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Bill,

Cook file
Stratigraphy, Wessson Salt
Sedimentary Petrology

File ?

~~GJS~~ nice summary
~~JDS~~
~~ETG~~

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DIAND
BOX 1500
Yellowknife, N.W.T.,
Canada. X0E 1H0,
March 17, 1975

W. L. Kurtz
ASARCO
P.O. BOX 5747
Tucson Arizona
USA 85703

Dear Mr Kurtz

I had hoped to have my paper on gold and iron formation in a presentable form by now. However, holidays, business trips + delays in draughting and photography have all contributed to an incomplete report. I have a very preliminary copy (full of typographical and scientific errors, no photos and poor figures) which I have enclosed. (Why bother? I feel it's not good enough to distribute outside the office - but it may be of ~~so~~ interest to you untill a better version is available.). I have had two competent people critically review it and I will be making many ~~consistent~~ changes including several significant modification i.e. more on the N.W.T. deposits and less on the Northern Ontario deposits, especially

Kirkland Lake. Neither my ~~[illegible]~~ critical readers ~~of~~ or myself like Figure 7.

I expect ~~to~~ submit my revised paper ~~to~~ the CIM Bulletin and will send you a revised paper, hopefully before ~~too~~ long.

Yours truely

Walter Sebbins

UNEDITED

Gold and Precambrian Iron Formation

by

Walter A. Gibbins

Department of Indian Affairs and Northern Development
Box 1500, Yellowknife, North West Territories.

ABSTRACT

Gold is found intimately associated with the sulphide minerals in several Precambrian iron formations. Arsenopyrite and pyrrhotite generally make up the bulk of the sulphide, while lesser amounts of pyrite, chalcopyrite, and/or loellingite may be present. Quartz, chlorite and carbonate are the common gangue minerals, however iron rich garnets and amphiboles may be present where metamorphism has reached the amphibolite facies.

Sulphide minerals at the Homestake and Contwoyto Lake deposits are the most obvious examples of sedimentary exhalitive origin, even though they have been highly deformed and metamorphosed. Sulphides at the Cullaton Lake deposit and Central Patricia Mine are related to brecciated and deformed zones in quartz magnetite iron formation. They are characterized by remobilization at lower (greenschist facies) metamorphism and excellent replacement textures present. These deposits are more intimately associated with volcanic rocks and represent a more proximal facies of exhalitive iron formation.

Gold deposits in the Little Long Lac area are of a similar type. All of these deposits show significant similarities and differences, even within a single area.

A model emphasizing an exhalitive origin and including modification by later events and contributions by other processes best explains the origin of these iron formations and their associated gold deposits.

INTRODUCTION

Spectacular increases in the price of gold recently have been accompanied by an equivalent increase in interest and activity in many known gold deposits. Gold deposits of particular interest in this regard are those related to Precambrian iron formation. The Homestake Mine is the largest gold mine in North America. It is a classic mineral deposit and is well documented in the literature of economic geology. Two other deposits, namely the Contwoyto Lake property of the International Nickel Company of Canada and the Cullation Lake "B Zone" of O'Brien Gold Mines Limited were discovered in the course conventional prospecting in the early nineteen sixties. Unlike many former producers that were high-graded or proved uneconomical even with the relatively low mining costs of the thirties, these deposits contain significant tonnages of ore grade material averaging 0.75 oz/ Au/ton. Their main disadvantages have been and are remoteness of location coupled with expensive capital costs relative to proven ore reserves. Several gold deposits in Northern Ontario are also related to sulfides in Precambrian iron formation, particularly in the Crow River, Little Long Lac and Kirkland-Larder Lake areas. These areas contain several long term profitable mining operations and several of which have also been the subject of recent feasibility studies and diamond drilling. The locations of known gold deposits of this type in North America are shown in Figure 1. Finally, the reader's attention is drawn to the reports of gold found in iron formations from Australia, Brazil, Central and Southern Africa, and India (Sawkins and Rye, 1974), however, these are beyond the scope of the present study.

The Homestake Mine

The Homestake Mine is located at Lead, South Dakota near the northern end of the Black Hills. It was discovered in 1978 during the working of rich placer deposits in Deadwood Gulch. During the 96 years it has been in operation, over

30 million ounces of gold and 7 million ounces of silver have been produced. The geology of the deposit (Figure 2) has been described by several company geologists, including Staughter (1968), Noble (1950), Noble et al. (1949), and Noble and Harder (1948).

All of the ore is confined to the Homestake formation, a fine-grained quartz-sideroplesite schist [sideroplesite + $(Fe_{.15}\ Mg_{.25})\ CO_3$] which is commonly further metamorphosed to a coarser grained cummingtonite-grunerite schist above the garnet isograd. This unit is approximately 200 feet thick but true stratigraphic thicknesses are obscured by thickening in the noses and thinning in the limbs of folds. Conformable with the Homestake formation are the underlying Poorman formation - 2,000 feet plus of grey laminated phyllite or mudstone and the younger Ellison formation - 3,000 feet of grey to black quartmica phyllite and interbedded quartzites.

Tertiary uplift due to intrusion of quartz monzonite stocks and porphyry sills created a large dome structure with Paleozoic sedimentary rocks dipping outward from a core of Eocene quartz monzonite stocks and Precambrian schists. Within the Precambrian schist area, rocks are tightly and complexly folded (Figure 2). Early isoclinal folds in which the rocks have deformed plastically during flexural slip folding plunge 10° - 45° to the southeast, with axial planes dipping to the northwest. In numerous instances the axial planes are themselves folded.

These folds vary from the dominant Poorman anticline (several miles in length) to much smaller folds that may become so tightly closed that some formations are separated into pods or lenses. A later phase of folding involves superposed "cross folds" caused by penetrative shear folding along planes at a small angle to the axial planes of the earlier folds (Chinn, 1970). These folds are often best developed in the noses and occasionally on the limbs of the early isoclinal folds, where they cause a pronounced thickening of the Homestake formation and form favorable structures for the localization of mineralization.

In three dimensions these mineralized structures form pencil or rod like ore shoots. These shoots may coalesce with other shoots and continue at depth until their fold structure dies out. Ore forms only a very small amount of the known Homestake formation (Norton, 1974).

The ore bodies are more or less completely chloritized portions of the cummingtonite or sideroplesite schist of the Homestake formation. The chloritized areas no longer contain the sedimentary quartz bands prevelant in other parts of the formation but rather abundant vein quartz which appears to be derived from the sedimentary quartz and may be localized in the cross folds (Plate V, Noble, 1950). The chlorite wall rock immediately adjacent to these veins generally carry good values of gold. The chlorite schist usually contains slightly less than ten percent sulphide minerals, mainly pyrrhotite or pyrite with a smaller amount of arsenopyrite. Pyrrhotite and pyrite may contain small inclusions of gold and occur as tiny grains and elongated lenses of grains often aligned along the bedding of the chlorite, cummingtonite, or sideroplesite schist.

Medium to coarse grained euhedral arsenopyrite crystals occur concentrated in zones parallel to bedding. Arsenopyrite is most abundant in the chlorite zones and contains most of the high grade gold in the form of tiny inclusions and veins. The average grade of ore from the Homestake Mine has been about 0.33 ounces of gold per ton of rock for several years.

In addition to the Homestake deposit and the recent placer deposits, gold has also been found in the basal conglomerate of the Cambrian Deadwood formation (believed to be a fossil placer) and in vertical fractures of Tertiary age found in Paleozoic rocks of the Lead area. In the early 1900's some production was obtained from gold-arsenopyrite mineralization related to plunging fold structures found in cherty iron rich meta-sediments similar to but stratigraphically higher than the Homestake formation in the Roubaix-Galena district southeast of Lead (Bayley, 1970) and in the Rochford area south of Lead (Bayley, 1972).

Tertiary geologic activity and mineralization have been used in the past to argue for a Tertiary hydrothermal origin for the Homestake ores (eg. Noble, 1950) versus a Precambrian hydrothermal or syngenetic origin.

The only strong evidence for Noble's Tertiary origin of the Homestake mineralization is the areal distribution of tertiary ore bodies. Chinn (1970) has shown that the "cross folds" to which the ore bodies are restricted were probably not formed by tertiary intrusives (Rye and Rye, 1974, p. 297). On the other hand considerable geologic and isotopic evidence (Table I) indicates a Precambrian origin in a sedimentary-exhalite environment followed by later 1,600 M.Y. Precambrian folding and metamorphism to produce the mineralized structures.

Folded iron formation (quartz-grunerite schist) south and south east of Lead are considered to be worthy of more exploration (Bayley, 1970, 1972 and Norton, 1974). Meanwhile, exploration and development continues at the Homestake Mine as it approaches the end of its first 100 years of production.

Contwoyto Lake

A number of gold occurrences have been discovered in iron rich sediments or amphibolites of the Yellowknife Supergroup in the Point-Itchen-Contwoyto Lake area, District of MacKenzie, of the Northwest Territories, approximately 250 miles northeast of Yellowknife (Figure 1). By far the most important deposit, however, is the "main showing" of the International Nickel Co. of Canada, located near the southwest shore of the north end of Contwoyto Lake, (Figure 3), latitude $65^{o}46'$ north, longitute $111^{o}14'$ west, N.T.S. 76 E/14. This was discovered in 1960 as the result of INCO's "gossan hopping" technique of prospecting. The gossan was spotted from a fixed wing aircraft, samples were taken out by helicopter, and assays resulted in interesting gold values. In 1961, INCO staked 314 claims to cover the deposit. This touched a staking rush which continued into 1962 during which several hundred claims were staked adjacent to the INCO property. A permanent camp was erected and an extensive program of diamond

drilling, trenching, geological and geophysical surveys were carried out at the main showing curing the summers of 1962 and 1963. One estimate of reserves at the main showing is several million tons of material exists that has a grade of 0.30 ounces per ton or better (Knutsen, 1974). No reliable figures of the size and grade of this deposit are available.

The regional geology has been described by Tremblay (1966 and in prep.) and Bostock (1967), while descriptions of individual mineral showings are given in Tremblay (1966 and in prep.), Baragar and Hornbrook (1963), Schiller and Hornbrook (1964), Schiller (1965) and DIAND assesment files. Most of these showings are gossans related to gold-sulphide mineralization in amphibolite lenses or beds within certain stratigraphic units of the Yellowknife Supergroup. They occur more or less continuously along a broad belt of Yellowknife sediments stretching northwards from south of Point Lake, carving eastward through Itchen Lake to Contwoyto Lake eventually passing southeastward along the soutwest shore of Contwoyto Lake (Figure 3). Similar deposits have been noted on the east and west sides of Bathurst Inlet (Thorpe, 1972) another 60 miles northeast of Contwoyto Lake.

In the Contwoyto Lake area, low to medium grade meta-sediments of the Yellowknife Supergroup frequently occur as frost-heaved blocks scattered in a chaotic fashion and form large areas of felsenmeer.. On the few outcrops that exist, it is not uncommon to find large blocks of meta-sediment which have been pushed straight up from deeply jointed bedrock by frost action.

Leucocratic medium to fine-grained quartz feldspar gneiss occuring as domes and grading into massive granite are the oldest rocks in the area. The Yellowknife Supergroup is mainly argillite and greywacke (phyllite and quartz-feldspar schist) and metamorphic equivalents. (i.e. nodullar cordierite-andalusite bearing quartz-biotite schist and gneiss.) Basic volcanic rocks and related gneisses and amphibolites form a distinct basal unit while garnet-grunerite amphibolite bands and lenses derived from iron rich sediments are restricted to

the youngest units of the Yellowknife Supergroup (Tremblay, in prep.). These rocks were intruded by gabbro (amphibolite) and then biotite-muscovite granite (2,495 M.Y. - Wanless et.al., 1974, p. 39) before the end of the Archean. Generally flat lying sedimentary rocks of the Proterozoic Goldburn Group rest unconformably on the Archean rocks. Diabase and gabbro dikes and sills cut all other rocks in the area.

Folding of Archean rocks in the Contwoyto Lake area is related to granite intrusion and metamorphism. In the vicinity of INCO's main showing isoclinal folding has occured; to the south west a dome structure predominates. Locally amphibolite bands may indicate refolding of earlier folds or appear relatively undeformed. Gentle folding of the Goldburn rocks took place at a much later time.

The main showing occurs in a 50 foot wide garnet-grunerite amphibolite which is enclosed in the greywacke-argillite sequence and has been deformed into a large steeply plunging fold structure (Figure 4). Within this folded unit, a complex variety of deformational features including pseudo-conglomerate or boudinaged quartz, stretched and pulled apart strata, local intrusive features, a great variety of drag folds (mainly congruent with the major fold but showing a large variety in size and style) and late quartz filled tension veins show that the pysical properties and style of deformation varied with time and lithology (Plates).

The amphibolite unit is generally thin bedded, with individual beds only rarely as wide as two feet across. Rocks vary from fine to coarse grained, schistose to massive, black to light green, zero to greater than 80 per cent almandine garnet, zero to 80 per cent sulphide, and include sugary textured quartz bands, chlorite schist, and several varieties of amphibolite or iron formation. Minor amounts of pyrite and magnetite occur, however, carbonate minerals are absent from the amphibolite due to non deposition and/or metamorphism. Where weathered the sulphide bearing amphibolite has a rusty surface or gossan.

Two large drag folds, one on each limb of the major fold contain most of the sulphide and gold mineralization and most of the larger late quartz veins. In these folds the rock is a laminated to thin bedded sulphide-bearing amphibole. The amount of sulphide is normally less than 20 per cent but may exceed 80 per cent of the rock in places. Pyrrhotite occurs as thin laminae, while coarse euhedral to subhedral crystals of arsenopyrite (FeAsS) with loellingite ($FeAs_2$) cores up to one inch long (Plate) are concentrated in bands parallel the foliation. These crystals carry most of the gold in the deposit with more than 70 per cent of the visible gold present at the loellingite-arsenopyrite boundary (Bostock, 1968, pp. 72-76). The late quartz veins generally give very low in gold values but occasionally native gold can be found in them.

Comparison of the Homestake and Contwoyto Lake Deposits

McConnell (1964) first pointed out several of the striking similarites found in the Northern Black Hills Homestake area and the Contwoyto Lake "main showing area" including "stratigraphy, metamorphism, structure and mineralization". Although differences also exist between the two areas, notably the absence of saloons, sideroplesite and other carbonates at Contwoyto Lake, the absence of loellingite and late diabase dikes at Homestake, different ages of subsequent granite intrusion, and a much greater proportion of mudstone or argillite to greywacke at Homestake; probably greater differences exist within the respective areas (eg. grades of metamorphism and intensity of folding).

In both areas: Grunerite-cummingtonite amphibolites derived from iron rich sediments are found in a similar sequence of argillite and/or greywacke of probable Archean age, several bands or lenses of amphibolite are known, as are many small showings, however, only one deposit in each area appears economic at present. These deposits contain similar structural controls (ore is confined to secondary folds), mineral assemblages and textures: coarse gold bearing arsenopyrite, fine-grained laminae of pyrrhotite, minor pyrite, chalcopyrite, and magnetite.

The gangue includes grunerite-cummingtonite, chlorite, almandine garnet and two generations of quartz, early sedimentary beds which have a sugary texture and late veins related to folding and mineralization with a vitreous or glassy texture. A complex history and style of structural deformation occurs in both areas, as do well defined examples of progressive metamorphism. Precambrian meta-gabbros or orthoamphibolites also occur in both areas.

Cullaton Lake

The Cullaton Lake deposit (Figure 1) is located 250 miles northwest of Churchill, Manitoba, in the Southern District of Keewatin, N.W.T. (latitude 61° 17'N, longitude 98° 31'W, N.T.S. 65 G/6,7). In 1961 H. MacDonald, a prospector in the employ of Selco Exploration Company, discovered gold in quartz-magnetite iron formation by panning crushed material from a rusty frost heaved boulder, in the area between Mountain Lake and Cullaton Lake. Following this discovery emphasis on Selco's exploration program was shifted from examination of Proterozoic quartz-pebble conglomerates to a search for and examination of the iron formations. Several more zones were located by sampling rusty boulders and outlined by magnetic surveys (Figure 5). Considerable work, including geological mapping, arsenic soil geochemical surveys, geophysical surveys (magnetic and EM), trenching and diamond drilling were done during the 1962 and 1963 field seasons. Most of these zones contained low erratically distributed gold values, however, only the "B Zone" appeared to be of economic interest and most of the work was done in this area.

The geology of the area has been described by Eade (1964, 1966 and 1975). Lenses of quartz-magnetite iron formation occur conformably in a thick greywacke-argillite-tuff unit of Archean age. These sediments overly and intertongue with volcanic rocks of predominantly basic composition. These rocks, known as the Henik Group, have undergone at least two periods of folding and have been intruded by both Archean (2570±90 m.y.) and Hudsonian (1,700±50 m.y.)

granites and show evidence of two periods of metamorphism (Eade, 1975).

Henik Group sediments show progressively higher grades of metamorphism in a northerly direction towards the contact with a large granite mass. Some of the iron formation occurring in the almandine-amphibolite facies of iron formation has similar mineralogy to the Contwoyto Lake deposit including quartz, magnetite, grunerite-cummingtonite, almandine garnet and minor sulphides (Eade, 1975).

A thick sequence of Proterozoic sediments, the Hurwitz Group which unconformably overlies the Archean rocks has been faulted and folded into a series of discontinuous synclines and anticlines. At the base of the Hurwitz Group is an orthoquartzite which forms most of the sparse outcrop in the area. The resistant nature of this unit causes much of the topographic relief in the area and makes this the most easily mappable unit. The Henik Group sediments, on the other hand, are represented by less than one percent outcrop (Figure) and vast areas of frost heaved boulders or felsenmeer predominate (Figure) making structural mapping virtually impossible. A few late diabase dikes cut all other rocks in this area.

The "B Zone" occurs approximately mid-way between Cullaton Lake and Mountain Lake. It consists of a mineralized unit of banded quartz-magnetite iron formation which is relatively unmetamorphosed but is locally highly folded and fractured. Consultants for the present owners, O'Brien Gold Mines Ltd. (1973) have calculated reserves of "approximately 185,000 tons after dilution of 0.97 ounces gold per ton" from more than 30,000 feet (68 holes) of diamond drilling on the B Zone. This band contains several lenses of magnetic iron formation over a strike length of half a mile. It strikes N 10° W and has an average westerly dip of 45°, but has a steep dip near surface, flattening to near horizontal at 200 feet and then steepening until it is cut by a sub-horizontal fault at 400 feet. The iron formation is frequently separated from the greywacke by 0 - 50 feet of a carbonate rich tuff unit on the hanging wall side and 0 - 20 feet on the foot wall side.

Mineralization is usually found in irregular and discontinuous quartz-chlorite-carbonate-sulphide rock. High gold values are associated with abundant chlorite and pyrrhotite, but high pyrrhotite and chlorite do not necessarily contain high gold. Abundant coarse grained arsenopyrite does not contain good gold values.

Four en echelon, steeply plunging ore shoots have been recognized in the B Zone. They cut across the bedding of the iron formation and appear to be related to fracture zones and/or folding.

An additional gold occurrance occurs in shear zones in the basal Proterozoic Hurwitz quartzite at Shear Lake three to four miles north of the B Zone. Only a couple of short intersections of economic interest were found in extremely oxidized gold-pyrite mineralization. Mineralization in the iron formations is not comparable to this.

Crow River Area

The Crow River area of Northwestern Ontario (latitude 51°30'N, longitude 90°W) lies 160 miles northeast of Ignace on the Trans Canada Highway or 215 miles north-northeast of Thunder Bay. Two important former gold producers occur in the area and both contain gold mineralization related to iron formation.

The Central Patricia Mine produced over 650,000 ounces of gold between 1935 and 1951 and the Pickle Crow Mine produced about 1,450,000 ounces of gold from 1935 to 1966.

The regional geology of the area has been mapped and described by Thomson (1939, p.5). Basic lava flows of Keewatin (Archean) age make up the predominant rock formation. Interbanded with the lavas are narrow bands of iron formation, other fine-grained sediments (greywackes) and fragmental rocks such as agglomerate, volcanic breccia and tuffs. Granite, porphyries and associated acid rocks intrude the older Keewatin complex. The gold deposits are generally associated with iron formation. Locally tuff may grade into ferruginous greywacke or lean iron formation with magnetite and quartz-siderite-magnetite laminae.

Bands of iron formation are found at several horizons in the volcanics, however, they seem to be concentrated in the upper part of the Keewatin series. The iron formation occurs in bands a few inches to 250 feet thick. Some of these bands can be traced for miles, while others pinch and swell or die out along strike. During regional deformation, the Keewatin rocks were tightly folded into a series of anticlines and synclines which strike and plunge to the northeast.

Only a small percentage of the area is rock outcrop and exploration has consisted of tracing magnetic iron formation with a dip needle and diamond drilling.

Gold deposits in the Pickle Crow area are characteristically associated with complex fracturing and tight drag folding of brittle iron formation and massive greenstone. Shear zones in the less competent lavas and undeformed iron formation do not provide favorable targets. "Two generations of quartz occur at the Central Patricia and Pickle Crow Mines. The later variety is white, unfractured and largely devoid of gold values" (Thomson 1939, p. 28).

a) Central Patricia Mine

The Central Patricia Mine occurs on the north limb of a large anticline and although several bands of iron formation are present only one contains ore. Several fairly irregular ore shoots were mined and most of these were confined to well fractured zones in the hanging wall (north) side of the iron formation (Figure 8, Thomson, 1939), however, a few angled across the iron formation from hanging wall to footwall. There is also a tendency for the fracture groups to occur near points of curvature along the hanging wall contact. Gold is associated with abundant pyrrhotite and arsenopyrite filled fractures in the iron formation. These fractures also contain abundant quartz, carbonate and green chlorite. The chlorite seems to be related to sulphide and gold content (Barrett and Johnston, 1948). Mineralized fractures vary in thickness from ¼ to

10 inches and in width from 2 to 40 feet. They strike across the band of iron formation and normally stop abruptly at the iron formation-greenstone contact. Both the ore shoots and mineralized fractures dip or "rake" eastwards at an average angle of 55 degrees. A complimentary set of joints and barren fractures dip to the west at an average of 55 degrees. According to Thomson (p. 39, 1939) "the iron formation adjacent to the fractures has been partially replaced by sulphides and carries low gold values."

"Arsenopyrite occurs as distinct crystals, largely in vein quartz and to a lesser extent in iron formation. Pyrrhotite is always in irregular shaped patches, small grains or stringers. It occurs as rows of tiny grains parallel to the bedding of iron formation, along fractured zones in arsenopyrite crystals and as veinlets in quartz (Thomson, 1939, p. 42)." This texture (top photo, p. 40, Thomson, 1939) is similar to those found at Homestake and Contwoyto Lake (Plate). A study by M.H. Haycock (1936) showed that 38 per cent of the gold was free in quartz-chlorite gangue, 28.3 per cent was associated with pyrrhotite, 18.9 per cent with arsenopyrite, 11.6 per cent with pyrite and 3.2 per cent with chalcopyrite. The average grade of the ore was about 1/3 ounce of gold per ton, although stringers assayed up to 11 ounces per ton (Barrett and Johnston, 1948).

b) The Pickle Crow Mine - The Howell Vein

The main ore zone, the Howell Vein, occurs less than five miles east of the Central Patricia Mine on the south limb of a northeasterly trending and northwesterly dipping isoclinally folded syncline. The vein is associated with the only known tight fold in this part of the series, which has produced a thickening of the iron formation (Corking, 1948, p. 374, Figure 1). The vein intersects the iron formation at an angle of 40 degrees on the east side to 10 degrees on the west side and extends into the enclosing lavas for several hundred feet on either side. The stresses that were relieved by shearing in the lavas, produced brecciation and shattering in the more competent iron formation. The

vein itself contains several large drag folds and many smaller ones. Gold content is generally higher along these folds. Regional and local fold axes and the line of intersection between the vein and the iron formation all have an average plunge of 70 degrees in a N 25°E direction.

Typical vein material is banded white quartz with chlorite and tourmaline where the host rock is greenstone and sulphides where the host rock is iron formation. In the greenstone, the grade, width (average is 3 feet), continuity and orientation of the vein are remarkably persistent. In the more brittle iron formation, stope widths up to 20 feet have been mined because of many parallel fractures filled with mineralized quartz. Locally, in mineralized sections and particularly in the area of large drag folds (eg. Figure 16, Thomson, 1938), massive sulphides (pyrite and pyrrhotite) appear to replace iron formation but the sulphides themselves carry low values of gold.

c) Miscellaneous Veins

Several other small gold deposits and showings have been discovered in the Crow River Area, descriptions of most of them can be found in Thomson (1938) and/or Ferguson (1966).

One of the most economically important of these is the Number 2 vein of the Pickle Crow Mine. Here the main vein is not associated with iron formatin, but a similarly competent "quartz porphyry."

In general, however, most of these smaller showings are closely related to the iron formation and contain considerable "quartz and minor sulphide zone" described by Ferguson (1966, p. 81-82) appears to most closely resemble the Homestake-Contwoyto mineralization discussed earlier.

Comparison of the B Zone and Central Patricia Deposits

This comparison was first made by Tavela in a report for SELCO (DIAND, 196). Several similarities are striking and the comparison appears to be a valid one. In both instances the iron formation plays what

appears to be an important role in the origin and depositional controls of the gold mineralization. The author believes that these deposits reflect a distinctive end member type in the larger classification of iron rich sedimentary-exhalitive deposits (eg. the Homestake-Contwoyto end member).

Little Long Lac Area

The Little Long Lac gold camp occurs in the townships of Lindsley, Errington and Ashmore approximately 125 miles northeast of Thunder Bay, Ontario. Geologically it is located at the east end of an east-west, trough-shaped belt of "Keewatin" metavolcanics (basic to intermediate lavas, tuffs and volcanic breccia) and "Temiskaming" meta-sediments (predominantly greywacke with lesser amounts of iron formation, conglomerate, arkose and slate) of Archean age. These rocks have been intruded by granite and granodiorite batholiths, albite porphyry sills and diabase dikes. Early regional folding about a roughly horizontal, east-west axis has been locally overprinted by a complex pattern of tightly folded minor folds and drag folds which typically plunge at 30 degrees in a westerly direction (Figure 6) and form fold patterns not dissimilar to those at Homestake Mine. (Figure 2). The regional geology and the geology of individual mineral deposits of the Long Lac area has been described by Bruce (1935, 1937), Pye (1952) and Horwood and Pye (1955).

Between 1934 and 1953 nearly two million ounces of gold were produced from several mines in the area. The gold mineralization largely occurs in iron formation, albite porphyry or greywacke and is frequently localized along fracture zones, drag folds and/or lithologic contacts, particularly where the competency of adjacent rock types differs.

The relationship between gold mineralization and iron formation is best developed in the "North or sulphide Zone" of the Hard Rock Mine and the adjoining MacLeod-Cockshutt Mine (Horwood and Pye, 1955 and Matheson and Douglas, 1948), although in several other deposits, including the Magnet, the Bankfield

and the Tombill Mines. Gold is found adjacent to or in the proximity of tightly folded bands of magnetite-hematite iron formation. In the north or sulphide zone (Figure 6), gold mineralization is closely associated with sulphides, predominantly pyrite, arsenopyrite and some pyrrhotite which "replace" the iron formation in the noses of folds and certain favorable sedimentary horizons. "In places that ore is beautifully banded[1] owing to the selective replacement of the sheared less competent greywacke laminae in the iron formation by the sulphides. In other places the replacement has been so complete that original sedimentary structures are largely obliterated and irregular masses of sulphides enclose only mere remnants and vestiges of partially replaced sediments (Horwood and Pye, 1955, p. 60). Many short irregular quartz veins occur in the sulphide zone but volumetrically are not important. The quartz is commonly barren except where it contains sulphides. Like other deposits of this type, mineralized ore shoots die out when their associated folds die out and not all folds or all sulphides are ore bearing. Finally mineralization is not restricted to one type even within a single mine.

1 Ore in the "No. 2 Vein"(Figure) is also "beautifully banded".

Larder Lake Area

Ridler (1970, p. 39) proposed that the gold bearing carbonate ore bodies of the Larder Lake area (eg. the Kerr Addison Mine) are in fact auriferous carbonate facies iron formation, probably correlative with the Boston iron formation. The siliceous pyritic carbonate horizon is folded conformably with the sediments and volcanics in which it lies and locally displays sedimentary "banding".

A unique feature of the Larder Lake area is the spectacular green color of much of the carbonate, due to chlorite and fuchsite - a chromium mica. Although chromium rich rocks are also reported to be related to auriferous iron formation in Brazil (Dorr and Miranda Barbosa, 1963).

In common with the other areas discussed, the country rocks have undergone a long history of facturing, folding and metamorphism. Modification by these processes explains much of the diversity observed in the gold deposits. According to the second stage of Ridler's genetic model, during metamorphism, the carbonate recrystallized and segregation of some of the silica and gold into dilational stockworks occurred. Locally the intensity of metamorphism and deformation was low enough that unveined cherty auriferous carbonate survived.

Similarities and Dissimilarities of Gold Deposits in Iron Formation

Common features of gold deposits in iron formation are summarized in Table II. The various deposits discussed previously are also compared and contrasted in Table III. Several of the features eg. high gold: silver ratios and abundant chlorite are common to many gold deposits of diverse origin and consequently of relatively minor significance relative to the origin of these unique deposits, however, other features like the facies of iron formation, the proportions of coarse clastic, fine clastic and chemical sediment are important and useful environmental parameters (Figure 7). These can be used to show more subtle differences between gold deposits in iron formation and outline subclasses of deposits, eg. the Homestake-Contwoyto Lake type versus the Cullaton Lake-Central Patricia type discussed previously.

Many features, including sulfur isotope analyses, detailed sulphide equilibria, fluid inclusion, petrologic and structural studies etc, await comprehensive analyses and evaluation at many of the deposits. They may or may not provide useful information.

The Origin of Gold Deposits in Iron Froamtion

Processes which have been used to explain the gold deposits in question are listed in Table IV. It can be seen that many of these processes are related and gradational with each other. It seems safe to say that the origin of any deposit is not the same as any other and no single process adequately explains any one of the deposits. Each process has its merits and failures. Like the transmission of light, more than one theory may be required to explain our observations.

When we are limited to a poorly exposed two dimensional slice of a three dimensional object and an even more clouded time dimension and all the variables that go with it, we are not in a position to develop rigid theories of origin. Most geologists, actively working with these rocks today, would probably favor

a working model involving an early volcanic exhalite chemical precipitate process which becomes important during relatively brief lulls in clastic sedimentation and a second, later metamorphic and deformational event which causes remobilization and localization of the mineralization.

Exploration Possibilities

Geophysics and geochemistry, used in association with careful geologic studies and prospecting, offer excellent exploration possibilities to finding any additional gold-iron formations that exist, and I'm sure that they do exist. Reconnaissance geology and magnetometer work and possibly lake sediment or whole rock sample geochemistry should be useful in outlining large areas with potential. Electromagnetic (eg. VLF) and induced potential surveys should indicate local anomalies. In the Homestake and Contwoyto Lake areas where the gold is intimately related with arsenic minerals, arsenic soil geochemistry appears to be very useful, however, its value in the other areas is definitely not as promising. In some cases it may locate arsenopyrite but not gold.

Gold is still where we find it, however we have found it in iron formation a number of times and will no doubt continue to find it and base metal deposits that are related to iron formation if we look for it. All of the deposits mentioned were ultimately found because someone looked for and found the gold. In several cases earlier geologists undoubtedly rejected the iron formation after a cursory evaluation as not suitable for iron ore. All of the areas discussed have seen further exploration activity in the last two years and are likely to see more if the price of gold continues to rise. Of particular interest and potential are the two deposits at Contwoyto Lake and Cullaton Lake in the Northwest Territories, there has been no commercial production from these deposits, in large part due to there remote location. In this regard, it should be noted that the Homestake Mine was also originally in a remote location.

Acknowledgments

The author would like to express his gratitude to many geologists who have helped him with this study. Worth of special mention are Gordon Nelson of the Homestake Mining Co. and his colleagues, J.E. Mullock and E. Pattison of the International Nickel Co. of Canada Ltd., Don Esson consultant for O'Brien Gold Mines Ltd., Drs. Bostock, Eade and Trembley of the Geological Survey of Canada kindly provided access to their unpublished data. Robert Hornal, of the Department of Indian Affairs and Northern Development, Yellowknife, N.W.T. introduced the author to the project and offered encouragement and support throughout. Douglas Bryan, also of DIAND, was a capable co-worker and appreciated companion during visits to Cullaton Lake and Contwoyto Lake.

TABLE I. Evidence for a Precambrian versus Tertiary origin of the Homestake Gold Deposit.

1. Fossil placer gold deposits in the basal conglomerates of the Cambrian Deadwood formation.

2. The ore is restricted to one stratigraphic horizon the Homestake formation of undisputed Precambrian age.

3. Ore textures can be interpreted as sedimentary or metamorphic.

4. Similar mineralization is found in folded Precambrian iron formation at Rochford (20 miles south of Lead) where Tertiary activity is absent and in other examples of gold in iron formation.

5. Sulfur isotope data (Rye and Rye, 1974) indicate that the sulfur in the Homestake formation and other Precambrian iron formations at Rochford are syngenetic and probably derived from the reduction of sea water sulfate.

6. Oxygen isotope data (Rye and Rye, 1974) from various types of quartz in the Homestake Mine show a strong dependence on local wall rocks but data from late Tertiary quartz are completely independent of wall rocks.

7. Fluid inclusions in quartz and arsenopyrite have high and variable CO_2/H_2O mole ratios and high CH_4 content compatible with a metamorphic origin of the mineralizing fluids (Rye and Rye, 1974).

8. Lead isotope data (Rye et al., 1974) on galenas from mineralized parts of the Homestake formation and other age data indicate metamorphism and intrusion in the Black Hills 1,600 m.y. ago, including deformation and mineralization in the Homestake formation. The Homestake formation may be 2,500 m.y. old, or it may incorporate abundant detritus of this age. Lead isotopes from Tertiary galenas have had different growth histories.

TABLE II. Common Features of Gold Deposits in Iron Formation

- These ore deposits are found in sedimentary iron formation host rocks.
- The iron formation typically occur as bands or lenses in a much thicker argillite-greywacke sequence.
- The iron formation commonly occurs near the top of the sequence, while associated volcanic rocks (tuffs and basic lavas) often intertongue at the base of the sequence.
- Iron formation facies types frequently show complex and detailed relationships.
- The iron formations are early Precambrian in age.
- Common ore mineral assemblages and textures are present: arsenopyrite (usually coarse subhedral to euhedral megacrysts) - pyrrhotite (fine grained anhedral and parallel bedding or banding) - pyrite (variable proportions) - chalcopyrite (rare) - gold (very rare).
- Common gangue and metamorphic minerals: abundant quartz (usually at least two generaltions) and ehlorite (tends to indicate mineralized areas) and variable carbonate (frequently siderite or ankerite, sideroplesite at Homestake), also grunerite-cummingtonite, almandine garnet (where metamorphism has reached the amphibolite facies) and abundant banded or minor disseminated magnetite.
- At least one and more commonly multiple metamorphic and deformational events. The later producing complex patterns of tight isoclinal folds, refolded folds and zones of brittle fracturing, which are important controls for the location of elongated ore shoots.
- Frequently gold mineralization not directly related to the iron formation are found nearby.
- The deposits all have high gold-silver ratios.
- Many of these areas are underlain by very poorly exposed outcrop and the iron formation must be traced by geophysical methods.

TABLE IV. Processes that might Contribute to the Origin of Gold Deposits Associated with Iron Formation.

Plutonic	Hydrothermal
Volcanic	Exhalite
Sedimentary	Chemical precipitate
	Clastic
	Placer
Metamorphic	Recrystallization (simple)
	Remobilization (metamorphic differentiation and segregation)

Captions to Figures

Figure I. Index map showing location of Precambrian gold deposits related to iron formation.

1. Homestake - South Dakota
2. Contwoyto Lake - Northwest Territories
3. Cullaton Lake - Northwest Territories
4. Crow River - Northern Ontario
5. Little Long Lac - Northern Ontario
6. Larder Lake - Northern Ontario

Figure 2. Geology of the Lead area, South Dakota (after Noble and Harder, 1948).

Figure 3. Geology of the Point Lake-Itchen Lake-Contwoyto Lake area, showing known gold occurances (after Bostock, 196).

Figure 4. Geology of the Main showing Contwoyto Lake.

Figure 5. Geology of the Cullaton Lake area (after SELCO 1964 DIAND assesment files).

Figure 6. Geology of the Hard Rock Mine property (from Matheson and Douglas, 1948).

Figure 7. Schematic representation of sedimentary facies of iron formation before overprinting of metamorphic facies.

TABLE III SUMMARY OF GOLD DEPOSITS IN IRON FORMATION

	Homestake, South Dakota.	Contwoyto Lake, N.W.T.	Cullaton Lake, N.W.T.	Crow River, N.W. Ontario.	Long Lac, N.W. Ontario.	Larder Lake, N. Ontario.
Main facies of iron formation	CO_3> Si>S	Si > S	Mt > CO_3>S	Mt > CO_3 > S	Mt > Hem	CO_3> S
Metamorphic facies of gold deposits.	green schist - amphibolite	green schist - amphibolite	green schist - amphibolite	green schist -	green schist -	green schist -
Structural control	- shoots parallel secondary or "cross folds"	- shoots parallel in drag folds	- shoots related to fracture zones - cut by faults	- fractured and drag folded iron formation	- fractured and drag folded iron formation?	quartz filled stockworks in folds and fault carbonate
Minerals associated with gold	Asp> Po>(Cpy) Qtz Chl Carb	Loel-Asp> Po(Cpy) Qtz Chl	Po> Asp> Py(Cpy) Qtz Chl Carb	Po-Asp> Py(Cpy) Qtz Chl	Py> Asp> Po(Cpy) Qtz CO_3	Py-Asp> Po(Cpy) CO_3 Qtz Chl
Gold mineralization not related to iron formation	-Tertiary joints in Paleozoics -Cambrian placers -Recent placers		-Shear zones in Proterozoic quartzite	Quartz porphyry	Deposits in other sediments and "porphyry"	Felsic plutons (syenite and trachyte)

CO_3	carbonate	grn sch	green schist	Loel	loellingite	Qtz	quartz
Si	silicate	amph	amphibolite	Asp	arsenopyrite	Chl	chlorite
S	sulphide			Po	pyrrhotite	CO_3	carbonate
Mt	magnetite			Py	pyrite		
Hem	hematite			Cpy	chalcopyrite		

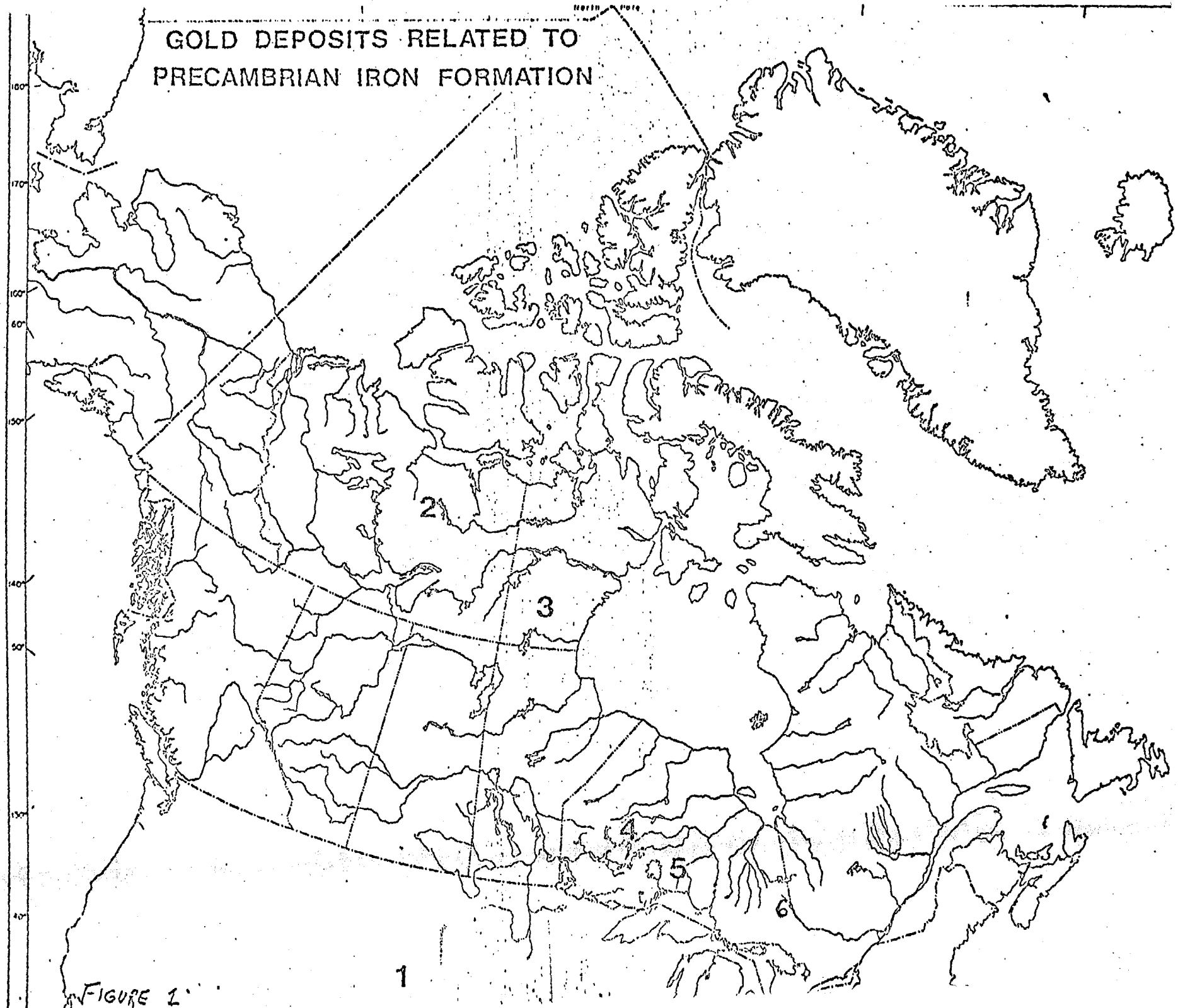
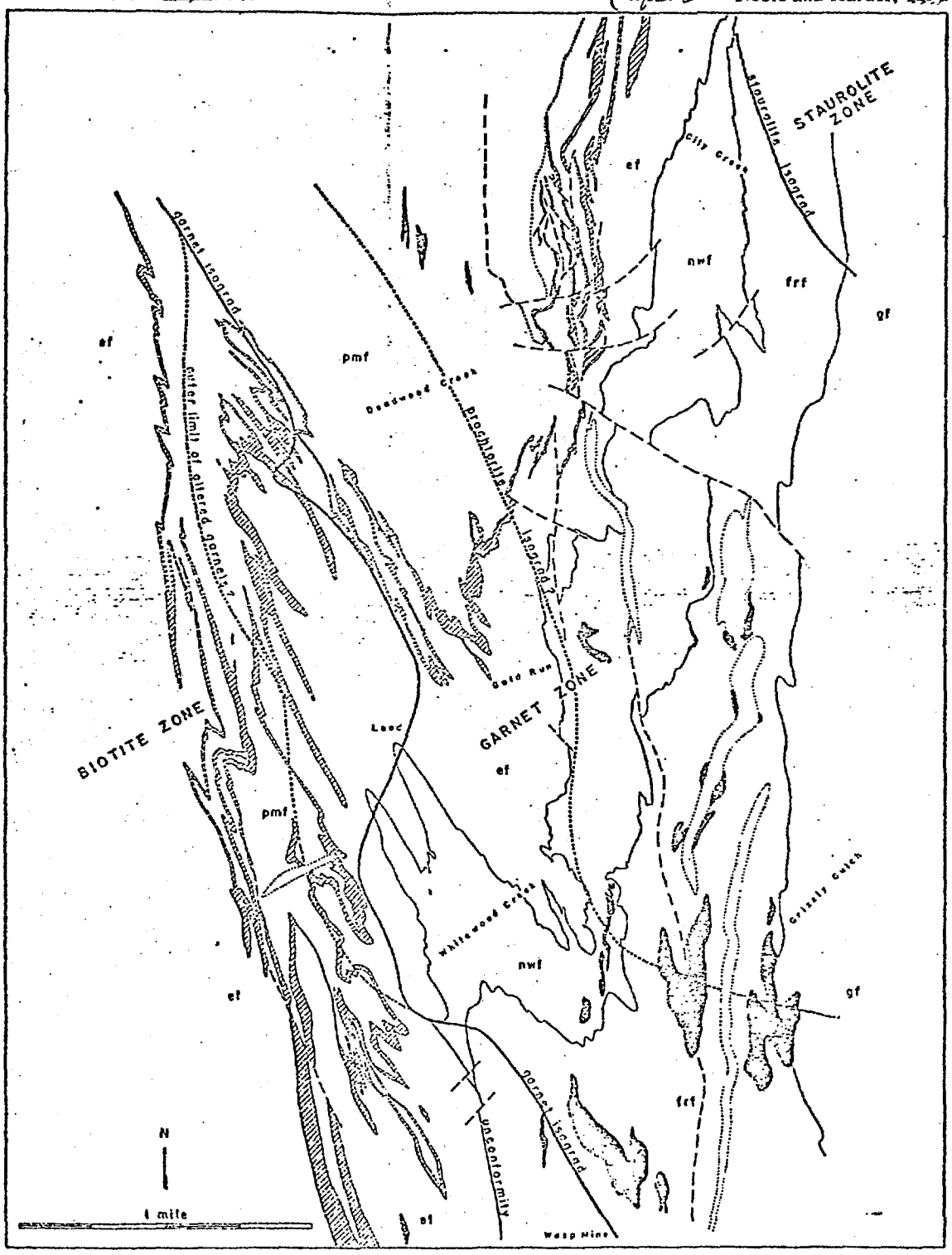
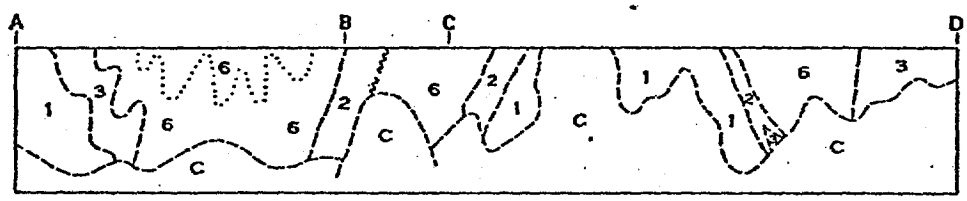

GOLD DEPOSITS RELATED TO
PRECAMBRIAN IRON FORMATION
1
2
3
4
5
6

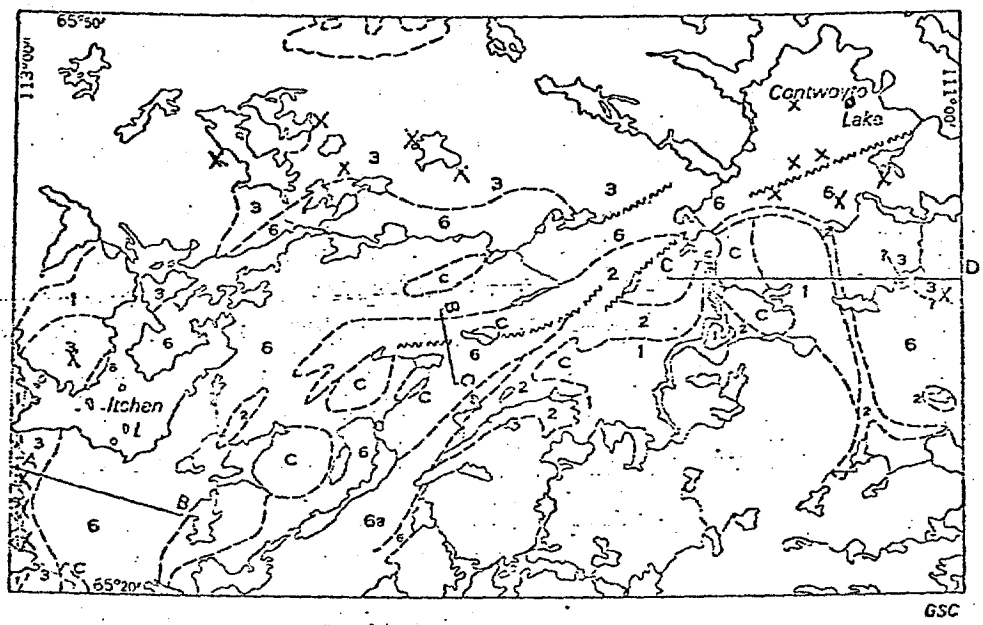
FIGURE 1



DISTRIBUTION OF THE PRE-CAMBRIAN SEDIMENTARY ROCKS AND THE METAMORPHIC ZONES IN THOSE ROCKS IN THE LEAD DISTRICT



Hypothetical section along lines A-B, B-C and C-D



LEGEND (Simplified)

6	Knotted schist, greywacke, phyllite; minor greenschist without amphibolite; 6a, rocks of lower metamorphic grade equivalent to 6
2	Volcanic rocks and related gneisses, amphibolite
3	Rock similar to 6 and 6a but including amphibolite
1	Siliceous gneisses
Fault	
C	Granitic rocks

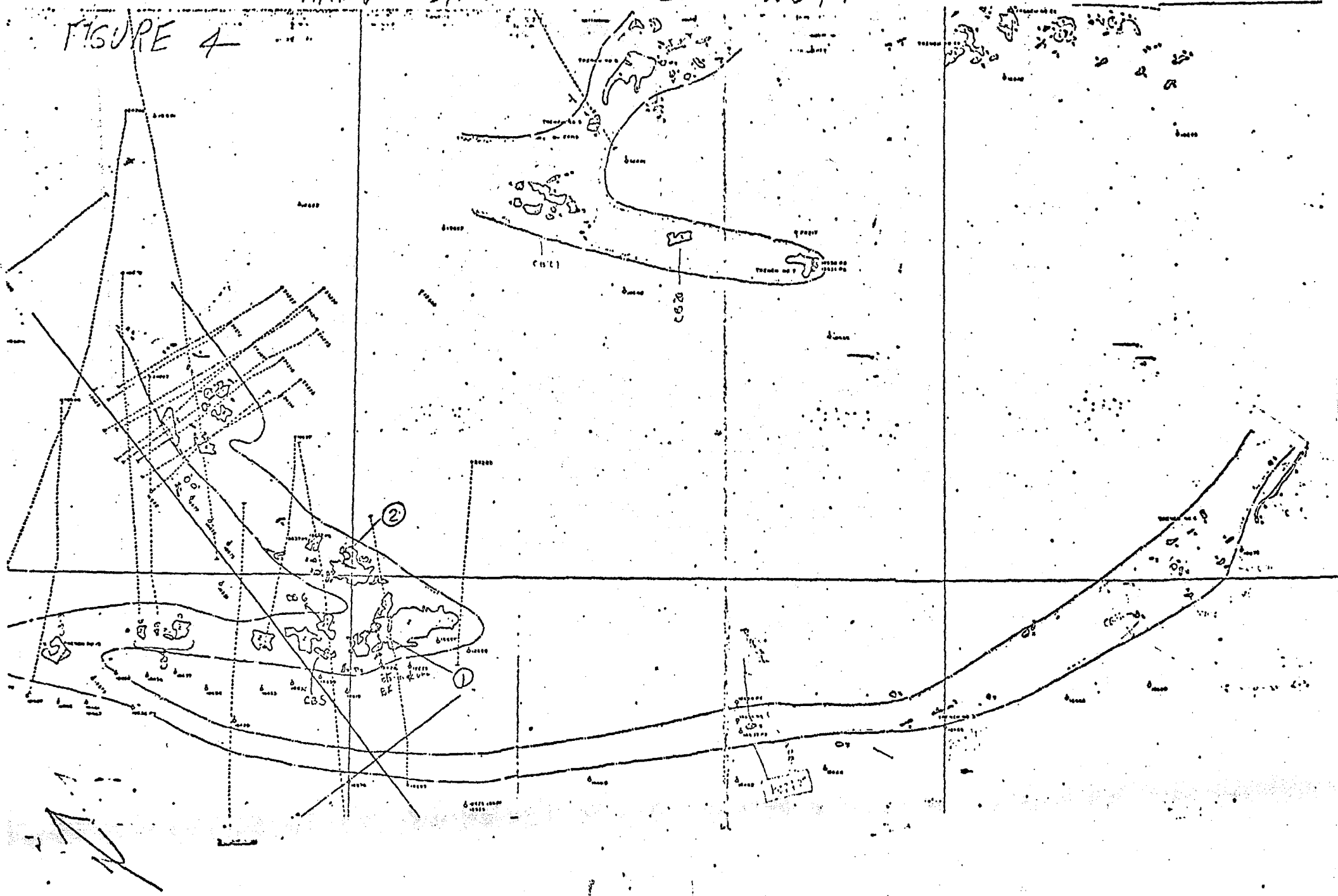
Miles 0 5 10 15

Figure 3. Hypothetical section and generalized map of the Yellowknife Group in Itchen Lake map-area. (after Bostock, 1967)

o GOLD DEPOSIT "MAIN SHOWING"

