J.R. Mowat

GEOLOGICAL
SURVEY
OF
CANADA

DEPARTMENT OF MINES
AND TECHNICAL SURVEYS

BULLETIN 72

MINERALOGY AND PARAGENESIS OF LEAD-ZINC-COPPER ORES OF THE BATHURST-NEWCASTLE DISTRICT, NEW BRUNSWICK

Supriya Roy

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PREFACE

The Bathurst-Newcastle district of northern New Brunswick came into prominence as a mining area following the announcement in January 1953 of the discovery of a large massive sulphide deposit, now known as the Brunswick No. 6 orebody. Interest in the district has been maintained since that time, and several similar deposits have been discovered.

This bulletin presents the results of a detailed study of the mineralogy and paragenesis of the base metal deposits of the Bathurst-Newcastle district. This study forms part of an overall investigation being made by the Geological Survey of Canada of the geology, geochemistry and origin of the base metal deposits in this district.

The author undertook his investigations in 1958 while attached to the Survey as a National Research Council post-doctoral fellow from India.

J. M. HARRISON,
Director, Geological Survey of Canada

OTTAWA, June 13, 1960

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Abstract

Two types of base metal sulphide deposits occur in the Bathurst-Newcastle district. One type, north of a prominent fault zone locally called the Rocky Brook-Millstream 'break', consists of veins cutting folded Silurian argillites and slates, and Devonian intrusive porphyry stocks. The other type, south of the 'break', consists of massive sulphide lenses localized mainly in drag-folds and in favourable synclinal folds in Ordovician meta-volcanic and sedimentary rocks.

The hypogene sulphide minerals in both the vein-type deposits north of the break and the massive, banded replacement deposits south of the break are the same, although the sulphides in the former deposits are coarse grained, whereas those in the latter deposits are fine grained. The generalized paragenetic sequence of the sulphides in both types of deposits is: pyrite, arsenopyrite, sphalerite, pyrrhotite, galena, tetrahedrite, and chalcopyrite.

Many of the massive sulphide deposits have well-developed gossans, and have secondary enriched zones that contain supergene covellite and chalcocite. Other supergene minerals include anglesite, minor amounts of freibergite and abundant marcasite. In the vein deposits, the gossan zone and the zone of supergene mineralization are very thin and in some deposits practically absent. The only abundant supergene mineral in these deposits is marcasite.

Résumé

Il existe deux types de gîtes de sulfures de métaux communs dans la région de Bathurst-Newcastle. L'un de ces types est situé au nord d'une zone de faille très importante, appelée localement la faille Rocky Brook-Millstream. Il se compose de filons qui coupent aussi bien des argilites et ardoises plissées d'âge silurien, que des stocks porphyriques intrusifs du Dévonien. L'autre type, situé au sud de la zone de faille, consiste en des lentilles de sulfures massives qui se rencontrent principalement dans des plis d'entraînement ainsi que dans des plis synclinaux favorables et au sein de roches sédimentaires et méta-volcaniques de l'Ordovicien.

Les minéraux sulfurés hypogènes présents dans les deux types de gîtes, i.e. dans les gîtes filoniens au nord de la fissure et dans les gîtes de substitution rubanés et massifs qui se trouvent au sud de la fissure, sont identiques, mais les sulfures du premier type de gîtes sont à gros grains tandis que ceux de l'autre type sont à grains fins. Voici l'ordre de succession ou la paragenèse des sulfures au sein des deux types de gîtes: pyrite, arsénopyrite, blende, pyrrhotine, galène, tétraédrite et chalcopyrite.

Plusieurs des gîtes de sulfures massifs présentent des chapeaux de fer bien développés et renferment des zones secondaires enrichies où l'on remarque de la

covelline et de la chalcosine supergènes. Les autres minéraux supergènes comprennent l'anglésite, un peu de freibergite et beaucoup de marcasite. Dans les gîtes filoniens, la zone du chapeau de fer et la zone de minéralisation supergène sont très minces tandis que certains gîtes n'en contiennent à peu près pas. Au sein de ces gîtes, la marcasite constitue le seul minéral supergène qui soit abondant.

INTRODUCTION

Scope of the Investigation

The investigation described in this bulletin forms part of an extensive study of the geochemistry, mineralogy, and origin of the sulphide ores of Bathurst-Newcastle district now being conducted by the Geological Survey of Canada.

Detailed sampling of type orebodies was carried out by the writer in the field, and polished sections made from these samples were studied under the reflecting microscope in the laboratory. X-ray powder photographs were made to confirm the identification of all minerals. The textural relationships of the various sulphide minerals were studied and interpreted and their paragenetic relationships in the various deposits have been drawn up and compared.

History of Exploration and Mining

The Bathurst-Newcastle district of northern New Brunswick gained widespread attention from the mining industry as a source of base metals in January 1953, following the discovery of the large Brunswick No. 6 massive sulphide orebody. Prospecting and some mining have, however, been carried out in the district sporadically since 1837. The history of mining exploration in the area is outlined in a publication by MacKenzie (1958)[1], from which the author has drawn much of the information that follows.

As early as 1837, the Gloucester Mining Association attempted to mine copper ore from Pennsylvanian sandstones on Nepisiguit River, but the venture was not commercially successful. Exploratory work was then directed northwestward and several veins of chalcopyrite with quartz were discovered on Tetagouche River, 8 miles northwest of Bathurst.

The first systematic geological mapping of the district was undertaken by R. W. Ells for the Geological Survey of Canada in 1879. Previous to this, however, Gesner (1843), Logan (1863), and Bailey (1864), carried out local investigations and added to the accumulating data on the presence and nature of the ore deposits. In 1879, veins of sphalerite and galena were found on Elmtree River, and sporadic development work was done by individuals and companies up to 1952, when the deposit was acquired by Keymet Mines Limited. At the turn of the century, other deposits of zinc and lead sulphides were discovered and explored on Rocky Brook, a tributary of the Millstream River, and these have been exploited in recent years by Sturgeon River Mines Limited. The Bathurst iron mine southwest of Nepisiguit Falls was discovered in 1902 and the deposit has been worked intermittently since then.

There was a comparative lull in the mining and exploration activity in the district from 1915 to 1930. In the next decade, however, active prospecting was

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[1] Dates in parentheses are those of references at the end of this report.

continued. Gold and small amounts of sulphides were discovered in shear zones along the Nigadoo River, and although the deposits did not prove commercial they opened a new area for prospecting and suggested favourable shear zones along northwest-trending dykes of granite porphyry. The sulphide orebodies at the Nigadoo mine were discovered in 1953. The discovery of pyritic base metal deposits in the Orvan Brook area in 1938 added considerable knowledge to the nature of the ore deposits in the Bathurst-Newcastle district. This deposit has been explored in recent years and is now held by New Calumet Mines Limited.

Since 1945 exploratory work in the district has been carried out more systematically using geological base maps and aerial photographs. An aeromagnetic survey by the Geological Survey of Canada of northern and central New Brunswick in 1950 and 1951 helped greatly in problems of geological interpretation and guided exploration.

In the Rocky Brook-Millstream River area, a combination of geological mapping, tracing float and gossan, ground magnetometer surveys, and drilling by the New Brunswick Department of Lands and Mines, led to the discovery of a number of new deposits of base metal sulphides. Some of these new showings were explored and exploited by Noranda Mines Limited, Sturgeon River Mines Limited, and others.

Exploratory work in search of base metal sulphides in the area north of the Bathurst Iron Mines commenced vigorously in 1952. An electromagnetic survey indicated the presence of conductors, and this survey was followed by an extensive drilling program, which outlined a large tonnage of massive lead, zinc and copper sulphides. This deposit, owned by the Brunswick Mining and Smelting Corporation Ltd. and known as the Brunswick No. 6, was the first large massive base metal discovery in New Brunswick. Consequent to the discovery of the No. 6, an aeromagnetic survey of the area by the Geological Survey of Canada indicated a strong magnetic anomaly some 5 miles to the northwest; an electromagnetic survey also indicated anomalous conditions in the area. Drilling was undertaken and in 1953 an immense tonnage of base metal sulphides was outlined. This deposit is now known as Brunswick No. 12.

The discovery of the Brunswick No. 6 orebody started a boom in exploratory work in New Brunswick and several new properties were explored and developed. Among these were the New Larder 'U' property, 6 miles west of Brunswick No. 6, and the Nash Creek base metal deposits, 30 miles northwest of Bathurst. Systematic exploration work utilizing both geochemical (soil testing) and geophysical surveys led to the discovery of the Nigadoo mine in 1953. In November 1954, the American Metal Company Ltd. announced an impressive base metal discovery near Little River Lake, 35 miles northwest of Newcastle. This deposit was taken over and developed by a jointly held company, Heath Steele Mines Limited. The Middle River Mining Company Ltd. and Conwest Exploration Company Limited discovered base metal orebodies in 1955 near the head of the Northwest Miramichi River. Their exploration was based on studies of the regional and structural geology of the area assisted by airborne electromagnetic surveys, and ground geophysical and geochemical prospecting. The same approach was followed by the Anaconda

Company (Canada) Limited and a major find was made in late 1955 on Fortymile Brook, near Caribou Depot, north of the upper Nepisiguit River.

In 1956 and the years following, exploration has continued in virgin country and several discoveries have been made. These include two finds by the American Metal Company, one near Fortymile Brook, the other north of Devils Elbow on the Nepisiguit River; two by Anaconda, the first near the head of Armstrong Brook, and the second near Rocky Turn on the Tetagouche River; two by Kennco Exploration, one on Eighteenmile Brook and the other along the middle course of the Nepisiguit River; the Consolidated Mining and Smelting Company's deposit near the junction of Fortyfour Mile Brook and the Nepisiguit River; and the recently discovered New Jersey Zinc deposit near Portage Lakes.

Geology of Bathurst-Newcastle District

Early geological descriptions of the district are contained in the reports by Ells (1881, 1883), Young (1911), Shaw (1936), and Alcock (1935, 1941).

The Survey commenced mapping in the Bathurst-Newcastle district on a 1-mile scale in 1949, and since then maps have been published by Skinner and McAlary (1952), Skinner (1953, 1955), and Smith (1957). In addition several ¼-mile geological maps have been published by the New Brunswick Department of Lands and Mines, Smith and McAllister (1956), McAllister and Smith (1956), Jones and Smith (1957), and Davies (1959).

In a recent paper, Smith and Skinner (1958) described the general geology of the district, from which the following is a summary. They recognized three regional structural units:

1. The Ordovician folded belt
2. The Silurian folded belt
3. The Pennsylvanian cover.

The Ordovician Folded Belt

Highly folded Ordovician volcanic and sedimentary rocks underlie the central part of the district. The Ordovician belt has a core of highly folded silicic volcanic rocks, which is surrounded and interlayered in part by sedimentary and basic volcanic rocks. Although the siliceous volcanic core has suffered intense dynamic metamorphism compared to the less metamorphosed sedimentary rocks surrounding it, no great age difference or any orogenic break between the two is apparent.

The siliceous volcanic core, generally termed in the district as the 'porphyry', is economically the most important rock type, because most of the base metal sulphide orebodies show a spatial relationship to it. The term porphyry as used in the field refers to rocks that are characterized by large 'eyes' of quartz and/or feldspar in a microcrystalline or schistose groundmass of quartz, feldspar, sericite and chlorite. The bodies of porphyry appear to be conformable with their surrounding rocks, and they occur at various stratigraphic horizons. The origin of the porphyry bodies is obscure because intense dynamic metamorphism has obliterated the original diagnostic fabric in most places and only rarely are original features partly preserved. That the porphyry bodies are not a facies of the granite intrusions of the district is certain, because they are cut and metamorphosed by the latter at several places. Some of the less deformed types of porphyry exhibit an igneous fabric with euhedral feldspars in a fine groundmass containing amygdules, or rounded and embayed quartz grains with euhedral feldspars in a highly altered groundmass of felsic material. These rocks resemble flow rocks in appearance and mineralogy and are interpreted as shallow sills or flows. By contrast, however, other rocks with conspicuous quartz and feldspar 'eyes' resemble the igneous porphyry but have a sedimentary fabric. Where undeformed, these rocks are bedded and contain rock fragments. Their larger grains are angular and the groundmass is poorly sorted.

