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MINERALOGY OF THE CARIBOU MASSIVE SULPHIDE DEPOSIT, BATHURST AREA, NEW BRUNSWICK

J.L. JAMBOR

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MINERALOGY OF THE CARIBOU MASSIVE SULPHIDE DEPOSIT, BATHURST AREA, NEW BRUNSWICK

by

J.L. Jambor*

ABSTRACT

The Caribou massive sulphide deposit consists of four upright, enechelon stratiform lenses of fine-grained pyritite of which 48 million tonnes grade 4.48% zinc, 1.7% lead, 0.47% copper, 58 g/t silver and 1.4 g/t gold. The main sulphide mineral is pyrite that has an average grain size of 0.017 mm and occurs predominantly as euhedral to anhedral grains and aggregates, much less commonly as polyframboidal masses. Sphalerite with up to 9 wt % Fe but probably averaging less than 6% Fe, and galena account for all primary zinc and lead, and chalcopyrite for nearly all the copper. Silver is contained mainly in tetrahedrite-group minerals and in galena; gold occurs as electrum. Magnetite is widespread and is locally a major component of the pyritite. Arsenopyrite also is widespread but averages less than 1 vol % of the pyritite. Caribou pyrite is commonly arsenian, but contents are low and arsenian grains occur erratically; the main arsenic carrier in the deposit is arsenopyrite. Marcasite and pyrrhotite are the most abundant among numerous other sulphides and sulphosalts that occur in small amounts. The major sulphides and magnetite commonly make up 70% to 90% of the volume of a sulphide body. Other than magnetite, the most abundant non-sulphides are siderite and lesser dolomite, and the most pervasive silicate is stilpnomelane. Chlorite, quartz, minnesotaite, talc and greenalite also occur in variable amounts at different sites, but the silicates generally are subordinate to carbonates.

The individual sulphide lenses all have a similar mineralogy, but proportions of the minerals and base metals differ from lens to lens. Equally pronounced variations, both parallel and normal to the stratigraphy, occur within each lens. The general mineral and metal patterns are described for each major lens, and the abundances and distributions of magnetite, arsenopyrite, and tetrahedrite-group minerals are shown for one horizontal and numerous vertical cross sections through the deposit.

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Caribou is in an area of low-grade greenschist-facies regional metamorphism; the bulk of the pyrite in the massive sulphide lenses does not seem to have undergone pervasive recrystallization. The presence of small but widespread amounts of primary marcasite indicates that crystallization temperatures of the pyritite probably did not significantly exceed 250°C, and other minerals in the assemblage point to crystallization at about 150°C.

In the supergene zone, the principal secondary sulphides are digenite and covellite. Various sulphates and oxides also are present, and much of the lead is present as anglesite. Copper sulphide enrichment occurred mainly by replacement of sphalerite and galena; incomplete replacement of sphalerite in particular seems to have been widespread, thereby reducing particle sizes and hindering liberation. Conventional processing of primary sulphides will require a grind finer than that used by other mills in the Bathurst area.

LA MINÉRALOGIE DU GISEMENT DE SULFURE MASSIF CARIBOU, RÉGION DE BATHURST, NOUVEAU-BRUNSWICK

par

J.L. Jambor*

RÉSUMÉ

Le gisement de sulfure massif Caribou est formé de quatre lentilles en échelon stratiforme de pyrite à grains fins dont 48 millions de tonnes sont composées comme suit: 4,48% zinc, 1,7% plomb, 0,47% cuivre, 58 g/t argent et 1,4 g/t or. Le principal minéral de sulfure est la pyrite dont la granulométrie moyenne est de 0,017 mm; il est présent surtout sous forme de grains et d'agrégats automorphes à allotriomorphes et sous une forme moins commune de masses polyframboidales. La sphalérite, comprenant plus de 9 wt % Fe mais probablement une moyenne de moins de 6%, et la galène renferment tout le zinc et le plomb primaires tandis que la chalcopyrite renferme la presque totalité du cuivre. L'argent est surtout présent dans les minéraux du groupe tétraédrite et dans la galène; l'or est présent dans l'électrum. La magnétite est répandue et, dans le cas présent, est une composante importante du pyritite. L'arsénopyrite est aussi répandue; cependant, elle ne représente en moyenne que 1 vol % du pyritite. La pyrite de Caribou est généralement arsénieuse, cependant les teneurs sont faibles et les grains arsénieux sont présents de façon irrégulière. L'arsénopyrite est le principal porteur de l'arsenic dans le gisement. Parmi les nombreux sulfures et sulfosels qui sont présents en petites quantités, la marcasite et la pyrrhotite sont les plus abondants. Généralement, de 70 à 90% du volume du corps sulfuré est composé de sulfures et de magnétite. A part la magnétite, les matières autres que les sulfures les plus abondantes sont la sidérite et la dolomite inférieure; le silicate le plus pénétrant est le stilpnomélane. Le chlorite, le quartz, le minnesotaite, le talc et la greenalite sont aussi retrouvés en quantités variables selon l'emplacement, cependant, les silicates sont généralement inférieurs aux carbonates.

Les lentilles de sulfure ont toutes une minéralogie semblable mais les proportions des minéraux et des métaux communs varient d'une lentille à l'autre. A l'intérieur de chacune des lentilles il y a des variations tout

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aussi prononcées, aussi bien parallèles que perpendiculaires à la stratigraphie. Les distributions minérales et métalliques sont décrites pour chacune des lentilles principales, et la quantité et la distribution des minéraux des groupes magnétite, arsénopyrite et tétraédrite sont démontrées pour une coupe horizontale et plusieurs coupes verticales à travers le gisement.

La région de Caribou est un endroit de métamorphisme du faciès de schiste vert à basse teneur; la majorité de pyrite dans les lentilles de sulfure massif ne semble pas avoir subi de recristallisation pénétrante. La présence de quantités menues mais répandues de marcasite primaire indique que les températures de cristallisation de la pyrite ne dépassent probablement pas 250°C et que les autres minéraux dans l'assemblage indique une cristallisation à environ 150°C.

Dans la zone supergène, les principaux sulfures secondaires sont la digenite et la covellite. Certains sulfates et oxydes sont aussi présents et la plupart du plomb est retrouvé sous forme d'angliesite. L'enrichissement du sulfure de cuivre est survenu surtout par le remplacement de la sphalérite et de la galène; le remplacement incomplet de la sphalérite en particulier semble être répandu ainsi réduisant la dimension des particules et empêchant la libération. Le traitement habituel des sulfures primaires demande un broyage plus fin que celui qui est effectué dans les autres usines de la région de Bathurst.

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INTRODUCTION

The Caribou massive sulphide deposit in northern New Brunswick is the largest of more than 30 unexploited Zn-Pb-Cu-Ag deposits known in the Bathurst-Newcastle area (Fig. 1). Indicated ore reserves for Caribou (Annis et al. 1978) are approximately 48 million tonnes grading 4.48% zinc, 1.7% copper, 58 g/t silver (1.7 oz/ton), and 1.4 g/t gold (0.04 oz/ton). The property, held principally by Anaconda (Canada) Co. Ltd., was equipped with a 900 t/d concentrator which was used in 1970-71 and 1973-74 to mill ore from an open pit in the supergene sulphide zone overlying the massive sulphides. About 910 000 t grading 3.4% copper, 2.6% zinc, and 1.1% lead were milled (Williams 1978). The property was maintained on a stand-by basis until November 1980, when the mill was dismantled. Efforts to achieve production from the main, unaltered massive sulphides had been thwarted by low metal recoveries; in 1981 Anaconda commenced new pilotplant tests to determine whether recoveries from the primary sulphides could be improved.

Several studies of the Caribou deposit have dealt with its general mineralogy (Cavalero 1970; Roscoe 1971; Davies 1972; Johnson 1975; Boorman et al. 1976). The initial phase of the present investigation was concerned with the distribution and mineral sources of silver in the deposit (Jambor and Laflamme 1978). The results of a more comprehensive study of the Caribou ore are presented here to provide basic documentation of the types of minerals and textural features that are characteristic of the Caribou massive sulphides. These data are part of CANMET investigations directed toward improving metal recoveries from Bathurst-area ores. Caribou is but a single unit in a broader study which will encompass numerous deposits so that mineralogical variations, and the effects of regional metamorphism on them, can be dealt with on a district scale. Field examination and sampling of Caribou, as well as of other deposits, was done in 1976, 1978, and 1979.

GENERAL GEOLOGY

The Caribou deposit consists of four steeply dipping, en-echelon stratiform lenses that have a total length of about 1500 m and widths that locally exceed 30 m. The lenses are part of the Ordovician Tetagouche Group, a sedimentaryvolcanic complex estimated by Skinner (1974) to be about 10 000 m thick. The stratigraphic succession in the Group is from basal quartzose metasediments to felsic metavolcanics overlain by mafic metavolcanic rocks (Helmstaedt 1971, 1978; Ruitenberg et al. 1977; Davies et al. 1979). The felsic metavolcanics are schistose and commonly porphyritic. Within this felsic unit are metasedimentary layers that include iron-formation in which the basal sulphide facies is present locally as massive sulphide deposits.

The Tetagouche Group has been polydeformed, with three to five episodes generally recognized (Davies et al. 1979). The first phase of regional deformation produced isoclinal folds and a schistosity, more or less parallel to lithological layering, that is the dominant deformational fabric throughout the region. The second major phase of deformation produced a penetrative crenulation cleavage with associated second folds, and the third phase in general produced large regional folds. Details of the metamorphic fabrics and structures have been discussed by Luff 1975; McBride 1976; Helmstaedt 1971, 1973a,b, 1978; Whitehead and Goodfellow 1978a,b; Davies et al. 1979; and others. There is general agreement that the major penetrative deformation occurred during the Taconic orogeny.

CARIBOU GEOLOGY

The geology of the Caribou deposit has been described by Roscoe (1971), Davies (1972), and in detail by Cavalero (1970). The stratigraphic succession in the mine area is metabasalt, graphitic argillite (graphitic schist), phyllite and massive sulphides, and meta-rhyolite schist (quartz sericite schist, quartz feldspar



Fig. 1 - General geology and principal sulphide occurrences in the Bathurst-Newcastle district, New Brunswick. Geology and chlorite-biotite subzones of regional metamorphism compiled from Helmstaedt (1973b), Irrinki (1973, 1974), Saif et al. (1978), and Plate 73-10, New Brunswick Mineral Resources Branch; potential producers are as indicated on Plate 73-10. The Caribou deposit, shown as a potential producer, also had a supergeneenriched copper zone that has been mined out.

2

augen schist). Regional metamorphism of the area has been weak: the rocks are in the chlorite sub-zone of the greenschist facies.

The configuration of the Caribou sulphide lenses is shown in Fig. 2. The lenses occur in a steep synform whose fold axis on surface strikes about N20°E and dips steeply west. The East Sulphide Body is on the eastern limb of the fold; the other bodies are on its western limb and rake to the north. The hinge zone of the synform has numerous symmetrical folds with amplitudes of up to 20 cm (Davis 1972).

The main footwall rock of the massive sulphide lenses is greenish phyllite that is underlain by dark grey to black quartz muscovite phyllite containing variable amounts of graphite. The graphitic zone is about 35 m thick, locally crumpled, and for the most part is barren to only weakly pyritiferous. Overlying the graphitic zone are phyllite and massive sulphides (Fig. 2). The phyllite is a thin-bedded metapelite, up to 25 m thick, that consists mainly of quartz and muscovite with minor chlorite. Some basal parts of the phyllite contain small amounts of fine-grained disseminated pyrite. Sulphide content increases towards the massive lenses, and laminae in which pyrite predominate are common in the upper half of the phyllite. Although phyllite forms the footwall of most of the massive sulphide zone. parts of the North and South sulphide lenses abut on a chlorite-pyrite unit (Fig. 2). Beneath the North Sulphide Body, this unit is heterogeneous, with parts muscovite-rich and only weakly chloritic. Underlying the South Sulphide Body is a discoid lens reported by Cavalero (1970) to consist of massive chlorite up to 3 m thick that contains cross-cutting chalcopyrite veinlets as well as numerous concordant layers of nearly massive chalcopyrite up to 0.6 m thick. A massive chlorite zone of this thickness beneath the South Body was not detected in the present study.

The massive sulphide lenses are overlain by quartzose K-feldspar muscovite schists and partly massive, pinkish "rhyolite porphyry" that are metamorphosed felsic tuffs. These are chlorite-poor, contain negligible pyrite, and are in sharp contact with the massive sulphide lenses.

GENERAL MINERALOGY

Most of the mineralogical study of Caribou was focused on polished section examination of drill cores from horizontal and vertical cross sections through the now-upright sulphide lenses. The horizontal section is the 6200 level in mine terminology and is 366 m (1200 ft) above sea level. As all Anaconda Caribou maps, drill-core lengths, logs and assay intervals were recorded in feet, and assays were in troy oz/ton, these units have been retained here. The descriptions that follow deal principally with hypogene minerals; other minerals are discussed in the section on supergene alteration.

The Caribou massive sulphide bodies consist largely of fine-grained pyrite (Fig. 3.4). Galena, iron-bearing sphalerite, and chalcopyrite account for all but traces of the lead, zinc, and copper in the deposit, and thus the proportions of these minerals are accurately reflected in the previously cited ore-reserve figures. Magnetite is widespread and locally abundant (Fig. 5). Also widespread are arsenopyrite, tetrahedritetennantite, and marcasite, but each makes up less than 1% of the massive sulphide lenses. Several other sulphides and native elements occur in relatively minute amounts; the most abundant or important of these are electrum, bournonite, and pyrrhotite. The major sulphides - pyrite, sphalerite, galena, chalcopyrite - occur in finegrained masses that, including magnetite, make up 70% to 90% of the volume of a sulphide body. This highly sulphidic rock is referred to as pyritite (Schermerhorn 1970).

The upper contact of each of the main pyritite bodies is sharp, and the stratigraphically overlying rocks are barren or contain insignificantly minute amounts of disseminated sulphides. Exceptions to this relationship are uncommon, but do occur, particularly at the extremities of lenses where lateral pinchout takes place by gradual diminution of multiple thin pyritite lenses inter-tongued with metasediment that contains variable amounts of disseminated pyrite. The characteristically abrupt appearance of barren rocks above the major pyrite lenses



Fig. 2 - Configuration of the major massive sulphide bodies of the Caribou deposit on the 6200 level, which is 366 m (1200 ft) above sea level and about 152 m (500 ft) below surface. From Anaconda Canada Exploration Limited.

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Fig. 3 - Typical layered structure in Caribou pyritite: sphalerite-rich layers (grey, sp) with variable amounts of pyrite inclusions are gradational to pyriterich layers (white, py) containing variable amounts of sphalerite. Sample from drillhole 56, hanging-wall zone of Northwest Body. Reflected light; air; bar scale 0.2 mm. S

Fig. 4 - Layered structure of Caribou pyritite: sphalerite layer (grey, sp) containing disseminated, partly embayed pyrite crystals (white) is flanked by pyriterich layers containing interstitial sphalerite and abundant silicate-carbonate minerals (black). Sample is from the Caribou western open pit; cracks in sphalerite are a network of supergene copper sulphides. Reflected light; air; same magnification as Fig. 3.

Fig. 5 - Layered structure in Caribou pyritite: magnetite-rich layer (medium grey, m) with abundant interstitial sphalerite (darker grey, sp) and associated pyrite (white). Drillhole 62-1, hanging-wall zone of South Sulphide Body. Reflected light; air; bar scale 0.1 mm.

contrasts markedly with that beneath the lenses: footwall rocks typically contain a variable abundance of disseminated sulphides that increases toward the pyritite and locally obscures the

PYRITE

contact.

Based on microscopical measurements of pyrite in 248 acid-etched polished sections from 25 drillholes, the average grain size of pyrite at Caribou is 0.017(4) mm. In pyritite from a hole bored across the stratigraphic layering, the average pyrite grain size in the total thickness of sulphides can be as low as 0.01 mm or as coarse as 0.03 mm. However, none of the individual major sulphide bodies has been found to be distinctly coarser grained than another. Substantial local variations which do occur generally reflect the predominance of a specific pyrite form such as polyframboids (Fig. 6-8) at a particular site.

Pyrite in all of the sulphide bodies varies from euhedral cubes to anhedral grains and masses. Colloform pyrite is commonly present but is quantitatively much less abundant than framboids and polyframboidal masses. All of these pyrite textures occur in each of the Caribou lenses but some general associations are evident. For example, the pyritite in areas with high-grade Zn + Pb is usually laminated and much of the pyrite is typically present as euhedral cubes in the sphalerite-rich layers. The cubes vary from scattered to closely crowded and are usually partly embayed by the sphalerite. Pyrite-sphalerite atoll textures occur in some samples, and rounded pyrite crystals in many.

As the amount of sphalerite in the pyritite decreases, which is the commonest trend in the progression from hanging wall to footwall, the proportion of pyrite generally increases and euhedra give way to anhedral masses or subhedral aggregates with crystal faces evident only at interstices. The other sulphides occur both in the interstices and in variable amounts throughout the coherent pyrite masses; silicate and carbonate minerals usually are concentrated among the pyrite voids. Massive pyritite containing only low percentages of base-metal and non-sulphide minerals is found typically in the stratigraphically lower two-thirds of a sulphide lens. Individual specimens in which pyrite makes up at least 90% of the mineral content are not unusual; nevertheless, proportionately few specimens are megascopically devoid of all indications of sulphide layering.

Lamination and coarser layering of the Caribou pyritite is its dominant structural feature. The so-called massive sulphides at Caribou, as in many stratiform bodies of this type throughout the world, consist of multiple thin layers of sulphides piled one atop another, with local intercalations of sedimentary rocks lower in sul-The layering reflects changes in the phides. proportions of the minerals, changes in their textures, or most usually a combination of both. Layering also is made apparent, or enhanced, by changes in grain sizes alone - especially for pyrite. All of the major and minor sulphide minerals, as well as magnetite and the silicates, have a distinct tendency to be concentrated in lavers. Changes in texture are almost always accompanied by changes in grain size, though the opposite is not necessarily true.

As discussed in a later section, Caribou pyrite is commonly arsenian, but the arsenian grains occur erratically. The detection of numerous grains of nickel-free, cobaltoan pyrite at Caribou is in accord with previous indications that Co/Ni in Bathurst-area pyritites is high (Sutherland 1967; Bralia et al. 1979).

SPHALERITE

Sphalerite at Caribou shows little variation in internal texture as revealed by etching. Optically homogeneous sphalerite masses almost always consist of a mosaic of anhedral grains, each containing lamellar twinning. Most massive sphalerite occurs as laminae in pyritite. Etching of these laminae, which invariably contain disseminated pyrite, reveals that most sphalerite is slightly coarser than the associated pyrite, and in some cases the average grain size of sphalerite is twice that of pyrite. In massive pyritite with a low zinc content, much of the sphalerite is in interstices where the pyrite is less tightly



Fig. 6 - A layer of pyrite crystals and associated dark interstitial sphalerite amidst a tightly packed, extremely fine-grained polyframboidal pyrite mass typical of the type of framboidal pyrite that occurs in the Caribou massive sulphides. Drillhole 58, at the hanging-wall contact of the Northwest Body. Reflected light; oil immersion; lightly acid-etched; bar scale 0.10 mm.