X GOLD LOCATION

FIGURE 4 MAIN SHOWING CONTWOYTO LAKE



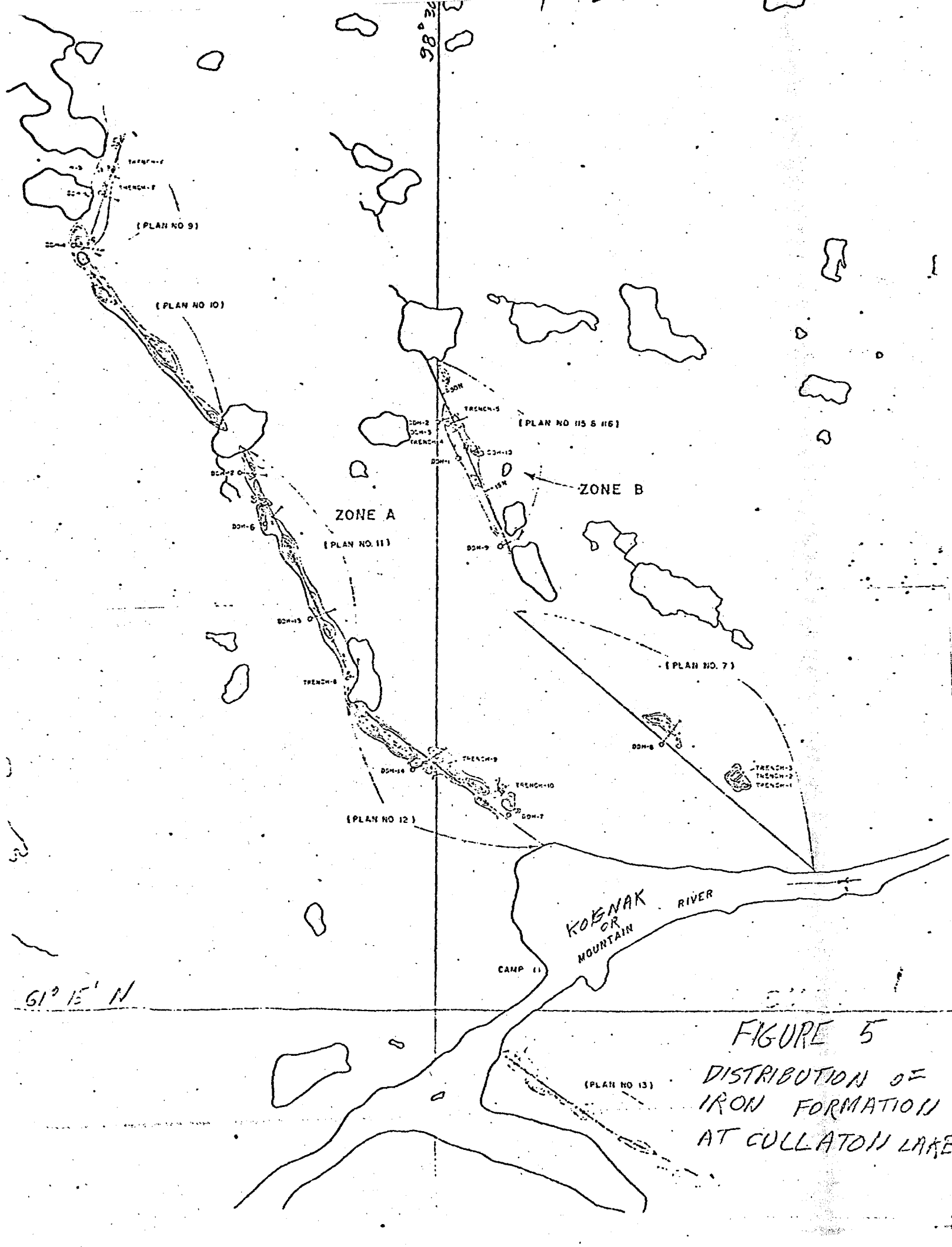


FIGURE 5
DISTRIBUTION OF IRON FORMATION AT CULLATON LAKE

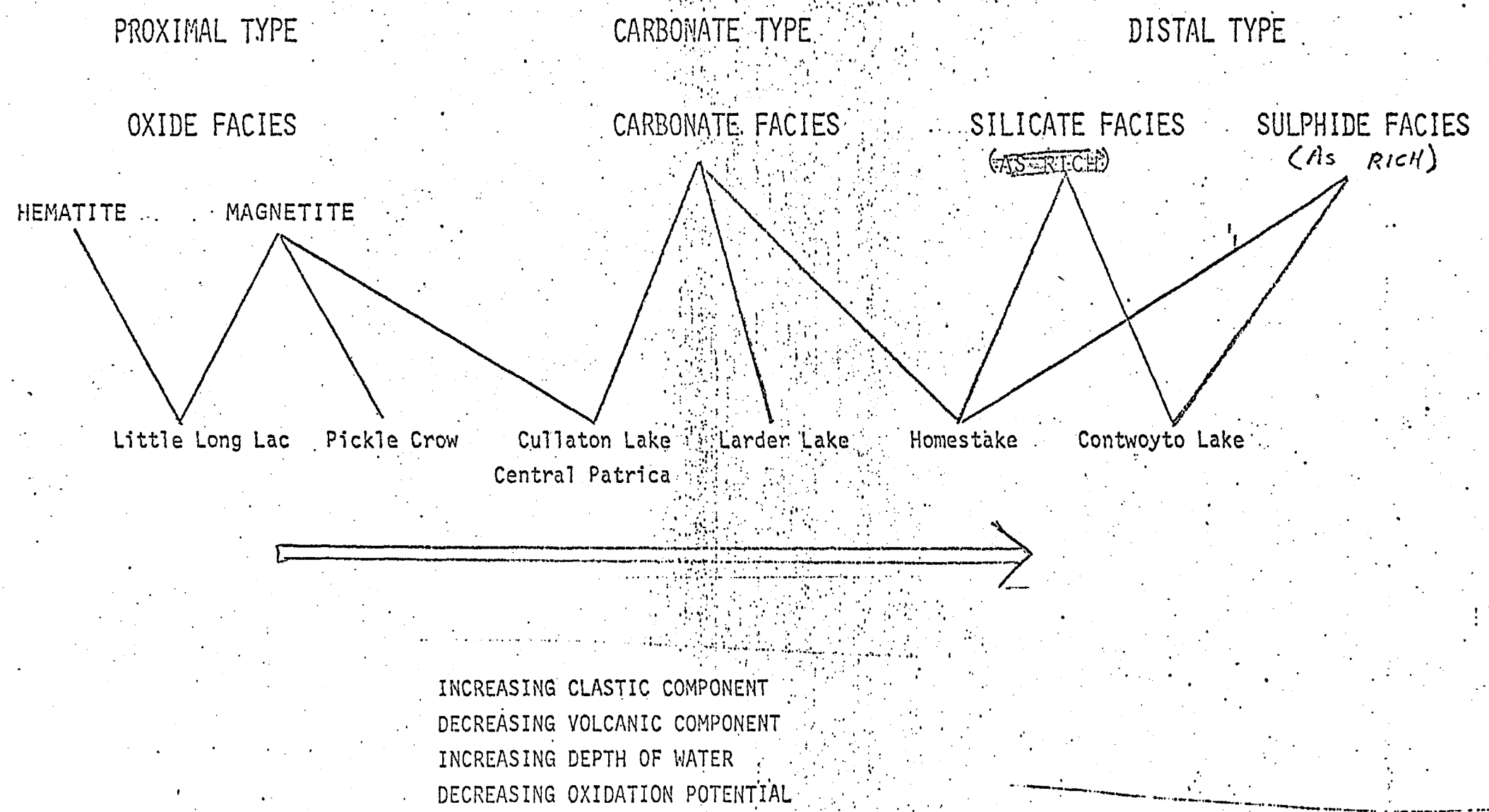

PROXIMAL TYPE
CARBONATE TYPE
DISTAL TYPE
OXIDE FACIES
CARBONATE FACIES
SILICATE FACIES
(AS RICH)
SULPHIDE FACIES
(As RICH)
HEMATITE
MAGNETITE
Little Long Lac
Pickle Crow
Cullaton Lake
Central Patrica
Larder Lake
Homestake
Contwoyto Lake
INCREASING CLASTIC COMPONENT
DECREASING VOLCANIC COMPONENT
INCREASING DEPTH OF WATER
DECREASING OXIDATION POTENTIAL

FIGURE 7

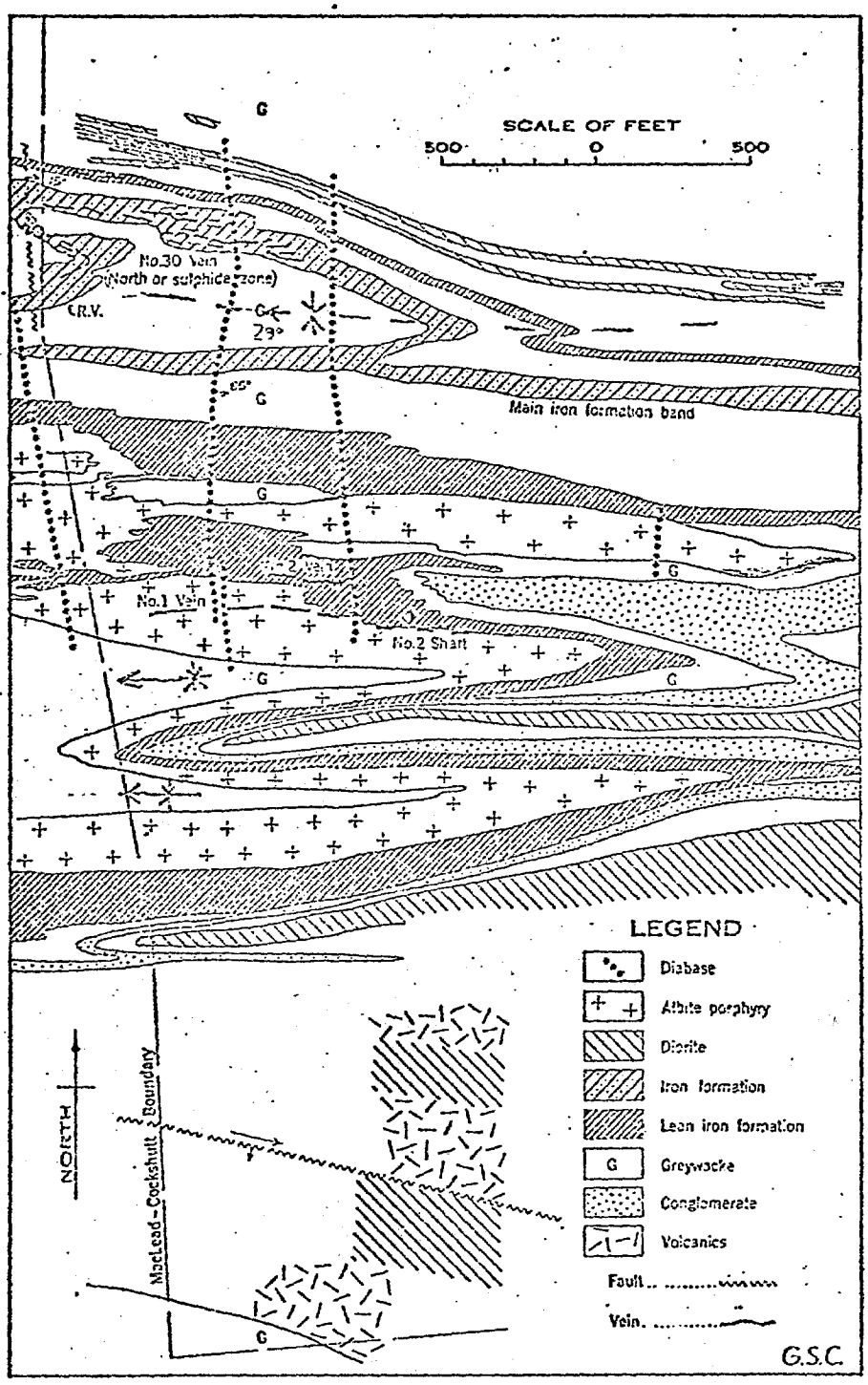


Fig. 2.—Geological plan, 250-foot level, Hard Rock mine.
6 (after Mathieson & Douglas 1948)

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in prep.

Copy: W.L.Kurtz ✓

For - Stratiform Deposits

AMERICAN SMELTING AND REFINING COMPANY
TUCSON ARIZONA

August 12, 1974

MEMORANDUM FOR: J.J. COLLINS

ANVIL MINE
FARO, YUKON

Cyprus' open pit operation, located 125 miles northeast of Whitehorse, was visited on July 13th with Messrs. Osborne, Ritchie, Anzalone and Gale. Newt Cornish, Manager, showed us around.

	Tons	Pb	Zn	Ag
Published reserve:	63 million	3.4%	5.7%	1.2 oz.
Production 1973:	2.9 million	4.6%	6.2%	?

Original mill capacity of around 7000 tpd was expanded and recently brought up to 12,000 tpd. However, the mine has not kept up with the mill and only a few weeks supply of ore is exposed in the pit. Mining is at the rate of 10,000 tpd ore and 60,000 tpd waste.

Exploration drilling was on a 300' grid with a few interspaced holes, but this proved insufficient for planning the pre-production pit, and far less ore than scheduled was mined during the first year of operation.

Mining cost, including indirect, was stated to be $1.00 per yard of broken rock. Taking ore (8.5 cu. ft/ton) and waste (12/ton) densities into account, the average cost per ton amounts to about $0.60.

The main ore zone, a flat lying tabular mass of pyrite, pyrrhotite, galena and sphalerite, is 2400' long, up to 1100' wide and up to 300' thick. The ore and the enclosing argillite stand quite well on 45° slopes; however, considerable bank failure was evident in the granitic intrusive rock on the north wall of the pit.

Mill recovery was reported to be 85-90%, with a 52% Zn concentrate and 70% Pb. Freight to Skagway, $20.00/ton.

The Anvil is one of the three stratiform ore deposits in Cambrian sediments, lying several miles apart along the northwest trend of the Pelly River, a major structural lineament. According to Brock (Geophysical Exploration Leading to the Discovery of the Faro Deposit, CIM Bull., Oct., 1973) massive sulphides of the Vangorda deposit (9 million tons of 9% combined Pb zm) were exposed in a creek and gossan outcropped at the northend of the Anvil zone.

However, attention was directed elsewhere and drilling of coincident magnetic and gravity anomalies resulted in the Swim discovery under 50' of overburden -- -- 5 million tons of 10% combined Pb-Zn and 20 million tons of massive pyrite. Ultimately, mineralized float was recognized in the Anvil area and the deposit discovered by drilling coincident geochemical and geophysical anomalies.

Tuffaceous greenstones are interbedded with the phyllitic host rocks and according to Campbell-Ethier (Sulphur Isotopes, Iron Content of Sphalerities, and Ore Textures in the Anvil Ore Body, Canada: Econ. Geol., Vol. 69, No. 4). The deposits were probably formed by volcanic-exhalative activity in a Cambrian marine basin and thus bear no genetic relation to the granitoid intrusives of Cretaceous Age. Although only traces of barite were detected in the isotopic and textural studies, an average barite content of 6-7% was reported on our visit to the mine.

J.H. Courtright

J.H. Courtright

JHC:vmh

cc: Sal Anzalone

WLK/ An interesting observation, and the comparison — Jerome-Ironking to Australian occurrences — may be valid —

But how valid is the assumption that pyrite-chlorite may represent (a part of) a halo?

The prevailing steep dips of Pre-€ in Arizona — ~~increase~~ increase the odds ~~for~~ against expl success —

JHR

THC — do you think any justification to look for there?

FILE: MASSIVE SULFIDES

AMERICAN SMELTING AND REFINING COMPANY
Tucson Arizona

W. L. K.
JAN 13 1972

January 5, 1972

cpy for Walk File

TO: W. L. Kurtz

FROM: J. D. Sell

Massive Sulfide
Exploration Technique
Jerome-Prescott Area
Yavapai County, Arizona

This is to transmit Mr. Peter Walker's file memo on the subject. Peter reviewed the literature while in Tucson and noted the similarity of features and geology of the Jerome area to other areas of Precambrian geology elsewhere in the world. His original sketch on C. A. Anderson's Bulletin 1324-C, Figure 3, paper is included for reference, although the redrafted figure clearly shows Peter's subdivisions.

As pointed out verbally by Walker, prospecting for new Jeromes and Iron Kings would be primarily along the two main horizons, but the other favorable zones could contain good mineralization. All pyritic and chloritic zones would be sampled in looking for indicative trace mineralization or halo effects. The down dip projections would then need to be drilled in looking for the massive sulfide zone.

USGS geologic maps, mainly at 1:24,000, are available for the area and would greatly facilitate an exploration program in the district.

James D. Sell

James D. Sell

JDS:lad
Enc.

AMERICAN SMELTING AND REFINING COMPANY
Tucson Arizona

December 10, 1971

FILE MEMORANDUM

Jerome-Prescott Area

A brief examination of literature on the massive sulfide deposits in the area, particularly the United Verde and Iron King deposits, indicates that these deposits show many features typical of the socalled "volcanic exhalutive" deposits found in many parts of the world, particularly in Precambrian rocks. In particular, these deposits show very similar features both on a regional and local scale to the large producers of this type found in Archean rocks.

The stratigraphic column in this area shows the same features of cyclic volcanism found in these other areas. In particular, they show several cycles of basaltic-rhyolitic volcanism with each successive cycle becoming more acidic as a whole ascending the column. In general, mineralization appears at the top of the rhyolitic phase immediately before the change to a more basic phase of volcanism and is usually confined to rhyolite fragmentals, but often with associated pipe-like bodies in the underlying rhyolites.

These bodies typically show a halo of chloritic alteration in the underlying rocks and around the pipe-like stockwork deposits as is shown at United Verde. At one deposit in Australia, this chloritic alteration zone showed as a prominent colour anomaly. The mineralized horizons often are highly siliceous and show marked concentrations of hematite and pyrite features well displayed apparently at the Iron King deposit.

Both the Iron King and United Verde occur near the top of the cyclic sequence at the close of the last full recognizable cycle (see attachment). Two full cycles can be recognized in the Ash Creek Group and three in the Big Bug Group. The tops of the lower sequences; e.g., the Buzzard rhyolite, the top of the Green Gulch Volcanics rhyolitic member, and of the Spud Mountain rhyolitic members, are also favourable zones for mineralization. Deposits of this type tend to form clusters near vent zones and may show very large variations in size in one area and a copper-zinc tabular ore body may overlie a pipe-like copper ore body.

P. N. Walker

PNW:lad
Attach.

cc: JDSell

Stratiform Deposits

Geology of the Millenbach Massive Sulphide Deposit, Noranda, Quebec

File: Molybdenum Deposits

Economic Geology
Vol. 67, 1972, pp. 731–758

Stockwork Molybdenum Deposits in the Western Cordillera of North America

K. F. Clark

Economi
Vol. 67,

* Pr

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Bunker, Missouri 63629

February 4, 1972

W. L. K.
JUL 26 1972

MEMORANDUM TO MR. JOHN J. COLLINS

Conference
Comparative Sedimentology

The following is a brief summary of five of the discussions that were given at the Conference on Comparative Sedimentology, Miami, January 27-30. Of the ten discussions, Del will summarize the first five, and I the remaining five.

The basic theme of the conference was the application of knowledge of recent sedimentary processes to ancient carbonates. The talks were extremely authoritative and well-documented. Frequent references were made to classic areas of study of recent sedimentary processes, several unknown to me. Concentration was on comparatively rapid facies changes, commonly those dominated or characterized by reefs, and little reference was made to widespread, blanket-like deposits, such as the Knox or the Upper Ordovician formations. The Bonneterre facies of Southeast Missouri fits very well into the "models" discussed.

The discussions by Bosselini and Zankl were closely related and are here considered together. Zankl briefly outlined the three-fold process of reef evolution: development of an organic framework with accompanying incrustations, sedimentation in cavities within and around the framework, and cementation. Carbonate cement was described as early fibrous and later blocky calcite. Comparison was made of carbonates of the northern and southern Alps. Bosselini divided carbonate platforms into two stages (epicontinental and oceanic) and summarized with a diagram showing the forms of Middle Triassic through Upper Jurassic carbonate platforms. These were compared with forms of platforms in other areas. An evolutionary process in the forms of carbonate platforms was implied.

Klovan described major reef development in western Canada. All reefs are underlain by a carbonate platform with an underlying unconformity. It was pointed out that the Leduc reef occurs in a basin. Possible tectonic controls of reefs were discussed. Fault control was considered, but no major evidence of this is known. Evidence of climactic control includes the hooked shape of individual reef bodies and the gradual slope of the windward side as compared to the leeward side. Pinnacle reef forms of the Rainbow area were attributed to reef development on mud mounds in the Keg River Formation. Water depth

during reef formation was indicated by the type of reef-forming organism present, and a depth sequence of organisms was outlined. This consists of corals (deep), tabular stromatolites (moderate), and massive stromatolites (shallow). The concave cross section of pinnacle reefs was attributed to differential solution during compaction.

The discussion by Wilson was of much interest. The environments of different carbonate facies were described. The topographic outline of a carbonate buildup (shelf-margin-basin) results from differential carbonate deposition, directly controlled by the degree of organic activity. As the area of optimum carbonate production is the optimum zone of organic development, climactic and tectonic controls were discussed. Climactic environments and accompanying sediments are summarized in the accompanying paper. Four tectonic environments of carbonate production were described: large off-shore platforms (the Bahamas); margins of tectonic blocks (the Delaware Basin); flat, gentle, positive areas (San Marcos); and margins of intracratonic basins (the Williston Basin).

In the discussion "Roots of Carbonate Platforms and Reefs", geophysical maps (residual gravity anomaly maps and corroborative evidence from seismic and other data) were shown to outline carbonate platform topography. Negative anomalies indicate basins, and positive anomalies indicate platforms. Anomalies were interpreted as resulting from density contrasts below the basin floors, and indicate that platform-basin topography is structurally initiated and controlled. Examples used were the Bahamas (initial form controlled by folding or faulting in the underlying Cretaceous) and the Texas Central Basin (primary control by a horst block). Reference was also made to the Canadian reefs. Amount of structural control varies greatly. Some exceptions to the successful application of anomaly maps were pointed out, a notable example being the Tampico Embayment.

In summary, the discussions were excellent. Unfortunately, abstracts of only two of the talks were distributed, and I did not recognize some of the references. If brief abstracts were made available prior to the discussions, a better understanding would result.

Adrian V. Greene

Adrian V. Greene

THE COMPARATIVE SEDIMENTOLOGY OF CARBONATES

Opening Conference of
The Comparative Sedimentology Laboratory, Fisher Island
University of Miami
Rosenstiel School of Marine and Atmospheric Science

Auditorium, 10 Rickenbacker Causeway

Friday, January 28, 9:00 - 12:30

Introduction: ROBERT N. GINSBURG

PAUL HOFFMAN Geological Survey of Canada	*The Earliest Carbonate Platforms: Northwest Territories, Canada*
EUGENE SHINN Shell Oil Company, Houston	*Comparison of Tidal Flat Deposits from the Bahamas and Persian Gulf*

2:00 - 5:30

Chairman: R. MICHAEL LLOYD

EDWARD PURDY Esso International, England	*The British Honduras Model of Carbonate Deposition*
BRUCE PURSER University of Paris	*Sedimentation and Diagenesis of Paris Basin Carbonates*

Saturday, January 29, 9:00 - 12:30

Chairman: PERRY ROEHL

PAUL ENOS, State University of New York, Binghamton	*Reefs, Platforms and Basins of the Mexican Cretaceous*
ALFONSO BOSELLINI Universita di Ferrara, Italy	*Evolution of Triassic and Jurassic Platforms in Italy*

2:00 - 5:30

Chairman: LLOYD PRAY

HEINRICH ZANKL University of Marburg, Germany	*Comparative Studies of Alpine Triassic and Holocene Reefs*
EDWARD KLOVAN University of Calgary, Canada	*The Anatomy and Evolution of Western Canadian Devonian Reefs*

Sunday, January 30, 9:00 - 12:30

Chairman: To be Announced

JAMES LEE WILSON Rice University, Houston	*Scale and Facies of Carbonate Platforms and Reef Complexes*
MAHLON BALL University of Miami	*The Roots of Carbonate Platforms and Reefs*

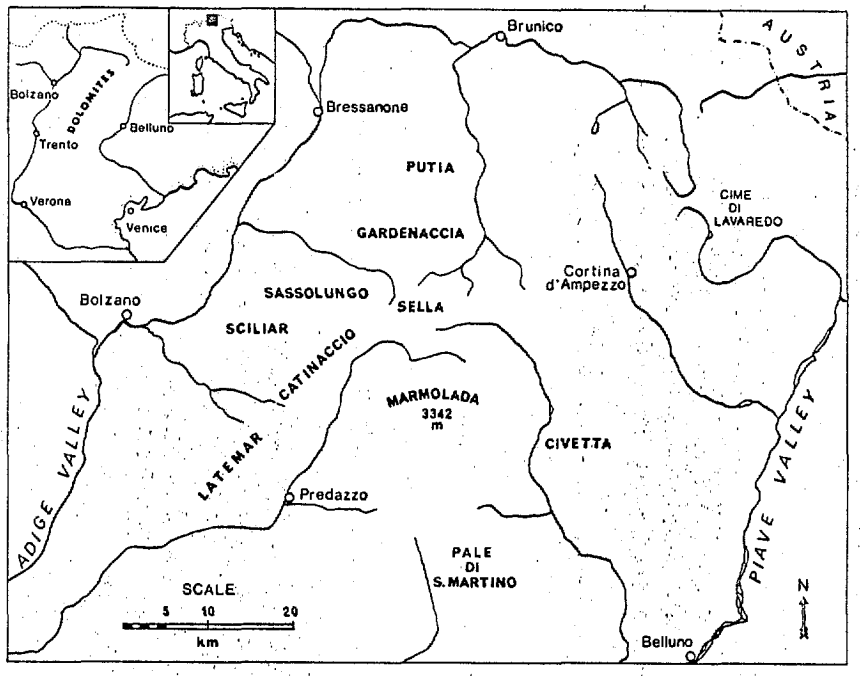


Fig. 1 - Location Map of the Dolomites and of the most important "reefs".

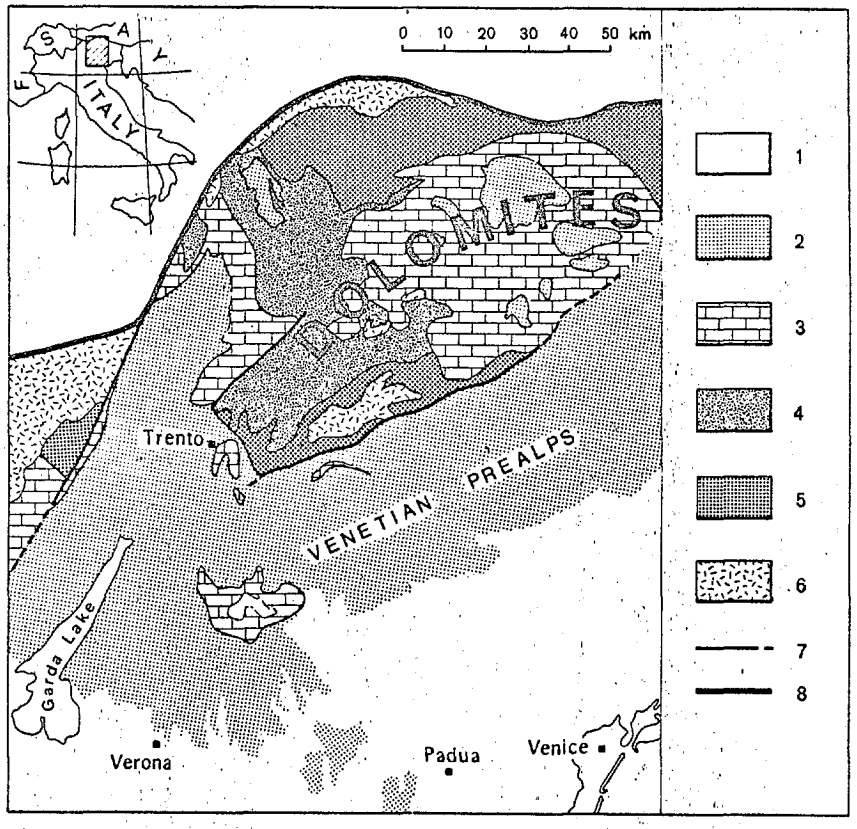


Fig. 2 - Regional geological setting of the Dolomites. 1. Alluvial plain; 2. Tertiary and Jurassic; 3. Triassic (with the "reefs"); 4 Permian ignimbrites; 5. Metamorphic basement; 6. Intrusions; 7. Major faults; 8. Tectonic boundary of the Southern Alps.

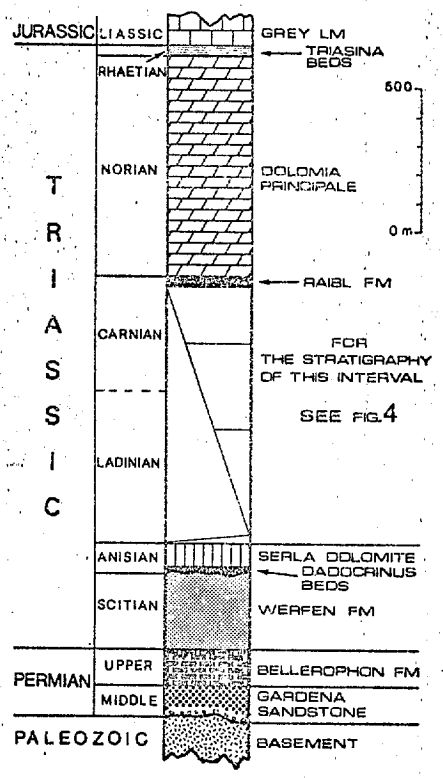


Fig. 3 - The stratigraphic column of the Dolomites.

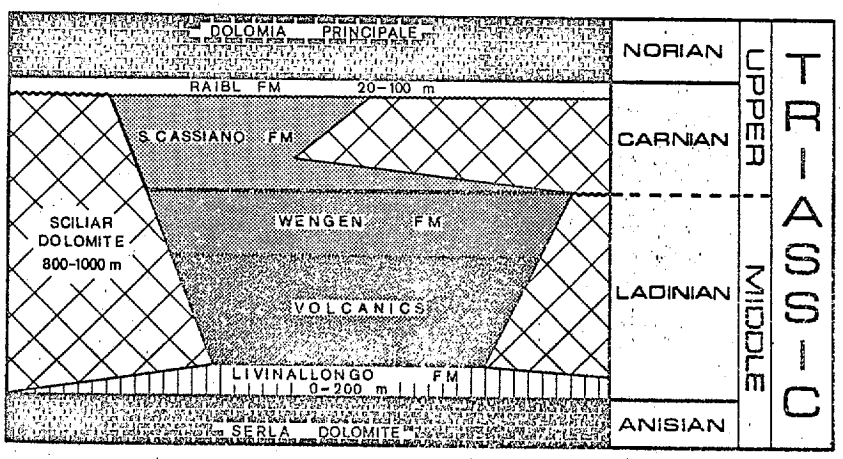
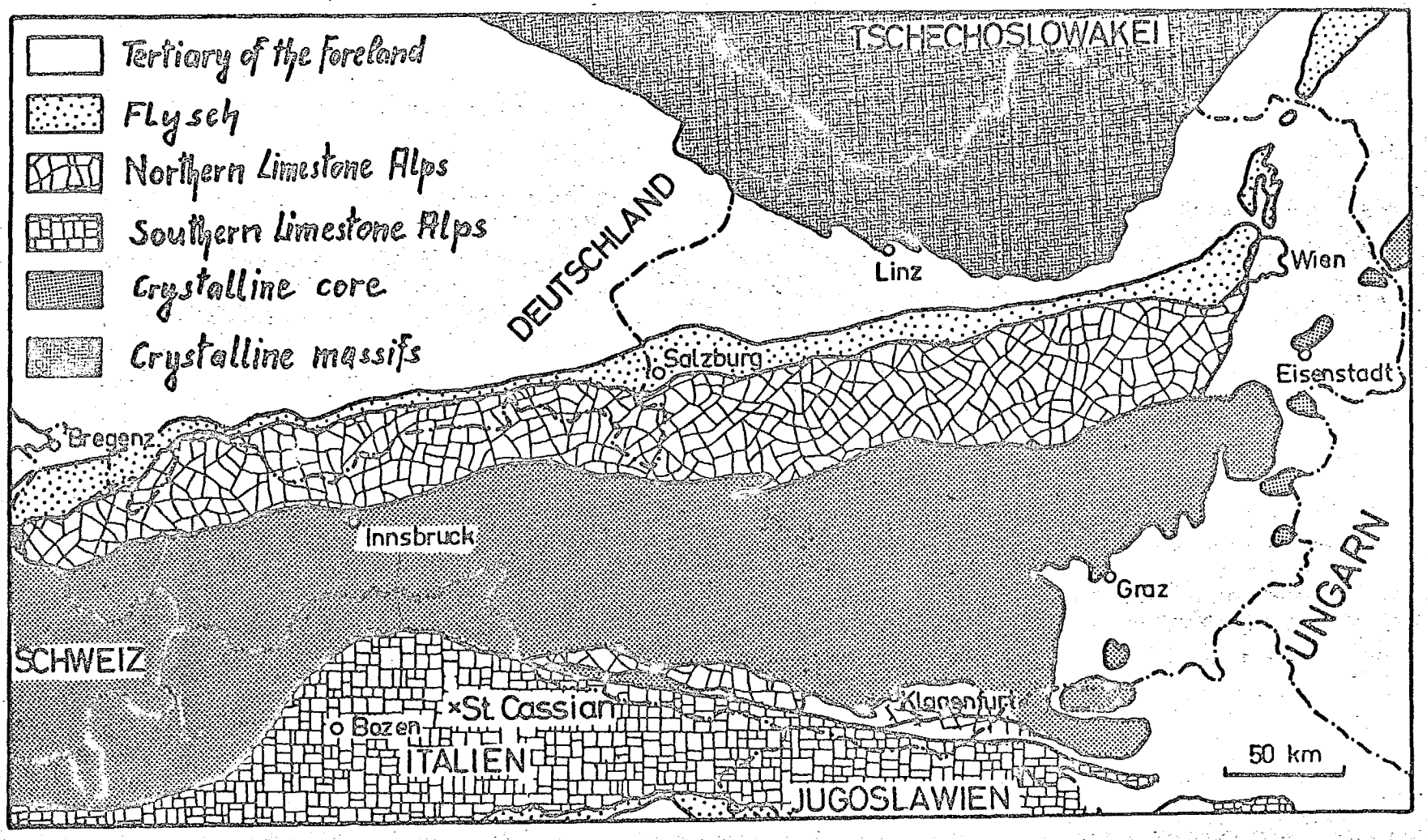
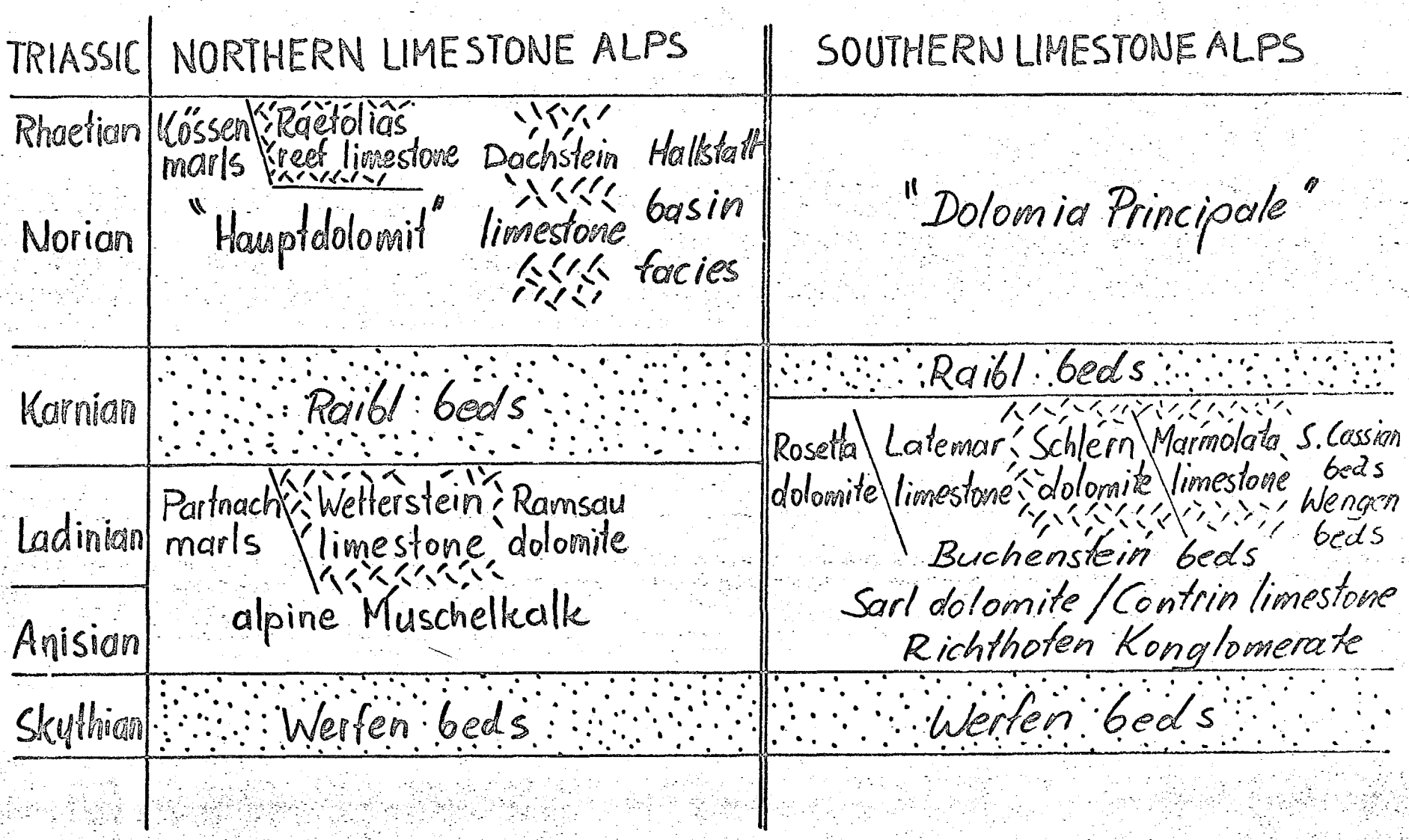


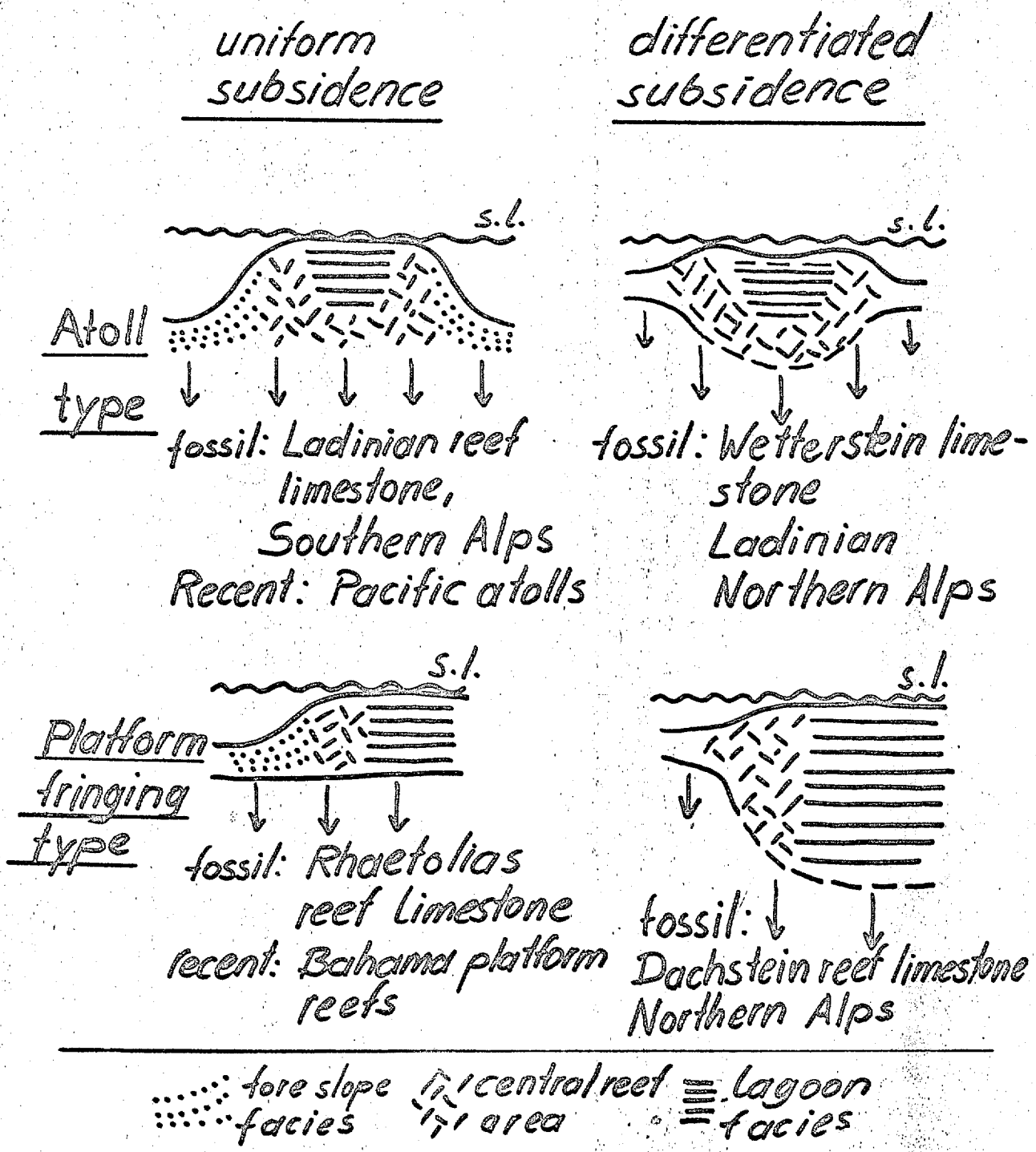
Fig. 4 - The "Dolomite sandwich"; schematic representation of the stratigraphic relationships existing between the basal Serla Dolomite and the Dolomia principale at the top.

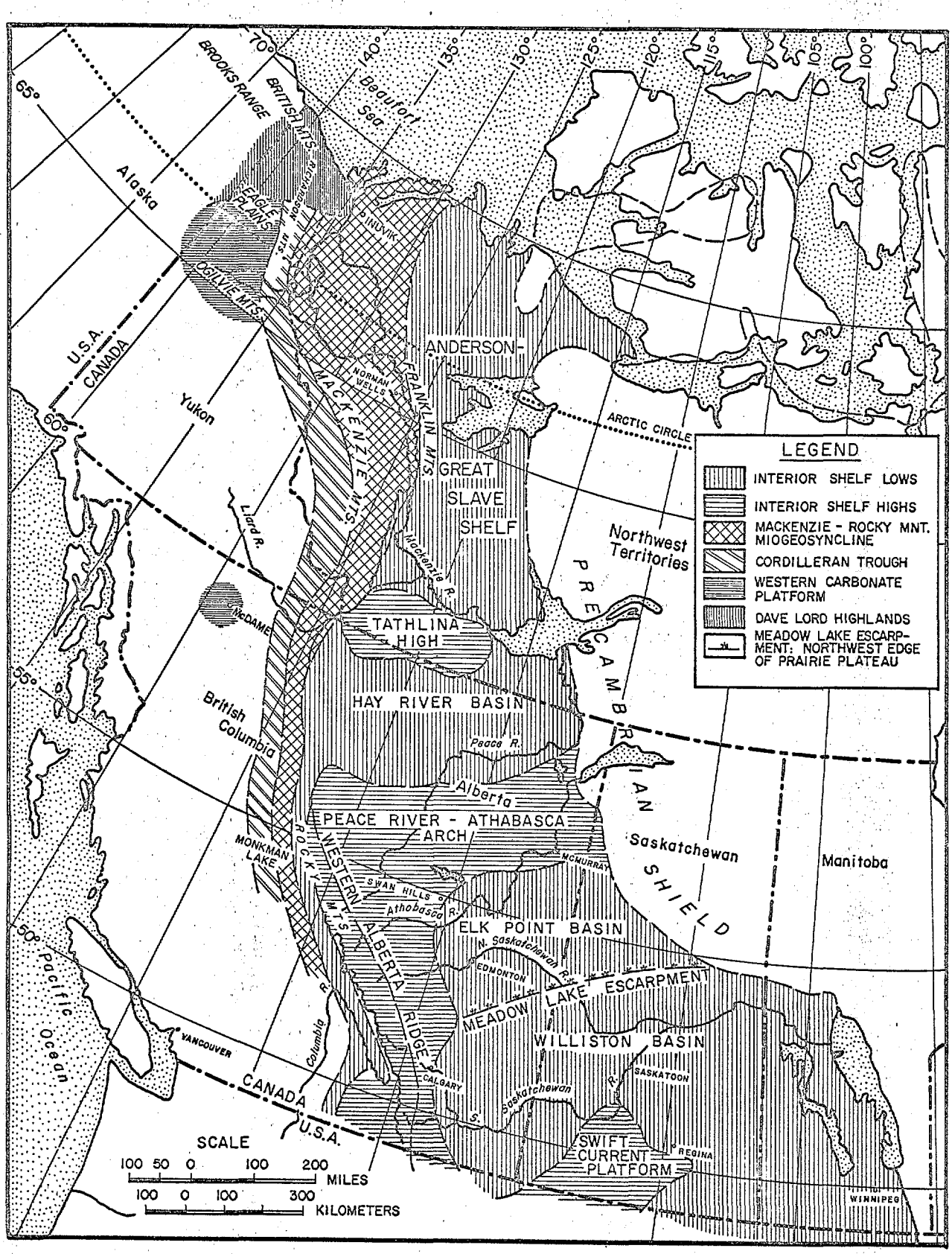


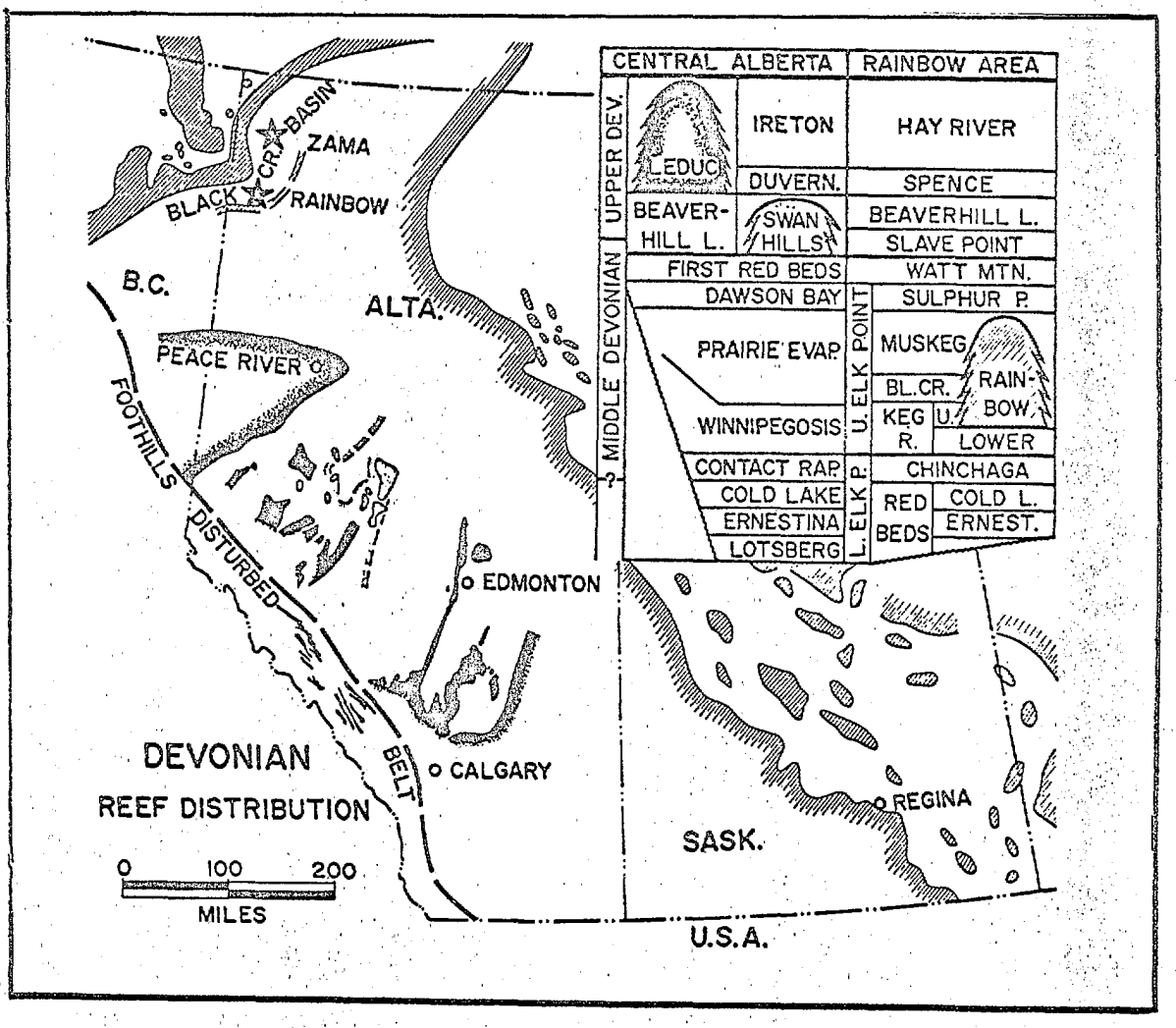
Schematic geological map of the Eastern Alps


TRIASSIC
NORTHERN LIMESTONE ALPS
SOUTHERN LIMESTONE ALPS
Rhaetian
Norian
Kössen marls
Raetolias reef limestone
Dachstein limestone
Hallstatt basin facies
"Hauptdolomit"
"Dolomia Principale"
Karnian
Raibl beds
Raibl beds
Ladinian
Anisian
Partnach marls
Wetterstein limestone
Ramsau dolomite
alpine Muschelkalk
Rosetta dolomite
Latemar limestone
Schlern dolomite
Marmolata limestone
S. Cassian beds
Wengen beds
Buchenstein beds
Sarl dolomite / Contrin limestone
Richthofen Konglomerate
Skythian
Werfen beds
Werfen beds

Triassic Reef Complexes and Modern Counterparts




LEGEND
INTERIOR SHELF LOWS
INTERIOR SHELF HIGHS
MACKENZIE - ROCKY MNT. MIOGEOSYNCLINE
CORDILLERAN TROUGH
WESTERN CARBONATE PLATFORM
DAVE LORD HIGHLANDS
MEADOW LAKE ESCARPMENT: NORTHWEST EDGE OF PRAIRIE PLATEAU
ANDERSON-
GREAT SLAVE SHELF
TATHLINA HIGH
HAY RIVER BASIN
PEACE RIVER - ATHABASCA ARCH
ELK POINT BASIN
MEADOW LAKE ESCARPMENT
WILLISTON BASIN
SWIFT CURRENT PLATFORM
PRECAMBRIAN SHIELD
WESTERN ALBERTA RIDGE
ROCKY MTS.
MACKENZIE MTS.
FRANKLIN MTS.
BROOKS RANGE
BRITISH MTS.
EAGLE PLAINS
OGILVIE MTS.
Beaufort Sea
Alaska
Yukon
U.S.A.
CANADA
British Columbia
Alberta
Saskatchewan
Manitoba
Northwest Territories
Pacific Ocean
ARCTIC CIRCLE
INUVIK
NORMAN WELLS
McDAME
MONKMAN LAKE
SWAN HILLS
McMURRAY
EDMONTON
CALGARY
SASKATOON
REGINA
WINNIPEG
VANCOUVER
Liard R.
Mackenzie R.
Peace R.
Athabasca R.
N. Saskatchewan R.
Saskatchewan R.
Columbia R.
SCALE
100 50 0 100 200 MILES
100 0 100 300 KILOMETERS



Devonian-reef distribution in Western Canada

DEPOSITIONAL FACIES ACROSS CARBONATE SHELF MARGINS

James Lee Wilson
Rice University
Houston, Texas

ABSTRACT

Nine depositional facies are described in idealized sequence across a typical carbonate shelf margin. These facies are: basinal, tidal shelf, basin margin, platform foreslope, organic reef, platform edge sands, open marine platform, restricted marine platform and platform evaporite facies. Each of these is characterized by sedimentological parameters, prevailing rock types, color, microfacies, sedimentary structure, terrigenous content, and characteristic biota. Description of this very widespread sequence should aid in location of reservoir rock.

