THE REDSTONE BEDDED COPPER DEPOSIT AND A DISCUSSION ON THE ORIGIN OF RED BED COPPER DEPOSITS

by

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ABSTRACT

The thesis is divided into two parts. In Chapter I a new bedded copper deposit at Redstone River, N.W.T., is described for the first time. Emphasis is placed on those aspects of the geology, mineralogy and mineralography which may have significance in considering the origin of the ore. It is concluded that the ores were emplaced at low temperature subsequent to deposition of the host rock. Some redistribution and possibly addition of copper occurred at a later date as a result of tectonic disturbance.

In Chapter II the problem of the origin of red bed copper deposits is discussed with the Redstone deposit considered as a typical example. An attempt is made to review the major aspects of the problem, including what the writer considers to be the most important ideas expressed in the literature. The writer discards the terms 'epigenetic' and 'syngenetic' as applied to such deposits and proposes new lines of research based on the difference in electric potential between host rocks and adjacent red beds.

ACKNOWLEDGEMENTS

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TABLE OF CONTENTS

Page

LIST OF ILLUSTRATIONS

CHAPTER I

INTRODUCTION

Foreword

The upper Redstone River drainage basin, Northwest Territories, was the scene of a discovery in 1962 of extensive stratiform copper deposits near the top of a thick red bed sequence. This discovery was made by prospectors employed by the Nahanni Sixty Syndicate, an exploration group sponsored by several mining companies. In 1963 Redstone Mines Limited was formed to explore the deposits and continue prospecting in the area.

Location and Access

Access to the deposits is from Little Dal Lake, at latitude 62° 42' north and longitude 126° 41' west (Glacier Lake map sheet, National Topographic Survey Index No. 95L). Little Dal Lake is about 1¼ miles west of a steep east-facing slope on which outcrops of cupriferous beds were first discovered. Aircraft can land on the lake. Watson Lake, Yukon Territory is the nearest transportation point approximately 185 air miles to the southwest (Fig. 1). A private road from Watson Lake to the presently dormant mining community of Tungsten is 70 air miles southwest of the Redstone property.

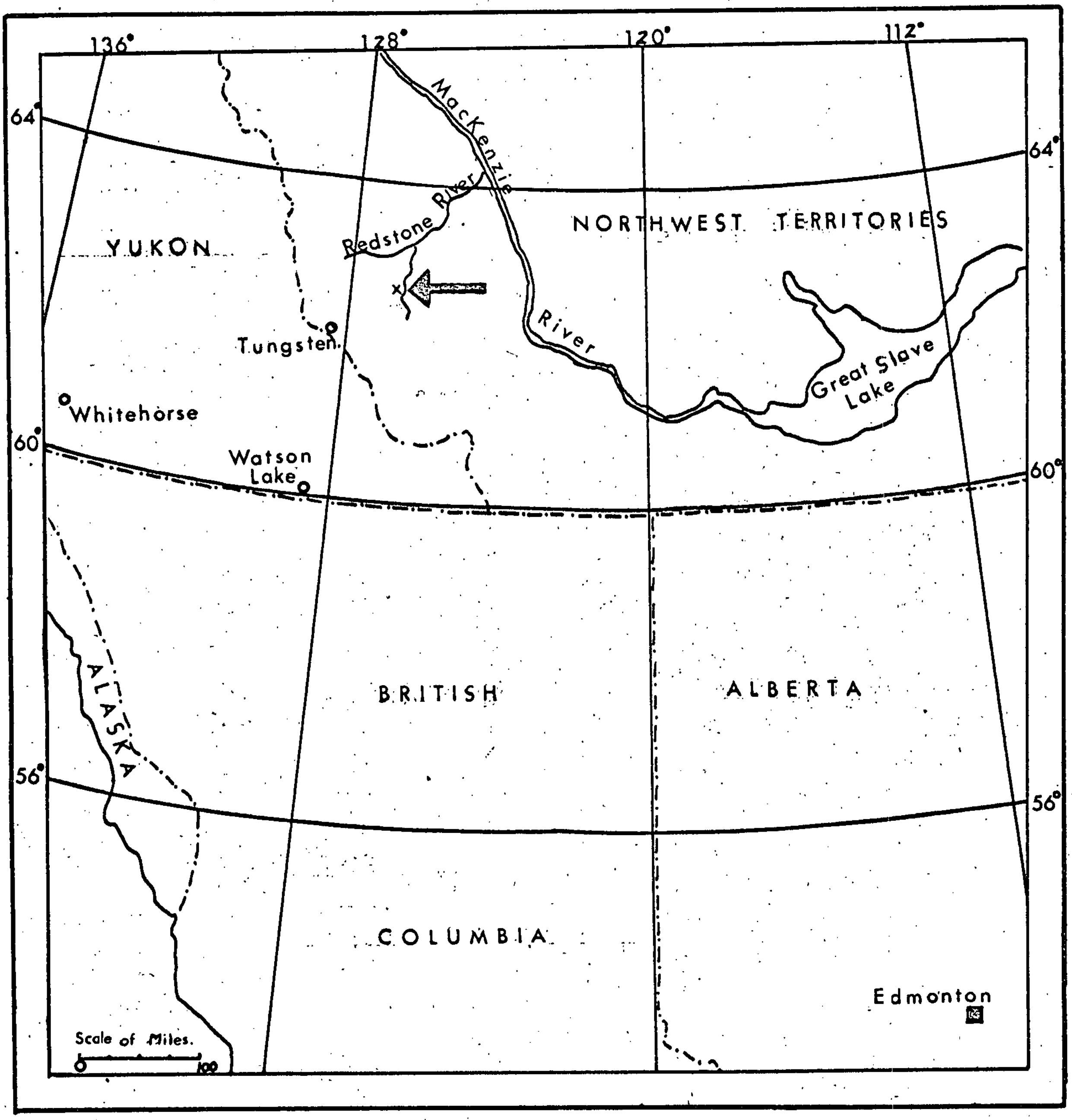

Fig. 1: Location map. Arrow shows location of bedded copper deposits.

Previous Work

Geologists of the Nahanni Sixty Syndicate did reconnaissance geological mapping in the area in conjunction with prospecting activities during the 1961 and 1962 field seasons. Following discovery of the main bedded copper deposits in 1962, some preliminary mapping and sampling of the deposits was done before the end of that season. Also in 1962 another bedded copper occurrence, apparently an extension of the main deposits, was discovered approximately ten miles north of the northern limit of the main showings. This newer occurrence, designated the "Kvale Extension", received only brief attention in 1962.

No published geological maps of the area are yet available though one is in preparation by the Geological Survey of Canada.

Field Work

The writer spent the period mid-June to mid-September of 1963 as geologist at the principal copper showings. Duties connected with diamond-drilling and trenching programs reduced the time available for study of the deposits, however, the writer was able to study most of the accessible exposures of the main deposit and the local geology. The writer mapped the exposures at 500 feet to one inch and selected areas at 50 feet to one inch. In addition, the writer logged the core from fourteen of seventeen diamond-drill holes and examined numerous trenches.

As the 'Kvale Extension' was not visited by the writer information on this prospect was drawn from reports by company geologists. Information on the geology outside the small area seen by the writer is drawn entirely from reports and maps by other company geologists.

TOPOGRAPHIC SETTING

Regional

The area is in the heart of the MacKenzie Mountains. Local relief is between 3000 and 4000 feet, with summit elevations ranging between 6500 and 7500 feet. The main valleys are broad, fairly flat and floored with alluvium and till. During the Pleistocene valley glaciers occupied these main valleys to about the 5500 foot contour, causing oversteepening of valley walls and overdeepening of valley bottoms. As the glaciers retreated tributaries built large alluvial fans out into the main valleys. The main streams are degrading but long stretches still show braided stream patterns.

The mountains are moderately rugged with steep but seldom vertical slopes (Fig. 2 and 3). Tree-line is at approximately 4200 feet elevation but where slopes permit the mountains are vegetated to the summit with shrubs and grasses.

Figure 2: View to east from Jan Marie Mountain

Figure 3: View to north from Jan Marie Mountain
Kvale Extension indicated by arrow

Jan Marie Mountain and Vicinity

Bedded copper deposits which form the chief object of this study are exposed on two mountains ten miles apart. As the writer did not visit the northern-most exposures, the 'Kvale Extension', this discussion will be mainly confined to "Jan Marie Mountain" (unofficial name).

Jan Marie Mountain is a hog-back ridge about four miles long separated into two parts by a deep saddle towards its southern end. It is bounded on the east by the valley of "Munro River" (unofficial name) which is the largest tributary of South Redstone River. Elevation of the valley floor is about 3200 feet. On the west the ridge is bounded by another broad valley containing Little Dal Lake at elevation 4200 feet. The lake drains south, opposite to Munro River and the general drainage pattern of the area. This valley terminates at the north end in a low ridge, trending at right angles to the valley, beyond which there is a north-facing scarp, perhaps a fault line scarp.

The crest of the hog-back ridge on Jan Marie Mountain reaches 6700 feet elevation. The ridge slopes down to Little Dal Lake on the west with an average slope of 23°; and to Munro River on the east with an average slope of 30°. South of the saddle the ridge forms a nearly conical peak rising to 5700 feet elevation.

The west face of the mountain is nearly devoid of outcrop and vegetated to the summit (Fig. 4). By contrast the east face is almost continuous outcrop or talus and remarkable for its lack of soil and

Figure 4: West face of Jan Marie Mountain

Figure 5: South-east face of Jan Marie Mountain

vegetation right down to the tree line (Fig. 5).

REGIONAL GEOLOGY

The MacKenzie Mountains are part of the eastern-most tectonic belt of the Canadian Cordillera and are bordered on the east by the Interior Plains. The rocks comprising the mountains are relatively unmetamorphosed and contain a high proportion of competent clastic and carbonate sediments. Tectonism is expressed in these rocks by reverse faulting, thrust faulting and concentric folding. Broad flat-lying or gently warped belts of sediment, which may be ten or fifteen miles wide, are separated by much narrower zones of more-or-less intense faulting where dips are steep or even vertical. Trend of the structures is north to north-west. It is within such a fault zone that the stratiform copper deposits are exposed. Known as the "Redstone Fault Zone" (unofficial name), this fault zone has been traced by company and government geologists for nearly 200 miles.

The sedimentary rocks of the MacKenzie Mountains have yielded fossils of Cambrian, Ordovician, Silurian, Devonian and Carboniferous age. In the Redstone Fault Zone some unfossiliferous rocks believed to be considerably older than the Middle Cambrian are exposed. Cretaceous rocks are infolded along the eastern margin of the mountain belt.

Granitic rocks have not been found east of the Redstone Fault Zone nor within twenty-five miles to the west. The writer found a glacial erratic of biotite granite in the valley of Munro River and other granite erratics at Dal Lake twenty-five miles north. The source of these is unknown. Basic intrusive rocks have been discovered in the Redstone Fault Zone. Such rocks, variously described as gabbrodiorite, gabbro, diabase, and basalt occur on "Mount Cleo" (unofficial name) about eight miles south-south-east of the nearest exposure of the stratiform copper deposits. This area includes a small plug of gabbro-diorite (?) and several tabular bodies mapped as basalt sills and dykes. A gabbro plug is exposed one mile south of the 'Kvale Extension' from which a diabase sill extends three miles south. Small amounts of copper mineralization occur in fractures and contact zones at the gabbro-diorite plug and minute specks of chalcopyrite occur in the gabbro plug to the north. There is no evidence of significant concentration of cupriferous minerals directly attributable to these intrusions. A thick basic dyke or sill outcrops seven miles south-east of Mount Cleo and has been traced south for a further eight miles parallel to the fault zone.

Major faults dip either east or west at moderate angles so that fault traces are normally sinuous across this mountainous terrain. Reverse faults appear to be the dominant type although normal faults of small displacement occur frequently. Undoubtedly much adjustment has taken place by means of bedding slip, and thrust faulting along bedding planes but this type of movement is difficult to evaluate, even when recognized. Along the east margin of the mountain belt Devonian rocks have been thrust easterly over Cretaceous rocks of the Interior Plains. Westerly-directed reverse fault movement is known on Jan Marie

Mountain.

The Redstone Fault Zone

Mapping by Redstone geologists and others has been practically confined to the Redstone Fault Zone. The general features of the stratigraphy are now fairly well known and several of the major faults have been located. The numerous faults are rarely observable in outcrop but some excellent stratigraphic sections can be seen on the steeper slopes. The task of unravelling the complex history of the zone has been dependent largely on stratigraphic work. The major rock units recognized in the area are shown in Figure 6 and described in the following section. Formation names are those used by company geologists and some at least of these units may correlate with previously-named units in this district.

Stratigraphy and Correlation

MacKenzie Creek Formation

Mapping to date indicates that this is the oldest formation exposed in the area. The rocks consist mainly of vari-coloured quartzites or quartz-sandstones with some dolomite and shale. The base of the formation is not exposed and thickness is unknown. These rocks are unfossiliferous and are tentatively considered Late Pre-Cambrian.