Fig. 7 - Aggregate of individual framboids and pyrite crystals, each surrounded by growth zones or by colloform pyrite. Framboids of this type are common but much less abundant than the compact framboidal masses shown in Fig. 6. Note also the contrast in grain sizes in that Figures 6 and 7 are at the same magnification. Drillhole 50 at 937 ft (first lens intersected, Fig. 29).

Fig. 8 - Same sample as Fig. 7 but with enlargement to show the progression from framboids to overgrowths, and to anhedral interstitial pyrite. Reflected light, oil immersion; lightly acid-etched; bar scale 0.01 mm.

packed. Thus high-grade Zn-Pb pyritite generally has a fairly large proportion of its sphalerite in laminar masses, whereas in low-grade pyritite the bulk of the sphalerite can vary from easily liberated to tightly locked in pyrite.

Footwall rocks beneath the Caribou massive sulphide lenses contain abundant disseminated sulphides, principally pyrite. The bulk of the associated sphalerite in these rocks is not widely dispersed as minute grains, but instead is concentrated in microscopically lensoid masses that occur discontinuously along the sedimentary layers.

Microprobe analyses of 45 selected grains and several large areas of Caribou sphalerite as reported by Johnson (1975) are given in Table 1. The specific source of the analyzed material is not known with certainty, but it is thought that most of the analyses are from sphalerite grains in a polished section of copper concentrate. The restricted range in iron content of 6.31 to 8.04 wt % reported by Johnson (1975) was extended considerably by Boorman et al. (1976), who obtained 0.99(6) to 7.74(7) wt % Fe from 99 microprobe analyses of sphalerite. Numerous additional determinations for the present study (Tables 1,2) have expanded the range to 0.1 and 9.0 wt % Fe. None of the major sulphide bodies seems to have sphalerite with a distinctive or characteristic , iron content. However, the indications from the new analyses are that the average iron content of Caribou sphalerite is less than 6 wt % rather than in excess of the 7 wt % that could have been inferred from the results reported by Johnson (1975). The suspicion that iron-rich sphalerite selectively reported to the Anaconda copper concentrates seems to be confirmed by additional analyses by D.C. Harris (Table 1), who independently obtained another Caribou copper concentrate via Noranda Research Centre, Point Claire, Quebec.

The few analyses for cadmium and manganese in Caribou sphalerite indicate low abundances for these elements (Table 1). Boorman (1975) reported that a zinc concentrate from Caribou was found to contain 0.005 wt % indium, and a sphalerite concentrate prepared in the laboratory from ore specimens gave 0.002 wt % indium. Only a few microprobe determinations for this element have been done (Table 1); although the analyses are not precise because of the low concentrations and short counting times, the results seem to confirm that indium is present, apparently erratically and in very small amounts.

GALENA

Galena is closely associated with sphalerite but is less abundant, is finer grained than either pyrite or sphalerite, and is paragenetically younger than sphalerite. The lower abundance and slightly later crystallization seem to have placed galena in a spatially subordinate position: the mineral rarely forms in concentrated layers as does sphalerite, but instead occurs mainly as patchy replacements of the sphalerite layers. Occasionally - especially in hanging-wall material - sphalerite and galena are associated in an emulsion-type texture (Fig. 9,10) in which galena is always the less abundant phase.

Galena is common as patches, blebs, and veinlets in pyrite, and is abundant as irregular grains associated with sphalerite that was deposited in interstices among pyrite grains. An indication of the relatively fine grain size of galena is that few grains of it reach the dimensions common for unetched sphalerite; moreover, small irregular blebs and patches of galena occur frequently in sphalerite, but not vice versa. Veining and partial irregular replacement of pyrite is much more common with galena than with sphalerite.

The composition of Caribou galena was investigated by Jambor and Laflamme (1978), who found that individual grains contained up to 0.11 wt % Sb, and up to 0.66 wt % Ag and 1.58 wt % Bi. Solid-solution Ag and Bi show a strong positive correlation whereas Sb is erratic.

CHALCOPYRITE

Although it is the least abundant of the economically important major sulphides, chalcopyrite is nevertheless a significant component of the pyritite, especially that of the Northwest Body wherein average Cu grade exceeds 0.7%.

		·	wt %, average and					
	No. of	Fe	Cd	Mn	In	Source		Ref.
Sample number	grains							
	>45	7.17(6.31-8.04)	0.10	0.11		Cu concentr	ate?	1
Cu-5-E	8	6.8 (6.5-7.5)	0.14(.1416)	0.08(.0610)		Cu concentr	ate	2
Cu-con	24	7.0 (4.0-9.0)				Cu concentr	ate	3
DDH 34-540'	8	4.64(4.4-4.8)				Northwest B	ody	4
-550'	7	6.36(6.1-6.5)						4
DDH 56-1070'	5	5.60(5.3-5.7)						4
-1143'	8	6.43(5.9-7.7)						4
DDH 74-1630'	8	1.15(1.0-1.4)						4
-1640'	10	5.03(3.7-8.0)						5
-1650'	10	1.01(0.8-1.3)						5
-1660'	10	7.32(6.4-8.9)						5,6
-1670'	10	7.57(7.0-8.3)						5,6
-1680'	10	2.27(2.0-2.7)						5
DDH 54-617'	8	4.86(4.1-5.6)		<u> </u>		North Body		4
-621'	6	3.54(3.4-3.7)						
6200-2	3	6.37(6.2-6.5)				South Body,	HW	4
	11	6.80(6.2-7.4)	0.14(.0923)	0.08(.0512)			HW	3
	4	5.12(5.0-5.4)					middle	4
	8	5.63(5.4-5.9)					FW	4
	12	5.23(4.1-6.6)	0.26(.1931)	0.01(.0003)	0.02(.0005)		FW	3
DDH 62-4-3'	4	4.03(4.0-4.1)	0.12(.0914)	0.23(.1925)	0.00			3
-8'	4	5.95(5.8-6.1)	0.12(.0917)	0.04(.0007)	0.00			3
-21'	7	1.52(0.7-2.3)	0.26(.0159)	0.01(.0003)	0.02(.0004)			3

Table 1 - Microprobe analyses of Caribou sphalerite

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Table 1 (cont'd)

		•	wt %, average and	l (range)			
	No. of	Fe	Cd	Mn	In	Source	Ref.
Sample number	grains		<u></u>				
DDH 12-277'	5	6.48(6.1-7.9)					4
DDH 13-509'	10	3.00(1.5-3.6)				East Body	5
-511'	7	4.53(4.0-5.1)					4
-518'	10	2.71(2.3-3.4)	· .				5
-5241	10	6.05(5.3-7.6)					5
-532'	8	6.39(6.1-7.0)					4
-540	8	3.99(3.7-4.8)					4
-5471	10	4.36(3.8-4.7)					5
-5521	10	4.18(2.3-5.3)					5
DDH 62-6-55'	8	1.06(0.1-1.6)	0.13(.0418)	0.12(.0026)			.3

1. Johnson (1975)

2. T.T. Chen, unpublished analyses, 1976

3. D.C. Harris, unpublished analyses, 1981

4. Boorman et al. (1976)

5. This study, based on analyses of 10 grains, or more than 10, spaced at odd intervals normal to sulphide layering

6. Pyrrhotite-bearing assemblage; see also Table 2

.

			wt %			
Area	Zn	Fe	Cd	S	Total	Association
1	59.6	6.7	0.1	32.9	99.3	With pyrrhotite and magnetite inclusions
2a	59.0	7.4	0.1	33.2	99.7	Pyrrhotite and pyrite
26	59.0	7.5	0.1	33.2	99.8	Pyrrhotite and magnetite
20	58.9	8.1	0.1	33.3	100.4	Pyrrhotite and pyrite
2d	58.4	7.9	0.1	32.9	99.3	Inclusion in pyrite
3	58.6	7.5	0.1	33.5	99.7	Pyrite only
4	58.3	8.2	0.1	33.5	100.1	Pyrrhotite only
5	58.3	7.9	0.1	33.5	99.8	Pyrite only
6	58.2	8.0	0.1	33.5	99.8	Pyrrhotite, pyrite, magnetite
7	57.7	8.5	0.1	33.2	99.5	Pyrrhotite, magnetite

Table 2 - Microprobe analyses of sphalerite in pyrrhotite-bearing assemblage, drillhole 74 at 1663 ft (Fig. 20)

Mn less than 0.02 wt \$ (limit of detection) in all analyses

Area 1: Zn range 58.8-60.2; Fe 6.4-6.9; Cd, S constant Area 2a: Zn range 58.4-59.6; Fe 7.2-7.8; Cd, S constant



Fig. 9 - Emulsion-type texture of fine-grained galena (white) in sphalerite layer with rounded grains of pyrite (py). Drillhole 62-4, hanging-wall contact of South Body. Reflected light, oil immersion; bar scale 0.1 mm.



Fig. 10 - Enlargement of part of Fig. 9, showing the fineness of the galena-sphalerite intergrowth. Reflection light, oil immersion; bar scale 0.01 mm.

Although the other Caribou lenses have lower copper contents, assay intervals with more than 5% Cu occur locally.

In chalcopyrite-rich rocks most of the mineral occurs as masses that have extensively replaced pyrite so that only residual inclusions of it remain. As chalcopyrite abundance declines, the initial trend is to have chalcopyrite veins as an irregular network along pyrite grain boundaries, and then to have only patches and minute blebs of chalcopyrite both in the pyrite and among its interstices. This last, dispersed type of occurrence, is typical for chalcopyrite throughout most of the deposit. Although chalcopyrite is also commonly in irregular contact with galena and sphalerite, the affinity for association with pyrite is pronounced. Dispersed chalcopyrite grains, which are seen best on etched polished surfaces, are very frequently less than 5 µm in diameter.

Blebs of "exsolution-type" chalcopyrite in sphalerite (Fig. 11) are widespread at Caribou. Although well-defined rows of chalcopyrite blebs in sphalerite do occur, this type of association is uncommon relative to the typical habit in which chalcopyrite is present as a fine-grained cloud of random blebs. Thus the texture is more appropriately referred to as an emulsion-type rather than an exsolution.

Emulsion-type chalcopyrite is nearly always absent from sphalerite that occurs as the predominant phase in laminae; rather, the association is mainly with sphalerite that crystallized in voids among pyrite. The chalcopyrite clouds are usually not evenly or centrally distributed in such sphalerite, but instead are concentrated in areas of sphalerite-pyrite contact.

In cores from some drillholes, emulsiontype chalcopyrite is widespread through the total thickness of pyritite. However, sphalerite in core from an adjacent drillhole can be almost wholly bleb-free; no systematic distribution was detected either within a sulphide body, or from body to body.

Additional study of the size and distribution of emulsion chalcopyrite at Caribou was done by M.R. Hughson of CANMET. Using quantita-



tion of chalcopyrite blebs in Caribou sphalerite. Drillhole 62-1, disseminated sulphate zone at footwall of South Body. Reflected light, oil immersion; bar scale 0.01 mm.

tive image-analysis methods and drill-cores from the 6200 level of the South and East Bodies, Hughson found that only about 0.5 wt % of total sphalerite in the South Body, and 1.6 wt % in the East Body, contained emulsion chalcopyrite. Blebs in sphalerite from the South Body are smaller but more numerous than those from the East Body. The above percentages for the amount of emulsion-bearing sphalerite seem low in comparison with microscopic observations, but the difference can be explained as follows: (a) sphalerite-rich laminae generally lack emulsion chalcopyrite but they are a significant part of total sphalerite area; (b) in image analysis only the part containing blebs, rather than the area of the whole sphalerite grain, is deemed to be emulsion-bearing; however, as has been mentioned, the blebs commonly are asymmetrically distributed within individual sphalerite grains.

MAGNETITE

Magnetite occurs mainly as disseminated euhedral to anhedral grains in pyrite and in sphalerite-rich laminae (Fig. 5), as coarse masses which form an integral part of the pyritite layering, and less abundantly as graphic or myrmekitic intergrowths with pyrite. Some of the coarse masses may be compact crystal aggregates as suggested by the presence of numerous crystal facets at the exterior boundaries. The graphic to myrmekitic intergrowths occur in fine-grained, typical Caribou pyritite.

Pyrite inclusions in magnetite are usually irregular in outline, but a few framboidal inclusions also have been observed. In several places magnetite masses contain spheres of greenalite. Magnetite masses commonly are cut by veinlets of chalcopyrite, sphalerite, or nonsulphide minerals, especially siderite.

The amount and distribution of magnetite as determined from the polished sections were found to be exceedingly variable, not only within a single sulphide lens, but even in adjacent drill-core samples. As these results led to doubts about the validity of the magnetite distribution patterns obtained by microscopy, all the drill-cores were checked with a hand magnet in a later field season. The field work provided additional fill-in data, but otherwise the results of the two approaches correlated exceedingly well. Magnetite distributions are shown in the figures which accompany descriptions, given farther below, of the individual sulphide bodies. A notable feature is that magnetite is strictly confined within pyritite and does not occur in footwall rocks even if they are extremely rich in disseminated sulphides.

Growth zoning of magnetite was detected in a few polished sections etched with HI. Although the composition of the mineral was not investigated in detail, several microprobe analyses of randomly selected grains did not detect the presence of minor elements.

ARSENOPYRITE

Arsenopyrite is widespread at Caribou and fairly commonly makes up 0.5 to 1.0 vol % of a

polished section; however, only rarely are values in the 5 to 7% range. Distribution of the mineral in the individual polished sections is usually uneven, with the majority of grains concentrated along one or more sulphide layers.

Arsenopyrite throughout the deposit occurs as single disseminated grains and as clusters of grains which typically are euhedral to subhedral and approximate the size range of associated pyrite. Less abundant, but common nevertheless, are groups of tiny anhedral grains that average less than 0.5 µm in diameter; frequently associated with these groups is slightly coarser euhedral arsenopyrite. Veinlets of arsenopyrite have not been observed. Etching shows that most Caribou arsenopyrite is growth-zoned, and in a few cases the mineral occurs as overgrowths on pyrite.

Microprobe analyses of 10 arsenopyrite areas in 6 samples from pyrite-bearing assemblages of the South and East Sulphide Bodies gave a range from 29.3 to 33.0 atomic % As and an average of 31.0 atomic % As. Kretschmar and Scott (1976) reported that a sample of Caribou arsenopyrite was found to contain 29.1 atomic % As.

Numerous grains of arsenopyrite from a pyrrhotite-bearing assemblage at Caribou were analyzed by microprobe and all except one were found to have variable Fe, As, and S contents. All grains contain variable Co, up to a maximum of 3.2 wt %, and all contain Sb which is of constant abundance in some grains and variable in others. The average Sb content for individual grains ranges from 0.5 to 1.3 wt %.

TETRAHEDRITE-GROUP MINERALS

The arsenic, antimony, and silver-antimony members of the tetrahedrite group are tennantite, tetrahedrite, and freibergite, respectively. One or more members of the group occurs in small amounts in all of the Caribou lenses, principally as disseminated grains that are always anhedral and almost invariably free of complex intergrowths. Where abundant, tetrahedrite and tennantite commonly are concentrated in specific layers in the pyritite. Minor amounts of tetrahedrite also occur in veinlets that cross-cut the sulphide layers. Microprobe analyses indicate that veinlet and disseminated grains generally have similar compositions.

Numerous microprobe analyses of tetrahedrite-group minerals were given by Jambor and Laflamme (1978), who concluded that these minerals account for about 75% of the silver content of the East Sulphide Body. In other Caribou lenses much of the silver is contained in argentian galena and only a minor part is attributed to the tetrahedrite group. A few microprobe analyses of the group are given in Tables 3 and 4; these results, as well as distribution patterns for the group, are dealt with in the descriptions of the individual sulphide bodies.

MARCASITE

Marcasite is common as a minor constituent in all of the sulphide bodies. The mineral occurs in two principal forms: (a) as fine-grained groups up to 0.3 mm in average dimension; (b) as disseminated grains which appear to be an integral part of the primary sulphide layering.

Type (a) marcasite consists of aggregates that commonly have a parallel, filiform array. The aggregates are associated mainly with silicates and carbonates in interstices among pyrite and magnetite. Less commonly, marcasite of this type forms veinlets in which some galena, sphalerite, and chalcopyrite occur occasionally, but are always subordinate to non-sulphide minerals. The

<u></u>	Drillhole				W	t %			
	& footage	Cu	Ag	Fe	Zn	As	Sb	S	Total
Northwest Body	62-20-441	35.3	3.4	2.6	6.7	3.5	23.4	26.3	101.2
	76-3148'*	33.3	5.7	5.8	2.6	26.8	0.4	25.2	99.8
								1	
North Body	62-20-10'	34.9	4.4	3.8	3.4	0.3	28.4	24.5	99.7
	-21,+	38.8	1.4	1.1	5.4	4.2	23.3	25.8	100.0
	62-16-103'+		1.3-3.3						
	62-15-199'	36.9	0.1	1.3	7.1	0.9	28.3	25.6	100.2
	62-18-0'	37.2	2.1	1.3	6.8	4.0	23.9	25.5	100.8
	62- 9-103	37.6	0.8	4.2	3.6	1.5	27.3	25.0	100.0
	62-17-182'	41.5	0.0	1.7	7.4	16.9	5.1	28.0	100.6
	62-17-191'	see Ta	ble 4						
	62- 4-47'	42.2	0.0	2.7	7.2	19.2	0.8	28.6	100.7
	62- 4-50'	42.5	0.0	2.0	7.0	19.4	0.0	29.1	100.0
South Body	62-12-55***	37.8	2.0	1.2	7.0	22.7	3.9	25.5	100.1
	62-17-111'	34.3	4.2	3.9	3.9	27.3	1.1	24.9	99.6
	-115'	35.7	3.6	3.6	4.3	26.2	1.0	25.2	99.6
East Body	62-14-487'	33.3	7.1	3.8	3.0	28.3	0.2	24.1	99.8

Table 3 - Microprobe analyses of tetrahedrite-group minerals

*Northwest or North Body

**Drillhole 62-12 was collared at the same site as 62-13 (Fig. 27) but was drilled at +21°
and on a slightly more northward bearing; projected on the 6200 level plan, 62-12 falls
between 62-13 and 62-11 (Fig. 22 and 27)

⁺Jambor and Laflamme (1978)

	<u>Area</u>	L, wt %	Area 2	, wt %
	average	range	average	range
Cu	37.5	37.0-38.5	39.1	37.9-39.5
Ag	0.0		0.0	
Fe	1.6	1.3-2.2	2.6	2.3-3.0
Zn	7.7	7.5-7.8	6.7	6.2-7.3
As	9.7	8.1-12.2	13.7	12.5-14.8
Bi	14.7	12.0-17.9	11.8	9.6-14.9
Sb	5.0	3.5-6.5	1.0	0.2-1.7
s	24.7	24.2-25.1	25.8	25.5-26.0
	100.9		100.7	

Table 4 - Microprobe analyses of bismuthian tennanite, drillhole 62-17, footage 191, North Sulphide Body

veinlets cut across the massive sulphide layers. Type (a) marcasite occurs most abundantly where there is evidence of disruption and deposition in discordant structures such as fault or breccia zones. Type (b) marcasite, on the other hand, is probably more abundant but is much less conspicuous because it occurs as minute grains in undisturbed pyritite. The grains occasionally occur tightly interlocked with pyrite, but most are closely associated with the main Zn-Pb-Cu sulphides, all of which, including marcasite, preceded the crystallizaton of primary carbonates.