Thus it may be seen that no single decisive mode of origin can be attributed to the group of rocks know as porphyry, and the problem is still one requiring further investigation.

The other rocks in the Ordovician folded belt are greenstones. These are commonly interlayered with sediments consisting mainly of either quartzose or argillaceous rocks including varicoloured slates. These sedimentary rocks are interbedded on a small scale and it is difficult to delineate areas composed mainly of one stratigraphic unit.

Among the basic rocks of the district, there are two distinct types. Grey-green diabasic dykes and sills are more common, particularly in the northeastern part of the district. The less common type is an olivine gabbro with disseminated nickel-bearing sulphides.

Large massive bodies of granite cut the folded rocks near Bathurst and in the southwestern part of the district. Small gneissic granite bodies are abundant in the southern part of the district.

The Silurian Folded Belt

Folded greywacke, argillites, slates and volcanic rocks of Middle and Upper Silurian age occur to the north of a major fault known as the Rocky Brook-Millstream 'break'. The rocks are generally not so deformed as the Ordovician rocks, but are cut by gabbro, granite, and porphyry stocks.

The Pennsylvanian Cover

Flat-lying red conglomerate and sandstone of Pennsylvanian age cover the eastern part of the district. In addition, outliers of these rocks occur near Tetagouche Lakes and on Clearwater Stream. The Pennsylvanian sediments lie unconformably on the older folded rocks and were deposited after the principal ore deposits of the district were formed.

Regional Setting of the Orebodies

Smith and Skinner (1958) made the following generalizations regarding the pattern of ore deposits in the Ordovician folded belt:

1. The deposits almost invariably occur in sedimentary rocks, the volcanic rocks being barren. Orebodies are, however, not restricted to any one type of sedimentary rock.

2. Many of the ore deposits are concentrated in sedimentary rocks in the interlayered sedimentary-porphyry-volcanic sequence. However, the localization of orebodies is not controlled by a simple contact relation between sedimentary rocks and porphyry as has been suggested by some geologists. The porphyry did not introduce the metals; its formation and deformation were prior to the period of mineralization. That the porphyry is not a requisite for mineralization is amply demonstrated by the New Larder 'U', Stratmat, and Kennco orebodies. The orebodies are also not necessarily confined to the interlayered zone as shown by the New Larder 'U', Kennco, and others, which are well outside this zone.

3. The granites appear to have played an important role in moving the metals to their present structural positions since the Brunswick No. 6 and No. 12, and the New Larder 'U' deposits show a definite spatial relationship to the Bathurst granite. Similar spatial relationships are also shown by a number of deposits around the Nepisiguit River granite.

4. Although there are numerous small mineral occurrences along the Rocky Brook-Millstream 'break', none of the larger ore deposits is directly related to regional fault zones.

Structural Localization and Nature of the Orebodies

Drag-folds and favourable synclinal folds are the principal structural controls for the massive sulphide deposits south of the Rocky Brook-Millstream break, and faults and fractures contain most of the vein-like deposits north of the break. A few examples of each type are briefly described.

According to Lea and Rancourt (1958), the Brunswick No. 6 orebody occurs in the trough of a drag-fold that developed on the west limb of an anticline. The orebody is a massive sulphide replacement of altered siliceous sediments and magnetite-hematite iron-formation. The Brunswick No. 12 orebody is likewise a massive replacement body of drag-folded siliceous sediments consisting of slightly graphitic slates, quartzites, siltstones and cherts. The northern end of the orebody replaces banded iron-formation. At the south end of the orebody, on the hanging-wall side, mineralization spreads partly into altered equivalents of the 'sheared porphyry'.

The Caribou sulphide body of the Anaconda Company (Canada) Limited occurs as a more or less continuous layer of massive banded sulphides ranging from 40 to more than 100 feet wide, extending around the trough of a synclinal fold. The fold, which has been described as a 'text-book type', is made up of argillite, slate, iron-formation, chlorite schist, and quartz-feldspar augen schist (Cheriton, 1958).

In the Nigadoo area north of the Rocky Brook-Millstream 'break' the country rocks are composed mainly of green schists and shales, graphitic schists and argillites, intruded by a differentiated porphyry stock. The porphyry is composed mainly of an acid phase having a light grey to white groundmass of quartz, feldspar and mica in which are set phenocrysts of quartz and feldspar. The less abundant dark phases contain a dark, fine-grained groundmass with phenocrysts of quartz and feldspar. The deposit is a series of lenses and short veins in a fault zone. Economic shoots lie mainly within the porphyry, or a short distance in the argillites from their contact with the porphyry.

At the Keymet mine the orebody consisted of lenses and veins of sulphides in a fault cutting across shale, conglomerate, and argillite.

Many of the massive sulphide deposits south of the Rocky Brook-Millstream break have well-developed gossans, e.g., Heath Steele and Brunswick No. 6. In these the principal mineral is limonite, which is accompanied by jarosite, anglesite, and other secondary minerals. In some deposits, e.g., Heath Steele and Brunswick No. 12, an enriched copper zone is developed below the gossans. The main secondary copper minerals in this zone are covellite and chalcocite.

North of the break the vein deposits have practically no gossan development, and secondary enriched zones are generally absent.

Acknowledgments

The various mining companies in the Bathurst-Newcastle district permitted the writer to collect samples, and afforded him the use of their facilities.

The X-ray powder photographs of the ore minerals were made in the X-ray laboratory of the Geological Survey of Canada. The photomicrographs accompanying the paper were taken in the Photographic Laboratory of the Survey.

Dr. R. W. Boyle of the Geological Survey of Canada kindly provided helpful criticism, discussion, and encouragement during the work.

The writer acknowledges his indebtedness to the National Research Council of Canada for awarding him a Post-Doctorate Fellowship, which made his visit to the Geological Survey of Canada possible.

MINERALOGY OF THE BASE METAL ORES

Publications on the detailed mineralogy of the base metal deposits of the Bathurst-Newcastle district are rather limited. The ores of Brunswick Mining and Smelting Corporation's No. 6 and No. 12 deposits were subjected to a mineragraphic investigation by Aletan, and Lea and Rancourt (1958) published a short account based on his investigations. The only other investigation of the mineralogy known to the writer is by Aleva (personal communication), who worked on a large number of samples collected from drill-cores and underground exposures in the Nigadoo mine. These two investigations, although important with respect to the relevant mines, do not compare the variable trends of mineralization in the different parts of the district, particularly in the areas north and south of the Rocky Brook-Millstream break.

The writer, therefore, has endeavoured to present a comprehensive account of the mineralogy and texture of the base metal ores collected from different type deposits of the district, and to draw their generalized paragenesis. For this purpose he selected the Nigadoo, Keymet and Sturgeon River deposits north of the Rocky Brook-Millstream break; and the Brunswick No. 6, Brunswick No. 12, Heath Steele, Anacon Lead Mines (New Larder 'U'), Middle River, and Anaconda deposits south of the break (*see* Fig. 11).

Summary Description of Metallic Minerals

Magnetite, the earliest ore mineral, occurs only in the Brunswick No. 6 and Brunswick No. 12 orebodies. It is part of the banded iron-formation and occurs as relicts within the sulphides. It is often veined and replaced by pyrite.

Hematite occurs as the primary specular variety in the Brunswick No. 6 deposit and as martite after magnetite in both No. 6 and No. 12 orebodies. The specular variety has a platy and irregular shape.

Pyrite is the most abundant mineral in the suite of metallic minerals. Two generations are present. The first occurs as euhedral to subhedral grains in all ore deposits of the district. The second generation is very fine grained and is disseminated. In the Nigadoo orebody it also occurs as small colloform masses, which are probably the result of hypogene colloidal deposition. Similar colloform texture exhibited by pyrite at shallow depth in the orebodies of the Heath Steele mine and Brunswick No. 6 deposit may, however, be the result of supergene processes (melnikovite-pyrite).

The highly reflecting, pale yellowish white grains of pyrite can easily be distinguished from all other sulphide minerals. The mineral was generally found to be truly isotropic, and no uniform anisotropic effect as alleged by Stanton (1957) was observed.

Arsenopyrite, an important mineral of the sulphide suite, is abundant in the deposits north of the Rocky Brook-Millstream break, e.g., Nigadoo. South of the break, it is present in minor amounts in all deposits. It occurs mostly in euhedral grains and is one of the earliest minerals of the sulphide group.

Sphalerite, abundant in all the ores, is one of the earliest minerals to crystallize among the sulphide minerals. It replaces and embays pyrite and arsenopyrite, and contains inclusions of all the sulphide minerals in the suite. Blebs of chalcopyrite oriented along the (111) crystallographic planes are common in the Nigadoo and Keymet ores.

The sphalerite is dark to light grey under reflected light and is isotropic between crossed nicols. Twinning is uncommon.

Pyrrhotite is common in the ores of all deposits. It crystallizes later than sphalerite but earlier than galena, and is commonly altered to marcasite.

Galena, a common mineral in all the deposits, replaces and embays all the minerals referred to above and hence has crystallized late in the paragenetic sequence. Near the surface it is commonly altered to anglesite. Supergene galena, in very fine grains, was noted in the Brunswick No. 6 and Heath Steele deposits.

Tetrahedrite occurs in small amounts in the Heath Steele, Nigadoo, Brunswick No. 6 and Brunswick No. 12 deposits. In the Nigadoo orebody it forms exsolution intergrowths with chalcopyrite; in the other deposits it occurs as irregular grains replaced by chalcopyrite and/or bornite.

Freibergite, the silver-bearing variety of tetrahedrite, was detected in the Heath Steele orebodies. It appears to be of supergene origin.

Bornite, which is very uncommon in most deposits but is present in small amounts in the ores of the Brunswick No. 6 deposit, appears to be of hypogene origin and is late in the sequence of crystallization. It replaces all primary minerals and is, in turn invaded by chalcopyrite.

Chalcopyrite is generally the latest mineral in the primary (hypogene) sequence in all deposits. In the Nigadoo, Keymet and Sturgeon River deposits, however, three generations are present: (i) as exsolution blebs in sphalerite, (ii) as host for exsolution intergrowths of tetrahedrite, and (iii) as veins and stringers replacing all primary minerals. In the Brunswick No. 6 deposit it occurs as exsolution lamellae in the (100) directions of bornite.

Native bismuth has been observed only in the Heath Steele orebodies. It occurs as a replacement of galena, pyrrhotite and chalcopyrite, and appears to be supergene. However, it has been detected at considerable depth where no other supergene minerals such as covellite, chalcocite, etc. (which occur at shallow depths in this deposit) are present. It is, therefore, tentatively treated as of primary (hypogene) origin.

Marcasite is present as a secondary mineral in practically all the deposits and in places, such as in the Nigadoo deposit, is the only secondary sulphide mineral. It is generally intimately associated with and commonly forms at the expense of pyrrhotite. It forms small irregular replacement masses in most occurrences and radiating needles in places.

Anglesite was detected replacing galena along cleavage planes and in an irregular fashion in the Heath Steele and the Brunswick No. 6 orebodies.

Covellite and chalcocite are common supergene minerals in the ores. Near the surface they replace the primary minerals in a random fashion and gradually diminish in quantity with depth.

