

PART II

THE FACTS: THE ORES, THEIR MINERALS, METALS AND DISTRIBUTION

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This part is largely factual. It is divided into four sections. In the first the megascopic features of the ore deposits and their classifications are considered. The second deals with the descriptive mineralogy and chemical characteristics of both metallic and non-metallic constituents in the general order of their abundance. In the third, the relationships, chiefly microscopic, of primary ore minerals to rock-forming minerals are reviewed for later consideration, and in the fourth data available on the distribution of the major and minor base and precious metals, as well as certain metal and mineral ratios are examined.

A. THE ORE DEPOSITS

The gross features of the sulphide deposits at Sudbury have been described in considerable detail by many authors, so that only a general summary of their characteristics need be given here. Referred to by some as "monotonously similar" they do, however, show a few distinctive differences from place to place. They have been well illustrated by Knight and others.

1. CLASSIFICATION OF THE ORE DEPOSITS

Coleman's original classification on a basis of distribution into *marginal* and *offset* types has been a most useful one, not only with respect to their geological location but also in emphasizing certain broad mineralogical differences. The terms, of course, refer respectively to those deposits which lie along the footwall or outer margin of the "norite," much the more important quantitatively, and those occurring in dyke-like bodies

of quartz-diorite, usually cross-cutting and more rarely paralleling the surrounding formations. Offset ores differ in themselves but in general appear more siliceous in places, carry a wider variety of mineral species, more complex intergrowths, and in some, a higher than normal content of the precious metals, including gold, silver and the platinum group. The largest of these, the Frood-Stobie deposit, displays a remarkable type of zoning not duplicated on the same scale in any other. As will be seen from the mineralogical studies which follow, these features suggest somewhat different conditions of formation compared with many of the marginal ores.

Physically the ores fall into four main types, designated "disseminated ore," "massive ore," "breccia ore," and "vein" or "stringer ore." A new sub-division of "massive ore" containing what were originally probably immiscible blebs of silicate liquid, is described here for the first time. Several or all of these may occur in any one deposit.

A mineralogical or chemical classification has also been referred to at times, where certain constituents predominate in contrast to what may be designated "common" or "normal" ore consisting chiefly of pyrrhotite, pentlandite and chalcopyrite. Thus, copper-rich ores have more abundant chalcopyrite and cubanite; arsenical ores, gersdorffite, niccolite or maucherite; marcasite ores represent replacements of normal ore by marcasite, pyrite, and in places, violarite; siliceous ores, as on the lower levels of the Frood contain a host of rarer species with lead, bismuth, tin, tellurium and precious metals. A recently described unique type (McKim mine) is a breccia ore composed chiefly of pentlandite and pyrite, while very late veins carry chiefly galena, sphalerite and usually marcasite.

Structurally, considered in their larger aspect, the majority of the ores are moderately dipping elongate, lenticular or sheet-like bodies, whether consisting of disseminated, massive, breccia, or stringer sulphide zones. Some of these are arranged en echelon both laterally and down dip. Some coincide with steep faults, more or less paralleling the norite contact. A few appear to lie in vertical zones, about normal to the contact. A rare "columnar" or "pipe-like" body occurs at Copper Cliff. The vertically zoned, sheath-like ores at Frood-Stobie, enveloping the large wedge-shaped body of disseminated ore-bearing quartz diorite and enclosed in the Frood breccia, is still another rare type.

The major features of the four physical types of ore will now be reviewed. This will be followed by a summary of genetic classifications which have been proposed and the basis on which they are founded. Consideration of mineralogical and chemical characteristics bearing on the origin will be delayed until these have been presented in detail.

2. PHYSICAL TYPES

(a). DISSEMINATED ORES

The bulk of disseminated ore is associated with the quartz diorite phase of the norite either bordering the norite or in the "offset" dykes. It also occurs in altered or quartzose (spotted) norite and in many breccias lying at or near the irruptive contact. It may pass rapidly into massive ore, or it may be cut by veins or stringers of almost solid sulphides.

There appear to be at least two types of disseminated ores, one, as will be indicated, clearly representing immiscible sulphide droplets trapped in the crystallized quartz-diorite or norite readily identifiable except where sheared; the other introduced into wall rocks or breccia matrix, as near massive ore in faults or fractures. The former would not be expected to show much evidence of replacement while the latter might very well do so, thus confusing the issue as to mode of emplacement.

Within the quartz diorite and norite and in breccias in which these rocks form the matrix the sulphides appear as rounded blebs, and in places, as Howe remarked, essentially in the same arrangement "as phenocrysts in a porphyry." Generally these are more or less equidimensional, except where the rocks have suffered shearing, varying in diameter from a millimetre or so to about 1.0-1.5 cm., with an average in the vicinity of 0.75 cm. In the leanest material they are widely separated, but as they become more abundant they eventually appear to coalesce, and ore may be seen in which the blebs have almost lost their individual identity and become aggregates of massive sulphide (Pl. XIV, XV). The latter is sometimes referred to as "massive disseminated" ore, distinguished from other massive ores by a finer grain and usually a sharp contact.

The major part of the disseminated sulphide is pyrrhotite, with chalcopyrite and pentlandite occurring in minor quantity. They are thus rather simple, mineralogically. In such sections as we have examined, individual blebs generally consist of at least 85 per cent pyrrhotite, with chalcopyrite present as rounded or irregular areas situated towards the sulphide boundaries. Pentlandite, where visible, occurs as marginal segregation networks and as "flames" (see later descriptions). Some blebs are entirely pyrrhotite, most contain pyrrhotite and chalcopyrite, and a small number show all three. It is noticeable that all of these occur within the more or less regularly rounded boundaries of each bleb, rather than, for instance, a pyrrhotite bleb to which individual particles of the other minerals are adhering. Rarely the blebs appear to be made

up entirely of chalcopyrite, but these seem to merge almost imperceptibly into normal pyrrhotite-rich material.

While disseminated ores occur in most of the major deposits, the Creighton and Froid are probably the most outstanding examples. It was in fact at the former where the apparent gradation from massive ore at the base of the irruptive to disseminated ore above, in the quartz diorite phase of the norite, led to the hypothesis of magmatic segregation. Other early observers, notably Howe, questioned this relation at Creighton as proof of the downward segregation of immiscible sulphides and the actual gradation of the one type of ore into the other. Yates (1948) noted that in places here, massive ore is clearly controlled by faulting, the disseminated ore, found both above and below it, fading gradually on either side within the limits of enclosing quartz diorite, and cutting out sharply as the contact is reached, implying its later introduction. This is, of course, locally true, but the overall distribution of disseminated sulphides at and close to the outer margin of the irruptive and within the Creighton embayment leaves little doubt as to their downward concentration from the norite as well. In addition disseminated sulphides in "spotted" norite with a width of 600 feet and a much greater length, now being mined, lie some distance above the base of the norite, and according to Coleman, Moore & Walker, show no evidence of having been introduced.

At the Froid the disseminated sulphides occur throughout the disconnected lenses of quartz diorite which wedge out at depth. The quartz diorite is characterized by large and small unmineralized inclusions of "recrystallized hypersthene gabbro," most of which have actinolitic rims. The sulphides consist of both magnetic and non-magnetic pyrrhotite, pentlandite, and chalcopyrite, many of which contain laths of cubanite. The abundance of the sulphide blebs varies greatly, increasing very decidedly, however, with both degree of shearing and with depth, and passing into more massive type ore. Where the latter is absent disseminated ore is much more sparse.

(b) MASSIVE ORES

These are composed almost entirely of sulphides with variable amounts of associated magnetite, and less commonly ilmenite or both. They vary in texture from fine, with grain size of a millimetre or less, to very coarse, with grains attaining dimensions of several centimetres. In addition to the normal pyrrhotite-pentlandite-chalcopyrite assemblage, cubanite may be a major constituent in some, as at Froid, and pyrite locally appears more prominently, as in some north range deposits. In most, very minor flecks of sphalerite and galena may be found here and there,

but very seldom do they appear in larger or appreciable local concentrations. The same applies generally to the arsenides of which gersdorffite seems to have the widest distribution and may even occur massive over widths as great as six inches. Ore of this type lends itself well to textural studies, details of which appear in Part III.

Massive ores may pass not only into disseminated ores but also, either gradually or sharply, into breccia ore. In many cases the massive ores appear closely related to faults, (Creighton, Garson, Falconbridge), but in others faulting is at least not now evident, and to what degree they owe their existence to large fracture fillings, to almost complete segregation of immiscible sulphide liquids at the base of the irruptive, or to almost complete replacement of adjacent rocks, is not always readily apparent.

(c) IMMISCIBLE-SILICATE-SULPHIDE ORE

A most interesting type is an ore which appears to be gradational into both disseminated and massive ore and is one which would be expected on consideration of the possible ways by which immiscible sulphide and silicate liquids may separate and crystallize. This is the counterpart of those disseminated ores in which drop-shaped sulphides are dispersed through the quartz diorite or norite. This new type lies below disseminated ore near the base and also in the pit area of the Froid offset and studies of it are still in progress. In it the sulphides are the continuous phase and rounded to elliptical and club-shaped as well as some larger irregular inclusions of fine grained quartz diorite, and only quartz diorite, ranging in size from less than one quarter inch to an inch or more across, are distributed throughout, in some sections showing a general alignment (*frontispiece*). As the inclusions increase in number, accounting for approximately one-quarter or more of the volume, it resembles some breccia ore except for the form and composition of the silicate bodies. The sulphides consist largely of medium grained pyrrhotite with readily visible spots of pentlandite and quite minor chalcopyrite. As will be discussed in more detail later (Part III, p. 160) this may in part represent the product of an immiscible sulphide-silicate liquid solution which separated from the dominantly silicate magma at high temperatures, settled downward by gravity, and further split into two immiscible liquids, the major one composed of sulphides and the minor one of silicates still with some dissolved sulphide, well before each began to crystallize. This is further demonstrated by the fine drop form of sulphides trapped within the silicate phase. The coarser, irregular shaped inclusions to which small globular bodies are attached, may be the result of silicate liquid rising from the original base of the offset and "frozen" in the descending

sulphide phase.¹ It thus may testify to the major role played by liquid immiscibility in the segregation of some ores *in situ*. It will be referred to as "immiscible silicate-sulphide ore." Forcible movement of such mixed liquids to other sites would undoubtedly result in the destruction of the textures exhibited.

(d) BRECCIA ORES

Breccia ores are everywhere quantitatively very important. In some mines, as at Falconbridge, Davidson estimated 80 per cent of the ore is of the breccia type. In general the term is used for ore containing fragments of any rock. They differ in some important respects from place to place but are essentially bodies containing rounded, sub-rounded to sub-angular fragments of a wide variety of rocks in a matrix ranging from almost massive sulphide to varying proportions of sulphide and fine silicate particles of wall rocks and inclusions. Some represent mineralized pre-norite breccias, others appear to have formed by the invasion of sulphides into fault zones, some of which have been highly altered to quartz and carbonate, affecting even faulted norite, so that fragments of schist, quartz, carbonate and norite are present (Garson). Some may be remobilized breccias (McKim).

As in the common Sudbury breccia, the dominant rock fragments vary with the locality. At Murray where a band of quartz-diorite-breccia ore lies directly below quite barren norite and is succeeded by massive ore, the abundant fragments are chiefly basic, grey, hypersthene-bearing lavas, older gabbros and even an odd fragment of norite. At Frood this type of ore consists of mineralized Frood breccia with a wide range of rock types, and on the north range fragments consist of granite and granitic to mafic gneiss (the Levack breccia). Coarser fragments on the whole are unmineralized but where foliated, or fractured the sulphides, often chiefly chalcopyrite, do penetrate and replace them. Again the essential ore minerals are dominantly of pyrrhotite with lesser amounts of chalcopyrite and pentlandite except where zoning with respect to distance from the norite contact accounts for an increase in the copper-nickel ratio. On the whole the sulphides are finer grained than in massive ores and where they carry abundant fine specks of silicate they may have a dull appearance. Also in contrast to massive ores, magnetite appears as either a very minor or negligible constituent, and pentlandite is much less visible to the naked eye and accordingly very difficult to separate from the pyrrhotite in which it is chiefly contained.

¹An ore of a very similar type has recently been described and illustrated by Erland Grip (1961) from the Lainijaur nickel deposit of Northern Sweden, but is regarded as of replacement origin, according to the caption.

In general the breccia ore is always close or immediately adjacent to the norite or quartz diorite, and usually attains its greatest development and thickness in irregular rolls or depressions in the footwall rocks, the embayments, whereas the higher elevations of the footwall surface contain much less or none at all. At Falconbridge, however, the breccia ore persists along strike and to great depth. Here Lochhead attributes it to mineralization of a pre-norite fault along which the irruptive was intruded, but one re-activated to yield also fragments of norite, prior to the upward injection of sulphides, so well demonstrated by the development of ore shoots on whichever side is hanging wall, as the dip changes from steeply north to steeply south. Ore dies out as the breccia fault zone leaves the norite contact at either end.

Distinction needs to be drawn between such "rheomorphic" or tectonic breccia ores and mineralized breccias in which foreign fragments are contained in an igneous matrix, such as quartz diorite, rarely quartzose norite (Gertrude), or even a "granitic" matrix, the latter consisting mainly of plagioclase and similar to quartz diorite but lacking feric constituents, as at Levack and Hardy. Some of these project into the norite as tongues or "dykes" and have either been injected or represent breccia caught up in the intruding norite. Where well mineralized they are more in the nature of disseminated ore, but some massive ore is described in "granite" breccia at the Hardy (Mitchell & Mutch).

The similarity of many such ores to unmineralized Sudbury breccia and their continuity with them led Speers to believe most represented mineralized Sudbury breccia adjacent to the irruptive, or breccia which had been engulfed in quartz diorite as in offsets or at the margins, and mineralized at about the same time. This is clearly not always the case as indicated by breccia ores following fault zones, developed to some extent after part of the irruptive had solidified as suggested by Lochhead. That the crystallization of the norite, the faulting and mineralization were not greatly separated in time is indicated both by the extent of the faults, the type of mineralization and its prevalence only near the contacts.

The mode of emplacement and varying degrees of replacement as between matrix and fragments in some, and in less sheared as compared to highly sheared and altered rocks in others, are questions to be discussed further below.

Although quite rare in the area as a whole a most interesting type of breccia ore has been described recently by Clarke & Potapoff in Murray granite at the McKim mine. Here the main ore zone is similar to that at the Murray mine. Just below the 1675 level footwall basic greenstones and gabbros pass downward into the complex "Murray" granite and in

this at least three ore-bearing breccia zones are found; one joins the main contact breccia ore along the footwall of the norite, another is completely isolated in granite and a third, pipe-like body lies normal to the strike and dip of the norite and is separated from "contact" ore by quartz-carbonate material. The latter, described as "disseminated pentlandite breccia ore" contains fragments identical with the main, normal breccia ore, including some norite, but has a matrix of pegmatitic material. Disseminated sulphides, making up about 10 per cent of the zone occur randomly but usually in the dark fragments and more rarely in the light coloured matrix. They consist of 50 per cent pentlandite, 30 per cent pyrite and 20 per cent pyrrhotite, and practically no chalcopyrite. The pyrite is clearly the youngest, replacing both pyrrhotite and pentlandite to a considerable extent, while quartz and carbonate replace both the sulphides and the pegmatitic material. A few fine stringers of pentlandite extend into fractures in the granite below the breccia. This ore is in marked contrast to the "contact" breccia ore (the matrix of which consists of about 80 per cent sulphides) in its relatively high content of pentlandite and abundant post-pentlandite pyrite. As will be shown below, a study of the pentlandite shows distinct differences in cobalt content from "normal" ore, and as suggested by Clarke & Potapoff, this type may have been formed during the development of the post-norite granite. The origin of this type will be considered in subsequent discussions. Peculiarly the other breccia ores contained in the granite are of a more normal composition.

(e) VEIN AND STRINGER ORES

This term is applied chiefly to nickel-copper ores essentially of the massive type but confined to fractures of varying widths. These often occur below or at the ends of the larger disseminated ore bodies, paralleling their major trends or faults within them, or taking off in various directions around the borders and pinching out in short distances. Though they may contain the three common sulphides, chalcopyrite is often the major constituent, particularly at their borders and tapering extremities. Most appear to have formed at about the same time as the other ore types but chiefly in the more brittle footwall rocks.

Post-main ore veins are also found throughout most of the deposits, both marginal and offset, cross-cutting massive sulphides. These are usually very narrow, seldom exceeding a few inches in width, with the exception of some quartz veins, and are characterized by a crustified structure, galena, sphalerite, pyrite or marcasite and quartz and carbonates. Quantitatively, however, they are not important and belong to a much later period of mineralization, dated as about 1200 m.y.

3. GENETIC CLASSIFICATIONS

With few exceptions the ores have long been considered genetically related to the Sudbury irruptive or its parent magma, and have been classified chiefly as either magmatic sulphides, segregated and crystallized *in situ*, or injected, on the one hand, or as hydrothermal replacement deposits, on the other. A third suggestion is that they are metasomatic and due to metamorphic effects of post-norite granites. As will be shown later, we believe the primary ores are dominantly of the first type, magmatic. Locally, however, hydrothermal effects have been superimposed on these, and one example of an ore, remobilized by post-norite granite is known.

Much of the controversy has arisen from different interpretations of the main geological events, as shown in the review of geological problems, especially the apparent separation in time of the norite, granites, quartz diorite and ore. The granites, except for a phase adjoining the Murray mass, are now regarded as pre-norite; the quartz diorite is a gradational phase of the norite and both norite and quartz diorite can be shown to be intimately related in time to many of the ores.² The mode of emplacement of the irruptive has also been a factor, obviously affecting the concentration of ore fluids, depending on whether it was injected (1) as a flat sheet and subsequently folded, (2) as a ring-dyke, or (3) much in the form in which it appears to-day, the latter of which is believed to be the case.

In addition much of the evidence for one or other of the main theories, magmatic *vs* hydrothermal replacement, hinges on the megascopic and microscopic relationships between the sulphides and the silicates and gangue minerals in contact with them, particularly in the disseminated ores in norite and quartz diorite. The literature on this aspect, which we shall now examine, is extensive and will be briefly reviewed, but our own findings will be presented later.

Coleman (1913) considered both sulphides and silicates in the irruptive rocks to have been formed essentially at the same time. He found sulphide both enclosed in and wrapping about associated magnetite and silicates, and lying between feldspar and dark minerals as if they were late, though normal, minerals of the fresh primary rock. Where the rocks showed evidence of later alteration and deformation and the development of metamorphic amphibole, biotite, and chlorite, he found the sulphides penetrating some of the silicates, but attributed this to reorganization of material already present rather than to distinctly later ingress of foreign materials.

²That most of these points have been accepted for many years by field geologists is indicated in Guide Books of the Sudbury Area, (1953 and 1957).

Howe (1914) in a balanced contribution on the petrography of the ores from the Frood and Creighton mines available at the time came to the conclusion that in their present form the sulphides could be attributed neither to magmatic segregation nor to hydrothermal agencies. The Frood rocks he considered to show both original and secondary minerals and evidence of both dynamic metamorphism and replacement in the silicates. He found nothing in the form of any of the sulphide masses to suggest that they had replaced other minerals but states, on his microscopic data, that, "it seems not improbable that the sulphides were present in the rock before its partial recrystallization." In the Creighton ore he found silicate-sulphide contacts to be generally sharp, with angular rock fragments of varying composition isolated within sulphide, and the latter forming well-defined irregular veins in adjacent silicate. Although he allowed for some local impregnation and replacement, Howe considered the bulk of the Creighton disseminated sulphides to have been originally introduced into their present positions while in a molten condition.

Knight (1917), though not commenting on microscopic features, refers to "fragments and blocks of rocks of all sizes, cemented together by sulphides" and states that "replacement is particularly well seen at the Creighton mine, where all gradations are found between coarse-grained granite fragments that are slightly replaced by pyrrhotite, chalcopyrite or pentlandite, to ore in which only a few specks of granite remain. Replacement or impregnation has also taken place in fragments of norite at Creighton." Basing his arguments on both evidence of replacement and associated quartz, carbonate, biotite and amphibole, in various deposits Knight concluded the ores were introduced in hydrothermal solutions, probably formed at a late stage from the norite-micropegmatite magma, as opposed to earlier ideas on their gravitative segregation as molten sulphides (Walker, Barlow and Coleman).

Although acknowledging the presence of (largely unconnected) sulphide blebs throughout the "norite," and that there was a clear concentration of sulphides towards its base, Phemister (1925) considered the microscopic sulphide-silicate relationships to be indicative only of replacement. In the "norite" he considered the sulphides to eat into both pyroxene and feldspar; he noted the projection of sharply crystallized sulphide into silicate, and he observed vugs in the sulphide blebs. In the micropegmatite he noted that pyrite and pyrrhotite have eaten into and broken across the primary silicates—usually hornblende. Where occasional blebs of sulphide occur in granites he considered that "microscopic examination shows clearly that they are replacements of the primary silicates." After careful consideration of both field and laboratory

evidence Phemister agreed with Knight that the fluids effecting the emplacement of the ore minerals were hydrothermal solutions and not necessarily melts genetically related to the norite.

