MINERALOGY OF THE YELLOWKNIFE BAY AREA, N. W. T.[1]

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ABSTRACT

The gold ores of the Yellowknife Bay area represent a type quite different from those found elsewhere in the Precambrian Shield of Canada, if not in all other parts of the world. They represent a close association of gold with the element antimony, with a virtually complete absence of the element tellurium.

From a study of polished sections of these ores, the author has arrived at some conclusions as to their chemical nature and their manner of formation.

The formation of the ores is believed to have taken place during several distinct periods by filling of zones of dilation accompanied by some metasomatic replacement. Each period was marked by the introduction of an ore-forming fluid of a composition dissimilar to those introduced during other periods. The emplacement of these fluids is believed to have been effected by successive dilations of the rocks in response to periodic deformations.

The first solution producing metallic mineralization, is believed to have been rich in Fe, As and S. A solution rich in S, Cu, Zn possibly Fe and minor Sn is considered to have produced the mineralization of the second period, whereas that of the third and last period

[1] Part of a thesis submitted to fulfill requirements for the degree of Master of Arts, Queen's University, 1952.

is believed to have been effected by an antimony-rich solution containing S, Au, Ag and Pb. Many of the elements contained in minerals formed during the last two periods, are believed to have been derived from older minerals which have been replaced. Gold appears to have been deposited principally within the last period of mineralization, in close association with a suite of antimony-rich sulphosalts. Visible gold is present in greatest amounts where sulphosalts are most abundant.

In all, 119 polished section of ores from eight gold properties in the Yellowknife Bay area, were studied. The metallic minerals identified include three native elements, 12 sulphides, one antimonide, 10 sulphosalts and one oxide. This extensive array of minerals is composed of relatively few chemical elements: Au, Ag, Fe, Cu, Zn, Pb, Sn, Sb, As and S.

Aurostibite, a relatively new mineral, is described and its economic importance is discussed. The importance of *x*-ray powder identifications in studies of complex ores, is noted.

INTRODUCTION

The summer of 1950 was spent by the writer on a reconnaissance party of the Geological Survey of Canada, operating out of Yellowknife, N.W.T. In June of that year, the author was asked by Mr. R. W. Boyle, a graduate student at the University of Toronto, to undertake a study of the mineralogy of the ores from the mines of the Yellowknife Bay area, as part of a general research project involving study of the structural geology, the wall rock alteration associated with the shear zones, and the temperatures of deposition of the pyrite and quarts.

A previous study of the Yellowknife ores by Ridland (1941), had indicated the presence of an astonishing variety of minerals, but it was felt that this required confirmation by more precise methods of mineral identification.[1]

During the summer of 1950, a suite of samples was collected by Mr. Boyle for study by the author. This suite included samples of ore from the Giant Yellowknife, Con, Rycon, Negus, Akaitcho, Lynx and Captain properties. Polished sections of these samples were prepared at Queen's University. Another suite of polished sections was suppled by Dr. A. W. Jolliffe, and included specimens from the Giant Yellowknife, Con, Rycon, Negus and Ptarmigan properties; some of these specimens comprised part of the suite that had been studied by Dr. Ridland in 1940. These two suites were studied under a reflecting microscope. Because of the fine-grained intergrowth of the minerals, and the fact that many of the minerals observed had very similar optical and physical properties, considerable use was made of *x*-ray powder diffraction methods in their identification.

[1] Minerals reported by Ridland which have not been identified in the present work, are: the sulpharsenides (jordanite, guitermanite and lengenbachite) and the tellurides (nagyagite, sylvanite, calaverite, altaite and rickardite); the presence of tantalite, leucopyrite and cobaltite is regarded as questionable. The author examined polished sections in which Ridland had identified the above minerals, and identified all minerals in them by *x*-ray powder diffraction methods.

GENERAL GEOLOGY

West of Yellowknife Bay, lava flows and interbanded fragmental rocks of the Yellowknife Group of Precambrian age, strike northeasterly and dip vertically or steeply southeastwards, with progressively younger members from northwest to southeast. They are intruded by many sills and dikes of altered diorite and gabbro, and by later unaltered diabase dikes. The whole belt is much disrupted by faults of two types: (a) early pre-diabase faults and (b) late post-diabase faults.

Most of the early faults are of the shear-zone type, along which chlorite schist or chlorite-sericite schist is developed across widths ranging from a few inches to several hundred feet. The post-diabase faults, on the other hand, are clean-cut, narrow fissures. The rock along them is brecciated, and a clay-like gouge may be present, but no schist has been formed.

The gold deposits of the area occur along the early shear-zone faults. They may be divided into two closely related types: (1) well-defined quartz veins introduced along narrow shear zones such as occur on the Rycon property, and (2) large lenticular masses of highly mineralized sericite schist and vein quartz that occur along shear zones, or systems of shear zones, up to several hundred feet wide. Included in the latter type are the Campbell Shear on the Negus property, and the large orebodies along the Con and Giant shear-zone systems.

For more detailed descriptions of the geology of this area, the reader is referred to works by Jolliffe (1942, 1946) and Henderson & Brown (1950).

Mineralogy—General Considerations

The mineralogy of the Yellowknife ores is very complex. This complexity is due to a number of factors: the variety of minerals present, the similar optical and physical properties of many of these, and the fine texture and intimate intergrowths.

At first sight in the field, the vein material appears to be nearly barren of metallic minerals. On closer examination, these minerals are found to occur in small clusters or nests, in fine seams or veins, and in disseminated grains throughout the vein quartz and intermixed carbonates.

Because of the aforementioned complexity of the mineralogy, x-ray diffraction methods were extensively employed in the identification of the minerals. It was found that not only could identifications be made of mineral particles which were much too small for investigation by etch reactions and microchemical methods, but also that these identifications were of a very positive nature, since each mineral produced a distinctive powder pattern. Hence a true picture of the mineralogy of ores of this nature, can be obtained with certainty, only by employing such methods.