PYRRHOTITE

Sparse blebs of pyrrhotite occur sporadically in pyrite at Caribou and in most other pyritites in the Bathurst camp. The blebs, which are usually about 5 µm or less in diameter, also have been observed, though rarely, in magnetite, arsenopyrite, and sphalerite. At several Caribou fault zones, pyrite has been recrystallized to coarse interlocking anhedral grains in which blebs and patches of pyrrhotite are more numerous and coarser than the pyrrhotite in undisturbed rocks.

Although widespread, bleb pyrrhotite at Caribou is no more than a trace mineral. More abundant, but of restricted occurrence, is pyrrhotite that is closely associated with the major base metal sulphides; all are of similar grain size and occupy interstices among pyrite in finegrained, undisturbed pyritite. Pyrrhotite of this type was observed in only a few polished sections, and in most the abundance is less than 0.3%. However, a 5-m interval near the footwall of the main lens intersected in drillhole 74 (Fig. 20) contains intermittent pyrrhotite-rich layers which make up to 7 vol % of individual polished sections. Pyrite grain sizes in this interval average about 0.02 mm, and pyrrhotite averages less than 0.01 mm. The textures of pyrite and other minerals are the same as those in assesmblages where pyrrhotite is absent.

Etching with HI, and microprobe analyses, indicate that most of the pyrrhotite grains from drillhole 74 are intergrowths of hexagonal and monoclinic phases; scattered among these are similar but apparently homogeneous grains of the monoclinic phase.

BOURNONITE AND OTHER SULPHOSALTS

Bournonite occurs in negligibly small amounts in all of the Caribou sulphide lenses, but seems to be slightly more common in the North and Northwest Bodies. Nearly all of the mineral is spatially associated with tetrahedrite, and the two also seem to be temporally related. Microprobe analyses of several bournonite grains consistently gave pure end-member compositions.

Trace amounts of several other sulphosalts occur at Caribou. A mineral with the composition and optical properties of polybasite was found in one sample from the South Sulphide Body (Jambor and Laflamme 1978). Stephanite was detected in Caribou copper concentrates (T.T. Chen, oral communication 1978), and luzonite is present in the supergene zone. An unidentified Pb-Bi sulphosalt occurs in core from drillhole 34 at 600 ft (Northwest Sulphide Body). The grains are too small for X-ray examination. A representative microprobe analysis is Pb 33.5, Cu 4.9, Bi 41.8, Sb 3.3, S 17.5, total 101.0 wt %; this and other analyses approximate $Pb_{16}Cu_8(Bi,Sb)_{22}S_{53}$. Meneghinite, ideally $Pb_{13}CuSb_7S_{24}$, has been detected in Caribou copper concentrates. A microprobe analysis of one grain gave Pb 60.4, Cu 2.3, Sb 19.1, S 17.7, total 99.5 wt %.

BORNITE

Bornite is extremely rare at Caribou; for the most part only a few randomly distributed, minute specks of the mineral were seen. The sole exception to this paucity is at the southern end of the South Sulphide Body. The footwall part of the pyritite at this site is extremely rich in chalcopyrite. Numerous bornite grains, nearly all less than 5 μ m in diameter, are scattered in chalcopyrite or occur at its grain boundaries as rims and minute veinlets. Some of the bornite is surrounded by sphalerite saturated with almost submicroscopic inclusions and rods of chalcopyrite; much of the bornite has the same inclusion-riddled texture.

The bornite-bearing pyritite appears to have suffered micro-brecciation and disturbance which produced a finely granular texture, presumably as a result of fault movement. The presence of bornite is interpreted to reflect readjustment of the sulphide assemblage to conditions different from those of primary deposition.

COBALTITE

Cobaltite was found in only a few polished sections, mainly as rare isolated grains in pyrite. However, cobaltite was found more abundantly in two polished sections from separate drillholes, both from the footwall disseminated zone. The mineral is present as sparsely disseminated subhedral grains, and abundantly as anhedral grains and sharp-edged fragments which are up to 0.25 mm across and are associated with pyrite of similar form and size. Both minerals have sustained in situ fracturing, with subsequent infilling and partial replacement by chalcopyrite.

Microprobe studies indicate that the cobaltite contains low but variable amounts of iron. Analyses of two large grains gave 4.7 and 3.4 wt % Fe, and compositions corresponding to:

(Co_{0.87}Fe_{0.14})As_{1.00}S_{1.00}

and

ELECTRUM

Caribou ore reserves include 0.04 oz Au/t (1.4 g/t). Gold values, in assay data available to the writer, reach a maximum of about 0.3 oz/t (10.3 g/t) over normal assay intervals of 3 to 5 feet. A positive correlation between gold content and Zn + Pb was reported by Mercer and Crocket (1976), but this relationship is not general.

All of the gold content at Caribou is concluded to be present as electrum. The East Sulphide Body has substantially below-average gold contents and is the only lens in which electrum was not observed in the polished-section studies. The East Body also has the highest silver content at Caribou, and thus has the lowest Au:Ag ratio.

Most grains of electrum at Caribou are 4 to $7\ \mu\text{m}$ in diameter, with the maximum about 35 μm . The grains occur isolated in galena and chalcopyrite, or along pyrite grain boundaries.

Microprobe analyses of several electrum grains are given in Table 5. Although the analyses are too few to establish firm trends, the results seem to indicate that Au:Ag in electrum is high in the two northern sulphide bodies and is variably high to low in the South Body.

	DDH	DDH	CW-77	DDH	DDH	6200-2	620	00-2 X-Cut [†]	
	32-276*	54-625 North	**		<u>50-1028</u> South	South	South Body		
	Body	Body _	av.(range)	Body	Body	Body	Grain 2	Grain 3	Grain 4
wt % Ag	30.8	33.8	42.1(41.4-42.5)	32.4	34.0	49.99	50.9	53.5-80.5	51.0
Au	69.7	64.7	<u>57.4(56.5-58.2)</u>	68.9	65.2	45.45	47.8	45.4-17.5	47.5
Total	98.5	98.5	99.5	101.3	99.2	98.44	98.7		98.5
at. % Ag	46	49	57	45	49	65	66	68-89	66
at. % Au	54	51	43	55	51	35	34	32-11	34

Table 5 - Microprobe analyses of Caribou electrum

*Drillhole number and footage

**Surface sample, Northwest or North Body; range is for 3 grains

***6200 level, No. 2 cross-cut; after Johnson (1975)

[†]Unpublished analyses by T.T. Chen, 1975

NATIVE Bi, Sb, AND Fe

Native bismuth was found in a few polished sections, mainly from the East Sulphide Body. The grains are up to 40 μ m across, but most are much smaller blebs and worms intergrown with galena and unidentified sulphosalts.

Native antimony was found in several polished sections. The largest antimony grain forms a polycrystalline narrow strip about 40 μ m in length, and is along pyrite grain boundaries. In most occurrences the antimony is present in galena or in chalcopyrite.

The presence of native iron at Caribou was reported by Chen (1978), who detected a grain of the mineral in a polished section of massive sulphides. A subsequent attempt to locate the grain for re-examination was unsuccessful (T.T. Chen, oral communication, 1980).

DIGENITE AND COVELLITE

These two copper sulphides are so closely associated at Caribou that only rarely does one occur without the other. The minerals are abundant only in the supergene-enriched, open-pit area. Some of the covellite has the optical properties of the blaubleibender type, and microprobe analyses are in agreement with this identification. Most of the material examined in this study consists of drill cores and in these the amounts of digenite and covellite are negligibly small. Occurrences are mainly at or near fault zones, where the minerals are present on chalcopyrite chiefly as veinlets and as rinds, both usually about 5 μ m wide.

OTHER SULPHIDES

Acanthite, Ag₂S, was detected by microprobe analyses of Caribou copper concentrates (T.T. Chen, oral communication 1978). Traces of mackinawite, Fe_oS₈, were reported by Johnson (1975) to be present only with chalcopyrite inclusions in pyrite. The mackinawite apparently occurs as irregular grains in the chalcopyrite, and as partial rims on it. Stannite, Cu_oFeSnS_n, has been detected in Caribou copper concentrates obtained from Noranda Research Centre, Point Claire, Quebec. An iron-copper sulphide which is probably the hydroxy-sulphide valeriite occurs associated with pyrrhotite inclusions in coarsegrained pyrite in a sample from the western open pit.

HEMATITE

Aside from hematite which has formed by superficial oxidation in the open pits and in fault zones, megascopically conspicuous hematite occurs in late-stage veinlets that cut pyritite at high angles to the sulphide layering. In the veinlets, which are up to a centimetre wide, siderite margins are overlain by well-crystallized hematite and a medial layer of quartz. The same assemblage occurs microscopically as non-veinlet, irregular patches integrated with the sulphide layering. Both the veinlets and patches are paragenetically later than the main pyritite sulphides and have only a random association with magnetite.

In a few polished sections, hematite alone occurs at the boundaries of magnetite and the above hematite assemblage is not evident. In some cases there has been minor replacement of the magnetite, but in others hematite patches abut on magnetite euhedra without affect. However, this hematite too appears to be postsulphide.

A sample, from the west pit, containing the siderite-hematite-quartz assemblage shows the succession siderite (wall) >hematite+marcasite >sphalerite+pyrite>quartz (centre). Microprobe analyses of 20 grains of the sphalerite gave Fe 6.4 to 9.6 wt %, Zn 55.8 to 59.4 wt %, and an average composition of Fe 7.7, Zn 58.6, and S 33.4 for a total of 99.7 wt %.

RUTILE

Rutile grains occur only sporadically in unmineralized sediments but are numerous in footwall beds containing disseminated sulphides, and in silicate-rich layers within pyritite. Most of the rutile occurs as prisms, 30 to 40 μ m long; grains up to 150 μ m in length have been seen but are extremely scarce. The prisms commonly contain numerous, minute non-sulphide inclusions.

Most rutile prisms are elongated parallel to the layering of the pyritite and associated sediments. The distinctive habit, light grey colour in reflected light, and pronounced internal reflection make the rutile conspicuous in microscopic studies; nevertheless, the mineral forms only a minute fraction of a per cent of the mineralized zone. Rutile is commonly a convenient bedding marker because the prisms frequently are concentrated along specific laminae.

ILMENITE

Ilmenite was observed in several polished sections, nearly always as grains morphologically identical to those of rutile. A few prisms consist of both minerals.

All ilmenite occurrences are in the highsulphide disseminated zone of the footwall, and in pyritite. Microprobe analyses of ilmenite in one polished section showed that the mineral contained about 1.3 wt % MnO₂ whereas associated rutile grains had no Mn.

CALCIUM SULPHATES

In drillhole 74 at 1634 ft (Fig. 20) a calcium sulphate veinlet, 2 1/2 cm wide, cuts massive sulphides. Along each of the veinlet walls is a 1 mm width of massive siderite capped with crustiform siderite, some of which has inclusions of anhydrite, CaSO₁₁. Massive anhydrite makes up most of the veinlet, but near one wall, and in places protruding into the anhydrite, is massive gypsum, CaSO4.2H20. In the same drillhole, less than a metre from the above veinlet, siderite and gypsum occur interstitially in massive sulphides. Also in the same drillhole, gypsum with anhydrite inclusions is associated with siderite that occurs abundantly with coarsegrained anhedral quartz bands up to 3 cm wide. The bands are in sulphide-barren footwall schist. A somewhat similar occurrence was observed in core from drillhole 50 in the South Sulphide Body (Fig. 29), where gypsum is associated with siderite in fine-grained quartzose laminae in footwall phyllite.

Bassanite, $2\text{CaSO}_4 \cdot \text{H}_20$, was observed in minute amounts in pyritite of the Northwest, North, and South lenses. The mineral is present as optically complex grains that are interstitial to fine-grained siderite in pyritite. None of the occurrences is near-surface, and most are in the deepest drillholes that penetrated each lens. Bassanite has not been detected by X-ray powderdiffraction patterns prepared directly from drillcore material, and it is possible that the sulphate formed by dehydration of gypsum during thin-section preparation.

BARITE

Barite was found only in the thickest pyritite lens intersected in drillhole 74 (Fig. 20). Barite and quartz occur abundantly as the principal non-sulphide minerals at the stratigraphic top of the pyritite. The barite-bearing zone has a thickness of between 1.5 and 2 m.

APATITE

In a drill-core sample of massive sulphides from the Northwest Sulphide Body, minute amounts of apatite are present as anhedral grains associated with siderite in voids among sulphides. An X-ray powder pattern indicates that the apatite has cell dimensions equivalent to those of fluorapatite. Another pyritite sample from the Northwest Body contains apatite in a siderite-chloritechalcopyrite veinlet that is sharply truncated by an asymmetrically layered veinlet of sideritequartz-anhydrite and gypsum-anhydrite.

A massive sulphide sample from the western part of the Caribou open pit contains seams of pink apatite along hairline fractures normal to the sulphide layering. On the same sample, minute spheres of apatite occur in a pocket containing hinsdalite, a supergene phosphate-sulphate mineral (Fig. 38,39). Several grains of subhedral apatite up to 0.15 x 0.3 mm also were found in quartz-rich layers of the sulphide-barren graphitic zone which underlies the South Sulphide Body.

GRAPHITE AND CARBONACEOUS MATERIAL

A few flakes of graphite occur sporadically in the footwall zone of disseminated sulphides, and only rarely amidst the pyritite. The flakes are generally 1 to 10 μm in length, with elongation parallel to the bedding.

One polished section from the disseminated zone underlying the East Sulphide Body has numerous particles of amorphous carbonaceous material concentrated in several sedimentary laminae. The particles are up to $20 \times 30 \mu$ m, have sharply angular to conchoidal edges, and have a wide size range; they appear to be clastic debris.

CARBONATE AND SILICATE MINERALS

CARBONATES

The principal carbonate mineral at Caribou is siderite. It occurs in all of the massive sulphide lenses, usually making up 1 to 5 vol % of the pyritite, and is commonly the principal non-sulphide mineral in rocks that consist of more than 90% sulphides. The bulk of the siderite is interstitial to the sulphides and is therefore fine-grained and relatively inconspicuous. More readily seen, but less abundant, are sideritequartz veinlets that cut the massive sulphides. Most veinlets are less than 1 mm wide, but many ramify so that patches of siderite may be widespread in individual specimens.

Siderite occurs throughout the stratigraphic thickness of the pyritite and in many samples is accompanied by only traces of other silicates and carbonates. In contrast to the relatively pervasive distribution of siderite, dolomite occurs erratically. In some places the mineral seems to have been deposited in lieu of siderite, whereas in others there has been replacement of siderite. The replacement is at least in part associated with late fracturing akin to that mentioned for siderite-quartz veinlets.

The siderite:dolomite ratio for Caribou is estimated to be about 80:20. Calcite is quantitatively insignificant relative to the other carbonates and also is nearly always subordinate even in individual specimens. Most calcite is in areas of fault disturbance, or is contained within fracture-related dolomite as microscopic veinlet networks and patches.

Rhodochrosite was found only in a sample from drillhole 11 in the East Sulphide Body (Fig. 32). The mineral occurs with siderite in undisturbed laminated massive sulphides. Adjacent drill-core samples, from less than 2 m stratigraphically above and below the rhodochrosite occurrence, contain only siderite.

Numerous X-ray powder diffraction patterns of Caribou siderite and dolomite indicate that, for the most part, their cell dimensions do not vary drastically. However, there is some fluctuation in minor-element content, and in the pyrrhotite-bearing assemblage the composition variation of siderite is extremely large (Table 6). As well, ankerite rather than dolomite cell dimensions were obtained from two samples from pyritiferous assemblages. The few microprobe analyses that have been done for Caribou carbonates are given in Table 6.

SILICATES

In massive pyritite it is usual for carbonates to be the predominant non-sulphides and to be accompanied by small amounts of a variety of silicates, of which stilpnomelane, $K(Fe,Al)_{10}Si_{12}O_{30}(OH)_{12}$, is probably the most prominant considering both abundance and pervasiveness. Chlorite and quartz also are widespread, though commonly only trace amounts of each are present. However, both minerals usually appear abundantly where the sulphide content of the pyritite is relatively low.

The general pattern at Caribou is to have silicate matrix minerals in the disseminatedsulphide footwall, and to have carbonates accompanied by silicates in the massive sulphide lenses. The footwall rocks adjacent to the pyritite are mainly phyllite in which sulphides largely but not exclusively pyrite - are dispersed among the quartz and muscovite that comprise the bulk of the rock. Lamination of the phyllite reflects variations mainly in quartz-muscovite content, but sulphides, too, are abundant in some laminae and sparse in others. Shreds of chlorite commonly accompany the quartz-rich or sulphiderich laminae, but chlorite on the whole is relatively minor until the footwall of the pyritite is approached. Along part of the phyllite-pyri-

tite contact, the disseminated sulphides are

contained in a matrix of massive chlorite which is thickest beneath the North Sulphide Body. The pyritite lenses are not uniformly massive; their laminar structure reflects not only the variations in sulphide mineralogy, but also diversity in the proportions and types of nonsulphide minerals. Where sulphide-oxide percentages locally drop below 70 vol \$, quartz almost invariably appears in substantial quantity. This association is especially evident in the East Sulphide Body, where individual drill-core specimens from within the pyritite may consist largely of siliceous sediment rather than sulphides.

This same intercalation of sediments and sulphides

Table	6	-	Microprobe	analyses	of	Caribou	carbonates
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	54-698'*	62-2	2-93'	62-11-17
wt % Fe	40.0	1.8	1.6	15.5
Mg	3.8	11.5	12.0	4.7
Mn	0.8	1.9	1.6	1.3
Ca	0.5	20.1	20.3	20.1
	siderite	dolo	nite	ankerite

Siderite associated with pyrrhotite, drillhole 74 at 1663 ft:

Area 1 av.(range)		Area 2 av.(range)	Area 3 av.(range)	Area 4 av.(range)		
wt % Fe	33.9(33.0-34.4)	32.9(32.5-33.4)	43.8(42.2-44.8)	45.8(c	onsta	nt)
Mg	4.3 (3.7-5.4)	5.1 (4.6-6.3)	1.2 (1.0-1.5)	1.1(11)
Mn	8.3 (7.4-8.8)	7.3 (6.3-8.0)	2.0 (1.7-2.3)	0.6(11)
Ca	0.2 (0.1-0.4)	0.3 (0.2-0.5)	0.6 (Constant)	0.3(**)

*Drillhole number and footage

occurs on a microscopic scale so that contacts are gradational.

Despite the complexity arising from the presence of intercalated low-sulphide sediments, there is nevertheless a fairly sharp distinction between the silicate-carbonate assemblage in the footwall versus that in the pyritite: (1) the footwall zone is barren of carbonates except for the very occasional patch of siderite in quartzrich laminae or in fractures, whereas siderite and dolomite are among the principal non-sulphides in pyritite; (2) muscovite, a main component of the footwall phyllite, is absent in massive and laminated pyritite except where highly siliceous low-sulphide layers are intercalated; (3) stilpnomelane occurs only sparingly in disseminatedsulphide footwall rocks, but is common in pyritite; (4) talc, minnesotaite, and greenalite have been found only in pyritite.

The silicate and carbonate minerals occur as specks, patches, and veinlets among the sulphides, and thus the proportions and grain sizes of non-sulphides are partly dependent on the tightness of packing of the sulphides. Quartz in the voids among sulphides is typically present as compact aggregates of anhedral grains with irregular boundaries and undulose extinction. Also commonly present in the same thin section are aggregates of parallel, generally curved, ribbonlike grains. Elongation of the ribbon-like groups is occasionally random, but more often approximates that of sulphide layering.

