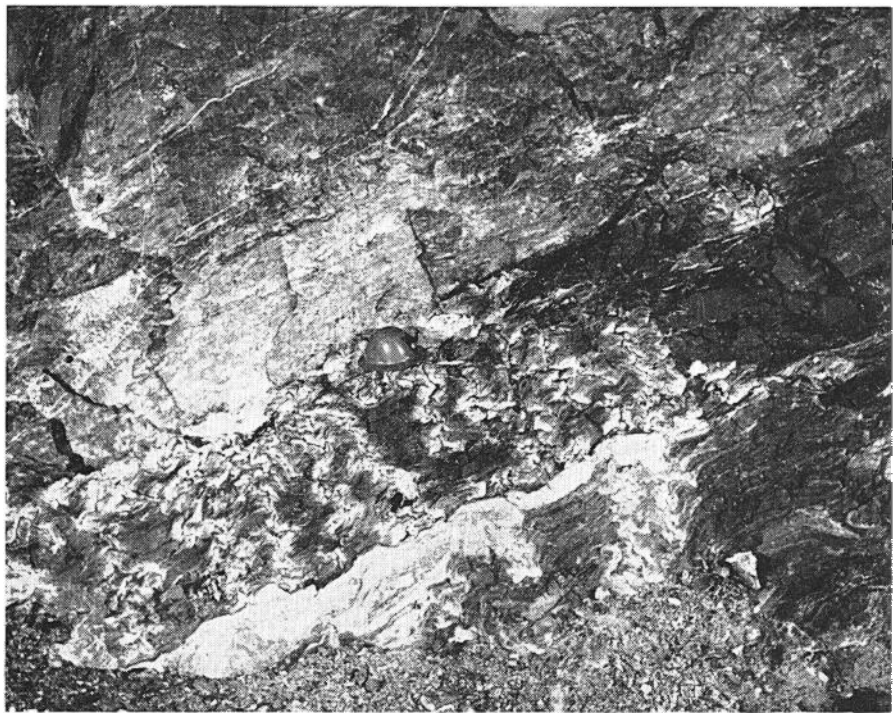


FIG. 3. Margin of an algal bioherm in dark gray argillite. Note the lighter colored mottled quartzite above the bioherm. See key diagram (Fig. 3A).

bed progressively becomes less argillaceous and more dolomitic, until, in the central part of the western basin, it is a slightly silty dolomite and generally characterized by peculiar contortions.

Where first discovered, in the 38/39 Boundary crosscut on the 1650-foot level, the stromatolites are exceptionally well developed and form biohermal ridges or reefs contrasting with coarse felspathic sand lenses and dark colored argillaceous rocks in the inter-reef channels.

In these structures, the stromatolites are nearly perpendicular to the bedding of the adjacent strata, and, in vertical section, consist of elongated columns 3–12 inches wide, with irregular outline. In the bedding plane, the length to width ratio of these bun-shaped structures varies from 3:1 up to about 6:1 (Fig. 2). Most individuals are continuous from the base

to the top of the Inter B/C dolomite horizon (except where interrupted by coarse sand lenses), thus attaining a height of some 10 feet. Thin sinuous bands of dark greenish-gray argillaceous material fill the spaces between the closely packed stromatolites in these reefs. (Figs. 3, 4).

The original top configuration of these stromatolite clusters has been preserved in places by a cover of coarse sand, and it appears that differences in elevation of up to 18 inches existed between the tops of different algal