Collins (1937) basing his conclusions more on megascopic than microscopic observations followed Coleman in holding to a magmatic origin for much of the ore, but acknowledged the evidence for considerable metasomatic replacement of ore minerals in footwall rocks, lavas, sediments, granite and gneiss. Much of the latter, however, he suggested, may have occurred under anhydrous conditions or by reaction to form rims of hornblende, biotite, quartz and sodic feldspar, the essential minerals of the "offset" rocks. As crystallization of the ores proceeded the end fluids would, he thought, be enriched in volatiles and thus account for late quartz, carbonate and lead-zinc veins both in the main nickeliferous ores and also within the basin to form copper-lead-zinc ores at the old Errington, now Consolidated Sudbury Basin mines.

Except for Collins, earlier investigators thus appear to have approached the problem on an "either-or" basis. From descriptions of different ore types it seems obvious that silicate-sulphide relations in any one may not be the same as in others. Such differences, however, must be reconciled. It is also apparent that all of the minerals found within the nickel-copper deposits have been attributed to one metallogenic epoch.

Accepting the magmatic origin for the main Sudbury ores Wilson & Anderson made some interesting suggestions from their study of metal ratios and the distribution of metals in different ores which they related to factors aiding in the partitioning of the metals in liquid sulphides and during crystallization. From such data they deduced criteria by which ores crystallized *in situ* might be distinguished from injected ores. Distinct differences in ratios in disseminated and massive ores, as well as zoning favour the first, while lack of these features is a characteristic of injected ores. This we find to be the case, though different emphasis is placed on the factors causing the zoned, "*in situ*" deposits.

Sullivan (1954, p. 572) taking Yates' (1948) conclusions regarding the relative ages of norite, granite, quartz diorite and ore as correct, cited the Creighton deposit as a possible example of the development of ore by the heat of the granite causing the migration of nickel and copper from the "intruded" norite. These age relations are now considered incorrect and the bulk of the Creighton granite is clearly pre-norite. None-the-less a new example can now be given of a deposit which does appear the result of post-norite granite, namely the pentlandite-pyrite breccia ore body at McKim. The processes by which this was formed, however, were probably quite unlike those envisaged by Sullivan, and this ore is best classed as a remobilized ore derived from previously deposited sulphides.

The main problem then is to determine to what degree magmatic or hydrothermal replacement processes, or both, have contributed to the formation of the primary ores.

B. THE MINERALS (DESCRIPTIVE MINERALOGY)

Minerals identified in this study or reported by others in the Sudbury ores are listed in the order of Dana (1944, 1951) in Table 2. These include forty metallic minerals, six hydrous secondary minerals, and eighteen non-metallic minerals. The majority of these have been noted in the literature at one time or another, but a few are recorded for the first time.

TABLE 2. MINERALS IN THE SUDBURY ORES

Type	Mineral		Occurrence
METALLIC MINERALS			
Native Metals and Semimetals }	Gold (Electrum)		rare
	Silver		"
Tellurides, Sulphides, Arsenides, Bismuthides }	Bismuth		"
	Tetradymite	$\text{Bi}_2\text{Te}_3\text{S}$	"
A_mX_n A_2X	Hessite	Ag_2Te	"
	Chalcocite (?)	Cu_2S	reported
A_3X_2	Maucherite	$\text{Ni}_{11}\text{As}_8$	rare
	Heazlewoodite	Ni_3S_2	"
AX	Bornite	Cu_5FeS_4	"
	Galena	PbS	minor
	Sphalerite	ZnS	minor
	Chalcopyrite	CuFeS_2	common
	Stannite	$\text{Cu}_2\text{FeSnS}_4$	rare
	Pyrrhotite	Fe_{1-2}S	common
	Valleriite	$\text{Cu}_2\text{Fe}_4\text{S}_7$ (?)	rare
	Nicolite	NiAs	minor
	Millerite	NiS	rare-secondary
	Pentlandite	$(\text{Fe}, \text{Ni})_9\text{S}_8$	common
	Cubanite	CuFe_2S_3	minor
A_3X_4	Violarite	Ni_2FeS_4	minor-secondary
A_2X_3	Bismuthinite (?)	Bi_2S_3	rare
AX_2	Pyrite	FeS_2	minor to common
	Pyrite (nickeloan)	$(\text{Fe}, \text{Ni})\text{S}_2$	rare
	Molybdenite	MoS_2	reported
	Sperrylite	PtAs_2	rare
	Michenerite	PdBi_2	rare
	Froodite	PdBi_2	rare
	Gersdorffite	NiAsS	minor
	Marcasite	FeS_2	minor-secondary
	Marcasite (nickelif.)	$(\text{Fe}, \text{Ni})\text{S}_2$	secondary
	Cobaltoan arsenopyrite (?)	$(\text{Fe}, \text{Co})\text{AsS}$	reported
	Parkerite	$\text{Ni}_3\text{Bi}_2\text{S}_2$	rare
	Smaltite (?)	$(\text{Co}, \text{Ni})\text{As}_{8-2}$	reported

Type	Mineral		Occurrence
Sulphosalts	Tetrahedrite (?)	$(\text{Cu,Fe})_{12}\text{Sb}_4\text{S}_{13}$	reported (?)
	Schaphbachite	AgBiS_2	rare
Oxides	Magnetite	Fe_3O_4	common
	Ilmenite	FeTiO_3	less common
	Magnetite-Ilmenite-intergrowths		minor
	Hematite	Fe_2O_3	rare
	Cassiterite (?)	SnO_2	reported
Hydrous Oxides } Sulphates, } Arsenates }	Limonite (Goethite)	$\text{Fe}_2\text{O}_3 \cdot n\text{H}_2\text{O}$	secondary
	Chalcanthite	$\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$	secondary
	Melanterite	$\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$	secondary
	Morenosite	$\text{NiSO}_4 \cdot 7\text{H}_2\text{O}$	secondary
	Annabergite	$\text{Ni}_3(\text{AsO}_4)_2 \cdot 8\text{H}_2\text{O}$	secondary
	Erythrite	$\text{Co}_3(\text{AsO}_4)_2 \cdot 8\text{H}_2\text{O}$	secondary
NON-METALLIC MINERALS			
Halides	Fluorite	CaF_2	rare
Carbonates	Calcite	CaCO_3	most common
	Dolomite	$\text{CaMg}(\text{CO}_3)_2$	less common
	Siderite	FeCO_3	rare
Silicates	Quartz	SiO_2	not uncommon
Feldspars	Albite	$\text{NaAlSi}_3\text{O}_8$	
	Labradorite	$(\text{Na,Ca})(\text{Al,Si})_4\text{O}_8$	
Pyroxene	Hypersthene	$(\text{Mg,Fe})\text{Si}_2\text{O}_6$	
Amphiboles	Actinolite		} chiefly in wall rock fragments and wall rocks
	Hornblende		
	Hastingsite		
	Sericite		
Micas	Biotite		
Chlorite	Clinocllore and peninnite		
Garnet	Almandine		
	Zircon		
	Titanite		
	Prehnite		

For the purpose of description the minerals are divided into two main groups. (1) metallic and (2) non-metallic minerals. The metallic minerals are further divided into four groups, based on general abundance and, in a secondary way, on their elemental or spatial affinities. The non-metallic minerals fall into two divisions, (a) those constituting the gangue of the ores and (b) secondary products of oxidation in gossans. The divisions of the metallic groups are:

(a) MAJOR MINERALS

These are the four most abundant minerals, pyrrhotite pentlandite, chalcopyrite, and cubanite, which constitute the major part of the many Sudbury ore deposits and are chiefly responsible for its economic exploitation.

(b) MINOR MINERALS

This category includes a large group ranging from common minerals, such as might be found as minor constituents of almost any sample (*e.g.*,

magnetite) to "trace" constituents such as stannite or valleriite. This group includes: magnetite, ilmenite and intergrowths of the two, pyrite, nickeloan pyrite, gersdorffite, niccolite, maucherite, heazlewoodite, bornite, valleriite, (galena) sphalerite, stannite, and, what are usually considered secondary and in part at least supergene, marcasite, nickeliferous marcasite, millerite and violarite.

(c) MINERALS OF THE PRECIOUS METALS AND ASSOCIATES

These are minerals such as sperrylite, the palladium bismuthides, michenerite, froodite, and an unnamed species; gold (electrum), silver, together with galena (described with this group because of its association), parkerite and other bismuth-bearing minerals, bismuth, bismuthinite (?), schapbachite (?) (matildite); the tellurides, hessite and tetradymite, and probably others.

(d) MINERALS REPORTED BUT NOT CONFIRMED

These include such species as chalcocite, molybdenite, tetrahedrite, smaltite, danaite, native copper, graphite and cassiterite, all of which are recorded in early workings.

Apart from the main divisions, the sequence of description does not imply a precise order of abundance. Abundances vary from place to place and will be considered in a later section, and furthermore it is quite impossible to reliably estimate the relative rank of the minor minerals. In this group, however, there has been some attempt to group these minerals having a distinctive element in common. Descriptions include the relationships of each mineral to others and have been kept as objective as possible. Where there is more than one age or generation of a species, such facts are noted and in Part III these are considered in their paragenetic sequence.

In addition to the rarer platinoids, cobalt and selenium do not form individual species. All of these probably occur in solid solution in minerals of both the major and minor groups and will be dealt with in later sections.

The non-metallic gangue minerals and products of oxidation are included for the sake of completeness but have in no sense been studied in as great detail as the metallics. Many of them are constituents of wall rock fragments, occurring as inclusions, particularly in the breccia-type of ore; others are abundant in the rarer siliceous ores found in certain deposits more than in others; the surficial products of oxidation are quantitatively insignificant.

I. METALLIC MINERALS

(a) MAJOR METALLIC MINERALS

Pyrrhotite

Pyrrhotite is by far the most abundant sulphide in practically every ore body at Sudbury.³ It occurs as disseminations in norite and quartz diorite and adjacent wall rocks, as large massive bodies, as veins and veinlets in fractured ore zones and country rock and as the chief matrix of the breccia type ore. Although it may occur in places with very little other sulphide, minerals such as chalcopyrite, pentlandite and the minor constituents are seldom found without some pyrrhotite. The pyrrhotite: pentlandite ratios in the majority of the mines of International Nickel Company fall within the range of 6.6:1 to 2:1.

Particle size is highly variable—from fine granular (less than 0.55 mm. dia.) up to coarse single grains several centimetres across. Grains are generally irregularly rounded and may show smooth or crenulate, interlocking boundaries. In many cases individual pyrrhotite grains, a mm. or so across, are partially separated from each other by discontinuous intergranular networks of pentlandite. In the larger, characteristic parting, parallel to (0001), is well developed and shows up clearly in both hand and polished specimens. The colour, pleochroism and double refraction are quite normal. Unlike the ores of Insizwa the pyrrhotite is almost always apparently quite homogeneous, with little development of the so-called β -form noted there. In only one specimen (Creighton) where magnetite grains are separated by rims of pyrrhotite, about 0.5 mm. wide, from a main body of cubanite, were fine saw-tooth lamellae of the α and β varieties discerned under crossed nicols, and are clearly distinguishable from twin lamellae. In a specimen from Falconbridge Nickel Mines an apparent two-phase aggregate of pyrrhotite (Pl. X, 56) in coarse pentlandite shows differences in colour in plane polarized light. Recently obtained specimens from McKim mine also show two phases present in pyrrhotite one of which is harder and slightly lighter in colour than the other. The difference becomes visible when polished to bring out relief. That two phases of pyrrhotite are present in many samples, though not optically visible is suggested by x -ray studies as noted below.

Twinning in the pyrrhotite is fairly common and varies from a regular lamellar type, parallel to $\{10\bar{1}2\}$, to quite irregular and is, in places, clearly

³A possible exception to this may be the altered ores of the Vermilion mine which were peculiarly rich in "polydymite" (probably violarite) as well as in platinum, palladium and gold. If, as suspected, the violarite is supergene any original pyrrhotite may well have been completely altered.

due to deformation. In some of the coarser grains, long clean spindles and laths, up to a centimetre or so long and several millimetres wide are developed and appear to be primary features. They are of some interest in that, firstly, they have frequently influenced the disposition of fine pentlandite "herring-bone" intergrowths (Pl. IX, 52) and secondly, they are sometimes cut by "veins" of pentlandite. Twinning due to deformation is accompanied by granulation, clear twisting of individual grains, and undulose extinction.

Both magnetic and non-magnetic pyrrhotite occur at Sudbury. As shown by Jensen (1942) and others the magnetic susceptibility of pyrrhotites varies with sulphur content. Michener & Yates (1944) report Sudbury pyrrhotite with sulphur below $\text{FeS}_{1.14}$ to be non-magnetic, whereas magnetic pyrrhotite has a higher content relative to iron. The non-magnetic variety is described as coming chiefly from the offset types of deposits. Unfortunately available specimens are of one type or the other and the two pyrrhotites have not been seen in contact by us, so their age relations are not known. It is noteworthy, however, that the non-magnetic material available contains intergrowths of pentlandite identical with those in the magnetic (normal) variety (Pl. IX, 54), and therefore may have been originally of the same type. X-ray study of this non-magnetic pyrrhotite according to the method of Arnold (1957-8) appears to confirm its hexagonal character, a sharp $(10\bar{1}2)$ peak having been obtained. The deviation, however, on eight measurements was high, giving an approximate (atomic) iron per cent of 47.25 ± 0.50 , $(\text{Fe}_{0.9}\text{S})_2$.

At least three different generations of pyrrhotite are indicated by study of polished sections. The most common is that which is host to various types of intergrowths of ex-solution pentlandite. This is later than early pyrite and various arsenides but is pre-chalcopyrite-cubanite as shown by rounded, corroded remnants of pyrrhotite in intergrowths of the latter. A second generation of pyrrhotite is a rare type, noted first by Newhouse (1931), in chalcopyrite-cubanite intergrowths from the Frod. This is clearly an exsolution type occurring as stringers or plates, crystallographically oriented in two or three sets (Pl. XVI, 93). All stringers in a set are in optical continuity, and in some cases, stringers of all sets behave similarly. Two sets are dominant in cubanite and the angle between them is bisected by the direction bounding the cubanite lamellae. In narrow lamellae of cubanite, braided, short stringers of pyrrhotite criss-cross it and end abruptly at the border with chalcopyrite. A similar, straight, polycrystalline stringer of pyrrhotite was also noted within chalcopyrite, but cutting across its twinning, and branching into



fine veinlets at right angles. As interpreted by Newhouse, such pyrrhotite is undoubtedly due to unmixing of FeS-rich copper bearing solid solutions but there is no indication of a "chalcopyrrhotite" phase now. A third generation of pyrrhotite occurs with late galena-sphalerite veins which cut massive ore in some ore bodies. This is present both as irregular replacement seams in chalcopyrite (Pl. XI, 64) and also within the veins where it lies chiefly between coarse galena in the centre and a selvage of sphalerite (Pl. XIII, 78), part of which shows terminated crystals. Some of the pyrrhotite shows a platy and shredded form, highly reminiscent of mica or chlorite. In some cases such pyrrhotite shows apparent bending very similar in appearance to that of deformed micas and it seems likely that this pyrrhotite has formed by replacement of some micaceous material (Pl. XI, 62).

Crystallographic studies of Sudbury pyrrhotites by us have been very limited and no single crystal investigations have been carried out. As noted above non-magnetic pyrrhotite was found to give a sharp peak reflection at $(10\bar{1}2)$ and is presumably hexagonal. Seven other samples of normal appearing pyrrhotite were examined, using Arnold's method and all gave broad or double peaks at $(10\bar{1}2)$. This may be due either to the samples consisting of two intergrown phases which are not apparent in polished sections, or to their monoclinic character. Mr. P. G. Thornhill⁵ determined some pyrrhotite from Falconbridge to be monoclinic, but further studies of this type are clearly needed.

A considerable number of chemical analyses of Sudbury pyrrhotites were made by earlier workers such as Dickson (1904) and Barlow (1904) to determine its Fe/S ratio and content of nickel and cobalt. Intergrowths with magnetite and with pentlandite made precise analyses difficult. Dickson concluded that the most satisfactory formula for Sudbury pyrrhotites was Fe_8S_9 ($\text{Fe}_{0.89}\text{S}$) while a few samples agree more closely with Fe_7S_8 ($\text{Fe}_{0.875}\text{S}$) and Fe_9S_{10} ($\text{Fe}_{0.9}\text{S}$). Common pyrrhotite as reported by Michener & Yates (1944) has a composition of Fe_7S_8 ($\text{Fe}_{0.875}\text{S}$). The presence of both magnetic and non-magnetic varieties suggests that in various ores the actual Fe/S ratio may vary within the above limits.

The occurrence of nickel and cobalt in this mineral was early shown by Dickson (1904) and Barlow (1904) to be due to finely intergrown pentlandite. With sufficient fine grinding and magnetic separation they felt they were able to remove practically all of the nickel in the form of pentlandite. Michener (1940) also determined the nickel content of magnetic pyrrhotite by making magnetic separations of it from pentlandite on nine different sizes ranging from 65-mesh to 600-mesh. Analyses of these products ranged from 1.61 per cent nickel for the largest size

⁵A. R. Graham, personal communication.

down to 0.58 per cent for -325, +400 mesh size. For smaller sizes there was a small increase in nickel content. Microscopical counts of pentlandite and chalcopyrite remaining in the pyrrhotite-rich fractions were checked against copper-nickel analyses and it was found in all cases that for copper the correct amount of chalcopyrite was present, but for nickel the pentlandite count was invariably low. The excess nickel in the pyrrhotite which could not be accounted for ranged from 0.40 to 0.50 per cent, and from this Michener concluded that there is a small amount of nickel present in the pyrrhotite either as finely divided pentlandite or held in the pyrrhotite structure.

Which of these two possibilities is the case is difficult to decide as pentlandite may occur in pyrrhotite in exceedingly small lamellae or flames, oriented along preferred directions so they are not always visible in polished sections of randomly oriented grains. Furthermore analyses of this fine type of pentlandite have never been made as pure concentrates cannot be secured, so whether it is identical with coarser interstitial pentlandite in nickel, cobalt and Ni/Co ratio is still unknown. In this respect, however, a recent study by Naldrett (1961) is of interest. Using a combination of wet and dry magnetic separation methods and flotation he prepared pyrrhotite concentrates from several deposits of both massive and disseminated ore. A summary of his analytical results on these is given in Table 3 and a plot of per cent nickel against per cent cobalt for the Hardy pyrrhotite is illustrated in Figure 2, after Naldrett. The points, as will be seen, fall along a line passing through the origin with a gradient of 1/44. This represents a nickel: cobalt ratio of 44 which agrees well with the mean ratio of the 21 analyses of 43.5. There is little difference between the massive and disseminated ores. The results for this one deposit indicate a rather constant relation between the amount

TABLE 3. COBALT AND NICKEL CONTENT OF SPECIALLY PURIFIED PYRRHOTITE AND PENTLANDITE

Mine	Ore type	No. samples	Pyrrhotite		Pentlandite	
			Average % Ni	Average % Co	Ni/Co	Ni/Co
Hardy	Massive	21	1.61	0.037	43.5	
Hardy	Dissem.	3	1.73	0.037	46.7	
Hardy		13				31.9
Falconbridge & East	Mass.	9	1.77	0.058	30.5	29.26
	Mass.	2				
	Mass.	8				
McKim	Mass.	2	2.65	0.060	42.5	
Frood	Mass.	5	0.76	0.023	33.0	
Frood	Dissem.	4	0.81	0.032	25.3	

THE SUDBURY ORES

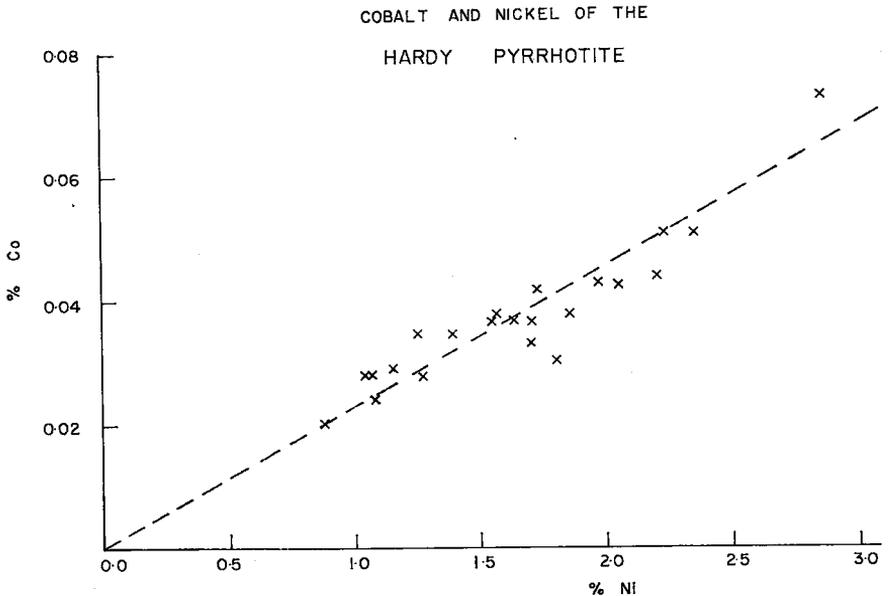


FIG. 2. Relation of nickel to cobalt in pyrrhotite from the Hardy mine (after Naldrett).

of the two metals as might be expected if both were confined to one structure, such as enclosed pentlandite. Analyses of the coarse variety of interstitial pentlandite from the Hardy Mine, however, give a Ni/Co ratio of 31.9, so there is either relatively more nickel or less cobalt in the Hardy pyrrhotite to account for its Ni/Co ratio, or, which seems more probable, the finer type of included pentlandite has a higher Ni/Co ratio than the coarser. Analyses of pyrrhotites from other deposits, however, do not fit the Hardy curve as shown by Ni/Co ratios, even though, as in the case of the Falconbridge samples (Table 3), this ratio (30.5) agrees well with that in eight pentlandites (29.26.) As will be shown later cobalt appears to be a somewhat mobile element in the sulphides where they have been affected by later changes. Because of this and the difficulty of securing pure pyrrhotite the analyses must be taken as only approximations.