Stilpnomelane is widespread and appears at all stratigraphic levels in the pyritite. The mineral occurs predominantly as laths, less abundantly as felted or partly sheaf-like aggregates. Most laths are less than 15 μ m long; the maximum is about 50 μ m.

Caribou stilpnomelane is typically dark brown to almost black at the maximum pleochroic absorption position. Light brown and green varieties are much less common and are apparently of random occurrence.

Chlorite is widespread, but in most specimens of pyritite it occurs only in trace amounts and thus is subordinate to other silicates and carbonates. Notable exceptions are at the hanging-wall and footwall contacts of the pyritite, where massive chlorite frequently is the principal non-sulphide in a zone 1 to 2 cm thick.

Chlorite habit varies from compactly intergrown masses to well-formed tabular grains that are mostly less than 10 μm long, and rarely up to 90 x 50 μm . Typically, however, the mineral is present as minute shreds associated with carbonates and other silicates. In rare cases, the edges of stilpnomelane clusters have been partly replaced by chlorite.

Microprobe analyses of 7 Caribou chlorites are given in Table 7. All the chlorites are iron-rich, but the two analyses with the highest MgO contents are at the hanging wall of the pyritite.

Locally the most abundant silicate is minnesotaite, and in other cases, talc. Both have been found only in pyritite, principally as matrix minerals in the voids among sulphides. Microprobe analyses of Caribou talc indicate that the mineral consistently contains substantial amounts of iron (Table 8). Appreciable substitution of Fe for Mg in talc is uncommon, but has been noted also in talc from altered rocks at the Mattagami massive sulphide deposit (Roberts and Reardon 1978).

Minnesotaite is more widespread than talc and is locally the predominant silicate in pyritite. In thin section, minnesotaite is typically fibrous and colourless to slightly brownish. In a few thin sections, both talc and minnesotaite are present. This association is unexpected if the two form a complete solid-solution series as was originally postulated by Gruner (1944). Although analyses given by Lesher (1978) and Miyano (1978a,b) support the proposed solid solution, (1980) has concluded, on chemical Muir Wood grounds, that minnesotaite is not a simple talc analogue. Microprobe analyses of Caribou minnesotaite are given in Table 9.

Greenalite, $(Fe,Mg)_6Si_4O_{10}(OH)_8$, the iron analogue of antigorite, occurs at Caribou as minute spheres in pyrite and magnetite, as finegrained greenish and greenish-brown masses in the matrix of pyritite, and as dark green rims on colourless minnesotaite. Microprobe analyses of

	- <u></u>	Drillhole, footage									
	62-1-5'*	62-1-67'	<u>62-1</u> -	-68' b	<u>62-1-</u> a	<u>118'</u> b	62-4-3'	62-4-50'	62-18-128'	<u>62-20</u> a	0 <u>-15'</u> b
wt % SiO2	26.2	23.6	25.2	24.9	23.6	23.3	26.7	23.3	25.9	25.9	25.9
Alo	20.0	21.3	20.8	21.3	21.3	21.7	20.3	20.0	19.0	20.8	19.3
Fe0**	23.0	33.1	28.1	27.6	33.1	31.6	25.3	37.9	35.0	32.5	34.3
MgO	16.2	7.8	13.2	13.3	7.8	9.5	16.5	7.2	9.5	8.5	9.1
MnO	0.6	0.8	0.6	0.6	0.8	0.2	0.5	0.2	0.2		
	86.0	86.6	87.9	87.7	86.6	86.3	89.3	88.6	89.6	87.7	88.6
Location	1	2	3		1		5_	6	7		8

Table 7 - Microprobe analyses of Caribou chlorites

*Drillhole number and footage

**Total Fe as FeO

1. Barren hanging wall of South Body, 1.5 ft above pyritite

2. Footwall zone, South Body; <10% sulphides

3. Footwall chloritic zone, South Body; <10% sulphides

4. Graphitic footwall rocks, South Body

5. In massive sulphides, exactly at upper contact of South Body

6. Southern tail end of North Body, at footwall; 20% sulphides

7. Chloritic schist underlying North Body

8. Barren footwall at northern end of North Body

Table 8 - Microprobe analyses of Caribou talc

	S	South Body, matrix	Northwest Body matrix	у,	Northwest spheres in p	Body, pyrite
		62-1-12'*	62-22-97'		38-589	1
Si02	58.7	58.5	58.8	53.5	53.2	53.7
Mg0	24.2	22.8	22.9	23.2	17.9	14.8
Fe0**	9.8	10.0	10.3	11.3	17.0	23.8

Recalculated on the basis of 11 oxygens

Si	3.99	4.04	4.03	3.90	3.97	3.97
Mg	2.45 3.01	2.35	2.35	2.52	1.99	1.63
Fe	0.56)	0.58)	0.59	0.69)	1.06)	1.47)
Fe/Fe+Mg	0.185	0.198	0.202	0.236	0.348	0.474

*Drillhole number and footage

**Total Fe as FeO

	Colourless sheaves			Brown	fibrous, in	veinlets
	wt %	recalc/ll	oxygens	wt %	recalc/ll	_oxygens
Si0 ₂	50.0	3.944 }	3.98	50.0	3.969	3.97
Al ₂ 03	0.4	0.037)		0.0	0.000)
Fe0**	36.0	2.375		37.5	2.489	1
Mn0	0.0	0.000		• 0.0	0.000	1
MgO	5.6	0.658	3.07	4.8	0.568	3.07
Ca0	0.1	0.009	1	0.0	0.000	1
к ₂ 0	0.3	0.030	/	0.1	0.104	1

Table 9 - Microprobe analyses of Caribou minnesotaite, drillhole 62-11 at 28 ft (North Body)*

*See also greenalite in Table 10

******Total Fe as Fe0

several samples (Table 10) show consistently high tetrahedral Si contents, a feature noted also in analyses reported by Klein (1974), Gole (1980) and others. However, homogeneity in these finegrained silicates is a problem, and Klein (1974) and others have attributed the high Si to submicroscopic intergrowths of chert. Two of the Caribou analyses (Table 10) have Mg > Fe, and one of these (62-22-97) has a weak X-ray diffraction line at 14.2 Å, as well as the normal very strong line at 7 Å. Most of the Caribou greenalites give diffuse powder-diffraction patterns which hinder precise identifications.

Kaolinite, rare at Caribou, has been observed as fracture fillings that are up to 1.5 mm wide. The fractures are in footwall rocks and are at steep angles to bedding. In one thin section, kaolinite is associated with gypsum, anhydrite, siderite, and mm-long rutile needles, all of which are in nodular quartzose masses in disrupted footwall schist. Kaolinite has not been found in pyritite.

ALLOGENIC SULPHIDES

Allogenic sulphides are those that crystallized and subsequently were deposited as particulate matter in their present sites. Thus some degree of transportation of the particles is involved, but reworking or comminution need not be. Reference to allogenic sulphides at Caribou is specifically to pyrite and minor arsenopyrite; some galena and sphalerite also may be allogenic but have not been recognized as such, possibly because their original forms did no survive postdepositional compaction and metamorphism.

Examples of allogenic pyrite, mainly from Caribou, are shown in Fig. 12. Nearly all of the recognizable allogenic pyrite at Caribou consists of composite grains rather than single crystals. The grains are not angular, but have no distinctive shape and are not accompanied by lithic clasts. The main distinguishing feature of the allogenic grains is their large and variable size relative to matrix sulphides (Fig. 13). Dropstone effects are observable microscopically and are seen most clearly where allogenic grains are sparse and are in finely laminated sediments containing abundant rutile prisms that serve as markers along the distorted bottom beds. The size of the allogenic pyrite grains, their crystallinity, and the absence of similar lithic material indicate that the pyrite grains crystallized as unconsolidated or loosely consolidated material prior to movement and redeposition.

	52-811'	62-11-28'	62-22-93'	62-22-971	54698
t % SiO ₂	35.3	36.2	39.6	37.0	34.6
Alooa	0.0	0.3	0.0	1.4	1.2
Fe0*	47.3	48.1	16.5	25.1	46.5
Mg0	5.0	5.2	27.0	20.7	5.2
Mn0	0.0	0.1	0.0	0.3	0.1
Ca0	n.d	0.0	0.0	0.0	
K ₂ 0	n.d	n.d.	n.d.	0.0	

Table 10 - Microprobe analyses of Caribou greenalite-antigorite

Recalculated on basis of 14 oxygens

Si	4.202	4.189 4.161	4.103
	4.202	4.229 4.161	4.271
Al	.000)	0.040) .000)	0.168)
Fe	4.709	4.655 1.450	4.612
Mg	0.887 5.655	0.897 5.562 4.229 5.679	0.919 5.531
Mn	.000)	0.010 (000)	.000)

*Total Fe as FeO; n.d. = not determined

52-811' : in massive sulphides, North Body

62-11-28': rim on minnesotaite in massive sulphides, North Body

62-22-93': in massive sulphides, Northwest Body

62-22-971: as above

54-698' : spheres in pyrite, Northwest Body; analysis of siderite from same section given in Table 6

Allogenic pyrite at Caribou is widespread: it commonly makes up a significant part of the disseminated sulphides in footwall rocks, is generally present in small amounts in the lowest parts of the massive sulphide lenses, and occurs locally near hanging-wall contacts. These generalizations aside, significant lateral variations also are present along the strike length of the Caribou deposit.

At the near-surface part of the Northwest Body, allogenic pyrite is an abundant component of disseminated sulphides that form a zone, averaging about 1 m in thickness, in footwall rocks adjacent to the pyritite contact. At depth, where multiple sulphide lenses are present, allogenic pyrite is present in only some of the pyritite lenses and at some of their contacts, but the variations do not aid the correlation of lenses from drillhole to drillhole.

The lower part of the North Body pyritite contains disseminated allogenic pyrite, and an appreciable portion of the sulphides in the footwall chlorite schist also is allogenic. Above the North Body, the extensively overlapping but thin extension of the South Body contains dispersed allogenic pyrite in only minor amounts and of a grain size finer than usual. Although the dispersed pyrite does not form a distinct zone, the number of grains decreases northward and at depth. Along the main part of the South Body, allogenic pyrite grains occur chiefly in footwall rocks adjacent to the pyritite; the grains are largely absent in the thick part of the pyritite, except for sporadic occurrences at the hanging-



Fig. 12 - Examples of allogenic pyrite: (a) massive sulphides at hangingwall contact of Northwest Body; large, irregular pyrite particles are dispersed in a fine-grained, predominantly pyrite matrix with disseminated base-metal sulphides, and with sphalerite-rich layers at top right. Drillhole 64-2 at 207 ft; core width 3.2 cm. (b) Various shapes and sizes of pyrite particles in a matrix of >90% muscovite. Drillhole 54 at 729 ft, footwall of Northwest Body. Core width 3.9 cm. (c) Pyrite in a black matrix of chlorite. Drillhole 62-17 at 200 ft, footwall of North Body at its southern end. Core width 2.9 cm. (d) Pyrite in phyllite in the sulphide clast zone underlying the East Sulphide Body (Fig. 30). Drilhole 62-7 at 86 ft; core width 2.8 cm. (e) Pyrite in finely laminated phyllite in the clast zone underlying the East Sulphide Body. Drillhole 62-6 at 98 ft; core width 3.0 cm. (f). Allogenic pyrite from the Murray Brook deposit (Fig. 1). Note the penetration of the pyritiferous layer beneath the largest pyrite particle. Placer Development Ltd. drillhole 19 at 553 ft; core width 5.2 cm.


Fig. 13 - Contrasting forms of pyrite at Caribou and examples of probable allogenic pyrite. Top left: large crystals of pyrite (py) with inclusions of sphalerite (sp) and associated etched arsenopyrite (asp) bordering laminae with disseminated framboids, some slightly squashed. Reflected light, air; bar scale 0.1 mm. Top right: dropstone structure in which a large particle of pyrite (py) has ruptured beds with fine-grained sulphides (arrow); continuation of disrupted beds is at extreme right, adjacent to top right of pyrite crystal. Note undisturbed overlying beds. Reflected light, air; bar scale 0.2 mm. Bottom left: two large pyrite grains in a field of extremely fine-grained, non-framboidal pyrite. Acid-etched; reflected light, air; bar scale 0.2 mm. Bottom right: large, unzoned pyrite crystals adjacent to fine-grained, growth-zoned crystals and poly-framboidal pyrite. Acid-etched; reflected light, oil immersion; bar scale 0.10 mm.

wall contact, but are common at depth where multiple sulphide lenses are present.

The proportion of allogenic pyrite in the Caribou sulphide lenses is highest in the East Body, wherein such pyrite grains are most abundant at footwall contacts, including those with intercalated phyllitic layers. Allogenic grains increase in abundance from west to east on the 6200 level, that is, in a direction away from the other sulphide lenses.

The East Body footwall phyllite is unusually thick (Fig. 30). In the phyllite is a pyritiferous zone, up to 2 m thick, that is fairly continuous on the 6200 level (Fig. 30). The zone contains abundant disseminated sulphides, allogenic pyrite, and layers up to 3 cm thick in which the sulphides are sufficiently abundant as to appear massive. Sphalerite occurs throughout the pyritiferous zone, but zinc content probably averages less than 1%; less abundant are galena, chalcopyrite, tetrahedrite, and arsenopyrite, the last occasionally as allogenic grains. Magnetite is absent, as is typical of all disseminated zones at Caribou.

Phyllite overlying this basal pyritiferous zone is conspicuously barren to within a few metres of the pyritite contact, where disseminated sulphides again increase. It may be of genetic significance that the stratigraphic thickness of phyllite separating the basal pyritiferous zone from the basal graphitic zone is similar to that which underlies the other Caribou pyritite lenses.

MINERAL DISTRIBUTION

NORTHWEST SULPHIDE BODY

The northernmost part of the Caribou deposit has been designated by Anaconda Company as the Northwest Sulphide Body (Fig. 2). The upper, central part of the massive sulphide zone is 15 to 20 m thick and gradually pinches out to the north. The southern part of the lens meets the remainder of the Caribou deposit in a zone of complex faulting and displacement (Fig. 14).

As is the case for all of Caribou, the main sulphide in the Northwest Sulphide Body (for convenience, the NW Body) is pyrite. Within the pyrite zone the base metals vary substantially, both in across-layer (stratigraphic bottom to top) and along-layer senses (horizontal-lateral as on the 6200 level, and vertically as in the different levels in the drillhole cross sections). Despite these variations, mineralogical studies and limited assay data available to the writer are sufficient to indicate that the NW Body has the highest magnetite and chalcopyrite contents of any of the Caribou lenses. The pyritite varies from uniformly massive to finely laminated, with the latter prevalent where sphalerite and galena are abundant. Rocks unusually rich in chalcopyrite vary from laminated to the more usual massive, the latter commonly accompanied by minor, randomly oriented and irregular chalcopyrite veinlets. Based on microscopic measurements of grain dimensions in acid-etched polished sections, the average grain size of pyrite in individual drillholes in the NW Body ranges from 0.013 to 0.030 mm; the average pyrite grain size for core from 10 holes is 0.017 mm.

The Northwest lens averages more than 0.7% Cu and substantial intervals in some drillholes have combined Pb + Zn exceeding 8%. The highest Pb + Zn averages generally occur in the hanging-wall half of the lens and Cu generally increases toward the footwall. Zn:Pb averages about 3:1 in the hanging wall, but changes to about 4:1 in the footwall half of the lens because the percentage decrease in Pb content is greater than for zinc. On the 6200 level, the lowest Zn and Pb contents are at the northwestern extremity of the lens (DDH 38, Fig. 14). In vertical cross sections the relations are more complicated because multiple lenses appear at depth. However, to summarize in general terms, the NW Body has a high-grade zone of Pb + Zn along its hanging wall, below which the pyritite contains only modest values of Zn, and Pb values are notably low.

The distributions of magnetite, arsenopyrite, and tetrahedrite-group minerals on the 6200 level are shown in Fig. 15. As all minerals have a pronounced propensity toward concentration in layers, the across-layer stratigraphic abundances are difficult to determine. However, a decline in magnetite content, both along-layer



Fig. 14 - Plan showing configuration of the Caribou North and Northwest sulphide lenses on the 6200 level.



LEGEND

38 ḥw	drillhole number hanging wall of pyritite	position of sample for polished or thin section
tw	footwall of pyritite	⊢ , relative abundance of mineral
	intonval with	not observed
m	maccive sulphides	sparse
	massive surprises	abundant

Fig. 15 - Distribution and relative abundance of magnetite, arsenopyrite, and tetrahedrite-group minerals in cores from the 6200 level, Northwest Sulphide Body (Fig. 14). Magnetite has a trend in which abundance decreases from >15 vol % in drillhole 38 to <4% in drillhole 62-20. Arsenopyrite averages about 2% in drillhole 38, and <0.2 in the others. Maximum tetrahedrite content, even within individual polished sections, is less than 1%.

and across-layer, towards the North Body is apparent in Fig. 15. Thus, in drillhole 38, magnetite composes almost half of the volume of individual polished sections and the average megnetite content is estimated to exceed 15%; moreover, this average persists almost to the hanging-wall and footwall contacts of the massive sulphide zone. Magnetite is similarly abundant in drillhole 64-2, but declines in 62-22, and the magnetite zone in both is contracted from the massive sulphide contacts. The trend continues to drillhole 62-20 in which the magnetite-bearing section is relatively narrow, sections with major magnetite are more sporadic, and average magnetite volume drops below 4%.

The distribution of magnetite in vertical sections of the NW Body is shown in Fig. 17, 19 and 21. The northernmost section (C'-C, Fig. 16) has the distinction of incorporating drillhole 76, which at the time of sampling was the deepest at Caribou. However, the downward projection of the NW Body is somewhat uncertain because of the appearance of multiple sulphide lenses at depth. It is assumed here that the sulphide intersections closest to the footwall are the main NW Body; the other, overlying lenses may be part of the NW Body, or they may represent discontinuous northerly extensions of the North Sulphide Body. In either case the footwall sulphide zone is characterized by persistent magnetite whereas the overlying lenses are devoid of this mineral. However, the variation in abundance of magnetite does not show a uniform trend: drillholes 38, 58 and 76A contain >15% magnetite whereas 72 and 76 contain <4%.

The southward trend towards lower magnetite contents is evident in section D'-D (Figs. 18, 19), where the magnetite-bearing zones are contracted from the massive-sulphide contacts. Even within the magnetic zones the magnetite content fluctuates drastically and averages about 10%. In the most southerly cross section (F'-F, Fig. 20), relations are complex because of faulting, the reappearance of multiple sulphide lenses, and proximity to the North Sulphide Body. However, the main lens intersected in drillholes 30 to 74 is interpreted to be the NW Body and to continue the trend to declining magnetite. In these drillholes the magnetic zones are commonly sporadic; magnetite content is highly variable but is estimated to be about a third less than that in the adjacent, more northern section, D'-D.

In summary, the principal trend is that magnetite content on the 6200 level decreases from north to south. A systematic change in abundance



Fig. 16 - Configuration of the massive sulphides in cross section C'-C of the Northwest Sulphide Body. Elevations are relative to sea level.



Fig. 17 - Distribution and relative abundance of magnetite, arsenopyrite, and tetrahedrite-group minerals in vertical section C-C', Northwest Body. Legend as in Fig. 15. Magnetite is absent in the upper lenses; vol % is for the lower lenses only. Arsenopyrite content of the lower lenses is erratic and locally reaches about 6 vol %; average for the pyritite zone is less than 1%. Tetrahedrite average is at the trace level.

is not evident in vertical cross sections, but the magnetite-bearing zones do shift toward the footwall half of the massive sulphide lens as it nears the North Sulphide Body.