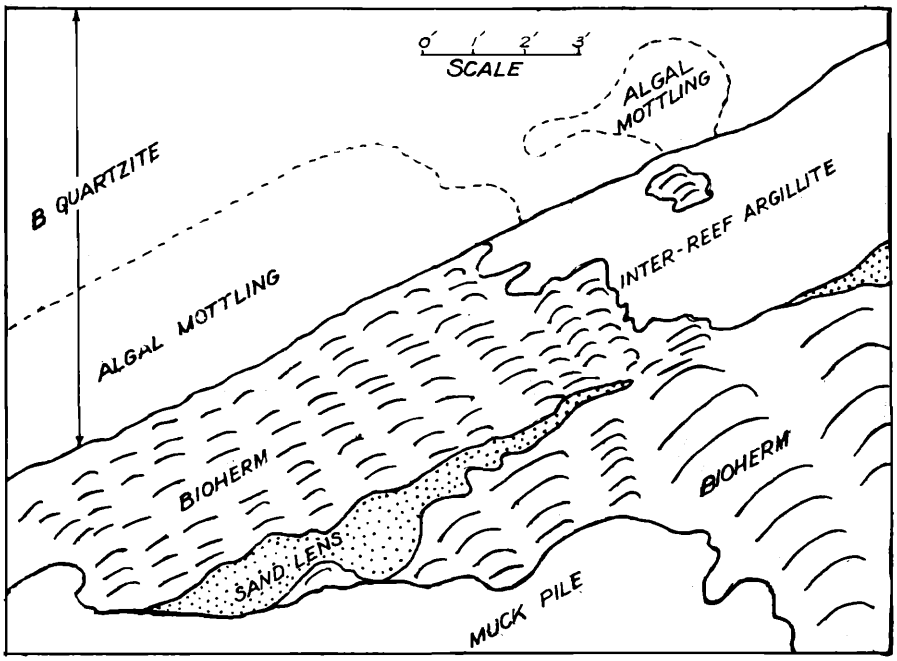


FIG. 3A. Explanation of Fig. 3.

colonies. At the base of the overlying "B" quartzites, slight erosional features are evident on a few stromatolites, but others were covered by the sand influx without any truncation of algal laminae. Dolomitic mottling of the "B" quartzite immediately above these reefs is discussed later.

The reef-building stromatolites have white to cream colored dolomite margins that contrast sharply with the dark-colored argillaceous material in the spaces between adjoining stromatolites. In detail, the margins of the stromatolites are irregular and ragged, and a very marked tendency exists for neighboring individuals to adjust to the irregularities in the outlines of one another. The cores of the stromatolites are appreciably more argillaceous and darker in color than the edges (Fig. 4). This argillaceous material occurs in conspicuous curved laminae (up to 1 mm thick), which alternate with carbonate-rich laminae. The convexities in these laminae point upwards. In the larger structures, the laminae are essentially flat in the central portions

and at the top of the stromatolites, while convexities project outwards (Figs. 3, 4).

Within the reefs, all gradations from collenia to cryptozoön structures can be seen in one column, and digitation of the columns is not uncommon (Fig. 4). These variations in shape and structure, therefore, appear to be adapta-

FIG. 4. Reef-building stromatolites. Note the digitation and suppression of some of the units. Argillaceous material in the core sections emphasizes the fine internal laminae.

tions to environmental conditions of growth, rather than to different biological species or genera.

The influx of the coarse sandy sediments inhibited or terminated growth on most colonies of algae. However, in a few instances, the algae managed to penetrate these sand wedges to "blossom" out anew in muddy overlying sediments.

In the channels between the algal ridges or reefs, scattered fairly large asymmetric "cabbage-like" stromatolites are found in the dark silty shales

(Fig. 5). In these instances, growing space apparently was not at a premium, as in the reefs, and hence they attained a greater lateral development, and, unlike the individuals in the reefs, they have a high percentage of argillaceous material in top laminae. Internally, these stromatolites are finely laminated, but the conspicuous light-colored dolomitic margins prevalent in the reef-building stromatolites are poorly developed or entirely absent. In plan, they show slight elongation parallel to reef elongation, which, in turn, is sub-parallel to the general trend of an underlying ridge in the sub-Katanga topography.

On the eastern limit of the Inter B/C dolomite, on a lower level (1900′ level), no large biohermal structures were developed. Instead, a flat algal mat, with low mound-like colonies, covered the sandy bottom. These roughly equidimensional mounds are seldom more than 10 inches high. The stromatolites in this area consist of dark gray dolomitic argillaceous siltstone with faint extremely fine, gently arched, internal laminations. The shape is that of a low mound or dome, i.e., the typical collenia. A thin lens of coarse