None-the-less it is of interest to examine the averages of analyses obtained from pyrrhotites of both the south and north ranges (Table 4). These include 103 samples concentrated only by magnetic means and are combined with the 46 analyses given previously.

Nickel determinations are generally much lower than analyses cited by Barlow (1904). The range in per cent nickel is from a low of 0.45 in a

TABLE 4. NICKEL, COBALT AND SILVER CONTENT OF PYRRHOTITE IN SUDBURY DEPOSITS

Location	No. samples	Average % Ni	Average % Co	Ni/Co	Average Ag (ppm)
South range	43	1.85	0.0875	21.1	2.70
	65				
North range	60	1.44	0.0455	31.3	1.57
	84				
Both ranges	103	1.62	0.064		1.82
	149				

sample from Froot, to a high 3.60 from McKim. Pyrrhotites from the south range include the two extreme values but show a fairly uniform distribution over the interval of 0.80—2.79 per cent nickel with an average of 1.85. Those from the north range show a bimodal frequency distribution with a peak in the 1.09–1.29 per cent range and a slightly lower one in the 1.49–1.69 range, with an overall average of 1.44 per cent nickel.

Cobalt in pyrrhotite is distinctly lower than nickel and like nickel is probably present in part at least in unseparated pentlandite. It ranges from a low of 0.0155 to a high of 0.255 per cent, shows a trimodal frequency distribution with peaks at .025, .055, and .085 per cent, but over three-quarters of the samples fall in the range .02–.10 per cent. The overall average is 0.064 per cent cobalt.

Considering the results on pyrrhotites from the two ranges, as both received uniform concentration, it appears that those from the south range contain somewhat more nickel but nearly double the cobalt compared with those from the north range, both apparently present in a less separable form. Accordingly the Ni/Co ratio for south range pyrrhotites is considerably lower than that of the north range pyrrhotites.

Other trace elements have only been determined in 103 samples of pyrrhotite. The range in silver found varies from 0.6 to 3.7 ppm. with an overall average of 1.82 ppm. The frequency distribution is unimodal with a peak at 1.25 ppm. Means for the two ranges are 2.70 for the south and 1.57 for the north range pyrrhotites, the south range samples showing a greater variance and standard deviation. In some cases it shows a relation to lead, increasing with it.

Cr, V, and Ti are all low and variable and at least some of the traces are attributable to minute silicate and oxide inclusions. Mo, Au, and Sn were found in all cases to be below the limits of detectability, namely 0.0025 per cent, 0.0025 per cent and 0.002 per cent respectively. The highest lead content is 0.107 per cent and is likely due to inclusions of galena; most contain much less and in many no lead could be detected. The range is from 0.7 to 10 ppm. and the average is 1.82 ppm. Pb.

Selenium determinations (Hawley & Nichol, 1959) give a mean content of about 60 ppm. on 101 samples. It is of interest again to note a higher content in south range pyrrhotites (72 ppm.) compared with north range pyrrhotites (54 ppm.). It is probable Se substitutes for S and it would be of interest to compare actual sulphur content of deposits from the two sides of the basin, were this figure available.

In summary, magnetic concentrates of pyrrhotite from deposits on the south side of the Sudbury basin contain greater quantities of nickel, cobalt, silver and selenium than do similar samples from deposits on the north. Possible reasons for such distribution will be considered later.

As it is the dominant constituent of the ores pyrrhotite may be found to show contact relationships with most of the other important minerals. The most common inclusions are of pentlandite, pyrite of more than one generation and origin, and marcasite. These are discussed under descriptions of these minerals and in a later section dealing with relationships and paragenesis. Illustrations of pyrrhotite will be found particularly in (Pl. I-IV, VII-X).

Pentlandite

Pentlandite and its association with pyrrhotite and other sulphides has already been the subject of several papers. Much experimental work on the Fe-Ni-S system in the past several years has also thrown considerable light on the relations which may exist between the mineral phases occurring in this system, but no very complete account of the characteristics and mode of occurrence of pentlandite covering the whole Sudbury area has so far been given.

(i) *Properties and composition.* Except for two rare and minor occurrences in all of the ores examined from this district, pentlandite appears to be remarkably similar in physical properties, as indicated by its straw yellow (pyritic) colour, octahedral cleavage and isotropism. The two exceptions, described separately below are a cobaltoan and an argenti-ferous pentlandite. The common variety varies chiefly in grain size from particles about 1 micron across to coarse grains with diameters as great as 2 inches. The finer material, occurring usually as "flames" and minute en echelon lenses, lamellae or veinlets within the pyrrhotite, cannot be separated sufficiently well to allow precise determination of its composition, and most of the available analyses are of the coarser type, usually interstitial to pyrrhotite. Even this may contain fine inclusions of pyrrhotite and other minerals as shown by polished surfaces and apparently weakly magnetic properties. Various types of pentlandite intergrowths are described and classified later.

Analyses of Sudbury pentlandites selected from the literature are given

in Table 5. Nickel, cobalt and Ni/Co ratios determined by *x*-ray and optical spectrographic methods are summarized in Table 6. The more complete analyses of the common pentlandite, as noted by Michener & Yates (1944), indicate that the composition is fairly constant regardless of the type of ore from which it is obtained, and that it is best expressed by the formula $(\text{Fe},\text{Ni})_9\text{S}_8$, as proposed by Lindquist, Lundquist & Westgren (1936) and supported by Chirkov (1940) and more recently by Ibrahim (1959).

TABLE 5. CHEMICAL ANALYSES OF SUDBURY PENTLANDITE

Locality	Ni	Co	Fe	S	Cu or gangue	Author
NORMAL PENTLANDITE						
1. Sudbury area	34.35		33.10	31.80	0.69	Michener (1940)
2. Sudbury area	34.90		31.60	33.10	0.40	Michener (1940)
3. Composite-Creighton	35.75		31.45	32.80		Michener & Yates (1944)
4. Vermilion	34.23	0.85	30.25	33.42	(0.67)	Penfield (1893)
5. Creighton	34.82	0.84	30.00	32.90		Dickson (1904)
6. Worthington	33.70	0.78	29.17	32.30		Dickson (1904)
7. Frood	34.98	0.85	30.04	33.30		Dickson (1904)
8. Copper Cliff	35.05		29.80	34.35		Browne (1893)
9. Copper Cliff	34.23	0.85	30.25	33.42		Dickson (1904)
10. Copper Cliff (hand picked)	35.00		30.30	33.50		Barlow (1904)
11. Stobie	34.70		29.90	33.90		Browne (1893)
12. Evans Mine	34.12		29.95	35.43		Barlow (1904)
13. Creighton (4) (*Ni+Co)	36.2*	(0.50)	30.10			Browne (1893) Ibrahim (1959)
ARGENTIFEROUS PENTLANDITE						
14. Frood	30.0	Ag 3.8	28.00	37.00		Michener (1940) approx. only
COBALTOAN PENTLANDITE						
15. Worthington	34.48	Co 1.28	30.68	32.74	(.56)	Walker (1915)
16. Garson	27.76	1.82	30.70	35.2	Cu=0.3	Michener (1940) 1 gram sample

The atomic ratio of Ni+Co/Fe on the average is 1.11 as noted early by Dickson (1904). The Ni/Co ratio (by weight) as shown in Table 6 for most pentlandites is about 34:1. With these ratios in the formula $(\text{Ni}, \text{Co})_{4.75}\text{Fe}_{4.25}\text{S}_8$ the weight per cent Ni+Co is ideally 36.5.

The relative constancy of the Sudbury mineral is in marked contrast with synthetic pentlandites. Ibrahim's recent syntheses indicate a range in composition from $\text{Fe}_{6.7}\text{Ni}_{2.8}\text{S}_8$ to $\text{Fe}_{2.6}\text{Ni}_{6.4}\text{S}_8$ which is even greater than found by Lindquist *et al.* whose products varied from $\text{Fe}_{5.22}\text{Ni}_{3.78}\text{S}_8$

TABLE 6. NICKEL, COBALT AND Ni/Co RATIOS IN SUDBURY PENTLANDITES (after Naldrett)

Locality	No. samples	Average % Ni	Average % Co	Ni/Co
Hardy	13	33.20	1.010	32.80
Other N. Range	2	32.55	1.005	33.30
Falconbridge	10	32.55	1.16	28.06
Garson	1	33.30	1.36	24.50
Frood-Stobie	6	30.98	0.97	31.90
Murray	2	33.50	1.04	32.20
Creighton	6	34.05	0.66	51.50
Other S. Range	3	34.40	0.466	73.82
Average N. Rge.	15	33.15	0.968	34.2
Average S. Rge.	28	32.82	0.940	34.9
Average Both Rgs.	43	32.94	0.95	34.7
McKim (normal ore)	1	32.90	0.540	61.0
McKim (Pn-Py ore)	2	33.80	0.089	380.0
McKim (Pn-Py ore)	2		0.115	

to $Fe_{3.78}Ni_{5.72}S_8$. The reason for the apparently limited range in composition of natural pentlandites in this and other areas such as Monche Tundra, Kola Peninsula (Chirkov, 1940), is still to be found. Analyses by more modern instrumentation such as the electron probe micro-analyzer, of the finer grained types of pentlandite may throw some light on this problem.

Nickel content of most pentlandites analyzed chemically ranges from 34.2 to 36.2 per cent. The partial analyses in Table 6 do not permit correction for impurities but here the variation is not great.

Cobalt content of a few samples analyzed spectrographically varies from a low of 0.009 to a high of 2.1 per cent, but excluding the two abnormally low samples from McKim mine, 43 samples average 0.95 per cent cobalt, while 15 of these contain over 1 per cent. The average of four McKim pentlandites averaging 0.10 per cent cobalt are from pentlandite-pyrite ore in the post-norite granite. Pyrite replaces the pentlandite and is enriched not only in nickel but also in cobalt (0.5–0.8 per cent). If this pentlandite was derived from normal ore with a higher cobalt content, it has apparently lost it by diffusion of cobalt into the more favourable pyrite structure. An almost identical case occurs on a small scale at Creighton where disc or spear-shaped pyrite replaces pyrrhotite-pentlandite. Here pentlandite inclusions in the pyrite contain 0.05 per cent Co but in pyrrhotite, outside the pyrite, pentlandite has 0.25 per cent Co and adjacent pyrrhotite only 0.036 per cent (Naldrett).

For the pentlandites with over 1 per cent cobalt it is a question as to the point at which the prefix cobaltoan should be used. Michener (1940)

describes a cobalt-rich pentlandite as being first noted by G. A. Harcourt in ore from the Garson mine where it occurred in nodular form along a shear zone, suggesting that it formed as a result of either secondary alteration or late stage hydrothermal activity. In polished section Michener found the cobaltoan variety to have a "rough" yellow surface, to be harder than normal pentlandite, weakly magnetic, and isotropic. The analysis gave approximately 1.82 per cent cobalt. This is much in excess of earlier analyses although one by Walker (1915) from the Worthington mine contained 1.28 per cent Co. New analyses of pentlandites from several mines on both the south and north ranges indicate amounts of cobalt intermediate between older analyses and Michener's type, with a fairly even spread, and one from the Stobie mine shows slightly over 2 per cent.

That there is a variation in cobalt in pentlandites in different deposits is indicated by the differences in Ni/Co ratios given in Table 6 even though the averages for north and south range ores are almost identical. The reasons for this are not readily apparent. They may be due to original differences in ore fluids, temperature and pressure conditions of deposition, or to subsequent rearrangements. That depth may locally be a factor is shown by analyses of pentlandites from Falconbridge and East Mine, Table 7, as determined by Naldrett, but further study is needed to determine if this is consistently so.

TABLE 7. COBALT AND NICKEL IN FALCONBRIDGE AND EAST MINE
PENTLANDITES

Mine	Level	Percent cobalt	Percent nickel	Ni/Co	Cell Edge Å
Falconbridge	575	1.28	34.7	27.1	10.038
Falconbridge	1400	0.76	34.0	44.7	10.042
East Mine	1500	0.96	31.2	32.5	
Falconbridge	1925	1.28	32.2	25.2	10.043
East Mine	2400	1.15	32.5	28.3	
Falconbridge	2800	1.10	34.6	31.5	
Falconbridge	3325	1.37	32.1	23.4	
Falconbridge	4025	1.45	31.0	21.4	10.040

In no case, however, have any cobalt analogues of pentlandite been found in the Sudbury ores, comparable with those recently described by Kouvo, Huhma & Vuorelainen (1959) containing up to 49 per cent cobalt.

A second peculiar variety of pentlandite, an argentiferous one has been reported by Michener (1940), but was not encountered in the present study although careful search has been made. The silver-bearing

pentlandite was identified by Michener in specimens from the lower levels of the Froid mine where, peculiarly, it occurred in oriented intergrowths with normal pentlandite, and also as small grains, less than a millimetre in diameter, associated with galena and normal pentlandite. Veinlets of quartz are also reported to contain small amounts of this variety of pentlandite. Its most distinctive feature in polished section is its fox-red colour. Its talmadge hardness is given as C, in contrast to a hardness of D for normal pentlandite (Uytenbogaardt). Etching with HNO_3 produces effervescence but for other reagents it reacts as normal pentlandite and, like it, is quite isotropic.

The oriented intergrowth of silver-rich and normal pentlandite, as illustrated by Michener, consists chiefly of the former with fine and coarse blades of normal pentlandite narrowing and intersecting one another at practically right angles, suggesting either a cubic or octahedral alignment. This is in contact with a very fine pseudo-eutectic intergrowth of chalcopyrite and pyrrhotite, not noted in our specimens, but apparently somewhat similar to chalcopyrite and niccolite intergrowths to be described later.

As shown by approximate chemical analysis (Table 5) the argentiferous pentlandite contains possibly as much as 3.8 per cent silver. Some bismuth was also present, but regardless of this, x -ray powder patterns indicate a structure identical with that of a normal pentlandite but with a small difference in the size of the unit cell, 9.55 Å for silver pentlandite as against 10.02 Å for the normal variety.

Spectrographic and x -ray analyses of pentlandite show it to be remarkably free of many common trace elements, amounts of Cr, V, Ti, Mo and Sn in many being below the limits of detectability. Lead varies similarly and in some attains a high of 0.1 per cent. Silver is invariably present and ranges from less than 1 ppm. to 14 ppm. Samples containing some lead usually have several ppm. Ag. Selenium determinations on 20 samples show that 16 pentlandites from the south range average 90 ppm. while four from the north range average 45 ppm., a variation similar to that shown by pyrrhotite.

In summary, Sudbury pentlandites show considerable variation in Ni, Co, Fe and S content but not nearly as much as synthetic pentlandites. Contamination with pyrrhotite and other minerals, even in coarse grained material may account for major differences in Ni and Fe, but the possibility that some variations are real should not be overlooked. As yet no analyses of the very fine grained type pentlandite are available. A frequency distribution curve of 40 analyses shows a unimodal peak in the range of 34–35% Ni with an overall variation between 21% and 36% Ni. Of 15 analyses for iron, the majority fall between 29% and 31%. It

is probable that the purest samples contain about 35% Ni and 30% Fe giving an atomic ratio of close to 11 Ni/10 Fe. Sulphur also shows a variation from 31% to over 35% with the majority falling between 32% and 34%, and the formula $(\text{Fe,Ni})_9\text{S}_8$ is accepted. New analyses confirm a cobaltoan variety indicated by Michener with between 1%-2% Co, although the majority fall just below 1% Co. An argentian variety containing about 3% Ag described by Michener is also reported. In other pentlandites silver ranges from less than 1 ppm. to 14 ppm. Selenium in pentlandites from the south range, as in pyrrhotite, is double the amount found in the north range (90-45 ppm. Se). Other elements have an irregular distribution.

(ii) *Cell edge of pentlandite.* While no attempt has been made to study in detail the structure of pentlandite, Naldrett recently made cell edge determinations on pentlandites from various depths as indicated in Table 7. Ibrahim (1959) in synthesizing pentlandites found a considerable variation in cell edge with composition and that his values were consistently higher by about 0.05 Å than those of natural pentlandites. On heat treating the latter at temperatures below 390° C he found that the unit cell had expanded and assumed a value similar to that of the synthetic specimens. Among the reasons advanced for the smaller unit cell of natural pentlandite was slow cooling and high pressure both of which would tend to minimize lattice flaws. Specimens obtained by Naldrett from Falconbridge and East Mine to a depth of 4000 feet afforded an opportunity to examine this possibility. Cell edge determinations on four pentlandites (Table 6), corrected for cobalt and iron content fail to show any appreciable difference with the depths indicated nor of the magnitude that might be expected.

(iii) *Mode of occurrence.* A three-fold classification of the various modes of occurrence of pentlandite in the Sudbury ores is suggested by a detailed study of several hundred specimens. In each of the three groups variations of one type or another give rather distinctive textures, some of which are clearly related to the orientation of the section being examined. Many of these textures are present in ores other than from Sudbury, notably those from Insizwa, South Africa, Lynn Lake, Manitoba, and the B.C. nickel deposit (Horwood).

The three chief modes of occurrence are: (a) Pentlandite within grain boundaries of pyrrhotite, and rarely chalcopyrite, (b) Interstitial pentlandite, chiefly between grains of pyrrhotite and varying from irregular, blocky areas to thin rims or partial rims around grains of pyrrhotite. (c) Coarse pentlandite in rounded ovoids, some with smooth boundaries, others with a scalloped or rosette structure in pyrrhotite, and coarse pentlandite in pentlandite-rich ore in which the ovoid form is not so

evident but with some interstitial pyrrhotite. Details of these occurrences follow:

(a) Pentlandite within grains of pyrrhotite and rarely chalcopyrite. *Lamellar ore*—narrow, straight lamellae of pentlandite (Pl. VIII, 46, 47) oriented parallel to the basal parting of pyrrhotite. In width these may be as small as a micron and a few mm. in length. Both these and coarser veinlets of similar orientation, under high magnification, show an echelon structure, the fine blades of pentlandite lying at a low angle to the parting.

Lenses or veinlets with smooth to ragged contacts against pyrrhotite. (Pl. VII, 38).—These consist of more massive pentlandite, usually of one orientation, and attain dimensions 2–3 mm. wide and up to 10 mm. in length. In some cases they too follow more or less along basal parting directions in pyrrhotite. Cut normal to the basal parting they may also show an echelon structure, whereas, in sections polished parallel to the parting they are more or less equi-dimensional with an arborescent or rosette appearance (Pl. IX, 49).

In rare instances narrow lenses of pentlandite have been noted in chalcopyrite, with a parallel and an echelon distribution, much as in pyrrhotite (Pl. XI, 66). In one case a coarser lens of pentlandite was found in a cubanite-chalcopyrite intergrowth in the form of three separate segments, each now offset slightly from the others, as if faulted or displaced. (See right side, Pl. XI, 65.) The similarity of such lenses to those in pyrrhotite suggests original development in pyrrhotite, followed by replacement of pyrrhotite by chalcopyrite and/or cubanite (Pl. X, 60). Gash-like veins and clusters of pentlandite grains following a curve suggesting a former fracture, interrupt blades of cubanite in chalcopyrite (Pl. X, 59). These too may represent remnants formerly in a pyrrhotite matrix. In addition to such intergrowths, however, are some rare but interesting oriented composite spindles of pentlandite and valleriite in chalcopyrite (see under valleriite). These seem clearly products of exsolution from a nickel-iron-rich solid solution.