<table>
<tr><th>AGE</th><th colspan="3">FORMATION</th></tr>
<tr><td>UPPER DEVONIAN</td><td colspan="3">UNNAMED SHALE UNIT</td></tr>
<tr><td rowspan="2">ORDOVICIAN
TO
DEVONIAN</td><td colspan="3">DAL FORMATION</td></tr>
<tr><td colspan="3">THUNDERCLOUD FORMATION</td></tr>
<tr><td>LOWER
TO
MIDDLE
CAMBRIAN?</td><td colspan="2">RAPITAN FORMATION</td><td rowspan="4">BASIC
DYKES
AND
PLUGS</td></tr>
<tr><td rowspan="3">PRE-CAMBRIAN?</td><td rowspan="2">REDSTONE FORMATION</td><td>CLEO FORMATION</td></tr>
<tr><td>JAN MARIE FORMATION</td></tr>
<tr><td colspan="2">MACKENZIE CREEK FORMATION</td></tr>
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Figure 6: Formations exposed in the Redstone Fault Zone.

Redstone Formation

Conformably overlying the MacKenzie Creek Formation is a very thick succession in which carbonate rocks predominate. The carbonates are mainly dolomite with lesser amounts of limestone. Algal structures have been observed frequently in the dolomites by Redstone geologists. Argillaceous and arenaceous interbeds are present and are more numerous towards the top of the formation. Age of these rocks is probably Late Pre-Cambrian.

A problem of correlation exists with respect to the Redstone Formation and a 3000 feet thick section on Jan Marie Mountain. Both company and government geologists[1] have noted an angular unconformity between the Redstone Formation and the overlying "Rapitan Formation". The base of the Rapitan Formation is fairly well exposed on Jan Marie Mountain (Fig. 7), but here the relations with underlying rocks are apparently conformable. Below the Rapitan here, at 'Kvale Extension', and one other point on the west side of Little Dal Lake, the underlying rock is a black limestone and shale sequence known as the "Cleo Formation". Below the Cleo Formation is a thick red siltstone sequence containing the cupriferous beds. The red beds and the Cleo Formation are not found at any other locality where the base of the Rapitan is exposed except for those mentioned above.

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1. H. Gabrielse, Geological Survey of Canada, Personal Communication.

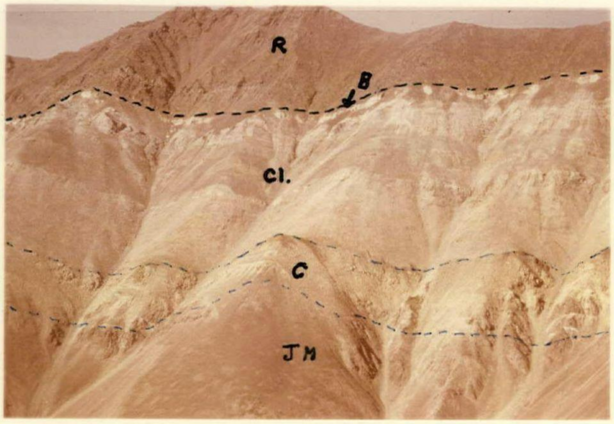

Figure 7: East face of Jan Marie Mountain

JM - Red beds; C - Cupriferous Zone;
CL - Cleo Formation; B - breccia;
R - Rapitan Formation

The work of Symonds[1] at the Kvale Extension provides the only clue so far as to the correct correlation of the Cleo and Jan Marie Formations. While mapping the Kvale Extension, Symonds noted a low-angle angular unconformity between the Rapitan and the Cleo Formation. This unconformity may be equivalent in age to the unconformity at the top of the Redstone Formation. Either the red beds and Cleo Formation were laid down in a restricted area of accumulation during part of the erosion interval below the Rapitan, or they represent uneroded remnants of Upper Redstone Formation rocks that once covered a wider area. The first possibility is preferred because of the apparent absence of the unconformity on Jan Marie Mountain. Some outcrops of conglomeratic red beds west of Little Dal Lake also support the hypothesis of a restricted basin of deposition. Thus the section below the Rapitan on Jan Marie Mountain is considered either a facies of the upper Redstone Formation, or younger than the Redstone Formation.

Jan Marie Formation

The Jan Marie Formation and the Cleo Formation are described later in discussing the geology of Jan Marie Mountain.

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1. Symonds, D.T.A. Unpublished report.

Rapitan Formation

Rocks of the Rapitan Formation are predominantly clastic. A basal conglomerate is generally present which may be several hundred feet thick. This purple or green conglomerate contains pebbles of a variety of sedimentary rocks similar to those of the underlying Redstone and MacKenzie Formations.

Above the basal conglomerate is a section more than 1000 feet thick of thin-bedded, mainly purple coloured, siltstones, mudstones, and locally some jaspilite. Volcanic cobbles occur in conglomerate interbeds and at least some of the siltstones contain tuffaceous material.

The purple siltstones are overlain by a heterogeneous sequence of green or light-coloured siltstones, greywackes, quartzites, sandstones and shales with minor amounts of dolomite and limestone.

The age of the Rapitan Formation is believed to be early Cambrian or older in age. Fossils of Middle Cambrian age have been found outside the Redstone Fault Zone at a horizon believed to be 9000 feet stratigraphically higher than the base of the Rapitan Formation.[1]

Thundercloud Formation

The Thundercloud Formation overlies the Rapitan Formation

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1. H. Gabrielse, Geological Survey of Canada, oral communication.

disconformably or with slight angular unconformity. The unit is highly fossiliferous and contains marine fossils of Ordovician to Devonian age. The principal rock is dolomite.

Dal Formation

The Dal Formation is a fossiliferous limestone sequence conformably overlying the Thundercloud Formation.

Unnamed Shale Unit

This unit consists mainly of black, dark grey or brown, fissile shales with some siltstone. Fossils are plentiful and a collection made by the writer contained Cyrtiopsis, a brachiopod of Late Upper Devonian age, according to D.J. McLaren of the Geological Survey of Canada. The bottom of this unit has not been observed. At the base of Jan Marie Mountain the unit is in fault contact with the red beds.

Structure

In the section containing the stratiform copper deposits the Redstone Fault Zone is two to five miles wide. It is apparently bounded by two major reverse faults, the "Redstone Fault" on the east and the "West Range Fault" on the west. The Redstone Fault has brought some of the oldest rocks of the area into contact with the youngest known unit.

Dip of the fault is uncertain but a few measurements suggest a westerly dip of about 40°. The West Range Fault dips eastward, also at a moderate dip. Between the two bounding faults are many lesser faults, mostly east-dipping reverse faults trending within 30° on either side of north.

Fold structures within the zone are not well known on account of displacement and distortion due to faulting. On Jan Marie Mountain the beds dip moderately to the west. At Kvale Extension the beds dip moderately to steeply east. Nearly vertical dips occur in the vicinity of some faults. Even the youngest rocks show steep dips within the Fault Zone whereas folds in adjacent areas are comparatively gentle flexures. The steeper dips within the fault zone may be caused partly by tilting of fault blocks, and partly by drag.

GEOLOGY OF JAN MARIE MOUNTAIN

On the steep east face of Jan Marie Mountain, approximately 4000 feet of section is exposed intermittently. This section includes the red beds of the Jan Marie Formation which give the mountain a striking red color. (Fig. 5); the entire 600 feet of the Cleo Formation; and part of the lower Rapitan Formation. The western face of the mountain is a dip slope of dark purple Rapitan shales. On gentle slopes outcrop is scarce or absent. Much of the east face is inaccessible owing to precipitous slopes.

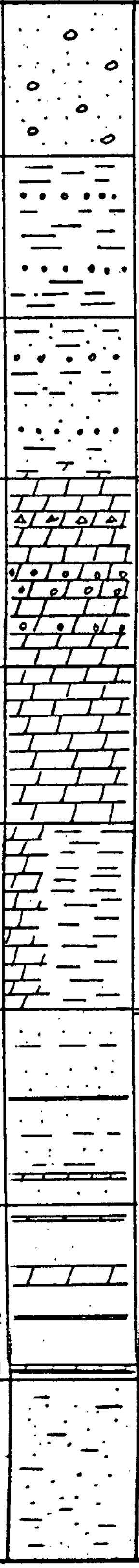
STRATIGRAPHY

A stratigraphic section is given in Figure 8, representing the stratigraphy as observed 1½ miles north of Pipit Saddle. Lateral variation is prominent within the Cupriferous Zone and in the Cleo Formation.

Jan Marie Formation

The apparent exposed thickness is 2300 feet, but as repetition by faulting is present the true thickness would be less. Siltstones with thin mudstone partings compose almost the entire section. The upper 350 feet of this formation contains the calcareous copper-bearing horizons. The siltstones are purple, maroon or brown in colour, rarely exceeding .01 mm. in average grain size. Small thin lenses of brown sandstone occur infrequently. The mudstone partings are purple or maroon in colour and seldom more than a few millimeters thick. Mudcracks are almost invariably present. The siltstones are cross-bedded, and fine-grained intra-formational conglomerates are frequently observed. These conglomerates consist of small, angular flakes of mudstone in a siltstone matrix, probably accumulated as a result of the redistribution of sun-dried mud flakes by flood waters. Throughout most of the section the mudstone partings are sufficiently close together to impart a banded appearance to an outcrop.

The upper part of the Jan Marie Formation contains the



Thickness	Unit	Fm.	Description
1000'+		RAPITAN FORMATION	**Plateau Greywacke** Green, conglomeratic greywacke, occasionally purple in colour. Some siltstone and shale. Cupriferous.
1500'+		RAPITAN FORMATION	**'Iron Formation'** Thin-bedded purple to red shale, siltstone and conglomerate. Local development of jaspilite.
60'		RAPITAN FORMATION	**Green Basal Member** Green or grey siltstone, shale, grit, fine conglomerate, calcareous shale. Pyritiferous. Cupriferous.
135'		CLEO FORMATION	**Lensing Limestones** Light or dark grey calcirudite and limestone breccia. Massive limestone. Some dolomite. Fragmental rocks contain cobbles of chert, black or grey limestone.
130'		CLEO FORMATION	**Black Limestones** Massive, thick or thin-bedded black or dark grey limestone. Finely crystalline. Some beds strongly fetid.
200'		CLEO FORMATION	**Black Shales** Recessive black calcareous shale; argillaceous or silty limestone. Grades laterally to silty grey carbon-flecked limestone. Sandy at base.
75'	6, 5	JAN MARIE FORMATION	**Cupriferous Zone** Upper Unit: resistant grey to greenish grey, limey, dolomitic and calcareous silt-stone. Pyritiferous. Mudstone partings with mudcracks. One to two thin cupriferous beds.
120'	4, 3, 2, 1	JAN MARIE FORMATION	Ore Zone: mainly red, purple or brown siltstone with thin mudstone partings. Interbeds of grey, laminated, silty cupriferous limestone. Green limey siltstone and dolomite.
2000'+		JAN MARIE FORMATION	**Redbeds** Purple, maroon or red siltstones with thin mudstone partings. Thin-bedded. Mud-cracks and cross-bedding very common.

Figure 8: Stratigraphic section on Jan Marie Mountain.

stratiform copper deposits and will be referred to henceforth as the "Cupriferous Zone." Its stratigraphy will be described in a separate section.

Cleo Formation

This formation has a thickness measured at one point of 600 feet. It is predominantly limestone with sandy beds at the top and bottom. At the south end of the mountain the upper members are dolomite.

The base of the Cleo Formation rests conformably on the uppermost calcareous bed of the Cupriferous Zone. South of Pipit Saddle, this horizon is overlain by a 30 to 50 foot bed of very pure grey quartz-sandstone. This bed contains normally minor amounts but sometimes several per-cent of small, disseminated cubic pyrite crystals. North of Pipit Saddle the quartz-sandstone is absent. Towards the south the sandstone becomes slightly conglomeratic and some outcrops south of the mountain are distinctly conglomeratic.

Black Shale Member

Above the sandstone, or above the Cupriferous Zone where the sandstone is absent, there is a section about 200 feet thick of calcareous black shale and silty grey or black limestone. The rock is thin-bedded to laminated and contains abundant finely-divided pyrite, visible only with a hand lens. Locally the black shale component gives way to a silty grey limestone characterized by abundant flecks of carbonaceous material on its bedding planes. The carbonaceous flecks resemble organic remains and the writer spent several hours searching these rocks for fossils. Nothing identifiable was found although certain forms occur more frequently than one would expect if the structures were inorganic. A fairly good impression showing arthropod-like segmentation and apparent bilateral symmentry could not be related to any known form.

Black Limestone Member

Overlying the shaly section is about 300 feet of dark grey to black, thick-bedded to massive limestone. These fine-grained limestones often yield a strong odour of H_2S which is noticeable even when walking on talus of these rocks. A sample of this rock dissolved in HCl yielded a black greasy residue which was insoluble in CCl_4 and did not fluoresce. Near the top of this unit some beds show abundant small grains of chert, occasionally rounded like oolites.