As the same approach outlined above for magnetite was used in the graphical representations for arsenopyrite and tetrahedrite, these two minerals are treated more briefly. On the 6200 level, the arsenopyrite content in drillhole 38 (Fig. 15) is locally about 5 vol % and the average for the massive sulphide zone is about 2%. Southward, the arsenopyrite-bearing zone is constricted and the average content drops to a low fraction of a per cent. Vertical patterns (Fig. 17, 19, 21) are complex but, with the exception of drillhole 74 (Fig. 20, 21), a notable feature is the general sparseness of arsenopyrite in the southern cross sections. Although the pattern for drillhole 74 seems to be an exception, the pattern is more a reflection of the persistent appearance of the mineral rather than of unusual abundance. Nevertheless, there is a 5-m interval which averages about 4% arsenopyrite.

Tetrahedrite-group minerals are scarce in the NW Body. Jambor and Laflamme (1978) showed that the bulk of the silver in the Caribou deposit is present as a solid solution in tetrahedrite, and thus silver in the NW Body should be low. This seems to be the case as the partial assay data available to the writer indicate that the average silver content of the NW lens is in the neighbourhood of 1.5 oz/ton (51 g/t). Values substantially above average are most conspicuous in the hanging-wall zone of drillhole 56, where tetrahedrite is not only relatively common (Fig. 19) but also contains up to 10.8 wt % Ag (Jambor and Laflamme 1978).

A few additional features noted for the NW Body deserve brief mention. In drillhole 38 the magnetite-rich polished sections commonly have blocks, up to 1×3 cm, of fine-grained pyrite in magnetite, and much pyrite is framboidal. Marcasite is abundant, generally in late fractures, and some has been partly replaced by chalcopyrite. Similar features are present in core from drillhole 64-2.



Fig. 18 - Configuration of the pyritite in vertical section D'-D of the Northwest Sulphide Body.

In section F'-F (Fig. 20) the base of the main pyritite lens contains abundant allogenic pyrite. Farther in the footwall is a thin lens (Fig. 20) which is predominantly semi-massive (50-60% sulphides), is low in copper but fairly rich in sphalerite and galena, and has abundant fine-grained allogenic pyrite. It is probable that the thin lens extends from drillhole 30 to drillhole 74.

In drillhole 74, the second deepest at Caribou, a pyrrhotite-bearing zone was intersected near the base of the main sulphide lens. Pyrite in the top half of the lens is fine-grained and contains numerous excellent examples of growth zoning and framboids. Pyrrhotite and magnetite are present only in the bottom half of the lens but are absent at the footwall contact of the pyritite and in the underlying zone of disseminated fine-grained pyrite, much of which is framboidal. Thus pyrrhotite and magnetite are restricted to a zone 5 to 7 m thick near the footwall of the massive sulphide lens. Within this zone, magnetite averages up to 10% of a polished section and commonly is concentrated, as are the sulphides, in layers. Some clean, anhedral magnetite is disseminated in fine-grained pyrite, and some is in complex intergrowths with largersized pyrite grains. Framboids of pyrite, which occur singly rather than in clusters, were observed in a few magnetite masses.

Pyrrhotite and marcasite occur as anhedral grains among pyrite and, rather than being intergrown with the pyrite, are mostly in interstices of the pyrite grains. Low grades of basemetal sulphides and non-opaque gangue minerals occur in much the same way. Maximum pyrrhotite + marcasite is about 40% of total sulphide, with marcasite:pyrrhotite ~4:1. Pyrrhotite content of the footwall part of the massive sulphide zone therefore reaches a maximum of 6-7% by volume.

The last 2-3 m of the footwall massive sulphides are devoid of pyrrhotite and magnetite. Thus, the downward stratigraphic succession is (1) a pyritiferous zone which extends from the hanging wall to near the base of the lens; (2) an assemblage of pyrite-pyrrhotite-marcasite-magnetite near the footwall; (3) a pyrite (only) zone at the footwall contact. Within the pyrrhotitebearing zone and adjacent rocks there are no signs of disruption such as fracturing, faulting, or unusual grain sizes. Indeed, the only feature that distinguishes this zone from the mass of similar Caribou pyritite is that the zone is pyrrhotite-bearing.

The distribution of silicate and carbonate minerals on the 6200 level of the NW Body was examined for drillholes 38, 62-22, and 62-20 (Fig. 22). Rocks bordering the pyritite are not discussed, but these consist mainly of muscovite and quartz with variable minor chlorite. In drillhole 38 the predominant gangue minerals are carbonates:

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Fig. 19 - Magnetite, arsenopyrite, and tetrahedrite-group minerals in section D'-D. Legend as in Fig. 15. Average magnetite content of each drillhole is 3 to 5 vol %. Arsenopyrite content is a low fraction of a per cent except at the top of drillhole 56, where the average for the zone is 3%. Average abundance of tetrahedrite is at a trace level, but concentrations occur locally, as at the top of drillhole 56.



Fig. 20 - Configuration of the pyritite in vertical section F'-F. The thickest lens intersected by drillhole 74 is interpreted to be part of the Northwest Body (see Fig. 21).

the progression is from a narrow zone of siderite at the hanging wall to a similar zone of dolomite at the footwall; the intervening area contains dolomite with minor siderite and traces of calcite. Traces of quartz are present in the stratigraphic upper half of the pyritite, and chlorite plus quartz are at the upper contact; otherwise, the main silicate throughout the hole is talc.

In drillhole 62-22, one specimen contains dolomite in an otherwise continuous section with siderite. In drillhole 62-20 the section is dolomitic except for a narrow siderite zone at the hanging wall. Silicates occur sporadically in both drillholes: 62-22 contains stilpnomelane, talc, and chlorite, whereas the other drillhole has these minerals plus very minor minnesotaite and widespread quartz.

Although the mineralogy in vertical cross sections was studied in less detail, the results indicate that the mineral assemblages are similar to those on the 6200 level, and the associations In the northernmost cross are equally complex. section, C'-C, both dolomite and siderite are present in abundance at depth. However, the pre-



Fig. 21 - Magnetite, arsenopyrite, and tetrahedrite-group minerals in cross-section F-F'. Legend as in Fig. 15. Thickest lenses in drillholes 30 to 74 are interpreted to be part of the Northwest Body; magnetic sections in these consist mainly of narrow, magnetite-rich sections interspersed with low-magnetite intervals; average for the pyritite is slightly less than 2% magnetite. Arsenopyrite averages less than 0.2% and tetrahedrite is present in only trace amounts.



Fig. 22 - Plan of the 6200 level showing distribution of carbonate minerals in the Northwest and North lenses. Siderite and dolomite are the principal carbonates and are locally cut by trace amounts of calcite. Blank areas along drillholes in the North Body are positions where carbonates were not observed in the cores.

dominance of talc in the upper level gives way to stilpnomelane, minnesotaite, and chlorite at depth. In cross section D'-D, drillhole 56 contains traces of bassanite and fluorapatite and has a central dolomitic zone about 15 m thick, but otherwise siderite predominance and the varied silicate assemblage are similar to those on the 6200 level. In section F'-F, the dolomite section of the 6200 level is supplanted by barite and siderite in drillhole 74; traces of gypsum and anhydrite also are present, and the principal silicates are chlorite and stilpnomelane.

In summary, the main non-opaque, nonsulphide minerals in the pyritite of the NW Body are carbonates: siderite and dolomite are generally abundant and either may be the prevalent mineral at a particular site; calcite occurs only locally and always in trace amounts. Silicates are numerous but subordinate to carbonates in quantity. Sulphates - gypsum, anhydrite, bassanite, and barite - are minor and seem to be present only in the deepest drillholes.

NORTH SULPHIDE BODY

The main mass of the North Sulphide Body on the 6200 level is low grade: Pb + Zn probably averages less than 3% and Ag less than 1 oz/ton (34 g/t). However, the first 2 to 3 m at the hanging wall have Pb + Zn that averages more than 8%. Thus there is stratigraphic zoning in these metals, but it occurs over a limited thickness of the pyritite rather than changing gradually through the main sulphide mass, wherein Pb averages less than 1%. Although copper content of the North Body averages only about 0.5%, an across-layer trend to enhancement of footwall copper grades is evident for several drillholes. A pyritiferous chlorite zone containing disseminated base-metal minerals underlies much of the North Body and locally has metal grades similar to those in the massive pyritic lens.

The northwesterly, faulted North Body segments penetrated by drillhole 62-16 (Fig. 22) are low in copper but rich in sphalerite and galena (Pb + Zn = ~10%). Thus the segments differ from the main low-grade pyritite but are similar to its hanging-wall zone. Based on the systematic changes in mineralogy that occur laterally (Fig. 23), the differences between the faulted segments and the main lens are interpreted to be normal along-layer mineral variations.

Horizontal and vertical changes in opaque mineral abundances in the North Body are shown in Fig. 21, 23 and 25. Magnetite occurrences on the 6200 level (Fig. 23) are strikingly condensed in comparison with those in the NW Body (Fig. 15).



Fig. 23 - Magnetite, arsenopyrite, and tetrahedrite-group minerals on the 6200 level of the North Body. Magnetite content shows a trend from nil to a peak of about 4% in drillhole 62-11. Average arsenopyrite content is less than 0.2%, even for drillhole 62-16 which has the most persistent occurrences of the mineral. Tetrahedrite is present in only trace amounts.

Magnetite content within the magnetic sections increases southward and peaks at an average of about 8% in drillhole 62-11 (Fig. 23), then very rapidly declines and disappears as the lens pinches out to the south. A similar pattern is evident in vertical section G'-G (Fig. 24, 25), where drillhole 62-11 is again the most magnetiterich.

Although arsenopyrite is widely distributed on the 6200 level of both the NW and North Bodies, substantially smaller amounts of the mineral are present in the North Body: only two polished sections from it contain more than 2% arsenopyrite, and in nearly all others the arsenopyrite content is only a small fraction of a per cent. Thus, in drillhole 62-16 (Fig. 23), most of the sulphide zone is arsenopyrite-bearing, much of which is persistently above trace amounts, but the average content is less than 0.2%. These low values continue southward to drillhole 62-11, where above-average values occur sporadically. However, a different picture emerges in vertical cross section G'-G, where the arsenopyritebearing zones are mainly near the hanging wall of the pyritite and average about 3% arsenopyrite for drillholes 10 and 52. The trend indicates that the lowest arsenopyrite contents in the cross section occur immediately above the 6200 level.







Fig. 25 - Magnetite, arsenopyrite, and tetrahedrite-group minerals in vertical section G'-G of the North Body. Magnetite content averages only a fraction of a per cent except for drillhole 62-11 (4%). Arsenopyrite averages, as shown, mainly reflect high values near the hanging wall.

The North Body contains about 1 oz Ag/t (34 g/t). Below-average silver values occur in the thick, low-grade mass of the lens whereas above-average values are common in the thin, highgrade hanging wall. As tetrahedrite is the main silver carrier at Caribou, the sparseness of this mineral, both in horizontal and vertical sections of the North Body (Fig. 23, 25), is appropriate.

Microprobe analyses of tetrahedrite-group minerals from the 6200 level of the North Body are given in Tables 3 and 4. The low silver contents of the minerals are commensurate with the feeble silver content in the lens. Also evident is an along-layer compositional trend in which tetrahedrite gives way to tennantite at the southern end of the lens. In addition to this major feature, of minor note is the presence of bismuthian tennantite in drillhole 62-17 (Fig. 27). Adjacent tennantite from the same drillhole lacks bismuth (Table 3) and is homogeneous, but the bismuthian variety is variable in composition even within individual grains (Table 4).

The most abundant non-opaque, non-sulphide minerals in the North Body are carbonates. On the 6200 level, siderite is, by far, predominant and is apparently the sole carbonate in the northern half of the lens. Siderite is also the most abundant carbonate in the southern half, but dolomite occurs sporadically and a large dolomitesiderite zone is present in the hanging-wall part of drillholes 62-9 and 62-11 (Fig. 22). Only traces of calcite are present. In vertical section G'-G, dolomitic zones occur in the footwall of the pyritite near surface, and near the hanging wall at depth (Fig. 26), but siderite nevertheless is the dominant carbonate.

The silicate assemblage reported for the NW Body is also present in the North Body, but the proportions differ. In the northern half of the North Body 6200 level, chlorite, quartz, and stilpnomelane are the principal minerals; in the southern half, the southward progression is from mainly stilpnomelane to mainly minnesotaite. Although talc occurs locally, it is sparse in comparison with its presence in the NW Body and seems to have been supplanted by minnesotaite.



Fig. 26 - Distribution of carbonates in vertical section G'-G of the North Body.

In vertical section G'-G the principal silicates in the near-surface drillholes are chlorite, stilpnomelane, and minor quartz. At depth, chlorite is confined to the pyritite contacts; minnesotaite and stilpnomelane are the chief silicates, and small amounts of quartz occur persistently. Traces of bassanite are in the deepest drillhole.

In summary, some of the features that characterize the North Body are its low magnetite content, especially in proportion to the large width of the pyritite, the predominance of siderite relative to dolomite, and the abundance of minnesotaite relative to talc. The overall low contents of Pb and Ag in the North Body reflect the paucity of galena and silver-rich tetrahed-



Fig. 27 - Plan of the Caribou South Body, 6200 level.

rite. Although the bulk of the pyritite on the 6200 level is low in Pb + Zn, the grade apparently increases northward. This lateral zoning is marked especially by higher Pb contents, so that Zn:Pb ratio decreases to the north.

The hanging-wall zone of the North Body has the laminated structure characteristic of most pyritite in which Pb + Zn is high. However, base metals are low in most of the remainder of the lens and thus parts of it appear to be megascopically featureless masses of compact, homogeneous pyrite. Other parts show various degrees of layering and are indistinguishable from the pyritite of other lenses. The North Body has no unique sulphide textures; rather, the massiveness seems to arise because a high proportion of the basemetal sulphides is uniformly dispersed among pyrite interstices instead of being concentrated in layers that alternate with pyrite. Tightly compact masses of colloform, of polyframboidal, and of anhedral pyrite add to the megascopic massiveness. Although the same textures also occur elsewhere, the proportion of anhedral pyrite in the North Body is distinctly higher than in other Caribou lenses.

SOUTH SULPHIDE BODY

The South Sulphide Body (or, for convenience, the South Body) overlaps almost all of the North Sulphide Body (Fig. 14) and is in turn partly overlapped by the East Sulphide Body. Most of the South Body pyritite shows some degree of layering, from rudimentary to well laminated, but a central zone in the thickest part of the lens consists of tightly compact, non-laminated pyritite similar to that in the North Body.

Metal variations in the South Body are not unlike those in the North Body. On the 6200 level of the South Body, the thickest part of the pyritite has a high-grade hanging-wall zone, about 3 m thick, in which Zn + Pb averages more than 11%, but the remainder of the lens averages less than 1% Pb, and less than 6% Zn + Pb. Aside from the presence of the high-grade hanging-wall zone

at this site, across-layer metal zoning on the 6200 level is very poorly developed. However, along-layer zoning is pronounced: the southward pinch-out is to low-grade pyritite, whereas the opposite trend occurs to the north. In drillhole 62-4 (Fig. 27), Zn + Pb is similar in grade to that of the hanging-wall zone and is continuous through the complete thickness of massive sulphides. Grade continues to improve northward along the gradually thinning lens. In section G'-G (Fig. 24), a 1-m thick lens which stratigraphically overlies the North Sulphide Body is interpreted to the continuation of the South Body and has Zn + Pb of about 20%.

The progressive northward increase in Zn + Pb is accompanied by a shift from Zn:Pb = ~4:1 in the south to Zn:Pb = ~2:1 in the north. Silver content, which averages less than $l \ oz/t$ for the lens, is below average in the south but undergoes a three- to four-fold increase towards the north.

Metal variations in cross section I'-I (Fig. 29) are complex in that high-grade intersections of Cu and of Zn appear intermittently. However, there are gross similarities to the patterns described for the 6200 level: a thin zone of medium to high-grade Zn + Pb + Ag along the hanging wall, low grades of these metals in the remainder of the pyritite, and high grades in the thin lens at depth.

Occurrences of magnetite, arsenopyrite and tetrahedrite-group minerals on the 6200 level South Body of the are shown in Fig. 28. Magnetite is not present in the thin northern extension of the lens (drillholes 62-13 in Fig. 25 and 62-17 in Fig. 28), but becomes progressively more abundant and more continuous as the pyritite widens. The magnetic sections of drillholes 62-1 and 62-3 average 10 to 15% magnetite and these high contents continue into the southern tail of the lens. Similar magnetite abundances occur from the surface to the 6200 level in section I'-I (Fig. 29), but at greater depths the width of the pyritite diminishes drastically and magnetite is absent in the deepest drill-intersection. In vertical cross section J'-J at the southern end of the lens (Fig. 30 and 32), the magnetic zone in drillhole 12 averages about 15% magnetite, but the zone is much contracted and is restricted to the stratigraphic upper quarter of the lens.

The distribution of arsenopyrite in 6200level drill cores (Fig. 28) shows that the mineral is widespread in trace amounts, but intervals



0 3 10-15

Fig. 28 - Magnetite, arsenopyrite, and tetrahedrite-group minerals in the South Sulphide Body, 6200 level. Average magnetite contents are as indicated on the diagram. Arsenopyrite contents averages about 2% in areas shown in solid pattern; overall average is therefore only a fraction of a percent. Tetrahedrite average is a low fraction of a per cent.



Fig. 29 - Vertical section I'-I of the South Sulphide Body. The first two thin lenses intersected by drillhole 50 are interpreted to be part of the East Body.

with more than 1% are very thin. More-persistent occurrences and slightly higher abundances are present in the main cross-section, and highest abundances are at the thin, southernmost extremity of the body. Study of a few polished sections from the northern part of the lens, where it overlaps the thickest part of the North Body, indicates that arsenopyrite content probably also increases northward.

Tetrahedrite-group minerals on the 6200 level of the South Body occur only sparingly (Fig. 28). Previous microprobe analyses (Jambor and Laflamme 1978) indicated that these minerals in the South Body are relatively low in silver, and that much of the silver content of this lens is contained in solid solution in galena. Supplementary microprobe analyses which extend the spatial coverage northward (Table 3) indicate that the silver content of tetrahedrite in this area is typical. However, in marked contrast, the mineral at the southern end of the lens (section J'-J, Fig. 32) is tennanite (Table 4 in Jambor and Laflamme 1978). Thus the same pattern noted for the North Body, wherein tetrahedrite gives way to tennanite at the southern extremity of the lens, also is present in the South Body.

Whereas dolomite forms a very high proportion of the carbonate minerals in the Northwest Body and a smaller proportion in the North Body, only siderite was detected in the South Body. The principal silicate mineral in most of the South Body is stilpnomelane; chlorite occurs near the base of the lens and sparse talc near the top. Only traces of minnesotaite and greenalite are present, and quartz is absent. Thus the main assemblage is siderite-stilpnomelane.

EAST SULPHIDE BODY

The East Sulphide Body partly overlaps the South Body as multiple thin lenses that are inter-tongued with hanging-wall metavolcanic schists. The lenses merge southeastward to form an arcuate massive sulphide unit striking easterly to northeasterly. The total length of the unit is about 700 m and maximum thickness about 25 m. However, the unit contains variable amounts of intercalated phyllite and schist so that the sulphide lens splits and coalesces in numerous places along its length. The eastern extremity of the lens consists of low-grade pyritite (Pb + $Zn = \langle 2\% \rangle$ which gradually thins and pinches out (Cavalero 1970).