The following mineralogical description and discussion is based on a study of 72 polished sections made from the suite of samples collected by Mr. Boyle, and of 47 polished sections, supplied by Dr. Jolliffe, which had been prepared at the Mines Branch Laboratories, Ottawa. Of these 47 polished sections, 33 were part of a suite studied by Ridland (1941) in connection with his doctorate thesis, at Princeton University, from 1938 to 1940.

Considerable differences exist between the mineral identifications made by Ridland and those made by the author. These discrepancies are attributed to the differences in identification techniques employed. It is the author's opinion that, although Ridland's work was of a very careful and thorough nature, he was seriously handicapped in that his identifications were based on etch reactions and microchemical tests, rather than on the more precise x-ray diffraction methods.

Occurrence and Distribution of Minerals

The following minerals were identified by x-ray powder diffraction methods:

1. Native Elements:
   - Gold — Au
   - Lead — Pb
   - Antimony — Ab
2. Sulphides:
   - Pyrite — FeS_2
   - Marcasite — FeS_2
   - Pyrrhotite — $Fe_{1-x}S$

Arsenopyrite	FeAsS
Gudmundite	FeSbS
Sphalerite	ZnS
Chalcopyrite	$CuFeS_2$
Stannite (zincian)	$Cu_2(Zn, Fe)SnS_4$
Galena	PbS
Stibnite	Sb_2S_3

3. Antimonide

Aurostibite	$AuSb_2$

4. Sulphosalts

Zinkenite	$Pb_6Sb_{14}S_{27}$
Semseyite	$Pb_9Sb_8S_{21}$
Boulangerite	$Pb_5Sb_4S_{11}$
Meneghinite	$Pb_{13}Sb_7S_{28}$
Berthierite	$FeSb_2S_4$
Chalcostibite	$CuSbS_2$
Jamesonite	$Pb_4FeSb_6S_{14}$
"Mineral Q"	Fe, Cu, Sb sulphide (minor Pb, Ag)
Vournonite	$PbCuSbS_3$
Tetrahedrite	$(Cu, Fe)_{12}(S_b, As)_4S_{13}$

5. Oxide

Cassiterite	SnO_2

Besides the minerals listed above, chalcocite and covellite were noted in polished sections in minor amounts and were readily identified on the basis of their distinctive optical properties. In hand specimens taken from weathered outcrops, the following secondary minerals were also noted: limonite, malachite and azurite.

The ores from the properties in the Yellowknife Bay area are, in general, of one mineralogical type. That is, the suite of minerals that occurs in the ores is consistent throughout. There are, however, some differences in the relative amounts of these minerals, in specimens from different deposits within the area.

On a quantitative basis, the general type may be subdivided into: ores in which sulphosalts are the principal metallic minerals (Type I), and those in which sulphides predominate (Type II).

Type I is exemplified by ores from the shear-zones on the Rycon property and those in the large shear-zones on the Giant property contiguous to No. 2 shaft. Other ores which fall in this group, are those from minor shears on the Con property and from those shears on the Negus property which represent extensions of the Rycon shears. All samples, studied by the writer, from the Akaitcho property belong to Type II, however it has been learned from Mr. Boyle and the geologists of that property, that a more representative suite would show Type I affiliations.

Ores from Con C4 Shear, the Campbell Shear on the Negus property and the Cameron Shear on the Giant property, are of Type II. Ores

from the Lynx and Captain properties also appear to belong to this group. However, the specimens obtained from these properties were collected at a relatively early stage in their development and may not be truly representative.

From the samples studied, ores of Type I are found principally in a gangue of quartz, which may, according to Boyle, be of at least three distinct ages. Stringers and segregations of carbonates occur in the quartz. The predominant metallic minerals are the soft, grey, sulphosalts, although sulphides (particularly pyrite, arsenopyrite and sphalertie) are present in appreciable amounts. Microscopically visible gold is more common than in ores of Type II and the particles in which it occurs are usually of larger dimensions.

The gangue for ores of Type II consists not only of quartz and carbonates but also sericitic schist. The principal metallic minerals are pyrite and arsenopyrite, with sphalerite and chalcopyrite in lesser amounts. sulphosalts are present, but neither in the quantity nor variety encountered in Type I. Gold, where present, is in fine disseminations.

Only three specimens from the Ptarmigan property were studied, an insufficient number to permit classification. No sulphosalts were observed in these samples, nor have they been seen in the field. The sulphides are of the same variety and relative abundance as those in other ores in the area, and their interrelationships appear to be the same. Gold occurs in one sample in several minute blebs, not in contact with the accompanying minerals.

MINERALOGY—PARTICULAR ASPECTS

In the succeeding sections, a number of theories are formulated concerning the relations of the metallic minerals to each other, and their paragenesis and mode of formation. These theories are postulated on the basis of the evidence available to date and hence represent only present probabilities. The author feels that hypotheses of this nature, which are within the realm of speculation, are justified even if they serve solely as a stimulus to further investigation.

The ores from the Yellowknife Bay area are very complex. Therefore. their paragenesis and mode of formation are probably also quite complex. To arrive at a positive conclusion as to the manner of their formation, study should be made of more samples having a wider distribution than those available to the writer. Until such a study is possible, the following observations and hypotheses may serve as a guide to an understanding of the mineralogy of this economically important area.

During the investigation, 23 ore minerals were identified which were introduced either prior to or during the period in which most of the

gold was deposited. Besides these, there are five more metallic minerals which were probably formed at a much later time, and are presumably of supergene origin. Their occurrence is of little import in a consideration of the formation of the ores.

In his work on the mineralogy of the area, Ridland (1941) stated " . . . practically every polished section examined added another mineral to the list of species already recorded. In other words, if the number of sections studied had been doubled, the list of minerals would probably be increased substantially." The author does not agree with this. The great majority of minerals identified in the present study, were noted at a relatively early date, and further work served principally to confirm their presence and associations, but added relatively few new members to the existing array. More intensive investigations would doubtless result in a few additions but these would probably fit into the general pattern already established.