Lensing Limestone Member

Apparently conformable on the fetid limestones is a section of dark grey to light grey limestones and calcirudites. Dense, fine grained limestones are inter-bedded with conglomeratic limestones to about 150 feet total thickness. Cobbles are mainly black limestone and chert. The upper 30 feet contain sandstone and shale bands which appear to pass upward conformably into basal siltstones and shales of the Rapitan Formation. Approximately 50 feet below the Rapitan an orange to white weathering bed of limestone breccia which can be traced for about one mile, is everywhere conformable with the Cleo Formation

(Fig. 7). However at two widely separate points this breccia contains large blocks clearly recognizable as belonging to overlying Cleo Formation or Rapitan beds. The breccia is approximately 30 feet thick and may represent a strong fault, dipping westward at a slightly flatter angle than the bedding. There is no other indication that the Rapitan might not be conformable on the Cleo Formation.

Rapitan Formation

Green Basal Member

The basal beds of the Rapitan Formation on Jan Marie Mountain are a heterogeneous sequence of siltstone, shale, grit and fine conglomerate with, locally, calcareous shales or siltstones. The dominant color is green. though towards the north end of the mountain the colour is grey. Total thickness of this green or grey unit is only about 60 feet. Traces of chalcopyrite with pyrite are characteristic features of the green beds.

Of interest in this unit is the presence of microscopic ellipsoidal or club-shaped bodies resembling the tests of primitive foraminifera. These bodies have smooth surfaces, are very regular in shape, and show a yellow metallic lustre as if composed of pyrite. The solid appearance is deceptive as they readily collapse when touched with a needle and appear to have very thin shells. A few, separated by crushing and panning the rock, were dissolved in nitric acid on a slide. Examination under a microscope showed that the metallic material dissolved completely leaving a transparent, apparently structureless mass that retained the shape of the original ellipsoidal or club-shaped body. Such structures may be compared with the pyritic micro-organisms described by Love[1] from the Kupferschiefer and other localities.

'Iron Formation'

The green beds grade upwards through a transitional zone a few feet thick to a very thick section of purple shale. The shales are fissile to massive, usually silty, and uniformly thin-bedded. The very smooth bedding planes have no mud-cracks or rainprints. Peculiar symmetrical markings occur on the bedding planes of some of the shales. These occur in great abundance at some levels and are apparently organic in origin. The pattern of the markings suggests affinities with graptolites but thecae are lacking.

Thin conglomerate beds, commonly containing cobbles that span the entire thickness of the bed, usually less than one foot, are interbedded with the shales. The cobbles are well rounded to sub-angular and one showed numerous striations on the underside after removal from its position in the bed. The writer considers that these conglomerates represent mudflows, either of the sub-aqueous turbidity current type, or a sub-aerial type that has come to rest in standing water.

Higher up in the shale section there is a colour change to bright brick-red and in these beds incipient development of hematite along bedding planes is observed. Locally the process has proceeded

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1. Love, L.G. Econ. Geol. v. 57, No. 3. 1962. p. 350.

far enough to yield impure hematitic iron ore with orbicular or banded jasper. Rainprints were observed in the red shale but no graptolite-like markings. Cobbles in the conglomerate interbeds are mainly limestone, dolomite and quartzite, with cobbles of green, fine-grained volcanic rocks appearing high in the shale section.

"Plateau Greywackes"

A covered interval obscures the relationship between the red shales and the "Plateau Greywackes" though from evidence to the north it appears that these predominantly green rocks are conformably overlying the shales. These are not typical greywackes as many beds contain scattered well-rounded cobbles up to eight inches in diameter. The cobbles are predominantly volcanic although cobbles of limestone, dolomite and quartzite also are plentiful. Two types of volcanic cobble were recognized. The dominant type is a dark green fine-grained massive rock which normally contains a few grains of chalcopyrite and occasionally exceptional concentrations of this sulfide. The chalcopyrite occurs usually as small interstitial grains averaging about 0.4 mm. in size. One such cobble assayed 0.3% copper. One green cobble was amygdaloidal and showed a few large grains (1/8") of chalcopyrite adjacent to an amygdule. A thin section of a green cobble showed the rock to be composed mainly of albite, chlorite, epidote and calcite. White leucoxene is a prominent accessory commonly showing relict parting outlined by black lines in three directions, and occasionally showing a core of violet-black ilmenite. Chlorite apparently replaces feldspar and was observed filling fractures, in, or rimming chalcopyrite grains.

Albite (An_{0-3}) has smooth boundaries against chalcopyrite, but diffuse boundaries against chlorite. This may indicate that chloritization of feldspars occurred later than crystallization of chalcopyrite. The large amount of lime in the rock may indicate an original basic composition.

A single cobble of purple amygdaloidal volcanic rock was found which showed abundant calcite-filled amygdules with stringers of chalcopyrite. Limestone cobbles have no chalcopyrite.

A thin section of the greywacke showed numerous well-rounded to angular grains of clear quartz and many fragments of volcanic rock, quartzite and dolomite. The matrix is very fine grained and composed mainly of chlorite, calcite, sericite and opaque material.

Some purplish units are interbedded with the green graywackes, and also minor quantities of sandstone and shale. Cross-bedding was observed in sandstone.

Intrusive Rocks

A number of dykes and a small plug are exposed on Jan Marie Mountain. The largest dyke has a maximum width of about fifteen feet and can be traced for 2000 feet horizontally and 500 feet vertically up the east face of the mountain. The dyke cuts the redbeds, the Cupriferous Zone, and part of the Cleo formation, appearing to pinch out under talus about half way through the limestone section. What is believed to be the same dyke reappears near the crest of the ridge on the west side and can be traced several hundred feet down the west side. The dyke pinches out just below the crest of the ridge. The rock is highly altered, generally dark green rock of fine grained to aphanitic texture. The colour changes from dark green to grey in passing from the red beds to the black shales and limestones of the Cleo Formation, and in the purple shales of the Rapitan Formation the colour is again dark green.

Within the red beds the dyke has disseminated crystals and clots of specularite and occasional metallic nodules to 1 inch diameter determined to be a mixed titanium-iron oxide. Xenoliths of calcite and fragments of adjacent wall rocks are also included in the dyke. No copper minerals were observed in the dyke below the ore horizons nor was any change in the character of the mineralization noted near the contact of the cupriferous beds with the dyke, although the actual contact was not exposed. Within the black shales a large amount of pyrite appears in the dyke and oxides of iron are not present. Apparently the dyke absorbed sulfur from the calcareous shales which combined with iron from the dyke. Here is a possible explanation of the colour change if insufficient iron were left available to form green chlorite. Above the cupriferous horizons on the east face no copper mineralization was noted in the dyke but the exposures near the crest of the mountain on the west side show some chalcocite in brecciated contact rocks. It is a matter for conjecture whether the copper came up with the dyke or was derived from the apparently uncupriferous purple siltstones and shales into which the dyke is intruded. No assays were made of these purple beds.

A very small plug or pipe of 'intrusive' rock best described as agglomerate, occurs on the south-east slope of the mountain. The plug is sub-triangular in plan with a maximum width of 50 feet. The rock is crowded with rounded to sub-angular inclusions, most being less than four inches in diameter, of various kinds of sedimentary rock, including red siltstone that forms the immediate wall rock. Other inclusions were limestone, quartzite, dolomite and chert. The limestone cobbles contained disseminated magnetite grains and some green chlorite. The matrix is a light green, soft material composed mainly of calcite and chlorite. Disseminated grains and nodules of bornite partly replaced by digenite occur in the matrix but the tenor is low. A strong mineralized fault zone has been exposed by trenching 250 feet west and 100 feet higher than the plug. On the west side of this zone the cupriferous beds have been located by drilling. It is feasible that the mineralization in the plug has been derived from the Cupriferous Zone hence speculation that the copper was introduced from much deeper levels during this igneous activity is dependent on proof that the plug does not intersect the ore horizons. The plug appears to be a diatreme. A basic magma intruding carbonate rocks would probably build sufficient CO_2 pressure to produce such a structure.

At least a dozen narrow dykes of similar agglomerate material occur within a 1000 foot radius of the small plug. (Fig. 9). One of these leads into the plug. No sulfide mineralization occurs in these dykes except where they cross the mineralized fault zone west of the plug. Here they may contain pyrite crystals and scarce stringers of chalcopyrite.

Thin sections of the dyke rocks show complete alteration of pre-existing minerals. Pseudomorphs after feldspar are recognizable, now consisting of calcite and chlorite. The rocks seem to consist of a high proportion of altered wall rock, now integrated as a heterogeneous mass of calcite, chlorite, dolomite, quartz and iron oxides (Fig. 10).

Veins

Veins are common on Jan Marie Mountain and the surrounding area. The character of the veins depends on the nature of the enclosing rock.

In red beds the only mineral that fills fractures over most of the exposed area is supergene gypsum. From one partly open fissure the writer collected several masses of pure selenite weighing several pounds each and from 1 to 2 inches thick. More commonly the gypsum occurs as crustiform efflorescences of finely crystalline material wherever there are open fractures. In the vicinity of the small agglomerate plug very narrow veins of calcite and specularite are found.

Within the cupriferous zone a number of veins of dolomite up to 6 inches wide were observed in a region of intense deformation. The veins are short both laterally and vertically and none could be traced more than 30 feet. No sulfides occur in these veins.

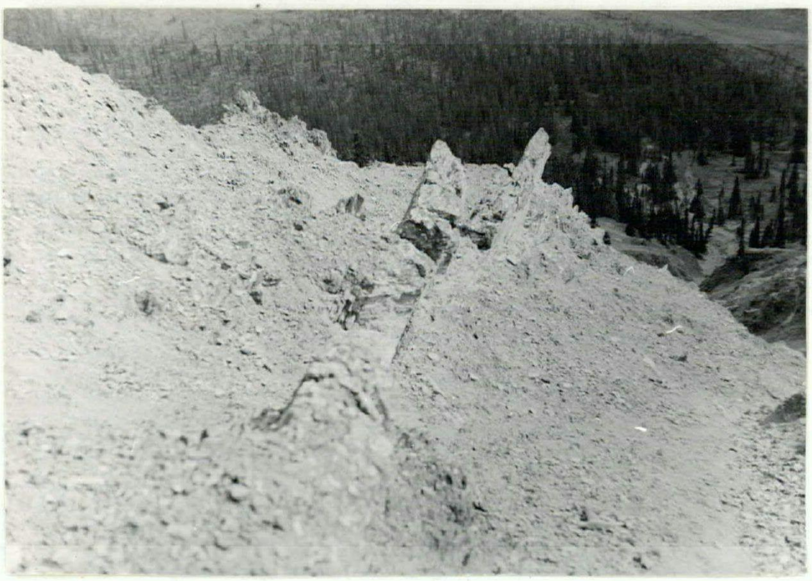

Figure 9. Agglomerate dyke, 1 foot wide.

Figure 10. Agglomerate dyke at siltstone contact, X $1\frac{1}{2}$.

Veins in the Cleo Formation black shales and limestones are composed of dolomite and possibly ankerite. Some of these veins are several feet wide and exceed 100 feet in vertical dimension. They occur in groups at several localities. The ankerite (?) weathers to a deep brown colour. No sulfides were noted.

The Rapitan Formation is cut by a number of veins up to 6 inches wide composed mainly of quartz with some dolomite, specularite, and massive dark green chlorite. At least one of these veins was parallel to a prominent joint set. The veins have comb texture of euhedral quartz crystals, and open cavities. Digenite with bornite occurs as small inclusions in quartz. One vein contained masses of yellow axinite. Fractures in the wall rock for a foot or two on each side of these veins are copper-stained and small black grains on fracture surfaces may be chalcocite or digenite. A five foot chip sample across one vein assayed 1.2% copper. The wall rock is slightly bleached. Quartz-specularite veins were observed cutting the Rapitan greywackes near a major fault.

No doubt some of these veins consist of material derived from the adjacent wall rocks, but the quartz veins are more difficult to explain. Bleaching of wall rock and the presence of sulfides suggest that the parent solutions were reducing in character. Axinite, a mineral with essential boron, is considered a mineral of pneumatolytic associations. It seems that some of these veins must owe their origin to the igneous activity in the area. Some support for this conclusion is given by one dyke which was traced up the east side until it disappeared under a talus at the foot of a bluff. The dyke could not be found in the bluff though several dolomite-ankerite veins appeared approximately on strike. Copper in the wall rock of the quartz veins could have been derived either from the underlying Cupriferous Zone by way of the vein, or from wall rocks.

Metamorphism

Metamorphic effects observed in this area are incipient in nature and probably some workers would include them under advanced diagenesis. All rocks observed by the writer with the exception of Late Upper Devonian shales which are relatively soft and fissile; were thoroughly indurated.