The main part of the East Body on the 6200 level is shown in Fig. 30. The lens differs from the others at Caribou in that it has good layering throughout and lacks a zone of tightly compact-massive, low-grade pyritite typified by the bulk of the North Body. The layering is emphasized by the presence of phyllitic beds which commonly contain laminae of sulphides and abundant allogenic pyrite. The massive sulphides in turn contain siliceous laminae so that quartz is more abundant in the East Body than in other lenses.



Fig. 30 - Plan of the East Sulphide Body, 6200 level.

The effect of these fluctuations is that the East Body is more dilute than others in terms of total sulphide and iron-oxide content.

The layered character of the East Body is also weakly enhanced by sulphide lamination related to a high base-metal content: Pb + Zn not only averages about 10%, but these grades extend from hanging wall to footwall. Zn:Pb is of the order of 2:1 and does not change significantly across or along the layers within the area studied.

Copper in the East Body averages slightly more than 0.3%. Across-layer zoning on the 6200 level is not well-defined, but there is a weak westward trend to higher copper. Although systematic vertical changes in copper content are not apparent, the aforementioned westward trend is reinforced considerably by the occurrence of copper-rich lenses in drillhole 14 of section J'-J (Fig. 32); some of these narrow, tail-end lenses average more than 1% copper.

Silver content of the East Body is probably about 2.5 oz/t (86 g/t) and thus is approximately 50% higher than the Caribou ore-reserve average. Across-layer trends are variable from drillhole to drillhole, but on the 6200 level the highest silver averages are at the western end of the lens and lowest at the eastern end.

Mineral variations for the 6200 level of the East Body are shown in Fig. 31. Magnetic sections are thin in comparison with the total thickness of the sulphide zone. The magnetite content of individual polished sections averages as high as 15%, but across-layer fluctuations are pronounced and reduce the average to 5-10% over the thicker magnetic intervals. In vertical cross section N'-N (Fig. 32), magnetite abundances and distributions (Fig. 33) are similar to those on the 6200 level. Intersections with abundant magnetite shift toward the footwall as the surface is approached. In vertical cross section J'-J at the inter-tongued northwestern end of the lens (Fig. 32), only the second down-hole intersection in drillhole 14 contains magnetite. In vertical section I'-I (Fig. 29), neither of the East Body lenses in drillhole 50 contains magnetite.

Nearly all of the East Body is arsenopyrite-bearing. On the 6200 level the main arsenopyrite zones (solid pattern, Fig. 31) reflect contents of 0.5 to 5%, with the overall average in the 2-3% range. Similar variations and abundances occur in vertical section N-N'



Fig. 31 - Magnetite, arsenopyrite, and tetrahedrite-group minerals on the 6200 level, East Body. The magnetite content in intervals with the solid pattern is 5-10%; arsenopyrite content in solid-pattern intervals ranges from 0.5 to 5% and averages 2-3%; solid pattern for tetrahedrite indicates 0.2-0.5% (Jambor and Laflamme 1978). Massive sulphide sections include minor intervals of phyllite.

Fig. 32 - Vertical sections, located on Fig. 30, of the East Sulphide Body.

(Fig. 33). Nevertheless, the East Body patterns do show general upward and westward increases in arsenopyrite.

Tetrahedrite in the East Body is more abundant and occurs more persistently than in the other major lenses. Numerous microprobe analyses of East Body tetrahedrite are given by Jambor and Laflamme (1978), who have concluded that this mineral is the main source of the above-average silver content of the lens.

The distribution of non-sulphide minerals in the East Body is complicated by the presence of intercalated phyllite, allogenic pyrite, and gradations from silicate-rich to massive sulphides. The silicate-carbonate-sulphide associations described by Jambor (1979) are generally applicable, but the distribution of quartz is not. In the present study, multiple thin phyllitic layers (simplified in Fig. 30) are interpreted to extend completely along the western part of the body so that the pyritite zone is a composite of at least two major lenses. Within the total pyritite zone, quartz is the principal silicate However, in compact-massive pyritite mineral.

with >85% sulphides, the main non-sulphide minerals are stilpnomelane and siderite. Chlorite also is commonly present, though usually in only small amounts. Occurrences of minnesotaite are uncommon, and talc has not been detected.

Minute amounts of siderite plus calcite are present in hanging-wall rocks on the 6200 level, but only siderite was detected in the pyritite zone. However, in vertical cross section N-N' dolomite and siderite coexist in the footwall half of the pyritite above the 6200 level, and siderite and rhodochrosite coexist in one sample from drillhole ll.

In summary, the East Body differs from the other Caribou lenses in that it has high-grade Pb + Zn with both metals abundant from hanging wall to footwall; the body also has a relatively low volume percentage of magnetite, has persistent arsenopyrite, has the highest silver values, and the highest proportion of allogenic pyrite. A thick zone of compact-massive, low-grade pyritite is not present and there is a general lack of across-layer metal zoning.

Fig. 33 - Magnetite, arsenopyrite, and tetrahedrite-group minerals in vertical section N-N', East Sulphide Body. Average magnetite content is about 2%, with slightly above-average values for drillhole 11. Arsenopyrite averages about 2% and is highest for drillhole 11 (3\%). Solid pattern for tetrahedrite indicates 0.2-0.5 vol %.

ARSENIC CONTENT OF THE PYRITITE

Arsenic is a deleterious element of major concern when dealing with effluents from mine workings, waste dumps, and tailings ponds. According to Davies and McAllister (1980), the average arsenic content of the Caribou deposit is 0.45%. The mineralogical studies have indicated that arsenopyrite accounts for the major proportion of the arsenic.

Arsenic contents of drill-core remnants from which polished sections had been cut are given in Table 11. Also listed are equivalent arsenopyrite contents calculated by assuming that all arsenic is present as stoichiometric FeAsS; the "equivalent" values are for convenience only and do not indicate the volume percentage of arsenopyrite in the analyzed samples, as do the four Quantimet analyses. The chemical analyses show that samples from the East Sulphide Body have the highest arsenic contents, and this result is in accord with the mineralogically determined abundance and distribution of arsenopyrite.

Other arsenic minerals and arsenic-bearing minerals such as tennantite and tetrahedrite are not abundant enough to account for significant amounts of arsenic at Caribou. However, Caribou pyrite has been noted to be arsenic-bearing (Johnson 1975; Chen 1978), and this mineral therefore was investigated specifically for its As content.

Microprobe analyses by D.C. Harris were obtained at 25kV using a LiF crystal and 100-s counting times with an enargite standard for As and Elba pyrite as a background standard. The PbMa line was monitored to detect potential enhancement of AsKa from lead in galena. The minimum detection limit for As was 0.03%.

Results from six polished sections are given in Table 12 and show that some of the pyrite is arsenian, but abundances are extremely erratic from grain to grain even in a single polished section. The highest arsenic detected is 0.60 wt %, and the average for the 72 grains analyzed (Table 12) is 0.05 wt %. The cobalt content of most grains is below the detection limit of 100 μ g/g (ppm); grains containing cobalt occur sporadically and do not seem to be specifically related to arsenian pyrite.

Microprobe analyses of 30 randomly selected pyrite grains in a Caribou scavenger tailing were reported by Johnson (1975). Only three contained cobalt (0.04 to 0.11 wt %), but six contained arsenic (0.24 to 0.97 wt %). Concurrently with the analyses of the pyritite samples in the present study, a Caribou copper concentrate provided by Noranda Research Centre, Pointe Claire, P.Q., also was examined. Chemical analysis of the concentrate gave 0.47 wt % arsenic, and microprobe analyses of 12 pyrite grains gave an average of 0.15 wt % arsenic and a range from 0.08 to 0.28 wt %. Sufficient arsenopyrite is present to account for the major part of the arsenic content.

In summary, Caribou pyrite is commonly arsenian, but the average arsenic content is low and arsenian grains occur erratically. Pyrite accounts for only a minor part of the arsenic content of the massive sulphides and arsenopyrite is by far the most important repository for the element. It is possible that the procedures used for copper-mineral concentration also have produced a concentration of arsenian pyrite, but there are too few analyses to prove this.

FOOTWALL ALTERATION

Hanging-wall rocks at Caribou are predominantly muscovite-rich schists derived from silicic tuffs (Roscoe 1971). The change from massive pyritite to these overlying sulphidebarren rocks occurs abruptly at each of the major Caribou sulphide lenses. In contrast, the mainly phyllitic footwall rocks contain abundant disseminated sulphides near the pyritite contact. Associated with these phyllites, which also are muscovite-rich, are local occurrences of rocks that consist almost wholly of chlorite and variable amounts of sulphides. These chloritic rocks are interpreted to be largely alteration-derived.

DISTRIBUTION

The East Sulphide Body lacks a footwall zone of massive chlorite except at the extreme

East Sulphide Body	DDH	Footage	wt %	Equivalent	Type*	Q**
			As	arsenopyrite		
Section N-N'	11	260	0.54	1.17	m	
		265	0.82	1.78	m	3.0
		275	1.21	2.63	m	2.2
		281	0.29	0.63	m	
		286	2.88	6.26	m	6.6
		290	0.29	0.63	m	0.6
		295	0.29	0.63	m	
		300	0.97	2.11	m	
			0.91	1.98	arithmetic	av.
				il.		
	13	509	0.49	1.06	m	
		513	0.49	1.06	m	
		518	0.08	0.17	đ	
		523	1.09	2.33	m	
		524	1.23	2.67	m	
		532	2.26	4.91	m	
		537	1.17	0.54	m	
		541	0.27	0.59	m	
		547	0.23	0.50	m	
		552	0.27	0.59	m	
		557	0.27	0.59	m	
			0.71	1.54	arithmetic	av.
Section I'-I	50	906	0.77	1.67	m	
		912	0.75	1.63	m	
		937	0.04	0.09	x	
		969	0.03	0.07	x	
			0.76	1.65	arithmetic	av., 2

Table 11 - Arsenic and equivalent arsenopyrite content of drill-core samples from the Caribou deposit

*Type: m = massive sulphides; d = disseminated sulphides; m-d = sulphide content 40-50%; x = sulphide content less than 5%

**Quantimet image analysis of polished section

Table	11 ((cont'	'd)
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East Sulphide Body	DDH	Footage	wt %	Equivalent	Туре*
			As	arsenopyrite)
6200 level	62-5	53	0.29	0.63	m
		56	0.44	0.96	m
		67	0.12	0.26	m
		72	0.38	0.83	m
		77	0.66	1.43	m
		83	0.13	0.28	m
		88	0.56	1.22	m
			0.37	0.80	arithmetic av.
Section I'-I	16	157	0.32	0.70	m
		184	0.11	0.24	m
		189	0.26	0.56	m
		201	0.10	0.27	m
		206	0.77	1.67	m
		220	0.54	1.17	m
		235	0.11	0.24	d
		260	0.02	0.04	d
			0.37	0.77	arithmetic av., 6 m
	18	450	0.29	0.63	m
		457	0.36	0.78	m
		465	0.20	0.43	m
		475	0.15	0.33	m
		484	0.17	0.37	m
		489	0.18	0.39	m
		497	0.08	0.17	m
		499	0.17	0.37	m
		521	0.09	0.20	m-d
			0.19	0.41	arithmetic av.

*Type: m = massive sulphides; d = disseminated sulphides;

m-d = sulphide content 40-50%; x = sulphide content

less than 5%

Table 11 (cont'd)

East Sulphide Body	DDH	Footage	wt %	Equivalent	Type*
			As	arsenopyrite	
6200 level	62-1	17	0.15	. 0.33	m
		22	0.29	0.63	m
		27	0.36	0.78	m
		42	0.18	0.39	m
		46	0.15	0.33	m
		50	0.28	0.61	m
		63	0.08	0.17	m-d
			0.21	0.46	arithmetic av.
	62-4	17	0.32	0.70	m
		21	0.11	0.24	m
			0.22	0.47	arithmetic av.
	34	546	0.12	0.26	m
		561	0.12	0.26	m
		570	0.17	0.37	m
		620	0.08	0.17	. m
			0.12	0.27	arithmetic av.
	56	1040	0.36	0.78	'n
•		1079	0.16	0.35	, m
		1130	0.03	0.07	m
		·	0.18	0.40	arithmetic av.

*Type: m = massive sulphides; d = disseminated sulphides;

m-d = sulphide content 40-50%; x = sulphide content

less than 5%

eastern end where interfingering of multiple thin sulphide lenses is present. The footwall along the remainder of the pyritite is muscovite-rich, and the phyllite lenses intercalated with the pyritite are similar.

Along part of the South Body footwall is a schist unit that overlaps the hanging wall of the North Body (Fig. 2). The schist unit is finely laminated, and in some places is spotted with megascopic pink K-feldspar grains that are a characteristic feature of volcanic-derived facies in the region; the unit is high in muscovite rather than chlorite. Along the remainder of the South Body, and also along the Northwest Body, massive chlorite, from 0.1 to 1.0 m thick, occurs sporadically but only where disseminated sulphides are abundant adjacent to the pyritite. For the most part, however, the footwalls of these bodies are muscovite-bearing to their pyritite contacts, and this relation persists to depth as indicated in cores from the deepest drillholes on the property.

Location	Drillhole,	No. of	wt %			
	footage	grains	Со	As		
North Sulphide	62-9-22'	7	n.d.*	n.d.		
Body		3	n.d.	0.11, 0.11, 0.13		
	-46 '	6	n.d.	n.d.		
		5	n.d.	0.04, 0.05, 0.14,		
				0.18, 0.60		
Northwest	62-22-46.5'	6	n.d.	n.d.		
Sulphide Body		6	n.d.	0.05, 0.06, 0.09,		
				0.14, 0.30, 0.34		
	-61'	15	0.12 av.	n.d.		
		2	n.d.	n.d.		
		2	0.02, 0.19	0.04, 0.09		
	-78'	7	n.d.	n.d.		
	-93'	5	n.d.	n.d.		
		8	0.06 av.;	0.13 av.;		
			range 0.02-0.16	range 0.09-0.25		

Table 12 - Microprobe analyses for cobalt and arsenic in Caribou pyrite

*n.d. = not detected

Only the remaining sulphide body, the North, has an appreciable footwall chloritic zone. It coincides approximately with the "chlorite schist" mapped by Anaconda (Fig. 14) and was described by Cavalero (1970) as "... an interbedded sequence of chloritic and pyritic schist, phyllite, and slate. The slatey zone occurs in the core of the lens as black, dense chloritic slate, weakly schisted and prone to conchoidal fracturing. Generally parallel to, but often cutting the slatey cleavage up to 20 degrees, are hard, shinyblack chlorite partings and abundant pyrite stringers, bands, and lenses up to 6 inches thick commonly rimmed by the hard, black chlorite."

The chloritic zone referred to in the present study does not encompass the total unit described by Cavalero, but is restricted to rocks in which chlorite is pervasive and quartz plus muscovite are negligible. These rocks, or chloritites, extend stratigraphically downward from the pyritite contact and locally penetrate to the footwall phyllite. The thickness of the chloritite zone is variable, and this irregularity also is manifested as relatively abrupt lateral changes. On the 6200 level, for example, chloritite extends from pyritite to the footwall phyllite at some drillhole sites, but is negligible at adjacent sites.

DESCRIPTION AND INTERPRETATION

In its most distinctive form the chloritite is dark greenish black, massive, and megascopically homogeneous. Less distinctive varieties contain variable amounts of sulphides, generally concentrated in layers, and variable amounts of greenish grey chlorite that alternate with sulphides and darker chlorite. In its megascopically least distinctive form the chloritite is laminated and similar to phyllite in appearance.

In thin section the chloritite is seen to consist almost totally of chlorite with variable amounts of sulphides. The sulphides, principally pyrite, occur exactly as they do in muscovite-rich phyllite. In many cases the chloritite contains clearly pseudomorphic features, such as the ribbon structure of quartz, faithfully reproduced grain-for-grain by the chlorite. Likewise, the original bedding commonly is evident from changes in the grain sizes of the intergrown chlorite masses from one layer to another. Disseminated pyrite and granules of rutile also mark the original lamination.

The above features point to pseudomorphism whereby the original quartz and muscovite of the footwall phyllite have been replaced by chlorite. On a microscopic scale the irregularity of the replacement is evident in a few thin sections which show a lateral transition from chloritite to unaltered phyllite, that is, replacement has occurred with pronounced discordance. This discordance is manifested on a much larger scale by the rapid lateral changes in the thickness of the chloritite along the pyritite footwall.

Although the chloritite is concluded to have formed by replacement of phyllite, the source of this alteration is another matter. As was pointed out previously (Jambor 1979), none of the drillholes at Caribou contains chlorite-pyrite stringers in a zone that has pierced the graphitic footwall. Nearly all of the sulphides in the chloritite zone are of the disseminated type and occur exactly as they do in phyllite unaffected by chlorite alteration. Veinlets of chalcopyrite and sphalerite, and occasionally pyrite, do transect bedding in a few cases, but the occurrences are rare and are by no means a feature that characterizes the chloritic zone. In some samples, chlorite in irregular, jagged seams up to 2 cm wide cuts the relict bedding in chloritite; however, the seams are a spatially restricted phenomenon and do not penetrate any deeper than the chloritite.

Thin-section examination of the footwall phyllite shows that its chlorite content is generally very low to negligible. Between this "endmember" and the pyritite contact are phyllites in which only a few shreds of chlorite occur in some laminae, and others in which chlorite-rich and muscovite-rich laminae alternate. Phyllite with up to 50% disseminated sulphides can have muscovite as the main layer silicate, but usually many of the laminae richest in sulphides are chloritic. The trend is for sulphide content to increase toward the pyritite contact, and thus there is in a general sense an increase in chlorite in the same direction. This chlorite-sulphide association is considered to reflect penecontemporaneous crystallization. The assemblage differs from chloritite in containing abundant quartz and occurring in conformable layers.

Although there is a spatial (footwall) link between chloritite and pyritite, their exact genetic relationship is difficult to specify. It seems likely that chloritite was a precursor to pyritite, and it is possible that chloritization is more closely allied with the penecontemporaneous chlorite-sulphide assemblage than with pyritite. Such relations would accommodate the distinct lack of correlation between chloritite presence versus the thickness, extent, or mineralogical character of the pyritite. The temporal progression from chloritic alteration to subsequent pyritite deposition would also explain why the pyritite contact locally marks not only an abrupt change to massive sulphides, but also an equally abrupt change from chlorite to other silicates such as stilpnomelane.

Chlorite and chloritite decline in abundance with increasing distance from the pyritite footwall contact. The conclusion is that chloritite in the drilled area of Caribou was formed by downward alteration rather than by upward penetration from stratigraphically lower conduits.

CRYSTALLIZATION SEQUENCE

Zoning of metals in massive sulphide bodies generally progresses from a copper-rich footwall to a hanging wall rich in zinc and lead. This zoning also is present at Caribou and reflects a change in proportions of base-metal minerals rather than absences of specific minerals. In addition to this gross pattern of metal zoning, fluctuations from copper-rich to zinc-rich pyritite also occur on a microscopic scale and commonly are manifested as micro-laminations of the sulphides. The initially crystallized laminae, i.e. the footwall contact at the thickest part of a lens, contain pyrite, arsenopyrite, base-metal sulphides, and tetrahedrite, but lack magnetite, pyrrhotite, and marcasite. In the observed upward stratigraphic succession, magnetite appears above the footwall assemblage, and subsequently is joined by marcasite with local pyrrhotite; all except pyrrhotite continue to the upper pyritite contact.