The present suite of ore minerals consists of a number of native elements, sulphides, sulphantimonites and antimonides, in which the metallic elements are Au, Fe, Cu, Zn, and Pb, with Ag and Sn present also in minor amounts. Presumably, any new addition would be composed of elements contained within the group: Au, Ag, Fe, Cu, Zn, Pb, Sn, Sb, As and S.

ORE MINERALS—DESCRIPTIONS AND RELATIONS

Pyrite, Arsenopyrite and Gudmundite

Pyrite is ubiquitous throughout the samples and is the most abundant metallic mineral. It occurs not only in the vein material, but also, in considerable amounts, in the adjoining wall rocks. Much pyrite in the ore zone is found in remnants of wall rock included in the quartz and carbonate vein material. Most of the pyrite is quite coarse-grained and exhibits development of crystal forms which, in many cases, have been modified either by fracturing and granulation, or else by partial replacement by gangue or later metallic minerals, A colloform and vuggy form occurs in specimens collected in proximity to late post-ore faults. This latter type is extensively replaced by or altered to marcasite, presumably through the action of late solutions circulating along the faults.

In all specimens where pyrite was noted in contact with other metallic minerals, the pyrite appears to be the oldest ore mineral present, with the exception of arsenopyrite. Remnants of pyrite are common within such minerals, or these minerals fill fractures within the pyrite (Fig. 1) or partially replace it. In some places, the age relations between pyrite and other metallic minerals are not apparent, but (again excepting arsenopyrite) in no case does the pyrite appear to be younger.
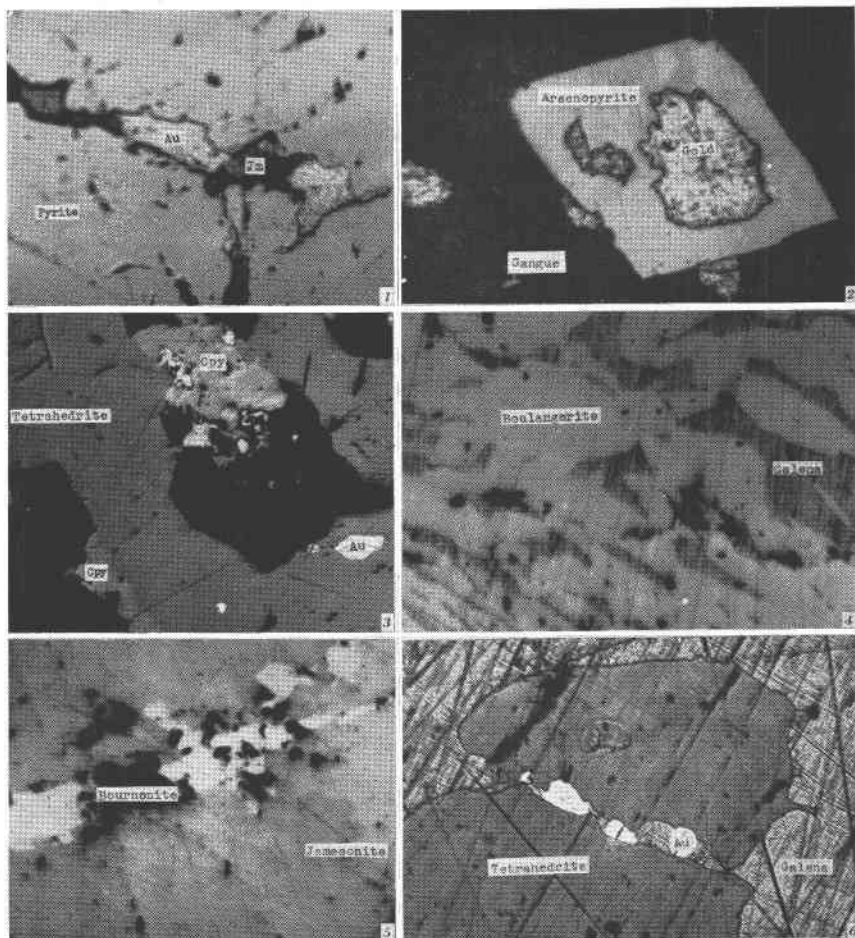
FIG. 1. Gold (Au) associated with jamesonite (Jm), veining pyrite, Rycon, vein EF, ×270.

FIG. 2. Gold replacing a crystal of arsenopyrite, Giant, first level, ×146.

FIG. 3. Tetrahedrite apparently invading chalcopyrite (Cpy) and gangue. The chalcopyrite probably was originally present as veins in the gangue and is evidently replaced to a greater extent than the gangue. Gold (Au) appears to be intimately associated with the tetrahedrite, Negus, vein 6, ×93.

FIG. 4. Galena, stained with FeCl₃, in boulangerite, Giant, 408 stope, ×134.

FIG. 5. Jamesonite, stained with KOH, veined by bournonite, Giant, 205 stope, ×122.

FIG. 6. Blebs of gold (Au) in a stringer of galena, stained with FeCl₃, which transects tetrahedite, Negus, 1399 stope, ×202.

Arsenopyrite, like pyrite, is a persistent mineral thoughout, but is quantitatively less important than the pyrite. Its two most common modes of occurrence are as well-formed diamond-shaped or rectangular grains, and as fine-grained granular masses.

In all observed instances, arsenopyrite appears to be older than all associated metallic minerals. It commonly forms euhedral inclusions within the younger minerals and in some cases such minerals are observed partially replacing grains of arsenopyrite (Fig. 2).

Gudmundite was identified in one sample only. It occurs as a fine-grained granular mass which may have been formed by the action of late antimony-rich solutions on a granulated mass of arsenopyrite. The occurrence of such masses of arsenopyrite within the same sample supports this idea.