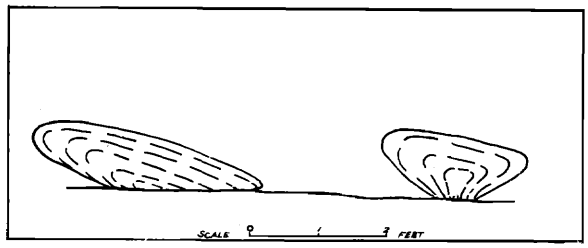


FIG. 5. Asymmetric stromatolites in the inter-reef argillites.

felspathic sand covered most of this algal mat with only a few of the taller mound-like colonies persisting through the sand as thin pencil-like columns, and then expanding to more normal dimensions in the overlying argillaceous sediments. This influx of sand preserved the uneven surface on top of much of the algal crusts. Flanking, and apparently shed by some of the collenias, are thin fans of algal debris that interdigitate with the sand.

Immediately above the sand lens, a few smaller, but essentially similar, stromatolites are found in the very argillaceous and silty dolomite. Upwards, this bed becomes less argillaceous and the stromatolites more diffuse, merging into contorted algal bedding typical of the Inter B/C dolomite.

Westward from the marginal zone of the Inter B/C dolomite, stromatolites are comparatively rare, and are mostly restricted to the more silty uppermost and lowermost 2 feet of this bed. These stromatolites are small in dimensions, diffuse and irregular in outline, and, because of the slight tonal contrast, rarely conspicuous. Algal crusts in these areas remained relatively simple as is shown by the algal bedding.

In the far western section of the mine, small collenia have been identified in the upper part of the Massive Shale (Table 2). Large stromatolites also occur in the highly carbonaceous Blue Shale at the top of the Intermediate

Dolomite (Table 1). None of these occurrences could be studied in detail as they are known only from drill-hole cores.

Algal Bedding.—This term, as used here, embraces all the small-scale disturbances or modifications of stratification, such as micro-folds, undulations, contortions, and dislocations, that are attributable to algal activity and are commonly found in calcareous or dolomitic beds. All those features of algal crusts normally classified as weedia type stromatolitic structures are incorporated here. There is evidence that algae do precipitate or entrap carbonates in such a fashion as to form a sediment, with perfectly parallel laminations, without any disturbances of the stratification (12).

Good examples of algal bedding, in the form of fine, gently arched or domal laminae, are to be found within the stromatolites already discussed. In many instances, the distinction between domal algal bedding and stromatolites, as defined in this text, is purely arbitrary as all gradations between these structures exist. Along the eastern margin of the Inter B/C dolomite, calcareous silty argillites commonly exhibit perfectly parallel laminations for tens of feet, abruptly terminating in a bulbous mass of dolomite similar to the margins of the stromatolites found in the reefs. Here, flat parallel-bedded algal crusts form the flat tops of gigantic lamellar stromatolites.

Minute domal structures, initiating on a base of perfectly undisturbed flat-lying laminae, are common in the Inter B/C dolomite. These domal laminae are commonly minutely crinkled. These miniatiure or incipient collenia are rarely over $1\frac{1}{2}$–2 inches high, and are more conspicuous in the true dolomite facies.

Other features, such as very thin laminations, commonly crinkled, bifurcated, broken, and dislodged, micro-folds, micro-breccias, and micro-unconformities, are ubiquitous in this dolomite, and are identical to those formed by both ancient and modern algal mats (1, 6, 7, 12).

Modifications of laminations identical to those found in the Inter B/C dolomite, are also known from the lowermost sections of the Intermediate and Upper Dolomites of the Upper Roan group (Table 1).

Algal Balls.—Near the base of the Intermediate Dolomite are thin beds of dark gray, finely laminated, slightly silty dolomite, containing scattered spheroidal masses of white dolomite. These white dolomite masses, up to 8 inches diameter, are commonly slightly talcose and generally roughly spheroidal to ellipsoidal in shape, although some highly irregular shapes are also represented.

Superimposed on the spheroidal or ellipsoidal outer surfaces of these white dolomite balls is a fine botryoidal or scalloped effect with convexities pointing outwards. Deep re-entrants between some of these convex surfaces are not uncommon. Internally they consist of structureless white dolomite (Fig. 6).

Clusters of these balls are common. In these clusters the dolomite masses dovetail neatly, and the areas of contact are marked by a thin dark suture, and the shape of individual masses within such a cluster may be highly irregular. The overall effect is that of an inverted bunch of large grapes. Less common are clusters that appear to be attached to the underlying algal dolomites.