This paper outlines an idealized schema of carbonate environments following a pattern developed so widely in the geologic record that it deserves to be generalized and thoroughly documented. The associated table (Figure 1) is from work begun by the writer when with Shell Development Company in 1965. Its essential outline was published as a discussion with W. Tyrrell in SEPM Spec. Pub. 14 (1969, p. 18) and in much more detailed form applied to Devonian carbonate complexes by J. Dooge (1966, see particularly appendices 6 and 7). Some of the general principles responsible for, and illustrations of, this common sequence of carbonate facies have been previously published by Irwin (1965), Shaw (1964), and in various papers by the following authors in SEPM Spec. Pub. 14 (1969): Tyrrell, Thomson and Thomasson, McDaniel and Pray, Laporte, and Griffith, Pitcher and Rice.

The development of this prevailing sequence of facies along any carbonate shelf margin is a natural consequence of some of the principles behind carbonate sedimentation. Carbonates are essentially of organic origin. Because of this, carbonate sediment will form well only in warm, clear, sunlit water free of clayey contamination. Such areas are apt to be somewhat removed from land and to lie down gentle paleoslopes paralleling ancient coast lines. Because the biota demands sunlight to flourish, its maximum productivity occurs only in relatively shallow water. Consequently, the mass of organic carbonate grows most rapidly on the upper part of any gentle seaward slope some distance from land but not in deep water. Continued inundation of a positive block with stable or rising sea level results in rapid organic growth and sediment accumulation along the initial growth centers and the formation of a line of shelf margin organic buildups, the gradual filling-in of the lagoon between the shelf margin and land, and eventually the construction of a ramp or platform surrounding the positive element. Not much sediment accumulates simultaneously in the area downslope from the shelf margin because, as the buildup occurs, the water becomes too deep. The normal result is a starved basin surrounded by carbonate ramps or platforms built out from the positive elements rimming the original depression.

1. *Basin facies (starved or filled) (Fondothem).* Euxinic conditions may develope below oxygenation level and below wave base. Water is from 100 to several hundred feet deep. Bottom water flowing off of surrounding shelves may become hypersaline and dense, preventing easy turnover. This situation, and lack of oxidation of the rain of organic plankton, increases the tendency toward stagnant reducing environment. Few burrowers can exist here and fine laminated sediment results. Deposition is dependent on the amount of influx of fine argillaceous and siliceous material and the rain of decaying plankton. These contributions may be slight for in a typical carbonate producing shelf, little such material crosses the surrounding shelves. A starved, rather deep-water, basin commonly results. In some cases, such basins are filled with evaporites or clastics. These may be deposited during lower sea level stands reciprocally with upbuilding of surrounding shelves, or even much later after complete formation of the carbonate platforms.

a. Prevailing rock types: Dark shale or silt, with thin limestones, some thin, bedded anhydrite. Thick salt deposits in certain instances.

b. Colors: Dark brown or black (up to several percent bituminous organic matter).

c. Grain types and depositional texture: Lime mudstones and calcisiltites, micropelletoids, microbioclastics.

d. Bedding and sedimentary structures: Very even planar thin lamination, ripple cross-lamination, small scale rhythmic bedding consisting of even beds of limestone intercalated with thin shales.

e. Terrigenous clastics: Somewhat admixed with carbonates and also interbedded in thin layers. Quartz silt and shale. Material windblown as well as water-carried. Chert very common, probably derived both from opaline organisms and from solution and replacement of quartz silt by carbonate.

f. Biota: Exclusively nektonic-pelagic fauna preserved in local abundance on bedding planes. Microfauna thoroughly admixed with fine sediment. Megafauna includes graptolites, planktonic bivalves, ammonites, and sponge spicules. Microfauna includes calcareous calpionellids, tintinnids, and calcispheres, and siliceous radiolarians and diatoms.

2. *Tidal shelf facies (deep Undathem).* Water tens or even a few hundred feet deep, generally oxygenated and of normal marine salinity. Good current circulation. Deep enough to be below normal wave base but intermittent storms effect bottom sediments. Such shelves are generally wide and sedimentation is quite uniform. This is the typical

realm of deeper neritic sedimentation and may consist of carbonate or shale.

a. Prevailing rock types: Very fossiliferous limestone interbedded with marls. Well segregated beds.

b. Colors: Gray, green, red, and brown due to variable oxidizing and reducing conditions.

c. Grain types and depositional texture: Bioclastic and whole fossil wackestone. Some calcisiltites. Much pelleting of micrite matrix.

d. Bedding and sedimentary structures: Sediment thoroughly burrowed, beds homogenized. Thin to medium, wavy to nodular beds. Ball and flow (shale/carbonate compaction structure) prominent in argillaceous limestones. Bedding surfaces show diastems, lag concentrates of fossils.

e. Terrigenous clastics: Quartz silt, siltstone, and shale commonly interbedded with limestones in clearly segregated layers.

f. Biota: Very diverse shelly fauna indicating normal marine salinity; preservation of both infauna and epifauna. Fauna locally less common, but generally present. Notable presence of brachiopods, corals, cephalopods, echinoderms (stenohaline forms) along with all other organisms.

3. *Basin margin or deep shelf margin facies (Clinothem).* Formed at toe of slope of carbonate producing shelf. Water of about same depth as preceding two facies. Situated at or below wave base and oxygen level. Sediments composed of carbonate and siliceous material derived from nearby shelf, the argillaceous matter having drifted or blown farther out into basin. May resemble basinal sediments but are non-argillaceous and somewhat thicker.

a. Prevailing rock type: Fine grained limestone, in some places cherty.

b. Color: Ranging from dark to light.

c. Grain types and depositional texture: Mostly lime mudstone with some calcisiltite. Some microbreccia beds.

d. Some beds are laminated with micrograding of lithoclastic and bioclastic debris from upslope. Locally exotic blocks.

e. Bedding and sedimentary structures: Some beds are laminated lime mudstones, other thicker-bedded units are of massive unlaminated lime mudstone. In other beds, lithoclastic and bioclastic fragments derived from upslope, show micrograding. Locally exotic blocks. Megaslump features within evenly bedded limestone cause major discontinuities in bedding. Mud bioherms in some places.

f. Terrigenous clastics: Rarely present except as fine shale partings. Chert is common.

g. Biota: Bioclastic detritus derived principally from upslope. Fauna is open shelf and normal marine types but may be a mixture of reworked forms derived from shelf, benthonic organisms living on slope, and some pelagic forms.

4. *Foreslope facies of carbonate platform (marine talus) (Clinothem).* Generally, the slope is located above the lower limit of oxygenated water and extends from above to below wave base. Composed of debris deposited on an incline formed seaward as the ramp grows. Incline may be as steep as 30°. Sediment is somewhat unstable and varies greatly in size and shape. There may be bedded, fine-grained layers with megaslumps, foreset bedded and wedge-shaped beds consisting principally of lime sand, and mound or lens-shaped masses of trapped and stabilized fine grained carbonate sediment.

a. Prevailing rock types: Limestone, the type depending on water energy upslope; lime muds and sands, boundstone, and sedimentary breccia.

b. Color: Dark to light.

c. Grain types and depositional texture: Lime silts and bioclastic wackestone-packstone. Lithoclasts of varying shapes and sizes derived from cemented strata upslope. Much reworked material with locally derived organic debris.

d. Bedding and sedimentary structures: Megaslumps in thinly bedded strata; large scale foreset bedding (wedges); large exotic blocks interrupting bedding; slope mounds of fine-grained sediment; syngenetic slumps, pull-aparts, and breccias; clastic injection dykes and fissure fillings.

e. Terrigenous clastics: Mostly pure carbonate but some shale, silt, and fine quartz sand drift downslope from above and admix with carbonate or fill cavities.

f. Biota: Mostly bioclastic debris from upslope but also colonies of in-place encrusting organisms. May be very fossiliferous. Fauna varied, open marine.

5. *Organic reef of platform margin:* Ecologic character dependent on water energy and steepness of slope, organic productivity, amount of frame construction, binding or trapping, frequency of subaerial exposure and consequent cementation. Three types of linear shelf-margin organic buildups may be discerned: (1) Downslope mud and organic detritus accumulations (2) low energy organic framebuilding reefs with isolated clumps or encrusting sheets of organisms growing up to wave base and stabilizing debris accumulations. (These exist in water a few tens of feet deep.) (3) frame constructing reefs like modern coral-algal assemblages with sessile forms growing up through wave base into the surf zone. Such fringes of organic growth at shelf margins may alternate with banks and shoals of winnowed sands (Facies 6).

a. Prevailing rock type: Massive limestone and dolomite in places consisting solely of organic skeletons.

b. Color: Light.

c. Grain types and depositional texture: Masses and patches of organic boundstone. Interstices may be filled with lime mudstone in downslope reefs and with grainstone and packstone in upslope accumulations. Some mounds formed by clumps of organisms growing in upslope position have solely mud matrix owing to protection from winnowing by reef frame. Interstices in boundstone of higher energy reefs are filled only with lime sand and gravel. Intermound areas consist commonly of grainstone and packstone.

d. Bedding and sedimentary structures: Massive organic framework with constructed (roofed) cavities. Lamination caused by organic growth swells and thickens upward. In mounds with considerable lime-mud matrix, stromatactis-like structure is common. Brecciation and fissuring of massive buildups common, injection dykes present.

e. Terrigenous clastics: Essentially absent.

f. Biota: Colonies of sessile framebuilding organisms may or may not dominate. Growth form determined clearly by water energy. Forms may also be low-lying and encrusting. Ramose or dendritic forms exist in more protected places. Communities of abundant accessory organisms dwelling in various ecologic niches may form beds (*e.g.* – layers of brachiopods, molluscs, or crinoids).

6. *Winnowed platform edge sands:* These take the form of shoal, beaches, off-shore or tidal bars in fans or belts, or eolianite dune islands. Depths of such marginal sands range from sea level to 20 or 30 feet. Much clean sand is winnowed by the waves and deposited by waves, or by tidal or longshore currents of 1 to 2 knots. The salinity is commonly normal marine because of good circulation. The environment is well oxygenated but not hospitable to marine life because of the shifting substrate.

a. Prevailing rock type: Cross-bedded calcareous or dolomitic lime sand.

b. Color: Light.

c. Grain types and depositional texture: Rounded and fairly well-sorted grainstones. Some are coated and oolitic. Others are merely rounded bioclasts.

d. Bedding and sedimentary structures: Marine sands with medium-to small-scale festoon cross-bedding. Eolianites have large scale cross-bedding. Surfaces representing stratigraphic hiatuses are common in both marine and non-marine environments. Eolianites have old soil horizons and root casts preserved.

e. Terrigenous clastics: Quartz sand may be present with the calcarenites.

f. Biota: Worn and abraided coquinas of benthonic animals living on reef and foreslope are common. Few indigenous organisms because of shifting substrate. Large bivalves (megalodonts) or gastropods are common as are fragmented remains of large dasycladacean algae and certain foraminifera.

7. *Open marine platform facies (Shallow Undathem).* Geographically such environments are located in straits, open lagoons and bays behind the outer platform edge. Water depth shallow, generally a few tens of feet deep. Salinity varies from essentially normal marine to hypersaline; circulation is very moderate. Water conditions are favorable for organisms but often the stenohaline forms are excluded. The sediments are texturally varied but contain considerable amounts of lime mud.

a. Prevailing rock types: Various limestones and, in some places, land-derived clastics.

b. Color: Light and dark.

c. Grain types and depositional texture: Great variety of textures, grainstone to mudstone, *e.g.*, lime-sand bodies, beds of bioclastic wackestones, mounds and lenses of organically produced sediment, and areas of clastics.

d. Bedding and sedimentary structures: Medium to platy bedded; burrowing and pelleting of sediment common. When clay is admixed, ball and flow compaction structures are present, as well as nodular and wavy bedding.

e. Terrigenous clastics: When present, generally in well-segregated beds intercalated with limestones.

f. Biota: Fauna may be abundant. Mollusks, sponges, arthropods, foraminifera, and algae particularly common. Patch reefs are present. Abundant marine grasses and trees play important role in trapping and stabilizing fine sediment in shallow water. Organisms requiring normal marine salinity are rare, *e.g.* brachiopods, cephalopods, echinoderms.

8. *Facies of restricted circulation on marine platform:* Includes mostly fine sediment in very shallow, cut-off ponds and lagoons, coarser sediment in tidal channel and local beaches, and the whole complex of tidal flat environment. The environment is extremely variable and is a stress environment for organisms. It includes fresh, salt, and even hyperslaine water, areas of subaerial exposure, both reducing and oxydizing conditions, and both marine and fresh-water swamp vegetation. Windblown clastics may contribute significantly in some places. Diagenetic effects are strongly marked in the resulting sediment.

a. Prevailing rock types: Generally lime-muddy sediment with much dolomite.

b. Color: Light.

c. Grain type and depositional texture: Highly varied, most sediments including lime mud; grainstone rare except for thoroughly pelleted sediment. Channels contain lithoclastic grainy sediment; clotted, pelleted mudstones and wackestones most common.

d. Bedding and sedimentary structures: Much laminated mudstone, fenestral (birdseye) fabric, algal stromatolite, small-scale graded bedding, dolomite and caliche crusts, channel sands show cross-bedding.

e. Terrigenous clastics: Rare except for windblown material; where present, usually in well-segregated layers.

f. Biota: Very limited fauna and flora, mainly gastropods, algae, foraminifera (miliolids), and ostracods. These organisms may occur locally in great abundance.

9. *Platform evaporite facies:* The supratidal and inland pond environment of the restricted marine platform developed in an evaporative climate----the areas of sebka, salinas, salt flats. Intense heat and aridity common, at least seasonally. Marine flooding sporadic. Gypsum or anhydrite formed from evaporating sea water in the sediments is both depositional and diagenetic. Dense evaporative brines refluxing through the sediment and capillary pull of evaporating interstitial waters to the surface are important processes.

a. Prevailing rock types: Nodular and wavy anhydrite, or gypsum interlaminated with dolomite. Such rock types commonly are associated with redbeds.

b. Color: Highly variable, red, yellow, brown.

c. Grain type and depositional texture: Very fine grain carbonate sediment; gypsum/anhydrite crystals often form a felted mat of tiny lath-shaped crystals or, when secondary, are large bladed and poikilotopic.

d. Bedding and sedimentary structures: Laminate, both wispy and planar types, mud cracks, stromatolite and spongiostrome structure, gypsum rosettes and selenite blades (pseudomorphed by anhydrite), and syngenetic, diagenetic and deformational structures such as nodular and chicken-wire (flaser) structure, ptygmatic (contorted) folding. Also diastem surfaces, caliche crusts are common.

e. Terrigenous clastics: May be very common, redbeds and windblown sediment.

f. Biota: Almost no indigenous fauna except for blue-green algal stromatolites, brine shrimp.

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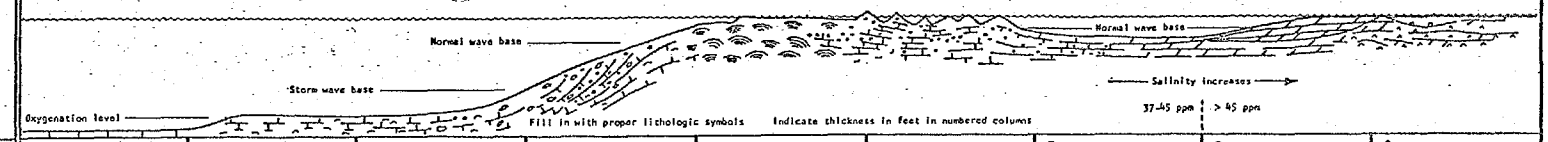
Scaled Cross Section

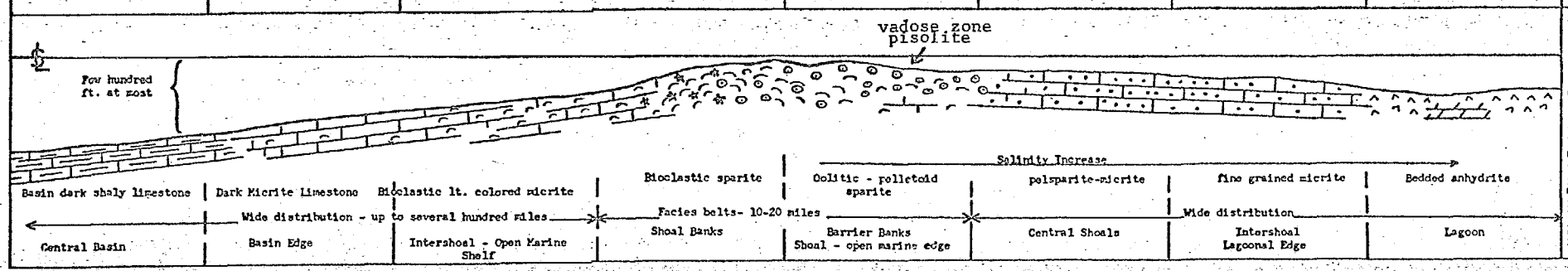
Sketch (x10 vertical exaggeration) showing true relative width of facies belts.

Diagrammatic Cross Section



Facies Number & Thickness	1 ____ feet	2 ____ feet	3 ____ feet	4 ____ feet	5 ____ feet	6 ____ feet	7 ____ feet	8 ____ feet	9 ____ feet
Facies	BASIN (EUXINIC OR EVAPORITIC) a. FINE CLASTICS b. CARBONATES c. EVAPORITES	TIDAL SHELF (UNDAFORM) OPEN MARINE NERITIC a. CARBONATES b. SHALE	TOE OF SLOPE CARBONATES	FORESLOPE a. BEDDED FINE GRAIN SEDIMENTS WITH SLUMPS b. FORESET DEBRIS AND LIME SANDS c. LIME MUD MASSES	ORGANIC (ECOLOGIC) REEF a. BOUNDSTONE MASS b. CRUST ON ACCUMULATION OF ORGANIC DEBRIS AND LIME MUD	SANDS ON EDGE OF PLATFORM a. SHOAL LIME SANDS b. ISLANDS WITH DUNE SANDS	OPEN PLATFORM (NORMAL MARINE, LIMITED FAUNA) a. LIME SAND BODIES b. WACKESTONE-MUDSTONE AREAS, BIOHERMS c. AREAS OF CLASTICS	RESTRICTED PLATFORMS a. BIOCLASTIC WACKESTONE, LAGOONS AND BAYS b. LITHO-BIOCLASTIC SANDS IN TIDAL CHANNELS c. LIME MUD-TIDE FLATS d. FINE CLASTIC UNITS	PLATFORM EVAPORITES a. NODULAR ANHYDRITE AND DOLOMITE ON SALT FLATS b. "LAMINATED EVAPORITE IN PONDS
Lithology	DARK SHALE OR SILT, THIN LIMESTONES (STARVED BASIN). EVAPORITE FILL WITH SALT.	VERY FOSSILIFEROUS LIMESTONE INTERBEDDED WITH MARLS. WELL SEGREGATED BEDS.	FINE GRAIN LIMESTONE. CHERTY IN SOME CASES.	VARIABLE, DEPENDING ON WATER ENERGY UPSLOPE. SEDIMENTARY BRECCIAS AND LIME SANDS.	MASSIVE LIMESTONE-DOLOMITE.	CALCARENITIC-OOLITIC LIME SAND OR DOLOMITE.	VARIABLE CARBONATES AND CLASTICS.	GENERALLY DOLOMITE AND DOLOMITIC LIMESTONE.	IRREGULARLY LAMINATED DOLOMITE AND ANHYDRITE, MAY GRADE TO RED BEDS
Color	DARK BROWN, BLACK.	GRAY, GREEN, RED, BROWN.	DARK TO LIGHT.	DARK TO LIGHT.	LIGHT.	LIGHT.	DARK TO LIGHT.	LIGHT.	RED, YELLOW, BROWN.
Grain Type and Depositional Texture	LIME MUDSTONES, FINE CALCISILTITES.	BIOCLASTIC AND WHOLE FOSSIL WACKESTONES. SOME CALCISILTITES.	MOSTLY LIME MUDSTONE WITH SOME CALCISILTITES.	LIME SILT & BIOCLASTIC WACKESTONE-PACKESTONE. LITHOCLASTS OF VARYING SIZES.	BOUNDSTONES AND POCKETS OF GRAINSTONE. PACKSTONE.	GRAINSTONES WELL SORTED. ROUNDED.	GREAT VARIETY OF TEXTURES. GRAINSTONE TO MUDSTONE.	CLOTTED, PELLETED MUDSTONE & GRAINSTONE. LAMINATED MUDSTONE. COARSE LITHOCLASTIC WACKESTONE IN CHANNELS.	
Bedding and Sedimentary Structures	VERY EVEN MM LAMINATION. RHYTHMIC BEDDING. RIPPLE CROSS LAMINATION.	THOROUGHLY BURROWED. THIN TO MEDIUM, WAVY TO NODULAR BEDS. BEDDING SURFACES SHOW DIASTEMS.	LAMINATION MAY BE MINOR. OFTEN MASSIVE BEDS. LENSES OF GRADED SEDIMENT. LITHOCLASTS AND EXOTIC BLOCKS.	SLUMP IN SOFT SEDIMENTS. FORESET BEDDING. SLOPE BIOHERMS. EXOTIC BLOCKS.	MASSIVE ORGANIC STRUCTURE OR OPEN FRAMEWORK WITH ROOFED CAVITIES. LAMINATION CONTRARY TO GRAVITY.	MEDIUM TO LARGE SCALE CROSS-BEDDING. FESTOONS COMMON.	BURROWING TRACES VERY PROMINENT.	BIRDSEYE, STROMATOLITES, MM LAMINATION, GRADED BEDDING. DOLOMITE CRUSTS ON FLATS. CROSS-BEDDED SAND IN CHANNELS.	ANHYDRITE AFTER GYPSUM. NODULAR, ROSETTES, CHICKEN-WIRE, AND BLADES. IRREGULAR LAMINATION. CARBONATE CALICHE.
Terrigenous Clastics admixed or interbedded	QUARTZ SILT AND SHALE, FINE GRAIN SILTSTONE. CHERTY.	QUARTZ SILT, SILTSTONE AND SHALE. WELL SEGREGATED BEDS.	SOME SHALES, SILT AND FINE GRAINED SILTSTONE.	SOME SHALES, SILT AND FINE GRAINED SILTSTONE.	NONE.	ONLY SOME QUARTZ SAND ADMIXED.	CLASTICS AND CARBONATES IN WELL SEGREGATED BEDS.	CLASTICS AND CARBONATES IN WELL SEGREGATED BEDS.	WINDBLOWN, LAND DERIVED ADMIXTURES. CLASTICS MAY BE IMPORTANT UNITS.
Biota a. General Description	EXCLUSIVELY NEKTONIC-PELAGIC FAUNA PRESERVED IN LOCAL ABUNDANCE ON BEDDING PLANES.	VERY DIVERSE SHELLY FAUNA PRESERVING BOTH INFAUNA AND EPIFAUNA.	BIOCLASTIC DETRITUS DERIVED PRINCIPALLY FROM UPSLOPE.	COLONIES OF WHOLE FOSSIL ORGANISMS AND BIOCLASTIC DEBRIS.	MAJOR FRAME BUILDING COLONIES WITH RAMOSE FORMS IN POCKETS. IN SITU COMMUNITIES DWELLING IN CERTAIN NICHES.	WORN AND ABRADED COQUINAS OF FORMS LIVING AT OR ON SLOPE. FEW INDIGENOUS ORGANISMS.	NORMAL MARINE FAUNA LACKING (e.g. ECHINODERMS, CEPHALOPODS, BRACHIOPODS). MOLLUSCA, SPONGES, FORAMS, ALGAE ABUNDANT. PATCH REEFS PRESENT.	VERY LIMITED FAUNA, MAINLY GASTROPODS, ALGAE, CERTAIN FORAMINIFERA (e.g. MILIOLIDS) AND OSTRACODS.	ALMOST NO INDIGENOUS FAUNA, EXCEPT FOR STROMATOLITIC ALGAE.
b. Organisms: dominant →									

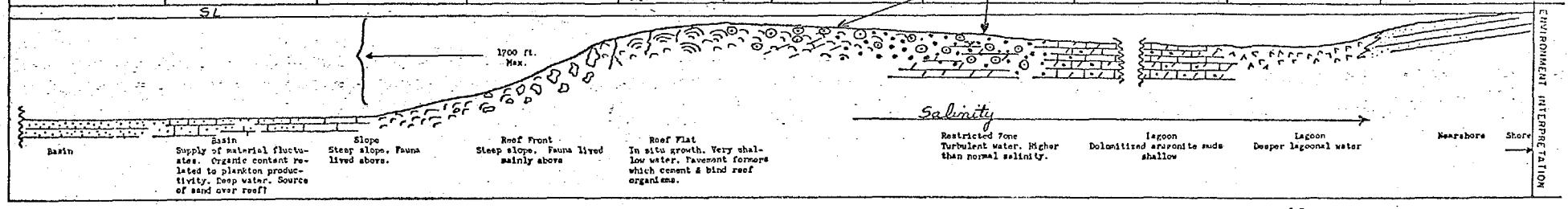
REFERENCE	FORMATIONS					AGE	LOCATIONS	
R.W.Edie - ASPG Jour. Vol. 5, p. 149 F.W.Beales- " " " ", p. 227	Upper Lodgepole - Upper Mission Canyon			Midale Porosity		Mississippian	So. Saskatchewan	
Dk. shaly - siliceous, dense limestone w/gray-brown chert. Thin bedded. Shale partings.	Dark gray limestone. Gray calcareous shale partings.	Cream-white chalky limestone Wide spread silt bands.	Cream white fossil fragmental limestone in banks. 5-10 mile band wide spread silt bands	Cream-white foram - oolitic - pelletoid limestone. 5-10 mile band Wide spread silt bands	Light buff pisolitic, oolitic, pelletoid. Intraformational conglomerate. Pure limestone. 4% silica, clay, Fe, Mg.	Lt. buff aphanitic and microgranular limestone. Scattered oolitic pellet. Silt bands.	Cream white chalky limestone. Earthy dolomite. Dark gray dense limestone, associated bedded anhydrite	ROCK TYPES
Micrite, Bioclastic calcisiltite - spicular	Calcisiltite, Micrite	Micrite Bioclastic	Bioclastic calcarenites - sparite, Slightly oolitic Chalk beds known locally.	Calcarenites - oolitic, skeletal w/oolitic coating. Pelletoid Micrite & sparite	Non skeletal calcar. 69% Oolitic-pisolitic 14 Non skeletal calcisilt 9 Skeletal debris 6 Lime mud 2 Micrite & sparite	Micrite	Micrite Very fine grained dolomite Primary anhydrite.	MICROFACIES
Sponges - spicules Scattered crinoid pieces	Crinoid pieces Brachiopods (whole, in situ)	Scattered crinoid pieces Bryozoa Brachiopods Zaphrentid corals	Crinoid Bryozoans alternating facies	Crinoid pieces Endothyroid forams. Other small forams Ortonella - (Codiacea)balls Ostracodes Few bryozoans.	Algal limestone Gastropods Calcispheres	Algae	Ostracodes	BIOTA



THE PERMIAN REEF COMPLEX

From the original interpretation of Newell modified by Dunham & Achauer

REFERENCE: Newell, N. et al. Permian Reef Complex.	FORMATIONS: Upper Guadalupian; Lower member of Bell Canyon - Capitan Limestone --- Carlsbad Limestone								AGE: Middle Permian	LOCATIONS: Guadalupe Mtns. Texas & New Mexico	
Gray laminated sandstone - siltstone and black shaly sandstone. grading to → Wide	Dark colored, bituminous, wavy bedded, laminated, unfossiliferous limestone. Dolomite 1-2%. Grading to metabentonite & green chert. Beds of fine grained qtz. sa. few inches thick unit thins from 200' to 20' in 14 miles. 1/2 mile insol increase 0-6% Distribution	Dark colored, thin tongues Bioclastic - calcarenite - coquina. Wavy bedding. Cut and fill flowage. Giant cross-bedding. 15 miles	Pink, coarse blocks of massive reef talus. More dolomitized - 4-25%. Stratified massive beds 20° - 35°. Submarine fluid slides. Less than 1 mile.	Reef wall Light grey, aphanitic, unstratified, pure limestone. Innumerable vugs. Less than 1 mile.	Back Reef Calcarenite - coquina. Dolomitized. Thick beds - 20' maximum. 1 mile band - maximum 1/2 mile from reef.	Pisolite (1 mile max. Pelletoids (band - thin bed (lagoon Flat lenses behind reef. Interbedded with calcarenite Fore with fine grained dol.	Fine grained dolomite. Light colored. Thin even beds to wavy. (1/2 - 1 ft) Very pure carbonate - 99%. 50-50 Mg - Ca. No fossils. Wide distribution	Evaporites Gypsum from anhydrite 6-9 miles (closest to reef)	Quartzose sandstone - brown to grey. Red sandy shale. Poor stratification. No ripple marks or cross bedding.	ROCK TYPES
Angular grains 20 - 80 microns. Lamination due to calcite cement and organic matter concentration.	Laminate - 3 m to .1 mm. Dark siliceous sponge spicules. Algal spheres in dk. organic layers with more calcite. Lt. layers of dol. and sd. grains. No graded bedding. Fine calcarenite.	Separated - sorted fossil remains. Textural gradient. Fusulines axis par. ripple marks. Slump folds. Micrite matrix, also sparites. Silicified fossils common.	Unsorted rock & shell fgmts. Cavities filled w/qtz sa., lime mud, calcarenite and cement. Oil stains.	Aphanitic limestone. ? Lime mud surrounding innumerable vugs. Filled by layers of fibrous calcite & qtz. sa. Is aphanitic limestone recrystallized algal limestone or lime mud coarser recrystallized?	A biosparite. Matrix 30-50 microns. Anhedral. Matrix 53% Fossil hash 20 Polydiexodina (coquina) 13 Lithoclast 7 Algae 2.5 Forams 2.5 Quartz 1	Matrix of dolomite - lime sand - gypsum. 10-1000 microns, coarser than in calc. oosparite Pelsparite Detrital qtz & calcite grns.	Anhedra of dolomite, 100-400 microns. Mutual boundaries		Quartz angular - averages 57%. Well developed sorting - sizing. Scattered very fine grains Dolomitic cement.	MICROFACIES
	Radiolarians Spicules Algal spheres - calcite Ammonites Nuculoid pelecypod } rare High spired gastropod)	Brachiopods, crinoids, bryozoan, fusuline - not farther than 10-15 miles out Ammonites - untransported with wide size range - filled with shell debris. Leiorhynchus common	Pedunculate brachiopods Bryozoans (Cryptostomes) Crinoids Fusulines	In situ - hydrocorallines. Algal crusts - stromatolites (recrystallization!) Algae Solenopora (Red) Girvanella-Ortonella Dazycladaceans - Diplopora, Kirzia Codiacese (Gymnocodium) Sycon sponges Bryozoan - Fistuloporoid.	Dazyclads - very abundant Codiaceans - abundant Polydiexodina Gastropods - in situ Scaphopods Pelecypods Algal spheres Fusulines abundant - worn Fauna largely allocthonous	Algal pisolitha Other fossils very rare	Few transported frgmts. No algal stromatolite			BIOTA



ENVIRONMENT INTERPRETATION

James Lee Wilson

JAS, → WLK

Other Type Rep Sediment

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AMERICAN SMELTING AND REFINING COMPANY
EXPLORATION DEPARTMENT
120 BROADWAY, NEW YORK, N.Y. 10005

JOHN J. COLLINS
DIRECTOR OF EXPLORATION

W. L. K.
JUL 26 1972

Air Mail

February 28, 1972

Mr. A. V. Greene - Missouri
Mr. D. D. Harper Knoxville

Sedimentology of Carbonates

Gentlemen:

Thank you for your reviews of this 3-day seminar. Can you apply what you learned to your current search for ore? I see you recognized some similarities between the lecture areas and our mineral districts, but I am curious to know what use can be made of this sort of course.

Could this division of the University of Miami organize a course better suited to Asarco's needs? Would it be worth planning a large exclusive Asarco attendance, say in connection with the next Exploration Annual Meeting at Knoxville-Mascot? Would field trips to coral areas be beneficial? For example, the November seminar (Calcareous Algae) went to Key West and to the Bahamas. I think I sent you copies of the lecture material. Perhaps Ginsburg and associates need to see East Tennessee mines?

It may be that this description of the carbonate environment is old stuff to recent students on Asarco's staff, but in any case I am sending copies of your memos to other regional supervisors and invite their comments.

Very truly yours,

John J. Collins

John J. Collins

cc:JHCourtright)
SAAnzalone)
RLBrown) with Xerox copies of Messrs. Harper's
MPBarnes) and Greene's summaries.
RKKirkpatrick)
WLKurtz)
DMFletcher)
RBSprague)
LPEntwistle)

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2640 Broadway, N.E.
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February 8, 1972

MEMORANDUM TO MR. J. V. DESVAUX:

The following comments and summaries pertain to the "Comparative Sedimentology of Carbonates" conference I attended on January 28-30, 1972. A schedule of the conference is attached.

The conference was well organized and all papers well presented. The theme of most speakers was to relate older rock carbonate lithofacies and their particular set of sedimentary features to active carbonate depositional areas such as the Bahamas, Persian Gulf, and Shark Bay, Australia. Carbonate platforms containing sharp facies changes at platform margins were the models in all cases. The degree of refinement of interpretative methods was impressive and at times overwhelming. Convincing photo and descriptive documentation was presented by all speakers.

The relationship of carbonate facies to stratabound sulfide deposits in carbonate rocks was brought to mind when considering the SE Missouri Lead District and the Pine Point District (NW Territories). Both of these districts are located at platform margins with mineralization seemingly controlled by sharp facies changes. Sulfide deposits in Lower and Middle Ordovician carbonates (Tennessee Zinc Districts and Upper Mississippi Valley District) do not occur in a platform edge condition.

The following comments pertain to the first five papers on the schedule -- Mr. Greene is commenting on the second five in a separate memorandum.

(1) Paul Hoffman "The Earliest Carbonate Platforms: Northwest Territories, Canada".

An abstract of Hoffman's paper is attached. His interpretation of the carbonate platform and associated facies changes was well documented by lithologic description and photos. A photo comparison of Precambrian stromatolites to living algal structures in Sharks Bay, Australia was especially striking.

The economic value of Hoffman's paper is to realize that the platform margins are areas which are favorable for

stratabound sulfide occurrence. Breccia and coarse grained epigenetic dolomite are noted to occur along the platform margins -- both are favorable host environments for sulfide deposition. Further economic considerations involve the aulacogens (see attached map) which are in effect graywacke arms extending into the carbonate platforms. It might be suspected that the graywackes could have served as conduits for solutions to move to a position of sharp lateral contact with platform carbonates which would be a condition favorable for sulfide emplacement. The recent discovery by Cominco in the Bathurst Inlet Area may be related to the Bathurst Aulacogen (I am uncertain as to the exact location and host unit).

(2) Eugene Shinn "Comparison of Tidal Flat Deposits from the Bahamas and Persian Gulf".

Shinn sought to point out basic differences in present day carbonate platform environments. Climate conditions as well as structural conditions can vary to cause different sets of carbonate depositional environments. The Bahamas (tropical climate) and Persian Gulf (arid climate) were used as comparative models.

(3) Edward Purdy "The British Honduras Model of Carbonate Deposition".

The main point of the paper was to relate the carbonate platform features to a template developed in underlying rocks by Karst. British Honduras was used as primary field model. Laboratory models were also presented. Features emphasized are as follows: (1) Edge of a Karst block would normally be a positive rim which would control localization of a subsequent barrier reef. (2) Pinnacles in well developed Karst would control localization of subsequent pinnacle or patch reefs. (3) Poorly developed Karst surface would form basis for extensive shallow tidal flat behind barrier reef. The British Honduras model shows strong Karst (ie patch reefs, deep water behind reefs, etc.) in southern shelf lagoon as opposed to poorly developed Karst (shallow water, flat lagoonal area) in Northern Lagoonal Area. The degree of Karst development is related to climatic conditions (arid vs tropical) plus bedrock type in water shed area (carbonates vs igneous and metamorphics).

(4) Bruce Purser "Sedimentation and Diagenesis of Paris Basin Carbonates".

Descriptive paper on carbonate platforms in Paris Basin Area of France. Comparison to Bahama platform showed definite similarities of carbonate facies -- oolite zone on platform margins with pelletoidal lime mud facies in lagoonal environment. Facies relationships of carbonate rocks shown on attached set of sections reflects geologic history of platform development and environmental relationships.

(5) Paul Enos "Reefs, Platforms and Basins of the Mexican Cretaceous".

Descriptive paper of Middle-Cretaceous Carbonate Platforms in NE Mexico. Lateral relationship of Upper Tamaulipas (Basin facies), Tamabra (platform margin facies) and El Abra (platform facies) described. Breccia zones common in Tamabra. Petroleum occurrence in platform margin units afforded reason for detailed study of area. Mine workings noted in photos of Tamabra outcrop units (another relationship of reef rock to strata bound sulfides?). Basinal units thin in relationship to platform rocks -- typical of basin units in most areas described. Although not specifically mentioned in this paper, it is noted that quite often platform carbonates are dolomite whereas basinal carbonates are shaly limestone. Platform margin rocks are often porous (epigenetic dolomite) and contain prominent breccia zones as does the Tamabra unit described in Enos' paper.

Plan map of carbonate platform and correlation chart attached.

I appreciate the opportunity to attend the conference. In regard to future meetings, conferences, etc. it is suggested that some Asarco personnel attend the "Economic Aspects of the Genesis and Diagenesis of Limestones" meeting on August 29 -- abstracts and schedule attached. Int. Geol. Congress, Montreal.

Delbert D. Harper

Delbert D. Harper

DDH:ad

Enclosures

Schedule & Gen. Information

THE COMPARATIVE SEDIMENTOLOGY OF CARBONATES

Opening Conference of
The Comparative Sedimentology Laboratory, Fisher Island
University of Miami
Rosenstiel School of Marine and Atmospheric Science

Auditorium, 10 Rickenbacker Causeway

Friday, January 28, 9:00 - 12:30

Introduction: ROBERT N. GINSBURG

PAUL HOFFMAN Geological Survey of Canada	*The Earliest Carbonate Platforms: Northwest Territories, Canada*
EUGENE SHINN Shell Oil Company, Houston	*Comparison of Tidal Flat Deposits from the Bahamas and Persian Gulf*

2:00 - 5:30

Chairman: R. MICHAEL LLOYD

EDWARD PURDY Esso International, England	*The British Honduras Model of Carbonate Deposition*
BRUCE PURSER University of Paris	*Sedimentation and Diagenesis of Paris Basin Carbonates*

Saturday, January 29, 9:00 - 12:30

Chairman: PERRY ROEHL

PAUL ENOS, State University of New York, Binghamton	*Reefs, Platforms and Basins of the Mexican Cretaceous*
ALFONSO BOSELLINI Universita di Ferrara, Italy	*Evolution of Triassic and Jurassic Platforms in Italy*

2:00 - 5:30

Chairman: LLOYD PRAY

HEINRICH ZANKL University of Marburg, Germany	*Comparative Studies of Alpine Triassic and Holocene Reefs*
EDWARD KLOVAN University of Calgary, Canada	*The Anatomy and Evolution of Western Canadian Devonian Reefs*

Sunday, January 30, 9:00 - 12:30

Chairman: To be Announced

JAMES LEE WILSON Rice University, Houston	*Scale and Facies of Carbonate Platforms and Reef Complexes*
MAHLON BALL University of Miami	*The Roots of Carbonate Platforms and Reefs*

THE COMPARATIVE SEDIMENTOLOGY OF CARBONATES

January 28-30, 1972

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THE COMPARATIVE SEDIMENTOLOGY OF CARBONATES

LIST OF ATTENDEES AT OPENING CONFERENCE
THE COMPARATIVE SEDIMENTOLOGY LABORATORY, FISHER ISLAND

January 28-30, 1972

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Hoffman Paper #1

THE EARLIEST CARBONATE PLATFORMS, NORTHWEST TERRITORIES, CANADA

Paul Hoffman, Geological Survey of Canada, Ottawa, Ontario K1A 0E8

Two thick carbonate platforms were deposited between 1750 and 2100 million years ago as parts of the Coronation Geosyncline in what is now the northwestern Canadian Shield. No skeletal organisms are known to have existed at that time, only the procaryotic bacteria and blue-green algae. Nevertheless, the facies differentiation of these ancient platforms is not unlike that in the Phanerozoic save for the absence, in addition to skeletal debris, of pelleted and burrowed sediments.

Platform interior.—Tens to hundreds of stacked shoaling-upward cycles characterize the platform interiors. The individual cycles range from 2 m to 15 m in thickness and can commonly be traced for tens of km across the platform and hundreds of km along its strike. A representative cycle comprises the following vertical sequence:

Top Unit 1: Thin intraclast packstone interpreted as a beach lag deposited during trangressive phase.

Unit 5: Black cherty dolomite composed of planar stromatolites with "microdigitate" fabric containing filament moulds and columnar stromatolites of "Conophyton" type, interpreted as a supratidal stagnant algal marsh deposit.

Unit 4: Light grey dolomite with discrete columnar, linked domal and planar stromatolites, discoidal oncolites and edgewise conglomerate, becoming cherty toward the top, interpreted as deposited on prograding tidal flats exposed to wave attack.

Unit 3: Light grey dolomite with rippled ooid-oncoid-intraclast grainstone interpreted as deposited on surf-built subtidal shoals.

Unit 2: Reddish-brown to black dolomitic shale with thin graded and rippled dolosiltite laminae, convolute laminations and syneresis dikes, progressively more dolomitic upward, interpreted as deposited on a sublittoral shelf.

Bottom Unit 1: Thin intraclast packstone interpreted as a beach lag deposited during transgressive phase.

Apparent megacycles result from vertical variation, through many cycles, in the proportion of dolomite and shale.

Platform margin.—At the platform margin the cyclic pattern breaks down. Commonly there is a belt, 1-2 km wide, of stromatolite mound-and-channel paleotopography. The mounds are up to 20 m thick and tens

of meters in diameter. They are elongate perpendicular to the platform edge and their tops stood 1-3 m above the floors of the anastomosing tidal channels between them. Internally, the mounds are made-up of large branching columnar stromatolites up to 1 m in diameter. The channels are filled by crossbedded intraclast grainstone and intraclast breccia. The platform margin commonly suffers epigenetic coarse vuggy dolomitization.

Foreslope of platform.—Poorly defined cycles, tens of meters thick, characterize the foreslope. A representative cycle comprises the following vertical sequence:

Unit 1: Black to dark green pyritic shale with small ellipsoidal calcareous concretions.

Unit 3: Light grey thin evenly bedded lime mudstone with shale partings, more calcareous and thicker bedded upward, recumbent slump folds and breccia beds close to the platform edge.

Unit 2: Dark green to brown calcareous shale with digitate calcareous growth structures possible of cryptalgal origin.

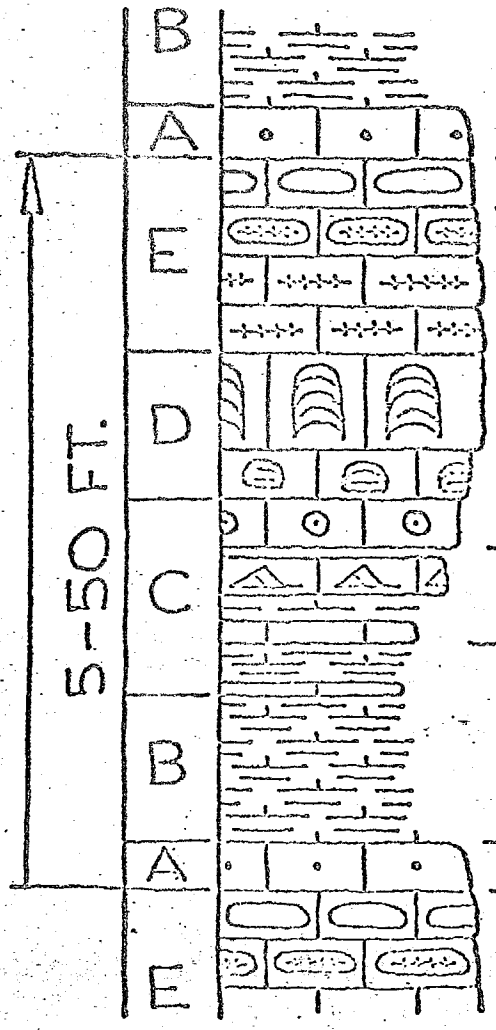
Unit 1: Black to dark green pyritic shale with small ellipsoidal calcareous concretions.

The cycles are interrupted by wedges of greywacke turbidites, derived from the other side of the basin, that wedge out against the foreslope of the carbonate platform.

Undifferentiated platform.—In some places and at some levels, the platform margin is poorly differentiated. Basinal shale with calcareous digitate growth structures (like Unit 2 above) with greywacke turbidite wedges, grade toward the platform into dolomitic mudstone with digitate growth structures of fenestral limestone. This latter facies, undoubtedly of cryptalgal origin, can form unbroken sequences hundreds of meters thick. Its depositional environment is uncertain.

Conclusions.—Lower Proterozoic carbonate platforms have facies zonations not unlike much younger platforms. They differ in the overwhelming abundance of stromatolites and other cryptalgal structures. Stromatolites, like many other fossil groups, underwent a gradual decline, not increase, in importance from an acme very early in their history.

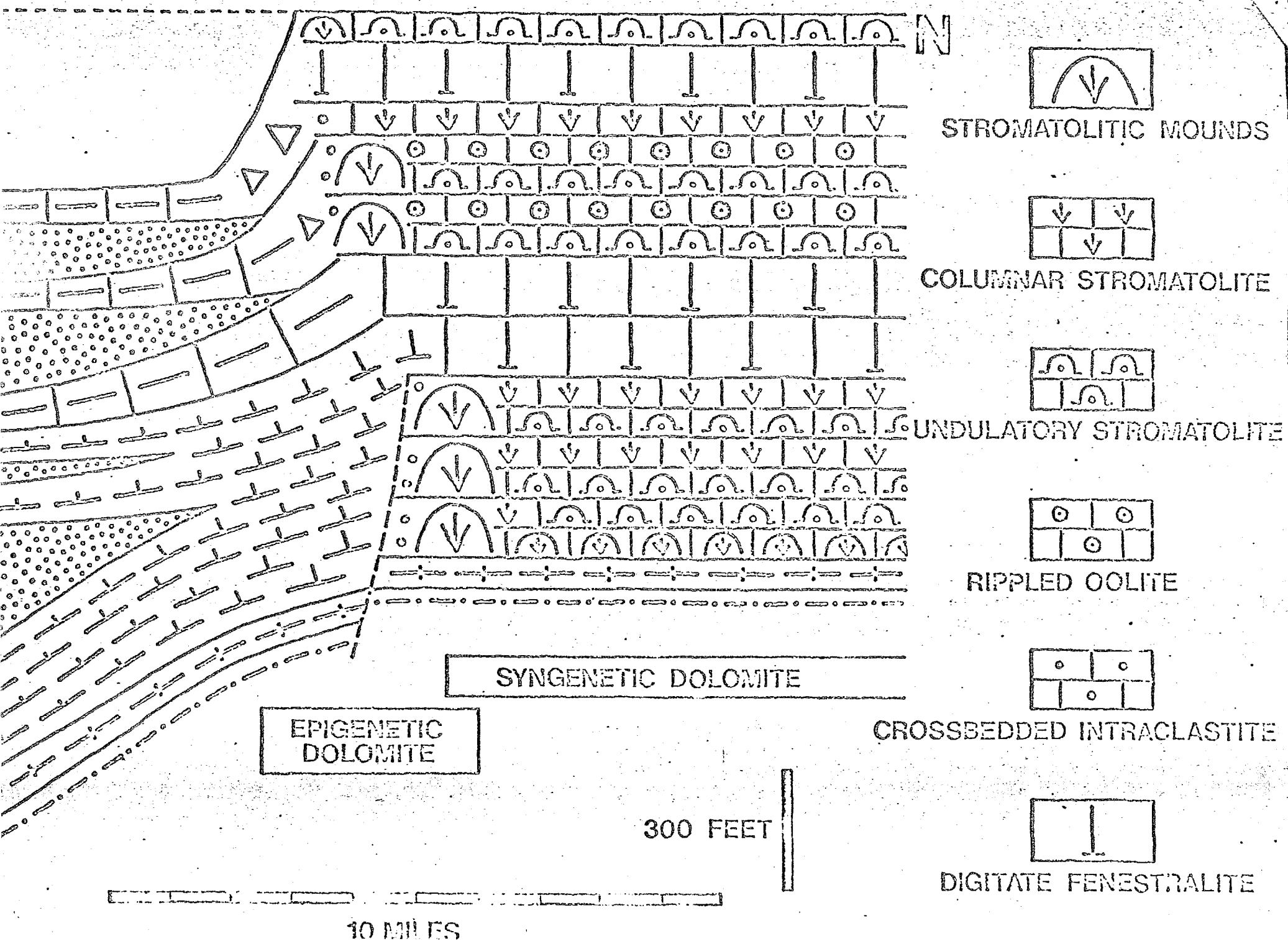
REPRESENTATIVE SHOALING-UPWARD CYCLE, LOWER PROTEROZOIC, N.W.T.