Flames or brushes of pentlandite in either single minute individual clusters or in larger aggregates (Pl. VIII, 43, 48; Pl. IX, 50, 51, 52). These consist of fine sub-parallel plates or needles with sharp to ragged borders. They occur either alone or add to the substance of coarser grained aggregates of pentlandite. Alone they may flare out from minute cracks or parting in pyrrhotite at more or less right angles to them. In other cases they may be essentially parallel to the basal parting of the large grains of pyrrhotite, particularly of the type in which ovoids or rosettes (Pl. IX, 49) of pentlandite occur, but are often rare in pyrrhotite rimmed by pentlandite. Some have been noted starting at grain boundaries and

projecting into and forming a collar about pyrrhotite (as noted by Scholtz in Insizwa ores) while others project into adjacent chalcopyrite (Pl. X, 57, 58) in which case individual laths of pentlandite are sub-parallel to each other and normal to the contact or fringe so formed. Such fringes or collars are quite different from thin rims of more granular pentlandite which form between grains of pyrrhotite.

Aggregates of flames of pentlandite are also found in twinned pyrrhotite. In places they may be present in one twin lamella and not in others; in some a rather beautiful herring-bone structure is developed by pentlandite flames on both sides of a twin boundary (Pl. IX, 52). Such occurrences as well as examples of irregular lenses interrupting the twinning in pyrrhotite suggest twinning was developed prior to the segregation of the pentlandite.

The flame type of pentlandite is identical in most respects to that exhibited by ores from Insizwa (Scholtz, 1936) and Middellaagte (de Bruyn, 1944) and also from British Columbia. In the latter instance, however Horwood (1936) in noting the presence of small needles of pentlandite projecting into pyrrhotite from narrow cracks, suggested that they were probably early in age and were deposited prior to the surrounding pyrrhotite. These are clearly a product of ex-solution from nickeliferous pyrrhotite and are generally recognized as such.

(b) *Interstitial pentlandite*. This consists of irregular, often blocky pentlandite grains, varying considerably in size, up to several mm. in width, which invariably lie between grains of pyrrhotite but never cut across grain boundaries (Pl. VII, VIII, 42-45). Such areas of pentlandite may include early magnetite of either first or rare second generation (Pl. I, 5, 6), or the pentlandite may be partly invaded and replaced by later chalcopyrite. In some ores characterized by a coarse granular type of pyrrhotite, with grain diameters up to 2-3 mm. interstitial pentlandite may be seen to pass directly into thin rims or partial rims between closely spaced pyrrhotite grains (Pl. VIII, 44). Boundaries between the pentlandite and pyrrhotite are normally sharp, but may be rendered ragged by additions of flame type pentlandite to the granular type (Pl. VII, 42; Pl. VIII, 43; Pl. X, 55). Such sharp rims however cannot be directly related spatially to one or the other grain of pyrrhotite on either side. In any case, whatever the cause of such textures, the coarser interstitial areas and the rims must have the same explanation, as will be dealt with later (p. 174).

(c) *Coarse pentlandite* appearing in some sections as rounded ovoids, (Pl. VII, 41) up to an inch in diameter, and presenting sharp boundaries to pyrrhotite are perhaps special modifications of the interstitial type of pentlandite.

Whether most of these are true ovoids is a question. One such mass (Pl. VII, 41) was cut and polished at high angles to the surface illustrated and was found to change from the oval form to an irregular vein-like body with sharp step-shaped contacts against pyrrhotite.

Some masses show a scalloped or rosette structure instead of a sharp smooth boundary (Pl. VII, 39, 40) and polished sections of these show that close to the contact of the coarse pentlandite (grains 10-15 mm. diameter), the pyrrhotite is fine grained and the pentlandite projects in deep cusps into the pyrrhotite and clearly replaces it. In the pyrrhotite close to such rounded segregations, fine flame type of pentlandite is notably absent, but may be present in coarser pyrrhotite, farther away.

The general aspect of such segregations of pentlandite in pyrrhotite is remarkably similar to metacrysts of pyrite developed in some pyrrhotite ores. The possibility that the pentlandite ovoids have formed in a somewhat similar manner needs consideration and is discussed later under paragenesis.

In various places in the Sudbury deposits local, coarse grained, pentlandite-rich ores occur in which the pentlandite may equal or even exceed the amount of pyrrhotite. Examination of such specimens indicates that in these too, pyrrhotite, though apparently interstitial to the pentlandite, (Pl. VII, 39) is earlier than the pentlandite and in places at least, is replaced by it.

Pentlandite in such ores, however, usually exhibits numerous small inclusions of pyrrhotite in small blebs or rods (Pl. X, 55). In some cases these blebs may be very numerous indeed, and develop a fine "sieve" texture in the large pentlandite areas. Some such blebs appear as remnants of early pyrrhotite; others with sharper boundaries, may be the result of ex-solution and hence are penecontemporaneous with the pentlandite. In a few cases, small rounded blebs of pyrrhotite in pentlandite resemble a eutectic mixture. In the section shown on Pl. X, 55, pyrrhotite adjacent to such pentlandite contains numerous flames of pentlandite, but is quite free of them farther away, suggesting segregation towards the coarse grains of pentlandite.

Like pyrrhotite with which it is dominantly associated, pentlandite appears later in age than early magnetite, early pyrite, and the arsenides such as gersdorffite, niccolite, and sperrylite (Pl. IV, 21). That it was deposited or segregated at least in part prior to the chalcopyrite seems fairly certain. In addition to evidence of replacement by chalcopyrite, noted above, veins of chalcopyrite cut across bodies of pentlandite, and where the latter occurs as granular aggregates, the chalcopyrite often forms a cement binding the pentlandite particles together, as along some "rims." Here and there too chalcopyrite (and cubanite) is found

invading the pentlandite along cleavages, as may be seen in Pl. X, 60, with the development of scattered "islands" in a groundmass of chalcopyrite. Unlike pyrrhotite, however, the pentlandite does not commonly include minor minerals such as sphalerite and galena. Small irregular flecks of these, together with a little native bismuth, partially corroded grains of sperrylite and minor particles of parkerite and bornite do occur here and there but they are not common. The relationships of pentlandite with cubanite are believed essentially similar to those exhibited with chalcopyrite, and grains of pentlandite interrupting laths of cubanite in chalcopyrite may well be remnants formed originally in pyrrhotite.

Both late generations of pyrite and pyrrhotite also replace pentlandite as do millerite-violarite intergrowths. Pyrite with wispy inclusions of pentlandite is well illustrated replacing coarse pentlandite in a specimen from the McKim mine where ore is enveloped in granite (Pl. III, 17). The preferential replacement of pentlandite as compared with pyrrhotite and chalcopyrite by violarite has been well shown by Michener & Yates (1944). The mixture of violarite and millerite resulting from similar replacement is shown in Pl. XIV, 79. Further discussion of the age relations of pentlandite to other minerals and the significance of its textures is given later.

Chalcopyrite

Next to pyrrhotite, chalcopyrite is the most abundant ore mineral and is ubiquitous in the Sudbury mineralization. In general it is greatly subordinate to pyrrhotite, the average pyrrhotite-chalcopyrite ratio for different mines varying up to 5:1. Locally, however, chalcopyrite may occur in important high concentrations and greatly exceed pyrrhotite in abundance.

As seen in hand specimens of massive ores it occurs in large amounts in many areas many inches across. In disseminated ores it occurs in composite blebs with pyrrhotite and as veins, veinlets and inclusions. In stringer ores it is the most common sulphide and veins may be composed almost entirely of it. In breccia ores it is usually disseminated through other sulphides in the matrix and of all the sulphides is the one most frequently found veining and replacing the larger rock fragments. In brecciated and fractured quartz diorite irregular mineralized stringers or veins of pyrrhotite-pentlandite are usually bordered by selvages of chalcopyrite and as the fractures narrow or pinch out, chalcopyrite is concentrated at the tapering ends.

Under the microscope it is seen always to be in the form of granular aggregates, individual grains as viewed between crossed nicols generally being more or less equidimensional, irregularly rounded, with mutual to

slightly interlocking boundaries. Grain size varies enormously, from less than 0.05 mm. across, up to several centimeters, with an approximate average of the order of 0.1–1.0 mm. largest dimension. A striking feature of some of the massive, coarse-grained chalcopyrite from the Froid mine is the beautifully developed lamellar twinning. In such material the twinning is so coarse as to be readily distinguishable by the naked eye. Most of the finer grained material, too, shows similar twinning when viewed between crossed nicols. Probably the coarser twinning is secondary and due to stress, but it has not been possible always to distinguish this from primary twinning.

Michener (1940) states that over 85 per cent of the copper produced in the Sudbury district is derived from chalcopyrite which, for the most part, occurs as a distinct clean mineral of constant composition. Two analyses given by Michener are reproduced in Table 8.

TABLE 8. ANALYSES OF SUDBURY CHALCOPYRITE

	Cu	Fe	S	Total
(1)	34.26	30.40	35.15	99.81
(2)	33.68	30.94	35.00	99.62
Theoretical CuFeS ₂	34.5	30.5	35.0	100.00

In some samples a dull dark, greenish-yellow variety of chalcopyrite borders the cleaner massive type. The former owes its aspect to very fine wall-rock inclusions.

Trace element content was determined on 28 samples of chalcopyrite from various deposits, all but three of which are from the southern part of the area. Nickel varies from as low as 0.008 per cent to a high of 3.70 per cent, with a peak in the 0.2–0.29 per cent interval. As shown by many polished sections (Pl. XI, 65, 66) probably most of the nickel may be accounted for by fine grained inclusions of pentlandite in the chalcopyrite. Cobalt values fall very largely in the 0.001–0.019 per cent interval, with a high of 0.08 per cent. When nickel is low or high, cobalt is also, and Ni/Co ratios fall largely in the range 20–30, as do most pentlandites, though in the purest, this may be as low as 6–10. Probable contamination, however, makes the results of doubtful value. As with pyrrhotite, chromium, vanadium and titanium are probably present largely as constituents of very fine oxide and silicate inclusions and vary considerably. Cr ranges from >0.03 to <0.003 per cent, V from 0.09 to <0.002 and Ti from 0.02 to <0.003 per cent. Molybdenum and gold were not detectable in any samples, but tin appears in about one out of three analyses, the largest quantity found being only 0.008 per cent. This is

quite compatible with microscopic observations, the source of at least some of the tin being the very fine blebs of stannite included in chalcopyrite. Lead is usually present in the range 0.01–0.02 per cent. Silver is always present and averages 183 ppm., varying to some extent with the lead content. Selenium, determined in 22 samples gives an average of 97 ppm. which is higher than pyrrhotites but close to the average of analyzed pentlandites. Its greater concentration in chalcopyrite compared with both pyrite and pyrrhotite is similar to its occurrence in non-nickeliferous sulphide ores. Our sampling of chalcopyrite was so largely from the south range that no comparison with north range ore can be made.

The minerals with which chalcopyrite is most frequently in contact are, of course, pyrrhotite and pentlandite. As has already been noted, chalcopyrite embays, veins, and includes optically continuous fragments of pyrrhotite. It may also vein and, apparently, corrode pentlandite. Much of it occurs as equigranular aggregates with pentlandite, the two forming composite veins and irregular areas in pyrrhotite. A common relationship between pyrrhotite, pentlandite and chalcopyrite in polished sections is one in which pentlandite forms discontinuous margins of lenticular form about pyrrhotite. Chalcopyrite follows the same boundaries as veins or irregular masses, often enveloping the pentlandite. In a few cases flames or blades of pentlandite lie at right angles to such contacts and project into the chalcopyrite (Pl. X, 58). Chalcopyrite is also the mineral most frequently associated with cubanite, which it includes as exsolution lamellae (Pl. X, 59; Pl. XI, 65) and with which it occurs in irregularly intergrown areas. To a minor extent it appears as exsolution laths in cubanite.

The chalcopyrite seems to show quite clear-cut relationships with the minerals tending to idiomorphism; veins of chalcopyrite, often associated with pyrrhotite, are quite common in magnetite (Pl. I, 2, 4). It also moulds about, embays and forms both fracture fillings and replacement veins in gersdorffite (Pl. IV, 22, 23; V, 30) and pyrite (Pl. II, 12), and veins or follows grain boundaries and replaces pyrrhotite (Pl. XI, 61) and sperrylite (Pl. IV, 20). It has also been observed forming veins and protuberances, apparently due to replacement, in niccolite and in the rare mineral maucherite (Pl. VI, 35) which it locally replaces in preference to niccolite (Pl. VI, 31). Its complex intergrowth with niccolite and maucherite (Pl. V, 29; XII, 67) is a minor but very noteworthy feature in samples of arsenide-rich ore of the Garson mine.

While much of the relatively scarce sphalerite and even rarer stannite occur as inclusions in chalcopyrite, excellent examples of sphalerite exploiting grain boundaries and replacing chalcopyrite have been seen.

Some of the chalcopyrite-rich ores, particularly those from the margins of some of the ore bodies, as at Frood, are of special interest in that they are hosts for most of the rare minerals of the ore as a whole, and particularly sperrylite. Most of the first generation galena (Pl. XII, 69), with its associated parkerite, hessite, native bismuth, bismuthinite (Pl. XII, 71–72) tetradymite and native gold (Pl. XII, 70; XIII, 73) are found in such copper-rich specimens. Other rare minerals include heazlewoodite, valleriite, an ex-solution product (Pl. XI, 66), and bornite, and, with bornite, a little silver (Pl. XIII, 74–76).

An insignificant amount of chalcopyrite occurs within distinctly late veins which transect the main ore bodies (Pl. XIII, 78), and is associated with late pyrrhotite, coarse galena and sphalerite. Such chalcopyrite has not been found to contain any of the rarer minerals.

Cubanite

This, though the only other important copper mineral, estimated to supply about 15 per cent of the copper, is greatly subordinate to chalcopyrite in most deposits. Its greatest known concentration is in the lower levels of the Frood-Stobie (Zurbrigg *et al.*). Here it occurs as a distinct zone below heavy massive sulphides which underlie disseminated ore in the quartz diorite intrusive. This zone consists of about equal parts of cubanite and chalcopyrite with lesser but still considerable quantities of pyrrhotite and pentlandite. Such cubanite continues downward also, into the "siliceous" mineral zone which is characterized by the presence of nickel arsenides, sperrylite, galena, palladium bismuthides and others. The segregation of the cubanite-rich zone poses an interesting problem to be considered later.

As far as is known cubanite appears of uniform composition, an analysis by Michener (1940) giving:

Copper	..	..	22.06 per cent
Iron	..	..	42.13
Sulphur	..	..	36.30
Cobalt	..	..	0.01
			100.50

Allowing for five per cent intergrown pyrrhotite, the formula was calculated as CuFe_2S_3 , using the size of the unit cell (Buerger, 1937 and Peacock & Yatsevitch, 1936) as $a = 6.45 \text{ \AA}$, $b = 11.07 \text{ \AA}$, $c = 6.21 \text{ \AA}$. Analyses of two samples by Naldrett gave 0.013–0.015 per cent Co and 0.36–0.47 per cent Ni, amounts very close to those obtained in chalcopyrite of the same specimens.

In polished sections the cubanite is pale to almost yellowish pink in colour, but distinctly paler in associated pyrrhotite. It shows distinct pleochroism, and under crossed nicols is almost indistinguishable from pyrrhotite except for its lower relief.

In the Frood ores cubanite occurs both as coarse and fine, irregular aggregates, with an interlocking mosaic texture, and as blades and laths within chalcopyrite. In other specimens it is present chiefly in the latter form or as finely intergrown aggregates replacing magnetite and pyrrhotite (Pl. I, 4), and also coarse pentlandite, as noted earlier.

The massive cubanite consists of grains up to 1 cm across, with highly irregular borders. Some contain minute laths of chalcopyrite following up to three different directions, clearly a product of unmixing. Intergrown with the granular type invariably is chalcopyrite of about the same grain size which may or may not contain typical exsolution laths of cubanite. In several sections chalcopyrite appears to invade, vein and replace the cubanite and to isolate "islands" in optical continuity with larger grains.

The lamellar type of cubanite (Pl. X, 59; XI, 65; XVI, 93-4) follows {112} planes in chalcopyrite and frequently shows a triangular arrangement. The lamellae vary in width up to about 0.5 mm. and in length, to almost 1.0 mm., some of the larger laths being made up of several finer parallel bands. In one or two instances this type of cubanite has been found, peculiarly, to extend across grain boundaries of chalcopyrite with no effect on its own orientation but its extremities are in such cases often rush-like. This is not unlike secondary parallel growth of twin lamellae in feldspars, the extensions across grain boundaries being controlled by the lath in the adjacent grain.

In still other sections, as described by Newhouse (1931) pyrrhotite like chalcopyrite, in the form of fine blades or lenses (and containing minute flecks of pentlandite) follows two or three crystal directions in cubanite. These lenses also traverse intergrown chalcopyrite as do a few fine polycrystalline stringers (Pl. XVI, 93), and the angle between two such sets is bisected by the cubanite lamellae. Valleriite is also present as very fine blades or strings in both chalcopyrite and cubanite. One set lies parallel to the lamellae and others occasionally cut them (Pl. XVI, 94). In similar specimens, Newhouse has also noted that cubanite with finer pyrrhotite lamellae were in part resorbed by still later chalcopyrite, a further complication in their history.

Minerals other than chalcopyrite present in cubanite are magnetite, pyrrhotite, and pentlandite, all of which appear as rounded and corroded remnants of formerly larger grains. Their partial, or in places possibly complete, absorption by surrounding copper-rich sulphide liquid probably

accounts in part for the development of much cubanite. The coarse granular type may represent direct crystallization of cubanite from such iron-rich liquids, whereas the oriented intergrowths of cubanite, valeriite and rarely pentlandite, have clearly resulted from unmixing of solid solutions. In all cases the latest copper rich fluid appears to have crystallized as chalcopyrite, and in the siliceous mineral zone, as very rare bornite.

(b) MINOR METALLIC MINERALS

Magnetite

Magnetite, although not a major constituent of the ores, is present in most specimens examined. In disseminated ore, and particularly in much of the massive sulphide, it may be quite abundant. In rich pyrrhotite and chalcopyrite ore, such as that of the Creighton mine, magnetite may form up to 20 per cent by volume of a sample, as pointed out by Michener (1940). At Hardy, Mitchell & Mutch (1957) note concentrations of magnetite at both foot and hanging walls of ore, in bands as much as one foot in width. In contrast, it is somewhat less noticeable in much of the breccia ore, and as far as can be seen it is completely absent from late galena veins.

The mode of occurrence, general features and particle size are for the most part remarkably constant, and though the major part of the magnetite is found in sulphides, it is commonly disseminated in silicates as well. Generally its distribution is even, but in some cases there is a tendency to linear arrangement in section, or to clustering, though this latter is not really common. Some particles are almost euhedral, with octahedral habit; many are subhedral, and the bulk are rounded subhedral to evenly rounded in outline (Pl. I, 1-4). Many of the evenly rounded grains, particularly where they are a little larger than usual, show smoothly curving embayments, long club-shaped protuberances and beautifully rounded inclusions of silicate or sulphide.

One of the most noticeable features of many sections of magnetite-rich sulphide is the obvious evenness of grain size of the granular magnetite over the whole area of the polished surface. In the disseminated ore particle size is remarkably even and constant, and generally within the range 0.25-0.10 mm. across. There does seem, however, to be a distinct change in size going from disseminated to massive ore; in the latter magnetite is far coarser and in some cases large numbers of subhedral magnetite grains up to 4.0 mm. across are present. Some of the magnetite, particularly in the disseminated ores, is slightly anisotropic, and there are minor colour variations, suggesting that some is titaniferous and intergrown with ilmenite.

As it is so widespread, the magnetite can be found in contact with most of the other minerals of the ores—the arsenides being notable exceptions. Some of the larger crystals of primary pyrite from the Hardy mine include as many as 10 magnetite grains and occasionally nearly euhedral pyrite crystals are found moulded about sharp outlines of magnetite (Pl. I, 1). Many magnetite grains enclosed in pyrrhotite, chalcopyrite, pentlandite or cubanite have been fractured and veined by these minerals. Small-scale veining by such minor minerals as sphalerite, bornite, stannite and galena has also been noted. Apart from occasional rounded inclusions pyrrhotite or chalcopyrite in some of the larger magnetites, which in any case are very possibly simply sections of embayments set at an angle to the plane of the polished surface concerned, no sulphide minerals are enclosed in the granular magnetite.