Sphalerite, Chalcopyrite, Pyrrhotite and Stannite

Sphalerite, chalcopyrite, pyrrhotite and stannite appear to be closely associated. Sphalerite is the most prominant of these four minerals, but is commonly accompanied by one or more of the other three. Conversely, nearly all occurrences of chalcopyrite, pyrrhotite and stannite are accompanied by abundant sphalerite.

Much of the sphalerite observed has a broken appearance, and, when polished, plucks readily to give a rough, uneven surface. Sphalerite appears to be older, in time of formation if not in time of introduction of its constituents, than all other metallic minerals excepting pyrite and arsenopyrite. Chalcopyrite and pyrrhotite, which were probably formed from the same solutions as the sphalerite, appear to be slightly younger than sphalerite in time of formation. In most cases, the later metallic minerals occur as rims about associated sphalerite, but in some cases they are observed veining it or containing inclusions of it.

Most of the sphalerite is probably of the iron-rich variety marmatite. In hand specimens, it possesses a dark brown to black colour, indicative of an appreciable iron content. Much of the pyrrhotite observed in the samples occurs as fine disseminated blebs throughout the sphalerite, possibly formed by exsolution from an iron-rich sphalerite after its crystallization.

Chalcopyrite, in most instances closely associated with sphalerite, has two principal modes of occurrence—either in discrete bodies (Fig. 3), or in round or elongate blebs within sphalerite, commonly aligned along its cleavages. This latter occurrence is suggestive of an origin either by exsolution from sphalerite, or by preferential replacement of sphalerite along cleavage planes. Both mechanisms may have been operative; the disseminated blebs are more likely to have been formed by

exsolution, whereas the aligned and elongated blebs and veinlets are more probably the product of replacement. Where larger bodies of chalcopyrite are observed in contact with sphalerite, the mutual relations either indicate contemporaneity, or else suggest that the chalcopyrite is the younger in time of solidification.

Zincian stannite[1] was found in only one specimen and in but minor amounts. Its association with other minerals was indeterminable, but its chemical composition and structure link it with sphalerite and chalcopyrite. This mineral probably accounts for much of the tin reported in assays of Yellowknife ores.

Galena

Galena appears to be closely associated with sulphosalts, and younger in age than all other sulphides except stibnite. It occurs alone or intimately associated with sulphosalts (Figs. 4, 6). In the latter association, galena appears to be either closely contemporaneous (Fig. 4) or slightly older. In a few instances, it appears to have formed at a slightly later date (Fig. 6), and embays or veins sulphosalts.

Stibnite

Stibnite was found in a few sections. It most commonly occurs as massive segregations in which are disseminated minor sulphosalts. In such samples, other sulphides occur only in minor amounts. The sulphosalts associated with such stibnite appear to have been formed contemporaneously or slightly later, possibly by reaction of stibnite with included sulphides. Native antimony is occasionally associated with massive stibnite and sulphosalts, and exhibits no definite age difference.

Some stibnite occurs in minor amounts in samples in which the relative abundance of sulphosalts to sulphides is high. In one sample, stibnite was noted in an intimate intergrowth with gold (Fig. 12). This occurrence will be dealt with in a later section.

In both modes of occurrence, stibnite appears younger than all associated sulphides since either it veins them or else they occur as remnants within it. Its age relations to the sulphosalts are indefinite, and it is probably either contemporaneous with them or slightly older. In no instance was it found in the vicinity of galena. Its presence is interpreted as indicating a localized high antimony-lead ratio in the mineralizing solutions, whereas the presence of galena suggests the opposite.

[1] Determined by its powder diffraction pattern, which is similar to that of stannite but exhibits the slight expansion of the zincian variety.

The Sulphosalts

Sulphosalt associations, both among themselves and with the sulphides, exhibit certain uniformities in the Yellowknife ores.

All sulphosalts observed in these ores are sulphantimonides. No true sulpharsenides have been identified by *x*-ray powder diffraction methods. Some of the tetrahedrite appears to be arsenical and grading into tennantite;[1] this is possibly the result of absorption of arsenic from arsenopyrite.

Where more than one sulphosalt appears in one specimen, the varieties present usually have some chemical similarity. Meneghinite was noted only in samples containing considerable galena, boulangerite or both. This suggests that meneghinite is able to form only in an environment in which lead is abundant, and in which the ratio of antimony to other metallic ions is low (Table 1). Zinkenite was found in specimens in which neither galena nor boulangerite occur, and in which stibnite is commonly found. This suggests that a favorable environment for zinkenite is one in which the ratio of antimony to other metallic ions is high.

The sulphosalts appear to have a chemical similarity to the associated pre-existing metallic minerals. Tetrahedrite is commonly associated with chalcopyrite (Fig. 3) and appears to replace it. Chalcostibite was found only where there were older copper minerals, as was commonly bournonite. Berthierite occurs principally with abundant pyrite or arsenopyrite. These associations suggest that some of the constituent metallic elements of the suphosalts, were present before the introduction of the solutions from which these minerals formed. Much of the sulphosalts may have been formed by reaction of pre-existing sulphides with an antimony-rich fluid.

All the sulphosalts seem close in age of formation, although minor apparent age differences are noted (Figs. 5, 7, 8). Jamesonite, which is most abundant, commonly appears to have been deposited at an earlier time than the others (Figs. 5, 8). This suggests that jamesonite may form more readily than the other sulphosalts, and hence would tend to form first from the antimony-rich solutions, with the varieties of subsequent sulphosalts formed, dependent on the residual constituents available.

Unlike the sulphides, the sulphosalts exhibit little evidence of having been subjected to differential stresses. Whereas the sulphides are commonly fractured and granulated, the sulphosalts exhibit only minor

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[1] From the Captain property in the North part of the area, which may have a different mineralogy than the properties to the South. Also, some tetrahedrites from wall rocks of the Giant and Negas properties, appear to be arsenical on the basis of dimensions of their unit cell.