Mineralogy and Texture of Individual Deposits

Deposits North of the Rocky Brook-Millstream Break

North of the Rocky Brook-Millstream break, the writer visited Nigadoo, Sturgeon River, and Keymet deposits. The Nigadoo mine was operating at the time of the visit and it was possible to collect samples both from the three levels where mining was in progress and from the diamond-drill cores available. At Sturgeon River and Keymet, however, the only accessible samples were from the dumps and diamond-drill cores.

Polished sections of the ores of these three deposits revealed a striking similarity in their mineralogy, grain size, and general texture. These ores are quite different, however, from those in the deposits south of the break.

Ore minerals identified in these orebodies were: pyrite, arsenopyrite, sphalerite, pyrrhotite, galena, tetrahedrite, chalcopyrite, and marcasite. Of these marcasite is of supergene origin, being a product of alteration, principally of pyrrhotite.

Pyrite occurs generally in euhedral to subhedral grains and appears to have been the earliest mineral to form. A later generation of fine-grained, granular pyrite is, however, often present, which invades and surrounds the earlier generation of pyrite, sphalerite, arsenopyrite, and in places galena and may be of either hypogene or supergene origin. A third form of pyrite, with typical colloform texture (Pl. IV B), may be the type associated with 'schalenblende', which is thought to be characteristic of hypogene colloidal deposition in certain sulphide deposits of North America (Lindgren, 1933). Alternatively, it may be the 'melnikovite-pyrite' type alternating with black colloidal hydrous ferrous sulphide and be of supergene origin (Schneiderhöhn and Ramdohr, 1931). Considering the depth at which such pyrite is abundant (800 to 900 feet) in the Nigadoo orebody, a hypogene rather than a supergene origin is more probable.

Among the other primary minerals, exsolution relationships exist between chalcopyrite and tetrahedrite, and between sphalerite and chalcopyrite. Typical curved lamellae of tetrahedrite (Pl. II B) are oriented in the chalcopyrite 'host'. According to Edwards (1946), solid solution between chalcopyrite and tetrahedrite can take place at a temperature of about 500°C. Exsolution intergrowths of sphalerite and chalcopyrite were observed in samples from both Nigadoo and Keymet mines, where the chalcopyrite is oriented in the crystallographic directions of the sphalerite in the form of tiny blebs and needles (Pl. III B). According to Buerger (1934), chalcopyrite unmixes in sphalerite from 350° to 400°C.

Hypogene replacement relationships among the primary minerals are abundantly represented in the three deposits. Arsenopyrite and sphalerite are clearly replaced by veins and irregular protrusions of chalcopyrite, and less definitely by pyrrhotite and galena (Pls. VII B and IX A). In a few sections, however, sphalerite appears to wedge into and tends to embay arsenopyrite (Pls. VI B and VIII A). Pyrrhotite is generally replaced by galena and chalcopyrite in an irregular fashion. Chalcopyrite appears to be widely distributed in the sequence of crystallization. As already stated, it occurs as exsolved blebs in sphalerite (exsolution temperature 350° to 400°C.), and as independent grains containing unmixed tetrahedrite (exsolution temperature about 500°C). The latter grains are invaded by galena and are cut by later stringers and veins of chalcopyrite, which also cut across all other primary minerals. Galena appears to be a very late entrant in the sequence of mineralization, being succeeded only by the latest generation of chalcopyrite as stringers and veins. Marcasite is always a secondary mineral.

The paragenesis of the metallic minerals in the three orebodies can be represented as shown in Figure 1. This paragenesis, however, is not in agreement with that drawn by other workers on the Nigadoo ores (Aleva, personal communication; Kalliokoski, personal communication). Aleva advocates two generations of pyrite, sphalerite, galena and chalcopyrite. According to his observations, arsenopyrite is a very late entrant in the field, later than all the first generation ore minerals. He also places the first generation galena and sphalerite as contemporaneous, and pyrrhotite as a later mineral than galena, sphalerite, and first generation chalcopyrite. For comparison, his paragenesis is given in Figure 2.

Kalliokoski also suggested a late crystallization for arsenopyrite and apparently considered pyrrhotite to be earlier than sphalerite and galena; that is, later than all the primary minerals except chalcopyrite. He did not indicate whether the minerals occur in more than one generation.

The present writer found no evidence in polished sections for a late crystallization of arsenopyrite. On the contrary, arsenopyrite is definitely veined, invaded, and embayed by pyrrhotite, galena and chalcopyrite (Pls. I A, IX A). Sphalerite and pyrite are the only minerals with which arsenopyrite does not show a clear-cut relation, except in certain sporadic instances where arsenopyrite fills cracks in pyrite, and sphalerite wedges into and appears to embay arsenopyrite (Pl. VIII A).

As regards the contemporaneity of the first generation of galena and sphalerite, the writer found no evidence in the Nigadoo ores to substantiate Aleva's viewpoint. Rather, galena appears to always replace sphalerite (Pl. VII B) and rarely shows any mutual boundary relationships with the latter. Kalliokoski considered pyrrhotite to be earlier than sphalerite, but the present writer saw no evidence for this in polished sections, and considers the paragenesis to be the reverse.

Deposits South of the Rocky Brook-Millstream Break

The base metal ore deposits south of the Rocky Brook-Millstream break are distributed more widely and are of larger tonnage than those north of the break. Systematic sampling was done at the Brunswick No. 6, Brunswick No. 12, Heath Steele, Anacon Lead Mines, Middle River, and Anaconda deposits, which are

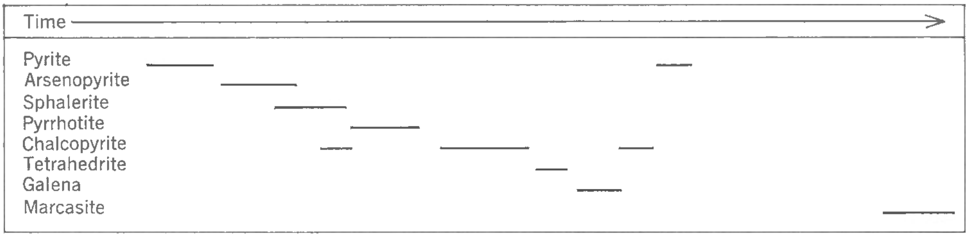

Figure 1. General paragenetic sequence of ore minerals of Nigadoo, Sturgeon River, and Keymet orebodies

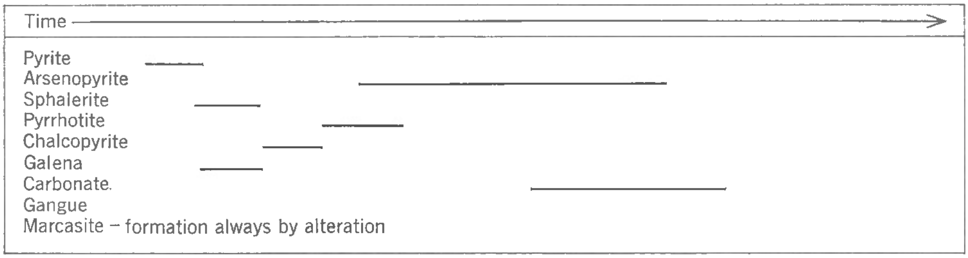

Figure 2. Paragenesis of Nigadoo ore minerals (Aleva, personal communication)

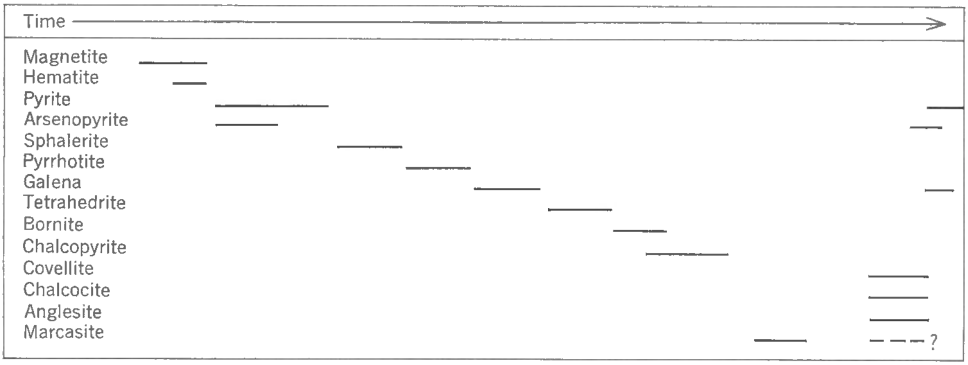

Figure 3. Paragenesis of the ore minerals of Brunswick No. 6 deposit

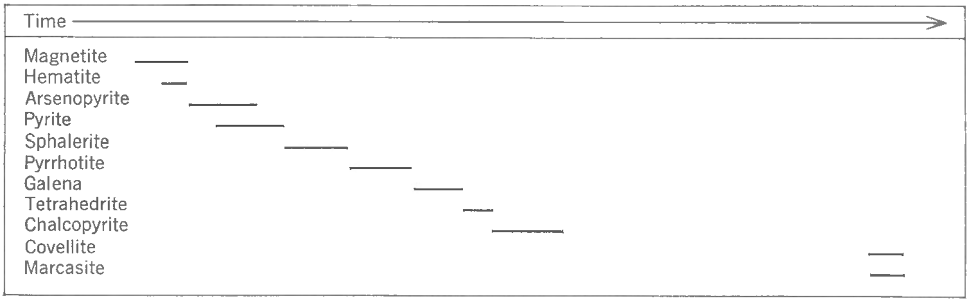

Figure 4. Paragenesis of the ore minerals of Brunswick No. 12 orebody

regarded as representative of the whole ore-bearing region. Most samples were taken from drill-cores, except at Anacon Lead Mines where only dump and unclassified core samples were available.

Brunswick No. 6 Deposit

The ores of the Brunswick No. 6 deposit are typical in mineralogy and texture of several deposits south of the break. The ores are very fine grained, compact, and are banded in places. Minerals identified from this deposit were: magnetite, hematite, pyrite, arsenopyrite, sphalerite, pyrrhotite, galena, chalcopyrite, bornite, tetrahedrite, covellite, marcasite, anglesite and chalcocite.

Magnetite and hematite are the earliest minerals in the suite, and evidently represent an original part of the iron-formation that has been replaced by the base metal sulphides. The magnetite occurs mainly in anhedral to rounded grains and exhibits no clear relationship with the lamellar to platy specular hematite. In a few places, however, the magnetite is oxidized to martite. The magnetite and hematite are partly replaced by pyrite (Pls. V B, VI A) and other sulphide minerals.

Among the sulphides, pyrite was the earliest mineral to crystallize, and it occurs generally in euhedral to subhedral grains. It commonly shows mutual boundary relations with arsenopyrite, but in a few places fills cracks and crevices in the arsenopyrite. From this it would appear that for part of the crystallization history of the ores, pyrite and arsenopyrite crystallized together with pyrite continuing to crystallize after the final precipitation of arsenopyrite.

Sphalerite, which wedges into and embays arsenopyrite and pyrite, is next in the paragenetic sequence. It is further replaced abundantly by pyrrhotite. Galena veins and replaces all the minerals mentioned above, and galena is, in turn, replaced by tetrahedrite, bornite and chalcopyrite. A fine-grained variety of galena that replaces all primary sulphide minerals and lies close to the surface is considered to be supergene. Tetrahedrite has been irregularly replaced (Pls. X A, B) by hypogene bornite. The minute needles of chalcopyrite that have exsolved in the (111) directions of the bornite (Pl. III A) confirm the hypogene nature of the bornite. The bornite is in places replaced by a late generation of chalcopyrite, which veins all the earlier minerals (Pl. X B).

Among the supergene minerals, covellite and chalcocite are the most abundant, closely followed by anglesite and marcasite. The marcasite occurs as an alteration product mainly of pyrrhotite and persists to a depth of 50 or more feet. It is, in turn, replaced by covellite and chalcocite. Anglesite is primarily an alteration product of galena. Covellite and chalcocite replace all sulphide minerals without any particular preference.