Where small in size (less than $\frac{1}{4}$ inch), these white dolomite spheres normally occur in great profusion, and the rock resembles a small pebble conglomerate. However, the absence of coarse sand grains, and the general configuration of the white dolomite "pebbles," militate against a detrital origin for these dolomite spheres, except perhaps by very restricted transport.

Doming of bedding over these dolomite balls, whereas underlying stratification is undisturbed, indicates an origin contemporaneous with deposition.

It is suggested that these balls are biogenic in origin and probably represent algal balls of girvanella type. This suggestion is subject to revision as more exposures become available for study.

FIG. 6. Roughly ellipsoidal white dolomite "balls," probably of algal origin, set in a matrix of dark gray silty dolomite. Base of the Intermediate Dolomite. Length of knife 5 inches.

In the Blue Shale, and associated with stromatolites, are similar balls zoned with a thin outer rim of clear white dolomite around a light gray dolomite core, in which delicate filamentous wisps and stringers of carbon, presumably of organic origin, may be distinguished.

Diffuse white to cream colored dolomitic spheres occur also in the dolomitic argillite succession immediately above the "Mudseam" in the western basin.

Dolomitic Mottling in Quartzites.—"Dolomitic mottling" is the term used to designate the peculiar light colored slightly dolomitic blotches found in the quartzites of the Lower Roan group, and more especially the ore-bearing quartzites on the fringes of the "B" and "C" orebodies. Generally, these irregularly lenticular, light colored blotches are parallel or sub-parallel to the

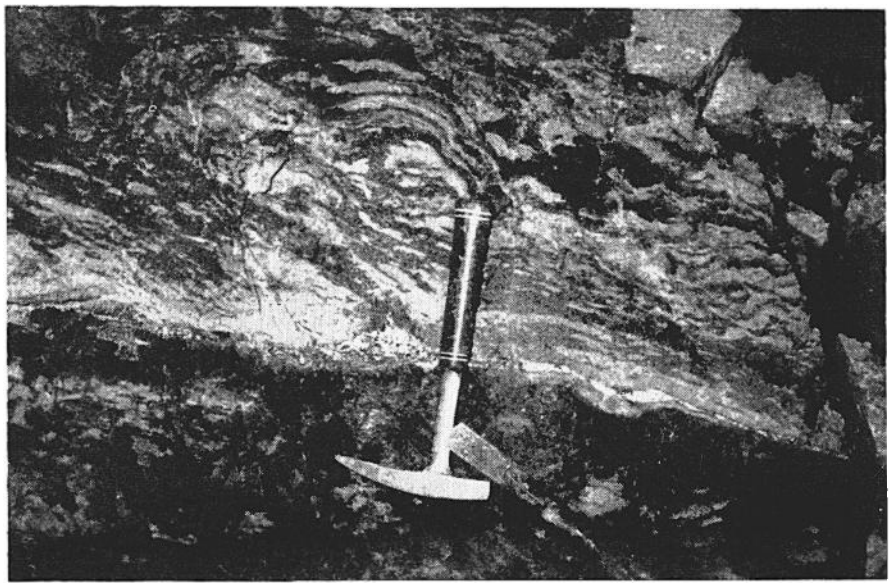


FIG. 7. Mottled quartzite on the western fringe of the "B" orebody, showing light colored dolomitic blotches set in a darker colored matrix.

stratification, though some show a low angle transgressive relationship. Bulbous patches are rare, although smooth mammillary outlines are developed on a few of the more irregularly shaped blotches (Fig. 7).

The carbonate content (dolomite) of these light-colored patches, though low, is appreciably greater than that of the surrounding darked-colored quartzite, whereas the copper sulfides are more abundant in the darker-colored portions of the rock. No difference in the size of the sand grains is evident between these differently colored quartzite patches.

There are all gradations of mottled quartzites between light-colored blotches enclosed in the darker-colored nondolomitic material, and the reverse. Some of the more intensely mottled quartzites resemble a chaotic diffuse breccia.