Qualitative spectrographic analyses of seven magnetite concentrates show the presence of manganese, vanadium, chromium, titanium, magnesium, aluminium, nickel, cobalt and copper. Cobalt and silver are present only in traces. These as well as nickel and copper may be due to the presence of minute amounts of sulphides in the magnetite.

Although the bulk of the magnetite of the ores is of this rather constant granular type and is pre-sulphide, a very small amount is found as rims around pyrrhotite grains, and as veins and intergrowths cutting these (Pl. I, 5, 6). The rims are generally not more than 0.01 mm. wide, frequently totally surround pyrrhotite grains of the order of 1.5 mm. across, and show precisely the same relationships to the pyrrhotite as the pentlandite networks—with which, in fact, the magnetite may be associated. Where the two do occur together the magnetite tends to form the central portion of the rim, with a selvage of pentlandite on either side, separating the pyrrhotite from the magnetite. Where magnetite alone forms the rim, pentlandite flames in the pyrrhotite are invariably abundant along the pyrrhotite-magnetite boundary. In some cases the magnetite may leave pyrrhotite grain boundaries and cut sharply across single optically continuous grains of pyrrhotite. Such cross-cutting veins may be quite irregular or they may be partially guided by parting in the pyrrhotite. In some cases pyrrhotite particles show well developed parting, which is beautifully paralleled by both pentlandite “flames” and magnetite veins. Such magnetite is obviously a second generation, formed after pyrrhotite.

Ilmenite and Intergrowths with Magnetite

Ilmenite has been noted by Michener as a characteristic accessory mineral in the Sudbury norite along with magnetite. In places the two are intimately intergrown (Pl. II, 7); in some cases ilmenite exceeds

magnetite in amount and is readily distinguished by its anisotropism and reflection pleochroism.

In the ore bodies for the most part, magnetite is the common oxide and ilmenite is relatively rare. The latter has been noted, however, in disseminated ores in quartz diorite, norite and gabbro (Creighton, Murray and Froot) and in breccia from Falconbridge, Mount Nickel and the McKim mines. In specimens from the latter two localities ilmenite is present in more or less rounded grains, comparable in size to magnetite elsewhere. The grain boundaries are invariably more irregular than those of magnetite and many grains show lamellar twinning with even to variable widths chiefly along one direction. It is also found as the chief black oxide in silicate inclusions of quartz-diorite in massive sulphide at Froot, the so called "immiscible-silicate-sulphide ore."

Michener notes that where composite grains of magnetite and ilmenite are present the magnetite is more readily replaced by sulphides than ilmenite. He has also observed ilmenite in quartz at the contact of ores where it occurs in sheet-like blades up to 1 mm. in width and several centimetres in extent. In some sections isolated parallel lamellae of ilmenite remain as remnants in sulphides such as pyrrhotite and pentlandite. The intervening material may have been magnetite or another oxide (rutile?) but is now completely replaced (Pl. II, 9). In addition many such lamellae show varying stages of alteration to an anisotropic non-metallic mineral, the identity of which has not been established. Less replaced aggregates consist of highly anisotropic, brownish lamellae along one direction in a weakly anisotropic grey metallic mineral. It is possible intergrowths of various titaniferous phases are present in addition to those with magnetite.

Pyrite

Pyrite is a minor constituent of the ores, but its diversity of habit, occurrence and relationships make up in interest for its scarcity. It is more plentiful in north range and offset deposits than elsewhere.

The earliest generation is found to be replaced by most of the other sulphides. A second has developed as crystals in and along grain boundaries of pyrrhotite, but before chalcopyrite. This will be referred to as "reaction" pyrite. Other varieties include several different types formed at the expense of pentlandite and/or pyrrhotite, some likely at elevated temperatures. A pink nickel-rich variety, deposited on early pyrite seems restricted to offset bodies. Others formed probably under supergene conditions but extend to considerable depths and are associated with marcasite. Some is found in stringers in late olivine diabase, while the latest occurs in mud seams of faults. The distinction between many of

these is not easy, but Naldrett (1961) has shown cobalt and nickel content to be a useful guide. They will be described in the above order. For some partial analyses see Table 9.

(i) *Early pyrite*. This occurs as cubic and octahedral crystals or combinations of them which range in size from 0.1 mm. to about 1 cm. They are found usually as scattered grains, occasionally as narrow seams, within the common sulphides. Most of the crystals have suffered some rounding and in places are corroded and embayed by pyrrhotite, chalcopyrite, pentlandite or sphalerite (Pl. I, 1; II, 10, 12). Such pyrite is moulded on earlier magnetite and also contains rounded inclusions of it. Some contain composite inclusions of pyrrhotite, chalcopyrite, and fine veinlets of chalcopyrite following minute cracks.

Similar pyrite has been described by Graham⁶ from several mines of the north range and from the south wall deposits, Falconbridge, occurring near ore shoot boundaries of the main ore zone. In all cases it is replaced by all other common sulphides except gersdorffite with which it is not found in contact. Graham reports that cell dimensions of two such samples did not differ significantly from that of National Bureau of Standards stoichiometric FeS₂.

Naldrett carefully separated pyrite of this type from Hardy ore and found five samples to average 0.049 per cent nickel and 0.56 per cent cobalt. There is perhaps some question whether the pyrite found moulded on magnetite and enclosing it is of this or the next generation to be described. In any case that which is corroded clearly by pyrrhotite would appear to have formed before the bulk composition and temperatures and/or pressures had been attained at which pyrrhotite alone became the stable phase, (Kullerud & Yoder, 1959). (This would not necessarily involve a *later* rise in temperature, as a decrease in pressure might accomplish the same result.) As in many other deposits early pyrite may also be a product of reaction between sulphur vapor and iron bearing minerals before the pyrrhotite ore fluid arrived.

(ii) *Reaction pyrite*. A second type of early pyrite is one noted also in north range deposits, Levack, Hardy, and Longvac. It occurs as sharp to slightly rounded octahedral or cubic crystals, 0.2 to 3.0 mm. across, both within or around grain boundaries of coarse pyrrhotite grains and at the interfaces of pyrrhotite and magnetite. In places it forms small chains of crystals projecting into pyrrhotite. Naldrett noted its best development in the uppermost level of the Hardy though it is also found at greater depth. (Pl. XVI, 91, 92). Against pyrrhotite this pyrite shows no sign of embayment, but against chalcopyrite it is slightly corroded and veinlets of chalcopyrite have engulfed it in places. It is thus post-

⁶Graham, A. R. personal communication.

pyrrhotite and pre-chalcopyrite. The resemblance of such pyrite to pyrite illustrated by Kullerud & Yoder (1959, Fig. 2) is very striking. This occurs around pyrrhotite grains and appeared to form "on quenching" after annealing at 850° C at 1000 bars for 74 hours. The natural example may well have been formed in a similar way, taking up sulphur from a vapor phase.

TABLE 9. PARTIAL ANALYSES OF SUDBURY PYRITES

Type	Locality	No. samples	Nickel (%)	Cobalt (%)	Silver (ppm)	Selenium (ppm)
Early (X)	Hardy	5	0.049	0.56		
Reaction (X)	Hardy	3	0.030	1.33		
Reaction (X)	Fecunis Lake	1	0.050	1.68	3	54
Early and reaction	Hardy	3	0.161	0.90		
Early and reaction (X)	Longvac	2	0.045	0.99	2	60
Reaction (?)	Levack	1	0.90	0.98	2	26
Reaction (?)	Levack	1	0.13	1.45	3	
Post-Pentlandite (M)	McKim	4	3.8*	0.59		
Post-pentlandite (M)	Creighton	1	5.15	0.24	10	130
Nickel-rich Walker Thomson & Allen	Murray	1	4.34			
	Worthington	1	6.50			
Early (X ?)	Milnet	1	0.20	0.18	2	56
Late (in mud seam (X))	Hardy	1	0.024	0.011		

(X) = Crystals (M) = Massive

*Samples known contaminated with pentlandite, but McKim pentlandite averages 0.10 per cent Co, and Creighton 0.05 per cent Co in these specimens.

As ore containing this type usually carries early, primary pyrite, separation of the two was made by Naldrett only from specimens examined microscopically. The results of analyses (Table 9) indicate a relatively high cobalt (1.33–1.68%) content for "reaction" pyrite while nickel is about the same as in primary pyrite. Analyses of probable mixtures of the two types from Longvac and Levack ore gave intermediate amounts of cobalt and somewhat higher nickel. As shown by other examples, pyrite formed at the expense of pyrrhotite and/or pentlandite at elevated temperatures, appears to take up cobalt preferentially. Results for silver

and selenium are given for a few samples, ranging from 2–3 ppm. and 26–60 ppm. respectively. Lead, though not listed, is present in amounts between 0.01 and 0.03 per cent.

(iii) *Hypogene replacement pyrite*. This is a relatively rare type found to date in two deposits, the McKim and Creighton, and since composition is similar they may have formed under somewhat similar conditions of temperatures and pressure though mode of occurrence is by no means identical.

At McKim a pentlandite-pyrite rich ore has recently been described by Clarke & Potapoff (1959) occurring in a carbonate-quartz-rich breccia zone in post-norite granite, dipping steeply and lying more or less at right angles to the margin of the nearby norite along the base of which more normal breccia ore is found. The two do not intersect but are separated by gangue or vein material. According to A. R. Graham (personal communication) this abnormal ore contains some early corroded cubic crystals of pyrite of normal cell edge as well as a later variety "appearing as braided replacements, veins and miniature stockworks, transecting gangue, cross-cutting and replacing pentlandite, pyrrhotite and chalcopyrite, and sometimes abutting directly against early pyrite or forming intergrowths upon them." Illustrations of the late variety of pyrite, examined by us (Pl. III, 16, 17), show fine feathery pyrite developed in pentlandite, and massive pyrite clearly replacing coarse pentlandite and enclosing many fine fragments and whisps of it. These are more easily discerned when stained. Such material would be quite rich in nickel because of such inclusions but Graham indicates it too has a normal cell edge and for some reason nickel has not entered its structure to any great extent although readily available. On the other hand this pyrite has about the same cobalt as early pyrite (0.59 per cent) whereas the adjacent pentlandite has abnormally low cobalt (0.089 per cent) according to analyses by Naldrett (Tables 6, 9). Whether or not such an ore represents normal type ore engulfed and partially reworked during its inclusion in younger granite is an interesting question. The prevalence of pyrite over pyrrhotite is in keeping with such an occurrence, as pyrite has been shown to be the more stable phase at temperatures and pressures under which granites form.

The occurrence of somewhat similar pyrite at Creighton, though a minor one, is none the less of interest. In one specimen of this ore a peculiar spear or disc-shaped seam of pyrite (Pl. III, 18) cuts normal, coarse pyrrhotite in which are several segregations of pentlandite. It has a maximum width of $\frac{1}{2}$ inch and a length of 2–3 inches. A clear seam of pyrite borders the "spear" and forms a medial seam, while the remainder has a lamellar form. Several inclusions of pentlandite are present within

it. The general form suggests the pyrite may be a pseudomorph of a coarse spear-shaped twin of marcasite, but this is not certain. In any case it replaces the pyrrhotite and has engulfed some pentlandite which may account for its high nickel content (5.15 per cent). Somewhat like the McKim pyrite just described, though not specially rich in cobalt (0.24 per cent) it seems to have acquired cobalt at the expense of contained pentlandite which now only contains 0.05 per cent as compared to pentlandite in adjacent pyrrhotite with 0.25 per cent. Peculiarly its selenium content is about twice that obtained in other types.

(iv) *Pink nickeloan pyrite*. Nickeloan pyrite is present in at least three deposits of the offset types, the Worthington, Foy, and Milnet. It has not been detected in samples examined from marginal deposits. A pink colour, a nickel content of 5–6.5 per cent, and its association with quartz and other gangue minerals are characteristic of this type of pyrite.

Thomson (1938) and Thomson & Allen (1939) have described nickelifferous pyrite from the Denison mine on the Worthington offset where it occurs with more normal pyrite "with quartz and other essential rock forming constituents of a quartz diorite . . . chiefly as small aggregates of crystals in somewhat concentric arrangement with ore-free bodies of gangue, between or disseminated through the gangue in concentric form, bands of ore alternating with bands of gangue." Chalcopyrite is noted as present in short vein-like forms in the pyrite which would thus appear to be pre-chalcopyrite in age. In this ore they describe three types—a cream type, denoted "A," a violet-cream type, "C," and an intermediate type, "B." Analysis of material consisting principally of "A" with minor amounts of "C" gave 6.5 per cent nickel. They suggest that all three probably contain nickel, and that "variation in colour is proportional to amount of nickel." Early *x*-ray measurements suggested the pyrite cell edge was not affected by nickel ions, but Peacock & Smith (1941) subsequently obtained a cell edge of $a = 5.419 \pm 0.002$ kX which is appreciably higher than normal pyrite.

Michener (1940) also notes that similar pyrite from the Foy offset has a larger than normal unit cell. The association with quartz, its concentric form, and the presence of vein-like chalcopyrite in it, suggest it is later than primary pyrite and possibly pre-chalcopyrite.

One sample containing pale to violet pink pyrite, very similar to that of the Denison material was obtained from the Milnet deposit. Though the usual pyrrhotite-pentlandite-chalcopyrite type of ore is present in this deposit these particular samples contain chiefly pyrite and chalcopyrite, in the latter of which are few irregular remnants of pyrrhotite. Both normal coloured pyrite, present in large, sharp, octahedral to cubic crystals, and chalcopyrite are riddled with abundant fine grains of

magnetite and non-opaque minerals. Carbonates and quartz are plentiful both between grains of sulphides and as curving colloform veinlets.

The pink pyrite forms veins or partial rims 0.05–0.01 mm. wide, around anhedral, normal pyrite grains (P. III, 13). Such rims merge into fine grained mixture of irregular rounded grains of pink pyrite, white marcasite in fine laths and wedges, and carbonate-quartz gangue (Pl. XIV, 80). Curving, concentric rims of pink pyrite also border geode-like fillings of carbonate and present scalloped or fretted borders against carbonate and quartz. It is quite clear that the pink variety is distinctly later than the larger idiomorphic crystals and has been in places simply "added on." Marcasite crystals, distinguished by their hard bluish white colour and distinctive anisotropism, appear to develop within and along the borders of the pink pyrite and also project into late gangue fillings as well, but the association of pink pyrite, marcasite and gangue is such an intimate one that the three must have formed much at the same time. Such areas are not in contact with chalcopyrite so we were unable to confirm their relative age.

The pink pyrite has no reflection pleochroism and, as far as observed, is isotropic. It takes a good polish and is a little softer than "normal" pyrite. Both 1:1 and concentrated HNO_3 produce a light brown etch and bring out some concentric zoning. HgCl_2 stains brown, leaving the associated normal pyrite unaffected, and 1:5 and concentrated HCl , KCN , KOH , and FeCl_3 are negative. The HgCl_2 etch appears anomalous in the light of the negative reactions obtained by Thomson & Allen (1939) on Denison material, though, as it was impossible to confine drops of reagent entirely to the mineral in question the test may have been affected by other minerals of the section. A sufficient amount of the pink variety could not be obtained for analyses. The normal type pyrite in this ore (Table 9) is relatively low in both nickel and cobalt.

The peculiar association of this nickel-rich variety with marcasite, quartz and carbonate in deposits which also contain the normal pyrrhotite type of ore suggests it is a late stage development and was formed from somewhat different ore fluids than early pyrite and normal ore. It is considered as probably hypogene, but must have formed under different conditions than normal appearing pyrite carrying some nickel, also associated with marcasite, and in places with galena and sphalerite as described below.

(v) *Late types of pyrite, hypogene or supergene (?)*. This classification is applied to those types of pyrite, both in crystals and massive, which are clearly secondary after pyrrhotite, are associated with marcasite and in some places with violarite and millerite and in others with galena, sphalerite, quartz and carbonate. All are probably related to late faults

and some extend to considerable depth. They were possibly all formed under relatively low temperature conditions but it is not so certain that they are all of supergene origin.

Coleman (1913, p. 21) describes an occurrence of this type on the east range as "separate masses, often as part of the fillings of veins crossing ore deposits and therefore later in age." Cubic pyrite, associated with quartz and calcite, as at the Elsie mine, he notes, carries essentially no nickel.

Michener & Yates (1944) have traced the development of disseminated cubes of pyrite in pyrrhotite into more massive pyrite, and note its occurrence in massive (normal) ore usually within 35 feet of open faults extending to depths of at least 1400 feet. Marcasite is associated with both types of pyrite and both carry some nickel. The common mode of occurrence of the disseminated type is as small subhedral to euhedral cubic particles of the order of 0.05 mm. across, arranged along parting planes in pyrrhotite (Pl. III, 14). They are usually partly rounded and, as carefully noted by Michener & Yates, are almost always partially bounded by circular pits so that the pyrite occupies a smaller volume than the original pyrrhotite. In spite of the tendency to idiomorphism the apparent control of the distribution of this pyrite by pyrrhotite suggests its later formation as does the similar occurrence of fine crystals of marcasite (in places inverted to pyrite) oriented at right angles to both parting planes and cross-cutting fractures in the pyrrhotite. The passage of such pyrite into more massive pyrite and non-opaque minerals by replacement of pyrrhotite is illustrated in Plate III, 15, in which the preservation of the basal parting may be clearly seen. Michener & Yates have already illustrated the almost complete replacement of pyrrhotite to massive pyrite containing blades of marcasite and attribute the development of both to low temperature acid solutions carrying nickel and iron sulphates, H_2S and S ions, penetrating deep faults. "Repeated microchemical tests on both pyrite and marcasite gave a nickel reaction." As noted later further stages in the alteration according to these authors leads to the formation of violarite and millerite.

Excellent descriptions of identical cubic pyrite disseminated in pyrrhotite in the Insizwa ores are given by Scholtz (1936) who also believed them to be secondary. Clarke (1946) notes pyrite and marcasite occurring at Falconbridge in cross fractures near fault zones cutting breccia-type ore to depths as great as 2800 feet (and others to over 4000 feet), and giving rise to what is known as "marcasite-type ore" in the south wall deposits. Here A. R. Graham (personal communication) describes the obviously "late" pyrite as of several types; "some as -200

micron, individual cubes and cubo-octahedrons with narrow gangue selvages, embedded in massive pyrrhotite; some as minute (-50 micron) pyritohedrons in gangue fracture-fillings in pyrrhotite; some is quite massive and anhedral, interfingering with massive to subhedral marcasite." "Cell edge determinations on the massive pyrite gave 5.417 ± 0.001 Å." Graham also notes: "In a specimen less than 15 feet farther into the south wall, on the fringe of the same marcasite-rich ore zone, near the western end of 3502 drift along the norite contact, tiny well-crystallized, non-corroded octahedrons of pyrite were noted embedded in pyrrhotite, amounting to nearly 5 per cent of the area of total sulphides. Each small pyrite grain had a selvage of gangue conformable to its outline." Cell edge on one of these crystals gave 5.435 ± 0.002 Å indicating a possible nickel substitution of up to about 8 per cent nickel. Drill core assays did not indicate any marked concentration of cobalt and the pyrite is presumably low in this element. On a concentrate of mixed pyrite and marcasite from such "marcasite-ore" Clarke earlier found on analyses about 3.75 per cent nickel. It is thus clear that form, habit and nickel content of such secondary types of pyrite may vary considerably, but all seem somewhat related to late stage faulting and fracturing.

While Michener & Yates have made a good case for the supergene origin of such secondary pyrite, the alteration must have been decidedly selective. As will be described later some pseudo-eutectic intergrowths of pyrrhotite and niccolite are found around the borders of pyrrhotite in the central part of which similar cubic pyrite has formed. As will be shown such pseudo-eutectic intergrowths are certainly not supergene, nor do they show any effect of alteration.

Also occurring in deep and shallow fracture zones at both Falconbridge and several other deposits, pyrite is present in gash-vein fracture fillings of carbonate and quartz, often with sphalerite and galena. The pyrite is relatively low in nickel as is some associated marcasite, and galena in such veins is quite low in silver or other precious metals, in contrast to much deeper occurrences of this mineral at Frood. This late stage mineralization of lead and zinc is clearly low temperature and fits well with Schneiderhohn's (1954) "secondary hydrothermal" type of deposit. Associated marcasite and pyrite are thus not necessarily supergene.

Not included in the above discussion are occurrences of pyrite in aplite dykes with carbonate as at Hardy (Mitchell & Mutch 1957) and in stringers reported in the late Keweenawan olivine diabase dykes. These seem of little significance with respect to the main ore deposits and are to be expected in any intrusives in a sulphide rich area. Samples of them have not been available for study.