Pyrite, exhibiting a colloform texture and alternating with black hydrous ferrous sulphide (melnikovite-pyrite), was observed in sections taken from near the surface (Pl. V A). This pyrite is presumably of supergene origin.

The paragenesis of the sulphide minerals of the Brunswick No. 6 deposit is shown in Figure 3.

Lea and Rancourt (1958) in their account of the mineralogy of the Brunswick No. 6 deposit mentioned the presence in the ore of all the above minerals except hematite, arsenopyrite and anglesite. In addition they identified a few others not found in the writer's polished sections, such as stannite, cassiterite, cubanite, native silver, and gold. These minerals probably occur in minute quantities, and hence are apt to be easily missed. Lea and Rancourt believed that both the pyrrhotite and chalcopyrite are late stage minerals. The writer agrees to the late crystallization of chalcopyrite, but questions that of pyrrhotite. In a number of sections pyrrhotite is replaced by galena, and it is therefore placed between galena and sphalerite in the paragenesis of the ores.

Brunswick No. 12 Deposit

The Brunswick No. 12 orebody is essentially a massive sulphide replacement of siliceous sediments (Lea and Rancourt, 1958). The ores are very fine grained and massive, and in places show a fine banding.

The metallic minerals identified in polished sections and by X-ray powder photographs are: magnetite, hematite, arsenopyrite, pyrite, sphalerite, pyrrhotite, galena, tetrahedrite, chalcopyrite, marcasite and covellite.

The mineralogy and paragenesis of the ores of the Brunswick No. 12 deposit are similar to those of the Brunswick No. 6 except that clear evidence was found that arsenopyrite, among the sulphide minerals, began crystallizing early. It was followed shortly by pyrite and the two minerals crystallized contemporaneously for some time, as mutual boundary relations are common. However, at places pyrite clearly invades the euhedral to subhedral arsenopyrite. Supergene 'melnikovite-pyrite' (Schneiderhöhn and Ramdohr, 1931) is conspicuous in this orebody near the surface. Supergene pyrite, marcasite, covellite, chalcocite and anglesite are the other secondary minerals; the last two, if present at all, are very rare. Bornite was not detected in the ores of the No. 12 deposit.

The paragenesis of the ores of this deposit is shown in Figure 4.

Heath Steele Deposits

The ores of the Heath Steele deposits are similar in their general nature to those of the Brunswick No. 6 and No. 12 deposits. They are massive, fine grained, and have a more or less common mineralogical assemblage.

The minerals identified from these deposits are pyrite, arsenopyrite, sphalerite, pyrrhotite, galena, chalcopyrite, tetrahedrite, freibergite, native bismuth, anglesite, covellite and chalcocite.

In Heath Steele, as in the other deposits, pyrite occurs in two generations, one early hypogene in euhedral to subhedral grains (Pl. IV A) and the other, probably supergene, in very fine disseminations. Arsenopyrite is definitely later than pyrite, but earlier than sphalerite and the other primary sulphides. The paragenetic relations between sphalerite, pyrrhotite, galena, tetrahedrite and chalcopyrite are the same as those stated for the Brunswick No. 6 deposit. Native bismuth was detected in a number of polished sections, where it replaces galena, pyrrhotite and chalcopyrite in an irregular fashion (Pl. XI A). Although at first glance the mineral appears to be of supergene origin, it has been detected at a considerable depth where other supergene minerals such as anglesite, covellite and chalcocite are absent. It is assumed, therefore, that the native bismuth formed by hypogene replacement of the primary sulphides. Anglesite is formed at the expense of galena and is, in turn, replaced by supergene covellite and chalcocite. A few occurrences of very fine grained galena were detected near the surface. This galena invades chalcopyrite and may be of supergene origin. Freibergite, the only silver-bearing mineral detected from this deposit, is probably secondary, though it has been replaced by covellite (Pl. XI B).

Middle River, Anacon Lead Mines (New Larder 'U'), Anaconda (Caribou) Deposits

These deposits, though rather widely scattered geographically, are grouped together because of their similar mineralogy and paragenesis. Pyrite, arsenopyrite, sphalerite, pyrrhotite, galena, chalcopyrite, marcasite, covellite and chalcocite constitute the general assemblage of minerals in these deposits.

Pyrite is the earliest mineral, followed closely by arsenopyrite. The pyrite appears to be of only one generation; arsenopyrite fills cracks and crevices in the pyrite. Sphalerite embays and invades both arsenopyrite and pyrite, but is replaced by veins and stringers of pyrrhotite. Galena is later than pyrrhotite, and chalcopyrite is the latest of the primary minerals, replacing galena in an irregular fashion. Marcasite and minor amounts of covellite and chalcocite are the principal secondary sulphides.

The sequence of mineral formation in these three deposits is similar, and a paragenesis, common to all of them, is presented in Figure 6.

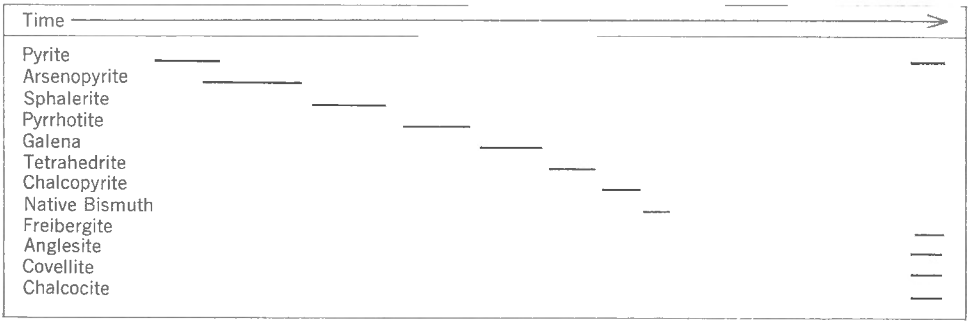

Figure 5. Paragenesis of the Heath Steele orebodies

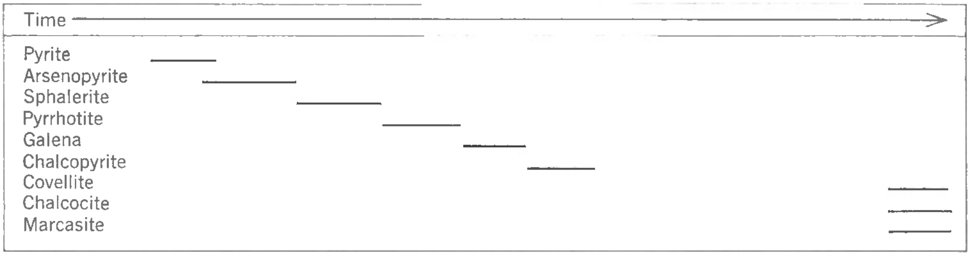

Figure 6. Paragenesis of the Middle River, Anacon Lead Mines (New Larder "U") and Anaconda (Caribou) orebodies

DISCUSSION OF THE TEXTURE AND PARAGENESIS OF THE ORES

Before any generalization is attempted, it is desirable to bring out the points of similarity and difference in the various ore deposits investigated, with respect to their geological setting and the microscopic character of the ores. In this respect, the Bathurst-Newcastle base metal ores can be broadly divided into two types:

(i) Those in the deposits north of the Rocky Brook-Millstream 'break' (Nigadoo, Sturgeon River, Keymet, etc.) in Upper and Middle Silurian rocks;

(ii) Those in the large massive orebodies south of the 'break', in Ordovician rocks (Brunswick Nos. 6 and 12, Heath Steele, Anacon Lead Mines, Middle River, Anaconda, etc.).

The ores of the deposits north of the break have a coarse grain size in contrast to the very fine grained, banded, and compact ores to the south. In the Nigadoo, Sturgeon River, and Keymet deposits, the gossan zone and the zone of supergene mineralization is very thin and in some cases practically absent. Thus the only supergene mineral found in these deposits in any amount is marcasite, which extends to considerable depth. By contrast, in some of the orebodies to the south, such as at Heath Steele, the gossan zone is well developed, supergene mineralization is rather prolific, and minerals like anglesite, covellite, and chalcocite are formed abundantly in the zone of secondary enrichment.

From a glance at the two paragenetic sequences it can be seen that in the areas both to the north and to the south of the break, pyrite was generally the earliest sulphide mineral to crystallize, except at Brunswick No. 12 deposit where arsenopyrite preceded it. To the south, relicts of banded iron-formation are found in the sulphides in some deposits (Brunswick No. 6 and Brunswick No. 12), and magnetite and hematite were thus the earliest minerals in the sequence. Arsenopyrite was definitely early in all deposits, and was partly contemporaneous with pyrite in some of the deposits south of the break (Brunswick No. 6 and No. 12, Heath Steele, etc.). After arsenopyrite, sphalerite was the next mineral to crystallize, followed closely by pyrrhotite. Following pyrrhotite, however, the sequence of crystallization was somewhat different in the deposits north and south of the break. In the Nigadoo, Sturgeon River, and Keymet deposits, chalcopyrite occurs in three generations, one minor generation as exsolution blebs in sphalerite, which was earlier than pyrrhotite in sequence, one major generation succeeding pyrrhotite and preceding galena, which is in exsolution intergrowth with tetrahedrite, and a final generation later than all the primary sulphide minerals. Thus, one major generation of chalcopyrite was earlier than galena, and a subordinate generation succeeds it. In the southern deposits, however, pyrrhotite was followed by minor generations of tetrahedrite and bornite. A minor phase of chalcopyrite has exsolved in the bornite, but most of the chalcopyrite entered later and was in fact latest

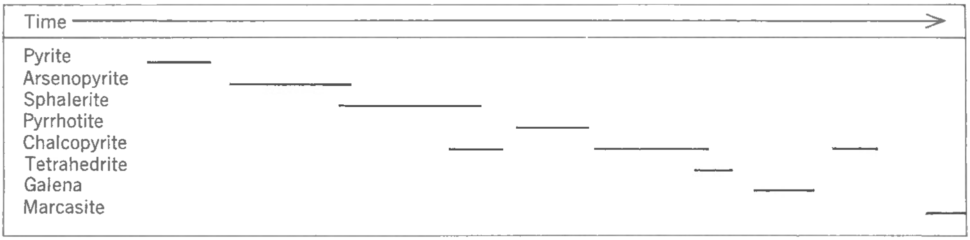

Figure 7. Paragenesis of the ore minerals of Nigadoo, Sturgeon River, and Keymet group of orebodies

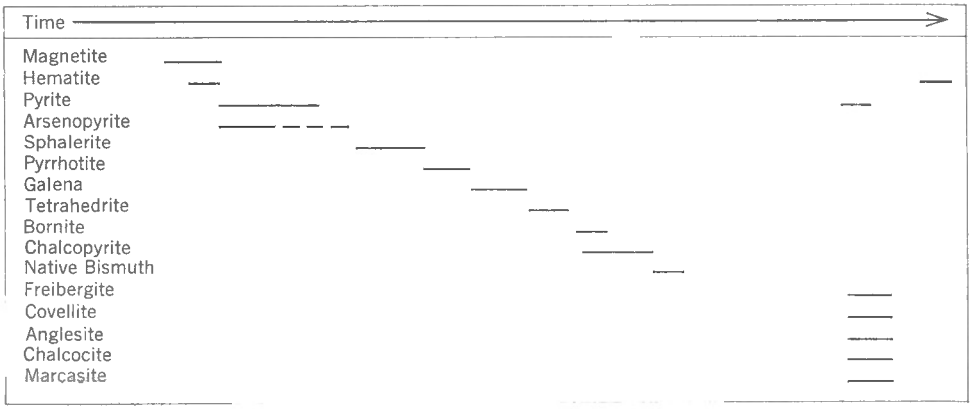

Figure 8. General paragenetic sequence of ore minerals from deposits south of the Rocky Brook-Millstream "break"