Aside from the above stratigraphic sequence of sulphides, other relationships are evident from the co-crystallization of minerals within individual laminae. Based on the microscopical textures, the crystallization sequence for the bulk of the pyritite was pyrite, then magnetite followed by arsenopyrite. Reversals of this trend have been observed on numerous occasions, particularly for pyrite and magnetite, but the amount of material involved is small relative to that adhering to the general trend. As well, however, there are widespread indication of magnetite-pyrite co-crystallization as myrmekitic intergrowths.

The main pyrite-magnetite-arsenopyrite assemblage commonly forms the basic package or framework whose voids were partly filled by crystallization of additional sulphides. Pyritemagnetite myrmekitic intergrowths span the range from framework-type to interstitial, with the latter in a few places closely associated with pyrrhotite and marcasite. These were in turn succeeded by the Zn-Pb-Cu sulphides and sulphosalts. In nearly all of the pyritite the general trend is to have sphalerite and tetrahedrite early and galena late; chalcopyrite is associated with all of these and seems to have crystallized at an intermediate position, that is, prior to galena. Departures from this general trend are not rare, especially where micro-fracturing is evident, but the volume of sulphides that does not follow the general trend is minute.

The iron-magnesium silicates such as minnesotaite, talc, and stilpnomelane vary from intergrowths with the sulphides to interstitial to fracture-controlled. The rare occurrence of greenalite spheres in pyrite suggests that they might have co-crystallized, but on the whole the silicates, as well as dolomite and siderite, seem to have mainly followed the sulphides. Among the non-sulphides, the progression usually observed is from silicates to carbonates to late sulphates. Rutile and graphite are associated with phyllitic components and are not considered to be involved directly in pyritite crystallization.

METAMORPHISM

REGIONAL CONDITIONS

According to Helmstaldt (1973b), spilitic rocks in the area extending from Caribou to the Armstrong deposits (Fig. 1) contain prehnite and pumpellyite which are rare relative to epidoteactinolite-calcite; from these assemblages the inference is that metamorphic temperatures were probably slightly less than 400°C, and pressure less than 9 x 10⁵ kPa (9 kbar; Winkler 1974). For the reaction prehnite = zoisite + grossular + quartz, Liou (1971) has experimentally determined the high-temperature stability limit of prehnite to be 403°C at 3 x 10⁵ kPa and 393°C at 5 x 10⁵ kPa where fluid pressure equals total pressure; if μ CO₂ is involved, the effect is to displace prehnite stability to lower temperatures.

Crossite has been recognized by Helmstaldt (1973b) and Skinner (1974) to occur in mafic volcanics near the Murray Brook, Caribou, and Armstrong deposits. The crossite-bearing area has been extended by Whitehead and Goodfellow (1978b) to the California Lake area (Fig. 1). If the crossite zone represents Brown's (1977) lower pressure regime of blueschist metamorphism, as suggested by Whitehead and Goodfellow (1978b), then it is probable that most deposits in the northern part of the district were subjected to metamorphic pressures of less than 4×10^5 kPa. In the southern part of the district the stilpnomelane-biotite isograd (Fig. 1) marks probable metamorphic temperatures of 445° C at 4×10^5 kPa and 460° C at 7×10^5 kPa (Winkler 1974).

LOCAL CONDITIONS

Metamorphism of the Caribou deposit is discussed by Roscoe (1971) and Davis (1972), both of whom have emphasized textures interpreted to have arisen from metamorphic recrystallization of the sulphides. Although deformation textures are present, the conclusion from the present study is that primary to very low-grade metamorphic textures are characteristic for the bulk of the Caribou pyritite. Aside from the low metamorphic grade indicated by the silicate-mineral assemblage in the pyritite, primary textures such as polyframboidal, colloform, and finely growth-zoned pyrite are not exceptional local features, but instead are widespread and sufficiently abundant as to constitute prevalent forms in masses of pyritite. The abundance of polyframboidal pyrite partly accounts for the low average grain size of <0.02 mm for pyrite at Caribou. The fine grain size attests to the lack of pervasive sulphide recrystallization that accompanies penetrative deformation regional metamorphism and (cf. Mookherjee 1976).

Pyrite in several places at Caribou is anomalously coarse and consists of anhedral, commonly interlocking grains quite atypical for most Caribou pyritite. Almost invariably material of this type occurs in proximity to the major faults that appear on Caribou mine maps. In some specimens micro-brecciation as well as coarsening of the sulphides is evident, and in others either feature may be absent. Aside from effects attributable to faulting, the deformation and fracturing of sulphide grains, such as those shown in Fig. 12 of Davis (1972), seem to have occurred mainly in the footwall zone of disseminated sulphides or where there is appreciable intercalation of siliceous rocks. For most part the deformational effects do not seem to have been transmitted through the massive sulphides, that is, the pyritite has been competent relative to the enclosing host rocks.

CRYSTALLIZATION CONDITIONS

Pyrite is the only iron sulphide that occurs throughout the Caribou deposit, and is the only iron sulphide or oxide that occurs precisely at the footwall contact of the pyritite. At some places magnetite appears only slightly above the contact, and pyrite and magnetite characteristically coexist and alternate through the bulk of the deposit. In addition, extremely fine-grained graphic to myrmekitic intergrowths of pyrite and magnetite are widespread and can also be considered as an indication that crystallization fluctuated at or near the magnetite-pyrite sulphidation-reaction boundary. The absence of hematite until late in the depositional sequence, and the characteristic presence of chalcopyrite and pyrite rather than bornite and pyrite imposes general constraints on S, activity as shown in Fig. 34. Additional constraint arises from the presence of pyrrhotite which occurs occasionally as blebs in pyrite, and at a few sites is also present as individual grains that are a substantial component of the pyritite layers. Although the latter pyrrhotite is mainly interstitial to coarser pyrite, magnetite, and pyrite-magnetite intergrowths, the interstices also occasionally contain myrmekitic pyrite-magnetite that is similar in grain size to pyrrhotite and is in contact with it. Thus the implication is that crystallization occurrred at the magnetite-pyrite-pyrrhotite triple point in minor parts of the deposit, and that crystallization in major parts was near the magnetite-pyrite stability boundary, but with pyrrhotite and hematite excluded.

The coexistence of the above minerals does not indicate that equilibrium was attained; on the contrary, textures indicating supersaturation (Barton et al. 1977) are common. Nevertheless, the constancy of the associations suggests that equilibrium conditions may have been approached, and it is common practice to treat the

Fig. 34 - Mineral stability fields at 250°C (after Barton et al. 1977). Dotted line represents contour for 10 mol % FeS in sphalerite; contour for 20 mol % coincides with the pyrrhotite field boundary. Abbreviations: bn = bornite, cp = chalcopyrite, py = pyrite.

mineral assemblages as though they had formed near the equilibrium condition (Kajiwara 1970; Barton et al. 1977) even though specific exclusions may be necessary. Two examples from Caribou are the exclusion of arsenopyrite from the pyrrhotite-bearing assemblage, and the non-equilibrium crystallization of late-stage hematite veinlets containing pyrite, marcasite, siderite, and iron-rich sphalerite. In the case of arsenopyrite, the assemblage pyrite-pyrrhotite-arsenopyrite is invariant at 491°C, at which temperature the arsenopyrite contains 33.0 atomic % As (Kretschmar and Scott 1976). However, microprobe analyses have shown that all of the Caribou arsenopyrite grains in this assemblage are compositionally zoned, not only in As, but also in Sb and Co. Thus non-equilibrium is indicated and the minor elements are too high to use the arsenopyrite geothermometer (Kretschmar and Scott 1976).

The pyrite-magnetite-pyrrhotite assemblage at Caribou is accompanied by abundant mar-

casite which is interpreted to be primary. Similar marcasite is also widespread in small amounts in non-pyrrhotitic parts of the deposit and occurs as well-crystallized interstitial grains that formed prior to the cessation of crystallization of some base-metal sulphides. The relatively early appearance of marcasite, which also has been noted by Williams (1978) in the McArthur River deposits, Australia, suggests that maximum temperatures of crystallization were below the marcasite stability limit of about 300°C (Barton and Skinner 1967). However, as the monotropic inversion of marcasite to pyrite occurs rapidly above 250°C (Skinner 1967), the widespread presence of marcasite at Caribou suggests that temperatures did not exceed this value. Possibly supporting relatively low maximum temperatures is the presence of dispersed grains of homogeneous, monoclinic pyrrhotite. Provided that the monoclinic grains have not inverted uniformly from high-temperature hexagonal pyrrhotite, their upper stability limit is 248°C (Scott and Kissin 1973). However, the fact that only part of the pyrrhotite is uniformly monoclinic means that alternative explanations cannot be eliminated: (a) pyrrhotite intergrowths may be primary hexagonal and monoclinic forms; (b) the intergrowths may be an indication that widespread inversion from hightemperature hexagonal pyrrhotite did occur; (c) maximum temperatures could have been near the hexagonal-monoclinic inversion boundary at 248°C. Only alternative (b) requires high temperatures. Considering the limited stability of marcasite and the occurrence of the mineral at Caribou, 250°C is accepted as the maximum temperature for the deposit. This value is also within the restricted temperature range generally recognized for crystallization of kuroko black ores (Kajiwara 1973; Urabe 1974) and other massive sulphide deposits (Large 1977).

The Caribou pyritite represents a sequential accumulation of layers of sulphides. Although the individual minerals commonly crystallized in a specific order, with some variation, this order is unlikely to represent temperature variations from layer to layer. There are, however, indications that crystallization or recrystallization continued as temperatures of the pyritite declined, and that temperatures in some parts of the deposit may have been initially lower than in other parts. Thus sphalerite coexisting with pyrrhotite has maximum FeS contents exceeding 14 mol %, suggesting that the upper temperature limit of 250°C may have been approached locally. Crystallization at this temperature and near the pyrite-pyrrhotite-magnetite triple point indicates that \underline{fS}_2 was about 10^{-13} and \underline{fO}_2 about 10^{-13} (Raymahashay and Holland 1969; Barton et al. 1977).

Sphalerite coexisting with pyrite has a considerable range in composition (Table 1). The pyritiferous assemblage contains various sulphosalts as well as native antimony and native bismuth, but bismuthinite and stibnite have not been found. The two native metals have not been observed together in a polished section, but both occur at several different sites in the deposit. Neither metal has been found in pyrrhotite-bearing assemblages, thus suggesting the possibility that the native bismuth crystallized at temperatures lower than 213°C, the point at which the pyritepyrrhotite and bismuth-bismuthinite univariant curves intersect (Barton and Skinner 1979). Similarly, the coexistence of native antimony with pyrite suggests that crystallization temperature was less than 200°C (Craig and Barton 1973). The detection of stephanite, Ag_5SbS_4 , at Caribou that temperatures did not suggests exceed 197 ±5°C, above which the mineral breaks down to pyrargyrite + argentite (Keighin and Honea 1969). Although stephanite has been found only in concentrates, pyrostilpnite, Ag₂SbS₂, has been observed in the pyritite. Pyrostilpnite is unstable above 192±5°C (Keighin and Honea 1969), at which temperature it inverts to pyrargyrite, a mineral not found at Caribou.

The silicate assemblage at Caribou consists mainly of stilpnomelane, minnesotaite, chlorite, talc, greenalite, muscovite, and quartz. The maximum stability temperature of greenalite at $\underline{P}(H_20)$ of up to 5 kbar is indicated by Muir Wood (1979) to be about 200°C. According to Miyano (1978a), at $\underline{P}(H_20) = 1$ kbar the assemblage greenalite-magnetite-minnesotaite is invariant at f0_10⁻⁴⁹ and 130-140°C for end-member compositions; above these values greenalite is no longer stable. For most of the Caribou pyritite it therefore seems probable that crystallization temperatures were less than 200°C and may have been much closer to 150°C. The main pyritite components crystallized along and near the pyritemagnetite boundary, with pyrrhotite and hematite excluded. Mol % FeS in sphalerite for the pyritesphalerite assemblage is highly variable, but most analyses give Fe contents above 4 wt %, which is about 7 mol % FeS. Thus the majority of analyses indicates that <u>fS₂</u> at 150°C was in the pyritemagnetite field near the Bi₂S₃-Bi and Sb₂S₃-Sb sulphidation boundaries, i.e., $\underline{fS}_2 = 10^{-18}$ to 10^{-20} and $\underline{f0}_2$ about 10^{-46} to 10^{-51} (Fig. 35). Coincidentally, this $\underline{f0}_2$ range straddles the $\underline{f0}_2$ limit for greenalite stability.

Silicates are absent in many Caribou samples and in these the gangue is exclusively siderite or dolomite. Where the silicates and carbonates coexist and have well-defined age relations, carbonates are generally younger than iron-magnesium silicates. Formation of siderite and dolomite may merely reflect higher CO, activity (cf. Klein and Bricker 1977; Einaudi 1977). In the pyrrhotite-bearing, higher temperature assemblage, $\underline{f}CO_2$ of 10^{-2} would permit crystallization of magnetite-pyrrhotite without encroachment by siderite, but with fCO, of 10° part of the magnetic field is overtaken by that of siderite (Holland 1965). The omission of magnetite and its replacement by siderite is a trend that is well-defined in Caribou samples. A higher range for $\underline{fC0}_2$ is considered to apply at 150°C: at $fC0_2 10^2$ the graphite boundary is near the pyrite-magnetite-minnesotaite boundary and is close to the field deduced for the bulk of Caribou pyritite crystallization.

The final stages of mineralization are not essential components of the sulphide layering, but are mainly fracture-related or are clearly irregular replacements of the minerals that form the pyritite layers. By far the most abundant of the late assemblages is hematite-pyrite-quartz, whose appearance in polished sections is made conspicuous mainly by the presence of hematite, 53

some of which has partly replaced magnetite. The widespread occurrence of the assemblage, together with its restriction to massive sulphide zones, strongly suggest that the assemblage is genetically related to pyritite formation. However, the hematitic assemblage is very minor relative to the volume or pyritite, and there does not seem to have been general equilibration with the main sulphide masses. However, at 150°C, minimum $\underline{f0}_2$ and \underline{fS}_2 conditions for an equilibrated hematitic assemblage would be defined by the pyrite-magnetite-hematite triple point at f0 approximately 10^{-44} and $fS_2 10^{-16}$ (Fig. 35). The late appearance of calcite, which is post-siderite and dolomite, as well as the late appearance of sulphates, especially anhydrite, indicate that fCO_{2} may have been near 10^{2} so that the calciteanhydrite boundary was entirely in the pyritehematite field (Fig. 35). On the other hand, the same results could have been achieved simply by reduction in temperature from 150°C to about 100°C.

Fig. 35 - Mineral stability fields at 150°. Field boundaries mainly after Robinson and Ohmoto (1973). Abbreviations: bn = bornite, cp = chalcopyrite, py = pyrite, C = graphite, Sb = native antimony. Sulphidation boundaries (1) Sb>Sb_2S_3; (2) Ag_3Sb>Ag_3SbS_3 (pyrostilpnite); (3) Bi>Bi_2S_3 (Craig and Barton 1973; Urabe 1974). Magnetiteminnesotaite-grunerite boundaries after Miyano (1978a) for system Fe-Si-O-OH. Boundary for CaCO_3-CaSO_4 is for conditions specified by Robinson and Ohmoto (1973) and $\underline{f}CO_2 \ 10^2$.

GENETIC ASPECTS

The possible genesis of the Caribou deposit was discussed previously (Jambor 1979); the additional studies since then have not altered the conclusions that the East Sulphide Body represents the most distal of the Caribou lenses and that the focal point of deposition for the deposit was in the vicinity of the North Sulphide Body. The results from deep drilling currently in progress along the length of the whole deposit will be examined at a later date and may provide new information about the source of the deposit. The new data and their possible implications concerning genesis will be reported in a separate paper.

SUPERGENE ALTERATION

INTRODUCTION

About 910 000 t of ore were mined by open pits along the Caribou massive sulphide lenses. This part of the deposit consisted of a copperenriched supergene sulphide zone averaging 3.4% copper. The ore was mined from 1971 to 1974, though operations were not continuous because of difficulties related to poor copper concentration.

According to Cavalero (1972), the supergene zone varied from a few metres to 45 m in thickness and was overlain by gossan enriched in gold and silver. In the supergene zone, near-surface copper was mainly present as covellite whereas at depth there was a sharp gradation to chalcocite-rich ore.

In the present study a few open-pit samples were examined to obtain a general impression of the mineralogy of the oxidized parts of the ore and to determine the nature of the "blooms" currently forming on the pit walls. Pyritite samples from the open pits also were studied because one objective was the determination of the depth of penetration of supergene minerals into the massive sulphide lenses.

SUPERGENE SULPHIDES

Many of the open-pit pyritite samples examined in polished sections are devoid of supergene sulphides, presumably because of complete removal of the supergene zone by mining.

Of the sections that do show copper enrichment, all have a basic similarity in that digenite is the principal supergene sulphide and it characteristically is most prolific in contact with sphalerite and, to a lesser extent, with chalcopyrite. Covellite is nearly as common as digenite and the two are usually associated intimately, especially where there has been replacement of sphalerite. Much of the replacement of sphalerite occurs initially as an extremely fine-grained network of digenite (Fig. 36); increased replacement is usually accommodated by broadening and coalescence of the network rather than by proliferation of fine-grained veinlets, thus leaving islands of sphalerite in a digenite-covellite matrix (Fig. 37). Digenite replacement or rimming by covellite is widespread, and this is in accord with the near-surface, downward progression from covelliterich to "chalcocite-rich" ore (Cavalero 1972). However, the profusion of digenite and absence of chalcocite suggests that Cavalero's reference is to digenite-rich rather than chalcocite-rich ore.

Luzonite, Cu₂AsS₁, constitutes only 1 or 2% of the supergene sulphides. It occurs as micrometre-wide coatings along fractures in covellite, as scalloped borders on covellite which lines voids in leached pyritite, and as one component in sulphide-sulphate mixtures that form pockets up to a square millimetre. Supergene galena has been observed rarely, usually in porous pyritite. The galana occurs as scalloped rims, only a few micrometres thick, that separate sphalerite from pores whose central areas are partly filled with scalloped luzonite.

Fig. 36 - Initial stage of supergene alteration Fig. 37 - Advanced stage of supergene alteration showing a thin network of digenite (dg) in selective replacement of sphalerite (sp) containing scattered crystals of pyrite (py); inclusions of pyrrhotite (po) are surrounded by a thin rind of chalcopyrite. West open pit; reflected light, oil immersion; bar scale 0.10 mm.

showing digenite (dg) with residual islands of sphalerite (darker grey, sp). Heterogeneity of the digenite in the upper half of the photo is partly due to minute inclusions of sphalerite, and partly to mottling arising from the presence of covellite. West open pit; reflected light, oil immersion; bar scale 0.10 mm.

NON-SULPHIDES

Pyritite in the supergene-enriched zone is commonly porous, apparently due principally to dissolution of siderite and other carbonates. Various silicates were also susceptible to attack, and in highly porous pyritite the main residual non-sulphide mineral is quartz. Voids in pyritite have been partly refilled with quartz, supergene sulphides, and abundant sulphates.