In the Red Bed siltstones, and also in the purple or red shales and siltstones of the Rapitan Formation, one occasionally observes sericite on bedding planes. The sericite flakes are minute and easily overlooked.

The brick-red shales in the upper part of the Rapitan shale section commonly show local incipient development of hematite as films or thin seams to 1/8 inch thick along bedding planes. Rarely this process will have advanced to a stage where 50% or more of the rock is hematized, leaving orbicular remnants of jaspery material, giving the rock a pisolitic aspect. Whether this is a diagenetic or metamorphic feature is not known.

The black fetid carbonates of the Cleo Formation are megascopically crystalline with an average grain size of about 0.5 mm. These are the most coarsely crystalline of the carbonate rocks observed. Other carbonate rocks appear non-crystalline to the naked eye though all thin sections examined showed micro-crystalline texture.

A single thin section of the conglomeratic Rapitan greywackes showed that the matrix was largely chlorite with some calcite and iron oxides. The rock as a whole is usually dark green in colour and gives the impression of being a low grade metamorphic rock. The impression is strengthened by examination of the included green volcanic cobbles which show completely albitized feldspar in a chloritic and calcitic matrix. However, locally the greywackes are purple in colour and cobbles of purple volcanic rock are found within green greywacke. The writer interprets the chloritization of the matrix as an effect resulting from diagenesis in a mildly reducing environment. The green and purple cobbles are considered to have arrived at their present location in their present condition. Whether or not the greywackes are green or purple (i.e. chloritic or hematitic) is considered to be mainly a function of depositional environment.

In summary, regional metamorphism has not affected these rocks to any appreciable extent. No true metamorphic rocks have been found in place or in conglomerates within the Redstone Fault Zone or adjacent area.

Contact metamorphism is restricted to bleaching of the wall rocks for a few inches at the contacts with the minor intrusive bodies.

PALEO-GEOGRAPHY

The region has a long history of tectonism and cyclic erosion and sedimentation. In brief, a long period of Pre-Cambrian sedimentation produced a very thick section composed mainly of quartzites and carbonate rocks. This period terminated throughout most of the area in Late Pre-Cambrian (?) time with tilting and uplift followed by a period of erosion. During or prior to this erosion interval volcanism was active and large volumes of basic cupriferous volcanics were laid down as flows and pyroclastic deposits. Apparently there followed a period of clastic sedimentation beginning probably in very late Pre-Cambrian time,[1] during which the products of volcanism were eroded and incorporated in the Rapitan Formation. A second major hiatus apparently separates the mid-Paleozoic marine rocks from the Rapitan Formation though without appreciable angular discordance. The mid-Paleozoic carbonates were followed by the grey and black, Late Upper Devonian marine shales which are the youngest rocks so far recognized.

The stratigraphy on Jan Marie Mountain shows a departure from this regional pattern indicating that sedimentation continued here throughout much of the long period represented by the unconformity under the Rapitan Formation. It is possible that a graben-like rift valley existed here at that time. The writer interprets the thick red-bed sequence as having been deposited by a large stream or river in a

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1. H. Gabrielse, Geological Survey of Canada, personal communication.

sub-aerial portion of its delta, under semi-arid conditions. The ubiquitous cross-bedding, and thin mudstone partings that invariably show mud cracks, are consistent with a hypothesis that the beds were laid down on a broad sub-aerial delta subject to intermittent flood conditions. The absence of any beds coarser than coarse sand (which occurs very infrequently), and the thorough oxidation, are consistent with an origin of this nature. The present delta of the Colorado River in Mexico is an example of such an environment.[1] A relatively sudden rise in water level preceded deposition of the lowest cupriferous horizon near the top of the red-bed section. The repetitious nature of the changes that produced the cupriferous beds, suggests periodic ponding of drainage by faulting or volcanism rather than fluctuations of sea level. The finely laminated or varved nature of the cupriferous beds is a further indication of ponding as this type of sedimentation developes typically in lakes subject to annual or periodic convective overturn.[2] The six calcareous copper bearing beds are intercalated with typical red siltstones showing that for a long time the contributing stream succeeded in either eliminating obstructions or filling the basins. The seventh cycle appears to have been interrupted during the deposition of a laminated grey siltstone by encroachment of marine conditions. This judgement is based on a gradual increase in carbonaceous matter and on the appearance of pure quartz sandstone at this horizon

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1. Sykes, G.G. 1937, The Colorado Delta: Carnegic Inst. Washington Pub. 460.
2. Bradley, W.H. 1940 G.S.A. Bull. 59, p. 635-648.

towards the south end of the mountain.

There followed a long period of hydrolysate and carbonate deposition under strongly reducing conditions. The limestone conglomerates at the top of this section which include rock fragments similar to underlying rocks, may indicate a renewal of block faulting. An angular unconformity between these rocks and the overlying Rapitan Formation was recognized at the Kvale Extension by Symons[1] but only conformable relations were observed on Jan Marie Mountain.

The redbeds, by virtue of their mineral composition and nature, are considered to be derived mainly from volcanic rocks. Between the siltstones and the first appearance of volcanic cobbles, the Rapitan Formation has about 1500 feet of stratigraphic section in which obvious volcanic material is absent. There are two possible reasons for this. Either there were two periods of volcanism or one long period continuing through the period represented by the red beds, the Cleo Formation and the lower Rapitan Formation. In the latter case one must infer that deposition of coarse volcanic detritus in this area was interrupted by the marine (?) transgression which deposited the Cleo Formation, and did not resume till well into Rapitan time. It has been noted previously that the 'Iron Formation' rocks are somewhat tuffaceous, and basic dykes cut lower but not upper members of the Rapitan Formation, nor the overlying mid-Paleozoic carbonates.

The later history of the area is impossible to decipher

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1. Symons, D.T.A. Unpublished Report.

because erosion has removed all rocks younger than Late Devonian. However, considerable uplift with attendant folding and faulting has occurred in more recent times. It is probable that pre-existent faults guided more recent movements. The faults have influenced sculpture by present streams so that blocks formerly depressed now stand in high relief.

ECONOMIC GEOLOGY

The Cupriferous Zone

The Cupriferous Zone consists of the upper 200 to 350 feet of the thick red bed sequence known as the Jan Marie Formation. A number of sections measured across the Zone ranged in thickness from 200 feet 1½ miles north of Pipit Saddle to 246 feet for a section ¼ mile south of Pipit Saddle. At the latter location only the upper part of the Zone was exposed. It was estimated that an additional 100 feet were concealed beneath talus. The Zone has been traced by outcrop, trenching or drilling, four miles along strike. At the south end of the mountain the Zone appears to arc around the nose of a complex synclinal structure and terminate against the West Range Fault. At the north end of the mountain the Zone is obscured by overburden on low ground which slopes gently down to the very broad valley at the junction of Redstone River and Munro River (Fig. 3). As the stratigraphy at the Kvale Extension is very similar to that on Jan Marie Mountain, the total length of the Zone may exceed 15 miles.

Essentially, the Cupriferous Zone records a period of heterogeneous sedimentation during a transition from red bed facies to black limestone-shale facies. Because of lateral changes in lithology within the Zone, especially in its upper part, correlation would be difficult were it not for the remarkably persistent cupriferous beds. There are six cupriferous beds. The lower two beds stand out as light coloured bands within the red or purple siltstones. Above the third bed the rocks assume a more heterogeneous character and colour. The actual number of cupriferous beds as seen in outcrops at any one place, varies from one to six, owing to complications of faulting, erosion, and perhaps local non-deposition. Nevertheless the stratigraphic relations and lithology are constant wherever the whole section is preserved so that having found and recognized one bed, one can predict the position and character of all others with a fair degree of confidence. A typical stratigraphic section is shown in Figure 11.

In addition to the presence of copper sulfides the cupriferous beds share certain distinguishing characteristics. All the beds have grey colour; have laminated and crenulated bedding (Fig. 12); and all are calcareous. All beds are somewhat silty, especially the upper four. The lower bed is fairly pure limestone, in places grading laterally to silty limestone. The No. 2 bed is distinctly sandy. None of the copper-bearing beds are in direct contact with strongly coloured red beds. A 'bleached zone', generally pale green or greenish buff in colour, borders each cupriferous bed. (Fig. 13). The lithology of the bleached

FIGURE 11: STRATIGRAPHIC SECTION OF CUPRIFEROUS ZONE AT PIPIT SADDLE

UNIT	FEET	DESCRIPTION
		Black Limestone
	7	Flaggy, grey, laminated calcareous siltstone.
	25	Massive grey-green calcareous and dolomitic siltstone. Mudstone partings with pyrite crystals. Mud-cracks.
	20	Reddish brown to greenish calcareous siltstone. Grain size increasing down section, lower 5 feet sandy.
	8	Red-brown calcareous siltstone with thin interbeds of green mudstone.
5	0.6	No. 5 bed, grey laminated dolomitic silty, lst.
	8	Cupriferous green to brownish silty, calcareous dolomite.
	20	Cross-bedded red-brown siltstone with purple mudstone partings.
	10	Green calcareous siltstone, thin green mudstone bands.
4	4	Grey, massive, dense silty limestone. Chalcopyrite.
	9	Green calcareous siltstone and mudstone.
	20	Reddish and greenish siltstones and fine sandstones.
	11	Green calcareous siltstone and mudstone.
3	14	Blue-grey, laminated, crenulated silty limestone. Some chalcopyrite and pyrite.
	9	Green siltstone and shale.
	35	Red to purple siltstone with purple mudstone interbeds. Cross-bedded, mud-cracked.
	5	Green dolomitic and calcareous siltstone.
2	0.3	#2 mineralized bed. Calcareous siltstone and sandstone.
	5	Green dolomitic and calcareous siltstone.
	40	Red to purple siltstone and mudstone. Cross-bedded. Mudcracks.
	8	Green calcareous siltstone and mudstone.
1	3.5	Grey, granular lst. Laminated. Mineralized.
	9	Green calcareous siltstone and mudstone.
		Red to purple siltstone with thin mudstone partings. Cross-bedding and mudcracks common.

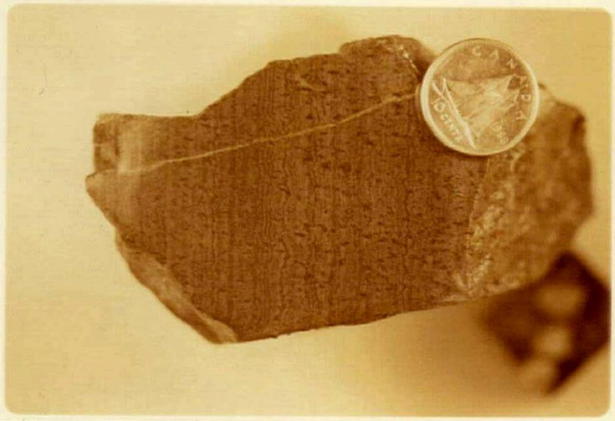

Figure 12: Polished specimen from No. 1 Cupriferous bed.
Dark spots cutting laminae are sulfides.

Figure 13: No. 1 Cupriferous bed exposed on vertical bluff.
Showing 'bleached' zones bordering the Cupriferous bed.

zones is usually identical to that of the red beds. Cross-bedding was observed within the bleached zones though mud-cracks were not noted.

The lowest bed, about 3 feet thick, is consistently richer in copper and silver than higher beds. Mineralization of this bed varies along strike though how much of this variation is due to supergene processes is not known. Commonly the bed is porous, or even vuggy, and only malachite occurs. In one area chalcocite is dominant though normally chalcopyrite is the chief mineral. Bornite occurs commonly, seemingly more abundant near cross-cutting or bedding slip faults. Pyrite is rare in this bed. Copper mineralization may extend a few inches to a foot or so into the bordering 'bleached zones'.

The No. 2 mineralized bed scarcely exists at all in some parts being only 3 or 4 inches thick. Locally it may reach 1 foot in thickness. The grade is consistently high. Certain characteristics of this bed, including a large amount of sulfide over a very narrow width, the strongly oxidized character which is persistent no matter what the state of oxidation of the other beds, and the wavy, undulating bedding surface, lead the writer to suspect some concentration by erosion or solution of an originally thicker bed before the overlying sediments were deposited. (Fig. 14).

The upper four beds are virtually identical in appearance and lithology. The average thickness ranges from 14 feet in No. 3, to 6 inches in No. 6, with No. 4 and No. 5 beds being 4 feet and 1 foot, respectively. Essentially, the rock is a grey laminated calcareous siltstone. The grain size is too small for ready determination of

Figure 14: Oxidized specimen from No. 2 mineralized bed

minerals but a spectrographic analysis of a sample from No. 3 bed, (Table 1) gives an indication of the composition.