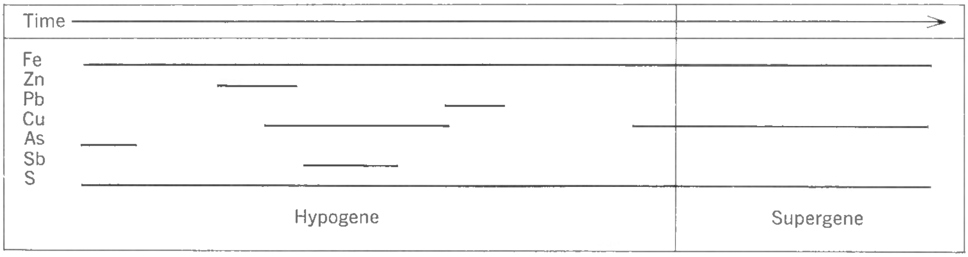

Figure 9. Sequence of elemental concentration in deposits north of the Rocky Brook-Millstream "break"

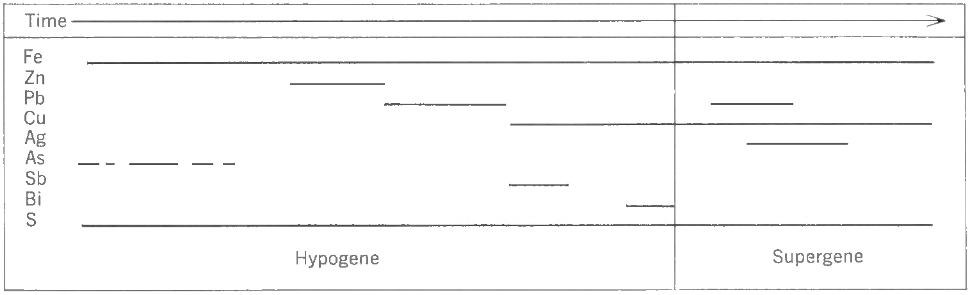

Figure 10. Sequence of elemental concentration in deposits south of the Rocky Brook-Millstream "break"

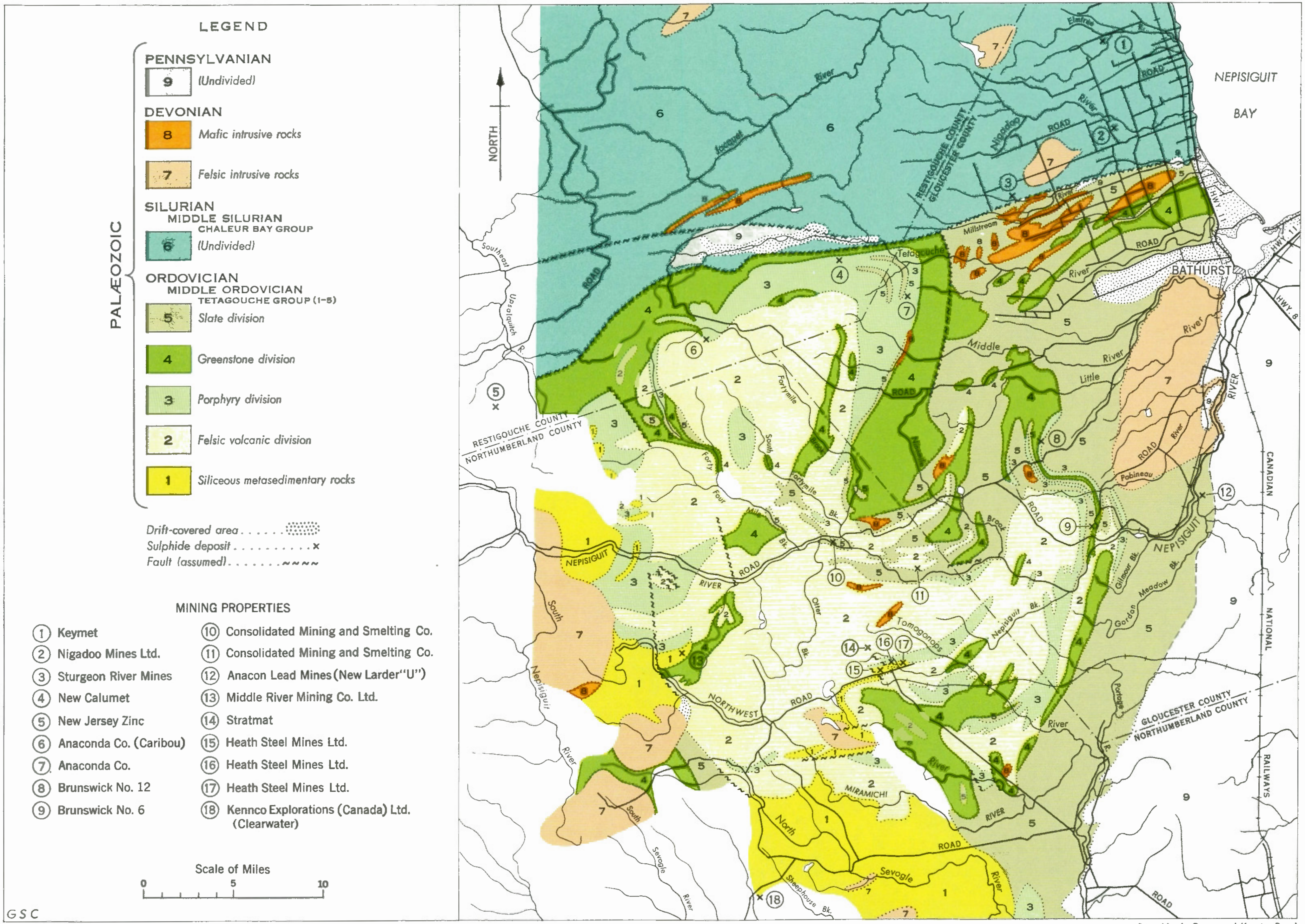

FIGURE 11. Principal base metal deposits, Bathurst-Newcastle district, New Brunswick

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among all the primary minerals. Among the supergene minerals, marcasite occurs abundantly in the northern deposits as well as in the deposits south of the break. Covellite, anglesite, chalcocite, and minor amounts of freibergite are present in the southern deposits.

From the sequence of crystallization of the different minerals in the base metal orebodies of the Bathurst-Newcastle area, the trend in the sequence of influx of different elements may also be construed. An attempt has been made below to correlate the influx of the major elements according to the crystallization sequence of the different minerals, disregarding, however, the elements that may be retained in solid solution without unmixing.

Figures 9 and 10 show that iron and sulphur decidedly enjoyed the highest elemental enrichment throughout the primary mineralization stage. Some iron, however, may have been derived from magnetite-hematite iron-formation in deposits such as the Brunswick No. 6 and No. 12, as suggested by Lea and Rancourt (1958). Arsenic followed iron and sulphur and was fixed in arsenopyrite. In all deposits both north and south of the break, zinc was precipitated next in order of sequence. The sequence of enrichment of lead and copper, however, varied. In the deposits north of the break enrichment of copper began early when sphalerite incorporated the element in solid solution and later exsolved it under lower temperature-pressure conditions. The influx of copper continued at a high level accompanied by some antimony (tetrahedrite in chalcopyrite) and both were succeeded by lead. After lead ceased to precipitate, copper entered again and continued to precipitate up to the end of the primary stage of mineralization. In the deposits south of the break, lead preceded copper, and the latter enjoyed a long period of enrichment and precipitation with the formation of bornite, tetrahedrite (with antimony), and chalcopyrite. In the Heath Steele deposit bismuth succeeded both lead and copper in the primary mineralization stage.

In the zone of secondary enrichment, iron, copper, lead, and silver are the principal enriched elements, though a small amount of silver is also found.

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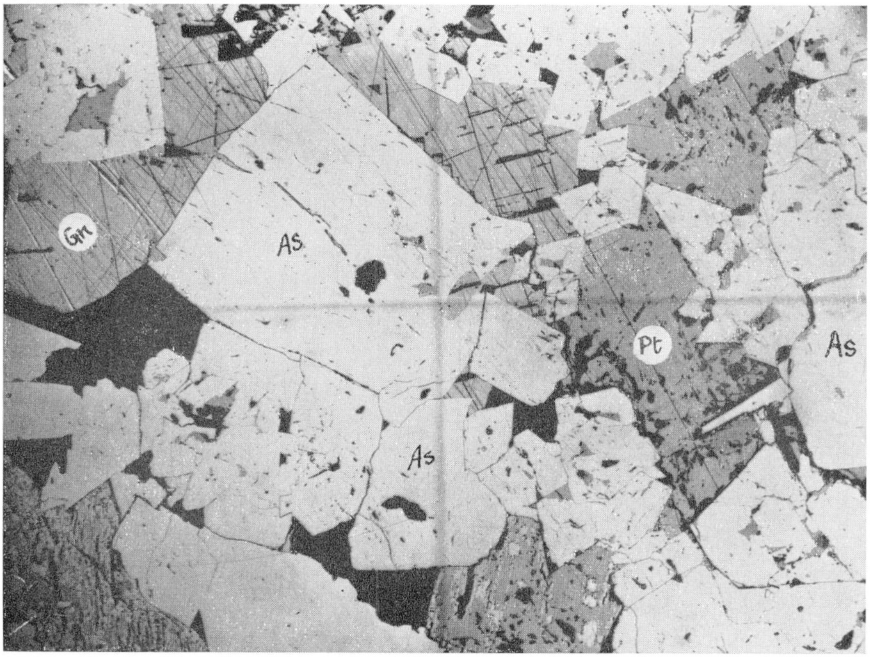
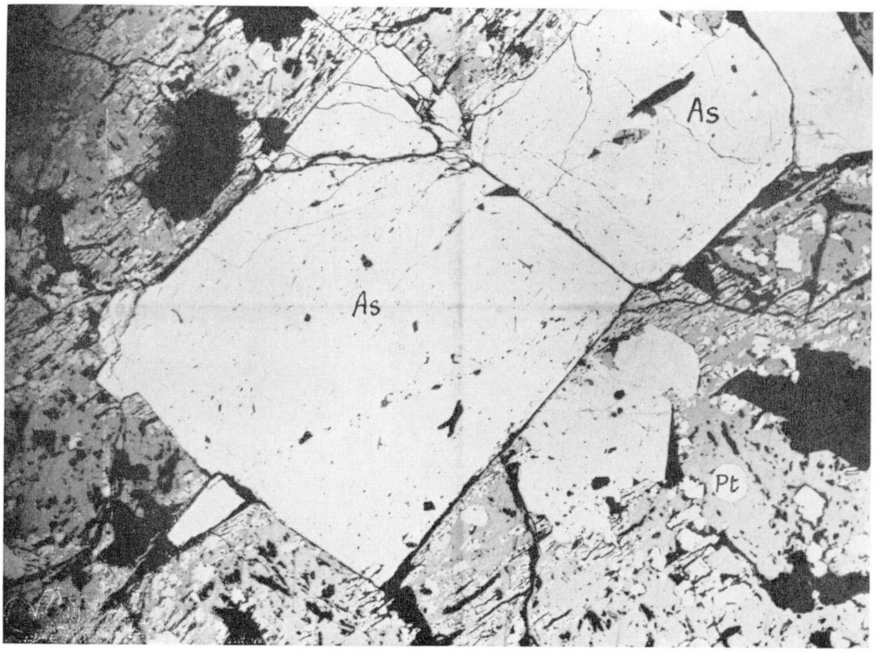
PLATES I to XI