TABLE 1. CHEMICAL ASPECT OF YELLOWKNIFE ORE MINERALS

Mineral	Formula	Other Metal Atoms Sb	Mol % S	Metal Ions
Gold	Au		0.0	Au
Aurostibite	$AuSb_2$	1:2 = 0.5	0.0	Au
Antimony	Sb	0:1 = 0.0	0.0	Sb
Stibnite	Sb_2S_3	0:1 = 0.0	60.0	Sb
Pyrrhotite	$Fe_{1-x}S$		50.0−	Fe
Pyrite	FeS_2		66.7	Fe
Marcasite	FeS_2		66.7	Fe
Arsenopyrite	FeAsS	1:1[1] = 1.0	33.3	Fe
Gudmundite	FeSbS	1:1 = 1.0	33.3	Fe
Berthierite	$FeSb_2S_4$	1:2 = 0.5	57.2	Fe
Chalcocite	Cu_2S		33.3	Cu
Covellite	CuS		50.0	Cu
Chalcostibite	$CuSbS_2$	1:1 = 1.0	50.0	Cu
Sphalerite	ZnS		50.0	Zn
Lead	Pb		0.0	Pb
Galena	PbS		50.0	Pb
Zinkenite	$Pb_6Sb_{14}S_{27}$	3:7 = 0.43	57.4	Pb
Semseyite	$Pb_9Sb_8S_{21}$	9:8 = 1.12	55.3	Pb
Boulangerite	$Pb_5Sb_4S_{11}$	5:4 = 1.25	55.0	Pb
Meneghinite	$Pb_{13}Sb_7S_{28}$	13:7 = 1.86	58.4	Pb
Chalcopyrite	$CuFeS_2$		50.0	Cu:Fe = 1:1
Tetrahedirte	$(Cu, Fe)_{12}(Sb, As)_4S_{13}$	3:1[1] = 3.0	44.6	Cu:Fe = 1:1[2]
Stannite	$Cu_2(Zn, Fe)SnS_4$		50.0	Cu:(Fe,Zn):Sn = 2:1:1
Jamesonite	$Pb_4FeSb_6S_{14}$	5:6 = 0.83	56.0	Pb:Fe = 4:1
Bournonite	$PbCuSbS_3$	2:1 = 2.0	50.0	Pb:Cu = 1:1

[1] One atom of As is considered the equivalent of one atom of Sb.

[2] An approximation.

evidences of strain. Under polarized light, some grains of anisotropic varieties have a wavy extinction similar to that exhibited by strained quartz. This, plus the occurrence of considerable polysynthetic twinning, suggests that the sulphosalts were subjected only to minor stresses.

Gold

Native gold occurs throughout the area. It appears to be closely associated with the sulphosalts although, in many cases, it embays them and is hence probably slightly younger. The quantity of visible gold is greatest in those specimens in which sulphosalts are most abundant, and in which they have the lowest ratio of other metallic ions to antimony (Table 1). Other minerals commonly associated with gold are aurostibite, arseno-
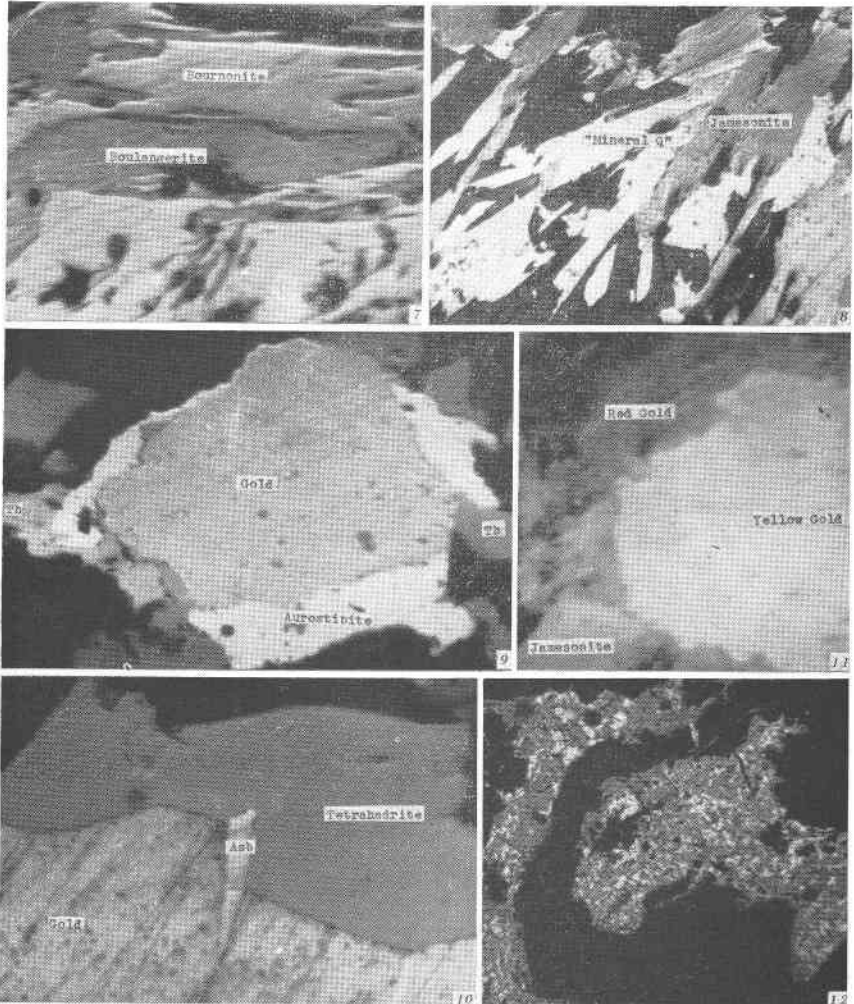
FIG. 7. Intergrowth of bournonite and boulangerite, stained with HCl fumes, Giant first level, ×81.