The stromatolite reef or bioherm featured in Figure 3 is truncated by the

TABLE 3

CARBONATE CONTENT OF THE MOTTLED QUARTZITES

	% CO_2	% Cu
'B' Quartzite		
(a) Light colored patches	5.9	0.07
(b) Dark colored patches	3.7	0.34
'C' Quartzite		
(a) Light colored patches	3.1	0.70
(b) Dark colored patches	0.9	1.4

overlying dark gray richly cupriferous "B" quartzite. On close examination, it becomes apparent that the mottling in the quartzite directly above the stromatolite reef is intense, but in areas not directly underlain by the reef, the mottling is very poorly developed and inconspicuous. In fact, the intensely mottled section above the reef rounds off the bioherm in a neat domal structure. It is suggested that the dolomite cement in these light-colored patches of quartzite is due to algal activity.

In this particular instance, the following tentative suggestions are offered regarding the biogenic origin of these dolomitic blotches. Burial of the algal Inter B/C dolomite by sandy sediments of the "B" quartzite indicates a drastic change in environment. To survive, the algae had to cope with a comparatively fast influx of sand, and, most important, time did not permit the formation of large defined stromatolitic structures.

With the influx of sand, the algal colonies and reefs were buried or much disturbed, and, to some extent, eroded, resulting in widespread "nucleation." The algae quickly spread into discontinuous algal mats, which actively precipitated carbonate in the settling detritus. Cleaner sand was trapped by the algae, but apparently the muddier sand collected in holes in the algal mat to form the darker-colored patches. It is apparent that the configuration and distribution of these dolomitic blotches, reminiscent of *Aulophycus* in the upper Cambrian Pilgrim formation of Wyoming (4), are dependent on the depositional environment, and that the action of the algae was primarily one of sediment binding and cementation.

POSTDEPOSITIONAL ALTERATION OF THE ALGAL STRUCTURES

Diagenesis, tectonic deformation, and metamorphism have caused postdepositional changes in the stromatolites. The combined effects of these processes on the general configuration of the algal structures are apparently insignificant as regards preservation of relative shapes, except for probable vertical compaction of the structures, indicated in extra contortion of the muddy infillings between columns. No tectonic deformation of any consequence has been recorded.

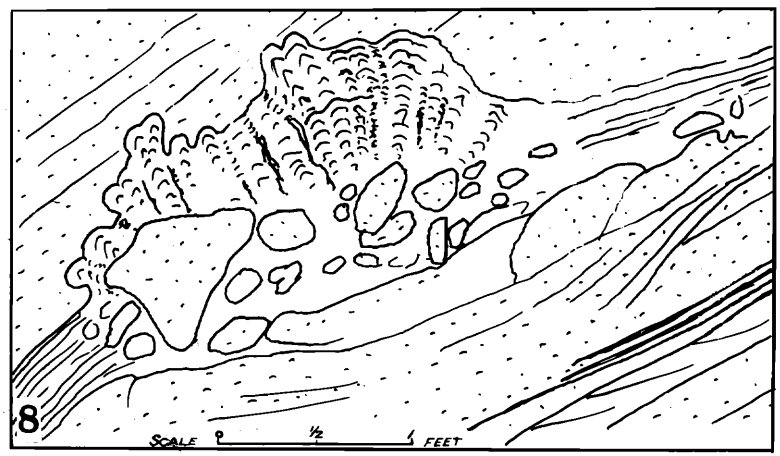
Partial to complete recrystallization of the carbonates constitutes the most important change. A few small dolomite saddle reefs in the core of one stromatolite are the only positive evidence of migration of material. Apart from this isolated instance, it appears that recrystallization of the carbonates took place in situ without appreciable migration of material. Argillaceous material, in the core sections of the biohermal stromatolites, is reconstituted as chlorite flakes with lesser biotite.

PALEOECOLOGY AND CONFIGURATION OF THE ALGAL STRUCTURES

Several authors (2, 6) have claimed that the shape of stromatolitic structures is environmentally dependent. This conclusion is supported by observations on the growth and distribution of the algal structures at Mufulira.