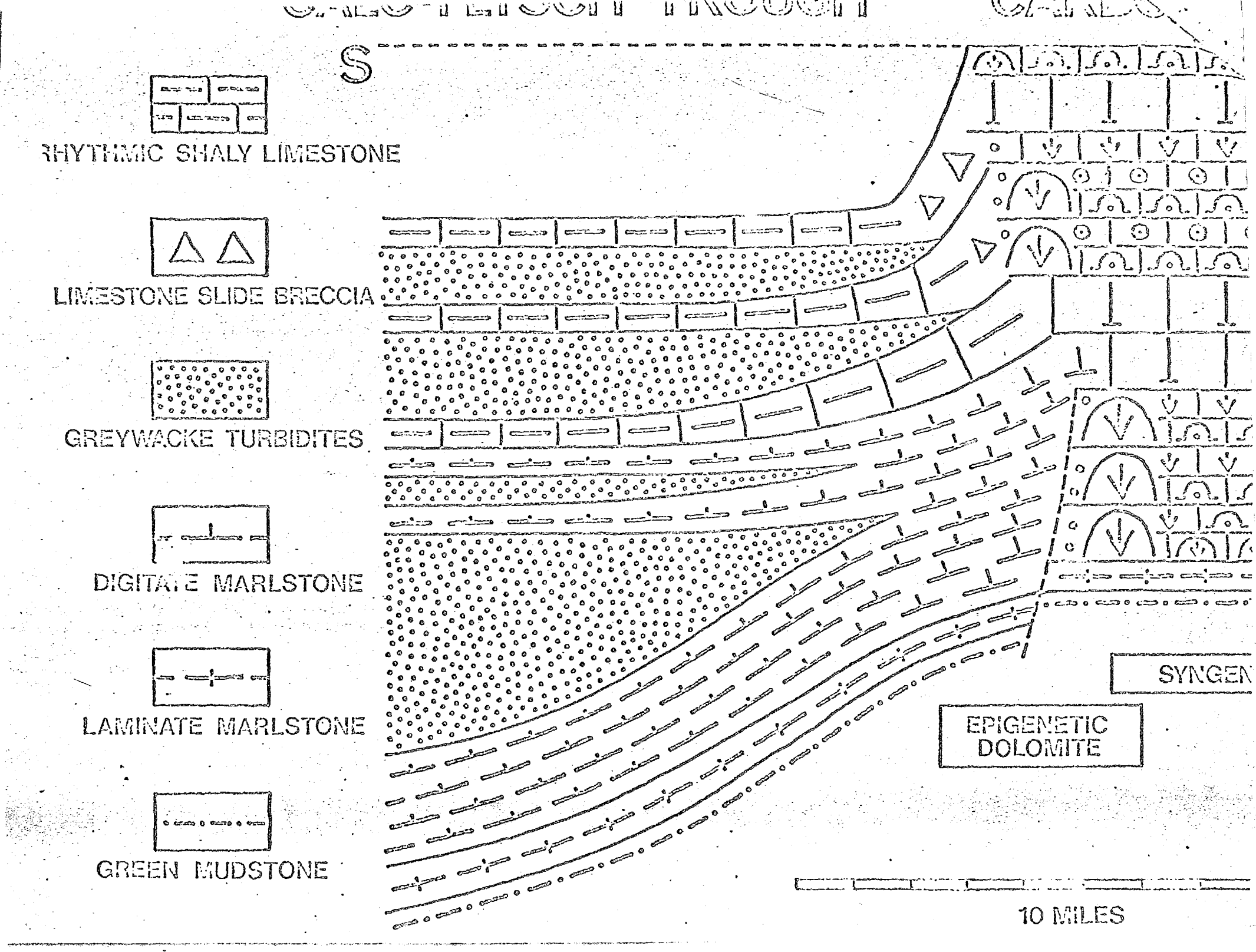


LITHOLOGY	ENVIRONMENT	
LIGHT CHERTY MICROBRECCIA	DEFLATION SURFACE	SUPRATIDAL
BLACK CHERTY LAMINITE	STAGNANT ALGAL MARSH	
BLACK LAMINITE WITH FILAMENT MOULDS		
LIGHT DISCRETE COLUMNAR STROMATOLITE	EXPOSED TIDAL FLAT	INTERTIDAL
ONCOLITE-INTRACLAST-OOID GRAINSTONE	SURF-BUILT SHOAL	
RIPPLED & GRADED CALCI-SILTITE WITH SHALE	NEARSHORE SHELF LAGOON	SUBTIDAL
CALCAREOUS SHALE WITH SYNERESIS CRACKS & THIN GRADED CALCISILTITE LAYERS	OFFSHORE SHELF LAGOON	
INTRACLAST PACKSTONE	TRANSGRESSIVE BEACH	INTERTIDAL

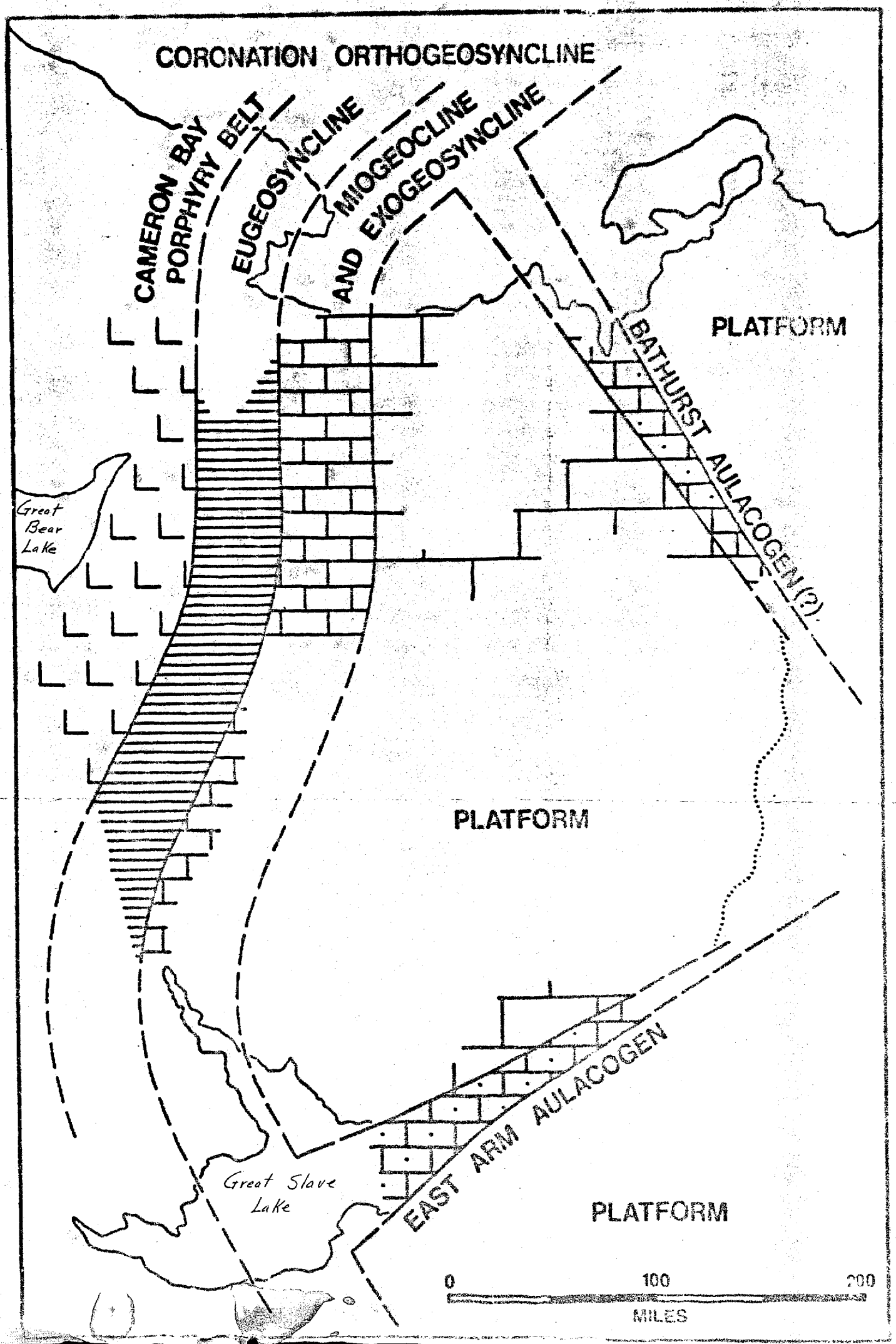
(HOFFMAN)

ROUGH CARBONATE PLATFORM

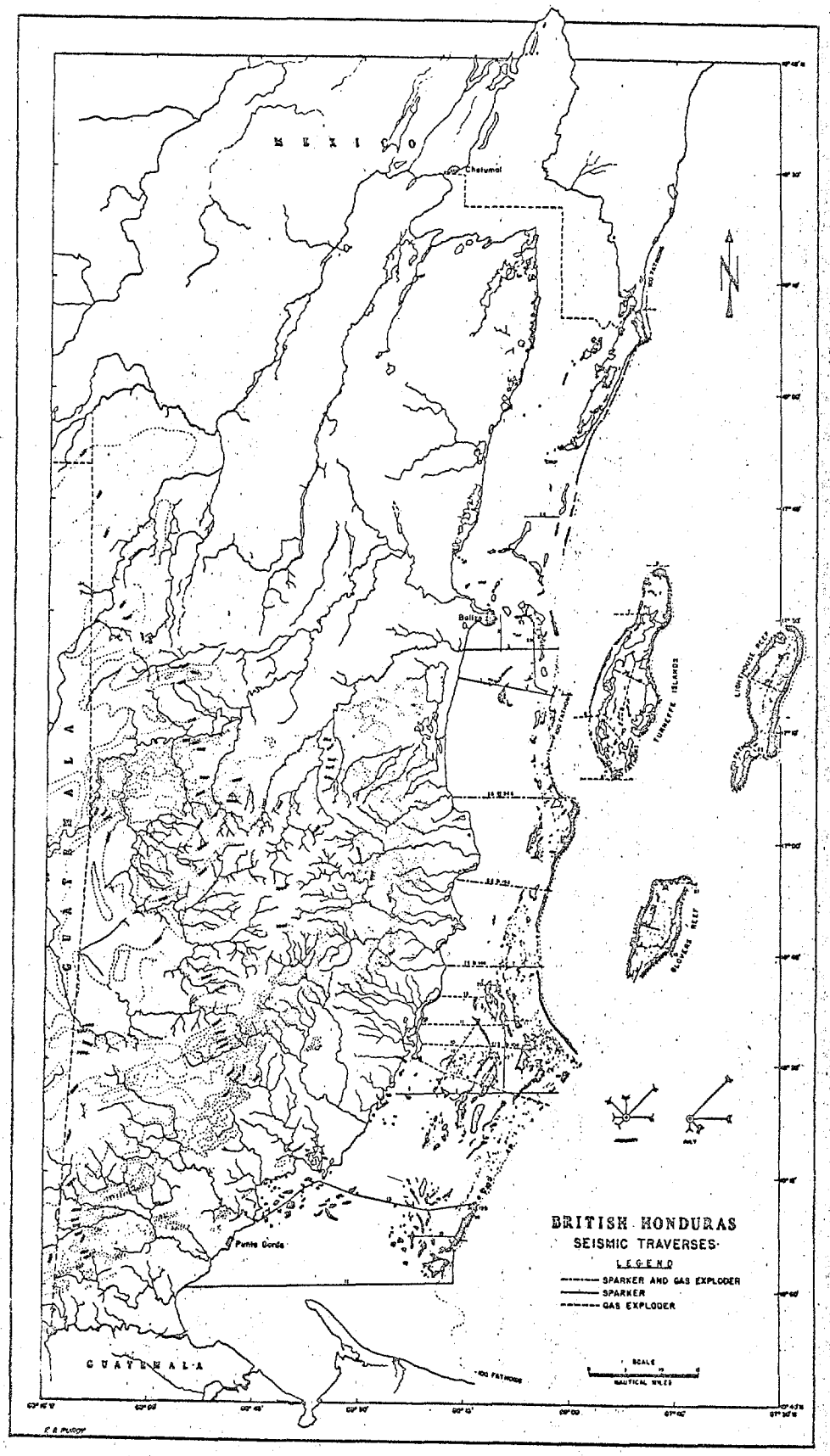


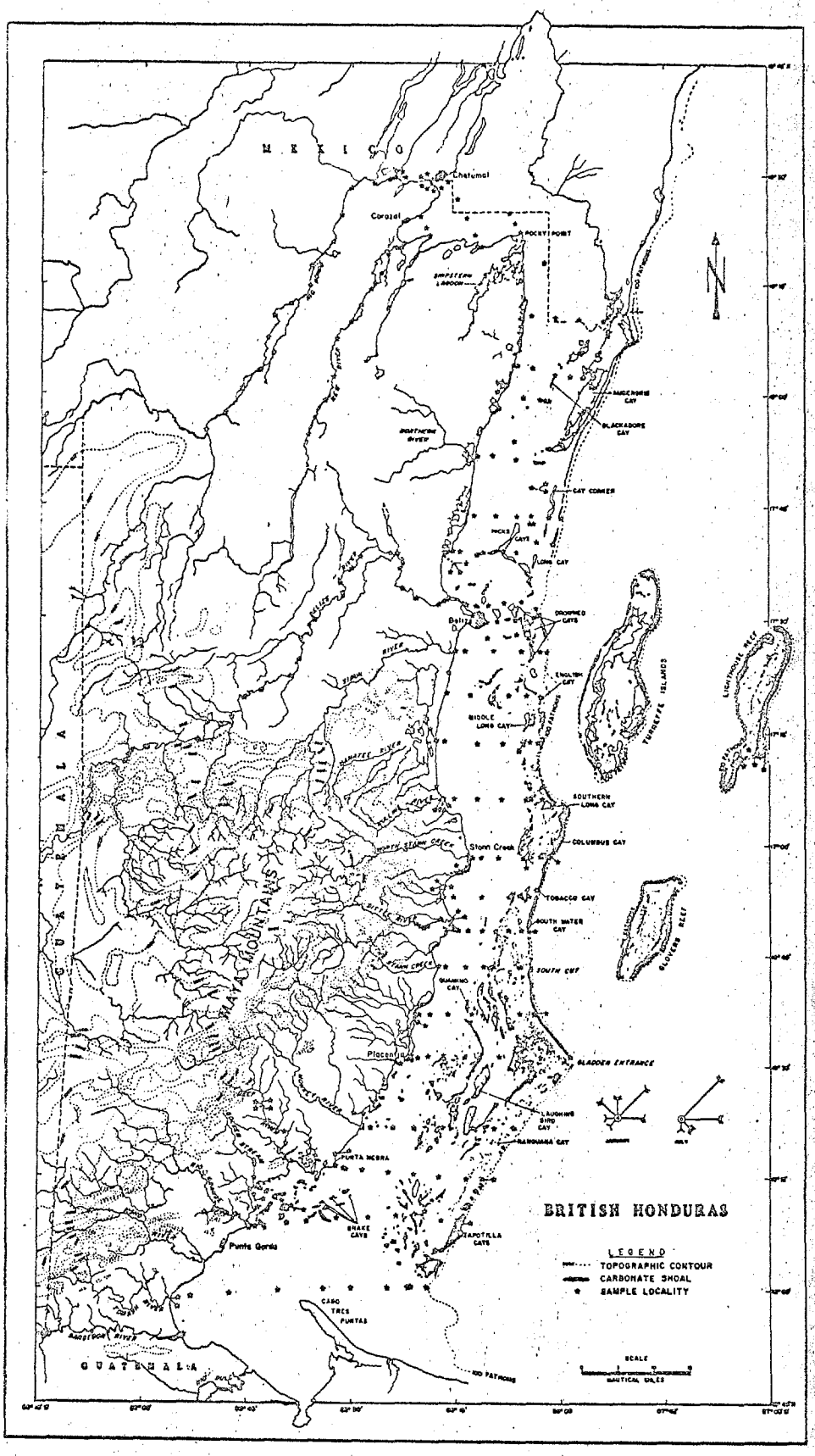

S
RHYTHMIC SHALY LIMESTONE
LIMESTONE SLIDE BRECCIA
GREYWACKE TURBIDITES
DIGITATE MARLSTONE
LAMINATE MARLSTONE
GREEN MUDSTONE
SYNGEN
EPIGENETIC DOLOMITE
10 MILES

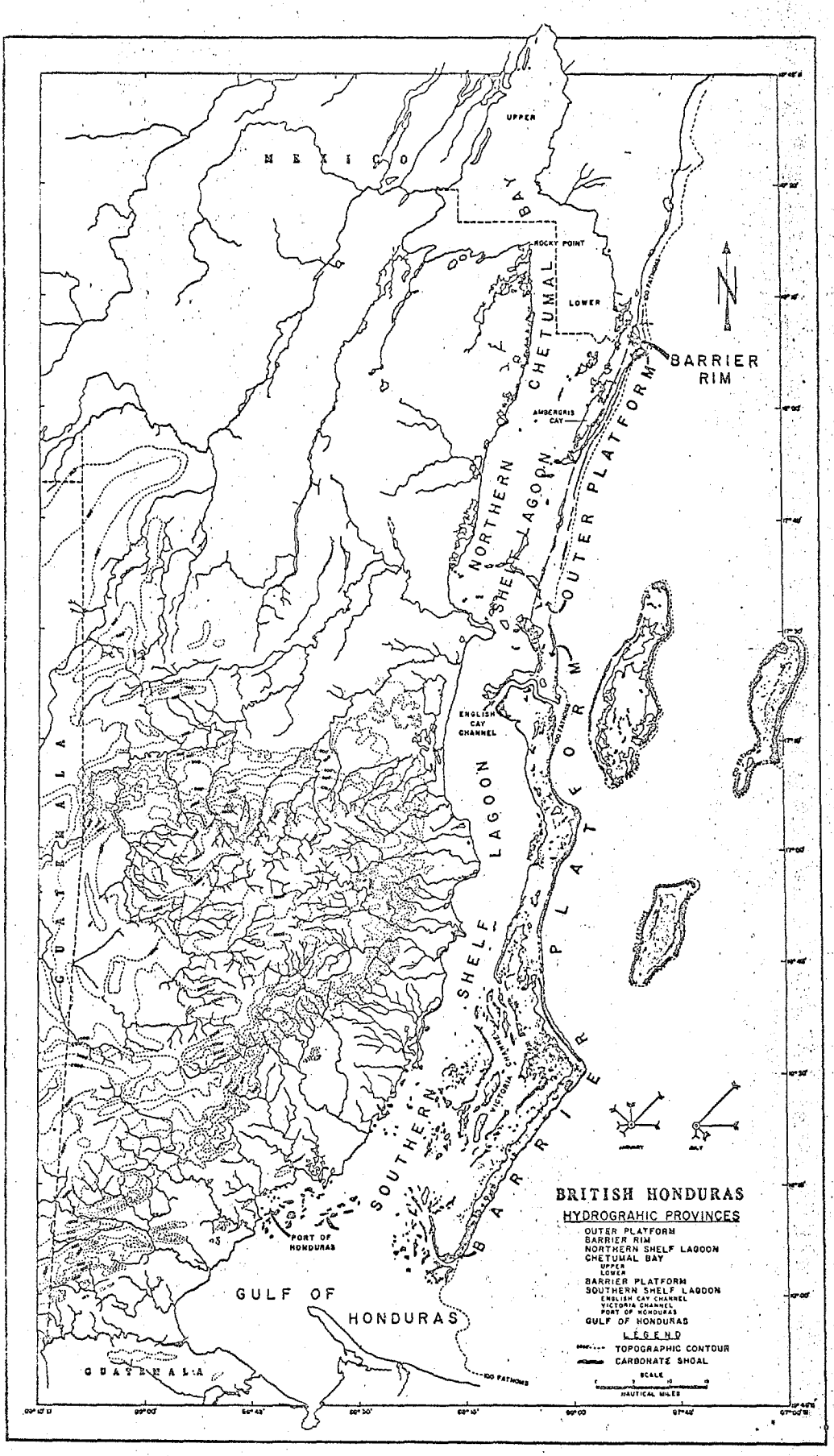
Anderson
Dease
Queen
Coronation
Gulf
Coppermine
Great Bear Lake
Port Radium
MACKENZIE
Back
YELLOWKNIFE
Great Slave Lake
Hay River
Pine Point
Fort Smith
Slave
Athabasca
Lake
Fort Nelson River
Hay River
Peace
River
Fort

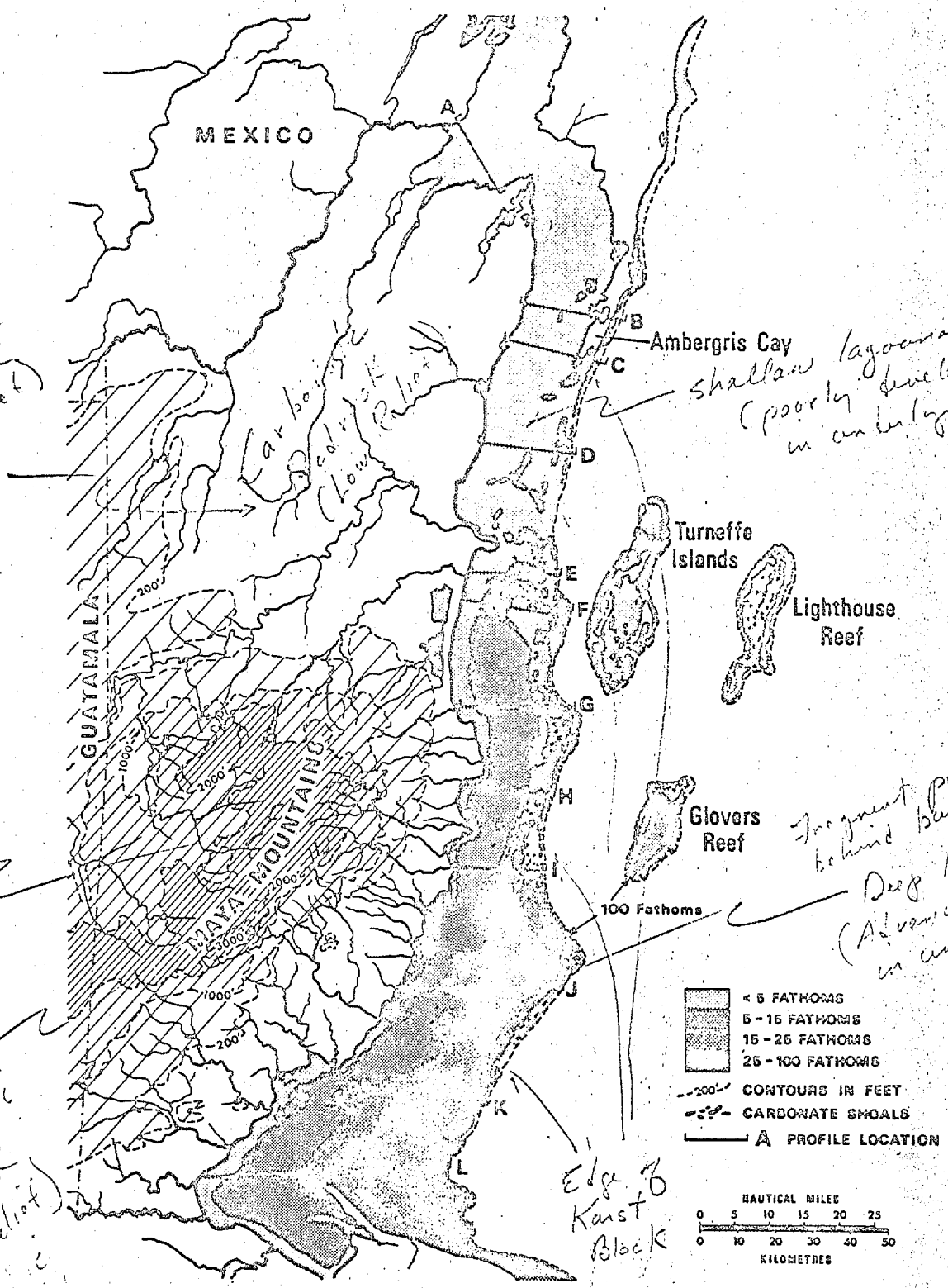

CORONATION ORTHOGEOSYNCLINE
CAMERON BAY PORPHYRY BELT
EUGEOSYNCLINE
MIOGEOCLINE AND EXOGEOSYNCLINE
PLATFORM
BATHURST AULACOGEN (?)
Great Bear Lake
PLATFORM
EAST ARM AULACOGEN
Great Slave Lake
PLATFORM
0
100
200
MILES

Purdy Paper # 3




MEXICO
Chetumal
Corozal
POCKET POINT
SHIPSTERN LAGOON
SHIPSTERN RIVER
MACKEREL CAY
BLACKADORE CAY
CAY CORKER
HICKS CAYS
LONG CAY
Belize
DROWNED CAYS
ENGLISH CAY
MIDDLE LONG CAY
TURNEFFE ISLANDS
LIGHTHOUSE REEF
BLUEFIELDS RIVER
STANN RIVER
MOPAN RIVER
SOUTH STANN CREEK
SOUTHERN LONG CAY
COLUMBUS CAY
Stann Creek
TOBACCO CAY
SOUTH WATER CAY
SOUTH CUT
GUANANI CAY
BLUEFIELD RIVER
STANN CREEK
GUATEMALA
MAYA MOUNTAINS
Placencia
BLADEN ENTRANCE
LAUGHING BIRD CAY
RAMONARA CAY
BLUEFIELDS REEF
PUNTA NEGRA
SNAKE CAYS
TAPOTILLA CAYS
Punta Gorda
CABO TRES PUNTAS
MOTAGUA RIVER
GUATEMALA
RIO PATNOSTRO
BRITISH HONDURAS
LEGEND
TOPOGRAPHIC CONTOUR
CARBONATE SHOAL
SAMPLE LOCALITY
SCALE
NAUTICAL MILES


BRITISH HONDURAS
HYDROGRAPHIC PROVINCES
OUTER PLATFORM
BARRIER RIM
NORTHERN SHELF LAGOON
CHETUMAL BAY
UPPER
LOWER
BARRIER PLATFORM
SOUTHERN SHELF LAGOON
ENGLISH CAY CHANNEL
VICTORIA CHANNEL
PORT OF HONDURAS
GULF OF HONDURAS
LEGEND
TOPOGRAPHIC CONTOUR
CARBONATE SHOAL
SCALE
NAUTICAL MILES
MEXICO
GUATEMALA
ROCKY POINT
AMBERGRIS CAY
ENGLISH CAY CHANNEL
PORT OF HONDURAS
GULF OF HONDURAS
BARRIER RIM
OUTER PLATFORM
NORTHERN SHELF LAGOON
SOUTHERN SHELF LAGOON
BARRIER PLATFORM
CHETUMAL BAY
UPPER
LOWER
GUATEMALA
100 FATHOMS
JANUARY
JULY



Carbonate Bedrock (Low Relief)

Carbonate Bedrock (Low Relief)

shallow lagoonal area (poorly developed karst in underlying rks.)

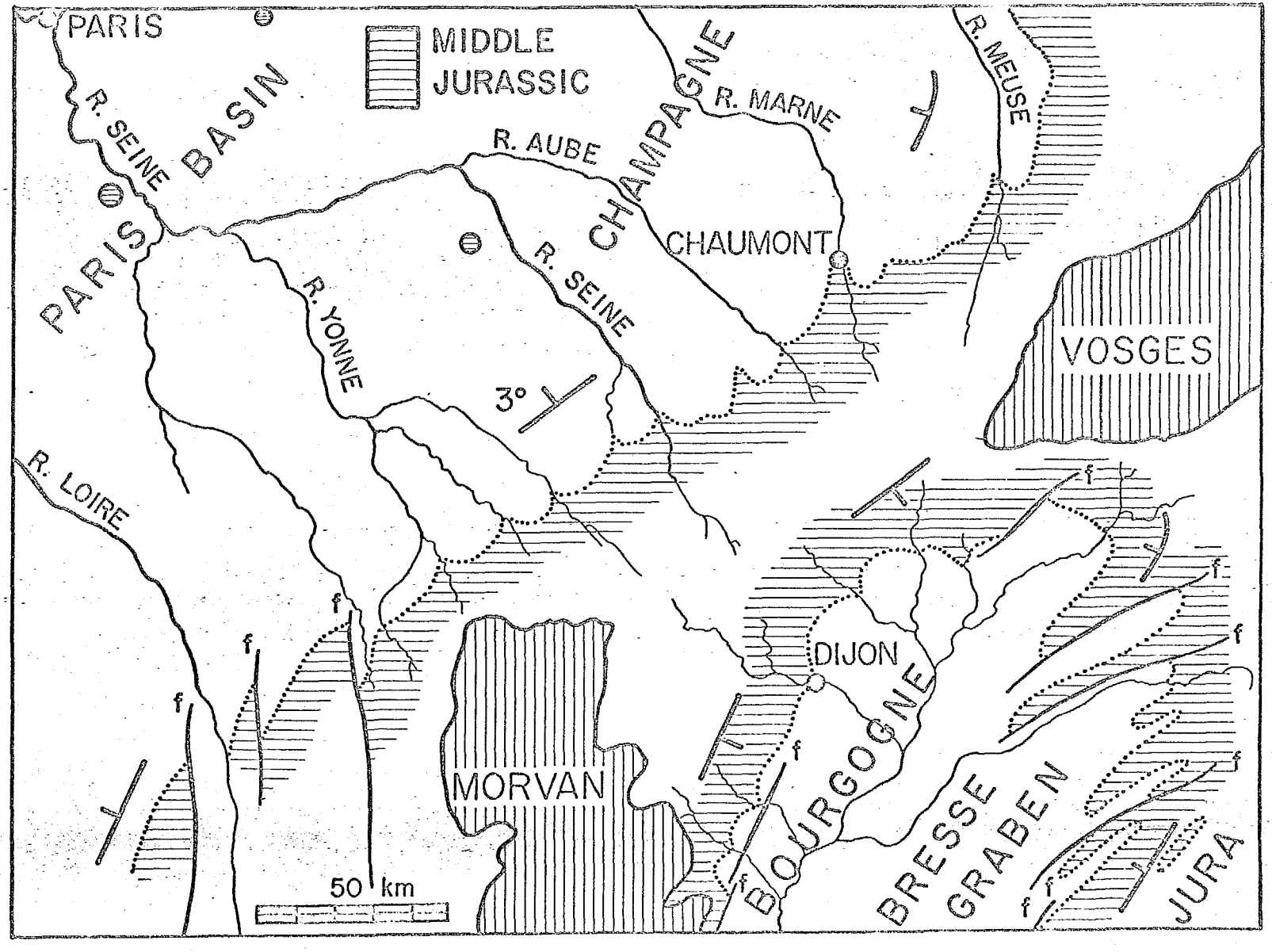
Higher rainfall area.

Fragment patch reefs behind barrier reef

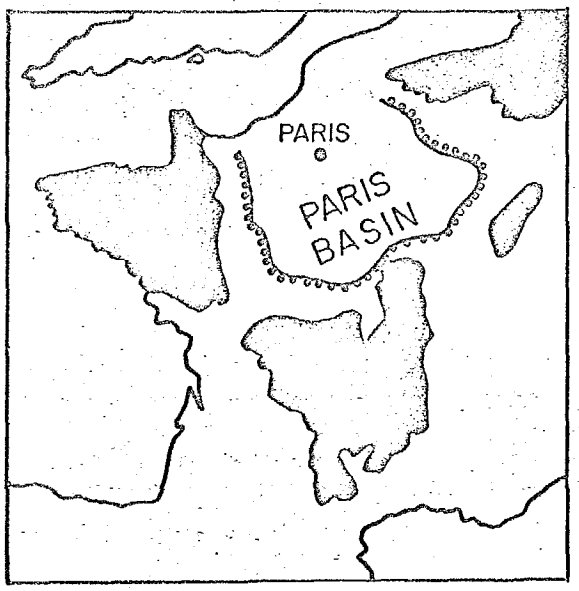
Deep lagoonal area (Advanced karst in underlying rks)

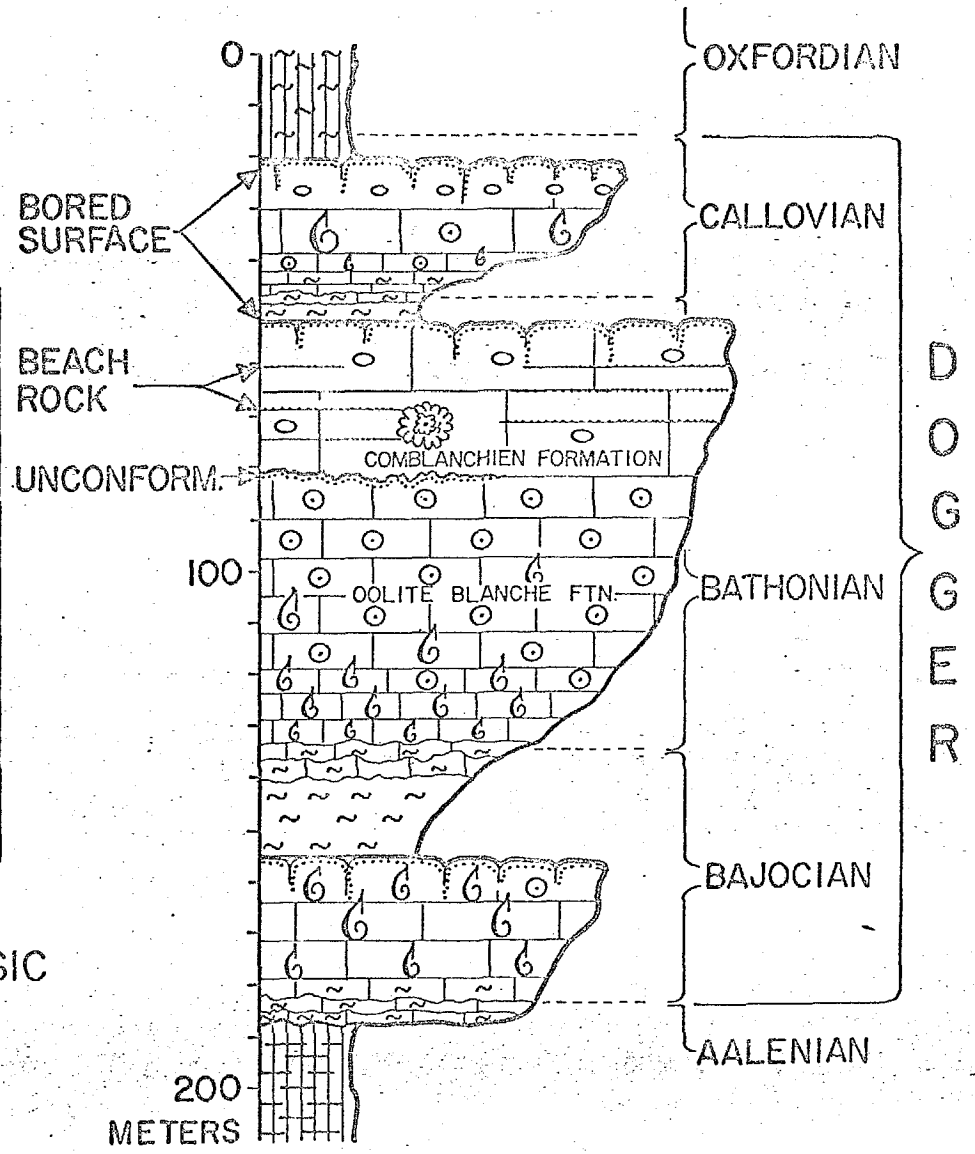
Igneous & Metamorphic Bedrock (High relief) Mixed carbonate & volcanic shed

Edge of Karst Block

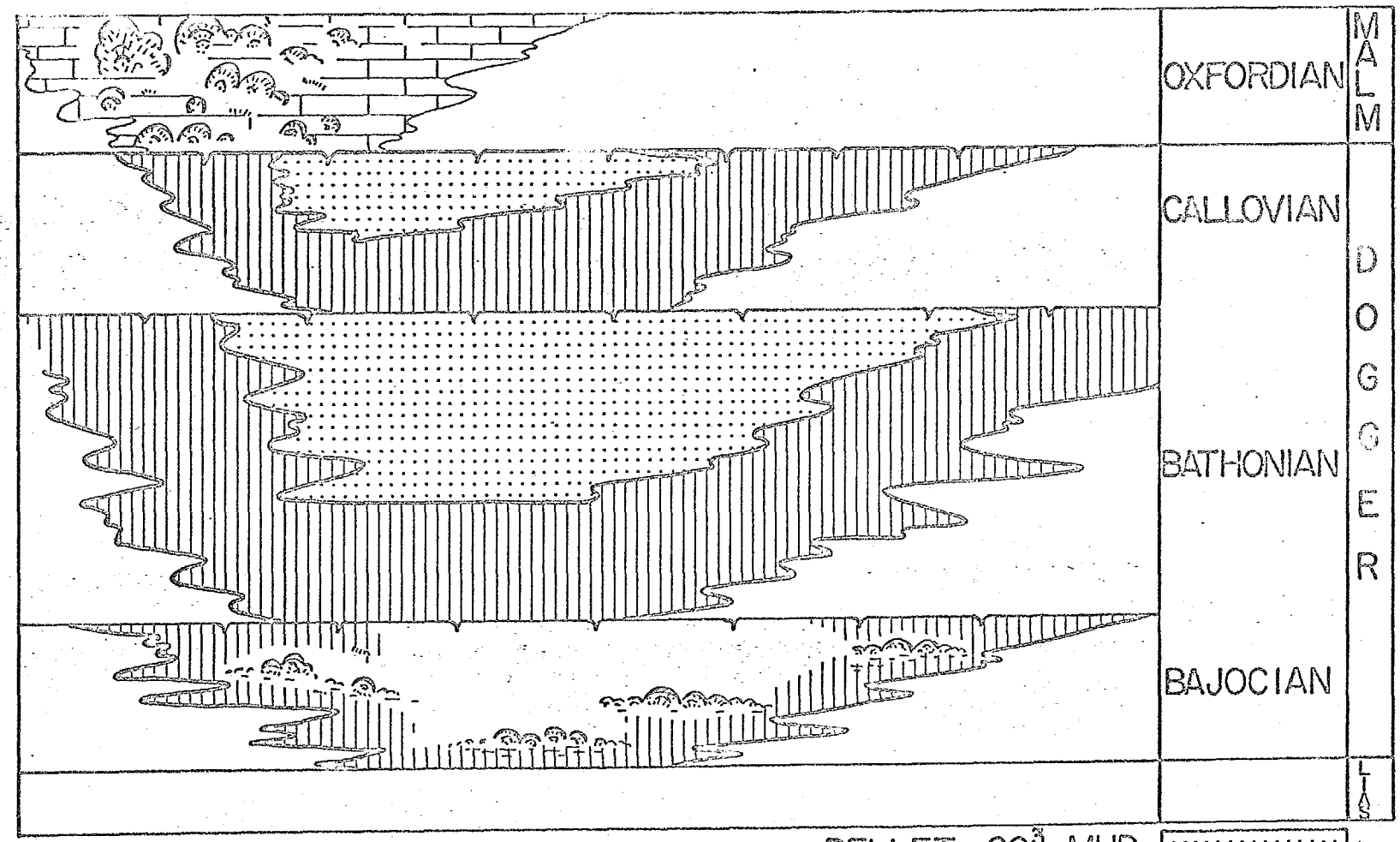


Purser Paper #4



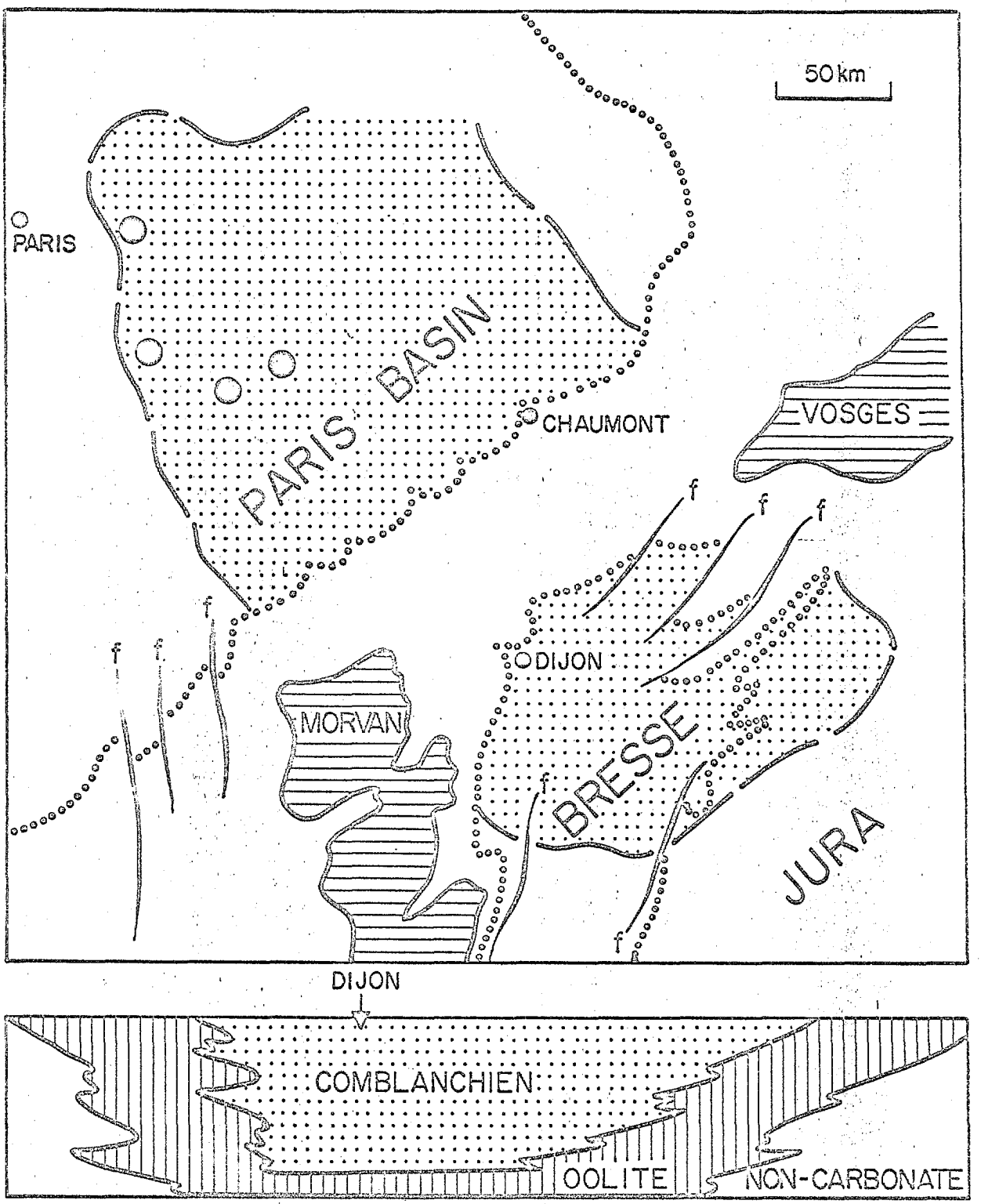


STANDARD MIDDLE JURASSIC SEQUENCE
S. E. PARIS BASIN

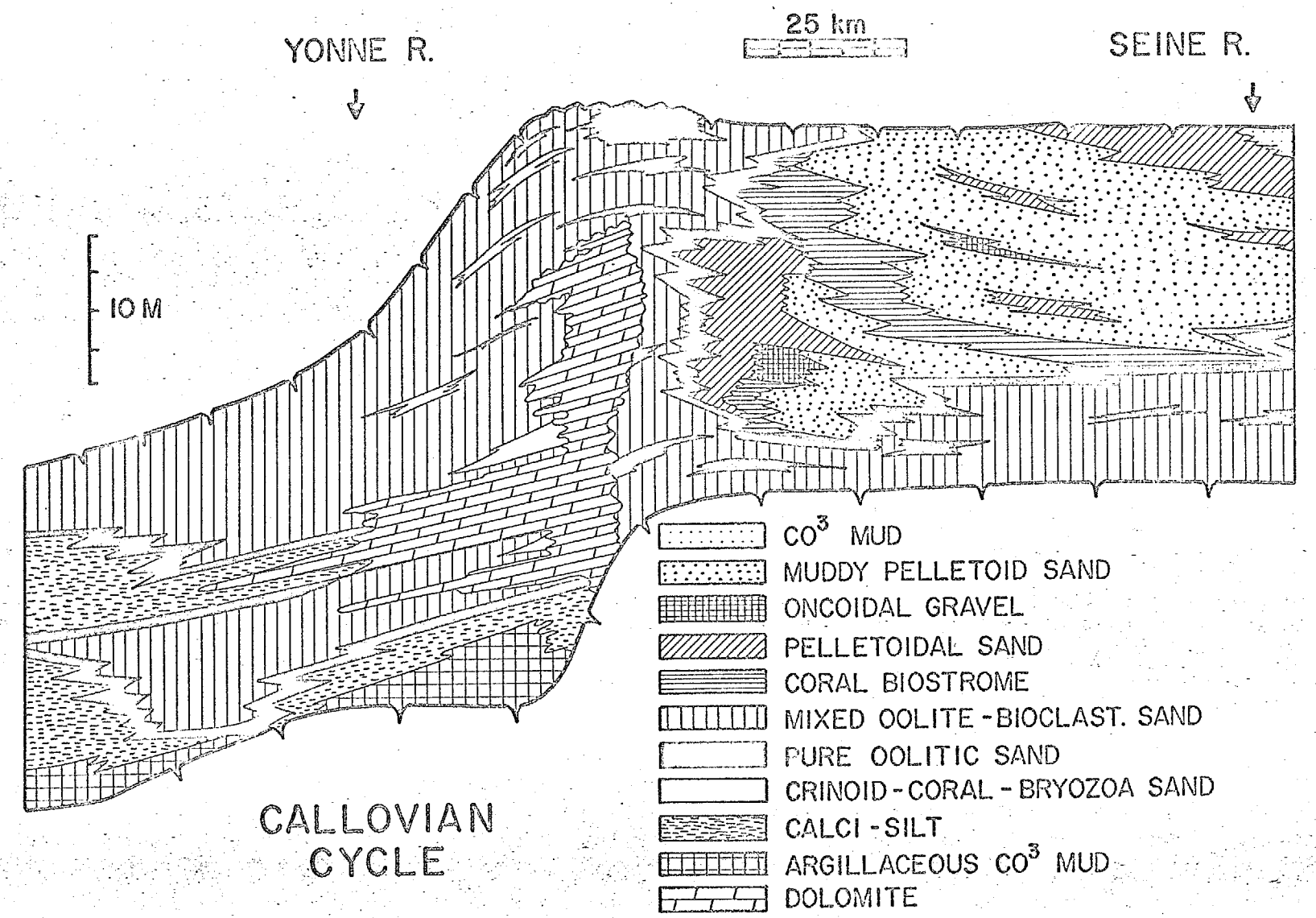


MIDDLE JURASSIC
SEDIMENTS
S. E. PARIS BASIN

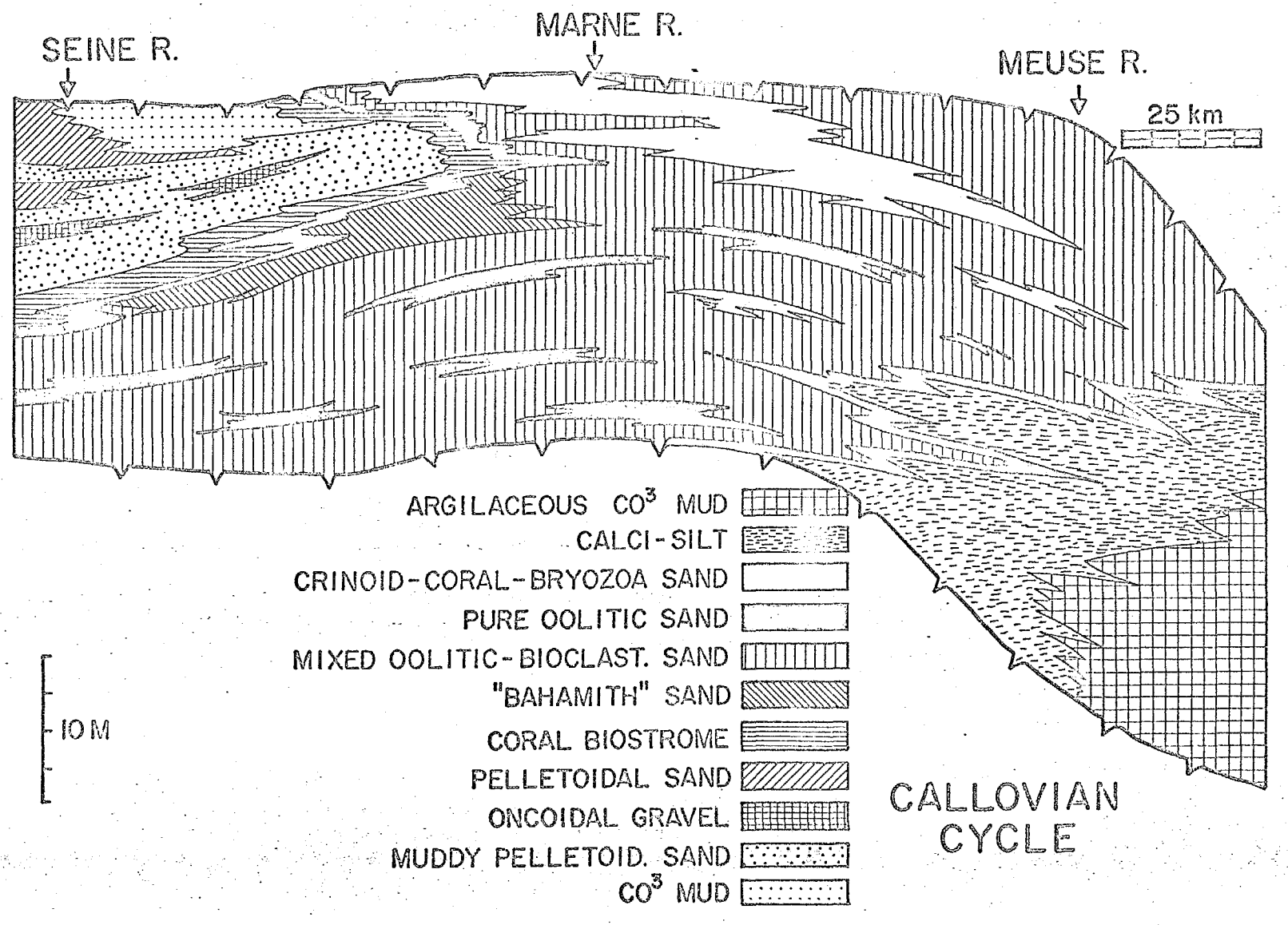
PELLET. CO^3 MUD
OOLITIC- BIOCLAST.
REEFOID
ARGILLACEOUS

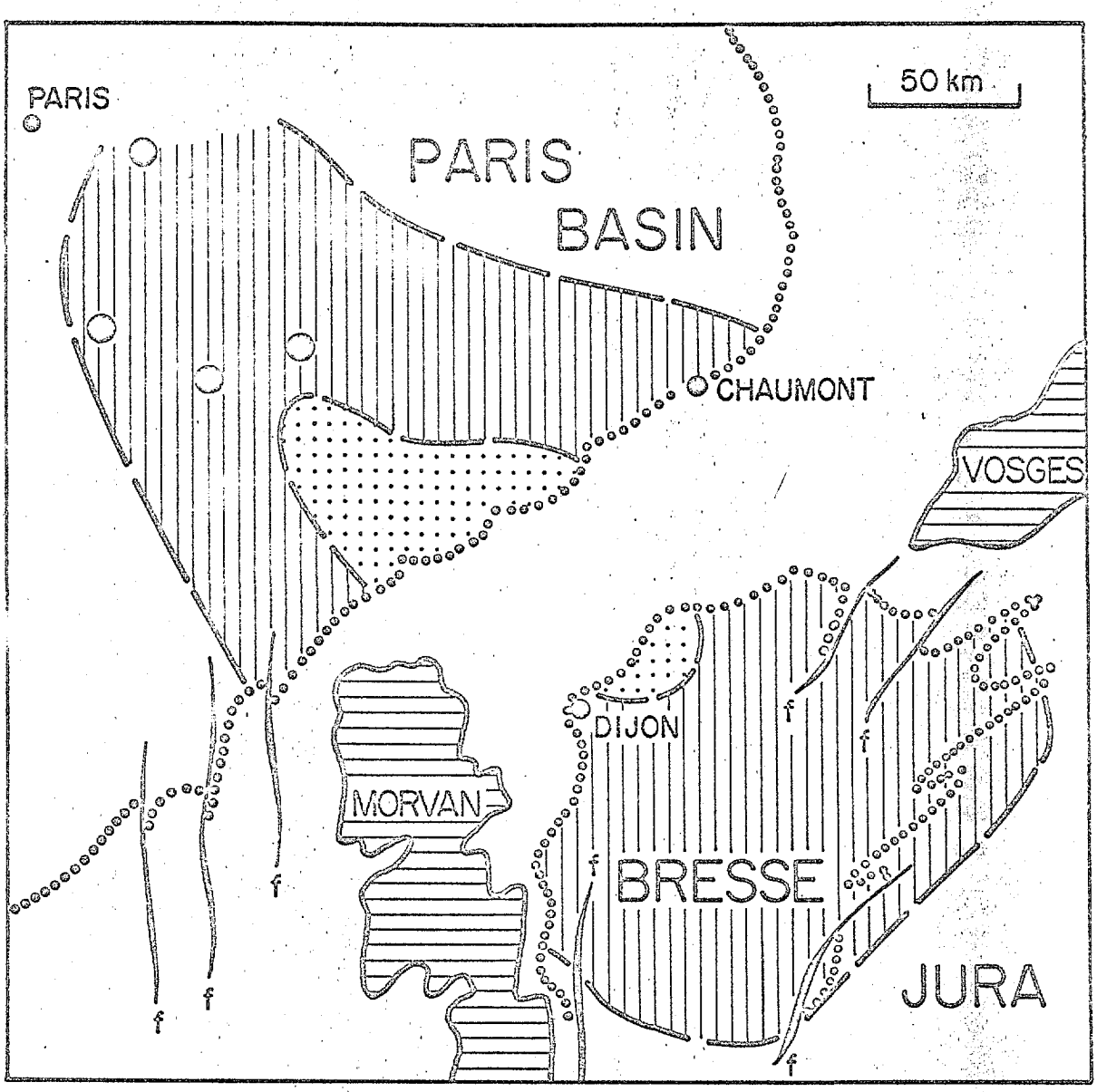


BATHONIAN CYCLE



CALLOVIAN CYCLE


SEINE R.
MARNE R.
MEUSE R.
25 km
ARGILACEOUS CO3 MUD
CALCI-SILT
CRINOID-CORAL-BRYOZOA SAND
PURE OOLITIC SAND
MIXED OOLITIC-BIOCLAST. SAND
"BAHAMITH" SAND
CORAL BIOSTROME
PELLETOIDAL SAND
ONCOIDAL GRAVEL
MUDDY PELLETOID. SAND
CO3 MUD
10 M
CALLOVIAN CYCLE