FIG. 8. Intergrowth of jamesonite, stained with KOH, and "Mineral Q," Giant, Brock Zone, ×81.

FIG. 9. Gold rimmed by aurostibite, in a vein of tetrahedrite (Th), Rycon, shear 57, ×202.

FIG. 10. Aurostibite (Asb) transecting a contact between gold and tetrahedrite, Rycon, shear 57, ×263.

FIG. 11. Yellow gold, rimmed by red gold, in jamesonite, Rycon, shear 51, ×182.

FIG. 12. "Purple Gold"—a fine intergrowth of stibnite (grey) and gold (white), Rycon, shear 54, ×284.

pyrite and sphalerite. The gold appears to be of more than one variety, and of possibly more than one depositional age. One variety (Type 1), which possesses a light yellow colour and hence is probably richer in silver, seems to be older than the others.

The most abundant type of gold (Type 2) has a rich yellow colour. It occurs deposited on crystal faces of arsenopyrite (Fig. 2), as blebs in sulphosalts (Fig. 6), as fairly coarse grains within the sulphosalts (Figs. 9, 10, 11) or within sulphides (Fig. 1), and as discrete particles in the gangue. Much Type 2 gold has aurostibite intimately associated with it (Figs. 9, 10).

The third variety (Type 3) has a reddish hue. This may be due to some dissolved copper, as suggested by Ferguson (1950), and this type is found only in the neighbourhood of copper minerals. "Type 3" was found only in samples containing "Type 2," and in most cases is closely associated with this variety. Contacts between these two varieties (Fig. 11), although indistinct, suggest that "Type 2" is the younger.

Spectrographic analyses were made of the different gold types but the results were inconclusive. A pure sample could not be obtained due to the close associations of "Type 2" and "Type 3" and the proximity of most of the gold particles to sulphosalts. The spectrographic analyses do, however, suggest that "Type 1" is considerably richer in silver than the other two varieties.

In several samples a purple mineral occurs, which was identified by x-ray powder methods as gold, suggesting still another variety of this mineral. However, on closer examination at high-power magnifications, this material proved to be an intimate, blotchy, intergrowth of gold and a grey anisotropic mineral identified by x-ray examination of the mixture as stibnite (Fig. 12). In the same samples aurostibite occurs associated with gold. Possibly, "purple gold" was formed by the reaction of some later sulphur-rich solution with aurostibite. It is postulated that antimony possesses a greater affinity for sulphur than for gold. This would result in the formation of stibnite accompanied by the precipitation of gold, when aurostibite comes in contact with excess sulphur.

Aurostibite

Aurostibite was observed only in the presence of "Type 2" gold. It occurs principally as rims on gold particles (Fig. 9), as extensions of gold grains, or along contacts between gold and other minerals. In a few cases, it veins other minerals in the neighbourhood of gold particles or even veins gold itself (Fig. 10).

The age relations between gold and aurostibite are commonly not clear-cut except where aurostibite veins gold. The formation of auro-

stibite[1] probably begins while gold is still being deposited, and continues for a short while after all the gold has formed.

Lead and Antimony

Native lead and antimony were found in minor quantities in specimens from a number of localities. Lead occurs in samples in which minerals containing a relatively low percentage of sulphur are abundant. It exhibits no significant relations with other minerals and is usually in discrete particles in the gangue. Native antimony was observed only as small grains in massive stibnite.

These two native elements are believed to indicate solutions somewhat deficient in sulphur. Most reported occurrences of native lead are regarded as supergene. Its presence in Yellowknife ores at a depth of 500 feet suggests that such a theory is not tenable in this case. Antimony also appears to be a product of hypogene mineralization, since it occurs at depths up to 750 feet. The specimens in which both these minerals occur are quite fresh in appearance, and exhibit no evidence of supergene mineralization. Shannon (1927) reports an instance where native lead is the principal ore mineral of a lead deposit, which is almost certainly of hypogene origin.

Secondary mineralization

Secondary minerals observed in the area include marcasite, chalcocite, cassiterite, limonite, malachite and azurite.

Marcasite occurs in appreciable amounts in the neighbourhood of late post-ore faults, and also in surface and near-surface specimens. In each case, it appears to be the youngest metallic mineral present, and is probably either a product of late solutions circulating along post-ore faults, or else of secondary sulphide deposition near surface.

Chalcocite was noted in a number of surface and near-surface samples. It occurs in fine stringers which transect copper-bearing minerals. Such chalcocite is more extensive in sulphosalts than in chalcopyrite. It is believed that all the chalcocite was produced by solutions, probably supergene in origin, which circulated through the ores at some time subsequent to the last period at which they were formed.

Sphalerite, possibly of secondary origin, is found in a number of localities in this area. This sphalerite forms small stringers which transect the other metallic minerals. It seems probable that both chalcocite and this sphalerite were formed during a period of secondary sulphide mineralization.

Cassiterite occurs in one weathered specimen, obtained from a surface

[1] This mineral is treated at greater length in a succeeding section.

trench, associated with sphalerite and intermixed with marcasite. Its occurrence in a weathered sample of ore suggests that it was formed as a product of secondary alteration of some pre-existing stannite. Its occurrence in the neighbourhood of sphalerite supports this idea.

Limonite, malachite and azurite were all noted in hand specimens from surface outcroppings of the veins. They appear to have been formed as a product of recent weathering.

METALLIC MINERALIZATION IN THE WALL ROCKS

Samples of wall rocks collected in the vicinity of the orebodies contain some of the metallic minerals which occur in the ores. Pyrite and arsenopyrite are usually present, accompanied, in places, by minor amounts of sphalerite and chalcopyrite. Galena and sulphosalts occur in minute disseminated particles in a few samples.