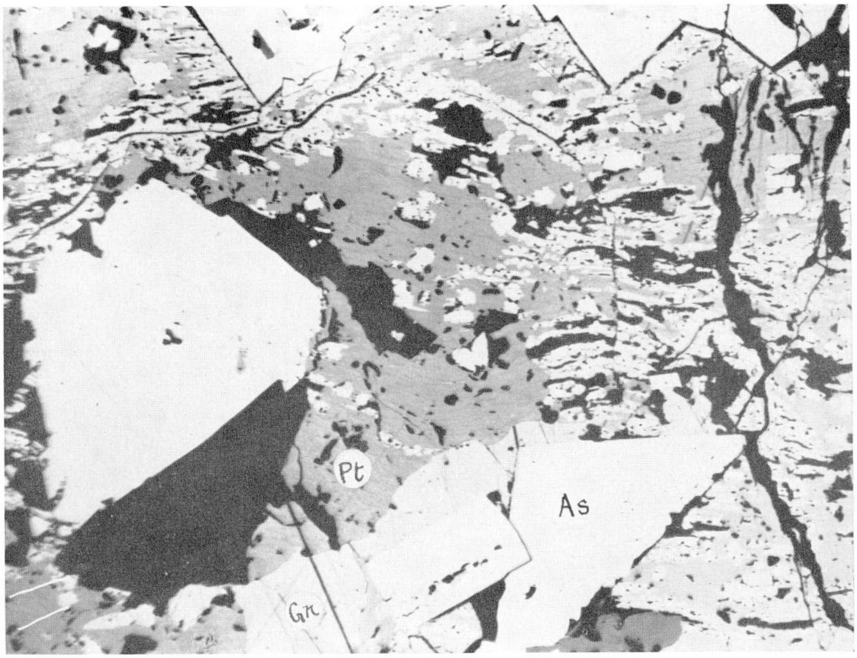


A. Arsenopyrite-pyrrhotite-galena assemblage. Pyrrhotite (Pt) and galena (Gn) occupy the interstitial spaces between euhedral arsenopyrite (As) grains and embay the latter. Keymet orebody. x100

Plate I.

B. Euhedral grains of arsenopyrite (As) set in pyrrhotite (Pt). Pyrrhotite is replaced along parting directions by marcasite. Nigadoo orebody. x100

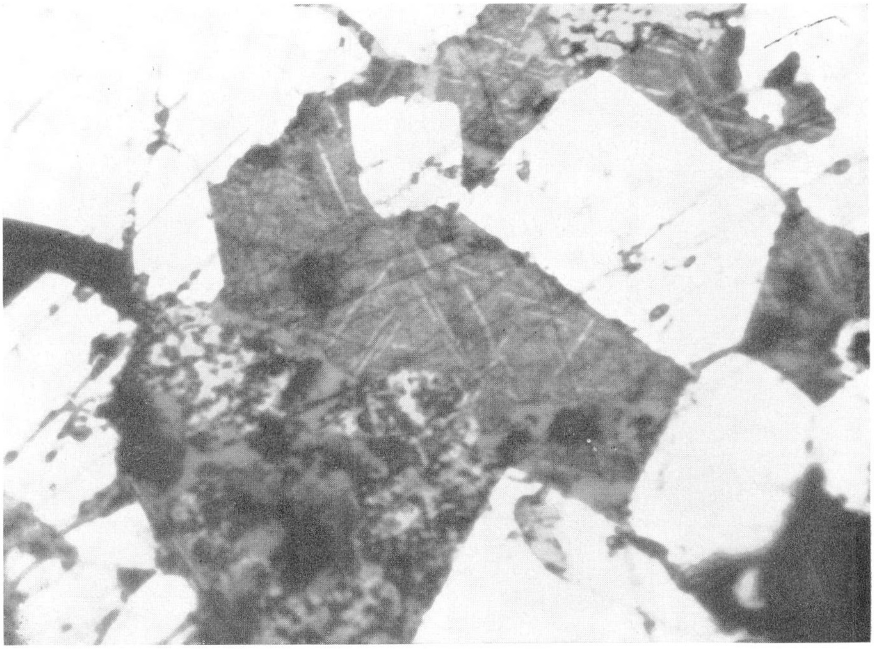




A. Arsenopyrite-pyrrhotite-galena assemblage. Pyrrhotite (Pt) largely replaced by marcasite (white) along parting planes. Galena (Gn) is interstitial. Sturgeon River orebody. x100

Plate II.

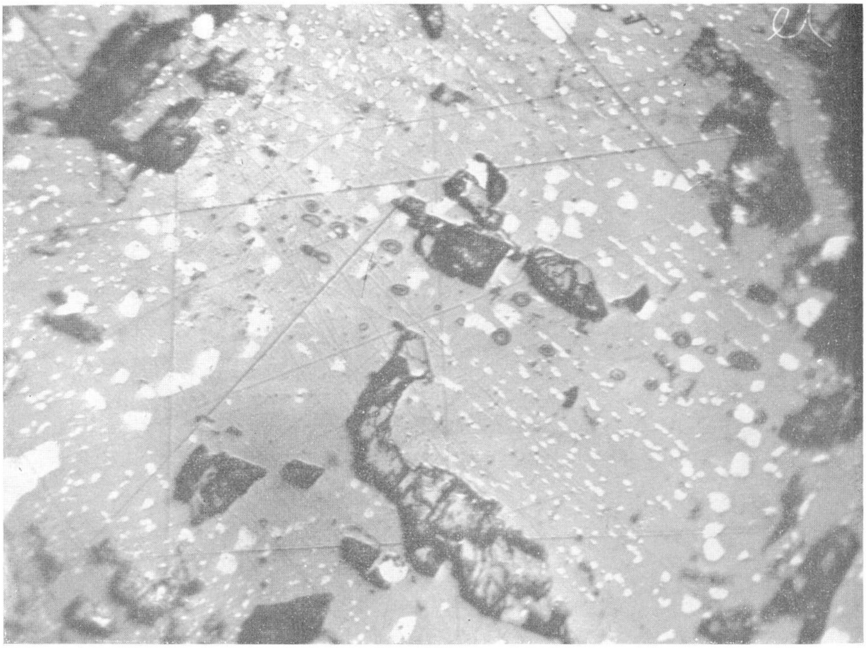
B. Chalcopyrite-tetrahedrite exsolution intergrowth. Curved lamellae of tetrahedrite (darker grey) in chalcopyrite (pale grey) host. Nigadoo orebody. x400

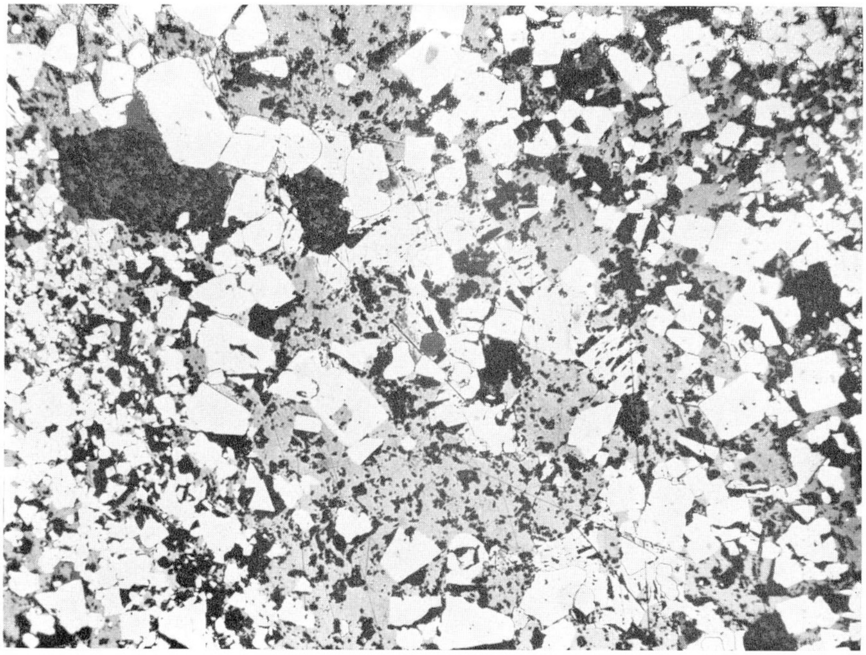


A. Bornite-chalcopyrite crystallographic intergrowth showing thin needles of chalcopyrite oriented in the (111) directions of bornite (dark grey). The white euhedral to subhedral grains are pyrite. Brunswick No. 6 orebody. Oil immersion x1050

Plate III.

B. Exsolution blebs of chalcopyrite in the crystallographic directions of sphalerite (grey host). Nigadoo orebody. x300

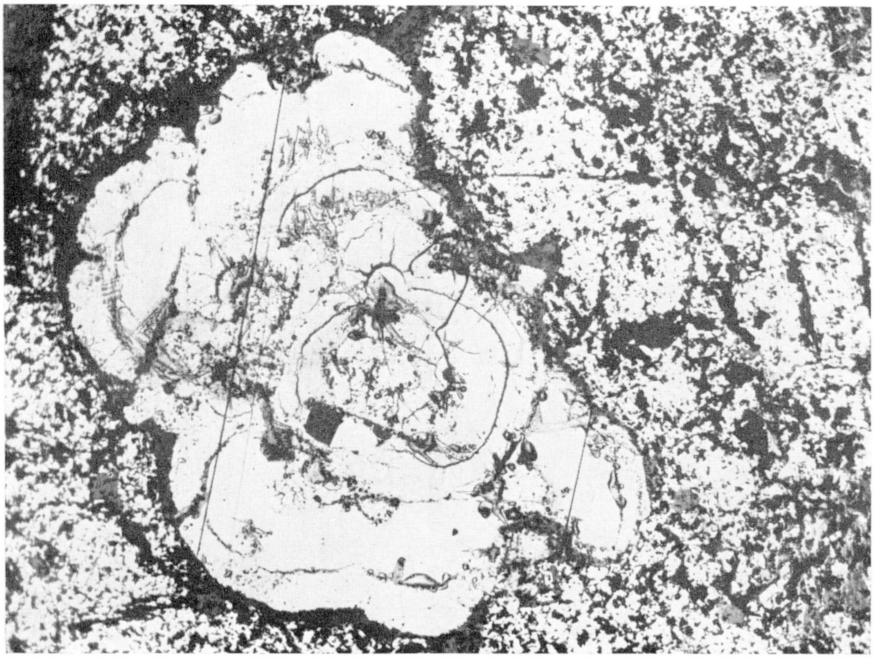


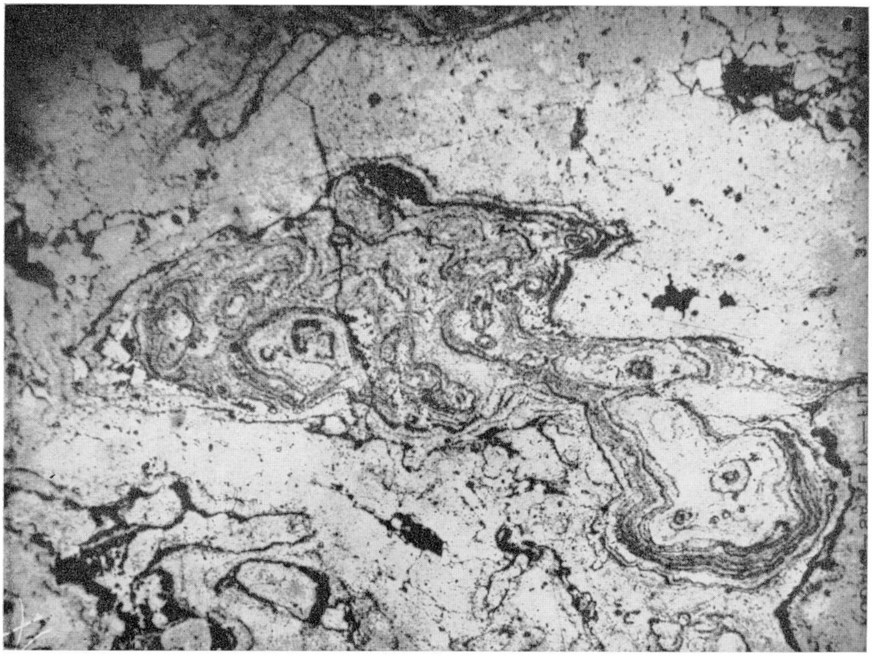


A. Euhedral grains of pyrite set in sphalerite base. The pyrite grains are also embayed and cemented by later galena. Heath Steele orebody. x100

Plate IV.