In the algal bioherms, where space was at a premium, the colonies grew in

slender, upright columns (Fig. 3). This lack of space is further emphasized in the way adjoining stromatolites mutually adjusted to irregularities in the outlines of one another. Suppression of individual stromatolites, or algal colonies, through crowding by their neighbors, is not uncommon (Fig. 4). In a few places, when more space became available, especially near the top of the bioherms or algal ridges, the columnar stromatolites expanded laterally to assume the more cabbage-like cryptozoön form. This tendency for lateral expansion, where the space problem was not critical, is well illustrated by the squat stromatolites found in the channels between the algal ridges (Fig. 5). However, there are areas in which no apparent lateral space problems existed,



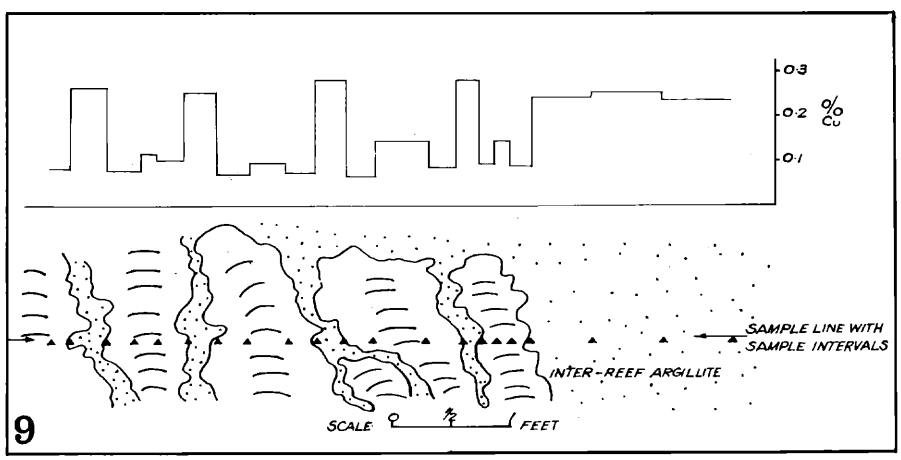


FIG. 8. Prolific algal growths on large fragments of an intra-formational breccia.

FIG. 9. Distribution of copper in an algal bioherm. Note the concentration of copper mineralization in the argillaceous facies.

and where the stromatolites grew in the form of simple low mounds (collenia).

The silt and clay content of the stromatolites appears to be related to environmental conditions. Stromatolites in the reefs are deficient in these constituents, compared with those found in the inter-reef channels and in other mraginal areas of the Inter B/C dolomite.

Where the Inter B/C dolomite rests on more argillaceous beds, as in the western basin, stromatolites are comparatively rare, more diffuse in outline, and seldom as spectacularly developed as along the eastern margin of this bed. In these areas the algae spread out in mats, and the resultant deposit is more evenly and thinly laminated, showing only micro-folds, minor undulations, and a few small-scale dislocations of bedding. The comparatively low silt and clay content of this dolomite suggests a depositional environment different from that found near the margins of the Inter B/C dolomite. Quiet, protected water conditions are suggested by the fineness and the low concentration of the clastic material in this dolomite, which probably represents a lagoonal facies.

Except for the few found in the inter-reef siltstones and argillites, most of the well developed stromatolites formed on a sandy or pebbly bottom. Intraformational breccias and channel deposits directly underlie most of the area, in which the reefs or algal ridges are found. Protuberances in the substratum invariably formed pedestals on which stromatolites grew (Fig. 8).

The above features suggest shallow-water conditions, where sunlight made possible the spectacular growth of the stromatolites. Along the eastern margin of the Inter B/C dolomite, shallow-water conditions are further indicated by the transgressive onlap of the bioherms onto the Inter B/C quartzites, where a promontory in the pre-Katanga landscape was still reflected as a topographic high during this phase of basin evolution.

RELATION OF COPPER MINERALIZATION TO ALGAL DEPOSITS

The distribution of the copper sulfides is of great economic importance, and a knowledge of the environmental factors favorable to the concentration of these sulfides is essential in the search for new orebodies. Controversy still rages as to the origin of the stratiform copper deposits of the Northern Rhodesian Copperbelt, but syngeneticists and epigeneticists alike agree on the sedimentary control responsible for the localization of the mineralization. Much of the detail of this sedimentary or stratigraphic control remains to be clarified, but as exploration and mining operations continue, the overall picture is emerging. In this connection, it is hoped the present study may prove to be of value.