Nickel-Arsenic-bearing Minerals: Gersdorffite, Niccolite, Maucherite

The three arsenic-bearing minerals, gersdorffite, niccolite and maucherite are usually found in intimate association, often with chalcopyrite and precious metal minerals, and more rarely separately. Their modes of occurrence may thus be considered together. They are most abundant in offset deposits such as the Worthington and Frood and to a lesser extent are present along the marginal parts of normal types of ore deposits of the south range, particularly Garson and Falconbridge. They do not appear to have been reported nor have our studies revealed them in deposits of the north range.

Gersdorffite and niccolite, from the Worthington offset are described by Barlow (1904). A specimen of the former, collected in 1891, appears to be the first of its kind recognized in Canada. Both are associated with the more common sulphides in fractures within and along the quartz-diorite intrusive. At the Gersdorffite mine they occur in a quartz vein as grains and disseminated masses along with some feldspar and carbonate. Lausen (1930) was first to describe maucherite associated with gersdorffite, quartz, niccolite and chalcopyrite, from the Worthington mine dump. Niccolite veins were reported to him as sharply cutting massive sulphides, pyrrhotite-pentlandite-chalcopyrite. This he felt was substantiated by polished section study of embayed and corroded pyrrhotite and pentlandite. Still later sphalerite-galena veins, cutting niccolite, were also reported. As will be seen later, the former age relations are different from our findings elsewhere.

At the Falconbridge mine, according to Davidson (1948), gersdorffite along with chalcoprite, has a tendency to favour the margins of the main sulphide ore zone. A large hand specimen in our collection contain crudely banded alternately fine and coarse granular gersdorffite, about 8 inches across, beautifully replacing chlorite-biotite schist and later invaded by pyrrhotite-pentlandite.

To Michener (1940), however, we are indebted for a more detailed description of the arsenic minerals at the Frood where they occur in part as an outer zone around normal sulphides and in the lowermost siliceous mineral zone chiefly as (1) a band lying between sulphide and hanging wall rocks, and (2) veins and stringers penetrating altered contact rock for a distance of several feet. Quartz, carbonate, hastingsite, and biotite schist are usually associated with such veins. Other occurrences include (3) "fillings in a mesh of hastingsite, and (4) rounded pellets or blebs embedded in chalcopyrite and evidently replacement remnants in this mineral." The close association with precious metal minerals at Worthington, with sperrylite, and at Frood with sperrylite, gold, hessite and two

palladium bismuthides, as well as other tellurides and bismuth minerals, is noteworthy.

Distribution of the arsenical ore at Frood, according to Michener shows a distinct structural control, greatest concentrations being found "on hanging wall contacts, especially where the dip is sharply altered by sudden change of direction, . . . and below a large roll or pendant of hanging wall rock." A general account of the Frood ore deposit has been given by Zurbrigg *et al.* (1957). and is referred to earlier (p. 31).

Michener has also noted zonal relations in arsenical ores:

Where niccolite, maucherite and chalcopyrite are seen occurring together along a contact they are arranged in the order named, with niccolite next to the contact rock. The occurrence may take the form of a stringer . . . or a band of arsenides between the sulphides and contact rock and . . . chalcopyrite has replaced the arsenides to a considerable extent, and apparently occupies a zone several feet in width between the arsenides and typical copper-nickel ores. No evidence has been found that the arsenides are preferentially deposited in one type of wall rock compared to another. They do, however, seem to extend further into acid types of rock than into basic. Alteration near such concentrations and next to the ore is to brown biotite which passes outward to granular quartz and sericite. Silicification follows streaks or stringer-like zones, and chlorite and talc are present where there is a strong development of biotite. In the biotite zone . . . blades of secondary hornblende (hastingsite) sometimes occupy a zone one to eighteen inches wide. Red and massive pink garnet are characteristic of the contact. Quartz is quite common as stringers . . . or as a band several feet wide separating rock from ore. Calcite, dolomite and siderite are all associated with the quartz . . . or occur as individual veins.

Thus the association of arsenides (and precious metals) with secondary silicates, quartz and carbonates appears in rather sharp contrast with the more common pyrrhotite-pentlandite-chalcopyrite ores of the district. At the Garson, from which some of our finely intergrown arsenides come, wall rocks are similarly reported as showing more than normal types of alteration. The difference between the marginal and offset deposits however, in prevalence of such arsenical ores as noted by Michener, may be simply "one of degree rather than of kind."

(i) *Gersdorffite*. Gersdorffite in our collection has come chiefly from the Garson and Falconbridge deposits. In the former it is intimately intergrown with maucherite, niccolite and chalcopyrite as described by Hawley & Hewitt (1948). As noted above at Falconbridge it occurs as a single mineral replacing chlorite schist wall rocks and passes into normal ore by replacement by pyrrhotite-pentlandite.

Under the microscope the mineral shows its typical bluish white colour and high reflectivity, and it readily takes an excellent polish. However, contrary to earlier descriptions of the mineral, it shows a

weak, but distinct double refraction, with colours of grey to light brown. This reveals clear, irregular twin structures and occasional poorly developed concentric zoning. Particle size is quite variable, ranging up to about 4.0–5.0 mm. in greatest dimension, and averaging somewhere in the range 0.25–1.0 mm.

Composition is variable, and there are notable quantities of cobalt and iron as first noticed by Barlow (1904) in material collected in 1891 from the old Gersdorffite mine. Michener (1940) also noted that gersdorffite from Froid and Garson varies a good deal from the ideal formula of NiAsS , and his analyses suggested atomic ratios of $(\text{Ni}, \text{Co}, \text{Fe})_{10} \text{As}_{11} \text{S}_{10}$. From x -ray powder photographs he notes that cell edge changes slightly with variation in composition. (Recent studies by Yund (1958–9) on the Ni-As-S system are of interest in this connection.)

To Naldrett we are indebted for additional analyses of gersdorffite from Falconbridge, Garson & Froid, made on the x -ray spectrometer with curves established from two samples analyzed chemically through the kindness of Falconbridge Nickel Mines Ltd. These with others are listed in Table 10. When the metal content of these is plotted (Figure 3)

TABLE 10. PARTIAL ANALYSES OF GERSDORFFITE¹

Location	Spec. No.	% Ni	% Co	% Fe	Total metals as 100%		
					Ni	Co	Fe
Falconbridge	Fa 4	15.90	9.55	6.90	49.14	29.52	21.32
	Fa 14	16.80	9.40	6.70	51.06	28.57	20.36
	Fa 18	18.80	7.40	7.35	56.04	22.06	21.90
	Fa 58	21.80	4.90	7.05	64.59	14.52	20.89
	Fa 69	22.54	4.26	6.99	66.71	12.60	20.69
	Fa 70	18.20	7.50	7.25	55.23	22.76	22.00
Garson	S 1a	21.20	5.60	6.65	63.38	16.74	19.88
	1b	25.60	2.36	6.35	74.61	6.88	18.51
	1c	25.70	1.98	6.65	74.86	5.77	19.37
	1d	22.80	3.85	6.80	68.16	11.51	20.33
	Ga 7	26.03	1.38	6.50	76.76	4.07	19.17
	Ga 9	22.30	6.95	5.95	63.35	19.74	16.90
	No. 2*	21.40	7.20	6.68	60.65	18.93	20.41
Froid	Ni. 501–1	27.70	2.50	5.40	77.81	7.02	15.16
	No. 1*	17.06	12.00	4.96	50.14	35.27	14.57
	Q–1	18.30	9.10	5.60	55.45	24.55	17.00
Worthington	1b†	26.32	2.01	7.90	72.64	5.55	21.81

¹After Naldrett, (1961).

*Nos. 1, 2, (from Froid and Garson, respectively) Analyses by Michener (1940)—No. 1 contains also As—48.42%, S—18.50%; No. 2 contains also As—46.81%, S—18.10%.

†No. 1b—Analysis by Barlow (1904), with As—46.96%, S—16.71%.

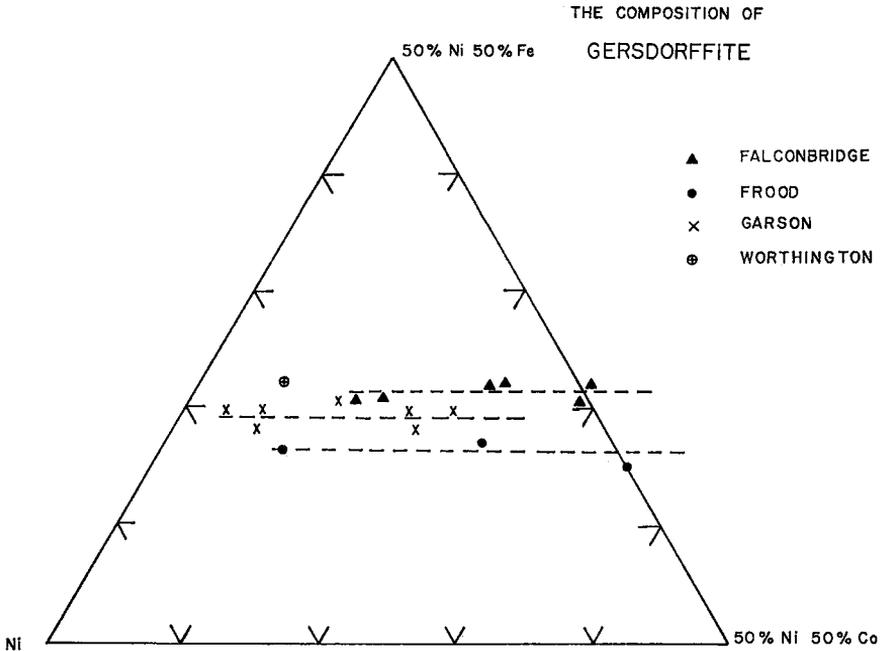


FIG. 3. Diagram showing composition of Sudbury gersdorffite (after Naldrett).

Naldrett found the interesting fact that the iron content for a given mine seems to remain very constant while cobalt varies inversely as nickel. Falconbridge and Worthington gersdorffite have about the same iron content and more than in the other two. Garson has less iron and Frood the least. In the three larger deposits cobalt varies considerably, but the reason for this is not apparent. Other elements found in traces in gersdorffite by Lewis (1950) include: Sb, Bi, Cu, Ag, Pd and Au.

Gersdorffite shows a strong tendency to idiomorphism (Pl. IV, 22-24) and where isolated in later sulphides may be completely bounded by sharp crystal faces. Where it occurs as granular masses of more or less pure gersdorffite, many of the particles are irregularly rounded and show a crystal face only here and there; small internal breaks in such aggregates occur however, and are often filled with chalcopyrite, pyrrhotite, niccolite, maucherite (Pl. V, 25, 26) or galena, which are moulded around the sharp crystal faces presented to them by the inner grains of gersdorffite. Relations between gersdorffite and associated sulphides are variable. It may, as already noted, present the sharpest of sharp outline against other sulphides in one case, and then in an immediately adjacent particle these will have obviously corroded it. It is not uncommon to

see a gersdorffite crystal showing sharp terminations on one side, and deep embayment on the other. In addition to corroding the gersdorffite, chalcopyrite, pyrrhotite, pentlandite, niccolite, sphalerite and galena frequently form fracture fillings and replacement veins in it, indicating their later formation. All these minerals too may be included as rounded and irregular blebs, either singly or as composite particles. Composites are most frequently of chalcopyrite-pyrrhotite or chalcopyrite-niccolite.

The relations between gersdorffite on the one hand and niccolite, chalcopyrite, maucherite and pyrrhotite on the other, are of some interest. Where any one of the latter group of minerals is in contact with gersdorffite the species in question is either moulded onto sharp crystal outlines of the gersdorffite, or appears to form quite normal veins or embayments in it. These are the features already described. However, if a pair, or a group of three of these minerals—always provided that at least one of the two arsenides is present—is in contact with the gersdorffite, the minerals commonly develop a very distinctive pseudo-eutectic replacement texture (Pl. V, 29: XII, 67). The “pseudo-eutectic” textures developed by niccolite-chalcopyrite-maucherite have been described recently elsewhere (Hawley, Stanton & Smith, 1961) and are reviewed briefly under niccolite and maucherite. A feature of probable significance is that these pseudo-eutectic textures develop most always in the presence of gersdorffite. The relationships, from only minor replacement to almost complete pseudomorphism of euhedral gersdorffite in massive maucherite, are shown in Plates IV, V.

One other peculiar feature of some gersdorffite, illustrated in Plate IV, 24, is the occurrence of a fine rim or seam of gersdorffite between pyrrhotite and niccolite. The pyrrhotite replaces gersdorffite grains (lower right) whereas other gersdorffite grains present sharp boundaries to niccolite. The thin seam mentioned joins one of these and may represent a remnant of a larger mass of gersdorffite, on the one hand, or a possible reaction product on the other. Recent experiments by A. Y. Smith (1961) in which niccolite was placed in close contact with pyrrhotite and heat treated at 750° C. for 18 hours in a current of H₂S has clearly demonstrated that niccolite can be converted over to irregular grains of gersdorffite along the grain boundaries. At the contact of niccolite and pyrrhotite such secondary gersdorffite was in turn altered to synthetic heazlewoodite as confirmed by an *x*-ray powder photograph. Such an origin for gersdorffite is not suggested for the natural well formed crystals, but remains a possibility for the thin seam of gersdorffite described along such contacts in natural ores.

(ii) *Niccolite*. Niccolite, next in abundance to gersdorffite is a relatively rare mineral. Its association with ores in the Worthington, Frood and

Garson mines has already been noted. No occurrence of this mineral along the north range has come to our attention. It shows its normal bright salmon-pink colour, high reflectivity and pronounced pleochroism. Anisotropism is very strong with characteristic tan to pale green colours, and it takes an excellent polish.

No complete analyses are available on pure Sudbury niccolite. Naldrett found four samples to average only 0.1 per cent cobalt; a fifth contains 0.57 per cent, not unlike an analysis of niccolite containing some gersdorffite reported by Barlow. Lewis found spectrographic traces of Sb, Bi, Ag, Au, Pd, Cu and Fe in samples he examined.

Niccolite occurs massive in interlocking grains, as seen in polarized light, or as a constituent of five pseudo-eutectic intergrowths already noted. Where free of other arsenides it is usually present as seams up to 3 cm. across in quartz veins or stringers with chalcopyrite. As described under gersdorffite it simply cements sharp crystals of this mineral without appearing to attack them, but in other cases veins and replaces them (Pl. IV, 23, 24), commonly centripetally or along apparent growth zones. Chalcopyrite, on the other hand, embays and veins massive niccolite in a normal manner in some specimens, but forms pseudo-eutectic intergrowths in it, especially when gersdorffite is also present. Relations to pyrrhotite are less clear as contacts are less numerous. Where they are found together a rare pseudo-eutectic intergrowth of pyrrhotite and niccolite is developed along the contact with the intergrowth appearing to embay the pyrrhotite (Hawley, Stanton & Smith, fig. 8). The same type of intergrowth also replaces gersdorffite. Zonal relations to chalcopyrite-cubanite ore containing residuals of pyrrhotite with pentlandite suggest the sulphides are normally later than niccolite. It may thus be that the intergrowth of pyrrhotite and niccolite is later than both contiguous grains of these minerals and has formed by a reaction between them. This is a slightly different interpretation than given earlier, elsewhere. Relations of niccolite to maucherite as noted above, have been interpreted in an opposite manner by other observers and is understandable from contacts we have seen. Under crossed-nicols, however, maucherite is clearly seen to replace niccolite and enclose odd "islands" in optical continuity with larger grains. Such an age agrees with Michener's observations at Frood, though the relation may vary in different places. The presence in some niccolite of many inclusions of pyrrhotite-pentlandite, maucherite, galena, mineral C (probably a palladium bismuthide), as well as others already noted, adds to the difficulty of deciphering its age.

In addition to its intergrowths with pyrrhotite, it forms similar ones with chalcopyrite, with maucherite, or with both of these and commonly

also with both pyrrhotite and chalcopyrite. Such intergrowths develop as fine, sponge-like aggregates of rounded blebs and interconnected club-shaped masses (Pl. V, 29; XII, 67) and are similar to other pseudo-eutectic textures. The association of niccolite, chalcopyrite and maucherite was first noted by Lausen in ores from the Worthington mine and later by Hawley & Hewitt (1948) from the Garson.

Niccolite is usually the dominant member, with chalcopyrite and maucherite present in that order. In spite of the fineness of the texture the niccolite, when viewed between crossed nicols, can be seen to be in the form of quite coarse (up to 1.5 mm. across) grains which are essentially similar in size to the grains free of other minerals. The actual size of the structurally continuous niccolite is thus of the order of ten to twenty times coarser than the intergrowth in which it is involved. Some of the inclusion-free areas of niccolite, too, are crystallographically continuous with some of the adjacent intergrown material. As noted earlier, these have a quite constant association with gersdorffite which can be found in all stages of replacement by them. That they are secondary reaction products is demonstrated by their textural relations and experiments. While the two-phase aggregates are not difficult to decipher those consisting of three are more confusing. It is in these that synthesis of similar intergrowths has been of assistance.

It has been shown by Hawley & Hewitt that niccolite-maucherite intergrowths may be formed by heat treatment of niccolite and artificial mixtures of NiAs and NiSb in vacuo at temperatures of 500° to 750° C. but not in cases where NiSb forms over 30 per cent of the mixture. A. Y. Smith (1961) produced similar intergrowths by heating gersdorffite alone or with chalcopyrite in sealed tubes with metallic arsenic (in 3.2 atmos. pressure) at a temperature of 750° C. for 24 hours. Gersdorffite as a result was badly corroded by a wormy eutectic-like mass of niccolite and maucherite, which, outward from the border of gersdorffite, became more club-like in form (as in natural specimens), passing eventually into solid maucherite. Where both gersdorffite and chalcopyrite were present in an atmosphere of arsenic, the chalcopyrite invaded and replaced the gersdorffite as well as the niccolite-maucherite intergrowth and preferentially replaced the maucherite leaving irregular inclusions of niccolite in the chalcopyrite. In a sulphur atmosphere however, no such reactions occurred, suggesting low rather than high sulphur pressures would be required for such intergrowths to develop in nature. The same may be true also of arsenic unless the temperatures were sufficiently high to render both gersdorffite and niccolite unstable. The preferential replacement of maucherite compared with niccolite by chalcopyrite in experiments is illuminating and may well account for the greater abun-

dance of niccolite-chalcopyrite intergrowths compared with those of niccolite and maucherite.

Although the simpler intergrowths of niccolite and pyrrhotite, with or without gersdorffite, were not duplicated experimentally, it is possible ferroan gersdorffite dissociated to form the niccolite and pyrrhotite, and at least the reverse reaction has been demonstrated. In any case these peculiar textures seem best explained as late stage developments at elevated temperatures under conditions allowing a distinct change of arsenic and sulphur pressure. Chalcopyrite seems the latest phase to enter such intergrowths. That this is not necessarily primary chalcopyrite (of the main period of sulphide mineralization) but may be a re-mobilized second generation, is suggested by experiments which clearly show its mobility under such conditions.

(iii) *Maucherite*. Maucherite $\text{Ni}_{11}\text{As}_8$ is even less common than niccolite with which, however, it is usually associated. It has been reported from the Worthington and Froid mines and is present also at Garson. A purplish tarnish on steel grey surfaces seems characteristic.

In polished sections maucherite, although always a grey shade, shows quite a distinct variation in apparent colour with change of background. Where intergrown with niccolite or chalcopyrite it is a distinct, soft grey with a faint mauve tint. Where, on the other hand, it is massive and isolated from other minerals it is simply an off-white, not very dissimilar from gersdorffite. The apparent paler shade of the larger areas of maucherite is greatly accentuated where pyrrhotite, which is much darker by comparison, is associated. Anisotropism is moderate, with no particular colours developed, and there is no pleochroism. Polishing characteristics are similar to those of niccolite.

The composition of Sudbury maucherite has been given by Peacock (1940) and is quoted in Dana (1944). Recalculated by Peacock to eliminate obvious impurities, this yields 51.75% Ni, 0.21% Co, 0.24% Fe, 47.52% As, and 0.28% S. A recent analysis by Naldrett gave 0.39% Co, while Lewis earlier detected traces of Sb, Bi, Ag and Pd, all of which appear in the other arsenides as well. Yund (1958-59) has noted a small change in unit cell with arsenic content and confirmed its incongruent melting at 829° C. Solid solubility of maucherite for $\alpha\text{Ni}_{1-x}\text{S}$ is limited and decreases with temperature. While Yund notes that assemblages of maucherite with niccolite and millerite might be used as a geological thermometer, the millerite phase is missing in maucherite specimens of Sudbury.