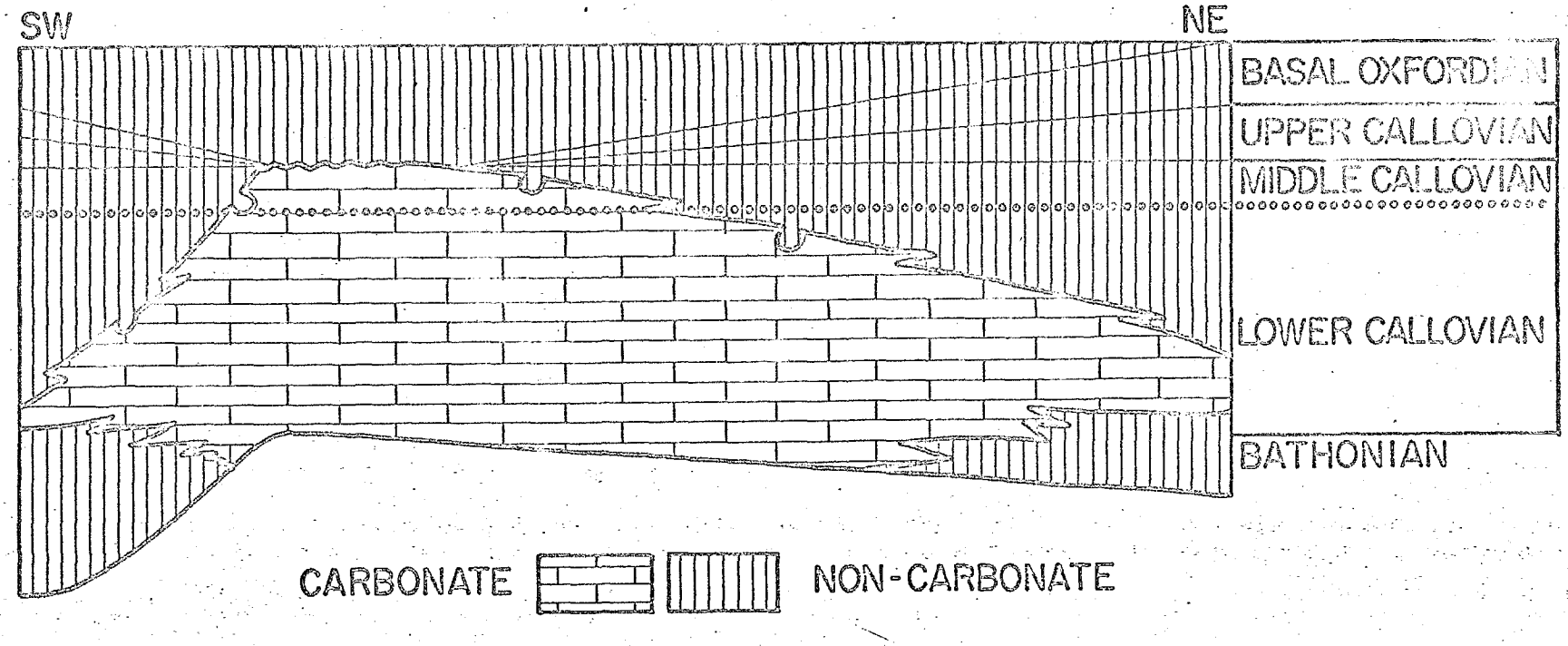


PELLET-ONCOID SAND-MUD

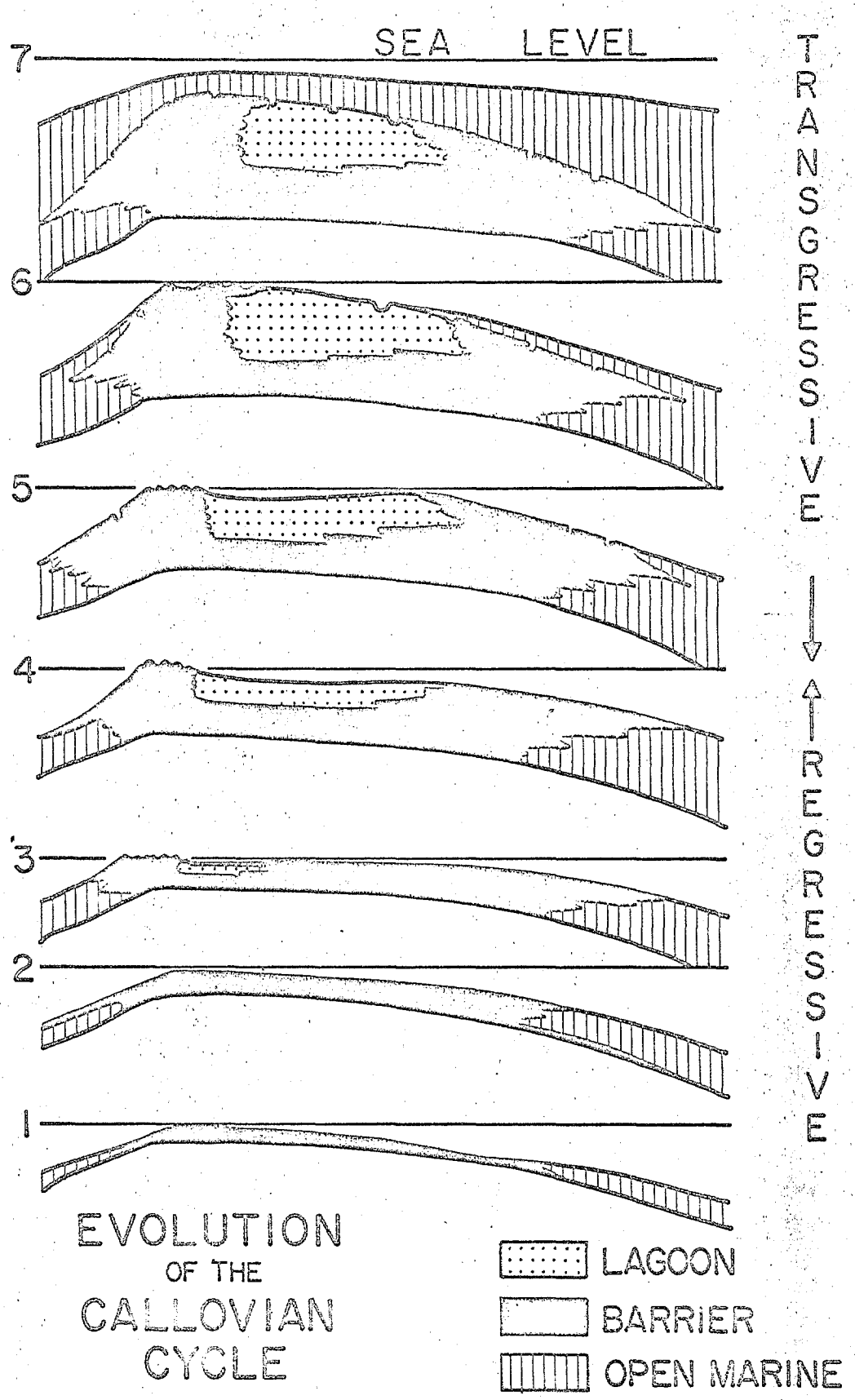
OOLITIC-BIOCLAST. SAND

CALCI-SILT. ARGILL. MUD

CALLOVIAN CYCLE

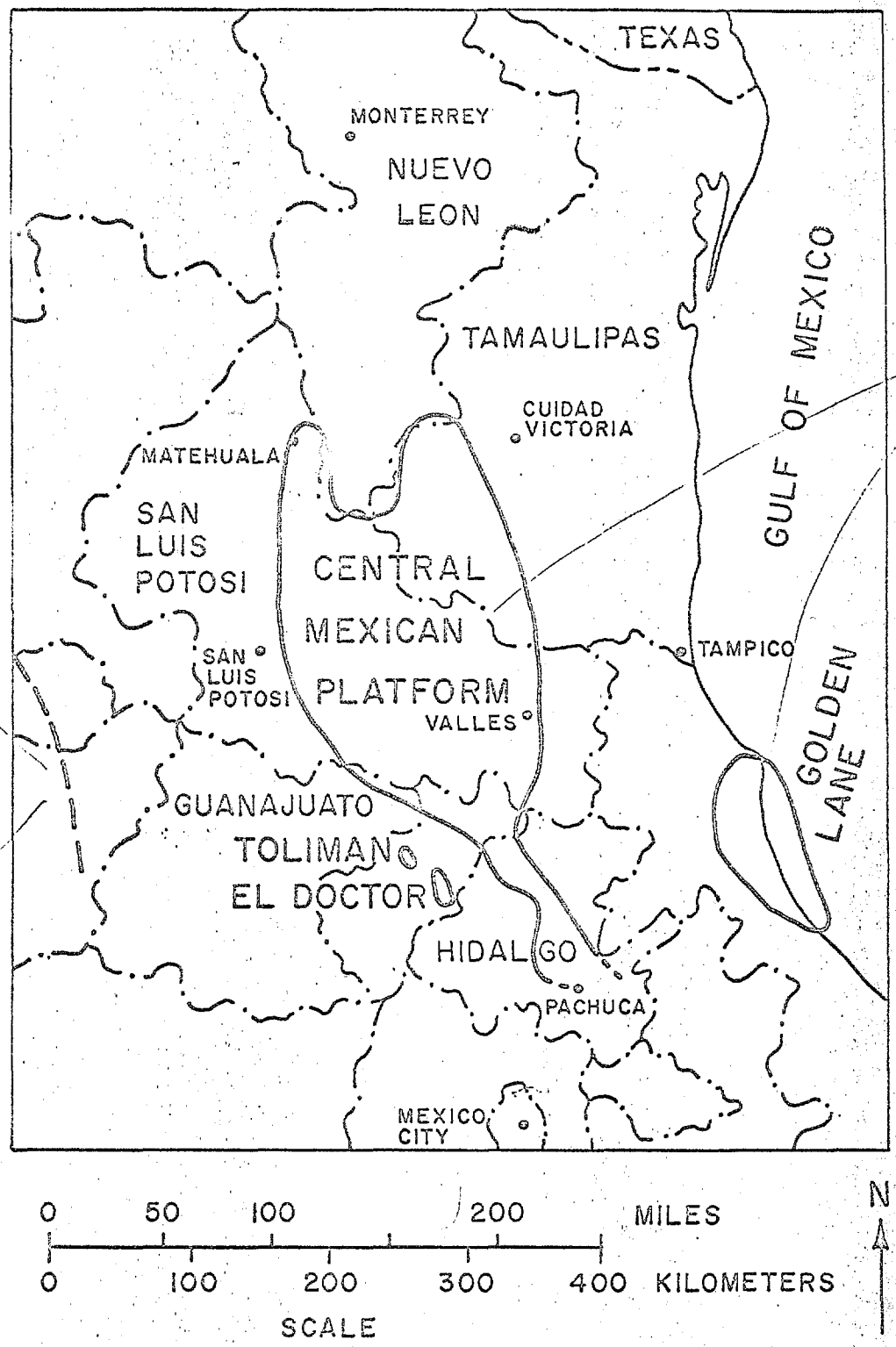


CALLOVIAN CYCLE
SEDIMENT:TIME



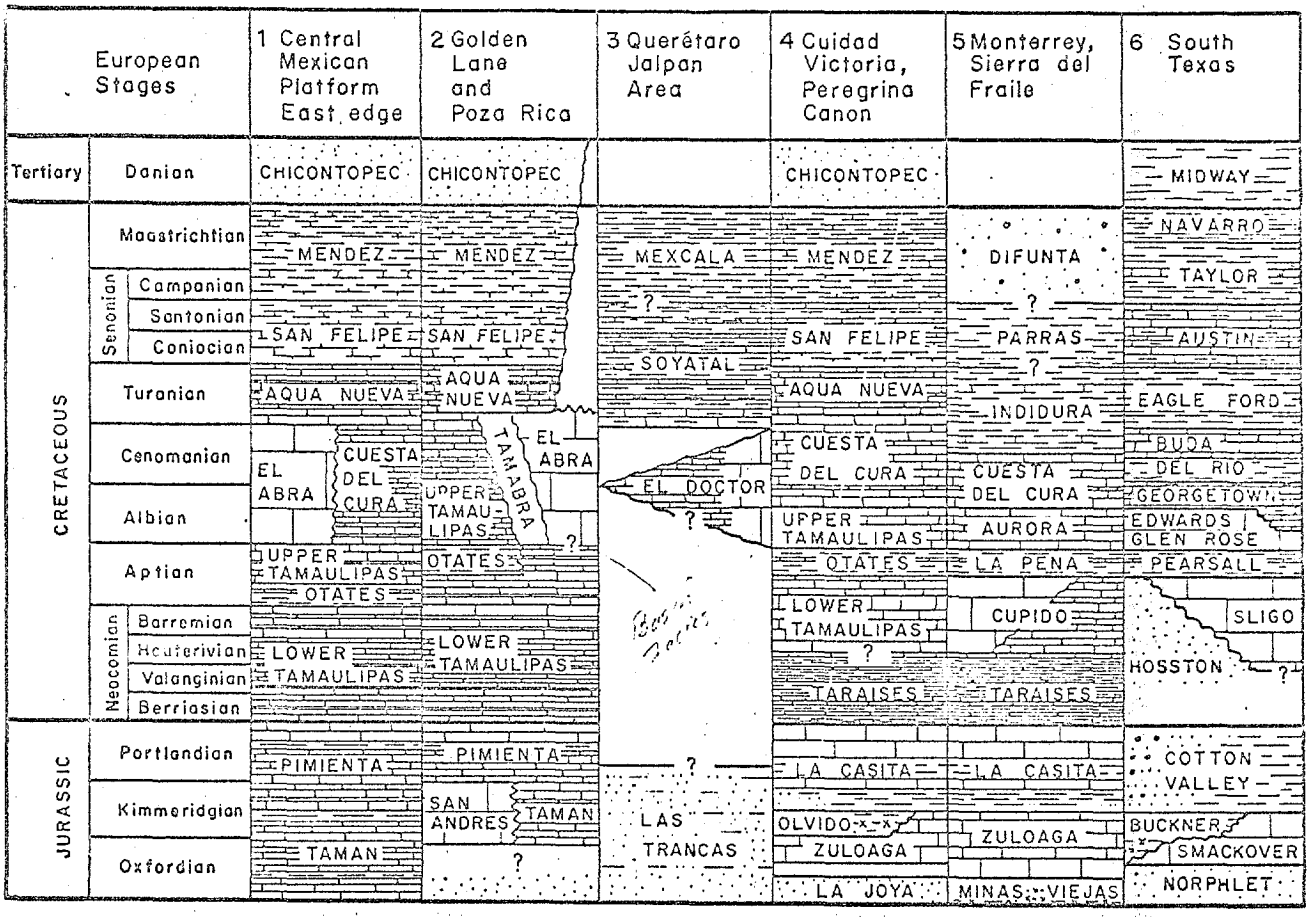
EVOLUTION OF THE CALLOVIAN CYCLE

Enos Paper #5



MIDDLE CRETACEOUS CARBONATE PLATFORMS
NE MEXICO

LATE MESOZOIC CORRELATION CHART, NORTHEAST MEXICO



1. Carillo Bravo, Jose, 1969, Inst. Mex. Petroleo, Seminario Sobre Exploracion Petrolera, Mesa Redonda 6, 19 p.

2. Well information, Petroleos Mexicanos; Barnetche, A. and Illing, L.V., 1956, 20th International Geol. Congress, Mexico City, 38 p.

3. Segerstrom, Kenneth, 1962, U.S. Geol. Surv. Prof. Paper 1104-C, p. 87-162; Carillo Bravo, 1969 (see 1).

4. Corpus Christi Geol. Soc., 1963, Field Trip Guidebook.

5. Humphrey, W.E. and Diaz Gonzalez, Teodoro, unpublished section.

6. Same as 4.

The Massive Sulphide Deposits of the Precambrian in Arizona WLK cpy 82

D. J. Alldrick

The Iron King Mine

Introduction:

The Iron King mine is located one mile west of the village of Humboldt and 75 miles NNW of Phoenix at 30° 34' N and 112° 15' 30" W (Figs. 1 and 3). Mining began in 1906 and continued sporadically until the property was purchased by Shattuck Denn Mining Corporation in 1942. Since then it has been in continuous operation and has a present mill capacity of about 1000 tons per day. Zinc and lead concentrates are produced, from which cadmium, gold, silver and copper are extracted.

Structure and Lithology:

The ore deposit occurs in a group of steeply-dipping, metamorphosed eugeosynclinal volcanic and sedimentary rocks of Precambrian age. Deformation and metamorphism of the host rocks has obscured original structures. The rocks are part of the Alder Group of the Yavapai Series (Figure 2). The Alder Group is made up of thinly bedded sediments of both volcanic and detrital origin with some flows and tuffs. The rocks in the mine area strike N26°E and dip 78° WNW. Structural studies indicate that the sequence represents the western limb of an overturned syncline and thus the succession is from west to east as listed below.

In the immediate vicinity of the deposit (Figure 6), the rock units are:

(1) The Spud Mountain Breccia

This unit is about 5,000 feet thick, lies to the west of the mine, and occurs stratigraphically below the ore horizon. It is andesitic in composition, and may represent either flow breccias or welded ash tuffs.

(2) The Lower Spud Mountain Tuff

This unit lies above the breccia (1) and is 2,000 feet thick. It is composed chiefly of interbedded chlorite—sericite schist and quartz-sericite schist. The chloritic schist represents metamorphosed andesitic tuffs and

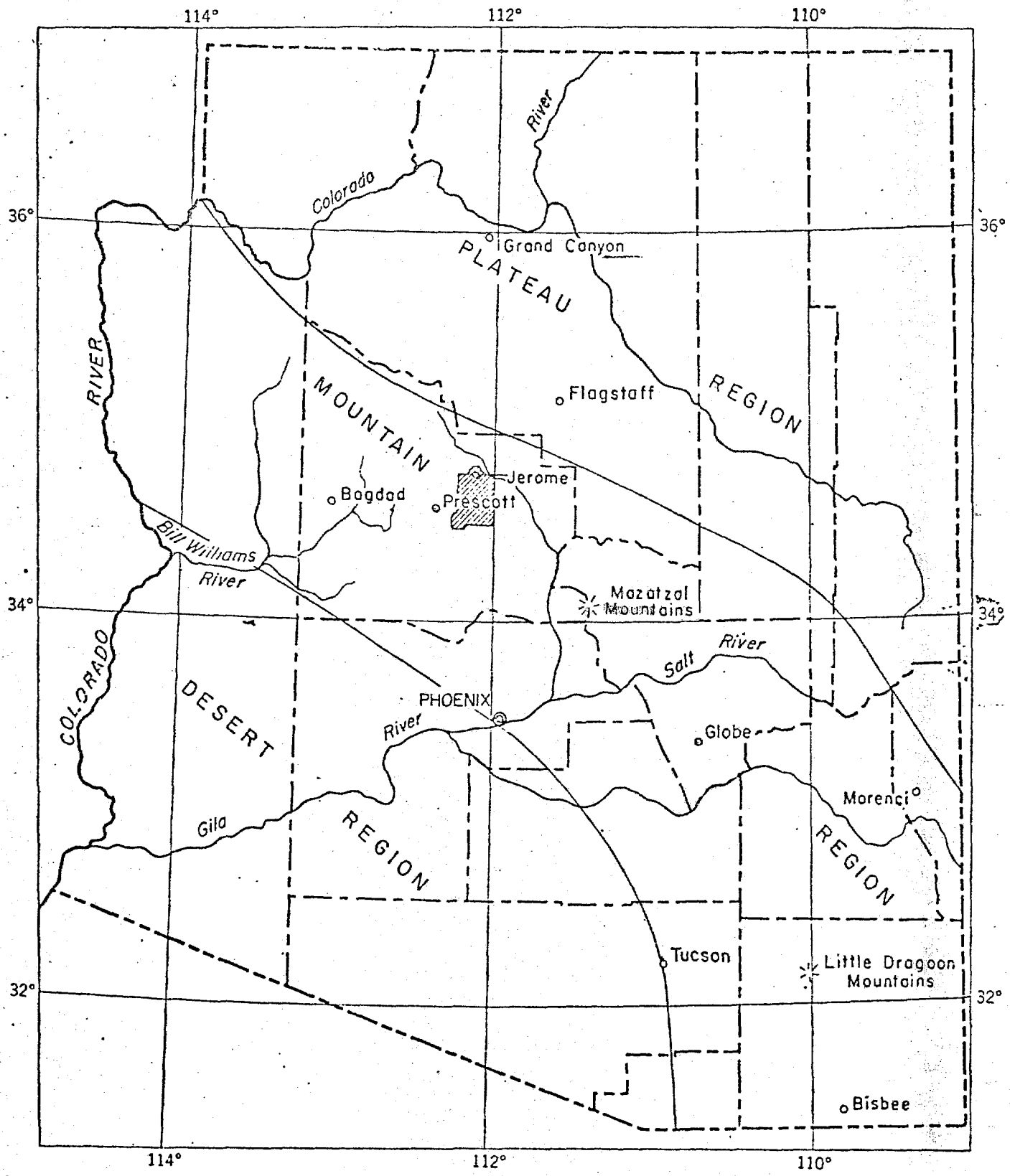


FIGURE 1.—Index map of Arizona showing location of Jerome area. Approximate position of the three principal topographic regions of Arizona outlined. The Plateau region is to the northeast, the Desert region is to the southwest, and the Mountain region lies between them. After Ransome (1903, p. 10).

WEST OF SHYLOCK FAULT

Yavapai series

Alder group

Probable stratigraphic succession

ika / ikat

Iron King volcanics

Andesitic and basaltic flows, ika *; tuffaceous sedimentary rocks,* ikat

smb / smt / smr / sma

Spud Mountain volcanics

Andesitic breccia and interbedded tuffaceous sedimentary rocks, smb *; fine-grained andesitic tuffaceous rock,* smt*; intercalated andesitic flows,* sma*, interbedded rhyolitic tuff,* smr

iha / ihr

Indian Hills volcanics

Andesitic and basaltic flows, iha *; rhyolitic flows,* ihr

Stratigraphic position not known

tgrt / tgps

Texas Gulch formation

Rhyolitic tuff and interbedded conglomerate, tgrt *; chiefly purple slate, containing lenses of limestone,* tgps

ca / cr

Chaparral volcanics

Andesitic tuffaceous rocks, ca*; rhyolitic tuffaceous rocks,* cr

ggv

Green Gulch volcanics

Andesitic-basaltic flows and fragmental rocks, andesitic and rhyolitic tuffaceous sedimentary rocks

EAST OF SHYLOCK FAULT

Ash Creek group

ggs / ggi / ggt / ggi / ggb / ggd / ggi / ggdi / gga

Grapevine Gulch formation

Fine-grained tuffaceous rocks and cherty beds, ggs*; lithic tuffaceous beds,* ggt*; volcanic breccia,* ggb*; dacitic flows,* ggd*; grading into intrusive dacite,* ggdi *; intercalated andesitic flows,* gga *; jasper magnetite beds,* ggi

db / dr / dag / da

Deception rhyolite

Rhyolitic flows, breccia, and tuffaceous beds, dr*; coarse rhyolitic breccia,* db *; intercalated andesitic agglomerate,* dag *; intercalated andesitic flows,* da

st / sb / sr

Shea basalt

Basaltic flows, sb*; intercalated tuffaceous sedimentary rocks,* st*; intercalated rhyolitic flows and breccia,* sr

Brindle Pup andesite

Porphyritic andesitic flows

Dacite of Burnt Canyon

Porphyritic dacitic flows

bt / br / bag

Buzzard rhyolite

Flow-banded rhyolitic flows, rhyolitic flow breccia, volcanic breccia, br*; fine-bedded rhyolitic tuff,* bt*; intercalated basaltic agglomerate and flows,* bag

gab / gar

Gaddes basalt

Chiefly pillow lavas, gab*; local intercalated rhyolitic flows,* gar

OLDER PRECAMBRIAN

PRODUCTS OF ALTERATION AND METALLIZATION

si

Quartz or jasper lenses, pods, and veins

Includes alteration zone at Iron King mine, and Kit Canyon and Silver Belt McCabe veins

Figure 2.

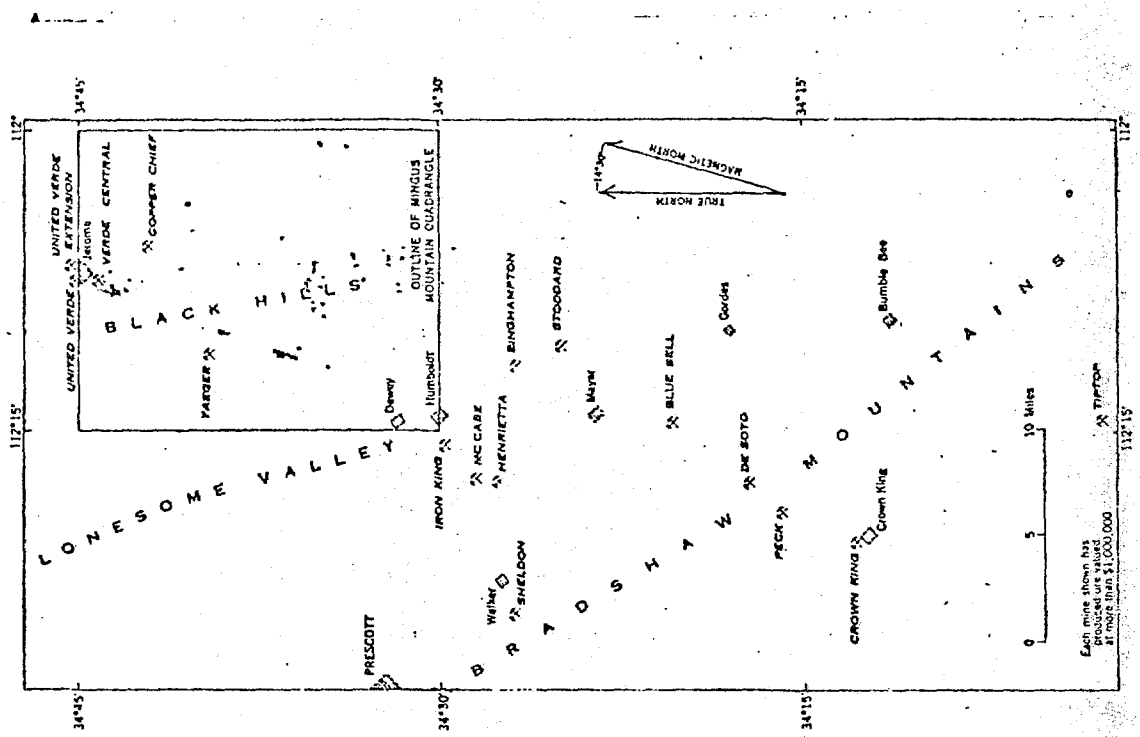


FIGURE 3.—Sketch map of Bradshaw Mountains and Black Hills showing location of principal mines.

Fig. 4.—*Comparison of the mineralogy of the Iron King and United Verde deposits with other massive sulfide deposits*

Iron King deposit, Arizona	United Verde deposit, Arizona	Huelva, Rio Tinto district, Spain (Bateman, 1927)	Shasta County deposits, California (Graton, 1909)	Sullivan deposit, Canada (Swanson and Gunning, 1945)	Rammelsberg deposit, Germany [1] (Lindgren and Irving, 1911)	Mandy deposit, Manitoba (Hanson, 1920)	Deposits at Kyshtim, Russia (Stickney, 1915)
Sulfide minerals							
Pyrite Arsenopyrite Sphalerite Galena Chalcopyrite Tennantite	Pyrite Arsenopyrite Pyrrhotite Sphalerite Tennantite Bornite Galena Chalcopyrite	Pyrite Arsenopyrite Sphalerite Galena Tetrahedrite Enargite Luzonite Famatinite Chalcostibite Whitneyite Umangite Hatchecornite Ullmanite Berthierite(?)	Pyrite Chalcopyrite Sphalerite Galena Bornite	Pyrite Arsenopyrite Sphalerite Chalcopyrite Galena Bornite Chalcocite Tennantite	Sphalerite Chalcopyrite Galena Pyrite Arsenopyrite	Pyrite Arsenopyrite Sphalerite Chalcopyrite Galena	Pyrite Chalcopyrite Sphalerite Tennantite Galena Bornite (rare)
Gangue minerals and hydrothermal alteration products							
Quartz Ankerite Sericite Apatite(?)	Quartz Ankerite-dolomite Chlorite Magnetite Specular hematite	Sericite	Quartz Calcite Barite	Chlorite Quartz Specularite Dolomite	Barite	Sericite Carbonates Quartz Chlorite Rutile	Quartz Barite Sericite Rutile

[1] Listed in order of abundance.

crystal tuffs. The quartz-sericite schists are likely metamorphosed rhyolitic tuffs and crystal tuffs.

(3) The Ore Horizon

The ore occurs as a series of overlapping conformable bodies of massive sulfides and associated lenses of massive quartz and quartz-sericite schist. A parallel zone of copper mineralization occurs within the stuctural hanging-wall rocks. The massive sulfide lenses lie at the contact of the metarhyolite of the Lower Spud Mountain Tuff and the meta-andesite at the base of the Upper Spud Mountain Tuff(Figure 6). The lenses of ore occur as "en echelon" layers in compound lenses (Figure 5). The massive sulfide zones are fine-grained and commonly banded, with gangue minerals consisting of quartz, carbonates, sericite and minor chlorite. Pyrite is the dominant sulfide, with lesser amounts of sphalerite, galena, chalcopyrite and arsenopyrite. The southern end of the ore zone grades into green-gray quartz-sericite schist; the northern end terminates sharply against greenish massive quartz which locally contains coarse crystals of sphalerite and galena.

The "Copper Zone" mineralization is a 400 foot wide band of chalcopyrite-tennantite occurring in veins and stringers with quartz and/or coarse black chlorite in the structural hanging-wall of (and therefore stratigraphically below) the massive sulfide horizon.

Gilmour and Still suggest that the orebody formed through the agency of a volcanic hot spring (yielding metal-rich, siliceous sinter deposits) on, or near, a submarine surface of deposition.

(4) The Upper Spud Mountain Tuff

This unit is stratigraphically above the ore horizon and outcrops to the east of the mine. It is a series of laminated to massive meta-andesites and interbedded sediments including tuff, crystal tuff and agglomerate. A thin bed of conglomerate containing chert and jasper pebbles occurs near the top

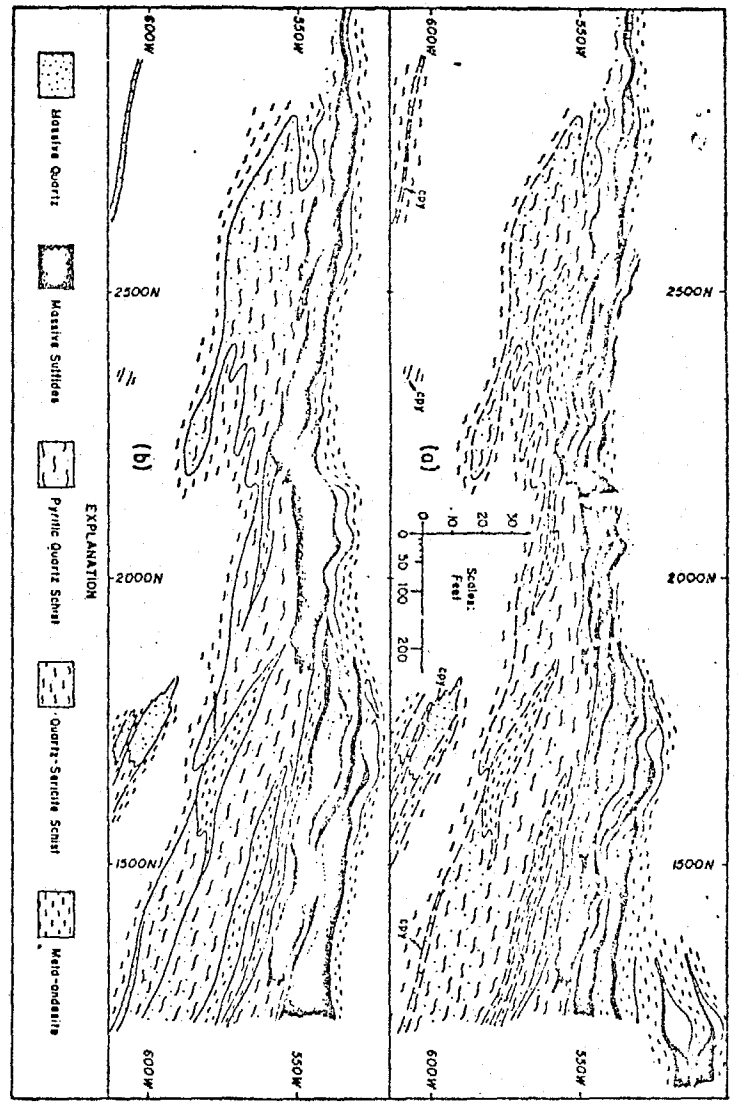


FIG. 5 *Plan of the 2200 Level Foreshortened along Strike by a Factor of Five.*
FIG. 5b. *Simplified and Idealized Version of (a).*

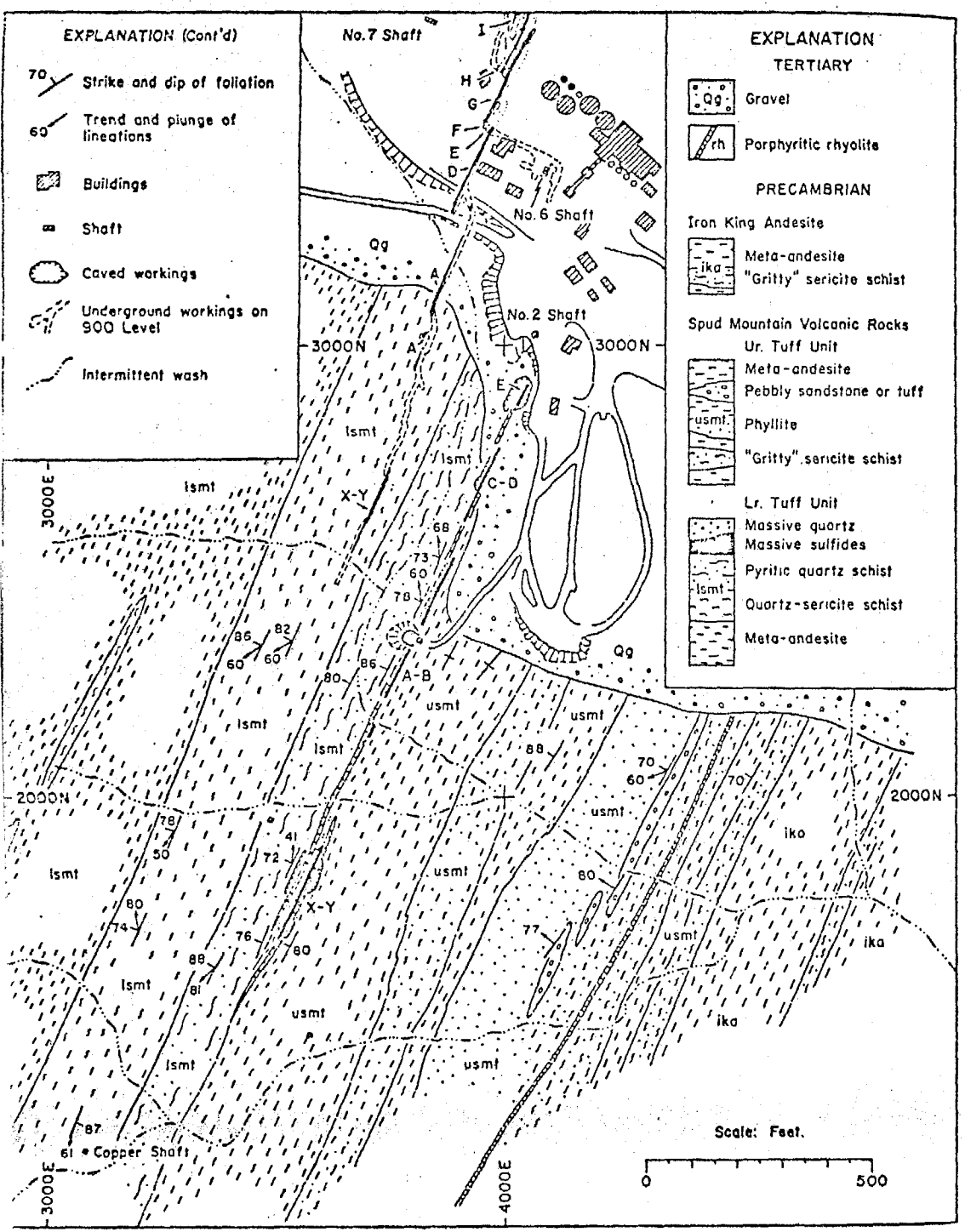


FIG. 6 *Geological Map of the Iron King Mine.*

of this unit.

(5) The Iron King Andesite

This unit succeeds the Spud Mountain Tuffs and outcrops further to the east than (4) (Figure 6). It grades upward (eastward) from pyroclastic material into undeformed massive andesite with locally preserved pillows.

The United Verde and United Verde Extension Mines

Introduction:

These two mines, owned by Phelps-Dodge Corporation, lie a mile apart, and about 20 miles NNW of the Iron King mine. Underground mining has ceased at both properties (United Verde Extension in 1938, United Verde in 1953), but open pit operations are still in progress at United Verde.

Lithology and Structure:

The massive sulphide deposits occur in the upper part of the Ash Creek Group which consists of thick units representing two cycles of basaltic to rhyolitic volcanics overlain by pyroclastics which are interbedded with chert. The great thickness of the Ash Creek Group (over 20,000 feet) suggests a eugeosynclinal environment of deposition while pillow lavas and ferruginous chert beds indicate a subaqueous environment. The rocks are folded along a NW axis and have been metamorphosed to greenschist facies but generally, relict textures and structures are preserved. The upper two formations of the Ash Creek Group (Figure 2), the Deception Rhyolite and the Grapevine Gulch Formation above it, contain the massive sulphide deposits at Jerome. The crystal tuff/quartz porphyry member of the Deception Rhyolite, called the Cleopatra Member, has been dated at 1,820 ± 10 million years.

(1) The Deception Rhyolite

This unit is approximately 4,000 feet of rhyolitic flows, breccias and tuffs with the Cleopatra Member about half-way up the section. The upper

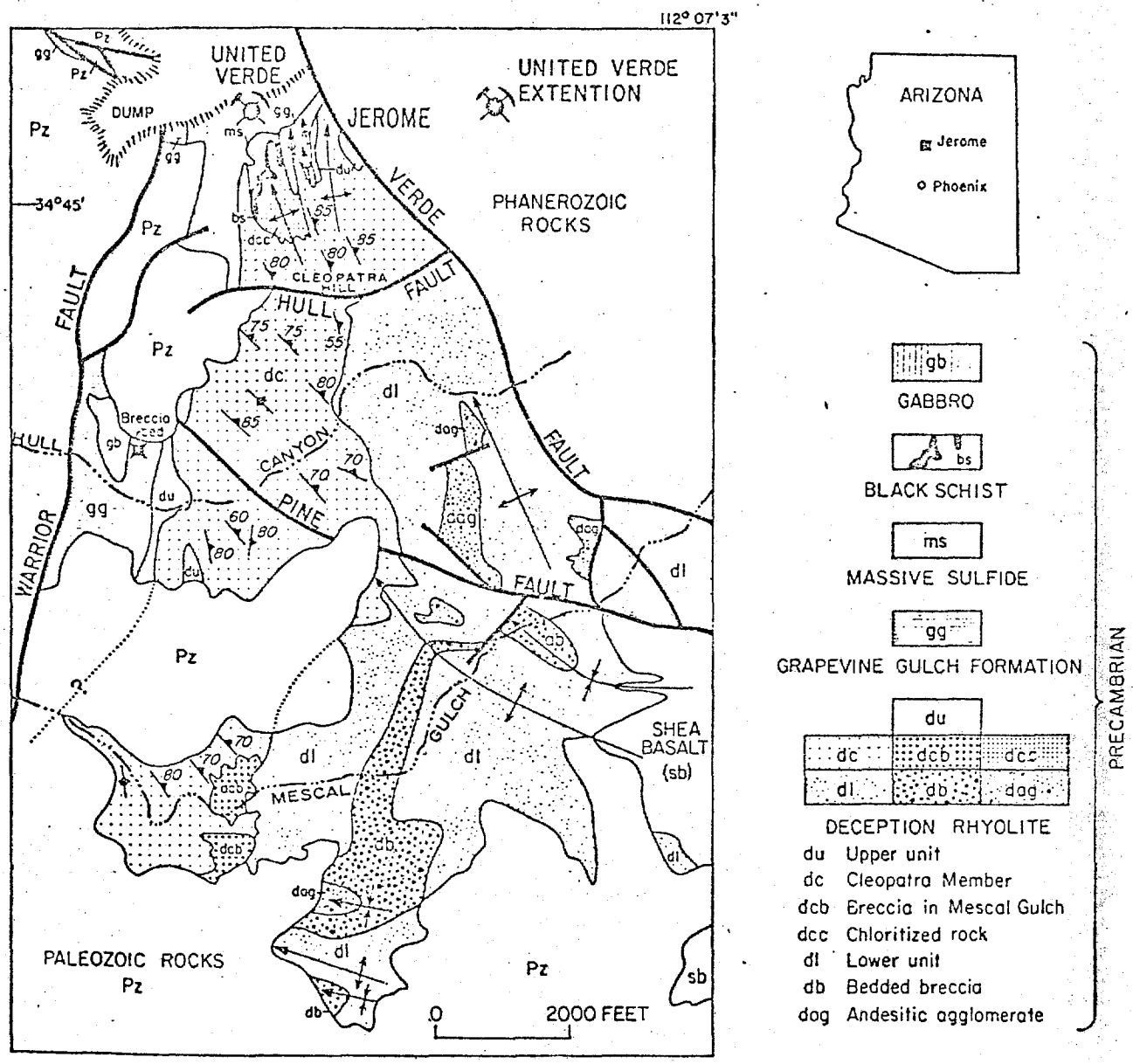


FIG. 7 Geologic map of area south of Jerome modified from Anderson and Creasey (1958, Pl. 1); inset shows location of Jerome.

half of the Deception Rhyolite is mostly breccia and crystal tuff with smaller beds of red siltstone.

(2) The Cleopatra Member

This unit represents an intertonging complex of flow-banded quartz porphyry, breccias and crystal tuffs. The crystal tuff zone contains numerous angular quartz clasts and large amounts of sericite and chlorite. The flow-banded quartz porphyry is a rhyolitic extrusion or shallow intrusion.

(3) The Grapevine Gulch Formation

Complex intertonging of flows, breccias, crystal tuffs and fine-grained tuffs is common in the Grapevine Gulch Formation and throughout the Ash Creek Group. The lower part of the Grapevine Gulch Formation has a sharp contact against the Deception Rhyolite and is composed of alternating bands of breccia, coarse- and fine-grained tuffs, cherty shales and chert beds. The fine-grained rocks of the Grapevine Gulch Formation intertongue with the massive sulphide lenses. Minor, purplish, quartz-bearing crystal tuffs are found intertonging with the major beds of the formation.

(4) The Ore Zones

The United Verde Mine has two ore zones, called the Main and North orebodies (Figures 8,9,10 and 11). The ore zones consist of massive sulphide lenses and related "black schist" and "quartz porphyry" ores.

The massive sulphide lens of the Main orebody is pipelike and plunges at 60°. The contact of the massive sulphide with adjacent rocks is usually sharp, but occasionally is gradational into disseminated pyritic rock. Quartz lenses, cut by veinlets of pyrite and chalcopyrite, occur along the hanging-wall and occasionally within the massive sulphide lenses. The contact between the massive sulphide and the Grapevine Gulch Formation on the hanging-wall side of the lens is conformable (bedding parallel) and occasionally intertonging. The North orebody occurs in the lower levels of the mine about 500 feet north-

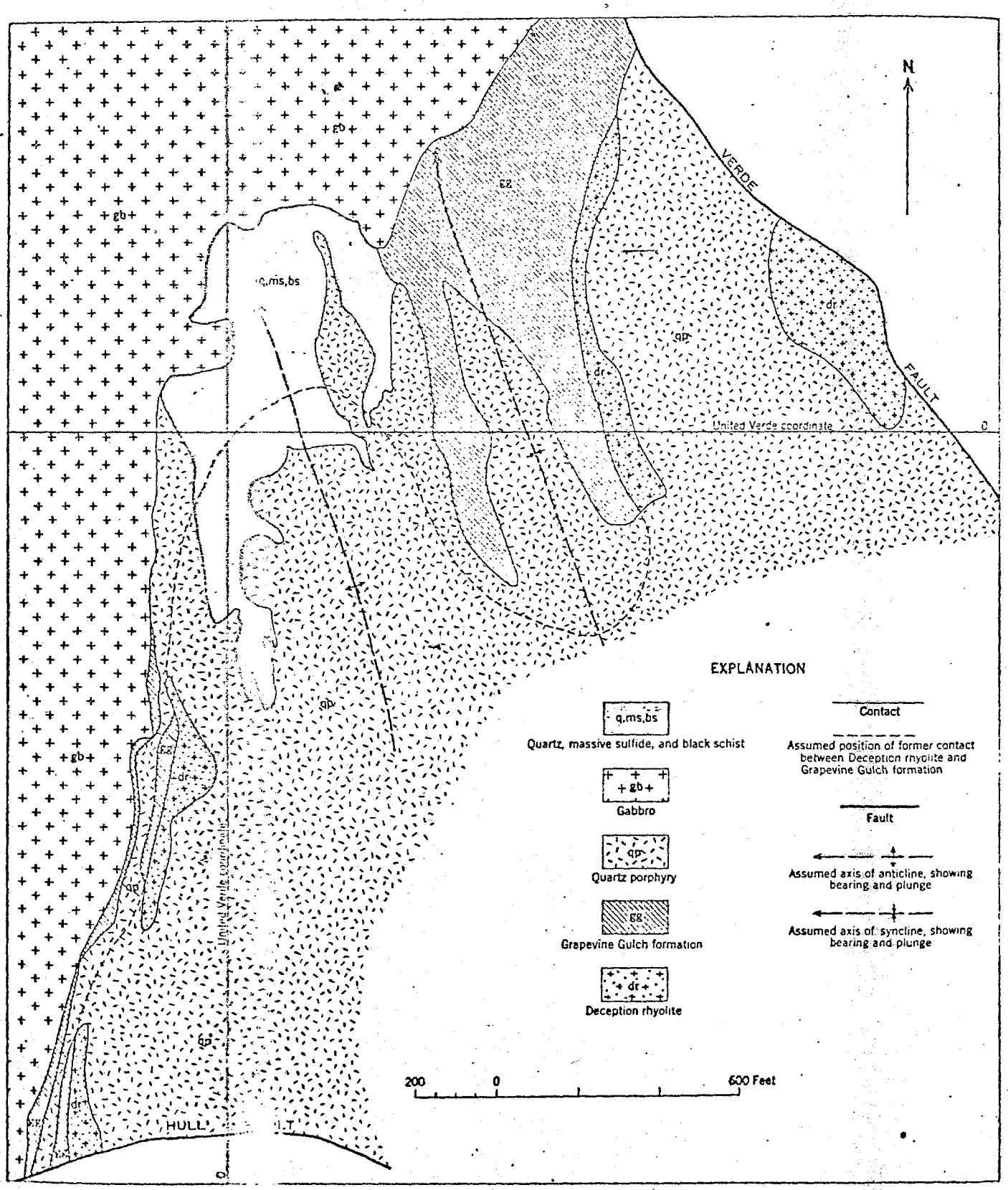


FIGURE 8 —Suggested structural interpretation at United Verde mine.

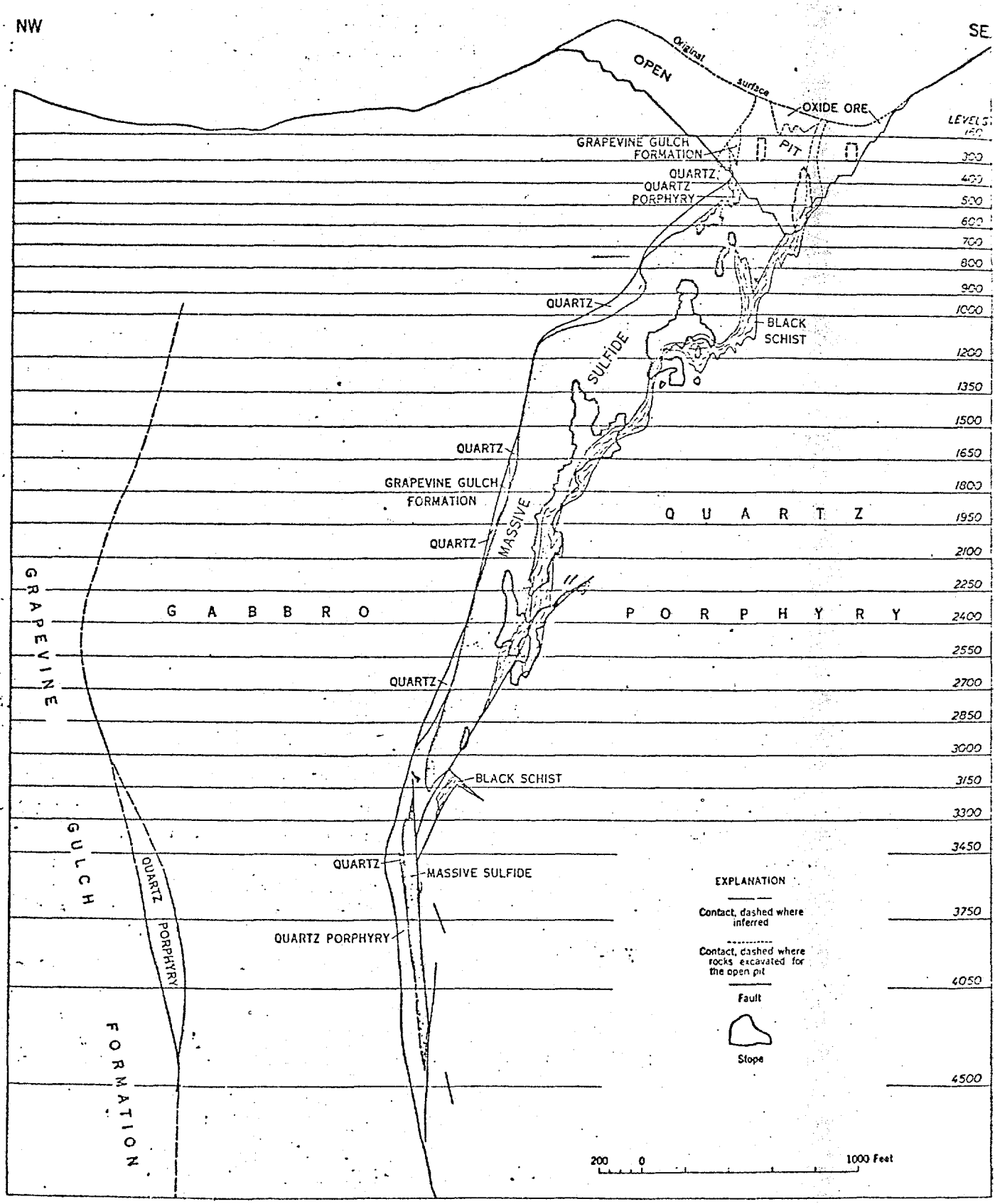


FIGURE 9.—Vertical section through United Verde mine. Compiled by P. F. Yates, Phelps Dodge Corp.