TABLE 1 SPECTROGRAPHIC ANALYSIS[1]

Lower 5 feet of No. 3 Bed

Al	-	10.0%	Co	-	Tr	Ni	-	0.005%
Sb	-	N.D.	Cu	-	2.5%	Si	-	Matrix
As	-	N.D.	Ga	-	N.D.	Ag	-	0.0004
Ba	-	0.03	Au	-	Tr.	Sr	-	Tr.
Be	-	N.D.	Fe	-	Matrix	Ta	-	N.D.
Bi	-	N.D.	Pb	-	0.008	Sn	-	N.D.
B	-	0.002	Mg.	-	5.0	Ti	-	0.5
Cd	-	N.D.	Mn.	-	0.2	W	-	N.D.
Ca	-	Matrix	Mo	-	0.001	V	-	0.07
Cr	-	0.002	Nb	-	N.D.	Zn	-	0.02

Notable features of the analysis are the values for aluminum, silica and magnesium indicating a large clay mineral component and, probably, dolomite and quartz. Silver determined by assay of the same sample ran 0.26 oz/ton. Vanadium is also fairly high.

Microscopic examination of the No. 1 bed shows calcite the dominant mineral. Irregular quartz grains are abundant. Much of the quartz includes very fine silt particles and may have formed during diagenesis. Albite is occasionally noted and also shows inclusions as if secondary. Other recognized constituents excluding sulfides, are chlorite and zoisite. Minute flakes, often bent, are colorless with

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1. Semi-quantitative spectrographic analysis by Coast Eldridge & Co. Ltd., Vancouver, B.C.

low birefringence and may be gypsum. No carbonaceous matter was noted and hematite is absent. Average grain size is approximately 0.01 mm.

The bleached zones apparently owe their green colour to tiny interstitial grains of chlorite. Hematite is absent except in gradational contact zones between red beds and 'bleached' rock. It cannot be determined whether hematite has been destroyed in the green zones or whether it ever was an important component. The rock consists of finely banded siltstone and mudstone with graded bedding in some laminae. Many microscopic slump structures distort the bedding. Calcite and minute rhombs of dolomite are prominent constituents. Grains of detrital quartz and twinned feldspar with minute pyritohedrons of pyrite were noted and also many opaque white grains, probably leucoxene. Staining tests confirm the dolomite content. Locally there may be 2 or 3 feet of dolomitic mudstone below the ore beds.

The sediments intercalated with the cupriferous zones are mainly siltstones with some fine sandstone, and dolomitic calcareous mudstone. Beneath the No. 3 ore bed the intercalated rocks are normal red beds consisting of banded purple siltstone and mudstone. Above the No. 3 bed color of the interbeds changes locally from purple to mottled reddish and greenish, to pale greens and browns. Beds of fine sand occur locally and there is a general increase in calcareous or dolomitic content. A very persistent unit up to 75 feet thick composed of greenish-grey calcareous and dolomitic siltstone with thin mudstone partings, is characterized by abundant development of pyrite crystals on bedding planes. Mud cracks are common and the upper very thin cupriferous bed, (No. 6), forms a marker in this unit.

The topmost member of the cupriferous zone is a laminated grey calcareous siltstone very similar to the cupriferous beds. At the south end of the mountain this unit grades upwards into a thick quartz-sandstone. Elsewhere it grades upwards into the black calcareous shales of the Cleo Formation. The bed is rich in finely divided pyrite but only at one point was a trace of chalcopyrite noted.

Copper Mineralization

Copper minerals in the Jan Marie Mountain area have several modes of occurrence, all either within or stratigraphically higher than the Cupriferous Zone. Besides the stratiform deposits there is economically significant mineralization in a strong fault zone discovered in 1963 near the south end. This zone is mineralized with chalcopyrite over a width of several tens of feet. Such mineralization may represent migration upwards for several hundred feet from the Cupriferous Zone. The Cupriferous Zone was intersected at a depth of several hundred feet adjacent to the fault zone where it was found to be somewhat enriched in copper. As the fault zone has not been explored below the Cupriferous Zone, it is not known if its mineralization persists to greater depth.

Another 1963 discovery was a small massive sulfide replacement deposit within the black carbonates of the Cleo Formation near the West Range Fault. Mapping indicates that the sulfides occur at a horizon not far above the top of the Cupriferous Zone. The sulfides are predominently pyrite though masses of fairly pure chalcopyrite also are found. The massive and granular sulfides are in a pod 3 feet wide and exposed for about 20 feet. Some cobalt bloom occurs and an assay revealed 0.12% Co. Several grains of tennantite were found in one sample. Some banded ore shows parallel laminae of graphite. White calcite and quartz are the gangue minerals.

Broad stratigraphic control is shown with respect to minor amounts of chalcopyrite mineralization which occurs in the green basal siltstones and grits of the Rapitan Formation. The chalcopyrite occurs as widely disseminated grains up to 2 mm. in size throughout the 60 foot thick unit. Pyrite is also present. A similar type of mineralization of equally low grade occurs in the greywackes of the Rapitan Formation.

Chalcocite mineralization associated with quartz veins and a dyke in the purple Rapitan shales has been mentioned previously. Very rarely one notes a few grains of chalcopyrite within the carbonaceous rocks of the Cleo Formation. An assay of apparently unmineralized Cleo Formation carbonates from one locality gave 0.06% Cu. Other minor occurrences of copper mineralization are found in calcite-filled fractures in a partly dolomitized area of Cleo Formation rocks in the low ground south of Jan Marie Mountain.

Mineralography of the Ores

The sulfide minerals of economic significance, in order of their observed abundance are: pyrite; chalcopyrite; bornite; digenite; chalcocite; covellite; tennantite and galena. Supergene minerals are: malachite; azurite; native copper and iron oxides grouped together as limonite.

Pyrite:

There is an inverse relationship between pyrite and copper sulfides in the cupriferous beds. Pyrite is rare or absent in the lower two beds which carry the most copper. The upper beds, where poor in copper minerals, carry abundant finely divided pyrite. Not readily visible to the naked eye, the mineral can be observed with a hand lens as evenly disseminated grains. Under the microscope the mineral appears as formless grains or as discrete or aggregated pyritohedrons. No tendency to spheroidal form was noted. The surface of anhedral grains is rough and often shows wavy black lines. Silt particles are included in pyrite. Grain size ranges from sub-microscopic to 0.1 mm. in the cupriferous beds. Pyrite in bleached zones or in the greenish inter-beds or basal Rapitan rocks may range up to 1 cm. in size. Pyrite is a common constituent of the mineralized shear zone, and of the quartz sandstone at the top of the Cupriferous Zone.

Chalcopyrite:

In the Cupriferous Zone chalcopyrite is found in all the ore beds, and it is the only copper sulfide found stratigraphically above the No. 3 bed. In the lower three beds it is the most abundant copper sulfide though locally it may be subordinate to bornite-digenite or chalcocite-bornite mineralization. The almost invariable mode of occurrence is in the form of small, disseminated grains, seldom exceeding 2 mm. in diameter.

In section the grains show an extremely irregular margin around a core in which several silt particles may be embedded. Smaller grains may consist of an aggregate of tiny connected particles interstitial to silt grains in the fashion of a cementing substance. Chalcopyrite is found to extend beyond the ore bed into the adjacent 'bleached' rock. When this rock is very fine grained calcareous mudstone the chalcopyrite grains assume very regular shapes and may even show a tendency to develop crystal form (Fig. 15).

In many outcrops chalcopyrite grains are elongated perpendicular to, or at high angles to the bedding and cut across the boundaries between laminae, (Fig. 16). The effect may be a response to stress.

Bornite:

Bornite is of more restricted distribution although it has been noted throughout the length of the Cupriferous Zone. The principal loci of bornite mineralization are in the lower two cupriferous beds near cross-cutting or bedding slip faults. As a subordinate component of chalcocite-bornite intergrowths it is found wherever chalcocite occurs.

Figure 15: Chalcopyrite in mudstone

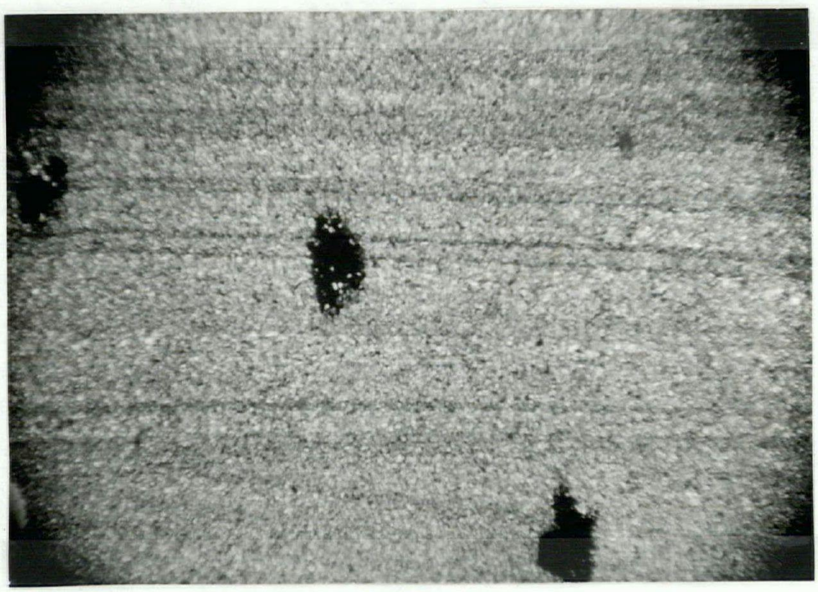

Figure 16: Chalcopyrite cutting bedding laminae x5

Almost invariably bornite grains are enclosed by a narrow rim of some blue or grey sulfide which also may enter the interior of the grains along fractures. Rarely bornite may develop partial rims on chalcopyrite.

The bornite may occur as minute disseminated grains or as vein-like masses to ¼ inch thick along bedding planes or in cross-cutting fractures. Secondary white calcite is associated with the latter type. Microscopic inclusions of galena and tennantite (?) were noted in massive bornite from one locality. Higher silver assays are associated with bornite but the nature of the silver bearing mineral is not known.

Nodules of bornite-digenite, to 3 inches in largest dimension, usually less than half this size, are found in the No. 1 bed. These nodules show colloform banding. Under high magnification most bornite from the Cupriferous Zone shows oriented laths of chalcopyrite arranged parallel to the 111 planes of bornite.

Replacement Rims on Bornite

A characteristic feature of bornite in polished sections is marginal replacement, or replacement along internal cracks, by phases consisting of mixtures and/or solid solutions of digenite, covellite, and chalcocite. The colour of the replacing phases varies from the deep blue of covellite to blue-grey, with all degrees of variation between. Oriented chalcopyrite laths in bornite that straddle the boundaries between bornite and the replacing phases indicate replacement of bornite.

The deep blue grains are decidedly subordinate in amount to those of lighter shades. The former show the characteristic strong pleochroism and anisotropism of covellite. Differing CuS content among copper sulfide grains in a section is shown by varying degrees of anisotropism and pleochroism. Although some covellite occurs in minute laths in blue marginal areas, as if representing exsolution, there is a strong correlation between obvious weathering effects and the occurrence of covellite. There is no doubt that surface oxidation has increased the amount of covellite in some sections.

Much of the material forming replacement rims on bornite is pale blue and isotropic. An X-ray powder diffraction pattern from a selected sample of this material resembled that of digenite with minor differences in spacing. The material was probably a bornite-digenite solid solution. Kullerud[1] reports appreciable solubility of bornite in digenite at low temperatures.

Further phases which may be present among the heterogeneous phases replacing bornite are bornite-chalcocite, digenite-covellite, or digenite-chalcocite solid solutions. All of these phases may form at low temperature.

'White chalcocite' (chalcocite appearing white under the reflecting microscope) does not occur in the rims nor in any manner in which it could be unequivocally designated as supergene. 'White chalcocite' was noted in two associations which will be described in the

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1. Kullerud, G., Ann. Rept. Geophys. Lab. Carnegie Inst. of Wash., Yearbook 59.

following section. Grey-blue, weakly anisotropic sulfide with abundant associated covellite in strongly weathered rock from some localities was identified as chalcocite by its reaction with $Fe\ Cl_3$. This was considered from its mode of occurrence to be supergene chalcocite, containing some covellite in solution.

'White Chalcocite'

A drill hole, centrally located along the strike of the cupriferous zone, encountered 'white chalcocite' mineralization in permafrost at a depth of 90 feet below ground surface. Repetition of beds by faulting poses stratigraphic problems in this area but the writer is of the opinion that this intersection represents the No. 1 or lowest bed. Intense fracturing of the rocks is a feature of this area, which is apparently in the axial region of a fold. Below the weathered zone the fractures are healed with gypsum. The mineralization is disseminated throughout a 3 foot limestone bed and shows no relation to gypsum-filled fractures (Fig. 17).

Chalcocite is white and weakly anisotropic in polished section. Bornite is frequently included, occasionally in graphic intergrowth, but in amounts that are small compared to chalcocite. Contact relations are sharp and not crystallographically controlled.