At Mufulira, the copper mineralization of the middle or "B" orebody is antipathetic to the development of the Inter B/C dolomite, i.e., the western fringe of the "B" orebody is coincident with a marked increase in the carbonate content of the upper part of the Inter B/C succession (Fig. 1). As at Mufulira, antipathetic relationships between the copper and dolomite content of the host rocks are known from other Copperbelt areas, as in the Irwin Shaft gap at the Roan Antelope, in a small area in the Chambishi orebody, in the

Kitwe gap between the Mindola and Nkana orebodies, and in the Pitanda Special Grant. Whether all these unmineralized dolomitic rocks are algal in origin is not known at present. However, in each case the geological setting is the same, that is, carbonate-rich rocks occur over, or in immediate juxtaposition to, topographic high areas in the pre-Katanga surface. At Mufulira, this dolomite is definitely a shallow-water biogenic deposit.

TABLE 4

CHEMICAL COMPOSITION OF STROMATOLITES AND ASSOCIATED SEDIMENTARY ROCKS

	A	B	C	D	E	F	G
Cu	0.25	0.06	0.08	0.15	0.26	0.21	0.10
SiO_2	58.9	78.8	20.9	20.8	52.0	60.4	25.10
Al_2O_3	15.7	5.3	9.1	11.4	13.6	15.0	6.4
MgO	6.4	1.7	13.2	10.1	10.0	5.1	14.9
CaO	6.2	6.4	22.2	21.5	7.9	5.8	20.2
MnO	0.18	0.13	0.21	0.81	0.18	0.18	0.50
FeO	2.9	1.2	2.4	2.5	3.2	3.7	2.2
K_2O	2.89	0.63	1.40	1.35	4.04	2.74	1.73
Na_2O	0.30	0.15	0.20	0.19	0.22	0.19	0.32
P_2O_5	0.15	0.08	0.17	0.10	0.20	0.20	0.08
CO_2	6.4	5.8	33.1	32.7	9.8	5.7	29.6
S	0.08	0.2	0.08	0.09	0.39	0.4	0.08
	100.42	100.45	103.04	101.69	101.79	99.62	101.21

A – Inter-reef argillite.

B – Coarse felspathic quartzite lens associated with algal reefs.

C – Dolomitic margin of biohermal stromatolite.

D – Argillaceous core of biohermal stromatolite.

E – Argillaceous fillings between biohermal stromatolites.

F – Dark argillaceous collenia.

G – Silty Inter B/C dolomite with algal bedding.

The dolomitic mottling in the quartzites previously described is particularly well developed on the eastern fringes of the "B" and "C" orebodies and less well represented on the western fringe of the "B" orebody at Mufulira. In every case, as the mottling and carbonate content increase towards the economic fringe of the orebodies, so the copper content decreases. An organic origin of these carbonate blotches is suggested and would indicate a shallow-water depositional environment.

This antipathetic relation of the copper mineralization towards sedimentary facies deposited under shallow, and probably oxygenated, water conditions, tends to support a syngenetic rather than an epigenetic origin (5).

Interesting is the distribution of the copper sulfide, chalcopyrite, in relation to the stromatolites in the bioherms. The stromatolite columns are separated by thin, dark-colored, sinuous bands of silty and argillaceous material comparatively enriched in copper sulfides, about 0.25% Cu. The clean dolomite margins of the stromatolites adjacent to these argillaceous bands are very low in copper, average 0.09%, but the central, slightly more argillaceous "core" sections have an intermediate copper content, average 0.12%. The dark