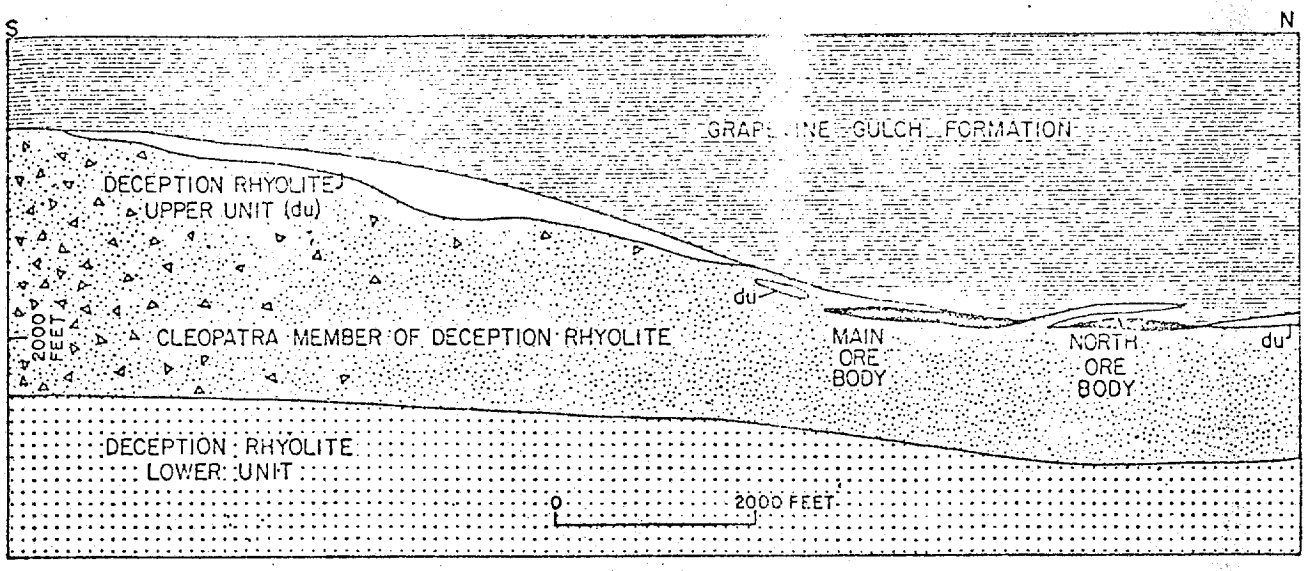


FIG. 10 Interpretative section of the Cleopatra Member and associated rocks after accumulation and before folding. In the northern part of the section, the Cleopatra Member is appreciably thinner and finer grained than to the south. The youngest crystal tuffs in the Cleopatra Member intertongue with the massive sulfide lenses, upper unit of the Deception Rhyolite, and lower beds of the Grapevine Gulch Formation.

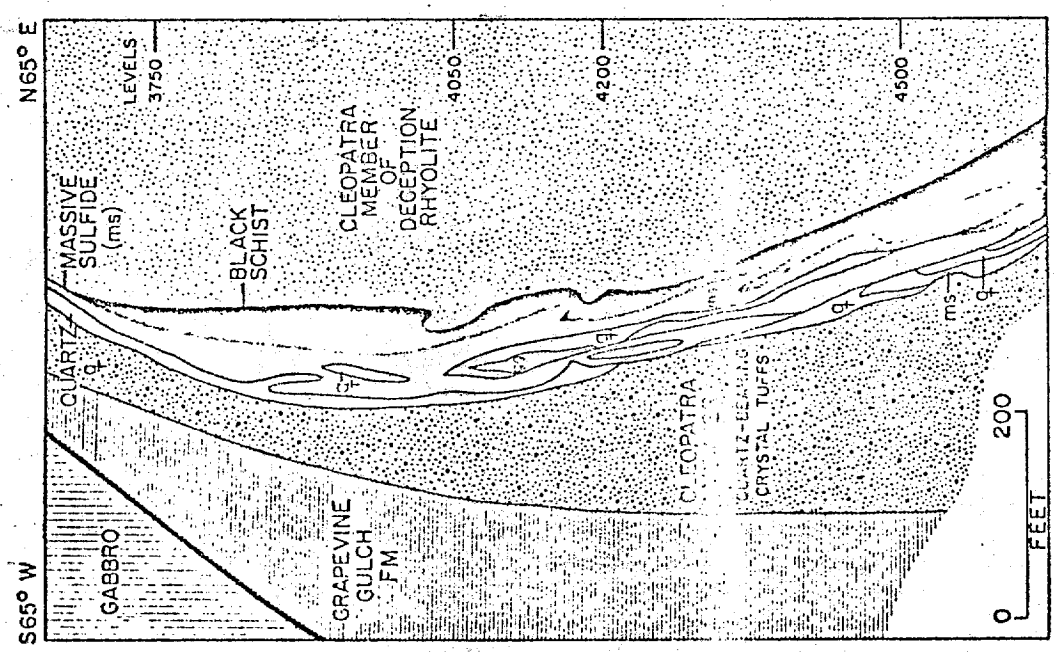


FIG. 11 Vertical section through the North ore body of the United Verde mine, showing intertonguing of quartz-bearing crystal tuffs of the Cleopatra Member with the fine-grained bedded rocks of the Grapevine Gulch Formation. Modified from Anderson and Creasey (1958, Pl. 7).

west of the Main orebody. It consists of a number of lenses all occurring within the fine-grained, bedded rocks of the Grapevine Gulch Formation.

The black schist rock consists of large masses of nearly pure chlorite that have been formed by Fe-Mg metasomatism of the Cleopatra Member and the Grapevine Gulch Formation. The chloritization is most intense adjacent to the massive sulphide lenses. Anderson and Nash suggest that the black schist rock is the result of hydrothermal alteration due to upwelling of hot, dense brines. The black schist rock locally contains sufficient chalcopyrite as fracture-fillings to constitute ore.

The "quartz porphyry" ore is formed by chalcopyrite infillings of fractures in the Cleopatra Member and it is essentially a downward continuation of the "black schist" ore zone.

At the United Verde Extension mine, the orebody occurs in the Cleopatra Member, in undifferentiated Deception Rhyolite rocks, and locally within Grapevine Gulch Formation rocks. The massive sulphide body has been modified by supergene enrichment which produced a chalcocite ore zone. Attempts have been made to show the pre-Verde Fault relationship between the United Verde and United Verde Extension orebodies (Figure 13). Correlation has been a problem because of subsequent erosion and lack of a marker horizon, but although earlier authors insist that the United Verde Extension represents the severed top of the United Verde orebody(Figure 13, location III), the most recent study of the problem, by Norman, Anderson, and Creasey (in Anderson and Creasey, 1958), suggests that the most likely original location for the United Verde Extension orebody is about 1300 feet ESE of United Verde (Figure 13, location IV).

Anderson and Nash (1972) suggest that the ore deposits formed contemporaneously with their host rocks, but that they are <u>not</u> volcanic exhalative sedimentary deposits. Their theory suggests that the ore is the result of

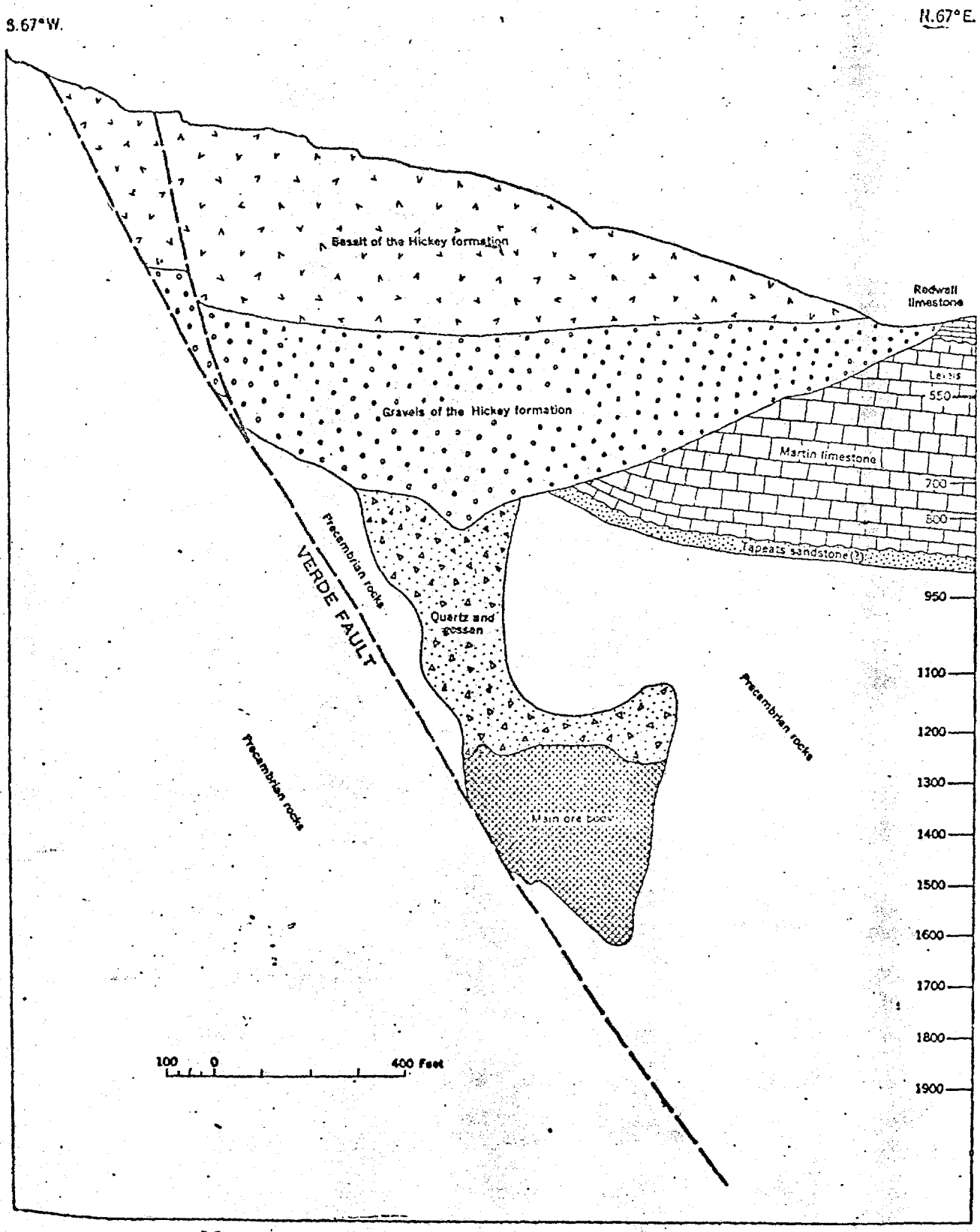


FIGURE 12—Generalized section through United Verde Extension mine. From Reber (1938).

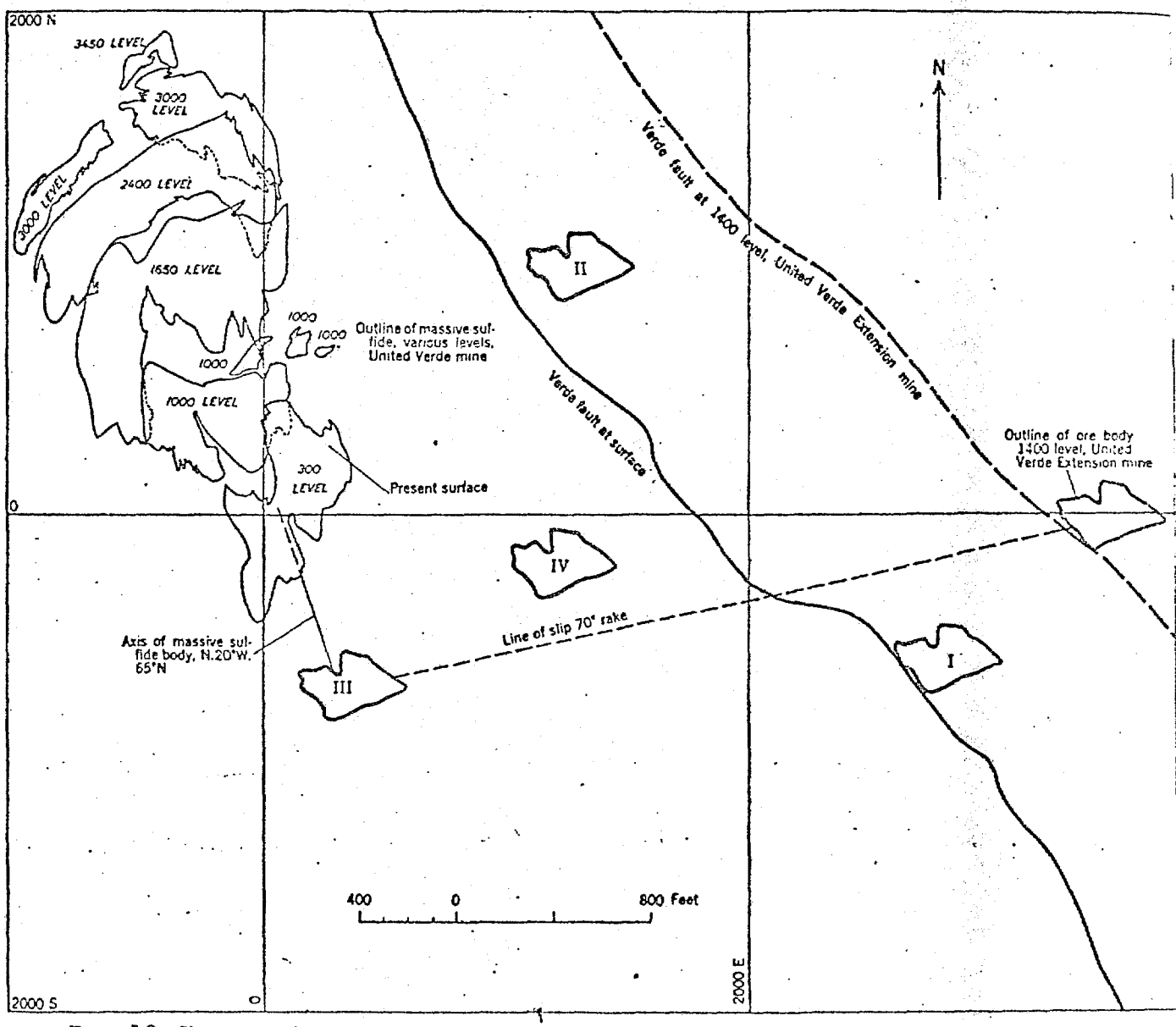


FIGURE 13—Sketch map showing interpretations of relationship of United Verde and United Verde Extension ore bodies.

hydrothermal mineralizing solutions, that is, hot brines which dissolved the base metals out of the volcanics further down in the Ash Creek Group, rose to the submarine paleosurface and deposited the massive sulphide lenses by precipitation, pore-filling, and complete large scale mineral replacement of the pyroclastic rocks which were at that time being deposited.

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(2) Anderson, C.A., and Nash, J.T., (1972), Geology of the Massive Sulphide Deposits at Jerome, Arizona--A Reinterpretation; in Economic Geology, Vol. 67, No. 7, Nov. 1972, pp.845-863.

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Sedimentary Deposits

Rip, strip, mine copper ore with Cats

Sedimentary overlayers W L Kerr

AMERICAN SMELTING AND REFINING COMPANY
Tucson Arizona

February 1, 1972

MEMORANDUM FOR: Division Supervisors

KUROKO DEPOSITS

Attached are copies of a few pages from a recent Japanese publication "Volcanism and Ore Genesis", University of Tokyo Press, 1970.

Over the past 20 years, newly discovered Kuroko deposits aggregate over 70 million tons of high grade lead-zinc-copper ores. The principal occurrences are stratiform and are believed to have been deposited on shallow sea bottoms during Miocene volcanism. However, epigenetic mineralization-----in stockworks, breccias, and chimneys-----is present in many cases. These structures are regarded as the probable source of the metals in the stratiform (syngenetic) deposits.

Similarities to deposits in much older rocks are evident. For example, at Buchans where barite overlies massive zinc-lead sulphides which are underlain (in part) by siliceous, copper bearing stockworks. Another feature in common here is the presence of detrital fragments of mineralization-----indicating erosion by turbidity currents, or otherwise.

The mineralized stockworks of the Kuroko deposits are depicted as being continuous in depth, in contrast to the evidence at Buchans and at Rio Tinto, Spain, where drill holes pass downward into unmineralized volcanics. In view of this lack of depth continuity, it has been theorized that the copper in the Rio Tinto disseminated ore body was derived by remobilization from adjacent cupriferous pyrite----- a process promoted by tectonics involved in the crest of a tight fold. If, however, the stockworks constitute the source of the stratiform deposits, they could occur in the flanks of folds or wherever stratiform occurrences are found, although gravity sliding* (of the massive sulphides) could have separated them in space. The latter could account for the absence stockworks beneath or near some of the Kuroko deposits and likewise at Buchans.

J.H. Courtright
J.H. COURTRIGHT

* L.J.G. Schermerhorn, The Deposition of Volcanics and Pyritite in the Iberian Pyrite Belt; Sociedade Mineira de Santiago (date missing)

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Encls: as noted

cc: J.J. Collins w/encl.
Eric Swanson, Buchans w/encl.

Kuroko Deposits in Japan, a Review

Toshinori MATSUKUMA
Akita University
Ei HORIKOSHI
Kyushu University

INTRODUCTION

The "Kuroko" deposit is a strata-bound polymetallic mineral deposit genetically related to submarine acid volcanic activity of Neogene Tertiary in Japan. The deposits have been exploited and mined since middle of the nineteenth century. Recently, they attracted the attention of all Japanese mining geologists and miners through the discoveries of new Kuroko deposits of more than 70 million tons of high-grade lead-zinc-copper ores over a period of twenty years.

Studies on the deposits in the early part of this century offered many interesting discussions. FUKUCHI (1902) and OHASHI (1919) presented the syngenetic hydrothermal theory for their origin, but KATO (1915) emphasized a hydrothermal replacement origin. KINOSHITA summarized his studies on the Kuroko deposits and proposed a low-temperature metasomatic theory (KINOSHITA, 1924, 1929, 1931, 1944). The theory was supported by most of Japanese geologists for a long time. Recently, WATANABE (1956, 1959) again suggested submarine volcanic sedimentary origin for the Kuroko deposits, and the syngenetic theory has been accepted by many mining geologists in Japan since then. They succeeded in prospecting the deposits based on this concept. On the other hand, recent development of the deposits has presented many opportunities for providing new field data. Especially, relations between volcanic activity and mineralization and evidences for submarine hydrothermal and exhalative sedimentary origin of the deposits have been accumulated.

"Kuroko," an old mining term in Japanese meaning essentially black ore, was named because of its black colour. HIRABAYASHI (1907) defined it as an ore which is a fine compact mixture of sphalerite, galena, and barite. KINOSHITA (1944) defined "Kuroko deposit" as a deposit genetically related to the Tertiary volcanic rocks, consisting of one or a combination of Kuroko (black ore), Oko (yellow ore), Keiko (siliceous ore), and/or Sekkoko (gypsum ore). He emphasized that the

Kuroko deposit should be limited to the deposit in which typical Kuroko occurs. He also proposed that the name "Kuroko-type deposit" be applied to such an ore deposit as allied types consisting of only pyritic or pyritic-siliceous ores, or as vein-type deposits formed along paths of mineralizing solution of the Kuroko deposits. On the contrary, OHASHI (1962) recently gave the name "Kuroko-type deposit" to one which is defined as bedded sedimentary deposit formed by submarine volcanism. Following him, HORIKOSHI (1965) gave another proposal from the viewpoint of metallogenesis, that a "Kuroko-type deposit" is a deposit formed under conditions of nearly neutral pH and sufficiently low Eh." The Kuroko deposits are, however, so complicated in their nature that these brief definitions are not sufficient to show their characteristics. It is desirable to have the nature of the Kuroko deposits understood through following descriptions on the deposits.

GEOLOGIC SETTING

All of the Kuroko deposits occur in the so-called Green Tuff region (cf. Part 1). Distribution of the Kuroko deposits in the Tohoku district is shown in Figure 1. Geology of the region in northeastern Japan is characterized by formations of thick geosynclinal sedimentary pile of about 3,000 meters in maximum thickness. Stratigraphic succession of the Miocene formations in the region is representated typically by that of Akita district where the large Kuroko deposits, such as those of the Kosaka, Hanaoka and Shakanai mines, are located nearby (Table 1). Though age of metallic mineralization of Miocene in this region is not single, the age of the major one is from middle to later Miocene at which structural development of the geosyncline changed its nature. The Nishikurosawan stage was a period of beginning of the geosynclinal sinking in the inner zone of the Tohoku district, northeastern Honshu. This sedimentary basin shows maximum sinking at the Onnagawan and Funakawan stages. But the eastern part of the basin, where upheaval movement of the basement began at the Nishikurosawan stage, offered the place of intense volcanism which was associated with Kuroko mineralization. As compared with the main part of the basin which is the most productive oil field in Japan, the eastern marginal part may be considered to be not an open sea, but an inland or a trench-like sea.

Based on our present knowledge of the mode of occurrence of the Kuroko deposits, we know that most of them occur in a definite stratigraphic horizon of the Nishikurosawan stage that is characterized by the accumulation of sandy and muddy sediments in which abundant molluscan fossils of warm current are found. The leading microfossils of the stage are as follows: *Globigerinoides triloba* (REUSS), *Nonion kidoharaense* FUKUDA, *Globorotalia cf. fohsi* CUSHMAN et ELLISOR, *G. Scitula* (BRADY), *Globigerinoides trilobus* (REUSS), *Ammonia tochigiense* (UCHIO), *Pullenia bulloides* (D'ORBIGNY), and *Gyroidina orbicularis* D'ORBIGNY. On the other hand, sediments of the Onnagawan stage conformably overlying the Nishikurosawan

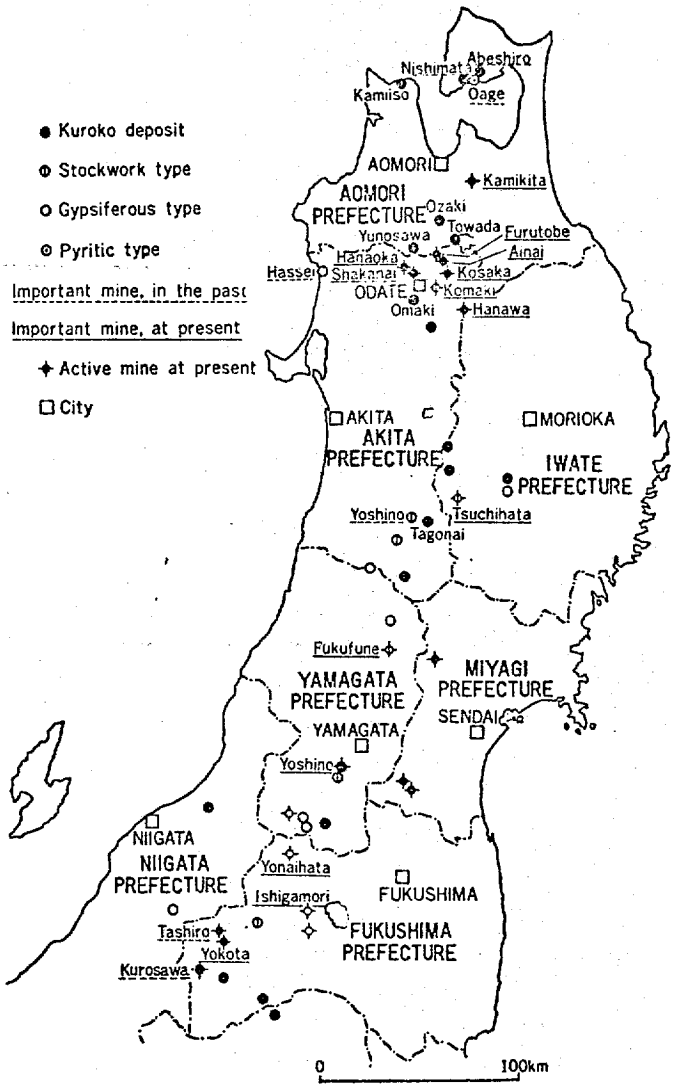

Fig. 1. Map showing distribution of the Kuroko-type deposits in the Tohoku district (Northeast Honshu).

formation, show homogeneous lithologic facies over all areas, and consist of thick well-stratified siliceous and hard mudstone intercalating thin acidic tuffs. The formation is considered to be cold current sediments, and is generally poor in fossils.

The fact that *Globigerina* sp., *Globorotalia* sp. and some others, seemingly the representative species of the Nishikurosawan stage, were found from altered muddy tuff in ferruginous quartz zone directly overlying Kuroko ores of the Uchinotai deposits, Kosaka mine (Ishikawa, 1964), is very important in the consideration

Table 1. Schematic geologic succession of the Miocene formations in the Akita district, northeastern Japan (after HUZIOKA, 1963)

Age	Stage	Lithology	Remarks
Late Miocene	Tentokuji	Rhyolite, dacite, andesite, mudstone, and sandstone (marine)	Dewa Disturbance
	Funakawa	Rhyolite, andesite-dacite, black mudstone (marine)	
	Onnagawa	Rhyolite, andesite-dacite, basalt, dolerite, siliceous hard shale (marine)	
Middle Miocene	Nishikurosawa	Rhyolite-dacite-andesite, basalt, quartz-diorite (holocrystalline granitoids), sedimentary rocks (marine)	Oil-bearing formation Kuroko deposits and allied veins
	Daijima	Rhyolite-dacite, basalt, sedimentary rocks (plant and molluscan fossils)	Regional sinking Metallic mineralization
Early Miocene	Monzen	Trachytic rocks, alkali-rhyolite, dacite, altered andesite, olivine basalt, sedimentary rocks (plant fossils)	Intensive and extensive volcanic activity
	Akashima	Altered andesite, dacite	
Pre-Tertiary		Granite and slate	

of age of the formation and genesis of the Kuroko deposits. At the Shakanai mine, zonal division by microfossils is utilized for correlation of formation boundary and ore-bearing horizon.

Volcanism of the earlier Miocene in the Akita district was characterized by the alkaline and tholeiite rock series. The latter continued to the Nishikurosawan stage. From the later Nishikurosawan to Funakawan stages, volcanism of calc-alkaline rock series was intensely active. It includes activities of various kinds of volcanic rocks, such as augite-olivine basalt, two-pyroxene andesite, hornblende-pyroxene andesite, dacite and rhyolite. Some acidic members are plagiorhyolite which has no mafic mineral, or dacitic rock which contains small amounts of biotite, hornblende and rarely pyroxene. The Kuroko deposits were formed in close relation with the activities of calc-alkaline rock series.

Based on his field observations, SATO (1968) concluded that the Kuroko mineralization of the Kosaka mine took place on a rather shallow sea bottom, probably 100–200 meters in depth, and the sedimentary basin was bounded by a barrier to open sea, though it was linked with the open sea through some channels. His conclusion may be applied to many other mineralized areas of the Kuroko deposits.

FORERUNNING VOLCANIC ACTIVITY

As the Kuroko deposits have close genetical relations with submarine volcanic activity, it has been required in particular to study the mode of volcanic eruption and mechanism of emplacement and sedimentation of pyroclastic materials in the sea.

According to the results of geologic surveys in the mining area, most of pyroclastic sediments under consideration are pyroclastic flows deposited from turbidity currents accompanying submarine eruption. They generally started first with massive tuff breccias rich in lithic fragments and then changed to notably stratified tuffs intercalating mudstone with double grading. Emplacement of lava domes and flows repeatedly took place during the period of pyroclastic sedimentation. Some of them are small in scale, but others extensively overflowed on the sea bottom.

Submarine lavas under consideration show auto-brecciated structure due to rapid cooling in many cases. Steam explosions also took place on the side of the dome during or after the formation of lava domes and flows. HORIKOSHI (1966) showed that the mass of these explosion breccias is only $30 \times 30 \times 10$ meters. Strongly altered rhyolitic lavas have been frequently reported to lie under the Kuroko deposits. It has not been confirmed whether they consisted of several flows or single one. They are called "white rhyolite" by mine geologists and they are generally poor in phenocrysts, massive but brecciated, and altered to quartz-sericite rock, white to light grey in colour in most cases. Their primary petrographic properties are not easily identified. Most of them found at the Kosaka and

Hanaoka mines are small lava domes, not more than several hundred meters in diameter. It is questionable whether or not rhyolite lava flows under the ore-bearing sedimentary complex continuously occupy the underground of the north Akita sedimentary basin from Odate to Kosaka as shown widely in geologic profiles by SAKAZAKI et al. (1965).

Most of the Kuroko mineralization are genetically related to activities of the lava domes of relatively small scale. Rhyolite masses in the Kawajiri formation around the Tsuchihata mine are composed of three types characterized by different petrographic properties. They are lava flows, lava domes associated with flow type in part and intrusive lava domes. Each mass is small in scale under 1 km^3 even in the largest one. Nine dacitic masses found in the Kosaka formation near the Kosaka mine are also lava domes of very small scale. The Kuroko mineralization seems to have genetical connection with exhalative action that followed the steam explosions. However, some of lava domes were accompanied by this kind of explosion, the others were not.

Though properties of the forerunning volcanic activity accompanied with lava domes have been gradually clarified in the Kuroko mining area, the Kuroko deposits are not always associated with volcanic activity of this type, and there are many deposits which occurred only in pyroclastic flows without any lava dome and flow. Such are distributed in southern area of the Tohoku district, some examples being deposits of the Yoshino mine, Yamagata Prefecture, and gypsum deposits of the Aizu district.

ALTERATION

Various modes of rock alteration are distinguished in the area of the Kuroko mineralization; (1) diagenesis, (2) regional alteration, (3) post-magmatic hydrothermal alteration, and (4) alteration directly related to mineralization. These alterations generally are not easily distinguished from each other, because they overlapped in many cases, especially in the mineralized area.

UTADA (1965) investigated rocks of zeolite facies of Mogami district, Yamagata Prefecture, and concluded that (1) Tertiary formations in the region may be divided into five zones of zeolite facies according to the assemblage of authigenic minerals replacing volcanic glass, (2) the boundary of each zone is not always concordant with stratigraphic boundary and geological structure, and (3) nature of regional zeolitization may be controlled not only by nature of sedimentary process and kinds of source materials, but also by some other processes acted after burial of the sediments. He classified the zeolite facies of the district as follows:

Zone I: Unaltered glass; (opal and montmorillonite)
Zone II: Clinoptilolite, mordenite, opal and montmorillonite
Zone III: Analcime, heulandite, adularia, chalcedony, quartz, montmorillonite, "intermediate clay" and chlorite; (albite and epidote)

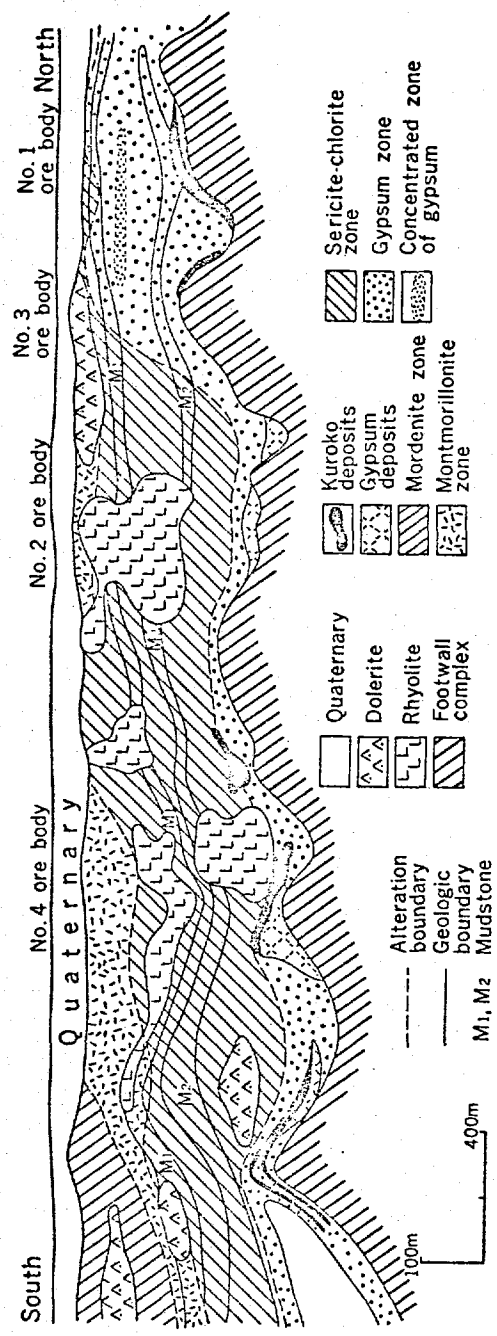

Fig. 2. Geologic section of the Shakanai mine showing zonal arrangement of alteration (After Shakanai mine, 1967).

Shakanai mine. Thickness of zone II at the southern corner of the Odate Basin reaches about 30 meters though the ore bed in the area is only a few meters in thickness. The boundary plane of each alteration zone crosses a stratigraphic boundary though it is usually low in angle.

Motoyama dacite lava domes is situated in the most western part of the distributing area of the Uwamuki tuff breccia, and the member can be subdivided into several unit beds near the lava domes by thin strongly argillized bed, and (b) petrographic characteristics of the lithic blocks of the Uwamuki tuff breccia and the Motoyama dacite are very similar. A large quantity of lithic blocks which compose the Uwamuki tuff breccia are inferred to have been formed by phreatic explosions of the dacitic magma brought into contact with sea water around the submarine vents.

Motoyama Dacite Lava Domes

Nine dacite lava domes are recognized in the Kosaka formation of the mapped area (Fig. 4). Their eruptive sequence, which can be determined by spatial relation of the neighbouring domes (HORIKOSHI, 1969), is indicated by numbered "M" suffixes. Though their shapes are more or less dome-like, three modes of emplacement are recognized among them, i.e., shallow intrusion (not pouring on the sea bottom), dome (partly pouring on the sea bottom) and lava flow (wholly pouring on the sea bottom) (HORIKOSHI, 1969).

Motoyama Volcanic Breccia

The volcanic breccia is accompanied by five lava domes, M_5 to M_9. The following features are observed in the volcanic breccia: (a) It occurs on the flanks of the lava domes, (b) it grades downward into the auto-brecciated parts of the lava domes, (c) it consists entirely of fragments of the lava, and (d) grading in the volcanic breccia is of a single cycle.

These features strongly suggest that the volcanic breccia were formed by steam explosions at the flanks of the lava domes just after their emplacement.

MINERAL DEPOSITS

DISTRIBUTION OF THE MINERAL DEPOSITS

The Kuroko deposits of the Kosaka district occur in and above the Motoyama volcanic breccia and, in some parts, in the Uwamuki tuff breccia. They are arranged in NNW-SSE direction as seen in Figure 4. The most marked feature with respect to the site of mineralization is the intimate relation of the dacite lava domes and the accompanying volcanic breccia with the mineral deposits. For example, the Uchinotai-nishi deposit is accompanied by M_9 lava dome, the Otarube deposit by M_7 lava dome, the Uchinotai-higashi deposit by M_8 lava dome and the Motoyama deposit by M_6 lava dome.

UCHINOTAI-NISHI DEPOSIT

General Remarks

Uchinotai-nishi deposit is the most western and earliest developed deposit in

the Uchinotai area. It is composed of two ore bodies, which are arranged in EW direction separated by a fault. There are two different sites of sulphide mineralization. One is a dissemination deposit in the Motoyama M_9 volcanic breccia, and the other is a stratiform deposit situated between the Motoyama M_9 volcanic breccia and the Kosaka-Tetsusekiei bed.

The stratiform deposit is generally divided by zinc content into zinc-rich upper half and zinc-poor lower half, and ores from these parts are called Kuroko (black ore) and Oko (yellow ore), respectively. The boundary plane between the stratiform deposit and the overlying Kosaka-Tetsusekiei bed is sharp and essentially parallel to the bedding plane of the overlying rocks.

The nature of ores changes gradually downward from the stratiform deposit to the disseminated deposit through a narrow transitional zone (less than 1 m). The disseminated ore is mostly highly siliceous and called Keiko (siliceous ore). The structure of the volcanic breccia is well preserved in the disseminated ore. The distribution of economic disseminated ore is restricted within the volcanic breccia. In the underlying brecciated part of the dacite lava dome (M_9), the amount of sulphides is decreased. Further downward, both the brecciation and mineralization become weak enough to call the rock altered dacite.

A gypsum ore body occurs at the eastern margin of the volcanic breccia in the shape of an irregular mass besides the above-mentioned sulphide deposits.

Mineral Assemblages and Zoning of the Ores

The main hypogene minerals constituting the sulphide ores are pyrite, chalcopyrite, sphalerite, galena, and minerals of tetrahedrite group with quartz and barite as gangue minerals. These minerals, and also some accessory minerals, show a remarkable vertical zonal arrangement. In the case of the western ore body of the Uchinotai-nishi deposit, the whole ore body can be divided into five zones according to the mineral assemblage. Vertical change of the mineral assemblages is shown semiquantitatively in Figure 5 and the distributions of the zones are shown in Figure 6 in a vertical section of the ore body.

Zone 1 is characterized by a pyrite-chalcopyrite-quartz assemblage. In the most western part of the ore body, minor amount of barite may appear in this zone, which corresponds to the disseminated part of the ore body.

Zone 2 has a simple assemblage of pyrite and chalcopyrite with considerable amounts of sericite and chlorite at the marginal parts of the ore body. Minor amounts of barite and sphalerite appear in the western part of the ore body. This zone corresponds to the lower part of the stratiform deposit.

Zone 3 includes many minerals such as barite, sphalerite, galena, minerals of tetrahedrite group (including freibergite), pyrite, chalcopyrite, etc. Figure 5 shows a decrease in chalcopyrite and pyrite and an increase in sphlerite, galena, and minerals of tetrahedrite group in this zone. Besides the above-mentioned minerals, bornite, electrum, argentite, stromeyerite, diaspore, and vaesite have been detected by microscopic examination in some restricted parts of this zone.

Sericite and chlorite occur also as tiny flakes along the grain boundaries of the above-mentioned minerals and, in some places, as bedded or lenticular accumulations (usually 10 to 30 cm thick) in the ore. At the northern part of the ore body, galena is concentrated in the uppermost part of zone 3 (up to 1.5 cm in width), characteristically co-existing with minor amounts of electrum and stromeyerite. This galena concentration and also the bornite-bearing part would be characteristic enough to establish subzones within this zone. Zone 3 corresponds to the upper half of the stratiform deposit.

Zone 4 is a bed above zone 3 characterized by barite and, in places, flour-apatite.

Zone 5 is a thin quartz-hematite bed in the uppermost part of the ore body. This zone corresponds to the siliceous variety of the Kosaka-Tetsusekiei beds described in the preceding section.

As shown in Figure 6, zones 2 to 5 are distributed roughly prallel with each other and to the boundary plane between the ore body and the overlying rocks. There is a general tendency for an upper zone to extend wider than a lower zone.

The peculiar occurrence of chimney-like siliceous ore in the central part of the

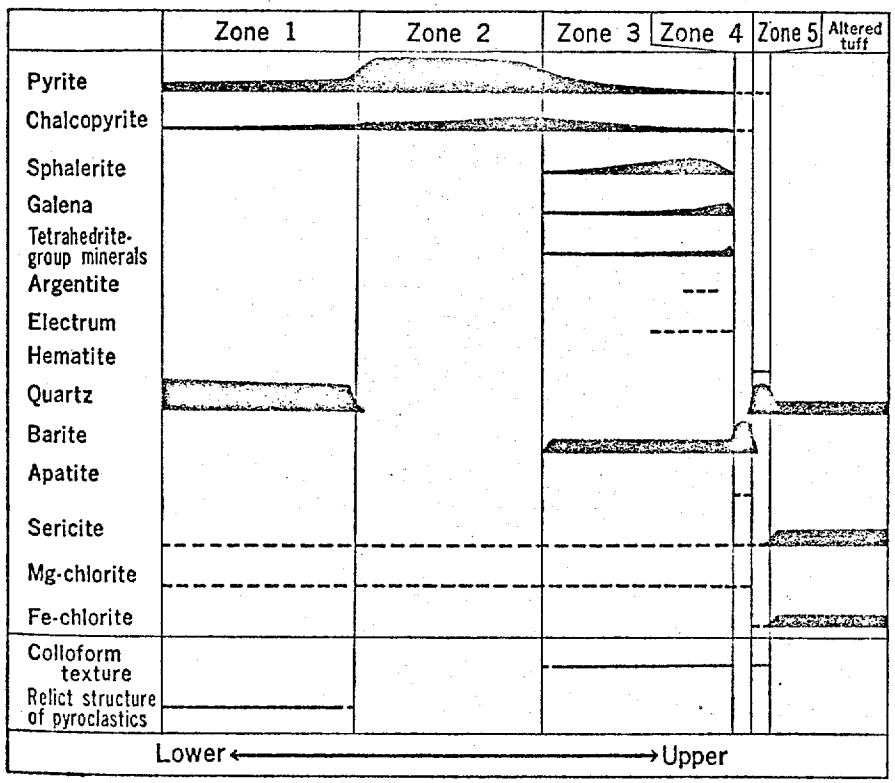

Fig. 5. An example of vertical change of mineral assemblages and textures in the ore body (along line 19, Level 120). Amounts of the minerals are shown semi-quantitatively by width of the bars.

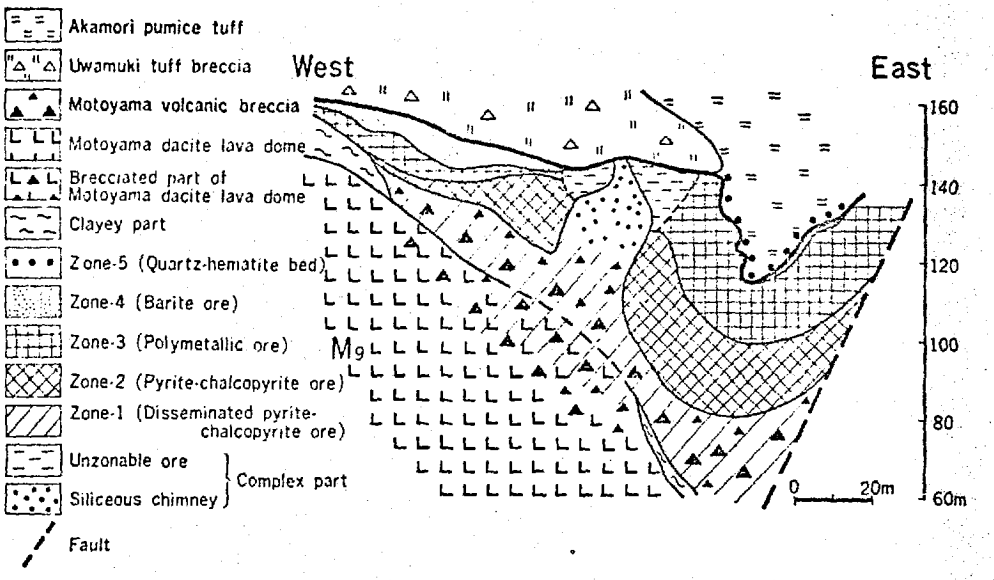

Fig. 6. Section of the western ore body of the Uchinotai-nishi deposit showing the distribution of the five zones and the complex part.

ore body is out of harmony with the general vertical zones as seen in Figure 6. In this part, pyrite and chalcopyrite are disseminated in fine-grained quartz rock with sporadic amounts of barite, sphalerite, and galena. Several veinlets, 10 to 30 cm wide but not of great length, of chalcopyrite with many druses occur in the center of this chimney. The ores surrounding the chimney have various mineral assemblages including some assemblages different from those of the above-mentioned zones, such as pyrite-chalcopyrite-barite and sulphides-barite-quartz. Together the siliceous chimney and the surrounding unzonable ores are called the complex part.

With the exception of a gypsum ore body and occurrence of dolomite above zone 3 (its relation with zone 4 is unknown), the main mineral assemblages of the eastern ore body of the Uchinotai-nishi deposit are almost the same as those of the above-mentioned western ore body. The gypsum ore body is situated in a lower horizon than that of the stratiform ore body. It consists almost entirely of gypsum with small amounts of chlorite and sericite.

Textures and Structures of the Ores

Both macroscopic and microscopic features of the ores are also different according to zones divided on the basis of the mineral assemblage. The features of the two ore bodies of the Uchinotai-nishi deposit are almost similar.

Macroscopically, relict structures of the explosion breccia are clearly observable in the ores of zone 1. Sulphides occur both in the matrix and the fragments of the

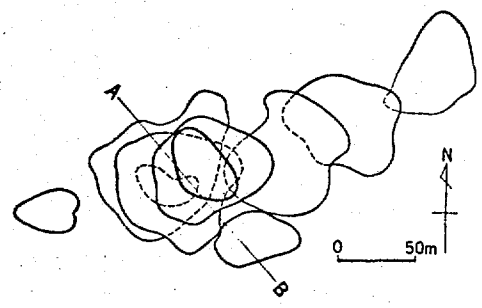

Fig. 2. Horizontal projection of No. 1 ore deposit, showing arrangement of ore bodies.

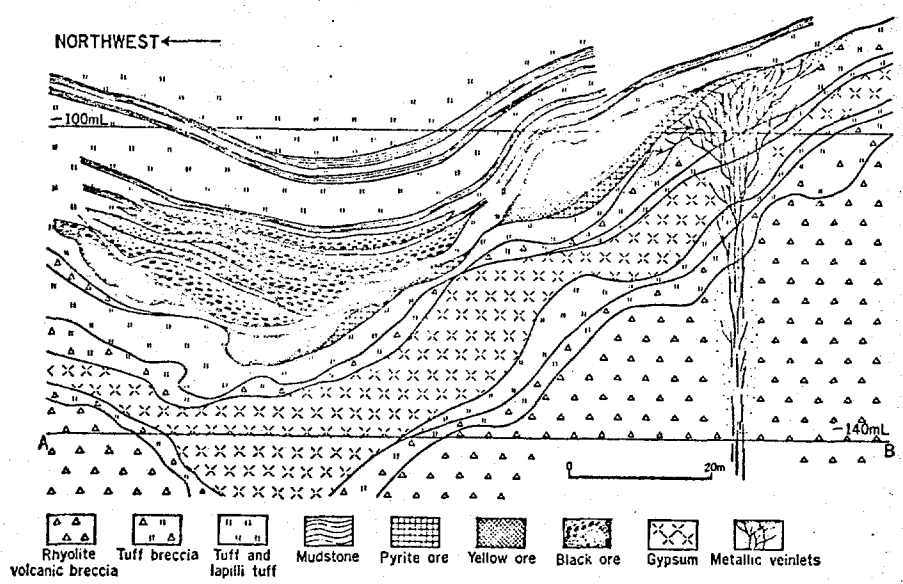

Fig. 3. Geologic profile of No. 1 ore deposit (along A–B line in Fig. 2).

and rests on the slope of the footwall rhyolitic rocks. The metallic ore deposit is composed of several ore bodies which lie along NE-SW direction as shown in Figure 2. The average scale of the ore bodies is about 50 m × 50 m in plan. Each of these ore bodies has an irregular, lenticular shape being overlapped and is composed of either massive ore or fragmental ore, or of a combination of the two. The gypsum deposit occurs in bedded form underlying the metallic ore deposit. Footwall rocks are sometimes silicified and mineralized in places.

Figure 3 represents the geologic profile of the No. 1 ore deposit, which shows the typical mode of occurrence of various kinds of ore. As is clearly shown in the pro-

file, Ryukako (pyrite ore), Oko (yellow ore), and Kuroko (black ore) are stratified in ascending order, and also several Kuroko ore bodies occur in layers.

Syngenetic Ores

One of the most significant features on mode of occurrence is that of fragmental ores, which gives us much unique information on the mode of deposition of the ores. Before proceeding with the description, let us mention some characteristics of the fragmental ores.

The fragmental ores are composed essentially of "ore fragments" and "ore matrix". Shape and size of the ore fragments vary widely. Colloform banding and compositional banding in the ore fragments can never be traced to the matrix and the arrangement of these banded structures is extremely random, which strongly supports the idea that the ore fragments are exactly clastic materials. The matrix usually consists of minute particles of ore fragments and has sometimes quite similar appearance to massive ore defined in the preceding section.

Within each deposit of fragmental ores, lateral and vertical size-grading of ore fragments can be recognized. Such ores can be called "graded ores". As is clearly shown in the geologic profile, it should be noted that lateral facies change, massive ore to fragmental ore, is also observed in some ore bodies.

Ore fragments in each ore body are usually composed of the same kind of ore. At the bottom of the lowest unit of ore bodies which are composed of fragmental Kuroko (black ore), however, some fragments of Oko (yellow ore) can be recognized. This fact strongly suggests that the Kuroko bed must have grooved the Oko bed. In the upper part of the ore deposit, tuff, mudstone, and fragmental ore alternate with each other, where mudstone and tuff are usually grooved by fragmental ore and are sometimes partly worn away.

An imbricate structure of platy ore fragments is frequently observed in the upper portion of each fragmental ore bed. Cross-laminae are also recognized sometimes in the uppermost fine-grained portion of each fragmental ore bed. Figure 4 is a schematic sketch showing a typical mode of occurrence of a fragmental ore bed.

Figure 5 is a geologic plan showing the mode of occurrence of fragmental ores. The lateral facies change, massive ore to fragmental ore, is clearly shown in the plan. Based on some sedimentary features such as size-grading, channeling or grooving structure, and imbricate structure, the flow-direction of each ore body as shown in Figure 6 can be determined. It should be emphasized that in following flow-direction upward we can find a silicified zone with metallic veins in the foot-wall rocks.

Thus, the features mentioned above strongly support the idea that fragmental ores must have been formed by slumping or sliding of accumulated sulphide masses after and during ore deposition. We must examine massive ores in detail in order to know the primary sequence of mineral deposition. Mineral paragenesis in the massive ores will be briefly discussed by the writer in another paper in this volume.

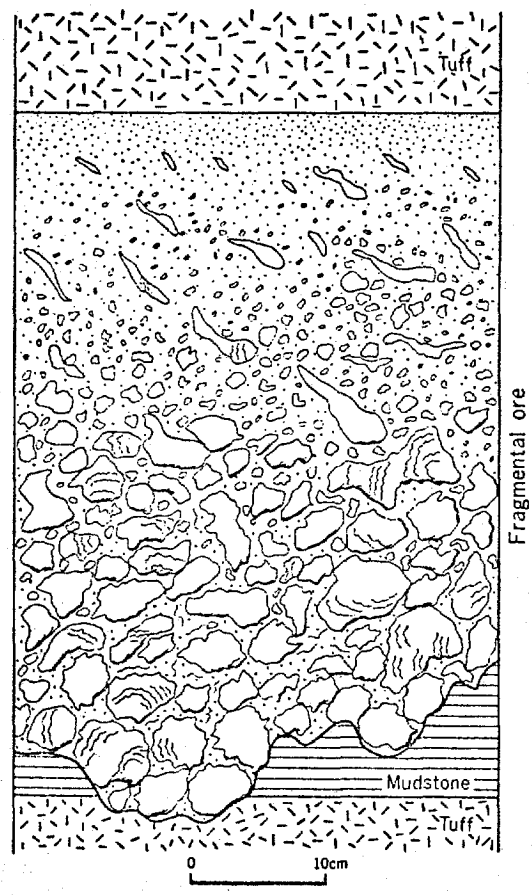

Fig. 4. Schematic sketch showing a typical mode of occurrence of a thin graded ore bed.

Note sedimentary features such as vertical size-grading of ore fragments, imbricate structure of platy ore fragments, and channeling or grooving structure at the bottom.

Silicified Zone and Epigenetic Ores

In the foot-wall rocks of the metallic ore bodies, "silicified zones" with metallic mineralization in places can be recognized. Such mineralized rocks are usually called Keiko (siliceous ore) in the economic sense. In the silicified zone, the textures of original rocks are sometimes well preserved. The chemical composition is characterized by extremely high silica content, low alkali, and low alumina in comparison with the original rocks.

Metallic veins and stockworks occur in the silicified zone in many places. Figure 7 represents their distribution superposed on the silicified zone. The metallic veins are sometimes zoned vertically; pyrite vein, chalcopyrite vein, and sphalerite

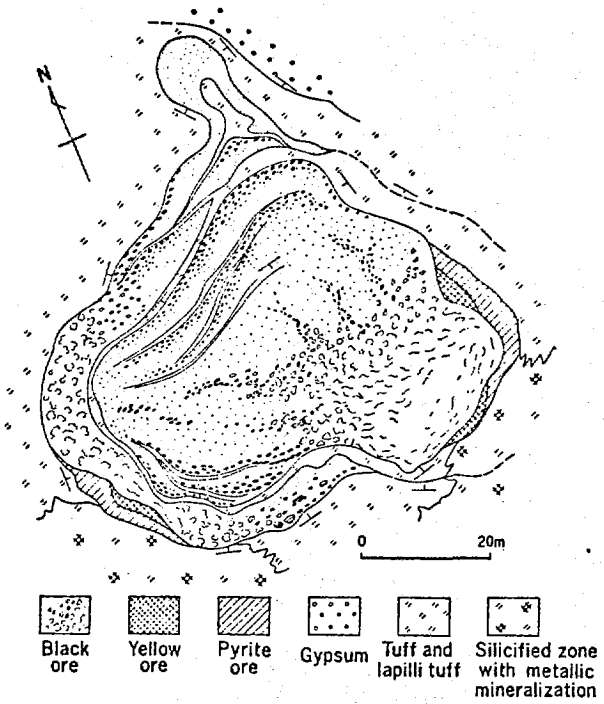

Fig. 5. Geologic plan of 115 ML.