Anglesite occurs in pyritite as coarse grains up to $0.1 \ge 0.25$ mm. In material showing intense supergene alteration, galena has been extensively replaced and anglesite grains are numerous; it seems likely, therefore, that anglesite accounted for a significant part of the assay values for lead in supergene-altered material.

Minerals that appear as coatings on oxidized material in pits also appear as interstitial minerals in altered pyritite. Anglesite occurs as pale yellowish to pale greenish coatings, the colours possibly arising from included impurities. Bright green coatings usually indicate the presence of brochantite, $Cu_4(SO_4)(OH)_6$, which also has been noted as microscopic linings of voids and as a filler of cracks in digenite (Fig. 36, 42). Goethite is common and abundant in the oxidized zone - hematite much less so. Bright yellow coatings are sparse and are usually mixtures in which beaverite, $Pb(Cu,Fe,Al)_3(SO_4)_2(OH)_6$, and hinsdalite, $PbAl_3(PO_4)$ (SO₄) (OH)₆, predominate. One sample was found to contain prisms and tablets of polycrystalline hinsdalite (Fig. 38, 39) associated with spheres of apatite. Jarosite, KFe₃ $(SO_4)_2(OH)_6$ also has been detected, and Cavalero (1972) reported that plumbojarosite, PbFe₆ $(SO_4)_4(OH)_{12}$, is present. A mineral tentatively identified as plumboferrite, PbFe₂O₄, was reported by Boorman (1975) to occur in the gossan zone.

Litharge, PbO, has been observed only in polished sections of cores from the North Sulphide Body. A minor amount of the mineral occurs as discontinuous microscopic seams in otherwise unaltered pyritite; most of the mineral is in other areas of the same polished sections where part of the carbonate-silicate gangue apparently has been leached and the pores refilled with litharge.

Meta-aluminite, $Al_2(SO_4)$ (OH)₄.5H₂O, was found in abundance in one area of the west pit, where the mineral fills cross-cutting fractures

Fig. 38 - SEM photo of hexagonal prismatic crystals of hinsdalite (after Pickwick 1977); bar scale 0.02 mm.

Fig. 39 - SEM photo showing hexagonal tabular form of hinsdalite (after Pickwick 1977); bar scale 0.02 mm.

that contain the siderite-hematite-quartz assemblage. Meta-aluminite occupies the middle of the fractures as white seams 1 to 2 mm wide and several centimetre long, and also fills pockets up to a centimetre in diameter. Although soft (hardness 2 1/2), the mineral was initially porcelainous and extremely difficult to comminute; however, after three years of exposure in the laboratory most specimens have spalled extensively. The X-ray powder pattern has not changed in this interval and the spalling therefore is attributed to expulsion of excess, absorbed water.

The identification of Caribou meta-aluminite was uncertain for some time because the properties of the mineral differ somewhat from those given in the original description by Frondel (1968). Chemical analysis of the Caribou mineral gave higher and lower H_O A1203 contents than formula requirements (Table 13), and the measured density was determined to be 1.95(1)g/cc by suspension in heavy liquids, as contrasted to Frondel's value of 1.85(2)g/cc. However, infrared spectra of meta-aluminite from Halle, Germany (Nat. Mineral Collection No. 14864) and Caribou are identical, and X-ray patterns of both are in good agreement with new data by Farkas and Werner (1980) who have shown that Frondel's (1968) pattern contains impurity diffraction lines.

The presence of meta-aluminite in a massive sulphide supergene zone is unexpected and is difficult to explain in terms of derivation and deposition. However, it is possible that the mineral accompanied the hematite-siderite-quartz veinlet assemblage which has been interpreted here to be late-stage hypogene.

Post-mining alteration is represented mainly by mixtures of water-soluble sulphates that have precipitated as white and blue blooms on the pit walls. Coatings in various shades of blue usually indicate the presence of chalcanth-CuSO₄.5H₂O; associated white ite, precipitates are rozenite, FeSO4.4H2O, and szomolnokite, FeSO₄.H₂O. These minerals and gunningite, $ZnSO_{\mu}.H_{2}O$, also have formed in minute amounts on sulphide rubble in the pits.

DEPTH OF SUPERGENE ALTERATION

As a high proportion of the massive sulphide samples collected from the open pits lacks supergene alteration, the inference can be made that the supergene zone has been largely mined out. However, the zone is irregular in profile and a concern has been whether significant local alteration might be present in the predominantly primary zone.

Underground development nearest the surface is at the adit or 6500 level (elevation 1500 ft), but these workings have not been accessible for several years. However, several of the drillholes studied here penetrate the massive sulphides

	fable	13		Chemical	analyses	of	meta-aluminite
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		Cari	bou	Frondel	Theoretical	
		Wet chemical	Microprobe	(1968)	Al ₂ (SO ₄)(OH) ₄ .5H ₂ C	
wt %	A1203	36.50	33.6	33.59	33.09	
	soj	26.42	27.7	26.25	25.98	
	H ₂ 0(-110°C)	13.66)				
	_	37.25	38.1*	40.15	40.93	
	H ₂ O(+110°C)	23.59				
		100.17	99.4	100.00**	100.00	

*By difference from total wt % loss of 65.8% on heating to 1100°C in a TGA apparatus; end product ${\rm Al_2O_3}$

**Recalculated to 100 wt % after deduction of 0.77 wt % SiO2 and 0.53% Fe203

at approximately the elevation of these upper workings. Microscopic study of the relevant drill cores indicates that oxidation and supergene alteration are insignificant except at one site in the North Sulphide Body, and at a few places where the pyritite has been disrupted by major faults. Even for the fault zones only minor alteration has been observed in polished sections, but it must also be cautioned that the samples collected generally represent the most cohesive of the drill-core remnants.

A small amount of supergene covellite is present in cores from drillhole 32 of the Northwest Body (Fig. 14), but the amount is negligibly small in terms of the volume of base-metal sulphides affected by covellite coatings. Alteration at this site may have been related to major faulting (Fig. 18).

The most extensive supergene alteration detected in the drill cores occurs at section G'-G in the North Body (Fig. 24). According to Boorman (1975), oxidation at Caribou reaches its deepest level in this area and apparently penetrates to within about 15 m above the adit level. Surface drillholes 10 and 26 intersected the massive sulphides above and just below the adit level (Fig. 24). Ten drill-core samples of pyritite from footages 105 to 168 in the upper drillhole were collected by the New Brunswick Research and Productivity Council, and 12 polished sections of these were examined in this study. Thirty-one samples, most collected by the writer, were available from drillhole 26 and all were examined microscopically.

Although supergene sulphides were not observed in the polished sections from drillhole 10, the middle part of the lens contains microscopic veinlets and pockets of litharge. In drillhole 26, supergene digenite and covellite occur erratically from the hanging-wall contact to almost exactly the middle of the pyritite. Most polished sections in this interval have no supergene sulphides, but some contain litharge. Drillhole 62-11 (Fig. 24) lacks supergene sulphides, but litharge is present in pyritite near the hanging-wall contact. The above results indicate that oxidation has penetrated the pyritite to an appreciable depth. However, the amounts of digenite and covellite are small, both in quantity and terms of the volume of base-metal sulphides that they coat. Litharge is more abundant, but most of it is concentrated in pockets in the silicate-carbonate gangue.

Supergene-type sulphides also are present in small amounts in one of the several thin lenses at the termination of the East Body where it overlaps the South Body. The occurrence is in a zone of disturbance, and is minor in terms of sulphide mass affected.

ALTERATION OF EMULSION-TYPE SULPHIDES

Two principal emulsion-type sulphide intergrowths are present in Caribou primary ore: galena in sphalerite (Fig. 40), and chalcopyrite in sphalerite (Fig. 41). In the supergene zone, galena rather than chalcopyrite or sphalerite seems to have been the most susceptible to replacement by digenite and covellite. Galenasphalerite emulsions show that pseudomorphism of galena by copper sulphides preceded any significant replacement of the enclosing sphalerite (Fig. 42). On the other hand, chalcopyrite blebs seem to have been more resistant to replacement than the host sphalerite. This resistance is especially evident in network textures wherein the chalcopyrite blebs are visible as residual islands in the digenite-covellite veinlets that cut the sphalerite. Thus, the ease of replacement seems to have been: galena (easiest), sphalerite, chalcopyrite, pyrite.

FLOTATION OF SUPERGENE COPPER ORE

The presence of lead and copper sulphate minerals in the interstices of massive sulphides at or near the bottom of the supergene zone suggests that these minerals were also in ore mined in the open-pit operations, and the relevant metals were lost to tailings. The sulphates commonly occur as coatings on primary sulphides and as complex intergrowths with the supergene sulphides; the effects are to hinder the liberation

Fig. 40 - Top left. Selective replacement in the Caribou supergene sulphide zone: scattered crystals of pyrite (py) in sphalerite (sp) peppered with minute blebs of galena (white) in emulsiontype texture. Galena and sphalerite have been partly replaced by digenite (lighter grey, dg) which appears to have largely followed microfractures in the sphalerite. West open pit; reflected light, oil immersion; bar scale 0.10 mm.

Fig. 41 - Top right. Same sample and conditions as for Fig. 40, but showing more clearly the exceptional selectivity of initial replacement: fine-grained galena (white) and coarse pyrite (py) in a matrix of sphalerite; on the right half nearly all of the galena has been replaced by digenite without significant destruction of the original galena-sphalerite intergrowth texture.

Fig. 42 - Bottom left. Advanced stage of supergene alteration in which the main component is digenite (dg) that has completely replaced sphalerite but has made only moderate inroads on chalcopyrite (cp); pyrite (py) unaffected. Cracks in digenite are partly filled with copper sulphates and other oxidation minerals. Reflected light, oil immersion; bar scale 0.01 mm.

of pure sulphides and also to reduce the size of sulphide grains.

Anaconda Caribou apparently was unable to produce separate copper and zinc concentrates from the supergene ore. The bulk concentrate contained more than 60 wt % pyrite, and almost half the copper and zinc from the ore was lost to tailings (Boorman 1975).

Little information concerning the nature of the minerals in the concentrates and tailings is available to this writer. However, characteristic features of the supergene ore are the fine grain size of much of the copper sulphides, their widespread occurrence as network veinlets in sphalerite, and their presence as rims on sphalerite and pyrite. A key factor hampering monomineralic liberation is that replacement of sphalerite by the copper sulphides rarely has been complete, even where sphalerite grains are very small. Thus the general effect has been to add another sulphide component per unit area rather than to have one-for-one substitution. In other words, grain-boundary contacts in a primary pyrite-sphalerite assemblage have changed from pyrite-sphalerite to, in the simplest supergene case, pyrite-digenite, pyrite-sphalerite, digenite-sphalerite. Grinding to a size adequate for pyrite-sphalerite liberation would be ineffective for most of the digenite-bearing assemblage.

PROCESSING PROBLEMS

Results from the examination of mill products from pilot-plant tests done at CANMET in 1974 are reported by Johnson (1975) and Petruk (1975a, b). The tests were done on bulk samples from cross-cuts on the 6200 level of the South and East Bodies.

The need for fine grinding to achieve acceptable levels of ore-mineral concentration with conventional flotation procedures is indicated by the low average grain size of Caribou pyrite. The size of the pyrite is of critical importance because it is necessary to separate pyrite inclusions that occur abundantly in the base-metal sulphides, or more frequently, to separate the sulphides that are interstitial to pyrite. Substantial variations in pyrite grain sizes occur locally and are partly a reflection of the proportion of framboidal-type pyrite in a particular area; these variations occur both laterally and vertically. In the practical terms of mining operations, there is no systematic variation in pyrite grain sizes from footwall to hanging wall, that is, between the low-grade and high-grade ores, nor do average grain sizes of pyrite vary appreciably from lens to lens. Thus pyrite crystals in all parts of the deposit are of the same general size and size range. As the Caribou pyritite is slightly finer grained than that at Brunswick No. 12 mine (Fig. 1), in specific terms this means that conventional processing will require that the Caribou pyritite be ground finer than the 65% -400 mesh (<37um) primary grind used by Brunswick Mining and Smelting Corporation (McTavish 1980).

ETCHED VERSUS UNETCHED GRAIN SIZES

A standard procedure used at CANMET to determine grain sizes and their distributions is to examine material in polished sections using a Quantimet image analyzer (e.g. Petruk 1975a, b). It should be noted that Quantimet grain sizes will not necessarily coincide with those reported here. For example, polyframboidal masses are common at Caribou, but they are clearly defined only after etching polished surfaces with acid, a procedure which was used throughout this study. However, etching of mill products is generally not feasible because of the minute size of the particles, and thus the multi-grain character of fine-grained, homogeneous pyrite aggregates might be undetected by image analysis: the value obtained would be the particle size rather than the grain size.

The same phenomenon can be illustrated with a hypothetical example in which a largely monomineralic layer or patch of sphalerite is present; without etching the particle size is apparently very coarse, but after etching the sphalerite, it can be seen to consist of a finegrained mosaic of grains. If alternate sphalerite grains in the mosaic were replaced by pyrite, the true grain size would be unchanged, but the apparent grain size, which is now the pyrite-to-pyrite distance, would be reduced drastically. In dealing with Caribou samples, grains of pyrite, galena, and magnetite are usually copiously incorporated in sphalerite, thereby reducing the extreme size differences noted for the hypothetical example. It is evident, however, that mineralogical and Quantimet values for "grain" sizes may be quite dissimilar (cf. Hughson 1981).

SULPHIDE LIBERATION

The expected recoveries of zinc, lead and copper can be inferred on the basis that pyrite is similar from lens to lens, and therefore the liberation characteristics of sphalerite, galena, and chalcopyrite also will be similar from lens to lens.

Zinc: in high-grade ore one of the typical features is that sphalerite occurs abundantly as laminae. These always contain variable amounts of galena, pyrite, and magnetite as inclusions, but on the whole the laminae have a relatively coarse liberation size. Adjacent to the laminae, or in their absence, sphalerite fills spaces among pyrite grains. Initially the largest areas only are filled, but progressively smaller areas are occupied as the amount of sphalerite increases. Therefore, in high-grade zinc ore, most of the sphalerite can be recovered, but some will be very fine grained and not amenable to ready liberation. The overall effect is that the highgrade heads will yield abundant zinc, but there also will be high zinc values in the tailings.

In low-grade zinc ores the proportion of sphalerite that occurs in laminae is much lower than in high-grade ores. Recoveries will be largely dependent on the amounts of sphalerite in coarse versus fine interstices, but in general it is thought that low heads will also yield tailings that have a lower zinc content than those of highgrade ore.

Lead: recoveries of lead should be much lower than those of zinc because galena is finer grained than sphalerite and often occurs in the smaller interstices. In high-grade ores much of the galena is intimately associated with sphalerite and should be liberated with it. In low-grade ores the association of galena and sphalerite is less intimate, but galena remains fine grained and a high proportion of it occurs as minute inclusions in pyrite masses. The anticipated effects are that high-grade lead heads will yield abundant Pb, but there also will be relatively high Pb in the tailings; low-grade lead heads will yield less Pb, and there will be high Pb content in the tailings.

Copper: recoveries of copper are more difficult to estimate than those for galena. In samples with several per cent chalcopyrite, most of the mineral occurs as relatively coarse grains and veinlets, and therefore good recovery would be expected. Only a very minor amount of the chalcopyrite in the deposit occurs in this manner.

In most of the pyritite, chalcopyrite is associated with galena and sphalerite, and also occurs abundantly in pyrite. The association with pyrite is especially conspicuous in footwall parts of the massive sulphide lenses where basemetal values are low and chalcopyrite occurs predominantly as numerous minute disseminated Pyritite of this type and with low Cu blebs. values will have very large losses to the tailings. In pyritite with either low-grade or highgrade Pb + Zn and with low Cu heads, it is anticipated that Cu in the tailings will be proportionately high. However, if Cu heads increase above a base level of about 0.4%, it is anticipated that the percentage loss from the Cu fraction above the base level will decline substantially.

Silver: the distribution and mineral sources of silver at Caribou were studied by Jambor and Laflamme (1978) who established that silver is not uniformly partitioned throughout the deposit. In the East Sulphide Body most of the silver is present in solid solution in tetrahedrite, whereas in the other sulphide lenses a very high proportion of their silver occurs in solid solution in galena. The East Body has the highest average silver content, but because of the importance of tetrahedrite, it is thought that Ag values in the tailings will be lower than for the other sulphide lenses. Most of the recoverable silver should report to a copper concentrate.

The South Sulphide Body is thought to have a silver content which averages less than the Caribou ore-reserve grade of 1.7 oz/t. Tetrahedrite occurs only sparingly, and most of the silver is in solid solution in galena. However, in the central, thickest part of the lens, Pb averages less than 0.7%. Galena, together with its contained silver, will suffer a high loss rate to tailings. Most of the silver that is recovered should be in the lead concentrates.

Silver in the North and Northwest lenses occurs partly in galena, and partly in tetrahedrite. The silver content of these lenses is low, and recoveries should follow patterns intermediate to those for the East and South Bodies.

Gold: all of the gold at Caribou is concluded to be present as electrum which occurs as isolated grains in galena and chalcopyrite, and along pyrite grain boundaries rather than as inclusions in individual pyrite grains. Thus there is no textural feature inhibiting liberation, which will be largely dependent on the fineness of grinding.

UNCONVENTIONAL PROCESSING

unconventional Various ore-processing methods such as chlorination, high-pressure leaching, and sulphation roasting have been under study by organizations attempting to achieve higher metal recoveries from Bathurst-type massive sulphides. It is hoped that the present study provides an adequate documentation of the character of the Caribou ore, thereby restricting the options for processing to those which recognize the constraints imposed by the fine grained nature of the base-metal sulphides. For example, assumptions that a crude grind will make the pyritite more amenable to chemical attack, or that an initial coarse grind will achieve significant liberation of either the base-metal sulphides or the silicates and carbonates, simply are not in harmony with the established character of the ore. Crude grinding of Caribou pyritite will achieve

little for processes that do not involve total consumption of the pyritite. The interstitial disposition of the silicates, carbonates, and much of the base-metal sulphides has been stressed; none of these minerals will be affected to a significant extent by a coarse grind.

OXIDATION EFFECTS

Some of the problems concerning the processing of oxidized ores have been dealt with in the section on supergene alteration. It should be noted that the presence of hematite or marcasite in mill products is not necessarily a sign that the samples have been oxidized: both minerals are also constituents of primary ore.

Of principal concern here is whether in situ oxidation of primary ore is a problem. According to Johnson (1975), one bulk sample of 25 t submitted to CANMET for pilot-plant tests of representative primary ore had to be rejected because it contained up to 10% covellite. Furthermore, covellite was reported by Johnson to be present in practically all of the mill products from other bulk samples. The present study has shown that covellite is not a constituent of unaltered primary ore, and thus rejection of the covellite-rich bulk sample was valid. However. the presence of large amounts of covellite in material that was specifically selected for tests of primary ore raises serious questions as to why the covellite was present. The possibility that in situ alteration has occurred in some of the mine workings cannot be resolved without further studies that are dependent on renewed access to the underground sample sites.

In addition to the problem concerning covellite, another difficulty that might arise in testing bulk samples is an effect readily seen on laboratory samples. Wet drill cores, especially those that are porous, upon drying commonly become coated with sulphate blooms. Fine-grained, compact pyritite usually does not develop a megascopic bloom, but frequently it is evident from the change in surface properties and taste that an invisible film of sulphate has formed on the cores. Under normal atmospheric conditions, exposure of wet pyritite can result in the pre-
cipitation of surface sulphates within a matter of hours.

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