Minute grains of chalcocite-free bornite also appear in the rock. Oriented chalcopyrite laths are absent from bornite in the two sections examined. Digenite, chalcopyrite and covellite were not

Figure 17: Chalcocite in drill core x 2
Dark bands are gypsum.

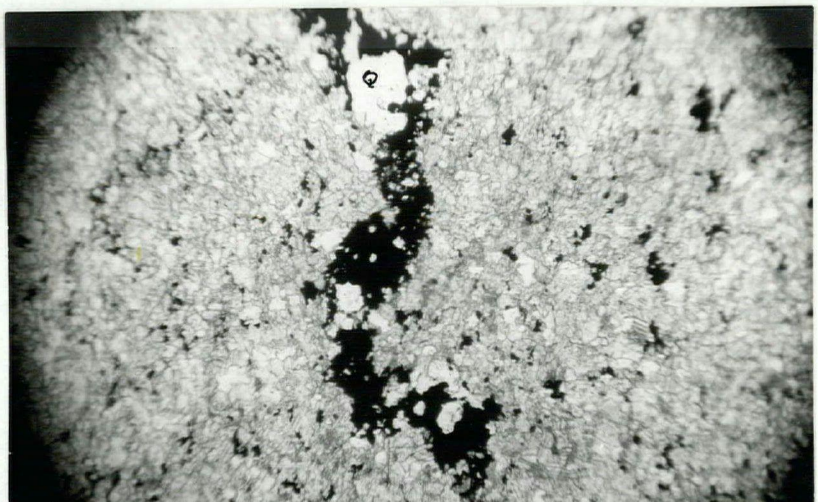

Figure 18: Chalcocite in thin section x 25
Black is chalcocite, Q = quartz. Matrix mainly calcite.

observed in the drill core though surface outcrops show much blue 'digenite' with some covellite.

White chalcocite with bornite also occurs in the brecciated contact zone of the dyke that cuts purple Rapitan shales near the crest of Jan Marie Mountain.

Tennantite:

A specimen from the No. 1 bed near the central part of the Cupriferous Zone showed a few microscopic inclusions of a mineral that may be tennantite. The grains were medium-grey coloured inclusions in bornite that did not respond to the normal etch tests. Associated inclusions in the bornite stringer were galena and chalcopyrite.

A few grains identified by X-ray as tennantite, (cell-edge 10.256Å) were found in specimens from the massive sulfide occurrence in the Cleo Formation. Pink cobalt bloom, probably erythrite, was noted at the same outcrop.

Galena:

As noted above galena was recognized in specimens from one locality as minute inclusions in bornite.

Native Copper

Very tiny grains of supergene native copper are occasionally observed in limonitic material from oxidized portions of the cupriferous beds. Microscopic grains were also noted with malachite and a black oxide, probably cuprite, in a part of the No. 2 bed that apparently was subjected to penecontemporaneous oxidation during sedimentation.

Malachite

In the No. 1 cupriferous bed malachite is commonly crystalline. It occurs as radiating groups, often botryoidal, wherever cavities exist. In less porous rock it may be intimately intergrown with crystalline calcite. Where all sulfides have been destroyed malachite may form up to 10% of the rock giving the rock a distinct green colour. In the upper, less permeable beds the malachite is confined to surface stain or coatings on fractures.

Azurite

Azurite occurs infrequently at several localities as coatings on fracture surfaces. No special conditions for its formation were noted.

Paragenesis

The principal sulfide minerals in the Cupriferous Zone are pyrite and chalcopyrite. The former is dominant in the upper four beds and chalcopyrite is dominant in the lower two. Field observations show that the amount of pyrite in the beds is inversely proportional to the amount of copper present. One would naturally infer that chalcopyrite has formed at the expense of pyrite. However, none of the ore specimens examined supported this inference.

Bornite occurs mainly near faults or bedding-slip planes. Where bornite occurs the amount of chalcopyrite is reduced. Although chalcopyrite inclusions do occur in bornite, evidence of replacement is lacking. One section showed partial rims of bornite on chalcopyrite which may not have been due to replacement. Development of bornite along fractures in chalcopyrite was not noted. Because assays reveal a significantly higher copper content in the ore wherever bornite is present, it would seem that at least part of the bornite represents direct addition of copper as primary bornite. Figure 19 shows a thin section from the No. 3 bed in which bornite occurs as very abundant minute grains and chalcopyrite forms much larger grains more widely disseminated. Chalcopyrite and bornite are not in contact and it would appear that the bornite is an additional discrete phase probable deposited under different physical conditions.

Oriented intergrowths of chalcopyrite in bornite are of interest in that they have often been cited to prove hypogene mineralization. Such intergrowths are undoubtedly due to exsolution of chalcoyprite from bornite and formerly it was thought that high temperatures were needed to form chalcopyrite-bornite solid solutions.

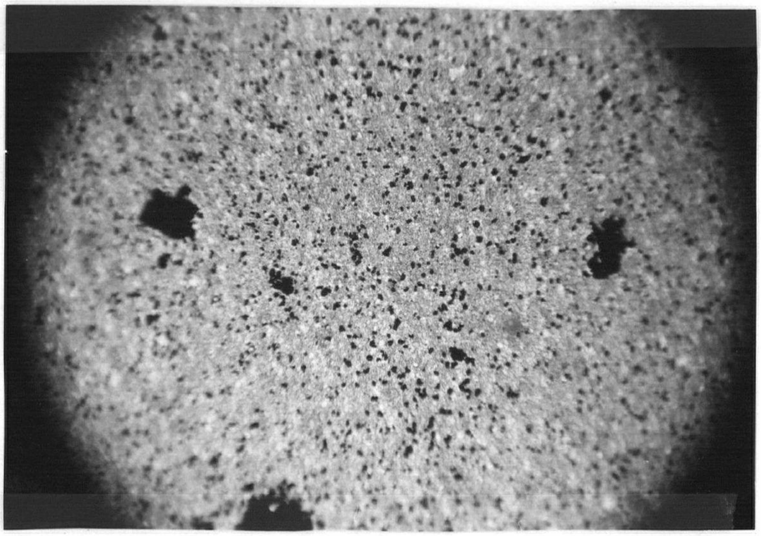

Figure 19: Chalcopyrite (Large black grains) and bornite (minute black grains) in thin section from No. 1 bed.

Experiments by Schwartz[1] in 1926, in which he was unable to homogenize bornite with exsolved chalcopyrite below 475° C, have been most frequently quoted in this respect. Brett[2] found that certain natural bornites, apparently homogeneous, could be made to exsolve chalcopyrite by heating, but only at temperatures greater than 75° C. Some of his specimens of bornite producing this phenomenon were from red bed copper deposits in Utah. Brett[2] states that "There is good evidence that the anomalous bornites never attained the temperature of approximately 75° C during their formation or later, as it is possible to cause chalcopyrite to exsolve from them at this temperature."

From the foregoing it is evident that chalcopyrite exsolution in bornite can no longer be used as a criterion for temperature estimation as such textures may result either from the cooling of a higher temperature bornite, or the heating of an anomalous low temperature bornite. If it be assumed that the bornite from Redstone is analogous to the red bed bornite from Utah, then a minimum temperature of 75° C must have been reached by the Redstone bornite.

Kullerud[3] has shown that isometric digenite is stable down to 65° C, below which temperature it inverts to a rhombohedral form. Hence, if digenite can be shown to possess isometric etch clevage then it may be inferred that the mineral formed above this temperature, or at least had been heated above this temperature. Etching of several

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1. Schwartz, G.M., Econ. Geol. V. 26, p. 186, 1931.
2. Brett, P.R. Carnegie Inst. of Wash. Yearbook 61., p. 159.
3. Kullerud, G., op. cit.

specimens revealed only one parallel etch cleavage, with some doubtful indications of another cleavage at right angles.

The 'white chalcocite' described from the central part of the cupriferous zone is interesting on account of the small proportion of included bornite. Edwards[1] states that similar material can be homogenized by heating to 100° C for 20 days. On cooling exsolution again occurs but some bornite remains dissolved in chalcocite giving it a blue colour. Thus here is an indication that the 'white chalcocite' has not been heated above 100° C.

In summary no conclusive evidence has been found that the ore minerals formed at high or even moderate temperatures. Such minerals and relationships as do occur are not inconsistent with the temperature of formation having been less than 100° C, possibly much lower.

It is possible that the rims on bornite are supergene replacement and even some bornite and chalcopyrite may be supergene. However the nature of the topography, the rapid rate of erosion, the presence of carbonate, the short frost-free season, and the shallow depth of permafrost in summer are all factors which should tend to reduce supergene enrichment to a minimum.

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1. Edwards, Textures of The Ore Minerals, A.I.M.M., 1954.

CHAPTER II

ORIGIN OF RED BED COPPER DEPOSITS

The Redstone River area bedded copper deposits have been shown to possess features which are duplicated in many such deposits the world over. Clearly there must be common factors operative in the formation of deposits of this type. A great many writers have considered this problem and many theories have been proposed, some of which directly contradict others. One great school refers such deposits to an igneous origin, the other principal school prefers to call on sedimentary or diagenetic processes. Commonly these two main theories are termed "the epigenetic theory" on the one hand and "the syngenetic theory" on the other. The nomenclature is unfortunate since the terms connote conditions of origin which do not fit the characteristics of such deposits. Lovering[1] introduced the term 'diplogenetic' for stratiform copper deposits but application requires knowledge of the origin of the various constituents, and hence the term is not practicable at this stage. Perhaps the well established term "Red Bed Type" will suffice to convey all concepts of origin once these are well established and accepted.

In the course of this study the writer has arrived at an understanding of these stratiform ore deposits which, in one form or another, has been arrived at by many workers who have studied them in more than a perfunctory manner. No essentially new ideas have emerged

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1. Lovering, T.S., Econ. Ceol. V. 58, No. 3, 1963.

but nevertheless the writer feels it would be worth while to attempt a review of the broader aspects involved in the formation of "Red Bed Type" copper ores. In essence, the writer envisages three fundamental requirements: a primary source; a secondary source; and a host rock. The nature of each will be discussed in turn.

Primary Source

The ultimate source of copper, apparently, lies in the basic rocks which arrive at or near the Earth's surface along linear fracture systems during periods of orogeny. The average copper content of such rocks is given by Sandell and Goldich[1] as 149 g/ton compared to 38 g/ton for intermediate rocks, and 16 g/ton for acidic igneous rocks. No doubt during the several cycles of an orogeny, copper from basic rocks is reworked and redistributed and may ultimately become incorporated in more acid rocks or their associated copper deposits. It seems though that Red Bed Type copper deposits are most frequently associated with basic rocks of the first, or at least the early cycles of an orogeny. The following deposits are illustrative of this deduction:

1. White Pine: The cupriferous Keeweenawan basic lavas are considered to be the source of the White Pine sediments.

2. Rhodesian Copper Belt: According to Pienaar,[2] there is no doubt that the basement rocks are cupriferous. Basic metavolcanics in the Lufubu system carry up to 0.4% Cu. The Mine Series is locally derived.

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1. Sandell and Goldich, <u>I.J.Geol.</u>, 51, p. 99.
2. Piennaar, P.J., <u>The Geology of the Northern Rodesian Copperbelt</u>, ed. F Mendelsohn, p. 32.

3. <u>Boleo Copper Deposit, Mexico</u>: The sedimentary series containing the ore is derived from basic andesites carrying 0.2% Cu.

4. <u>Redstone Copper Deposit</u>: Basic cupriferous volcanics are the source of much of the local sediment. One volcanic cobble in conglomerate gave 0.3% Cu.

Others could be cited. A feature of all the above deposits is their close spatial relation to great fracture systems in the crust. This feature is illustrated at White Pine by the White Pine and Keeweenaw faults; at Boleo by the San Andreas fault, and at Redstone by the Redstone Fault Zone. A major fault system is not yet demonstrated in the Rhodesian Copperbelt though the fact has been noted that most deposits can be referred to a linear pattern.

Secondary Source

The normal processes of erosion and transportation break down the cupriferous rocks and transport the detritus to areas of accumulation. Typically these areas are terrestrial basins, such as existed in the Rhodesian Copper Belt, or subsiding linear depressions as at Corocoro. Climatic conditions are frequently arid or semi-arid so that the sediments are stained red by the oxidation to the ferric state of adsorbed iron compounds. A low water table is necessary to allow for thorough oxidation of detritus hence one must envisage intermittent deposition, during rainy spells or during periodic transgressions of the depositing waters. An accumulation of such oxidized sediments, generally arkosic or conglomeratic, constitutes a potential secondary source.