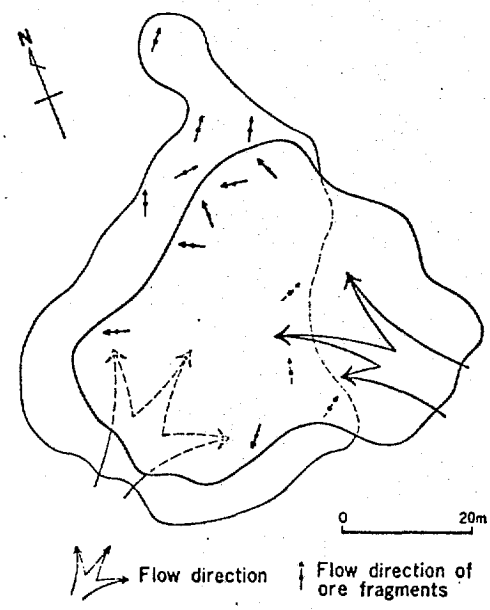

Fig. 6. Flow direction of Kuroko (black ore). Small arrow marks represent flow direction estimated from imbricate structure of platy ore fragments.

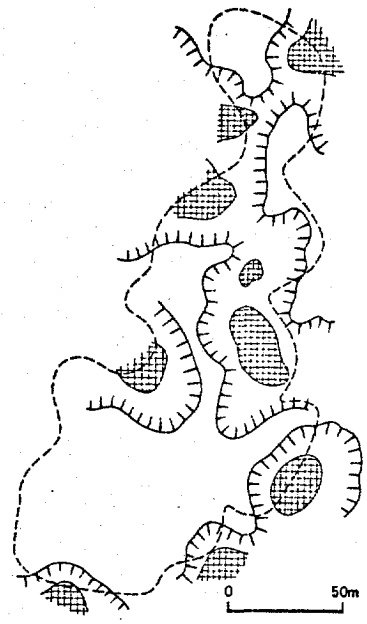

Fig. 7. Silicified zone (inside dented line) and distribution of metallic veins (cross-hatched area). Broken line represents the outline of the ore deposit.

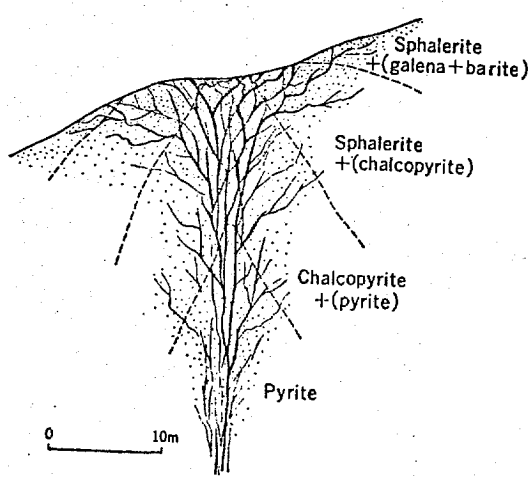

Fig. 8. Schematic diagram showing a typical mode of occurrence of metallic veinlets.

vein in ascending order. Barite and galena sometimes occur at the top of the veins. A typical mode of occurrence of epigenetic mineralization is shown schematically in Figure 8.

Judging from spatial relations among massive metallic ore bodies, silicified zone, and metallic veins, it is evident that original cracks and fissures in the silicified zone with metallic veins must have been principal feeder channels through which the ore-forming solution was supplied.

CONCLUDING REMARKS

The mode of occurrence of the No. 1 Kuroko deposit of the Shakanai mine has been briefly described here. Among many features the writer have focussed attention especially on syngenetic features in the metallic ores. Sedimentary features in the ores are summarized as follows:

1. Graded bedding of ore fragments (lateral and vertical size-grading of ore fragments).
2. A channeling or grooving structure at the bottom of each graded-ore bed.
3. An imbricate structure of platy ore fragments within each graded-ore bed.
4. Cross lamination of fine ore fragments at the uppermost part of a graded-ore bed.
5. Lateral facies change, from massive ore to fragmental ore (massive→blocky →breccia→powdery), in an ore body.

These features strongly support the idea that several occurrences of submarine sliding or slumping took place after and during the Kuroko deposition.

Mode of occurrence of epigenetic ores was also briefly touched. Convincingly, the original cracks and fissures in the silicified zone with metallic veins are suggestive of feeder channels through which the Kuroko-forming solution was supplied.

As is shown in the geologic profile (Fig. 3), it may be clear that the metallic mineralization took place somewhat after the gypsum deposit was formed. This may suggest that gypsum was not deposited from the same ore-solution from which metallic minerals were precipitated.

Acknowledgements

I wish to express most sincere gratitude to Professor Takeo Watanabe and Professor Tatsuo Tatsumi of the University of Tokyo, who have given me much advice and criticism on this work. Thanks are also due to Dr. Toru Otagaki and other geologists at the Shakanai mine who were kind enough to aid me during my field survey.

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~~Stratiform Cu~~ Sedimentary Cu Deposits

AMERICAN SMELTING AND REFINING COMPANY
ROCKY MOUNTAIN EXPLORATION DIVISION
1805 SOUTH BELLAIRE STREET. DENVER. COLORADO 80222

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TELEPHONE 303-757-5107

W. L. K.
OCT 3 1972

September 26, 1972

Mr. J.J. Collins
Director of Exploration
120 Broadway
New York, New York 10005

SANTA ROSA SOUTH
Heisen Leases
New Mexico

Dear Sir:

On Thursday, September 21, Mr. Hoskins and I met Mr. Charles Heisen in Albuquerque, on our way to Iron Mountain, at Mr. Heisen's request.

Mr. Heisen has a sound theoretical knowledge of roll fronts, and was a co-worker of Rackley and Shockey when they wrote their authoritative papers on the subject. He has picked up about 35,000 acres of state leases, scattered along a north-south strip east of the Pecos River, from approximately Santa Rosa, New Mexico to east of Roswell, New Mexico, in a strip about 90 miles long.

He has drawn an approximate position of an oxide-sulfide contact in the Santa Rosa sandstone, a unit about 120 feet thick, based on examining oil well cuttings in holes spaced about 10 miles apart. In cuttings on the oxide side of the front, sparse malachite occurs. Copper, lead, etc. in pyrite on the high pyrite side of this front are quite anomalous.

Mr. Heisen wants essentially $200,000 as advance royalty for his efforts, plus a one percent carried interest.

Neither Mr. Hoskins nor myself regards the Santa Rosa as an outstanding potential copper host, although the Pintada and Stauber mines both occur at the north end of Heisen's area, and another approximately 750,000 tons at .7% Cu has apparently been drilled out about 15 miles southwest of the Stauber.

I told Mr. Heisen that it was my opinion that this was too risky a business for us in its present state, but if he had some holes in ore, we might then look at the proposition more favorably. Mr. Heisen believes that he will have no trouble disposing of the property on about the terms outlined and believes that Conoco will probably accept the deal.

Conoco has a number of geologists in Albuquerque working on stratiform coppers, concerned with worldwide occurrences. They are also establishing a research team in Ponca City, in their Research Department, concerned solely with stratiform coppers. They have done some drilling in New Mexico in occurrences we would regard as essentially worthless. In the light of all this, it is possible that Conoco may accept such a proposition, although it seems to us that Heisen is expecting $200,000 for no work except obtaining some state leases, part of which are misplaced.

Very truly yours,

Stephen Von Fay

Stephen Von Fay

cc: JHC
WLK

STRATABOUND COPPER SULFIDES IN THE PRECAMBRIAN BELT SUPERGROUP,

NORTHERN IDAHO AND NORTHWESTERN MONTANA, U.S.A.

1970
Proceedings on IAGOD, Tokyo

By Allen L. Clark

SLIDE I

INTRODUCTION

The stratabound copper sulfide deposits described in this report occur locally in a zone approximately 120 miles long and 40 miles wide that extends south-southeast from southern British Columbia along the Idaho-Montana border to near the Coeur d'Alene mining district, Idaho (Fig. 1).

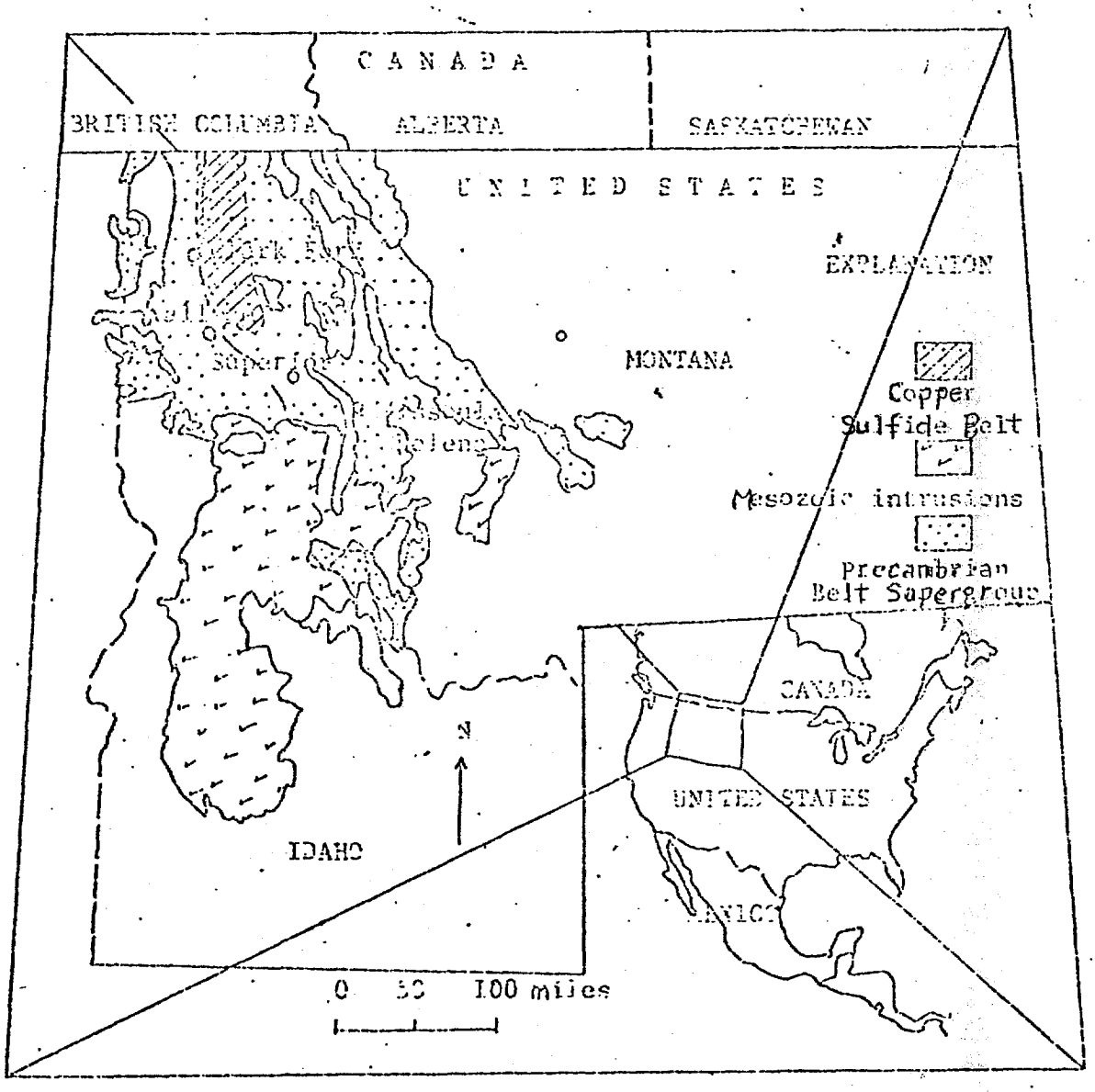

Figure 1. Generalized distribution of Belt Supergroup rocks in the western United States and copper sulfide Belt.

Much of the data on individual deposits is confidential material of several mining companies. The purpose of this paper, therefore, will be to discuss the general distribution, mineralogy, paragenesis, zonation and stratigraphic controls on copper sulfide distribution.

Copper sulfides occur locally in the Precambrian Belt Supergroup of northern Idaho and western Montana and in the stratigraphically equivalent Purcell series of southern British Columbia. The Belt Supergroup and Purcell Series are a thick sequence of shallow water marine deposits that crop out over an area in excess of 50,000 square miles (Fig. 1) and attain a thickness of over 40,000 feet.

GEOLOGY

Belt Supergroup

The major subdivisions of the Belt Supergroup were defined by Ransome and Calkins (1908, p. 23) and Shenon and McConnel (1939, p. 3). The formations from oldest to youngest are the Prichard, the Burke, the Revett, the St. Regis, the Wallace, and the Striped Peak.

Detailed descriptions of Belt Supergroup rocks are given in numerous other report & I would refer you to ~~The interested reader is referred specifically~~ to descriptions by Harrison and Jobin (1963) for the northern portion of the area and by Hobbs and others (1965) for the southern part of the area.

According to Harrison and Grimes (in press), rocks of the Belt Supergroup range from unmetamorphosed to greenschist facies.

The Belt Supergroup ranges in age from 900 million years to more than 1,300 million years (Obradovich and Peterman, 1968, p. 746). Lithostratigraphic equivalents of the Belt formations in which the copper sulfide deposits occur were deposited at about 1,100 m.y. and 1,300 m.y. (Obradovich and Peterman, 1968, p. 746).

Structure

The major structural elements in the study area are northwest-southeast trending high-angle faults, most of which have a large component of strike-slip displacement. The area is bounded on the west by the Purcell Trench and on the south by the Osburn and associated faults.

Sl. Dc II The major folds of the area are large-scale open synclines (Fig. 2) and anticlines. Locally, recumbent isoclinal folds are formed.

Figure 2. Contact between Revett Formation ($P_{\epsilon}R$) and overlying St. Regis Formation ($P_{\epsilon}Sr$) exposed in broad open syncline.

Sulfides in the Belt Supergroup

Stratabound copper sulfide occurrences have been observed in all of the formations of the Belt Supergroup. However, the major concentrations of possible economic importance that I have seen are in only the Revett Formation. Locally significant occurrences can be found in the overlying St. Regis and underlying Burke Formations.

Regardless of the formation in which the copper sulfides occur, they are characteristically confined to the quartzite and siltite members of the formation and are most abundant in the coarser phases of these members.

The following discussion will deal primarily with sulfides in the Revett Formation. However, the general features are applicable to copper sulfide occurrences in the other formations.

Revett Formation

The Revett Formation has been measured in several areas and shows a wide range in thickness. In the Coeur d'Alene mining district the formation ranges from 1,200 to 3,400 feet (Hobbs and others, 1965, p. 37). Harrison and others (1963, p. K-11) measured a thickness of approximately 2,000 feet in the Pend Oreille area and I have measured sections ranging from approximately 300 feet to more than 4,000 feet in western Montana.

In the Pend Oreille area (Harrison and Jobin, 1963, p. K-11) and near Troy, Montana, the Revett Formation can be divided into three units of massive quartzite; one at the base, another near the middle, and the third near the top of the formation. Southward from these exposures toward the Coeur d'Alene district the Revett appears to thicken and become an intercalated sequence of quartzite members and argillitic quartzite and siltite members.

SLIDE III

The Revett Formation is typically crossbedded (Fig. 3) on a scale which ranges from microscopic to large foreset beds over 4 feet high. The large-scale crossbedding, essentially uniform direction of dip, shallow water features, and internal sedimentary structures indicate a near shore environment and suggest that much of the Revett is composed of beach and bar deposits.

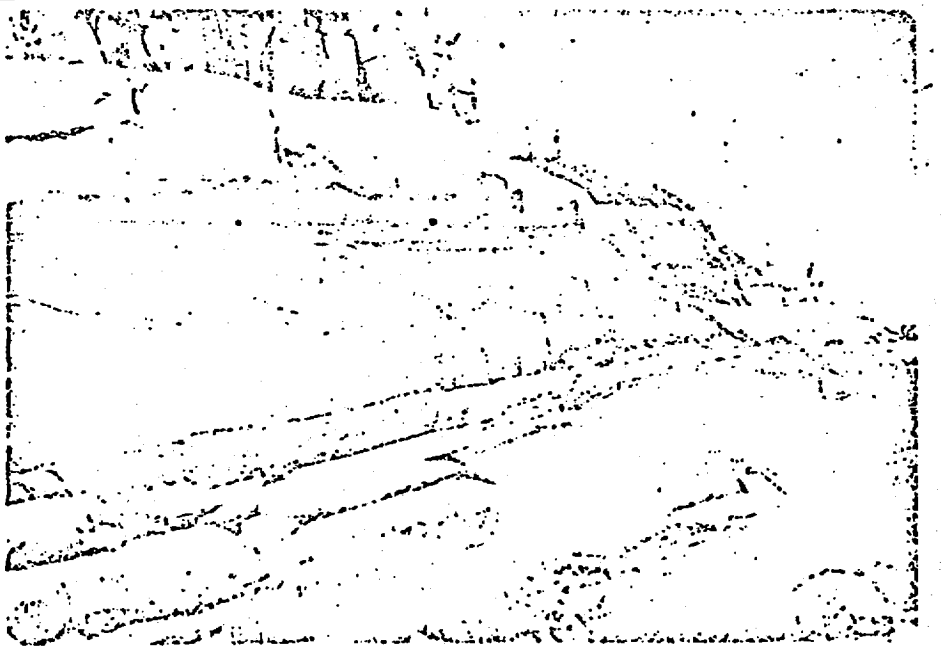

Figure 3. Massive crossbedded Revett quartzite showing blocky fracture.

Locally the Revett is calcareous or dolomitic. Many of the carbonate-rich quartzite members appear to be the host rock for the copper sulfides.

The quartzite members of the Revett Formation are remarkably uniform in mineral composition. Table 1 contrasts the modes of Revett quartzites in the Pend Oreille area (Harrison and Cambell, 1963, p. 1417) with mineralized Revett quartzites from within the study area.

TABLE 1. Average modes in volume percent of Revett quartzites

Area	Quartz	Albite-oligoclase	K-feldspar	Sericite	Chlorite	Biotite
Pend Oreille	70	15	7	6	Tr	1
Mineral Belt	70	13	3	4	1	2

	Calcite	Dolomite	Sulfide
Pend Oreille	1	0	0
Mineral Belt	4	0	3

Units of argillitic quartzite and quartzitic argillite vary in composition from the quartzites primarily in containing more sericite and less plagioclase and quartz.

The quartzites generally have an equigranular granoblastic texture with weakly sutured borders between mineral grains.

STRATABOUND COPPER SULFIDE OCCURRENCES

Mineralogy of Occurrences

The surface expression of the copper sulfide occurrences is generally very subtle. Surficial leaching and oxidation has normally produced a "rind" on mineralized quartzite which ranges in thickness from 1/4 inch to more than 1 foot. The leached and oxidized zone characteristically contains small amounts of malachite, azurite, brochantite, goethite, and jarosite. In areas where galena is common, minor amounts of cerrusite have been detected. The oxidation products generally occur only on fracture surfaces and the exposed outcrop surfaces show little or no evidence of mineralization.

The principal copper sulfide mineralogy of most of the stratabound occurrences is remarkably similar. In order of decreasing abundance, the sufides are bornite, chalcocite, chalcopyrite, covellite, tetrahedrite(?) and diginite(?).

In addition to the mineral listed above, galena, native silver, and native copper have been observed locally and spectrographic analyses indicate a minor amount of gold (<.08 ppm).

Copper Sulfide Distribution

The copper sulfides occur as disseminations, discrete blebs, as bedding plane concentrations, and, where locally remobilized, as fracture filling veinlets. The most common occurrence of sulfide is as a dissemination throughout the quartzite host (Fig. 4). The primary disseminated mineral is bornite which occurs as individual platy grains or as cusp-shaped grains which appear to have corroded and replaced quartz and carbonate grains. The average grain size of the bornite is 0.08 mm. and size ranges from a microscopic dust to 0.3 mm.

Large blebs of sulfide occur locally. Most of the blebs are polymineralic. The most complex have a central core of chalcopyrite which is surrounded by bornite and chalcocite (Fig. 5). The most common type of bleb has a central core of bornite replaced by chalcocite (Fig. 6). Monomineralic blebs composed of either chalcopyrite, bornite, chalcocite, or galena occur locally but constitute less than 10 percent of the total sulfide occurrence. Sulfide blebs range from 0.2 cm. to over 8 cm. with an average diameter of 3.5 cm.

Polished section studies show that the blebs are rarely all sulfide and generally contain 30 to 50 percent corroded quartz grains of the host rock (Fig. 7).

Throughout the occurrences copper sulfides were observed in thin bedding plane concentrations (Fig. 8). Some of the individual sulfide laminae have been followed for several tens of feet in the outcrop. Polished section study shows that such occurrences are generally associated with carbonate-rich, coarse-grained clastic phases of the quartzite.

Locally, copper sulfides occur as fracture-filling veinlets. Occurrences of this type are most common near major fault zones or along minor shear planes.

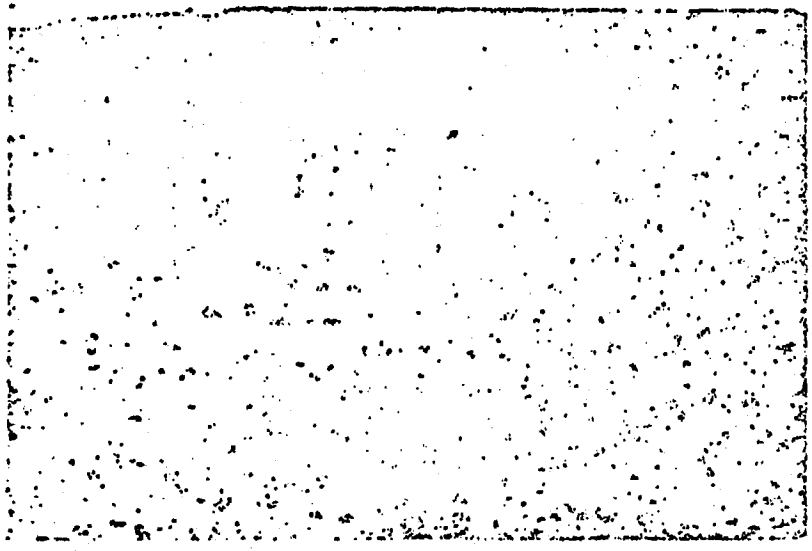

Figure 4. Disseminated bornite and chalcocite in massive Revett quartzite. b-c (bornite and chalcocite)

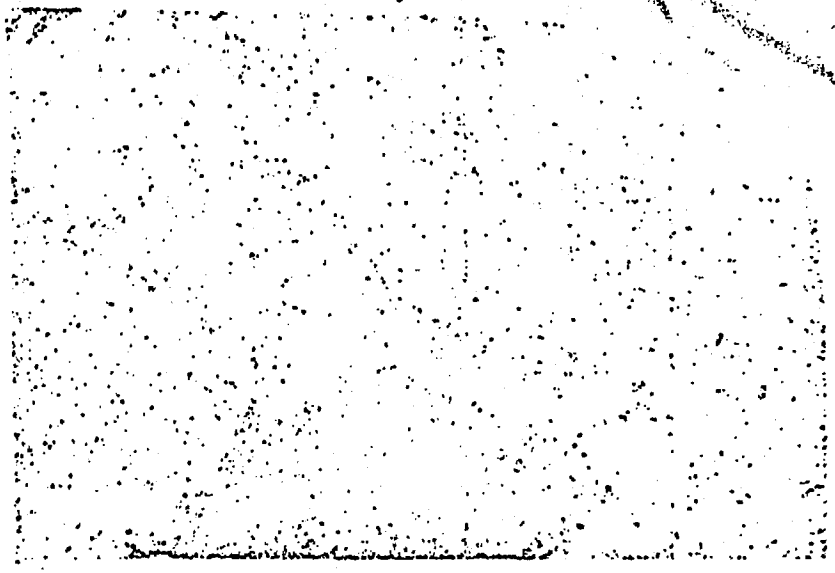

Figure 5. Complex sulfide bleb in massive quartzite. d = chalcopyrite, b= bornite, c = chalcocite.

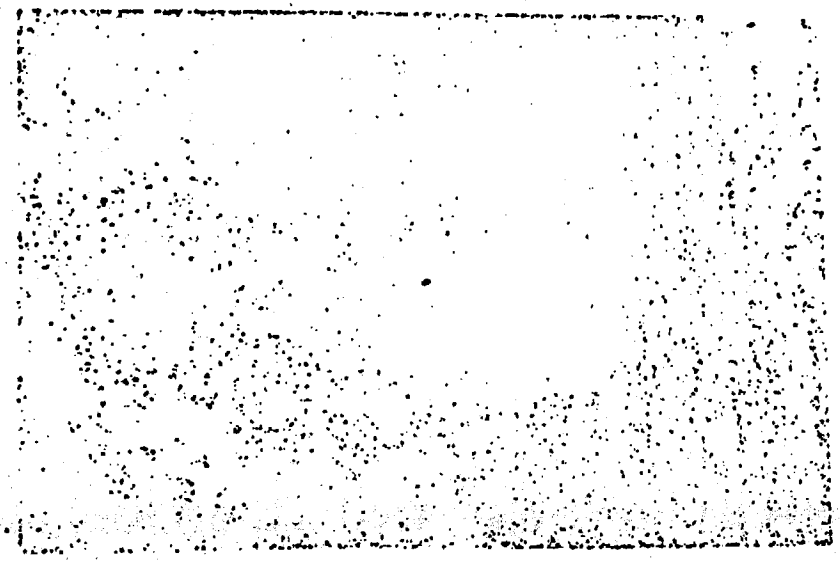

Figure 6. Complex sulfide bleb of bornite (b) by chalcocite (c) replaced.

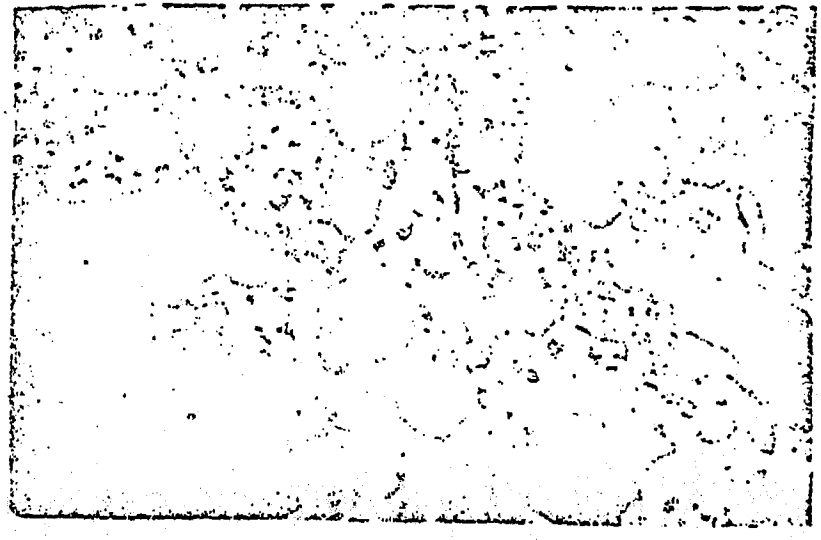

Figure 7. Photomicrograph of a complex sulfide bleb with included quartz grains. Q = quartz, b = bornite, c = chalcocite, and d = chalcopyrite.

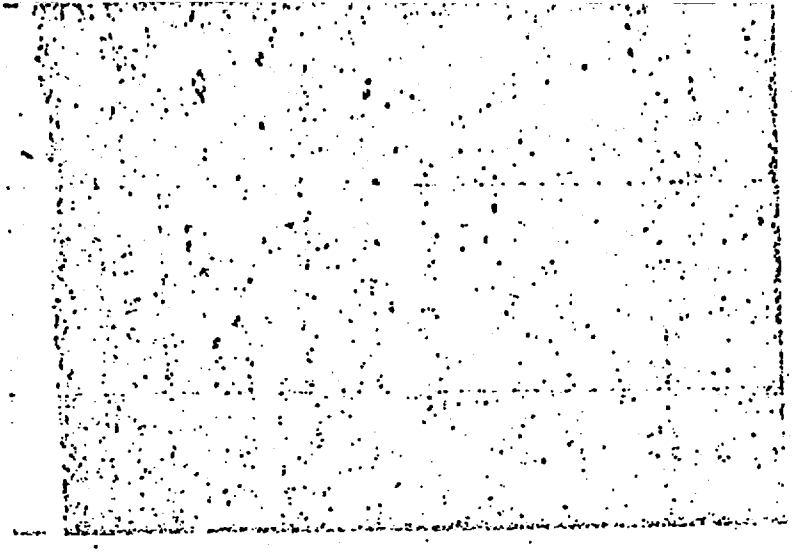

Figure 8. Thinly laminated argillaceous quartzite showing bedding plane concentration of sulfides. d = chalcopyrite, b = bornite.

Sulfides within an individual quartzite bed generally display a regular pattern of distribution. The largest concentration of sulfides occurs at the base of the bed at the contact with the underlying argillite-rich unit. The contact is commonly gradational over several inches. Above the basal sulfide-bearing zone there is generally a zone of lesser concentration which is in turn overlain by a second sulfide-rich zone of comparable thickness to the basal zone. The two rich zones and intervening low grade zone generally occur in the basal two-thirds of the bed. The upper one-third of the bed contains only a minor amount of disseminated sulfides.

Controls of Sulfide Distribution

The distribution of sulfides within the individual units show definite physical controls, primarily grain size and sedimentary structures.

The grain size of the disseminated copper sulfide minerals, primarily bornite and chalcopyrite, generally varies directly with the grain size of the enclosing host rock. The direct relation is particularly striking when the grain sizes of argillaceous units and quartzite units of the same member are compared. The grain size also appears to control the richer portions of the mineralized members. Almost without an exception, the coarser grained phases contain the greatest amount of sulfide mineralization.

Sedimentary structures and sulfide distribution are very closely related. Specific examples of this close association are:

1. Graded bedding - Sulfide minerals are commonly concentrated in the basal portion of graded beds. Associated with the concentration of sulfides is a large concentration of heavy minerals, particularly zircon, tourmaline, and rutile.

2. Crossbedding - Crossbedded sequences of the Revett Formation appear to be the most favorable horizons for sulfide concentrations. The sulfides are disseminated throughout the sequences but show a strong preferential concentration near the basal zone of individual beds (Fig. 9).

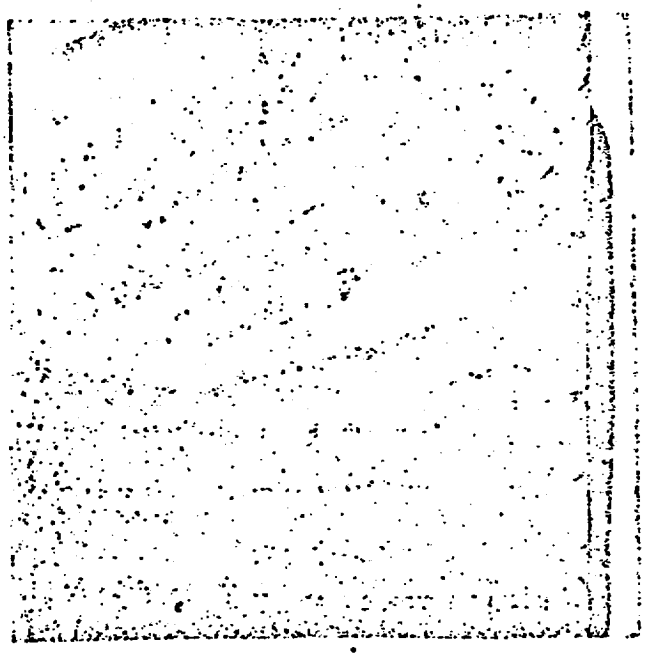

Figure 9. Crossbedded Revett quartzite and bornite. b = bornite.

3. Scour and cut-and-fill structures - Sulfide concentrations are very common in the basal portion of scour and cut-and-fill structures. The sulfide concentration is also higher throughout the fill material than in the surrounding country rock.

4. Bedding controls - ~~Perhaps the most striking control on mineral distribution is bedding~~. From the largest to the smallest scale the sulfide concentrations are conformable with bedding (Fig. 8) and associated with the coarse-grained quartzite units. Lateral continuity with an individual bed over several hundreds of feet is not uncommon.

Slide 6

Paragenesis

The paragenetic sequence given in Table 2 was based on polished section studies of samples collected throughout the belt. Not all of the minerals are present in any single occurrence. The sequence represents a compilation of relations observed ~~in several occurrences~~.

TABLE 2. Decreasing Age

	Primary	Secondary	Remobilized	Secondary	Supergene
Chalcopyrite	———		———		
Galena	———		———		
Bornite	———		———		
Chalcocite		———		———	
Covellite		———		———	
Tetrahedrite(?)		———			
Digenite(?)		———			
Native Ag		———			———
Native Cu					———
Oxides					———

Slide 7

In the larger grains (Fig. 10) a central core of chalcopyrite is commonly surrounded by bornite and the entire chalcopyrite and bornite grain has a thin outer zone of chalcocite which may contain small particles of native silver. Chalcocite also occurs along fractures that extend through the bornite and chalcopyrite core.

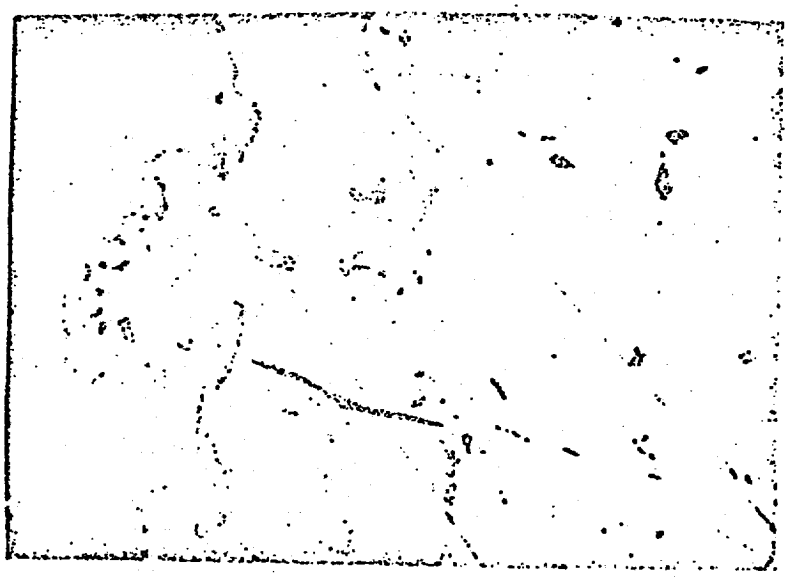

Figure 10. Chalcopyrite (d) core replaced by bornite (b) and chalcocite (c) replacing both minerals along margins and veinlets. Native silver (Ag) occurs in bornite.

Chalcocite grains commonly show a needle-like intergrowth of covellite. Covellite is most common in areas where chalcocite is in contact with clastic grains of quartz. Chalcocite replacement of bornite and chalcopyrite also is most common around quartz grains that have been included in the sulfides.

Locally, particularly near fault zones and minor shears, thin veinlets of chalcopyrite and bornite cut across all of the sequences described previously and are probably related to local remobilization associated with structural deformation. The secondary alteration is similar to that described above for the primary sulfides.

Tetrahedrite(?) and digenite(?) have been identified tentatively in three specimens and without exception occur at the contact between bornite and chalcocite. Their exact paragentic relations are unknown but probably close to that shown in Table 2.

Native silver occurs as inclusions in chalcocite that surrounds bornite. The silver is believed to be derived from the bornite during secondary enrichment.

Native copper, malachite, azurite, brochantite, goethite, jarosite, and cerussite are commonly found in the leached and oxidized surface outcrops and are the youngest minerals observed in the deposits.

Origin of Sulfide Blebs and Bedding Plane Concentrations

Large concentrations of sulfides in the form of blebs and bedding plane concentrations are particularly important in interpreting the distribution of sulfides and the processes that have affected the occurrences.

Detailed polished section study and spectrochemical analyses of whole rock show that the concentration of sulfides into blebs and along bedding planes are accompanied by depletion of sulfides from the surrounding rock (Fig. 11). Similar depletion is also noted along small quartz-bornite veinlets which occur locally. Therefore, these features are a modification of the pre-existing disseminated sulfide deposit. The significance of this will be discussed under the heading of genesis of deposits.

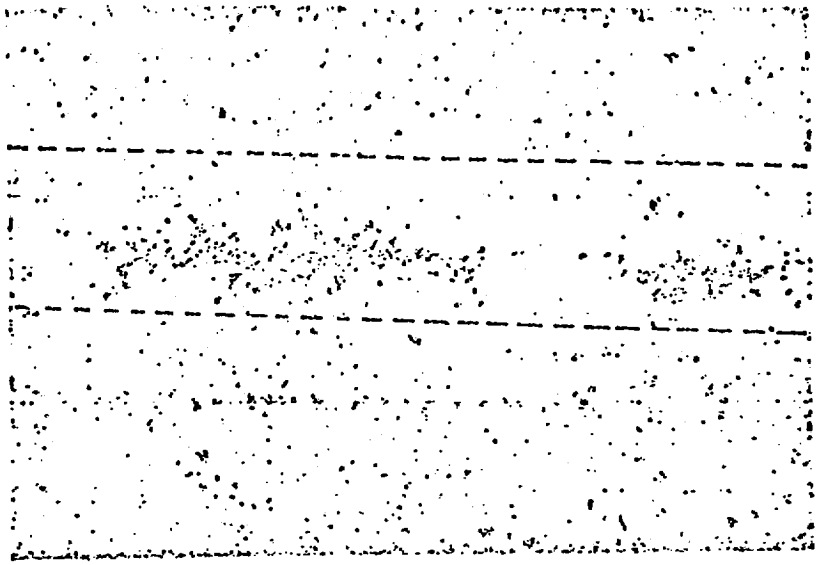

Figure 11. Bedding plane concentration formed by depletion of sulfides from host rock. Depletion zone shown by dashed lines.

SLIDE 10

Zonation of Occurrences

The zonal arrangement of sulfides within individual ore bodies is incompletely known because of lack of adequate exploration. From the occurrences studied ~~However,~~ a general zonation has been observed by the author in a deposit near Troy, Montana.

Known deposits are elongate in shape with a long dimension commonly 4 to 5 times that of the width. A long dimension generally a couple thousand feet The mineral zones appear to have the same form as the deposits. The thickness of an individual mineral zone varies considerably depending on thickness of the host quartzite and position within the ore body (Fig. 12).

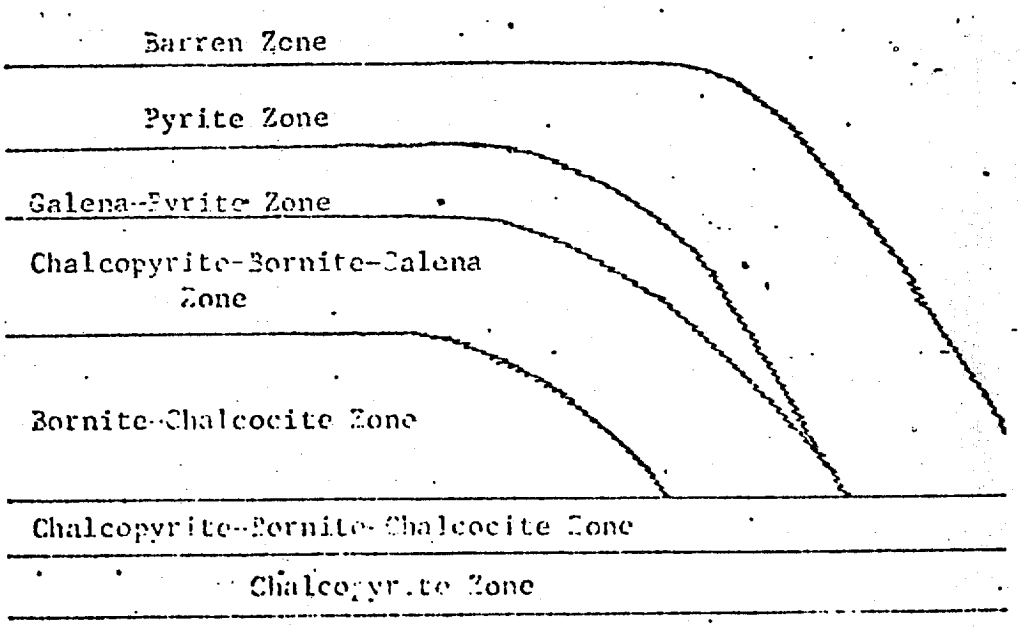

Figure 12. Zonation of copper sulfide occurrence.

The zonation (Fig. 12) appears to be composed of a series of overlapping zones which grade from a barren periphery inwards through an ~~underlying~~ peripheral pyritic zone characterized locally by framboidal pyrite ranging in diameter from 1 mm. to over 1 inch. The pyritic zone is underlain by a galena rich zone which ranges in thickness from 5 to 10 feet. Underlying the galena rich zone and occurring primarily near the lateral margins of the deposits is a chalcopyrite-bornite rich zone which underlies and overlies a central core of bornite and chalcocite. The chalcopyrite-bornite rich zone ranges in thickness from 10 to 20 feet. Bornite-chalcocite mineralization forms the core of the mineralized zone and ranges in thickness from 10 to 14 feet.

Beneath the ore body minor amounts of disseminated chalcopyrite occur throughout the argillite and quartzite but rarely exceeds 0.5 percent (Fig. 12).

The barren and pyritic zones which surround the deposit appear to coincide with facies changes in the quartzite units where the quartzites grade laterally into argillaceous quartzite. The change also is reflected by a decrease in the carbonate content of the barren and pyritic rocks and by a marked decrease in the size and magnitude of crossbedding.

SLIDE 11

AGE OF OCCURRENCES

R. E. Zartman of the U.S. Geological Survey has done extensive lead isotope dating of deposits within the belt described in this paper and in adjacent areas of northern Idaho and northwestern Montana. According to Zartman (personal communication) two distinct families of lead isotopes have been identified in ore deposits of northern Idaho and northwestern Montana; he interprets one family as being "Laramide" in age and the other as being Precambrian in age, probably about 1,100 m.y. to 1,500 m.y. old. Lead isotopes from ores within the described zone of Revett Formation ~~Ravalli group~~ concentrations are all Precambrian.

I believe that the deposits are closely related to sedimentation of the Revett Formation.

The following features indicate that the copper sulfides in the Revett Formation were formed essentially contemporaneous with the enclosing sediments:

1. The distribution in an elongate narrow belt of sedimentation.

2. The distribution of sulfide concentrations in a narrow time interval of Belt Supergroup sedimentation.

3. Essentially the same radiometric ages of sediments and sulfides.

4. Close association and control of sulfide distribution by sedimentary structures and processes.

5. Presence of sulfide material closely resembling clastic grains of sulfide.

6. Late stage formation of blebs; bedding plane concentrates and veinlets formed by migration and resultant depletion of pre-existing sulfides.

7. Absence of regionally associated structures and intrusions that might have been the source of mineralizing solutions.

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From to

Subject: STRATIFORM COPPER DEPOSITS AND GEOCHEMISTRY OF ARSENIC, ANTIMONY, COBALT AND NICKEL

B. E. Kilpatrick
GE 513
October 20, 1966

STRATIFORM COPPER DEPOSITS

Introduction:

In a brief treatment of such a large and complex subject, it is only possible to treat a few major topics -- generalizations which run the risk of over-simplification. Three major topics seem pertinent to this discussion:

1. What is a stratiform deposit?
2. What are the environments in which stratiform copper deposits occur; and
3. What is the probable mode of origin for such deposits?

In addition, some of the best-known stratiform copper deposits are listed and, time permitting, these might be discussed briefly.

Characteristics of Stratiform Deposits:

As is unfortunately the case with many geological terms, no rigid definition exists for stratiform deposits. In general, one thinks of ore found in sedimentary rocks, usually confined to a given horizon; however, there are some specific characteristics which distinguish truly stratiform deposits from other strata-bound deposits, as Lombard and Nicolini (1962, p. 231-246) have pointed out.

1. Stratiform deposits occur in sedimentary rocks or in their metamorphic derivatives.
2. Ideally, stratiform deposits occur within a single continuous horizon throughout a sedimentary basin; theoretically, they disappear only where the ore-bearing horizon does not occur (in areas of non-deposition). However, natural stratiform deposits may have gaps or modifications in the mineralization because of several other factors. To summarize, stratiform deposits must be concordant with the host rock.
3. There are two subtypes of stratiform deposits: (a) disseminated stratiform deposits where the grain size of the ore is often very similar to that of the country rock (aggregates may appear to be large crystals) or (b) stratiform fissure deposits, where the ore fills cavities (joints, shears, etc.) and the grain size of the ore is independent of that of the host rock. Generally, the second type is found with the first and is subordinate to it.
4. In stratiform deposits, mineralization usually conforms with the sedimentary structures; e.g., in the hollows of ripple marks. Also, the mineralization may be related to the fineness of the bedding; i.e., grade increases with finer bedding.

Another type of strata-bound deposit that should be mentioned is the peneconcordant variety, as originally distinguished by W. I. Finch (1959), for it represents a distinct type of mineral deposit, different from truly stratiform deposits. Peneconcordant deposits are stratiform on a regional scale, but are discontinuous on a smaller scale and more or less unconformable to the ore-bearing country rock. The mineralization does not always appear to be a normal constituent of the country rock, but often appears to be extraneous, introduced from outside the country rock. Peneconcordant deposits are more often confined to a given facies, not a given horizon; they tend to occur in paleo-channels. In addition, they may cut across sedimentary structures such as cross bedding.

Examples of peneconcordant deposits are the "red-bed" copper deposits and the Colorado Plateau uranium deposits. Stratiform deposits are typified by the Kupferschiefer of Mansfeld, Germany, the Nonesuch Shale at White Pine, Michigan, or the copper deposits of the Lower Roan System in Northern Rhodesia.

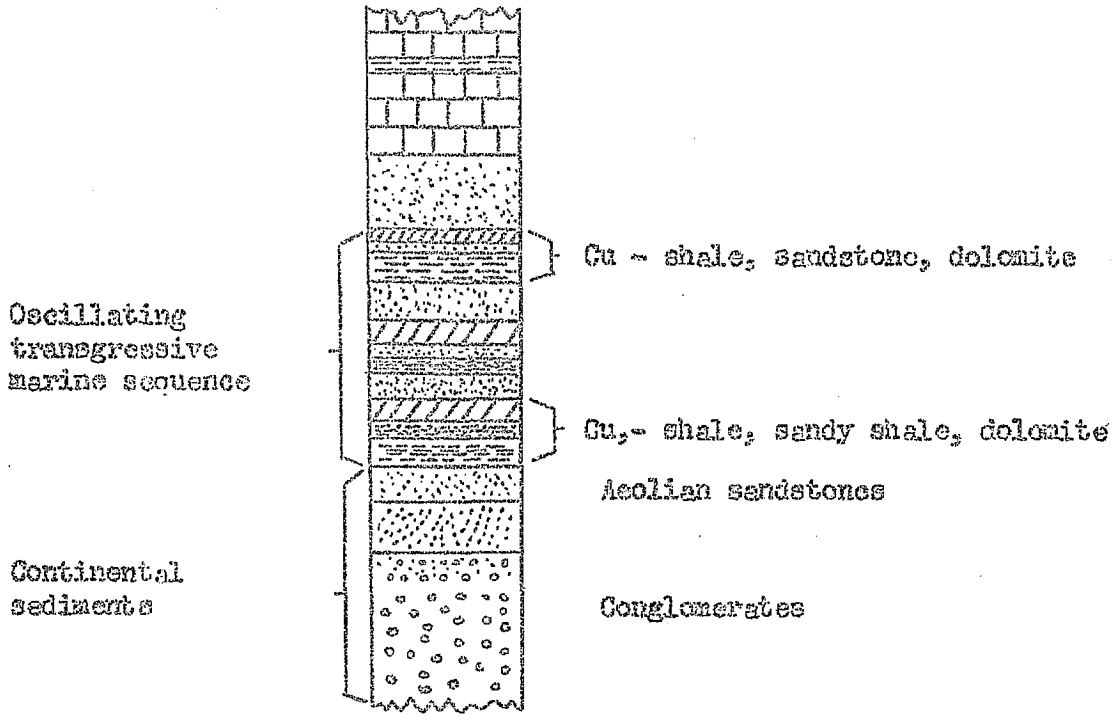
Economically, stratiform deposits in general may be more attractive than peneconcordant types, for only high-value ores such as gold, uranium, vanadium, etc. are apt to be economic in peneconcordant deposits because of their discontinuous nature, whereas the more widespread, continuous stratiform deposits may be economic for marginal grade ores.

Environments of Stratiform Copper Deposits:

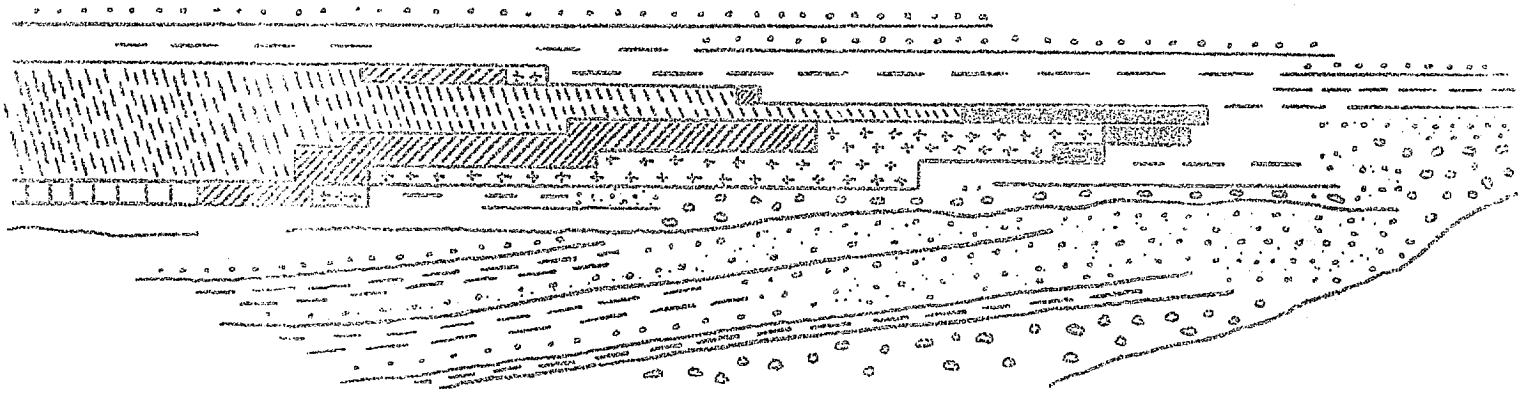
As previously mentioned, stratiform copper deposits are confined to sedimentary rocks or to their metamorphic derivatives; furthermore, they seem to be confined to a rather restricted type of depositional environment. It is possible to make the following generalizations:

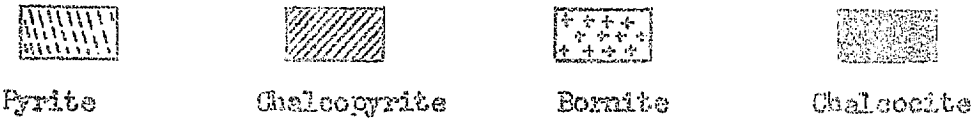
1. Most stratiform deposits occur in continuous marine sediments or in sediments representing marine transgressions into restricted basins which represented strongly subsiding areas.
2. Stratiform deposits frequently occur in gray or black sediments, rich in organic matter; i.e., they are found in reducing environments.
3. Stratiform deposits generally occur in sediments characteristic of warm, arid climates and are often associated with evaporites. Copper deposits are usually lacking in sediments which are indicative of cold climates; e.g., tillites.
4. Stratiform copper deposits appear to have a definite spatial relationship to paleoreliefs. Although stratiform deposits in general appear to represent relatively near-shore, shallow-water sediments (neritic?) to transitional sediments (lagoonal?), copper concentrations seem to be highest further away from old basement highs, whereas lead-zinc deposits appear closer to paleoreliefs.
5. Reef environments do not seem to be favorable sites for stratiform deposits; this is probably because of several factors; e.g., reefs represent "highs", areas of relatively greater water turbulence and higher Eh conditions.
6. Stratiform copper deposits appear to be related to a special lithologic sequence; several workers, especially Lombard and Nicolini (1960 and 1962), have called attention to this fact. In general, copper mineralization occurs at the beginning of a transgressive trend which overlies a long sequence of continental deposits, usually conglomerates and aeolian sandstones. The ore tends to be concentrated in argillaceous (shaly) sediments, but is often found in dolomites and sandstones as well. Copper is usually localized around oscillating transgressive sequences (marine to non-marine and back), but the continental sediments usually are barren of mineralization. Where the transgressive cycle is repeated, copper may be deposited in the marine (or transitional?) sediments; however, the copper concentration generally seems to be highest in the basal parts of the first transgressive cycle.
7. Stratiform deposits often display distinct zoning of their mineralization, which appears to be related to old shoreline trends and in some cases, to old current directions. In general, mineral zones tend to parallel ancient shorelines for long distances. The width of the zones varies greatly, but in general, widths are much less than the length; widths are greatest where ancient offshore slopes were gentle.