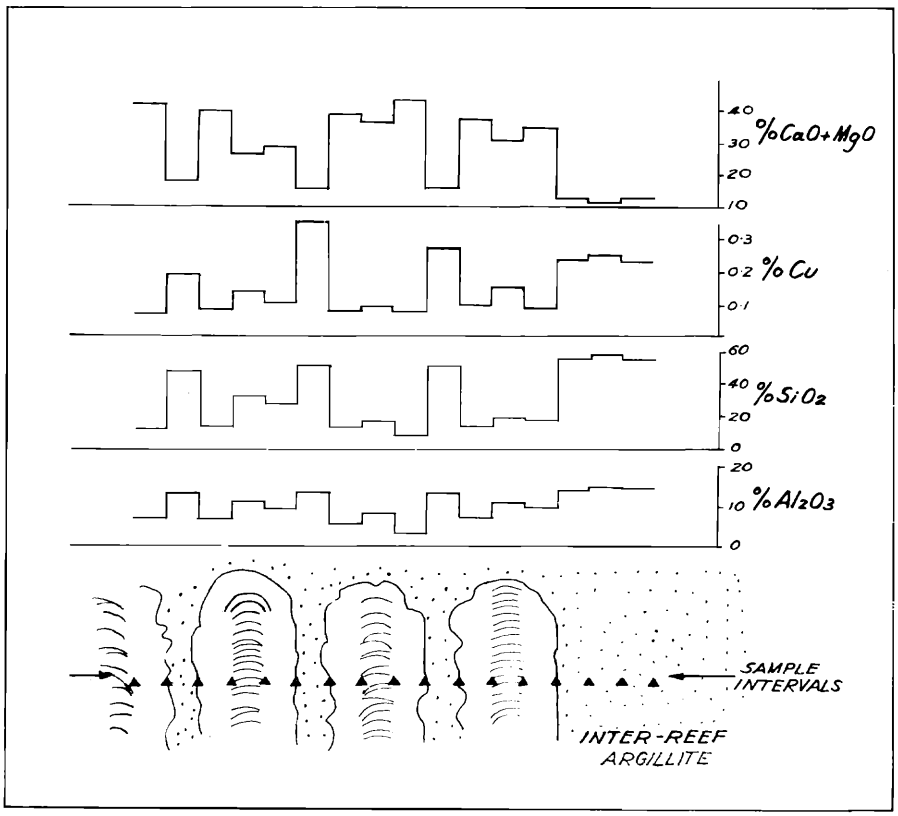


FIG. 10. Idealized section showing the distribution of (CaO + MgO), Cu, SiO_2 and Al_2O_3 in biohermal stromatolites and associated argillites.

inter-reef silty argillites are identical in copper content and overall composition to the material filling the spaces between the stromatolites in the reefs (Fig. 9, Table 4).

From the analyses, it is evident that an antipathetic relationship exists between copper and combined lime and magnesia, but the variations in the alumina and silica content is accompanied by sympathetic variations in copper content (Fig. 10). This strongly suggests that the copper and the clastic silt and clay material were introduced contemporaneously. In the finely

laminated core sections of the stromatolites, where argillaceous and dolomitic laminae alternate, the chalcopyrite is found in and along the thin argillaceous laminae. This introduction of copper into the basin with the sediments raises some problems to which the answers are not clear. Copper-bearing solutions, at fairly low concentrations, are toxic to most forms of life, and it has to be assumed that the copper was in the form of non-ionic colloidal sulfide gels or even, perhaps, as undissociated metallo-organic complexes. A better knowledge of the metabolism of the algae and their resistance to toxins is essential to clear up these questions.

CONCLUSIONS

Until the recent discovery of stromatolites at Mufulira, the only factual evidence of primitive life during the Katanga cycle of sedimentation in Northern Rhodesia were the sulfur isotopic studies of Jensen and Dechow (9), who also reported that Love recognized "framboidal pyrite" (pyritized bacterial organisms) in Copperbelt sulfides. Recognition of algal deposits further confirms suspicions of long standing that biogenic processes were operative during this period, and their widespread distribution suggests that these processes were of prime geological importance.

At Mufulira, as in other parts of the world, the configuration of the stromatolites can be related to environmental conditions of growth. However, at this early stage, a number of paleoecological aspects remain to be clarified.

Although it is not claimed that the distribution of the copper mineralization, in relation to the algal structures and deposits, proves syngenetic mineralization, it appears to favor that possibility rather than epigenesis. In the case of the biohermal deposits, it is difficult to visualize hydrothermal copper-bearing solutions permeating the algal reef complex only to precipitate the copper selectively in the more argillaceous and silty facies, leaving the dolomites unmineralized. In fact, this is the reverse of what one would expect, as the carbonate-rich stromatolites seem to be chemically a more favorable environment for metasomatic processes than the associated more argillaceous rocks.

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