Garlick[1] has postulated that copper travels in solution to basins of deposition but this view has little support from the facts. Any text on geochemistry shows the amount of copper in either stream water or sea-water to average very much less than one part per million. The modern prospector knows that copper in transport is tied up in the sediment along stream courses, with the highest copper values being found in the finest fractions. The copper is readily extractable in weak acid and hence must be held by adsorption, perhaps by colloidal ferric hydroxide coating sedimentary particles, or by the actual surface charges on mineral fragments especially those of clay minerals. The insoluble nature of copper under these conditions dictates that it must remain adsorbed until the sediment finally comes to rest at the site of accumulation. Post-depositional dehydration of ferric hydroxide and the formation of ferric anhydride stain the sediments to reddish or purplish colours. Some copper may be released at this stage. Sulfate, as gypsum and anhydride accumulates in strongly oxidized sediments. Here too, is one of the few terrestrial environments where soluble salts of the halogens are precipitated.

The oxidation potential and the pH, of a sedimentary lithofacies, once established, tend to persist throughout geologic time. The evidence for this is readily demonstrated by the stability of the

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1. Garlick, W.G., The Geology of the Northern Rodesian Copperbelt. Ed., F. Mendelsohn p. 152.

mineral assemblage in any given lithofacies. The geologist may confidently expect to find pyrite and carbonaceous matter in a black shale, or hematite and gypsum in red-beds, no matter what the age of the sediments may be. For red-beds it may be predicted that the rocks will comprise an oxidizing environment due to the large concentration of ferric iron, and that the pH of this environment will be in the acid or weakly alkaline range. The latter is demonstrated by the general absence of calcite which is unstable below pH 7.8, and the former by the absence of pyrite, which is unstable under positive Eh conditions in natural environments. Figure 18 is illustrative of these concepts which have been developed by Garrels et al.

Thus it can be shown that the red-bed facies are sedimentary units of positive oxidation potential and pH less than 7.8, and the evidence indicates that these conditions have not changed since the sediments were laid down. This then is the nature of the 'secondary source' from which red-bed type copper deposits are derived.

Host Rocks

There is no such thing as a typical host rock for stratiform copper deposits. The one prime requisite is that the sediment be laid down under reducing conditions. At the Redstone deposit such conditions ensued when a body of standing water transgressed the sub-aerial delta on which the red-beds were being laid down. The writer infers that the laminated nature of the ore beds indicates lacustrine deposition,

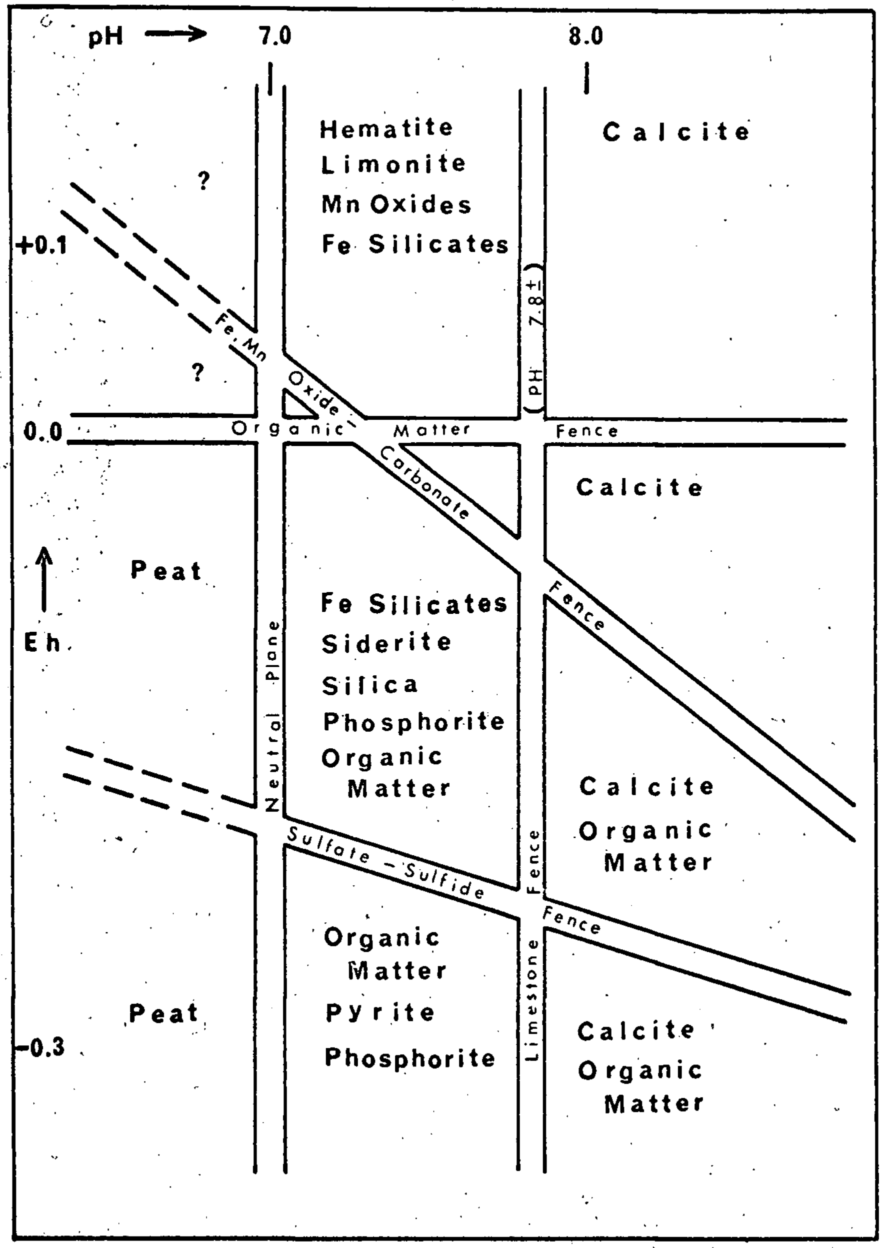

Figure 20: Limits of the natural environment with respect to Eh and pH. (Modified after W.C. Krumbein and R.M. Garrels, 1952. Origin and classification of the chemical sediments in terms of pH and oxidation-reduction potentials, J. Geol. 60,26).

the laminations being due to periodic convective overturn. Similar laminated ore horizons are described from several deposits, notably White Pine and Roan Antelope. Evidence of reducing conditions is given by the presence of pyrite and carbonaceous matter. Under oxidizing conditions organic matter is completely destroyed owing to oxidation of carbon to CO_2. Calcite is normally present.

Where the copper deposits occur in conglomeratic or sandy stream-deposited sediments, such as at Corocoro, Bolivia, or many of those in the southwestern United States, the deposits are linear and lenticular and tend to migrate laterally up or down section. The reducing environment in stream sediments of an aggrading stream is maintained in portions of the stream channel and will be preserved only if the water-table remains above the level of the reduced sediments. Fragments of wood and plant remains are commonly found in such channels in the younger sediments. The Coro-coro deposit in Bolivia is believed by the writer to be of this type, though here the channels, or cuvettes as Ljunggren and Meyer[1] call them, are super-posed one above the other.

The host rocks then may be any sedimentary unit having a negative potential relative to the adjacent rocks. Alkalinity is generally indicated but data in the literature are insufficient on this point. Certainly the Kupferschiefer, the ore-shale at Roam Antelope, Nchanga and Chombishi to mention a few, are distinctly calcareous. Some authors make no mention of calcite.

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1. Ljunggren, P. and Meyer, H.C., Econ. Geol, V. 59, No. 1, 1964.

Time Relations

There is considerable evidence that copper began to deposit soon after the sediments were laid down. On the other hand equally convincing evidence indicates that migration of copper occured at a later date during tectonic activity. Evidence of the first kind includes such features as undeformed cell structures in plant remains that have been replaced by chalcocite. This type of replacement apparently only affects undecomposed organic material since carbonized plant matter is very resistant to sulfide replacement (Papenfus 1931). Sulfidized fish heads have been found in the Kupferschiefer without evidence of compression. Evidence of the second kind includes features such as enrichment of copper adjacent to faults and fractures. This phenomenon is very well illustrated at the Redstone deposit, and also at White Pine. Enrichment in structural highs has been claimed but is less well documented. However there is general agreement that the copper mineralization was mainly if not all deposited prior to tectonism and metamorphism. This conclusion has been reached by workers in the Copperbelt, in the Corocoro Basin and at the Kupferschiefer.

Ore Transport

The problem of how copper finds its way into the ore beds

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1. Papenfus, E.B., Econ. Geol. V. 26, 1931, p. 314.

has been the subject of excited controversy since the days of Werner. The writer is concerned only with the problem of moving copper from oxidized sediments into overlying, intercalated, or underlying reduced sediments. Consideration of this problem involves the chemical and physical processes which may be said to begin as soon as the sedimentary 'couple' is established.

Physical Processes

Noble[1] has made the suggestion that 'water of compaction' may be responsible for the formation of stratiform uranium and also copper deposits. Since red-beds are primarily granular sediments, relatively incompressible, the period of settling and compaction must be fairly short with near maximum compaction being attained at shallow depth of burial. Thus the evidence of the undeformed cell structures is not incompatible with this hypothesis.

Another physical process which has often been suggested is downward percolation of meteoric water. With the renewal of clastic sedimentation after deposition of a hydrolysate or carbonate bed, it is probable that under arid or semi-arid conditions the water table would drop to considerable depth and the surface sediments would oxidize and accumulate sulfates and chlorides. Downward percolation of infrequent rain waters or flood waters would carry down the solubles to be trapped

1. Novel, E.A. Econ. Geol. V. 58, 1963, pp. 1145-1156.

by the reduced sediments below. This mechanism fails to account for the higher copper content being at the base of the ore horizons at Redstone and at the Kupferschiefer.

One might envisage also periodic up and down fluctuations of the water table with the groundwater collecting metal above the reduced horizon and depositing metal as it dropped through this bed again. Neither is there any serious objection to lateral percolation up an inclined hydraulic gradient as postulated by Noble.[1]

That fraction of the formation water which does not move by any of the above processes, may at later date be mobilized under the influence of increased temperature. Without tectonism it seems reasonable to expect that fluids driven out by increasing temperature at depth would follow the same hydraulic gradients as those mobilized by compaction pressure. With the advent of folding and faulting the hydraulic gradients are necessarily disturbed, and the effects of this disturbance should be reflected in the distribution of ore.

At Redstone these effects are perhaps demonstrated by the notable increase in grade of ore adjacent to some of the faults, or even minor fractures. The opening of fractures in a rock under load must immediately set up a low pressure area towards which any fluids will flow until equilibrium is re-established or the fluids are exhausted. Conspicuous at Redstone is the partial change in mineralogy from chalcopyrite to bornite-'digenite' near some faults, especially

1. Noble, E.A. (1963) op. cit.

bedding-slip faults. Concomitant with the entry of bornite-'digenite' into the paragenesis is a slight deepening of the green colour of the sub-jacent and super-jacent bleached zones. These effects are noted here to show that some support can be raised for the hypothesis that heated solutions migrating towards low pressure areas can affect the pattern of mineralization. It should be noted that at Redstone there is absolutely no sign of copper mineralization in or adjacent to any fracture below the stratigraphic level of the lowest ore horizon. Similar relationships have been noted at White Pine and the Copperbelt.

From the foregoing it should be apparent that aqueous solutions, physically capable of transporting copper may pass through any given horizon one or several times during the period after burial and before being exposed once again to erosion.

Chemical Processes

The chemical processes which allow entry of metals into solution at one point and their deposition at another, although probably simple, are not yet resolved. A discussion of the problems at low temperature is given by Barton[1] with an extensive bibliography. Present data have so far not yielded precise determinations of the chemistry of ore solutions but field observations do lend insight to the problem.

1. Barton, Paul B., (1959), Researches in Geochemistry, Editor P.H. Abelson, J. Wiley & Sons, Inc.

With regard to bedded copper deposits the writer has previously stressed the important differences in oxidation potential and pH between the enclosing rocks and the host rock. The actual mechanism by which copper is deposited has not yet been agreed upon. A frequently recurring suggestion is that copper is deposited as replacements of carbonaceous matter. The chief difficulty here as already pointed out, is the chemical inertness of carbon at low temperatures in a reducing environment. Papenfus[1] exposed carbonized wood to copper sulfate for 50 days and failed to observe any replacement. There is no doubt that actively decomposing organic matter can be replaced by sulfides but acceptance of this as the principle mechanism seriously restricts the length of time required for deposition. Further the mechanism fails to explain the deposition of very large masses of native copper as at Corocoro nor the mineralization at Redstone where there is little or no carbonaceous matter in the ore beds. The commonly observed association of metals and carbonaceous matter is probably due partly to the remarkable adsorptive capacity of carbon for gases, including H_2S, and partly to the electronegative character of carbon under reducing conditions.

There has been considerable discussion of the possible role of sulfate reducing bacteria in forming stratiform copper deposits. Baas Beckling and Moore[2] have demonstrated the bacteriogenic formation of copper sulfides in the laboratory, but their cultures were not

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1. Papenfus, E.B., op. cit.
2. Baas Beckling, L.G.H. and Moore, D., 1961, "Biogenic Sulfides," Econ. Geol., v. 56, p. 259-272.

representative of natural solutions. Nevertheless the importance of bacteria in producing the necessary sulfide is well recognized, and probably their presence helps to maintain and intensify the reducing environment. Direct reduction of sulfate by inorganic processes is quite possible. Pyrite or marcasite appear to be the first sulfides to form when reactive sulfur species become available and their replacement by copper sulfides has often been described.