Generalized lithologic sequence characteristic of Stratiform Copper deposits (not to scale)



Copper mineral zoning, some deposits, Northern Rhodesian Copperbelt (after Garlick, 1961.)





Transgressive and regressive "copper facies"

Thickness of zones apparently is dependent upon many factors, but the major parameters appear to be maintenance of constant depositional conditions and metal supply over a long time.

A general zoning sequence has been reported from Northern Rhodesian deposits (Garlick, 1961, p. 160): barren sediment, disseminated chalcocite, bornite, chalcopyrite, and pyrite, occuring in the general direction of current flow and facies change from near shore to offshore sediments. However, there is no rigid relationship between sulfide zoning and sedimentary type and furthermore, mineralization may cease in a given horizon although there is no change in lithology. Sulfide zones may overlap one another in different stratigraphic sequences, advancing or retreating in transgressive or regressive phases.

8. In general, stratiform deposits tend to have high sodium, aluminum, magnesium, and perhaps boron, contents. These facts are the reflection of the geochemistry of the sediments in which stratiform deposits occur.

9. In stratiform deposits, the relationship between tectonism and ore concentration varies with individual deposits. Faults may modify the deposits, but they are formed independently of shear mechanisms. Stratiform deposits are often found in folded sediments and may have been subjected to varying degrees of metamorphism. Metamorphism may also affect ore minerals, causing them to recrystallize or even to move about; e.g., into fissures in or around the ore horizon which tends to obscure the original sedimentary features. In highly eroded terranes, ore horizons may be preserved in synclines, but ore concentration is generally independent of folding.

10. Stratiform deposits usually are not the only mineralization within a given province; generally there are other deposits which may be older or younger. Peneconcordant deposits are often associated with stratiform deposits. However, this mineralization apparently has no direct relationship to the stratiform deposits.

In summary, stratiform copper deposits generally occur in rather limited environments characterized by transgressive marine sediments laid down in reducing conditions under a warm, arid climate. They generally have a definite relationship to ancient shorelines and paleoreliefs, such that ore horizons vary in mineral type and grade with proximity to shallower areas of deposition. The major processes affecting stratiform deposits appear to be sedimentary, although subsequent tectonism and metamorphism may modify the original sedimentary features of the deposit.

Probable Mode of Origin for Stratiform Copper Deposits:

The origin of stratiform deposits in general has been the cause for much speculation and the source of much controversy. The question is not as academic as it might seem, for needless to say, theories of ore genesis largely influence exploration programs.

The controversy, of course, is whether or not stratiform deposits are to be considered syngenetic or epigenetic; i.e., whether the ore has been deposited during the sedimentary processes that created the host rock or has been introduced (by various mechanisms) from sources external to the host rock, after it was consolidated.

Criteria for Syngenetic Origin: Admittedly, most of the criteria concerning stratiform deposits presented in the preceding sections has been biased toward a syngenetic origin for these deposits. This report cannot hope to solve the problem, nor even to present all the evidence, pro and con, in the argument. However, I feel that in the case of truly stratiform deposits, the syngenetic theory is most plausible, for some of the following briefly stated reasons:

1. The ore is found in sedimentary rocks, concordant with given horizons and is associated with a distinctive lithologic sequence.
2. Ore distribution is closely related to ancient shoreline trends and displays a zoning strongly suggestive of control by water depth and associated Eh-pH relationships.
3. In connection with No. 2, mineralization may occur in several different lithologies and it may also cease in a given horizon even though there is no change in lithology.
4. Mineralization closely follows sedimentary structures such as ripple marks and pre-consolidation slumping.
5. Where folding and metamorphism have occurred, the ore distribution is not affected (except by differential erosion and recrystallization); the ore deposition in most cases is clearly pre-tectonic in origin.
6. No clear-cut relationship between intrusive rocks--or other epigenetic sources--and stratiform deposits exists.

Syngenetic Theory: There is a chemical theory which may explain the mineral zoning from shallow to deep water. Shücman's Law (1888) arranges mercury, silver, copper, bismuth, cadmium, lead, zinc, nickel, cobalt, iron, and manganese into a series "in which a solution of a salt of any of these metals will be decomposed by a sulfide of any succeeding metal and the first metal will be precipitated as a sulfide" (Garlick, 1961). Thus, in the presence of limited amounts, iron, cobalt, or zinc would tend to remain in solution until most of the copper is precipitated as a sulfide.

More recent work by Garrels (1960) and others has demonstrated that the relative solubilities of sulfides under given conditions may largely control the precipitation of sulfides under specific Eh-pH conditions (stability fields).

The overall syngenetic process may be outlined as follows:

1. Metal in suspension (colloidal?) and in solution is carried by rivers into a sedimentary basin, along with other materials.
2. In the near-shore zone, sandy material is deposited, but because of water turbulence and consequent high Eh (oxiding conditions) no sulfides are deposited. During compaction and diagenesis of these sediments, with subsequent reducing conditions, some pyrite may form.
3. At the edge of the oxygenated zone, some very minor amounts of uranium and tungstic oxides, along with molybdenum sulfide may be deposited.
4. In somewhat deeper water and in more reducing conditions, copper is predominantly deposited.
5. Farther offshore, there is a zone where roughly equal amounts of copper and iron are precipitated.
6. In the interior of the basin, copper is deficient (being deposited closer on shore) and iron is the predominant precipitate.

These metal sulfide precipitates were probably originally in a colloidal form and were diluted by varying amounts of mud or sand. The actual minerals chalcocite,

bornite, etc. probably formed during diagenesis or later metamorphism.

Typical Stratiform Deposits:

Northern Rhodesian Copperbelt: The Northern Rhodesian Copperbelt runs along the divide separating the drainages between the Indian and Atlantic Oceans. Along with the neighboring Belgian Congo, it forms a metallogenic province approximately 650 kilometers long and 400 kilometers wide.

The copper mineralization occurs near the base of the Katanga System (Precambrian) in the so-called "Ore Formation", which is comprised of a varying lithology and averages about 14 meters thick. The ore horizon consists of fine-to medium-grained, sometimes shaly argillaceous sandstones which may grade locally into black shales. Thin beds or laminae of dolomite are almost always present.

The strata under the ore horizon consists of generally light-colored sandstones and conglomerates with some argillaceous members. The strata above the ore horizon are alternating gray, medium-grained, argillaceous quartzites and lighter colored medium-grained sandstones. Aeolian cross-bedding occurs in the sandstones below the ore horizon.

Traces of copper have been found in nearly all the members of the Lower Katanga System, but they are economically concentrated only in the Ore Formation and immediately adjacent beds. Copper sulfides are the major ore, mainly as chalcopyrite with some bornite. The mineralization is disseminated in the host rock as aggregates of grains or as thin veinlets along the bedding or cross-cutting veinlets with quartz and carbonates.

Mansfeld (Kupfershiefer): The lithologic sequence, the mineralization, and the sulfide zones at Mansfeld strongly resemble those of the Rhodesian Copperbelt. The Copper Shale is underlain by a red conglomerate and by aeolian sand dunes, making up the Saxonian Formation (500-600 meters thick). The Zechstein Formation in which the copper shale (Kupfershiefer) lies is a transitional marine or lagoonal sequence. Copper occurs mainly as chalcopyrite and bornite with associated pyrite in the lower shale member of the Zechstein; this member is overlain by limestone, gypsum, anhydrite, and salt beds.

White Pine Copper, Michigan: Copper, mainly as chalcocite, occurs in the lowest beds of the Nonesuch shale over an area of many square miles near White Pine, Michigan. The "shale" is 600 feet thick and is largely composed of gray siltstone; it is Precambrian (late Keweenawan) in age. It overlies 2,300 to 5,500 feet of red sandstones and conglomerates, the Copper Harbor conglomerate, which in turn overlies the Middle Keweenawan Portage Lake lava series that contain the well-known native-copper deposits of the south shore of Lake Superior.

The copper-bearing strata at White Pine occur mainly in the lower 20 to 25 feet of the Nonesuch shale. This copper zone is divided into four units (in ascending order) called the lower sandstone (the top bed of the Copper Harbor conglomerate), the parting shale, the upper sandstone, and the upper shale. Cyclic sedimentation is indicated by very similar lithologic sequences in the upper and parting shales.

Most of the copper occurs in the upper and parting shales, except in a small area near the White Pine fault, where it is abundant in the upper and lower sandstones. Copper occurs in five different layers in amounts averaging from 1 to 3 percent. Copper percentages are usually greatest where the beds are thick; the thickest areas occur in depressions. Copper content in shales decreases as sand content increases.

The local occurrences of copper in the sandstone beds around the White Pine fault is explained as the result of hydrothermal transportation from the fault up the dip of a permeable sandstone to the crest of an adjacent anticline. However, the distribution of copper in the parting and upper shales appears to be completely independent of local structure, faults, and rock permeability; the overall control of ore deposition in the area is lithologic and stratigraphic.

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B. E. Kilpatrick
CH-601
October, 1966

REVIEW OF THE GEOCHEMISTRY OF COBALT AND NICKEL

Chemistry:

Co and Ni belong to the "iron triad" of the transition elements; some of their properties are listed below, along with those of Mg.

Element	Atomic No.	Atomic Weight	Oxidation# Potential	Ionic# Radius	Ionization Potential
Fe	26	55.85	+0.44 v.	0.74 Å	7.90 e.v.
Co	27	58.94	+0.28	0.72	7.86
Ni	28	58.71	+0.25	0.69	7.63
Mg	12	24.32	+2.37	0.66	7.64

M^{++}, coordination number 6

Nickel: The chemistry of Ni is essentially that of the +2 state; in aqueous solution, Ni exists as Ni^{+2} or as a complex ion. Ni complexes are very stable to air oxidation. Ni^{+3} is very rare; however, $Ni(OH)_2$ can be oxidized by ClO_3^- to form a dark-colored oxide of indefinite composition variously described as NiO_2, Ni_2O_3, or Ni_3O_4, which is a powerful oxidizing agent.

Cobalt: Co is found both in the +2 and +3 states. The Co^{+2} ion is very stable to oxidation; most cobaltous solutions are pink and probably contain the hydrated ion $Co(H_2O)_6^{+2}$. Co^{+2} forms many complexes which are easily oxidized. In aqueous solution Co^{+3} is a powerful oxidizing agent and can oxidize water to form O_2 (the oxidation potential $Co^{+2} \rightleftharpoons Co^{+3} + e^-$ is -1.84 volts). Unlike the simple Co^{+3} ion, the complex ions of Co^{+3} are very stable to reduction and there are a tremendous number of these ranging from simple $Co(CN)_6^{-3}$ and $Co(NH_3)_6^{+3}$ to complicated polynuclear complexes in which several Co atoms are bridged together by shared complexing groups.

Mineralogy:

Important Co & Ni Minerals	Chemical Formula	Remarks
Cobaltite	$CoAsS$	vein deposits
Bravoite	$(Fe,Ni)S$	nickeliferous pyrite
Annabergite	$Ni_3(AsO_4)_2 \cdot 8H_2O$	grn. second. mineral
Erythrite	$Co_3(AsO_4)_2 \cdot 8H_2O$	pink second. mineral
Linnaeite	Co_3S_4	second., in coal
Millerite	γ- NiS	low-temp., needles
Niccolite	$NiAs$	minor ore
Skutterudite	$(Co,Ni)As_3$	end, solid-soln. series
Smaltite	$(Co,Ni)As_{3-x}$	part of "Skutterudite Series"
Chloanthite	$(Ni,Co)As_{3-x}$	part of "Skutterudite Series"
Pentlandite	$(Fe,Ni)_9S_8$	22-33% Ni, most important Ni ore
Garnierite	$xNiO \cdot yMgO \cdot SiO_2 \cdot H_2O$	lateritic Ni ores
Pyrrhotite	$Fe_{1-x}S$	may contain Ni, Co, Cu

Ores:

Many Ni ores occur in serpentine rocks, which are the alteration products of ultrabasic rocks. Pyrrhotite-pentlandite deposits are usually associated with norites (hypersthene gabbros) and less commonly with peridotites (olivine and pyroxene ultrabasic rocks). These are the most important Ni ores. Co- and Ni-bearing vein deposits usually contain As and S and are associated with diabases (fine-grained gabbros) and other basic rocks. Ore deposits that are found in silicic igneous rocks usually contain little or no Co and Ni, except for the Ni-bearing Co-U-Ag veins found in some granites. The percentage of Ni in segregated sulfides increases with increasing content of Ni in the silicate minerals of the hostrock.

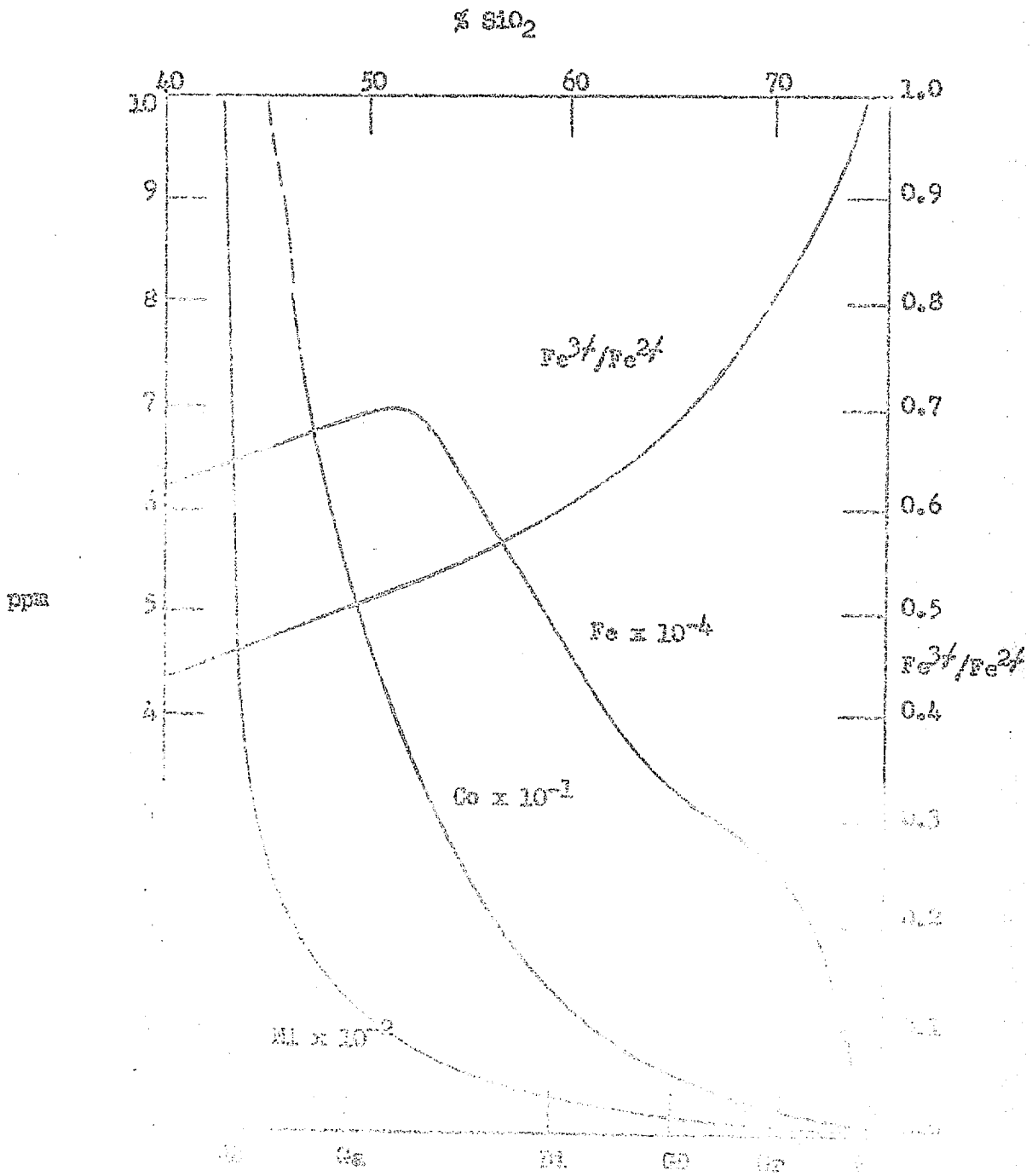
Lateritic ores of Ni are becoming more important; these develop from the weathering of serpentinitic and ultrabasic rocks. Ni (and much lessor amounts of Co) become enriched in garnierite and Ni-bearing clays.

Geochemistry:

The geochemistry of Ni and Co is important in that it can explain the occurrences of these elements and their associations with other elements in ore deposits. Researchers differ in their appraisals of the behavior of Ni and Co (especially in regard to Fe and Mg), depending upon whether their results come from the study of ultrabasic rocks (highest Ni-Co content) or from the study of more "normal", less basic, rocks. It seems that an understanding of the different relationships of Ni and Co in various geologic environments - including sedimentary and metamorphic - is essential [illegible] using Co and Ni effectively in geochemical prospecting.

Content of Fe, Ni, and Co in Igneous Rocks

(after Smith, F. G., 1963, p. 406)



Most igneous rocks regularly contain some Ni and Co and most contain small amounts of common sulfide minerals such as pentlandite, pyrrhotite, or pyrite. However, most of the Ni and Co found in igneous rocks occurs in silicate minerals, specifically the ferromagnesian silicates. If no sulfides are present, silicates will contain all of the Ni and Co in the rock.

Co and Ni are most abundant in ultramafic and mafic rocks; the contents of Co and Ni decrease sharply as the rocks become more silicic, as Ni and Co are concentrated in the early-formed ferromagnesian silicates, which are most abundant in the mafic rocks. Ni^{+2} and Co^{+2} replace Fe^{+2} and Mg^{+2} diadochically; the contents of Fe and Mg decrease as rocks become more silicic and the contents of Ni and Co follow suit. Although there is some question as to the behavior of Ni in respect to Fe and Mg, apparently it usually is more closely related to the Fe content of a given rock type than to the Mg content. In contrast to Fe, Co seems to substitute readily for Mg and there is a linear relationship between Co and Mg contents over large ranges of rock composition. The relative abundance of Co over Ni increases as rocks become more silicic, so that the Co content eventually reaches the same order of magnitude as the Ni content.

Ultrabasic rocks, such as peridotites and dunites, contain an average of 0.3 to 0.4 percent NiO in solid solution in olivine and pyroxenes. However, some large ultramafic intrusives, which have normal Fe contents, have lower Ni contents; this fact demonstrates that the variations in Ni and Fe contents of ultramafic rocks are not closely related to one another, as has been reported for gabbroic rocks. There has been a well defined inverse relationship between the Ni and Fe contents in olivine of gabbroic rocks, but according to Shteinberg and Malakhov (1963, p. 1028), this does not hold true for ultramafic rocks. They report that Ni tends to follow Mg, rather than Fe, in ultramafic rocks.

In more "normal" rocks, Co and Ni behave somewhat differently. In mafic rocks Ni is concentrated mainly in biotite, hornblende, and magnetite. In intermediate rocks it occurs mainly in hornblende and biotite, and in the silicic rocks Ni is carried by the feldspars. According to Seryich (1964, p. 886), the Ni content of the granitoid rocks is directly related to the Fe^{+2} content and not to Mg content of rocks.

<u>Nickel and Cobalt in the Geochemical Cycle</u>: Ni and Co are closely associated in igneous rocks, but they vary in their manner of occurrence there and they also behave differently in their geochemical cycles. Ni is seldom, if ever, found in the +3 state, whereas Co readily achieves it. The coördination number of Co^{+3} is always 6, but Ni^{+2} may have a coördination number of 4 as well as its usual 6.

<u>Nickel and Cobalt in Water</u>: According to Ginzburg (1960, p.207), the presence of Ni and Co in water depends upon pH and although they behave differently in aqueous solution, both of them precipitate at a pH of 6.8 and are not found in more alkaline conditions. Ni^{+2} is very stable in aqueous solutions under the proper conditions but will precipitate in alkaline solutions as hydrated silicates and Ni hydroxides. Ni sulfates and bicarbonates are soluble. The solubility of $Co(HCO_3)_2$ is 1-1/2 times lower than that of $Ni(HCO_3)_2$, but as Co forms no silicates, in contrast to Ni, the Co:Ni ratio increases in water and may become greater than 1, especially where the original Co contents are high.

The content of Co and Ni in sea water is very low, as most of the Co and Ni transported to the sea is deposited in the hydrolyzate sediments (the very-fine-grained clastics and insoluble derivatives of weathering such as bauxite, clay, shales, etc.) Co is removed, in additional amounts, by adsorbtion in oxidate sediments and as a result may become enriched over Ni, contrary to the case in other sediments.

Small amounts of Ni and Co occur in the sulfides of marine sediments and thus they may tend to concentrate in reducing environments characterized by black shales.

Nickel and Cobalt in Laterites: When ultrabasic rocks are altered to serpentine, their original Ni and Co contents remain essentially unchanged. However, when ultrabasic rocks or their serpentinitic derivatives are weathered, Ni forms various complex hydrosilicates, the nickelian chlorites and silicates (related to clay minerals). These minerals become important in the development of lateritic soils over ultrabasic rocks as Ni and Co becomes concentrated in the lower horizons of the laterites. As the MgO is leached out of the soil, the CO_2 in meteoric waters becomes available and it reacts with Ni, which probably goes into solution as $Ni(HCO_3)_2$. The Ni-bearing solutions percolate down to lower horizons, which have a higher MgO and SiO_2 content, where Ni is redeposited as garnierite and Ni-bearing clays in the transitional zone between the laterite soil and bedrock.

Cobalt does not form hydrosilicates during weathering as does Ni, but it goes into solution as a bicarbonate much like Ni. $Co(HCO_3)_2$ is apparently less soluble than $Ni(HCO_3)_2$ and it is re-deposited with Mn, largely as cobaltian wad (absolan), somewhat higher than the Ni. However, the separation of Co and Ni is not complete and some Co accumulates with Ni in garnierite.

Nickel and Cobalt in Biological Cycle: Small amounts of Ni and Co are found widely distributed in plants and animals. Trace amounts of Co are necessary for sheep and cattle to remain healthy; Co deficiency causes a disease known as "enzoötic anaemia". Plants apparently do not require Co or Ni, but these elements may be found in plants, the highest concentrations being in the leaves. Relatively high contents of Co in the humous layer of soils (over lower Co contents in deeper horizons) have been attributed to plant action.

Co and Ni may become enriched in coal, where crystals of linnaeite and millerite sometimes occur. The content of Ni and Co in petroleum and its derivatives may be high (up to 3,000 ppm in asphalt). Ni forms organometallic compounds which are usually concentrated in the paraffins.

Geochemical Prospecting, Case Histories:

Use of Cobalt in Geochemical Prospecting (Canney and Wing, 1966)
Cobalt has been found to be very useful in geochemical prospecting, especially as a pathfinder for Ni-Cu-Co deposits associated with mafic rocks, even though this fact is not widely appreciated, perhaps because of the lack of reports in the literature.

Canney's work in west-central Maine has shown that anomalous amounts of Co are likely to be present in active sediments of streams draining areas of mafic rocks mineralized with Ni-, Cu-, and Co-bearing sulfides. Stream sediment samples from the vicinity of a gabbro-norite mineralized with sub-economic amounts of pyrrhotite and chalcopyrite were analyzed for total Cu, Co, Ni and cold-extractable Cu and Co. Highly anomalous values of both total and cold-extractable Co were found within and downstream from the zone. Ni values did not show as distinct an anomaly as did Co. There was a weak cold-extractable Cu anomaly which correlated with the Co peaks and the mineralized area; however, total Cu values were all within background range. Co, both total and cold-extractable, seems to be an excellent indicator in prospecting for similar deposits.

When the Cu:Co and Ni:Co ratios in fresh and weathered mineralized rock is compared with the same ratios in sediments, the increase in Co with respect to Cu and Ni is striking. These data imply that Co is more mobile than Ni or Cu. Canney suggests that Ni and especially Cu are trapped by secondary iron oxides while Co is more mobile in such an iron-rich oxidizine environment. Therefore, the primary Cu:Co and Ni:Co ratios would have to be very high before Co would be of subordinate value to Ni or Cu as an indicator element.

Another study was conducted in the Blackbird Co-Cu district, Idaho, where the ores are hydrothermal replacement deposits of Cu-Co minerals that occur in pod-like masses. Principal primary sulfide minerals are cobaltite, safflorite, chalcopyrite, pyrite and pyrrhotite. Cu:Co ratios of oxidized and unoxidized ore indicate a high mobility for Co; apparently the Co is not adsorbed or precipitated by limonitic material.

Cu and Co in active stream sediments and in stream water below the Blacktail ore body were analyzed; in an approximately two-mile interval below the ore body the Cu content of the stream sediment decreased by a factor of 125 whereas the Co content decreased only by a factor of four. The Co content of the stream water decreased much more rapidly and was much less persistent than the associated Co stream-sediment anomaly. Only limited pH studies were made, but the pH of waters in the mineralized area was about 6.5 and the pH of stream waters in background areas was usually above 7.

Although Hawkes and Webb (1962) assign an intermediate mobility to Co, comparable to Cu, Ni, and As, Canney feels that Co is normally a highly mobile element, more so than Ni or Cu, in the supergene environment. As a consequence, it should be more widely used in geochemical reconnaissance using stream sediment and water surveys.

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Geochemical Prospecting Investigations in the Northern Rhodesian Copperbelt (Tooms and Webb, 1961)

Studies in the Northern Rhodesian Copperbelt have shown that the presence of Cu-Co ore deposits beneath thick overburden can be detected by the analysis of near surface samples of the freely drained lateritic and seasonal swamp soils. Total copper and cobalt anomalies related to mineralization have a considerable lateral extent and are normally extended asymmetrically downslope from the sub-outcrop.

The ore consists of disseminated pyrite, chalcopyrite, bornite and chalcocite, which show a zonal tendency, laterally and in depth. The ore horizons vary greatly in width and grade but average from 2 to 5 percent Cu over widths of 30 to 50 feet. The ore is found in the Katanga sediments, mainly in shales and sandstones, and the ore horizons show strong stratigraphic controls.

The Co:Ni ratio found in soils over mineralized ground is usually greater than one; however, in soils over non-mineralized gabbroic intrusives, the Co:Ni content decreases to less than one and the total Cu, Ni, and Co values in the soils is much greater than over the sediments.

Anomalous Co values have a similar lateral distribution to those of Cu and the Cu:Co ratio in soil samples closely reflects that of the primary ore (from 10:1 to 20:1). However, Tooms and Webb report that factors affecting the dispersion of Co do not seem to be similar to those affecting Cu. Cu shows a tendency to accumulate with the sesquioxides of the laterite horizon, but Co does not. Near mineralization Co increases with depth regardless of the soil horizon, but in background areas the Co content shows little variation throughout the soil profile. Thus it is probable that Co is not adsorbed or co-precipitated with hydrous iron oxides. In areas of ground water seepage, there was a marked accumulation of both Co and Cu.

The authors imply that Cu is more useful than Co in prospecting for stratiform Cu deposits in Northern Rhodesia.

Geochemical Prospecting at Cobalt, Ontario (Koehler and others, 1954)

A geochemical prospecting program in glacial deposits overlying known ore bodies composed of thin veins of Ag, Ni, and Co arsenides in the Precambrian shield of Canada was carried out during the summer of 1952. The cobalt concentration in samples of glacial material, collected on a horizontal and vertical grid over an area of proven mineralization at depth was determined in order to test the applicability of geochemical prospecting techniques in locating similar ore bodies.

Samples were taken on a one hundred foot grid pattern with a tube-like auger that penetrated down to bedrock. Sediments consisted of surface soil, sand, sandy clay, and clay. It was found that, depending upon topography, sandy areas were either relatively enriched in Co or depleted, because of ground water flow through relatively more permeable areas. Clay seemed to adsorb Co readily.

A detectable anomaly over mineralized bedrock was found in the area. The Co values increased with depth and in cross-section the anomaly appeared dome-shaped, which suggests that the anomaly is the result of upward migration of Co since the deposition of glacial material.

The sampling interval is critical in the detection of an anomaly and with sufficiently close spacing (depending upon the size and grade of the ore body) surface sampling above would be sufficient to detect an anomaly. The work done demonstrates that secondary dispersion halos in glacial material can be of sufficient magnitude to be detected by geochemical prospecting methods.

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General Chemistry of Arsenic and Antimony

Arsenic and antimony belong to the Group V elements of the periodic chart, in which there is a complete change of properties from nonmetallic to metallic in going down the group. The lighter members of the group, nitrogen and phosphorus, are nonmetals and form only acid oxides; arsenic and antimony, the middle members, are semi-metals and form amphoteric oxides. Bismuth is the heaviest member and is metallic in all its properties.

Properties of Arsenic, Antimony, and Bismuth

Element	Atomic Number	Atomic Weight	Ioniz. Pat. (e.v.)	Oxid. Pot. (v.)	Valence States
As	33	74.91	10	-0.23 (As_4O_6)	-3, +3, +5
Sb	51	121.8	8.6	-0.21 ($Sb(OH)^+_2$)	-3, +3, +5
Bi	83	209.0	8	-0.32 ($Bi(OH_2^+)$)	+3, +5

Arsenic: Arsenic can exist as a metallic modification (gray arsenic) or as a nonmetallic one (yellow arsenic). The metallic form is stable at room temperature; yellow arsenic is made by sudden cooling of arsenic vapor, consists of tetratomic molecules (As_4), and is volatile.

The principal oxidation states of arsenic are +3 and +5. The -3 state, represented by arsine (AsH_3) is unstable. As^{+3} forms arsenious oxide (As_4O_6), "white arsenic", and when treated with water, it forms a slightly acid solution containing the amphoteric hydroxide, $As(OH)_3$ or H_3AsO_3. Arsenious sulfide, As_2S_3 has a tendency to form colloids that are stabilized by the adsorbtion of negative ions. These colloids can be coagulated by addition of H^+ or other positive ions. In the +5 state, As mainly forms arsenic acid (H_3AsO_4) and its derivatives; As^{+5} is an oxidizing agent. As_2S_5 is insoluble in acid.

Arsenic compounds are well-known systemic poisons and they are practically tasteless; however, sensitive tests for traces of As have made them unpopular in modern times for homicidal purposes. Useful antidotes for arsenic poisoning are limewater, $Ca(OH)_2$, and epsom salts, $MgSO_4 \cdot 7H_2O$, because they precipitate oxyanions of As.

Antimony: Elemental antimony exists in several allotropic forms, the stable one at room temperature being gray antimony. Yellow antimony (the analogue of yellow arsenic) is stable below -90°C. Explosive antimony is prepared by electrolysis of $SbCl_3$ and is a black material which converts violently to the ordinary gray form upon being scratched. Although ordinary gray antimony has a metallic appearance, it is actually a poor metal.

The -3 form of Sb forms a very unstable compound, SbH_3 (stibine). This, like arsine, is quite poisonous and is easily oxidized to the metal. Sb^{+3} forms Sb_2O_3, which is an amphoteric oxide. The orange sulfide, Sb_2S_3, resembles As_2S_3 in many respects. In the +5 state, Sb forms Sb_2O_5, which is an oxidizing agent. It is practically insoluble in acid, but dissolves in base to give $Sb(OH)^-_6$. Unlike As_2S_5, Sb_2S_5 is soluble in acid, but Sb^{+5} is reduced to Sb^{+3}.

Geochemistry of Arsenic and Antimony

Igneous Rocks: In general, antimony and arsenic are rather rare elements in the earth's crust; Hawkes (1962) gives the average amounts of arsenic and antimony in igneous rocks as 2 ppm and 0.3 ppm, respectively. Arsenic and antimony form no independent silicate minerals but they combine readily with sulfur, selenium, and tellurium, and form sulfosalts, arsenides, and antimonides with various heavy metals, preferably copper, iron, nickel, and cobalt. The native elements are also found in many veins. Arsenic forms many arsenates in which the AsO_4^{-3} anion is analogous to PO_4^{-3} in the phosphates.

Arsenic and antimony are mainly found in rocks and minerals representing late-stage igneous activity. Some arsenic is found in early magmatic segregations such as sperrylite ($PtAs_2$). In general, arsenic begins to separate first at high temperatures after the main stages of magmatic crystallization (pegmatitic stage); antimony is associated with mercury and represents the last, low-temperature stages of hydrothermal activity. Arsenic, as arsenopyrite, is particularly characteristic of pyrometasomatic deposits (tactites) and is associated with cassiterite and scheelite; however, it also may be an important constituent of hydrothermal vein deposits.

Geochemical Cycle:

Average Contents of Arsenic and Antimony (ppm), after Hawkes, 1962

Element	Igneous Rx.			Sedimentary Rx.			Soils
	Unaf.	Maf.	Fels.	Sh.	Bk.Sh.	SS	
As	2.8	2.0	1.5	4	75-225		1-50
Sb	0.1	0.15	0.4	3	--	1	--

Antimony and arsenic have generally low mobilities; however, arsenic is apparently more mobile than antimony, which is found mostly as a detrital mineral (stibnite). Arsenic tends to be coprecipitated with iron, as AsO_3^{-3} with limonite, or to form ferric arsenates ($FeAsO_4$, scorodite). In iron-poor environments, arsenic becomes more mobile and may even form dispersion trains in stream water (Mather, 1959). Arsenic tends to become enriched in oxidate sediments, especially iron-rich bauxites and glauconitic marine sediments. It also concentrates in pyrites of black shales and coal deposits.

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Arsenic is universally present in plants and animals. In marine organisms, it replaces phosphorus and thus is found in marine phosphate deposits. It becomes very much enriched in plants growing over arsenic-bearing mineral deposits. Pyrites in coal beds may be especially rich in arsenic and as a result, it becomes enriched in coal ashes and coal smoke. Antimony may become enriched in plants growing over stibnite deposits (Sainsbury, 1957).

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Important Minerals of Arsenic & Antimony

Mineral	Chemical Formula	Remarks
Native arsenic	As	Found combined in mineral
Native antimony	Sb	"allemontite", hydrothermal veins
Arsenopyrite	FeAsS	Most abundant As mineral, high temp.
Stibnite	Sb_2S_3	Low temp. veins, etc. most important Sb mineral
sperrylite	$PtAs_2$	
cobaltite	CoAsS	
loellingite	$FeAs_2$	
orpiment	As_2S_3	yellow
realgar	AsS	red-orange
tetrahedrite	$(Cu,Fe)_{12}Sb_4S_{13}$	solid-solution series
tennantite	$(Cu,Fe)_{12}As_4S_{13}$	
enargite	Cu_3AsS_4	
bournonite	$PbCuSbS_3$	
boulangerite	$Pb_5Sb_4S_{11}$	
skutterudite	$(Co,Ni)As_3$	"skutterudite series"
smaltite	$(Co, Ni)As_{3-x}$	
chloanthite	$(Ni,Co)As_{3-x}$	
niccolite	NiAs	
breithouptite	NiSb	
arsenolite	As_2O_3	
sênarmontite	Sb_2O_3	
pyrargyrite	Ag_3SbS_3	
proustite	Ag_3AsS_3	"Ruby Silver"

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Abstract on Geochemical Exploration in the Kantishna Area, Alaska, by R. M. Chapman

Soils and stream sediments in the Kantishna Area of interior Alaska were studied geochemically to determine the relation of their metal content to ore deposits. Bedrock in the area is predominantly schist. Metals occur in gold-quartz veins, silver-bearing galena veins, and stibnite veins. Sphalerite, arsenopyrite, pyrite, and chalcopyrite are accessory minerals of the gold and silver-galena veins.

The soil cover over the veins is thin; the A horizon is about 0.4 feet thick, and the B and C horizons together range from 0.5 to 3.0 feet in thickness. Soil samples were collected from both the A_1 and C horizons. Stream sediments (finer-size fraction) were sampled at 47 sites in several streams that drain the mineralized area. All soil and stream sediment samples were analyzed for lead, zinc, copper and arsenic; some samples were analyzed for antimony.

Anomalous amounts of arsenic and/or lead in the soil, particularly in the C horizon, are the best indicators for the gold and silver-galena veins. Although zinc contents are anomalously high at some sites, copper values seldom rise above background amounts. Metal values in the C horizon were greater than in the A_1 horizon.

In the stream sediments, lead, zinc, antimony, and arsenic show significant variations that correlate with the known distribution of the metals, but copper contents are generally low. Stream sediments from 12 sites to the east bear much smaller amounts of these metals.

Abstract on Arsenic and Antimony, from Observations on Geochemical Exploration in Tropical Terrains, by J. S. Webb

A number of preliminary examinations and some detailed studies, principally in East, West, and South-Central Africa, have demonstrated a wide field of application for geochemical exploration techniques in tropical terrain. Examples are given, mainly from unpublished material, covering a variety of mineralizations and conditions, including copper-cobalt, lead-zinc, gold-arsenic-antimony, molybdenum, tungsten, tin, niobium, chromium, and diamond-bearing kimberlite deposits. Certain features of observed metal dispersion are briefly discussed, with special reference to the influence of soil type, climate, topography, vegetation and bedrock geology.

In many areas of Africa, especially Southern Rhodesia and West Africa, gold occurs in association with arsenic and, occasionally, antimony. Because (sic) of the lack of a rapid field test for gold and because, in some areas, gold is subject to leaching and redistribution near the surface, arsenic and antimony have been studied as pathfinder elements for gold.

In Southern Rhodesia, gold occurs associated with arsenopyrite and occasionally stibnite, in mineralized shear zones and quartz veins traversing greenstone or sandstone host rocks. The terrain is flat to undulating, with occasional hills and ridges, and bedrock is generally covered by a residual lateritic overburden varying from 2 to 8 feet deep.

In highly ferruginous soils developed over basic bedrock, there is no marked variation in arsenic content with depth, apart from a slight enrichment in the topsoil and possibly in zones of maximum iron accumulation. Good soil anomalies are developed over mineralization at a depth of about one foot. There appears to be little leaching of arsenic during weathering and such lateral dispersion that occurs is probably largely mechanical. This relative immobility of arsenic has been found elsewhere and where smelter fumes have contaminated soils with arsenic, the arsenic is confined to the upper horizons of the soil.

In contrast to the relatively restricted dispersion of arsenic in highly ferruginous soils (probably because of the formation of insoluble iron arsenates), there is evidence that arsenic may be appreciably more mobile in soils developed over sandstones and other rocks with low iron contents.

Similar results have been obtained in Sierra Leone, where lenticular gold-quartz veins associated with arsenopyrite and base metal sulfides occur in sheared talc-carbonate schists. The overburden on higher ground consists of several feet of indurated laterite, or duricrust, overlying 2 to 3 feet of nodular red loam grading into weathered bedrock. The area is being actively dissected and the duricrust horizon is missing on the valley slopes. There is considerable contrast between the background metal content and anomalous profiles (up to 500 feet wide) which rise to metal values of 600 ppm. The duricrust is missing in the valley slope soils; this is where most of the work has been done although other studies indicate that near-surface anomalies are also developed in the duricrust.

The few samples analyzed at the time of the study indicate that only under special circumstances would antimony prove to be a better indicator than arsenic. This is because antimony is more sporadically distributed in the ore and also because of the more tedious analytical procedure for antimony.

B. E. Kilpatrick
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Abstract on Geochemical Exploration for Antimony in Southeastern Alaska, by C. L. Salisbury.

Preliminary geochemical prospecting by the U.S. Geological Survey was carried out in 1952 in muskeg-covered ground at Gamano Point, Cleveland Peninsula, Alaska, in an effort to find areas of stibnite concentration. The areal geology was known in general; however, the details of structural controls of ore deposition were imperfectly known. Thick vegetation obscured the bedrock; this, combined with heavy rainfall, made surface exploration slow and costly. The only ore mineral present is stibnite, which is exceptionally pure and contains only traces of arsenic. The ore occurs as replacement of limestone and as fracture fillings in host rocks of brecciated limestone interbedded with limey slate and subordinate phyllite of Mesozoic Age.

The soil cover above limestone bedrock consists of a layer of decayed organic matter grading downward into a yellow to red clay and thence downward into limestone. At other places a till zone occurs between the humus and clay zones. Muskeg and pear bogs several feet deep have formed on larger flat areas, especially in poorly drained areas in reworked glacial material.

Samples were collected by using a 3/4-in. pipe fitted with a wooden plunger; the pipe was pushed down into the clay zone and then through to, or near, bedrock. Three or four samples were collected from different holes at each station. The pipe was cleaned to avoid contamination of low-grade samples by high-grade samples.

Initial work established a preliminary range of values indicating normal (background) and anomalous concentrations of antimony in the soil. There were no determinations of greater than 2,000 ppm of antimony, for this value seemed sufficient to indicate ore. Traverse lines radiated out from the known ore zone. Twelve groups of samples were taken to determine the vertical distribution of antimony in the soil profile; two zones of concentration were found to occur: one immediately overlying bedrock and one at the base of the humus layer, both separated by a zone of lower concentration. The enrichment in the humus layer probably is the result of plant action; that of the lower zone is the result of the solution of limestone, leaving insoluble antimony minerals behind.

The background content of the lowest soil zone depends in large measure upon the composition of the underlying bedrock. In areas of unmineralized limestone, background values of antimony run 30 to 40 ppm; over limestone-free bedrock background is less than 10 ppm. The threshold value of antimony (near mineralized areas in limestone) ranges from 100 to 1,000 ppm. Anomalous values range from 1,000 to 10,000 ppm. Threshold and anomalous values largely depend upon the depth of ore bodies. This study was designed to find near-surface orebodies within reach of 20-ft. drill holes.

Results proved the feasibility of finding ore through geochemical soil sampling methods. Two new areas of high antimony concentration were found during the preliminary studies. The major significance of the study is that new ore zones were discovered easily and cheaply; three additional orebodies were discovered at a total cost of less than $750. It is concluded that antimony ores, particularly stibnite, are detectable by soil sampling methods, at least in residual soils, because the dispersion halo is restricted in extent and the anomalies lie close to the ore zone. It is suggested that antimony-bearing sulfide ores might be explored for using antimony as an indicator element.

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Abstract on Geochemical Exploration Near the Getchell Mine, Humbolt County, Nevada, by R. L. Erickson and others.

The U.S. Geological Survey began geochemical investigations at the Getchell gold mine in 1961 to study the arsenic-gold association and to test the idea that determination of arsenic in soils and rocks at the surface would aid in finding concealed gold ore.

The area is in the north-central part of the Osgood Mountains, whose general geology consists of complexly folded and thrust-faulted Paleozoic sedimentary rocks intruded by a Cretaceous granodiorite mass. Most of the orebodies of the area occur in the Getchell fault zone that extends along the eastern front of the Osgood Mountains.

The gold orebodies are sheetlike masses extending 7,000 feet horizontally and 800 feet downdip; they vary in width from a few feet to 200 feet, averaging about 40 feet wide. The highest gold contents are closely associated with soft black carbonaceous material and abundant arsenic sulfide (realgar and orpiment). Other ore-associated minerals are arsenopyrite, stibnite, ilsemannite and cinnabar. Analyses of the ore show that arsenic is the most abundant metal; arsenic, tungsten, and mercury are the only metals consistently present in all composite ore samples; and molybdenum, antimony and silver probably have only limited usefulness as an indicator of gold ore.

Rock, fracture filling, and soil samples were spectrographically analyzed for several metals around the ore zones; typical anomalies occur in fracture fillings from the north workings of the Getchell Mine, along an adit perpendicular to the strike of the ore shoot. Arsenic, tungsten, and mercury show the greatest amounts of enrichment; arsenic and mercury are enriched 100 times and tungsten is enriched 10 times. Studies indicate that a coincidence of these three metals is a good indicator for a nearby gold deposit. Arsenic anomalies without the accompanying tungsten and mercury anomalies may indicate weak mineralization or that gold mineralization is further removed from the sample site (tungsten and mercury haloes were depleted closer to the deposit.)

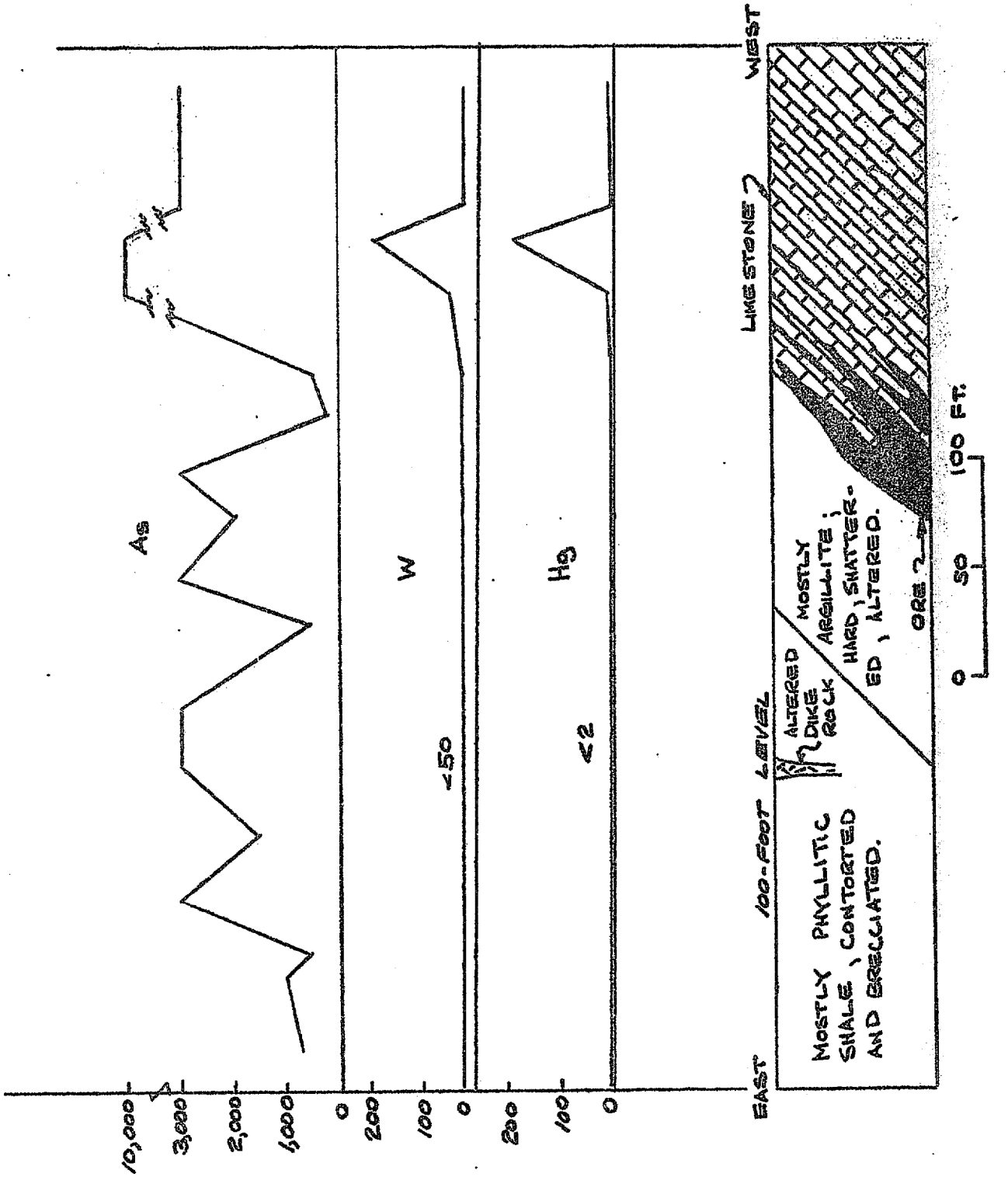
In general, geochemical work at the Getchell Mine indicates that arsenic-tungsten-mercury anomalies occur over the gold deposits and that these anomalies are not broad haloes but are restricted to the mineralized area. The highest metal values occur in oxidized iron-rich material along fractures and bedding planes in barren bedrock, lesser values in caliche coatings on exposed bedrock, and lowest, but still anomalous, values in soils.

Mining operations demonstrated that the outline of the surface geochemical anomaly conformed to the outline of the underground arsenic-gold orebody.

The writers suggest that since arsenic and tungsten are strongly oxyphile, they tend to form oxides or hydrated oxides and remain in the oxidized zone. Arsenic and tungsten may be absorbed by precipitating iron hydroxide or by forming ferric arsenates and tungstates. The amount of arsenic remaining in the oxidized zone probably is controlled by the amount of iron available to form arsenates or arsenic-adsorbing hydroxides. In the Getchell Mine, there is more arsenic than

Geochemical Profile of 100-Foot-Level Adit, North Workings, Getchell Mine, Nevada

Modified after Erickson and others, 1964, p. 8.



As, W, Hg Parts Per Million

iron in the primary ore; as a result, there is insufficient iron in the oxide zone to fix all the available arsenic. Excess arsenic probably remains in solution as the negatively charged anion or as negatively charged arsenate complexes ($H_2AsO_4^{-1}$ and $HAsO_4^{-2}$) over a constant Eh and wide range in pH. Evaporation of oxygenated alkaline water could precipitate arsenic-bearing caliche. The small amounts of arsenic in soils over gold deposits could be the result of upward diffusion of arsenic by surface and ground waters or the diffusion of arsine gas from arsenic concentrations in bedrock.

Abstract on Geochemical Prospecting Studies in the Bullwacker Mine Area, Eureka District, Nevada, by A.T. Miesch and T. B. Nolan.

The general geology of the Bullwacker mine area consists of faulted Paleozoic sediments intruded by a quartz porphyry sill. Mineralization is largely confined to limestone beds adjacent to steep crosscutting fissures (also mineralized). The orebodies are oxidized lead-silver-gold replacements consisting largely of anglesite, cerussite, plumbojarosite, and limonite, mainly after galena. The oxidized ore contains arsenic (beudantite); primary sulfides contain pyrite, galena, sphalerite, and arsenopyrite.

Samples were taken from the upper 3 or 4 inches of residual soils over the bedrock in the mine area. Lead and zinc were analyzed using dithizone and carbon tetrachloride; arsenic was determined by the Gutzeit method involving the passage of gases evolved from an acidified sample solution through lead acetate to a confined spot on mecuric chloride paper.

Anomalous values of lead, zinc, and arsenic were obtained from soil samples taken over the old orebody. Contamination from mining operations is considered to be negligible. Background values of arsenic ranged from 15 to 50 ppm; anomalous values ran as high as 150 ppm arsenic. Lead, zinc, and arsenic anomalies in the soil clearly reflect shallow bedrock mineralization; however, the zinc anomaly was more dispersed than the lead and arsenic anomalies. The lead anomaly was the strongest, probably because of the relative abundance of galena in the ore compared to sphalerite and arsenopyrite. Deep mineralization (800-1,100 feet below the surface) was not reflected in soil anomalies.

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Abstract on The Rate of Arsenic as a Pathfinder in Biogeochemical Prospecting by H. V. Warren and others.

The authors report that arsenic has been used sucessfully as an indicator for tetrahedrite mineralization, for cobalt, for tungsten, for gold, and for silver, primarily in soil sampling. However, they found that the arsenic content of different soil horizons varies greatly; also, they point out that in many areas soils are poorly developed. As a result, they turned to biogeochemical methods in using arsenic as a pathfinder element in various mineralized areas of British Columbia.

The analytical method used was based on Marsh's method of evolution of arsine, modified by Varsak and Sedivek, who react the arsine on a solution of silver dithyldithiocarbamate in pyridine (Liederman and others, 1959).

The mineralized areas consisted of lead-zinc veins, arsenic-gold deposits, and antimony-gold deposits; all the deposits contained arsenic in varying amounts. Arsenic values were enriched in the A_2 soil horizon over deposits with significant amounts of arsenic ($As \geqslant 3\%$). However, over the deposits with less arsenic, there was no significant arsenic anomaly in the soil samples. Biogeochemical sampling revealed anomalous amounts of arsenic over all the deposits.

The plant which had the greatest concentrations of arsenic was found to be the Douglas Fir; the highest arsenic content were found to be "tips" of new growth. Second-year growth, although anomalous, contained lesser amounts of arsenic.

Background values of arsenic in the ash of Douglas Fir "tips" (from unmineralized areas) generally are less than 1 ppm arsenic. The amount of arsenic contained in the various growths appears to depend upon the time at which the samples are collected; nevertheless, it is interesting to note that regardless of when samples are collected, they invariably are anomalously high in arsenic over mineralized areas that contain even small amounts of arsenic.

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