From evidence of movement noted in the field, and from microscopic textures of the metallic minerals, it seems reasonable to consider dilation of the rocks the principal factor causing the introduction of the mineralizing solutions. During each period of deformation or movement, the same stresses would act on all rock types. The various members would, however, possess different physical properties and hence their response to deformation would be varied. Differences of response to the same stress could produce marked differences in dilation of the various members, and thus act as an important factor in localizing the introduction of mineralizing fluids.

Quartz-carbonate veins would, expectably, become more dilatant than a schistose shear zone, when both are subjected to the same deformation. Evidence of more than one introduction of gangue, as reported by Boyle (1952), suggests that the size of the veins with respect to the enclosing shear zones, was increasing with each successive period of mineralization. If this was the case, the ratio of dilatability within the veins to that within the surrounding schists, would increase with each successive mineralization period, and hence later minerals would be confined more and more to these veins.

PARAGENESIS

In the paragenesis of the Yellowknife ores, the following periods of mineralization are postulated, with the oldest first:

1. A solution rich in sulphur, iron and arsenic, was introduced from which arsenopyrite and pyrite formed. Much of the arsenopyrite was formed before deposition of pyrite commenced.

2. A solution rich in sulphur, zinc, iron and copper, and containing minor tin was then introduced. It may have been relatively free of iron,

with the iron contained in minerals formed at this time, being derived from pre-existing pyrite and arsenopyrite.

Sphalerite was the first mineral to be formed from this solution, followed by chalcopyrite, pyrrhotite and stannite. Some of the chalcopyrite and pyrrhotite associated with the sphalerite, may represent exsolved material, but some may have resulted from the reaction of residual solutions with sphalerite.

3. There was, possibly, an early introduction of gold. If such a period did occur, the gold formed was a light coloured variety (Type-1), rich in silver.

4. An antimony-rich solution was then introduced, which contained sulphur, gold, silver and lead, and possibly some copper and iron. Much of the iron, copper and arsenic contained in minerals formed at this time may have been derived from pre-existing metallic minerals during the processes of replacement.

Evidence from polished sections indicates that there may have been more than one deposition of gold during this period. If this is so, gold of Type 3 was probably formed early in the period. Its formation may have been caused by the reaction of the solutions with pre-existing metallic minerals on first reaching the site of ore-formation, with incorporation of copper producing the red colour of this gold.

Galena and stibnite were probably formed during this period wherever the available supply of antimony or of lead, was insufficient for the formation of sulphosalts.

No uniform paragenesis was found for the galena, stibnite and sulphosalts within this major period. The varieties of minerals formed in any one place, and their order of formation, was probably a function of the concentrations of the constituents available for mineral formation. Differences in available proportions of those constituents which could not have been derived from pre-existing minerals, may have been caused by a filtering effect imposed on the solutions by impounding structures. Differing degrees of dilation throughout the host quartz-carbonate veins, accompanied by varying degrees of mobility of the solution constituents, is a possible alternative.

Aurostibite and gold of Type 2 probably formed late in this period, with aurostibite forming shortly after the gold by reaction with excess antimony. Native lead and antimony were probably among the last minerals to form, and indicate an appreciable deficiency of sulphur during the later stages of mineralization.

5. Late faulting accompanied or succeeded by circulation of supergene or hypogene solutions, caused the formation of a second age of sulphides.

The Ore-forming Fluids—Their Character and Emplacement

The mineralizing fluids seem to have been of a hydrothermal type similar to those postulated by Graton (1940) and Neumann (1948). That the mineralization appears to have taken place by the introduction of several successive solutions of differing compositions, agrees with Neumann's idea of "endomagmatic hydrothermal differentiation." The wall rocks adjoining the ore deposit show no definite evidence of either acidic or alkalic alteration associated with the emplacement of the metallic minerals. The presence of large quantities of carbonates in the ores does suggest that the solutions may have been alkaline.

The manner in which the gold was transported, is uncertain. It may have been transported in the form of a sol, or in true solution, either as gold or as a salt. The affinity of gold for antimony, as evidenced by its ability to combine with antimony, suggests that the gold might be transported as a soluble antimonide complex. Since aurostibite reacts readily with both nitric and hydrochloric acids, and with potassium hydroxide, it would probably be equally soluble in both acidic and alkalic solutions.

The manner of emplacement of the ore-forming fluids seems quite clear. In each instance of introduction of a solution, there is evidence that deformation or movement took place previously, and subsequent to the formation of the pre-existing minerals. Any movement or deformation of the brittle veins in which these ores occur, would undoubtedly be accompanied by dilation, which would serve as an adequate mechanism to initiate the introduction of the ore-forming fluids.

This type of deposit appears to be a combination of filling of zones of dilation and of replacement. Ore minerals fill fractures in gangue as well as in earlier metallic minerals, and, in addition, show many manifestations of replacement processes.

Aurostibite—Its Occurrence and Implications

Aurostibite is of particular interest mineralogically, not only for its novelty as a mineral species, but also because of the economic and mineralogical implications of its occurrence.

This mineral was first described by Graham & Kaiman[1] (1952). Crystallographically, it is a member of the pyrite group, and the unit cell contains Au_4Sb_8, with $a = 6.659 \pm 0.003$A. In polished section it has a hardness of $C-$, is isotropic and has an extreme white colour which gives it a slightly pinkish appearance in contrast with galena. The standard etch reactions in the order of reactivity are: HNO_3, $FeCl_3$, HCl, KOH positive; $HgCl_2$ and KCN negative. It occurs, intimately associ-

[1] Geological Society of America, Annual Meeting, November 1951.

ated with gold, late in the paragenetic sequence, and, in many instances, appears slightly younger than the gold.

This mineral has considerable economic significance. Not only does it represent a new naturally occurring gold compound, but its relative insolubility in a cyanide solution poses important recovery problems. The fact that it armours gold is many occurrences, would, as Graham & Kaiman (1952) have mentioned, cause losses in ordinary cyanide mill-circuits, out of all proportion to the amount of gold actually present in the mineral itself. Furthermore, the possibility that this cyanide-resistant mineral may actually be synthesized in roasting ores of the Yellowknife type has to be considered.