One of the most frequently recurring statements in descriptions of the mineralogy of these deposits is that native copper or copper sulfides replace the cement of the host rock. Commonly the cement is calcareous as at Redstone though here the writer was not able to show actual replacement of pre-existing minerals. The relations observed could equally well be interpreted as re-crystallization effects contemporaneous with the growth of crystalline calcite. Carpenter[1], however, shows a photograph of indubitable replacement of twinned calcite by chalcocite. Replacement of calcite, chlorite and carbonaceous matter is reported from the Copperbelt.

None of the above mechanisms account for the manner in which copper is dissolved and transported to the host rock, and no one has as yet provided a satisfactory solution to this problem. It was pointed out previously that sulfates and halides tend to accumulate in strongly oxidizing environments under arid conditions. It may be significant that the sulfate and the hydrated cuprous chloride are the most soluble

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1. Carpenter, R.H., Econ. Geol. V. 58, p. 643.

of inorganic copper compounds. Goldschmidt[1] reports 6000 ppm of chlorine in the Kupferschiefer.

The suggestion is often made that copper is transported to the ore beds in the colloidal state. This interpretation is based on the occurrence of nodules of copper sulfides showing colloform texture. These have been reported by several students of red-bed copper deposits and have also been noted at Redstone. Pyrite is often mixed with the copper sulfides and may be the primary mineral.

The writer would like to point out that the paragenesis of red bed copper deposits, excluding those which have suffered metamorphism at higher temperatures, is essentially similar to that of supergene enrichment of epigenetic copper ores. Chalcocite is easily the most abundant sulfide of copper and pyrite the associated iron sulfide. Replacement of pyrite by chalcocite is commonly reported. The unsolved problems of supergene enrichment, namely how copper migrates from the zone of oxidation down to the zone of enrichment or how it migrates laterally, are exactly the problems in red bed copper deposits. Further it is still unexplained how supergene enrichment occurs above the water table or oxidation persists to depths of 2,500 feet.

With this in mind the writer suggests that these problems should be viewed in terms of electro-chemistry rather than solution chemistry. In the case of a pyrite-copper ore body in the zone of oxidation at the ground surface, the sulfide body is a zone of negative

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1. Goldschmidt, V.M., 1954, Geochemistry, Clarendon Press, Oxford.

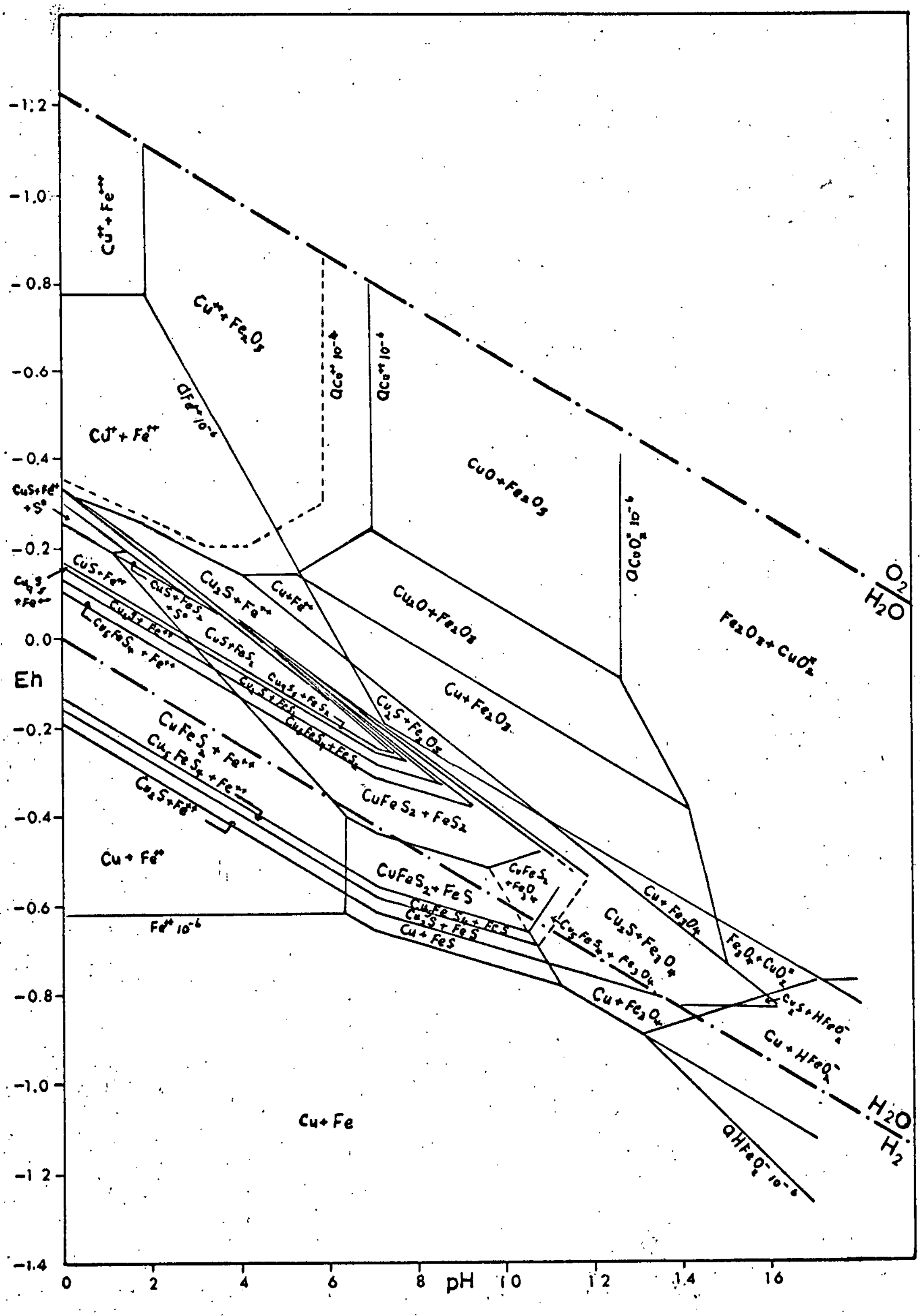

Figure 21: The system Cu-Fe-S-O-H (in part) at 25° C and 1 atmosphere total pressure. Total dissolved S = 10^{-1}m. (After R. Natarajan and R. Garrels.) Note the narrow Eh range shown by the fields of the various Cu-Fe-S assemblages.

potential relative to the adjacent oxidized overburden. If groundwater containing positive and negative ions embraces the ore body then the system satisfies the requirements of an electrolytic cell. There should be a flow of electric current providing the sulfides are sufficiently concentrated to form a conductor. Anions would be attracted to the 'anode' and cations should migrate to the negative pole. Since atmosphoric oxidation increases potential then the anode should be located at the surface. A current flow in this direction should create a measurable negative potential. A phenomenon frequently measured by geophysicists known as "spontaneous polarization" or "self potential", must be of this nature. The effect is most pronounced when the ground is saturated after heavy rains which may indicate a possible solution to the problem of supergene enrichment above the water table.

There should be sufficient potential contrast between red beds and intercalated 'reduzate' beds to initiate the functioning of such a cell even below the water table. Those cations (or positively charged colloids) which are unstable under the potential difference should tend to migrate towards the negative pole where one might expect to find zoning according to the redox potential of the various couples involved Fig. 21. Further since potential is apparently inherited during sedimentation it does not seem unreasonable that planes of equipotential should correspond with bedding planes, which might account for the remarkably faithful reflection of bedding planes by mineralization of this type.

Considerable geochemical and geophysical research, not warranted in the present study, is needed to validate these proposals. However the writer feels that this type of approach is necessary and fundamental in any endeavour to understand ore genesis.

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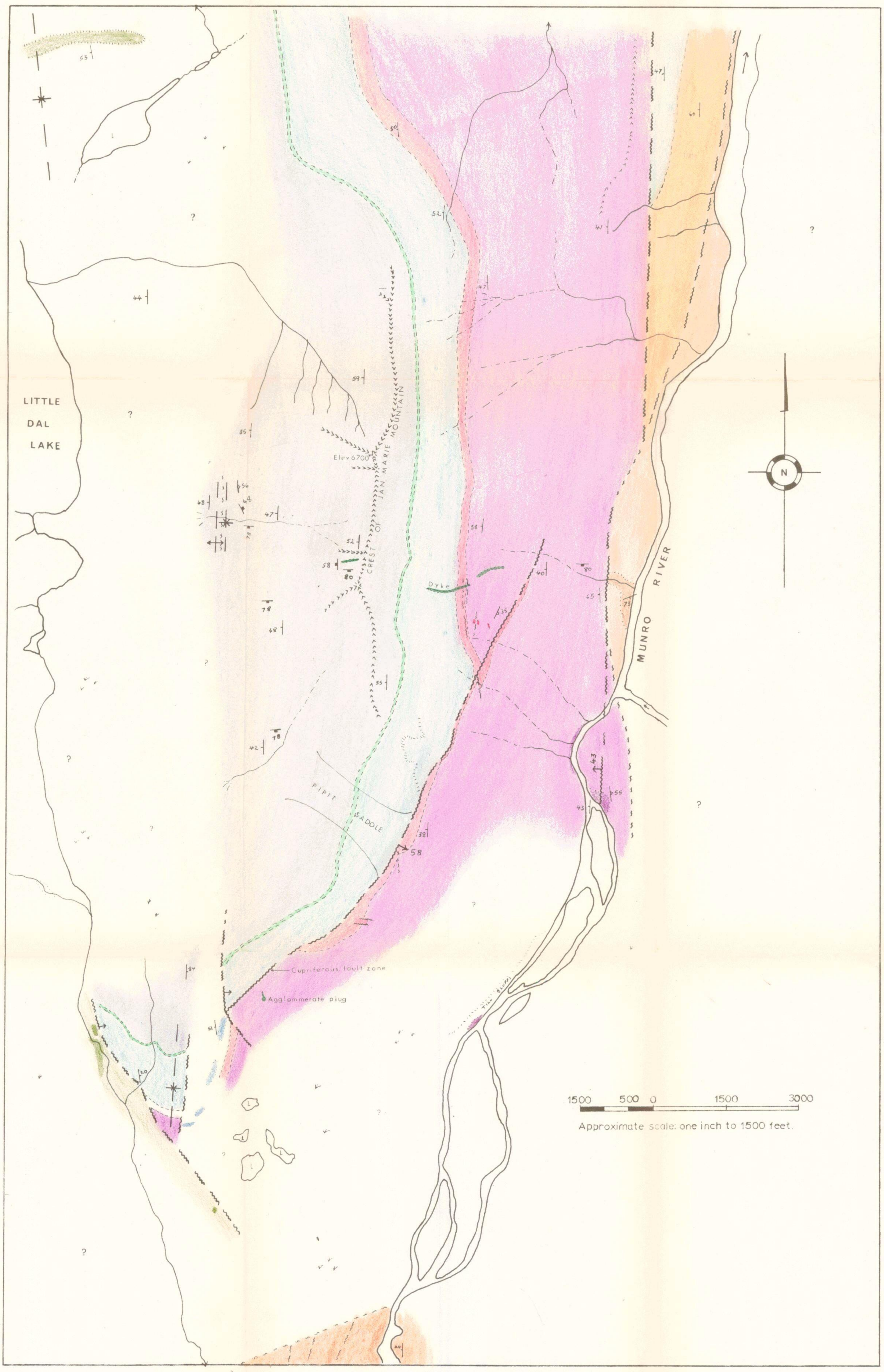

LEGEND

UPPER DEVONIAN

Unnamed Unit

- Shale, Siltstone.

DEVONIAN OR OLDER

Dal Formation

- Limestone.

Thundercloud Formation

- Dolomite

LOWER CAMBRIAN ?

Rapitan Formation

- Greywacke
- Purple shale; siltstone; conglomerate.
- Green siltstone; grit; conglomerate

PRE-CAMBRIAN ?

Cleo Formation

- Black limestone; shale; calcirudite.

Jan Marie Formation

- Cupriferous Zone
- Red Beds: siltstone.

Redstone Formation

- Dolomite

SYMBOLS

- Fault: defined; approximate; assumed.
- Attitude of bedding.
- Attitude of joints.
- Attitude of fracture cleavage.
- Fold axes: syncline ; anticline.
- Geological boundaries.
- Crest of ridge.
- Area of outcrop.
- ? Bedrock unknown.
- Swamp
- Bluffs

Geology by D. Symons: P. Hudec & J.A. Coates

GEOLOGY OF JAN MARIE MOUNTAIN AREA