The maucherite occurs in two distinct forms—massive (Pl. VI, 32) or as fine intergrowths. One concentration of about 3.0 cm. across has been found to be composed of quite massive maucherite, with associated small

quantities of pyrrhotite, pentlandite, niccolite, gersdorffite, chalcopyrite and precious metal minerals. The pyrrhotite, with associated flames and grains of pentlandite, forms veinlets and embayments in it, and under crossed nicols can be seen to exploit grain boundaries. As noted above it has been found replacing niccolite but the opposite relation has also been reported. One Frood specimen shows massive maucherite deposited against grey quartz and clearly replaced gradually over a distance of 3 inches by intergrown cubanite and chalcopyrite, so that only rounded particles of maucherite, 1–3 mm. diameter, eventually remain. Such particles show radiating cracks around their periphery and locally are veined by the sulphides. In some cases fine pentlandite flames develop at the border and project into cubanite, suggesting a reaction relationship. The maucherite is thus definitely earlier than these sulphides. Similar massive material is associated with amphibole bearing wall rocks (hastingsite), and is moulded upon and forms distinct veinlets and embayments in subhedral crystals of the latter (Pl. XIV, 81).

Euhedral and subhedral crystals of gersdorffite are occasionally found enclosed in massive maucherite; in some cases beautiful lozenge-shaped near pseudomorphs of pseudo-eutectically intergrown pyrrhotite and maucherite, after gersdorffite have been formed (Pl. VI, 33–36). Hessite and michenerite are also very minor constituents of the massive material (Pl. XIII, 77).

The participation of maucherite with niccolite and chalcopyrite or pyrrhotite in pseudo-eutectic intergrowths has already been mentioned. In these niccolite is the major continuous phase while maucherite and chalcopyrite or pyrrhotite give way to one another in a continuous fashion within the limits of their own network. Synthesis of such textures (Smith, 1961) confirms that chalcopyrite (and probably pyrrhotite) preferentially replaces the maucherite and that both niccolite and maucherite can be so formed as a replacement of gersdorffite, as appears to be the case in the natural ores.

Heazlewoodite (?)

A mineral resembling heazlewoodite (Ni_3S_2) yet differing in a few respects, has been seen in only two sections, both of bornite-rich ore from the lower levels of the Frood mine. Unfortunately no particles large enough for *x*-ray powder photography could be found and so the determination must be accepted with a good deal of reservation.

The mineral occurs as small rounded aggregates and strings of grains, showing excellent polish, in chalcopyrite and bornite. Areas of such aggregates vary up to about 0.1 mm. across, with an average of about 0.07 mm. The individual grains, which can only be distinguished between

crossed nicols, vary up to about 0.05 mm. across and average about 0.02–0.03 mm. Colour in ordinary light is just a little paler than, but very similar to, pyrite. Reflection pleochroism of this mineral differs from the observations of Peacock (1946) and Williams (1958) on Tasmanian heazlewoodite and here, is quite pronounced, with colour varying from cream to bluish-white. Anisotropism is on the strong side of moderate, with pinkish-brown to slightly bluish grey interference colours. A little fine multiple twinning has been noted in one or two grains. Individual grains show up clearly between crossed nicols and the development of a mosaic texture is characteristic. Hardness is possibly slightly greater than that of chalcopyrite and bornite.

Etch tests show a fair similarity to those obtained by Peacock on the Tasmanian material, though the reaction with FeCl_3 appears a little different. HNO_3 (1:1) stains grey to greyish-brown; HCl (1:5) stains a very faint brown in some cases, and is negative in others; HgCl_2 stains brown; FeCl_3 instantly stains iridescent, then goes grey, showing up grain boundaries and mosaic texture—a rather stronger reaction than suggested by Peacock (who found FeCl_3 and KOH to stain faint brown). KCN is negative. These reactions differ from those of millerite which however does show reflection pleochroism.

The mineral appears to have crystallized before chalcopyrite and bornite and to have been enclosed by these. There is no evidence to support any other relationship. In recent experiments by Smith (1961) artificial heazlewoodite was prepared by heat treatment of niccolite and pyrrhotite in close contact, in a stream of H_2S at a temperature of 750°C .⁷ The heazlewoodite appears to have developed from gersdorffite which formed first as a reaction product in and along the contact of the niccolite with pyrrhotite. There is, however, no indication in the natural specimens described here that heazlewoodite formed in such a way, as no remnants of other nickel minerals are present.

Bornite

Bornite is a very minor mineral of the ores and so far has been detected by the writers only in copper-rich material from the lower levels of the Froid, where it occurs as irregular veinlets and pockets up to three or four centimetres long and a centimetre or so wide, in the so-called siliceous mineral zone. This is quite a different occurrence to that, reported as having been noted along with secondary chalcocite by Dickson (1904)

⁷Kullerud & Yund (1958–9) state the mineral may be readily synthesized in the dry state from suitable mixtures of nickel and sulphur. A high temperature phase develops between 800°C and 637°C , which readily inverts to hexagonal heazlewoodite at $550^\circ \pm 10^\circ\text{C}$.

and Barlow (1904) at the Vermilion mine. There Coleman (1913) regarded both as supergene as neither were in evidence at any depth. In places tarnish on weathered chalcopyrite erroneously gives the impression of bornite being widespread. In the Froid ore bornite is almost invariably associated with some chalcopyrite. Minor quantities are present in a complex fine-grained specimen in which parkerite and galena are relatively abundant, with lesser amounts of pyrrhotite, chalcopyrite, minute grains of heazlewoodite (?) gold, hessite, tetradymite and quartz. Other specimens show bornite (with chalcopyrite) associated closely with native silver, bismuthinite (?), and native bismuth.

Under the microscope it has no special features other than minor development of tapered, spindle shaped twins which show up very clearly in slightly tarnished surfaces. With chalcopyrite it forms composite areas and veins in wall-rocks. Boundaries between the two are normally mutual, but in places bornite clearly appears to corrode, embay and cut across grain boundaries of chalcopyrite; in others the opposite relation might be inferred. Occasionally fine spindles of chalcopyrite included in bornite show a clear preferred orientation, with the development of a triangular pattern, indicative of ex-solution. Small particles of bornite are frequently isolated in chalcopyrite, but are quite irregular in size, shape and distribution. Other small irregular to smoothly bordered grains lie at the edge of chalcopyrite grains in contact with magnetite, galena, hessite, parkerite and quartz, as if developed locally. Stanton noted in the present study that where "second generation pyrrhotite developed as linear veins or veinlets in chalcopyrite, apparently exsolved from and guided by the chalcopyrite structure, it is often accompanied by small amounts of very fine bornite." In places bornite forms a partial rim around magnetite and also about hessite and encloses a fragment of the latter in optical continuity with the central hessite grain. Much of it is thus later than chalcopyrite and later than hessite. Galena enclosing odd grains of bornite appears later than chalcopyrite, hessite, and bornite.

Irregular grains of parkerite are surrounded by bornite and appear corroded by it (Pl. XIII, 76). Rounded grains of parkerite are also rimmed by native bismuth and both also are enclosed in coarse grains of bornite. Spongy chalcopyrite lies in bornite between areas of parkerite-bismuth (Pl. XII, 71, 72), and exsolution lamellae of chalcopyrite appear alone in the bornite as well.

Its association with native silver and chalcopyrite is well illustrated in Plates XII, 69, and XIII, 74, 75. Veins and blebs of native silver in chalcopyrite are almost invariably separated by an irregular narrow fringe of bornite which has clearly formed at the expense of chalcopyrite. This is further discussed under native silver.

In addition to these occurrences bornite has been found to include heazlewoodite and native gold. Most of the rarer "exotic" minerals appear rather late in the paragenetic sequence. Their association with quartz suggests they were formed from more aqueous fluids than the main sulphide ores, but the presence of exsolved chalcopyrite in the bornite indicates temperatures were still relatively high at this stage. Unmixing of the two occurs below 475° C. (Schwartz, 1931).

Valleriite

Valleriite is also a very minor constituent of the Sudbury ores, but is not uncommon in copper-rich materials. Scholtz (1936, p. 170) was first to note it in material from Sudbury, and more recently it has been encountered in our collections.

Its features are characteristic and therefore quite striking: reflection pleochroism is very strong, colour changing from pale yellow (lighter and brighter than the surrounding chalcopyrite) to a mauvish grey, distinctly darker than pyrrhotite. Double refraction is strong with colours bright yellowish white to blue-grey. Extinction is sharp and there are four extremely clear cut changes on a 360° rotation. The valleriite occurs frequently as long spindles less than 0.01 mm. wide which in some cases are clearly aligned by the crystal structure of the enclosing chalcopyrite (Pl. XI, 66). In places they are arranged en échelon and either cross cut or lie parallel to twin lamellae of chalcopyrite and blades of ex-solved cubanite (Pl. XVI, 94). In some of the material examined the chalcopyrite is very coarse and as a result the valleriite crystals occur as a triangular network with, however, one orientation greatly preferred. Not only do the spindles show a remarkably regular pattern in this way, but under crossed nicols all appear in the one optical orientation within a single grain of chalcopyrite.

The above properties and relations indicate quite clearly this mineral is a distinct species and a product of exsolution. None was of sufficient size to allow its separation from chalcopyrite for chemical analyses, so we are unable to state how it compares in this respect with Mackinaw, Washington, material described recently by Milton & Milton (1958) who mention in a footnote that their material is "an undescribed species of iron sulphide" in contrast to Kaveltorp (Sweden) valleriite which appears to be a Cu-Fe-Mg-sulphide.

The mineral identified as valleriite in the Sudbury ores is in chalcopyrite rich specimens containing the usual rounded remnant of pyrrhotite and pentlandite and ex-solved cubanite. The coarse grained chalcopyrite contains abundant oriented laths and spindles of pentlandite ranging in size from 0.05 to 0.01 mm. dia. and 0.10 mm. or more long. The larger

of these have very ragged borders as if replaced and valleriite lies along side or parallel to them, but many of the finer laths of pentlandite appear continuous with fine spindles of valleriite. Chromic acid stains the pentlandite blue but barely affects the valleriite which retains its pleochrism and anisotropism. Cubanite staining solution conversely stains the valleriite dark grey to black and gives only a brownish cast to the associated pentlandite. The surrounding chalcopyrite appears more reactive with this solution than normal chalcopyrite, turning red to blue but no cubanite is present in the immediate vicinity. The textures described suggest that some pentlandite and pyrrhotite may have entered into solid solution with chalcopyrite during replacement of these minerals, and that on cooling both pentlandite and valleriite have exsolved along crystal directions in the chalcopyrite. Elsewhere cubanite laths do occur in the chalcopyrite. These are cut or paralleled by rods of valleriite which is clearly later.

Sphalerite

Sphalerite of three generations is present but apparently is nowhere concentrated in masses of sufficient size to constitute a zinc ore. It is a common minor constituent of the copper-rich ores in which it is present always as fine microscopic particles. With galena it forms a part of quite late veins, filling fractures in massive sulphides as at Froot, and in chloritic faults, as at Falconbridge, and other mines where it is associated with pyrite, marcasite, calcite and quartz.

Sphalerite associated with chalcopyrite is of two generations and has two modes of occurrence. One, contemporaneous with chalcopyrite, is developed as fine asterisks in it and in cubanite, clearly the result of ex-solution. These are quite rare. The other consists of quite irregularly shaped flecks, blebs or fine aggregates with variable particle size up to 1 mm. across and more rarely of veinlets cutting both pyrite and pyrrhotite (Pl. II, 11). Much of it occurs apparently within chalcopyrite and many larger particles, when viewed in ordinary light, show bays and cusps suggesting chalcopyrite is replacing it, but under crossed nicols the sphalerite is found to be localized for the most part between grains of chalcopyrite and to exploit the grain boundaries to yield the irregular and rounded contacts. Plate XII, 68, shows sphalerite with abundant chalcopyrite inclusions embaying and replacing chalcopyrite. Elsewhere it is also present as irregularly rounded inclusions in both early pyrite and pyrrhotite. One of the most notable features of sphalerite is its close association, in rare specimens, with stannite, much of which is within or attached to larger particles of sphalerite, suggesting an ex-solution relationship. At Froot, such sphalerite rims galena. Whether such

sphalerite is contemporaneous with non-stannite bearing sphalerite is a question. The latter may well be a much later concentrate. Late sphalerite, third, or fourth generation, occurs as fracture fillings in massive sulphides and in late faults. In the former (Pl. XIII, 78), it forms a selvage along a vein of galena, cutting normal sulphide type ore. Peculiar pyrrhotite (Pl. XI, 62), pseudomorphous after chlorite or biotite occurs between the sphalerite and galena. In late faults in wall rocks at Falconbridge it appears slightly later than marcasite which it in part encloses, and earlier than galena.

Stannite

To the writers' knowledge this is the first published report of stannite in the Sudbury ores, though earlier spectrographic recognition of tin in chalcopyrite, cubanite and galena suggested its possible presence. (Michener (1940) observed small grains, which he suspected were stannite, in galena-bismuth ores of Froid.) It is a common "minor constituent" of a number of polished sections examined but has so far only been detected in copper and lead-bismuth-rich ore from the Froid mine. The stannite can be detected only with the microscope, and occurs always as small, irregular particles of characteristic brownish-grey colour. Grain size is very irregular, varying up to a maximum diameter of about 0.1 mm. with an average of the order of 0.03–0.04 mm. Most of the material is optically anisotropic in shades of blue, grey-blue, to yellow-grey. Very occasionally fine lamellar twinning has developed.

The most frequent and intimate associate of the stannite is sphalerite, which in turn, as already noted, shows a distinct preference for chalcopyrite-rich patches of ore. Most frequently the stannite has developed as minute blebs within sphalerite, either randomly distributed or near the marginal portions of sphalerite grains. The outlines of some of these included stannite particles, and their arrangement, are much like the "drainage" textures developed by stannite in sphalerite from the Conrad mine, N.S.W., described by Edwards (1952). In other cases stannite and sphalerite now appear simply in contact, with smooth "mutual" boundaries. A very minor amount of stannite occurs, in precisely the same form as the sphalerite, as discrete flecks distributed irregularly here and there in the larger areas of chalcopyrite.

After sphalerite, the most frequent associate of stannite is minor pyrrhotite included in the chalcopyrite-rich material. The stannite occurs as rounded blebs here and there in pyrrhotite and along chalcopyrite-pyrrhotite boundaries. It also occurs in similar fashion within and adjacent to galena. Occasionally small composite particles of galena and stannite occur isolated in chalcopyrite or pyrrhotite, and in rare instances

stannite has been found forming incomplete rims to small galena particles. Other minerals with which stannite has been found in contact are cubanite, bornite, parkerite, tetradymite and pentlandite. It has not so far been observed as veins within other minerals, though it not infrequently occurs as particles within composite veins, the major part of which are composed of other more common minerals.

Violarite

This mineral though of rather limited development was first identified as polydymite as long ago as 1899. Samples of the steel-grey material associated with chalcopyrite from the Vermilion mine yielded on analysis a composition of Ni-43.18%, Fe-15.47%, S-41.35% from which the formula Ni_3FeS_5 was deduced. Later Short & Shannon (1930) re-examined the mineral (from both the Vermilion and Levack mines) and determined it as a member of the linnaeite family, with the formula $FeS.Ni_2S_3$, corresponding to violarite of Lindgren & Davy (1924). Its association with millerite was noted and it is possible the admixture of this mineral in the original material accounts for the high nickel content originally found. From their microscopic studies Short & Shannon came to the conclusion that the violarite was of hypogene origin, and emplacement earlier than quartz was suggested by the alignment of idiomorphic crystals of this mineral along cleavage cracks of violarite. Chalcopyrite was interpreted as replacing violarite; millerite, regarded as supergene, was considered an even later replacement.

More recently Michener & Yates (1944) restudied violarite-millerite specimens particularly from the Victor property, east range, and other gossans throughout the area and indicated clearly, as had other authors, that violarite was an intermediate product in the oxidation of pentlandite to violarite, millerite, and eventually iron oxides, a near surface alteration related to open faults but extending to considerable depths. They thus regarded both violarite and millerite as supergene.

They emphasize that violarite has never been found in primary ores where there is no sign of oxidation. At greater depths alteration of pyrrhotite-pentlandite ore is chiefly to secondary (nickeliferous) pyrite and marcasite, already described, but even in these violarite (and millerite), in both "compact crystalline aggregates" and a black earthy gouge-like matrix impregnated with violarite grains," is present along with unaltered primary chalcopyrite, sphalerite and galena. They suggest the violarite (and millerite) "was formed by solutions which carried the nickel in the form of soluble salts some distance before deposition." As they note, the origin of the violarite in such ores is more obscure than in near surface deposits and old drill core. Chemical reactions are suggested

by which the nickeliferous ores are converted to secondary nickeliferous pyrite, violarite or millerite, depending on proportions of iron and nickel sulphates and pH of the solutions. Local concentrations of sulphuric acid may account for the rapid destruction of violarite as evidenced in drill core and under near surface conditions, with limonite resulting as an end product. These seem reasonable, but it would be well if all such occurrences of disseminated secondary pyrite in pyrrhotite could be checked to see if it is always an intermediate product in the development of violarite and not an earlier development on which the violarite has been superimposed.

Only a small amount of violarite has been examined by the present authors, and this is closely associated with millerite and chalcopyrite. In some cases violarite quite clearly develops in pentlandite along cleavages, showing a pale violet tint in contrast to the yellow of pentlandite. In other cases, the alteration yields a pulverent black material which cannot be polished. It is only where the alteration of pentlandite is incomplete that the true relations of violarite which selectively replaces it, to chalcopyrite can be discerned. As noted earlier chalcopyrite is later than and replaces pentlandite and the same apparent relations hold for violarite and millerite pseudomorphs of pentlandite. From their textural relations millerite has been interpreted as somewhat later than violarite, but their intimate association and "fuzzy" contacts make the evidence of such age relations rather doubtful and it is probable that in places they may be essentially contemporaneous.

Marcasite

Marcasite is a relatively minor constituent of the Sudbury ores. It has at least three modes of occurrence, (1), as an alteration or replacement of normal nickeliferous pyrrhotite ore, giving the so-called "marcasite" ore, as at Falconbridge, East Mine, McKim, and also along the east range, and on a minor scale as an alteration of pyrrhotite along partings, (2), in offset deposits (Worthington and Milnet) where it seems intimately associated with nickeloan pyrite, and (3), as seams and nodular masses in late veins cutting normal sulphide ore or wall rocks, associated usually with nickel-poor pyrite, sphalerite, galena, calcite and quartz. The veins of type 3, are often present in or near the "marcasite ore."

Both nickeliferous and non-nickeliferous marcasites have been reported but tests show that even the latter contain minor amounts of nickel, down to 0.01 per cent. Coleman (1913) records nickeliferous marcasite from several deposits along the Worthington offset, analyses of which by Hillebrand confirmed T. L. Walker's earlier determination of 4.57 per cent nickel. The actual nickel content of marcasite in "marcasite" ore

is not known. Fine grained mixtures of such marcasite and secondary pyrite are reported by Michener & Yates (1944) to contain about 2 per cent, while Clarke (1946) obtained 3.75 per cent in a similar composite sample, but in neither case is it clear how much of this is in the marcasite and in the pyrite. The presence of nickel, however, in such occurrences is quite understandable. "Non-nickeliferous" or low-nickel marcasite, on the other hand, is confined chiefly to late gash veins, the amount of nickel no doubt varying with their proximity to primary ore. Marcasite replacing nickeliferous pyrrhotite of both breccia and more massive ores develops first as fine feathery forms along cracks and partings of the pyrrhotite. In many sections it appears to have inverted to pyrite and is now isotropic. Fine cube pyrite with a selvage of gangue is usually present in the same pyrrhotite grains (Pl. III, 14). Michener & Yates note that as the alteration increases with the complete destruction of the pyrrhotite, marcasite is present as blades in massive secondary pyrite, and in about equal amounts. Altered ores of this type are reported from depths of 1600 feet along fault zones. Clarke described similar material from a depth of 2800 feet at Falconbridge and informs us some extends to depths of over 4000 feet.

Marcasite in the Milnet deposit, associated with nickeloan pyrite is illustrated in Plate XIV, 80, where the two occur as very fine granular aggregates in which large numbers of primary magnetite particles are included, in a gangue of quartz and carbonate. Parallelism of isolated grains of marcasite in places, suggests a replacement origin as do ragged borders of some larger grains of (early?) pyrite and embayed borders of chalcopyrite. Bordering such aggregates are thin curving seams of fine nickeloan pyrite, followed inward by either quartz or carbonate, filling irregular vugs.

Marcasite in the late veins varies considerably. Where these cut massive ore at Murray, Coleman cites Walker as reporting good crystals of non-nickeliferous marcasite. In places, however, some such marcasite may give a good test for nickel while some contains only trace amounts. In crustified veins it occurs in nodular masses, $\frac{1}{2}$ inch or more in width, and is succeeded by non-nickeliferous pyrite and finally in the central parts of the vein, by carbonate and quartz. Where such veins contain sphalerite and galena these sulphides appear somewhat later than the marcasite as indicated by contained fragments and embayments. The coarser grained marcasite (up to 5 mm. or so in length) shows a radiating structure and both simple and lamellar twinning. Minor granular marcasite occurs along grain centres or margins, or is interstitial to the bladed type. Some radiating clusters of marcasite appear surrounded by gangue, and the whole enclosed in coarse sphalerite.