B. Colloform pyrite set in vug in pyrrhotite. Nigadoo orebody. x200

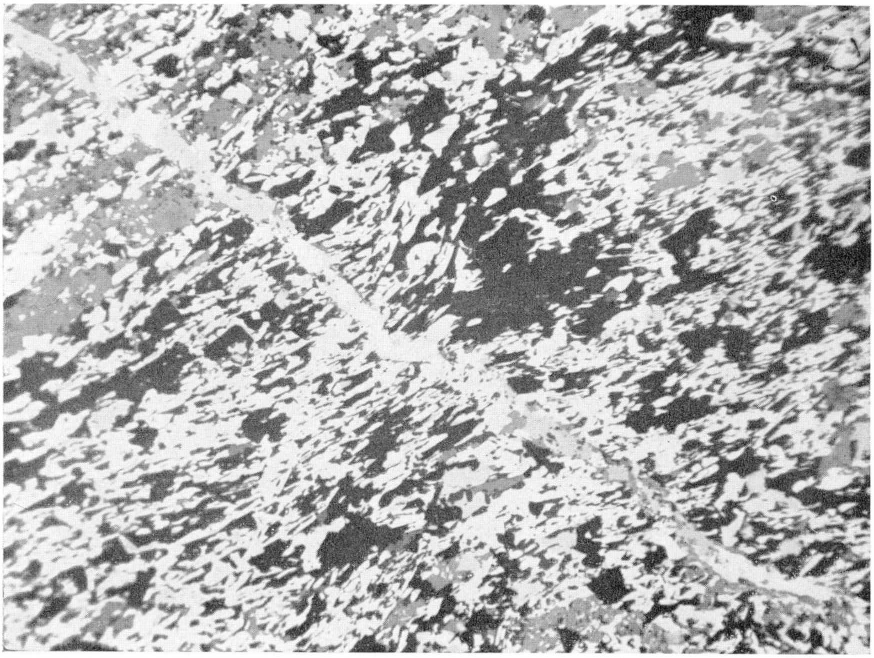


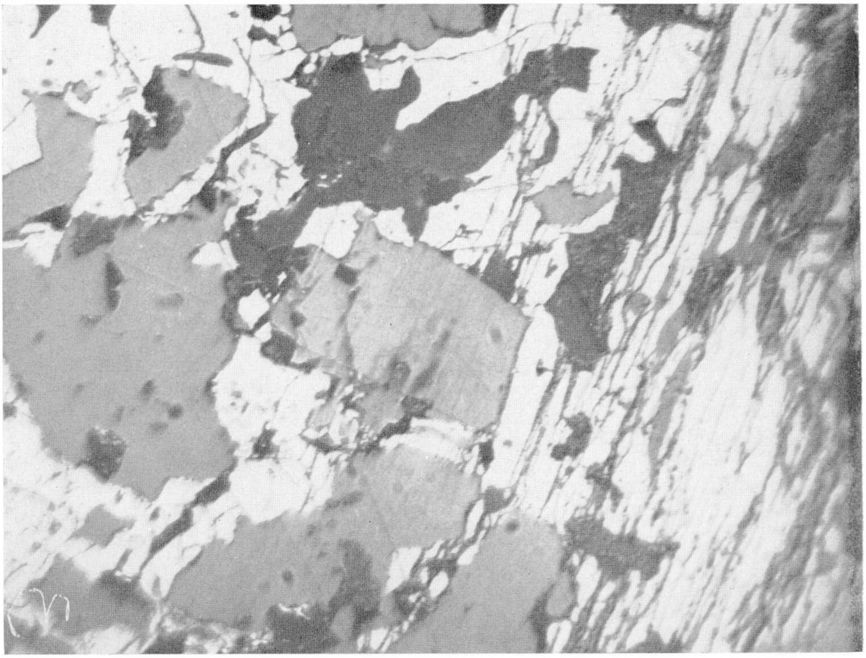


A. Colloform texture exhibited by pyrite and very fine grained black mineral (hydrous ferrous sulphide?), (Melnikovite-pyrite). Brunswick No. 6 orebody. x200

Plate V.

B. Pyrite vein cutting specular hematite and magnetite. Brunswick No. 6 orebody. x50

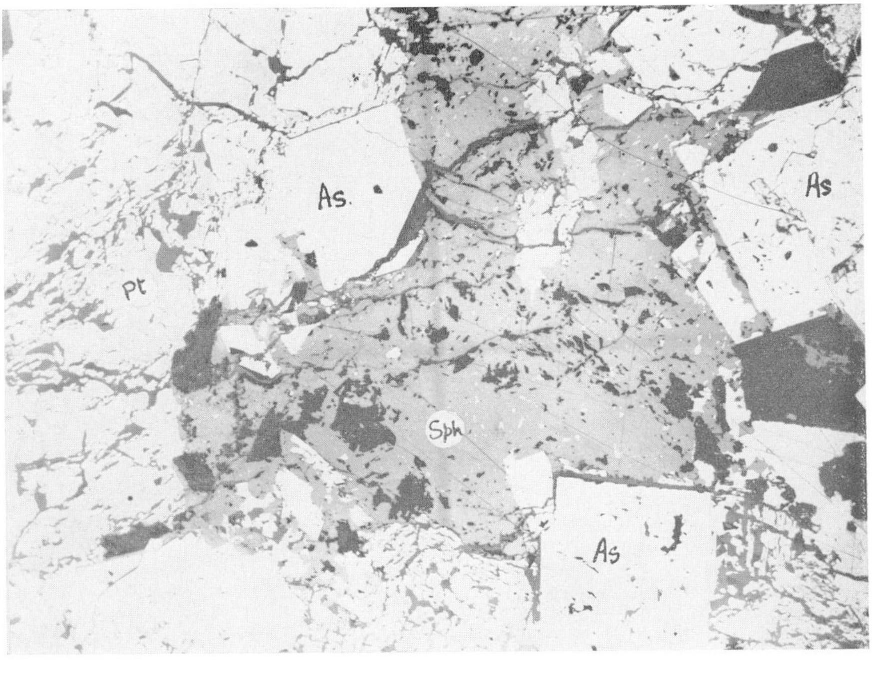


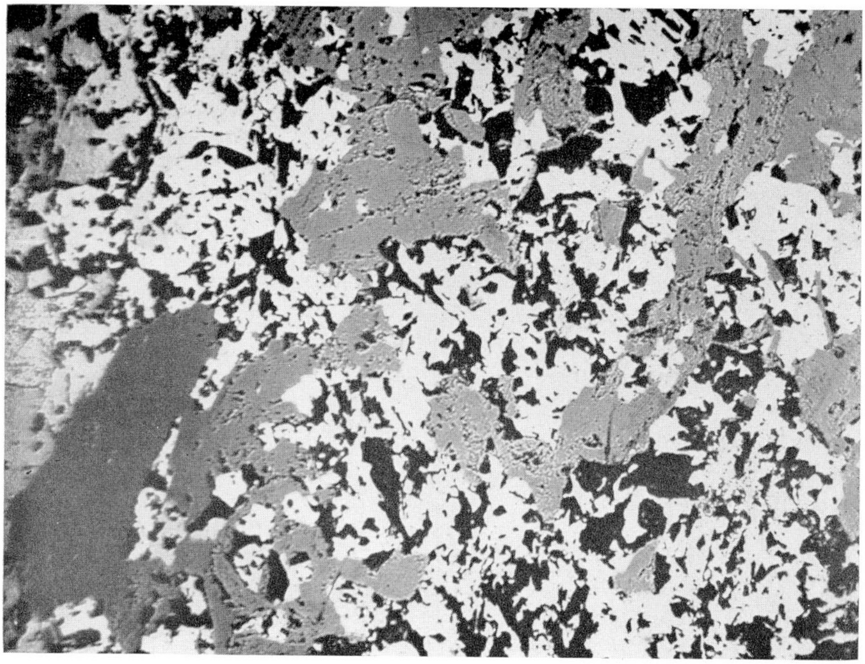


A. Pyrite (white) replacing magnetite (dark grey) along grain boundaries and parting planes. Such replacement is not widespread. Brunswick No. 6 orebody. x200

Plate VI.

B. Sphalerite (Sph) containing inclusions of pyrite and arsenopyrite, embaying larger grains of arsenopyrite (As). Pyrrhotite (Pt), largely replaced by marcasite, is in contact with sphalerite. Keymet orebody. x200

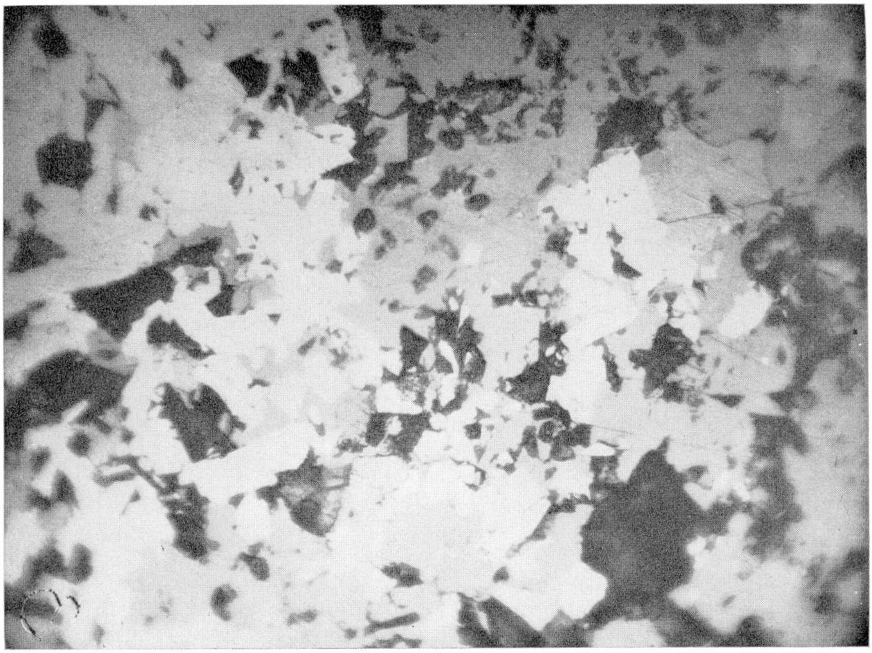




A. *Pyrrhotite (almost white) replacing sphalerite (dark grey). Anacon Lead mine. x100*

Plate VII.