Mines in the Yellowknife Bay area, in the past, have reported relatively high losses in their gold recoveries. At least some of such losses may be due either to the presence of aurostibite, or to its formation during roasting.

Summary and Conclusions

The gold deposits of the Yellowknife Bay area represent a type different from those found elsewhere in the Precambrian Shield of Canada. The intimate occurrence of gold with sulphosalts rich in antimony, has not been reported in this country, and is quite different from its more common association with tellurides. In Yellowknife ores, tellurium appears to be virtually absent.

Because of their novelty , the depths to which these deposits should extend are not known. High formational temperatures seem improbable, although a depositional environment having temperatures in the order of several hundred Centigrade degrees is quite plausible. The mines in this area have, in several instances, reached mining depths exceeding one thousand feet and, so far as is known, the gold values show no significant change.

Further study of the chemical and mineralogical relationships between gold and antimony should prove of great interest and economic significance. If ores of this type are to be treated efficiently, such research is of great importance.

A number of conclusions may be drawn from the present investigations which, although hypothetical due to the scope of the study, appear reasonable:

1. Gold exhibits a close affinity with relatively low temperature minerals rich in antimony. The quantity of microscopically visible gold present in any one locality, appears to be greatest where such minerals are abundant.

2. Although the mineralogy is quite complex, its chemical constituents

fit into a relatively simple pattern. Any additions to this array should be composed of these elements.

3. The formation of the Yellowknife ores took place in a number of successive stages, with minerals formed during each period incorporating elements from earlier formed minerals.

The postulation of replacement as the mode of origin of an ore deposit has, in many instances, produced the criticism that this would require not only the introduction, but also the removal of material. The idea that much of the material which was apparently replaced, was in reality incorporated into later minerals, helps satisfy any such objection.

4. The paragenetic sequence of the period in which gold and sulphosalts were formed, is not definite. The minerals formed at this time exhibit numerous reversals in age relations. The order in which they were deposited in any one locality was probably a function of the concentrations of minerals constituents that were present at that place.

5. The ores have been formed by filling of zones of dilation accompanied by some metasomatic replacement.

6. Mineralogical investigation indicates that dilation accompanying deformation was an important factor in controlling the emplacement of these ores.

7. Investigations of complex ores, particularly those containing sulphosalts, are greatly facilitated by x-ray powder studies. Identification by etch reactions and microchemical tests is unreliable with ores of this character.

APPENDIX—"MINERAL Q"

In one specimen, a grey acicular metallic mineral was noted, whose x-ray powder spectrum did not correspond to that of any reported mineral. This mineral is tentatively referred to as "Mineral Q."

The type locality for this mineral is a surface trench on the Brock Zone of the Giant property. It occurs as discrete needles in gangue and intimately associated with jamesonite (Fig. 8), in specimens of ore in which pyrite and arsenopyrite are also present. It seems to be slightly later in time of formation than the jamesonite since blades of it transect intergrain boundaries of jamesonite.

Due to its intimate association with jamesonite, no chemical analysis of this mineral was possible. A very small amount was obtained for a spectrographic analysis, which indicated the presence of the following elements in probable order of decreasing importance: Fe, Cu, Sb, Pb, Ag.

A single crystal fragment of this mineral was obtained from the polished section for x-ray measurements. Owing to its acicular habit, only one axis of adjustment was available. This direction of elongation proved to be the crystallographic b-axis of a monoclinic lattice.

Rotation and Weissenberg films about the axis of elongation yielded the lattice dimensions:

$$a = 19.06 \text{ A}, \qquad b = 4.11 \text{ A}, \qquad c = 17.26 \text{ A}, \qquad \beta = 95°50'$$

No systematic omissions of diffractions were observed, therefore the space group is $P2/m$, if the class is holohedral.

The x-ray powder spectrum for "Mineral Q" is:

I	θ(Cu)	d(meas)	I	θ(Cu)	d(meas)	I	θ(Cu)	d(meas)
s	12.2°	3.65 A	w	15.45°	2.89 A	m	22.1°	2.05 A
vs	13.3	3.35	s	16.05	2.79	m	24.2	1.881
m	14.3	3.12	vw	17.1	2.62	w	25.4	1.797
vw	14.9	3.00	w	20.25	2.23	w	26.65	1.719

The appearance, associations and lattice dimensions of "Mineral Q" suggests that it is undoubtedly a sulphosalt. The existence of a new monoclinic sulphosalt in which the b-axis is the axis of elongation, is of some interest. None of the well-established monoclinic sulphosalts have their direction of elongation parallel to the b-axis. There are, however, two cases in which such minerals have been reported and it is of further interest that, in both cases, the cell elements of these minerals were very close to those of "Mineral Q."

Berry (Peacock & Berry, 1940), reports the presence of one such mineral in an intimate intergrowth with another mineral having a platy development. This intergrowth had originally been named "seleniferous galenobismutite." The other of these minerals is an artificial sulphantimonite (Phase II with Pb:Sb = 3.4:5.4) which was synthesized by Robinson (1948). He believed that this synthetic material and the Pb, Bi, Se, S mineral reported by Berry, might be isostructural. It is possible that "Mineral Q" is also isostructural with these two minerals.

The rotation and Weissenberg x-ray films of Robinson's phase II and Mineral Q are essentially identical in position and intensity of diffractions, they differ markedly in the shape of the spots.

The cell dimensions for these three minerals are:

	Mineral Q	Robinson (1948)	Peacock & Berry (1940)
a	19.06 Å	19.20 Å	18.07 Å
b	4.11	4.13	4.05
c	17.26	17.43	17.57
β	95°50'	96°24'	94°29'
Space group	$P2/m$	$P2/m$	$P2/m$

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