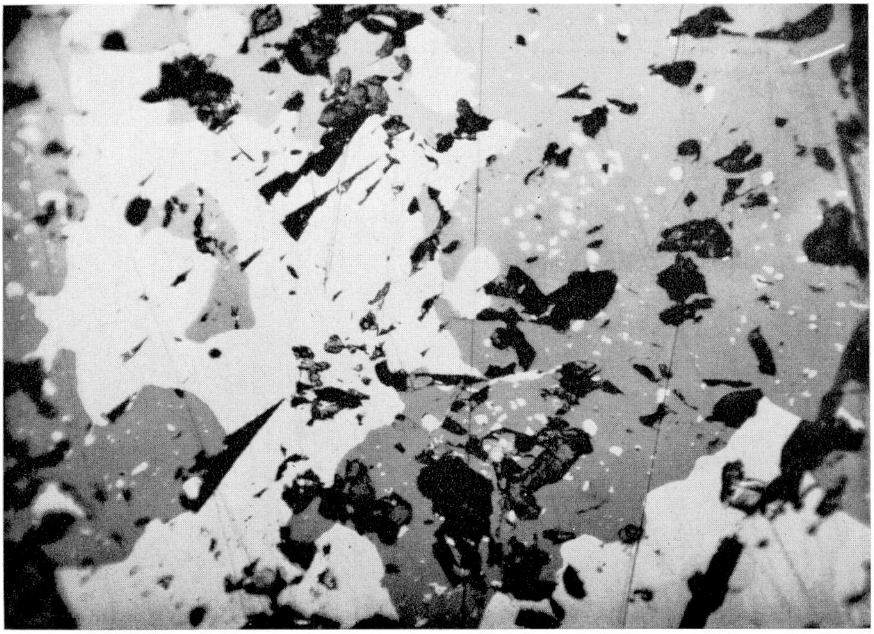
B. *Galena (white) replacing and embaying sphalerite (grey). Nigadoo orebody. x100*

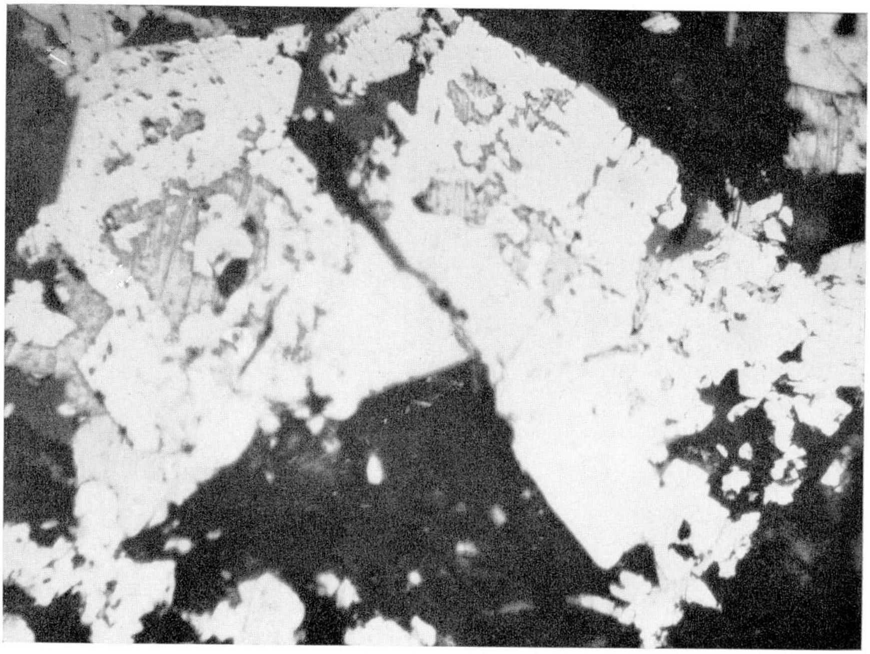


A. Sphalerite (grey) replacing and embaying arsenopyrite (white). Nigadoo orebody. x300

Plate VIII.

B. Second generation chalcopyrite (white) replacing sphalerite (grey) containing exsolution blebs of first generation chalcopyrite (white blebs). Nigadoo orebody. x200

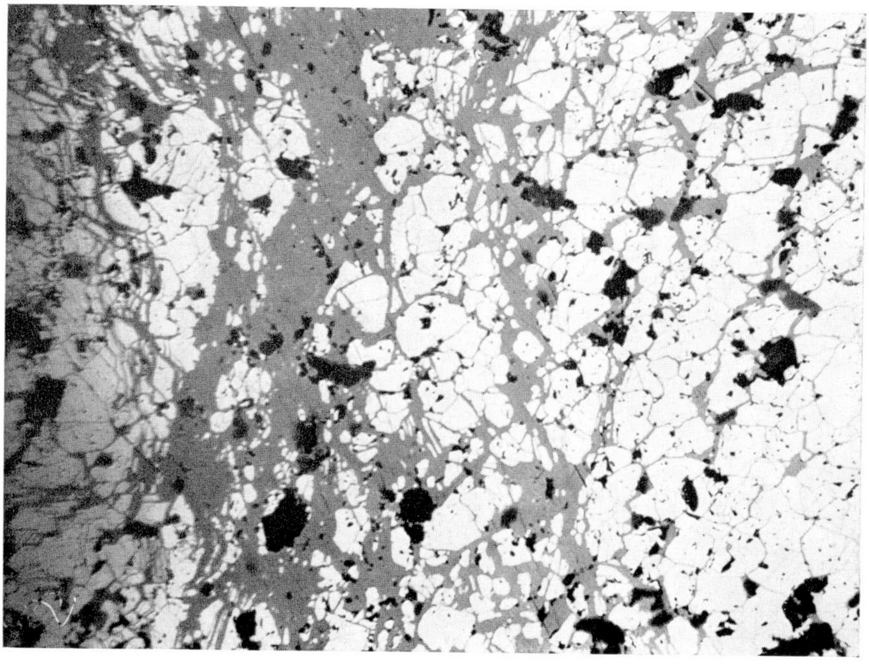


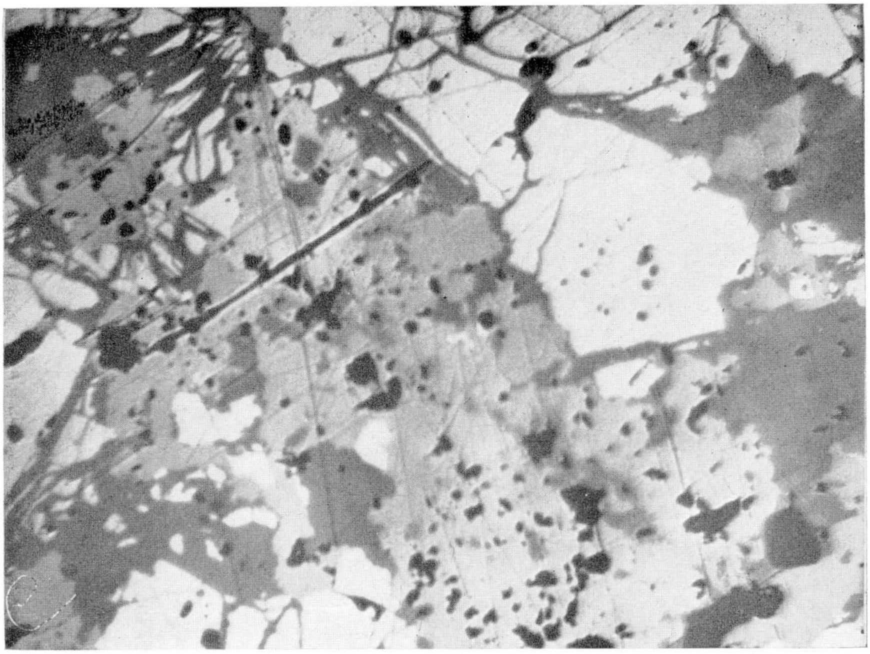


A. Galena (pale grey) replacing arsenopyrite (white). Nigadoo orebody. x300

Plate IX.

B. Bornite (grey) replacing pyrite (white) along the grain boundaries. Brunswick No. 6 orebody. x100

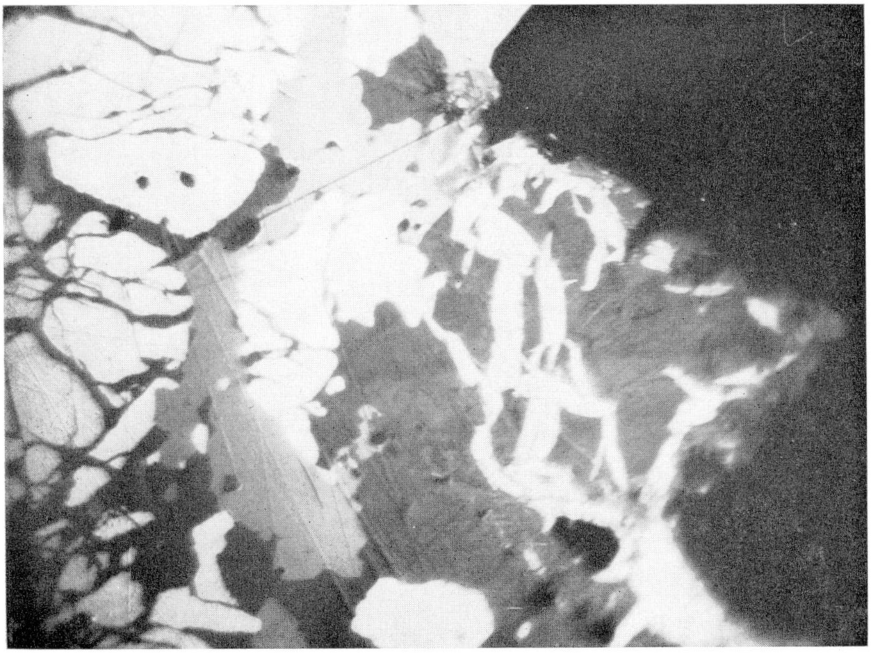


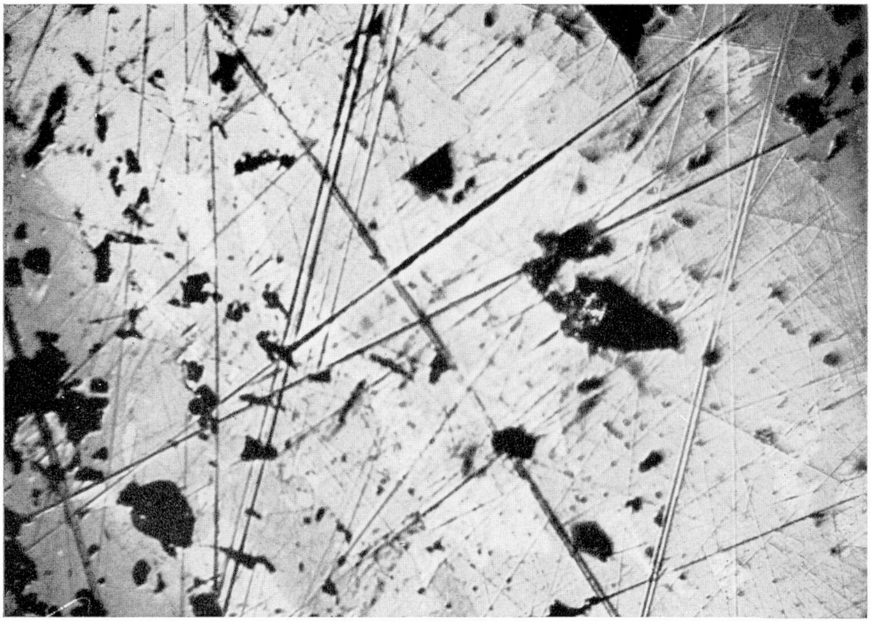


A. Bornite (dark grey) replacing both tetrahedrite (lighter grey) and pyrite (white). Tetrahedrite replaces pyrite. Brunswick No. 6 orebody. x200

Plate X.

B. Tetrahedrite (light grey) replacing pyrite (white fractured). Bornite (dark grey) replaces tetrahedrite, and chalcopyrite (bright white) stringers replace bornite. Brunswick No. 6 orebody. x400





A. *Native bismuth (pale grey) replacing galena (dark grey) in an irreglar fashion. Heath Steele orebody. x400*

Plate XI.

B. *Freibergite (grey) replacing chalcopyrite (white) in an irregular fashion. The freibergite appears to be supergene. Heath Steele orebody. Oil immersion x650*