Partial analyses of low-nickel marcasites are given in Table 11. In these cobalt is also low but shows little relation to the nickel. Lead in all but one is in excess of nickel. These are in marked contrast to analyses mentioned above.

TABLE 11. PARTIAL ANALYSES OF MARCASITE

No.	Locality	% Ni	% Co	% Pb	Remarks
1	(Fa 23) Falconbridge	0.078	0.004	0.155	
	(Fa 25) Falconbridge	0.067	0.018	0.125	800' Level vug
3	(Fa 26) Falconbridge	0.110	0.007	0.090	
4	(Fa 29) Falconbridge	0.026	0.011	0.113	
5	(Fa 37) Falconbridge	0.009	<0.003	0.040	Fract. filling
6	(K 8) McKim	0.052	0.027	0.103	Vug filling

Marcasite is thus either a secondary mineral formed chiefly at the expense of pyrrhotite, either alone or intergrown with secondary pyrite, or a vein mineral associated with sphalerite and galena. In offsets its occurrence with pink nickel-rich pyrite and gangue minerals suggests both are related but conditions giving rise to the latter are not known. Development of secondary "marcasite" ore has occurred to great depths in the vicinity of fault zones and its apparent gradation to ores carrying typically supergene violarite and millerite may indicate it too is supergene as noted by Michener & Yates. The great depth to which such alterations extend and their association with marcasite-bearing sphalerite-galena veins, formed in a later Precambrian epoch, raises the question as to whether all such marcasite is supergene or in part hypogene and of a "secondary hydrothermal" character as is suggested by the mineralogy of the veins and their widespread character.

Millerite

This mineral, always regarded as a secondary, supergene mineral at Sudbury, is first referred to by Barlow (1904) who noted its occurrence on the 150' level of the Copper Cliff mine and considered it a replacement of pentlandite. Short & Shannon (1930) describe millerite in close association with violarite from the Vermilion mine and illustrate another example from Levack. The violarite they considered to be earlier than associated chalcopyrite, and hence hypogene, whereas the millerite, apparently formed along cracks in the violarite and at its expense, was considered supergene. More recently Michener & Yates (1944), in discussing the oxidation of primary nickel sulphides at Sudbury confirm the alteration of pentlandite to violarite and the replacement of violarite by millerite which they suggest is "an intermediate stage of iron re-

moval" in the eventual oxidation of violarite over to limonite. Both violarite and millerite are thus regarded as supergene.

During the present study millerite has been encountered with violarite in several specimens from unknown Sudbury localities and in some from the Frood mine. It is a pale cream and very similar to pentlandite in colour, and shows strong characteristic double refraction. Interference colours range from straw or lemon yellow to a pronounced iris blue and violet. Most of it shows a mosaic and concretionary arrangement, and like violarite is entirely developed in areas of former pentlandite. As well illustrated by Short & Shannon it forms thin rims about violarite with sharp contacts against chalcopyrite but "fuzzy" contacts with violarite. Zones of millerite lie within areas of violarite with suggestions of a linear arrangement, but in places curving and concretionary. Along thin cracks containing gangue, millerite is not always adjacent to these as illustrated by Short & Shannon but is separated in places from them by a thin rim of violarite. The ragged or fuzzy character of the contacts between millerite and violarite does not give very convincing evidence of exact age relations, but the writers agree that both are supergene and are formed selectively at the expense of pentlandite.

Hematite

Only a very minor occurrence of this mineral is known in the Sudbury ores except such as may be present in the limonitic gossans. In a specimen of coarse grained dolomite, reported from the Frood mine, thin plates of specular hematite are present along cleavages. It contains traces of titanium but insufficient to confuse it with ilmenite. Its association would suggest that not all the carbonates are of rather low intensity type of mineralization, but not enough is known about it to allow any other inference as to its source.

(c) MINERALS OF THE PRECIOUS METALS AND THEIR ASSOCIATES

Minerals of the precious metals include one of platinum, sperrylite, possibly three of palladium, michenerite, froodite, and a third unidentified species; gold or electrum, native silver, the silver telluride, hessite; and bismuth-bearing schapbachite. No individual species containing the other platinum group metals, rhodium, iridium, ruthenium or osmium, in appreciable quantity have been identified. As discussed in a later section these are present to some extent in solid solution in other minerals. Associated minerals include galena, parkerite, native bismuth, bismuthinite, and the telluride, tetradymite. Chalcopyrite might well be added to this list because of the frequent occurrence of sperrylite within it. The

association of palladium, bismuth and in places gold with the arsenides, gersdorffite, niccolite and maucherite has already been noted.

Sperrylite

Sperrylite has long been known to be the only important mineral of platinum of the Sudbury ores, though some spectrographic evidence suggests that a part of the platinum as well as the platinoids may be present in solid solution in the common sulphides or, if in the form of discrete mineral particles, of such fineness as to be unidentifiable.

The mineral was first found in the gossan of the Vermilion mine along with some cassiterite, and was first described and named by Wells (1889) and Penfield (1889). Analyses of this material proved it to be the diarsenide of platinum with only a trace of palladium, but with 0.5 to 0.75 per cent rhodium and it has been suggested as the principal source mineral of rhodium. Nicol & Goldschmidt (1903) gave a detailed crystallographic description of the Vermilion sperrylite, some crystals showing a wide variety of isometric forms, but chiefly cubes, pyritohedra and octahedra.

In specimens available to us its principal occurrence is in chalcopyrite-rich ores from relatively few mines. At the Froid, as described by Michener, it is commonly embedded in coarse-grained massive chalcopyrite, (Pl. IV, 20) in which it can often be discerned megascopically as bright silver cubic to octahedral crystals with edges generally in the 0.5–2.0 mm. range. Much of it, however, occurs in pyrrhotite-pentlandite ore (Pl. IV, 19), within coarse pentlandite (Pl. IV, 21), and there is a common association, at the Froid mine, of sperrylite with the nickel arsenide zones about the margins of some ore bodies and massive mixed sulphides on the lower levels. It has also been reported in footwall rocks at Froid.

In polished section the mineral shows up strikingly by virtue of its hardness, whiteness and high reflectivity. It readily takes a brilliant scratch-free polish and, if cloth laps are used, it immediately stands above the surrounding softer sulphides. Some crystal faces are usually developed, and the majority of sperrylite particles are completely bounded in section by beautiful developed, sharp faces. Where such faces are not shown the boundaries are usually smoothly curving, and have the appearance of having been corroded, similar to that of some of the larger magnetite particles already mentioned. The sperrylite shows very slight anisotropism, but no zoning or twinning and only occasional mechanical deformation. Many of the grains observed are close to 1.0 mm. in diameter; some up to 5.0 mm. across have been seen and are reported by Michener (1940).

Although the major part of the sperrylite is enclosed in chalcopyrite or pyrrhotite, it has also been found in contact with pentlandite, cubanite, galena, sphalerite, and stannite. All appear to be moulded about it. Rounded corners and smooth embayments suggest replacement by the sulphides. Where obviously fractured (Pl. IV, 20) chalcopyrite forms the cement binding the particles together.

At least half of the sperrylite observed has been found to contain inclusions of other sulphides. These are most commonly chalcopyrite and pyrrhotite which occur as rounded blebs, frequently composite, up to about 0.1 mm. across. Small irregular inclusions of sphalerite have also been noted, and in addition Michener (1940) has observed the inclusion of palladium minerals, gold, and hessite. The association with cassiterite in the gossan of Vermilion mine has not been checked, but it seems possible the latter may have resulted from oxidation of stannite, now known to occur in these ores.

Palladium Bismuthides: Michenerite, Froodite and Mineral C.

The problem of the manner of occurrence of palladium in the Sudbury ores has long been recognized. Owing to its general fine dispersal, and the softness, non-descript appearance and solubility in ordinary acids of palladium compounds, no definite species had actually been isolated until C. E. Michener carried out his investigation in 1939. With his co-operation two palladium bismuthides in these ores have been recently named michenerite and froodite (Hawley & Berry, 1958). A third compound of palladium and bismuth, Mineral C, indicated only by spectrographic evidence, has been observed by the junior author during the present study. All occur with other precious metals associated with nickel arsenides and copper-lead rich ores in the siliceous mineral zone of the lower levels of the Frood mine.

(i) *Michenerite*— PdBi_2 (?). This mineral was separated by Michener from a fine precious metal mill-concentrate. It has also been identified tentatively in small composite particles with hessite, enclosed in massive maucherite (Pl. XIII, 77), and lies along a grain boundary.

As noted by Michener, the mineral is greyish white in colour, has a dull metallic lustre, black streak, with no visible cleavage. It is brittle, has a hardness of *B*, and a specific gravity between sperrylite and galena, probably about 9.5.

Chemical analysis by Michener on three samples gave an apparent ratio of $\text{Pd}:\text{Bi} = 2:3$ and *x*-ray powder data showed it could be indexed on a cubic lattice with a cell dimension of 6.68 Å, and is similar to gersdorffite-ullmanite. Hawley & Berry (1958) however, on the basis of its similarity to the low temperature $\alpha\text{-PtBi}_2$ (Wallbaum, 1943 and

Groeneveld Meijer, 1954) and to aurostibite, AuSb_2 (Graham & Kaiman 1953), suggest its composition is more probably PdBi_2 , although the possibility is recognized that the structure may be deficient in bismuth and hence might approach the composition Pd_2Bi_3 .

Under the microscope it is quite isotropic. Etch reactions are: HNO_3 , effervescence slow, blackens; FeCl_3 , slowly stains dark, some negative; aqua regia, instantly stains black; HCl , KCN , KOH , all negative.

Insufficient evidence is available to allow any statement as to its position in the paragenetic sequence. Of the palladium minerals it is believed the most common.

(ii) *Froodite*. This was found by Michener as flat cleavage fragments and rounded grains in mill-concentrates, but has not been identified by the writers in any polished sections of the Sudbury ores. The mineral is named after the Frood mine, the only locality in which it has been found.

According to Michener it has the following properties: Colour grey, streak-black, lustre-metallic, splendent on fresh cleavage, tarnishes quickly; fracture-uneven, brittle; hardness—2.5; specific gravity—12.65, 12.5 (by G. A. Harcourt). *X*-ray studies as reviewed by Hawley & Berry, indicate it is monoclinic, cleavage, (001) very perfect, (100) less perfect; $a = 5.71$, $b = 4.29$, $c = 6.37$, $\beta = 102^\circ 27'$; $a:b:c = 1.33:1:1.49$.

Comparison of *x*-ray powder data on froodite with that on α - PdBi_2 , prepared by Burr & Peacock (1942) shows there is no doubt that the two are the same. Analyses by Michener however yielded a ratio of $\text{Pd}:\text{Bi}$ close to 1:3 and the discrepancy between this and PdBi_2 must somehow be accounted for. As noted later, native bismuth is also a constituent of such ores and what is taken to be a third palladium compound, but of unknown composition, has also been recognized. The presence of either of these might account for the apparent difference.

Etch reactions, after Michener, are HNO_3 —effervescence slow, turns brown with production of granular surface; KCN —slowly stains dark; FeCl_3 —instantly stains black; HCl , KOH , HgCl_2 —all negative. Synthetic α - PdBi_2 differs slightly in giving, according to Burr & Peacock, a faint brown stain to negative with KCN , and a brown to iridescent stain with FeCl_3 which also brings out grain structure and lamellar twinning. Our own results on the same material show KCN negative, only a brown stain with FeCl_3 , and a faint brown stain to negative with concentrated HCl .

(iii) *Mineral C—palladium bismuth mineral*. This has been detected only in sections cut from one particular specimen of nickel arsenide-rich ore from the Garson Mine. This specimen is composed largely of the niccolite-maucherite-chalcopyrite intergrowths already described, to-

gether with gersdorffite and some very subordinate pyrrhotite, pentlandite and magnetite.

Using high magnification and oil immersion the mineral can be seen as abundant rounded and droplet-shaped blebs in the larger areas of niccolite, to which it seems to be confined. For the most part the blebs are randomly distributed but here and there groups of five or six, of more elongated shape, show sub-parallel orientation. Particle size is generally in the 0.01–0.02 mm. range, with a maximum of about 0.04 mm.

The mineral is white with a very faint cream tint. When viewed near gersdorffite it is far whiter than the latter, contrasting with the bluish white of the gersdorffite and having a much higher reflectivity. Under oil immersion no reflection pleochroism can be detected but anisotropism is marked with well-defined and consistent pink to blue-grey interference colours. The mineral is harder than niccolite or gersdorffite and takes an excellent polish. Etching could, of course, only be carried out in the presence of other minerals, but gave the following results: HNO_3 (conc.)—blackened most particles but negative in some cases; HgCl_2 —light brown stain which rubbed off readily leaving no sign of an etch; HCl , KCN , FeCl_3 , KOH —all negative.

Comparison of mineral C with synthetic froodite and PdBi_2 (prepared by Burr & Peacock) showed the two to be dissimilar. As far as could be determined their colours are essentially the same, but interference colours clearly differ; those of the PdBi_2 are shades of yellowish brown and grey, compared with pink to blue-grey of mineral C.

Etch reactions of mineral C differ from those of michenerite, froodite and artificial $\alpha\text{-PdBi}_2$ chiefly in lack of observed effervescence with HNO_3 and a negative reaction with FeCl_3 which stains all the others. It thus is clearly not the same as any of these.

In addition, mineral C and $\alpha\text{-PdBi}_2$ show different hardnesses. In a section containing both synthetic $\alpha\text{-PdBi}_2$ and natural niccolite mounted adjacent to it, niccolite is clearly the harder of the two, whereas, as already mentioned, mineral C is harder than niccolite.

That the mineral in question is a palladium bismuthide is suggested by some of the similar etch reactions and by analyses of samples of this particular material which gave over 7 oz. palladium per ton and indicated the presence of bismuth (Hawley, Lewis & Wark, 1951). Unfortunately no material of sufficient size for concentration and analysis has been found.

Native Gold (Electrum)

Native gold has been detected in only a few polished sections, (Frood) though in some it is quite an abundant minor constituent. It occurs

typically as irregularly shaped, rounded particles, scattered through the sulphides. Average grain size is in the 0.05–0.03 mm. diameter range, with a maximum of about 0.15–0.20 mm. Relative grain size is fairly even.

There is no doubt, from its pale yellow colour, that fair quantities of silver are alloyed with the gold, and that the mineral is actually an electrum. Bulk analyses of this by Michener have shown 60% Au, with spectrographic traces of palladium and iridium in the more gold-rich material.

The major part of the gold seems to be either enclosed in chalcopyrite, or more generally lies at the margin of this, rather than within the body of any chalcopyrite particle (Pl. XII, 70). It is found similarly with galena and along the contact of galena and chalcopyrite (Pl. XIII, 73) and, very occasionally, within bornite, pyrrhotite and gersdorffite. No other mineral has been found to act as host, though gold has been found in contact with magnetite, parkerite, (both of which tend to show sharp faces against the gold) sphalerite, niccolite, tetradymite and hessite. None has been found as veins in any of the sulphides, but Michener (1940), reports that it occurs most abundantly in small fractures in the contact rocks, adjoining the siliceous mineral zone at Frood, and as plating on secondary hornblende, and that it seems to have selected the silicates as a host to a greater extent than the sulphide minerals.

Native Silver

Native silver has been found in both galena-parkerite-rich ore and also in bornite-bearing ore from the lower levels of the Frood Mine. As shown (Pl. XII, 69) it appears to replace part of a galena cube and bornite which forms a rim next to surrounding chalcopyrite. In bornite ore it occurs chiefly as veinlets, (Pl. XIII, 74, 75) which are usually quite long and continuous, up to a centimetre or so in length and 0.10 to 0.05 mm. in width. These form borders to, or less commonly cut through, the copper sulphides, and are occasionally isolated in gangue.

Where silver rims or cuts through areas of chalcopyrite-bornite, it is invariably separated from the chalcopyrite by a thin zone of bornite. This and the fact that where silver veins run parallel to, but not quite in contact with the chalcopyrite, the latter shows no border zones of bornite, suggest that the emplacement of the silver was distinctly later than that of the sulphides and that the solutions carrying it were capable of changing the earlier chalcopyrite to bornite. In one or two cases the silver has been found as irregular particles rather than veinlets (Pl. XIII, 76), but here again it occurs in bornite rich ores, and the relationship between chalcopyrite-bornite and the silver remain the same.

Hessite

Hessite is a not uncommon mineral constituent of lead-rich ores (Frood) and has also been detected with massive maucherite. It is only found as irregular grains of up to about 0.2 mm. across, averaging about 0.05 mm. With the common background of galena it has a faint brown tint, with only the faintest reflection pleochroism. It shows strong and characteristic double refraction in shades of blue, orange, and golden brown with the typical patchy and "shredded" extinction beautifully developed. Very occasional lamellar twinning has also been noted. Some particles show quite a good cleavage, and the mineral is distinctly softer than galena. In view of its small particle size and its general occurrence with galena, all etch tests have had to be carried out in contact with the latter. HNO_3 produces very slight effervescence, with no stain; HCl (1:5) slowly stains black; KCN slowly stains black; FeCl_3 stains iridescent; HgCl_2 stains only a very light brown, and KOH is negative.

The hessite generally occurs as irregularly shaped rounded (as distinct from ragged and sharply angular) blebs here and there in the galena. It is often closely associated with the tetradymite within the galena, the two tellurides forming small composite particles, or, in some cases, the tetradymite forms sharply defined blades cutting across, and terminating at the boundaries of the hessite or is partly enclosed in it. Hessite also occurs quite frequently moulding itself around parkerite (Pl. XII, 70), though it has not been seen included within the latter. Where it occurs in massive maucherite (Pl. XIII, 77), the hessite generally shows highly irregular, somewhat cusped boundaries, in contrast to the rounded ones developed against galena. This, when a crossed nicols examination is made, is clearly due to the localization of the hessite along maucherite grain boundaries. It is only in association with this interstitial hessite in massive maucherite that michenerite has so far been found by the writers. Hessite is also found in smoothly rounded grains intergrown with chalcopyrite, bornite, magnetite and quartz. As noted under bornite, a rim of this mineral has been noted partly surrounding hessite, etching the hessite slightly and enclosing a small fragment in optical continuity with the central grain. It is thus probably earlier than bornite and slightly later than parkerite, but with tetradymite and parkerite, is closely related in age with galena. The secondary character of much bornite after chalcopyrite near silver veinlets has already been noted. Some bornite in association with hessite may likewise be of secondary development, but hessite occurs next to chalcopyrite without any bornite.

Mineral B—Schapbachite (?) ($\text{Ag}_3\text{S}\cdot\text{Bi}_2\text{S}_3$)

Only one particle of this mineral, approximately 0.2×0.1 mm., has been detected with many of the other less common minerals in the

copper-rich ore of the deeper levels of the Frood mine. The particle observed was enclosed in galena, from which it was almost indistinguishable in ordinary light. It shows only the faintest reflection pleochroism (less than is normal for the mineral) but quite strong anisotropism—the feature by which it was initially distinguished from the galena. On close examination the schapbachite (?) appears to have a slightly better polish than the surrounding galena, though because of the very similar colour, hardness and reflectivity it is extremely difficult to “draw a line between” the two in ordinary light. No typical interference colours are visible, which is normal, but the absence of lamellar twinning must be regarded as unusual.

Owing to its small particle size, and to its being completely enclosed by other minerals, really satisfactory etch tests could not be carried out. Standard reagents gave the following reactions, however, HNO_3 (1.1), slowly stained brown; HCl , slightly differential brown staining proceeding in parts from edge of particle; KCN , FeCl_3 , KOH , HgCl_2 , all negative. The negative FeCl_3 etch appears anomalous though this may have been due to the surrounding minerals.

The particle examined, although entirely within galena, lay in contact with parkerite and native bismuth. With galena it showed mutual boundaries; parkerite appeared to show some development of sharp crystal edges against it, and the native bismuth, as far as could be seen, simply showed a mutual boundary relationship.

As noted by Uytendogaardt (1951) Ramdohr gave the name schapbachite priority over matildite.

Galena

Galena occurs as a very minor constituent of the normal massive and breccia type copper-nickel ores, chiefly as irregular minute flecks in chalcopyrite. It is not an uncommon constituent of the siliceous mineral zone at the Frood deposit where it is quite an important host of precious metal minerals and is of significance mineralogically for its close association with parkerite, hessite, and tetradymite. Here it is in intimate association with chalcopyrite, pyrrhotite and pentlandite, but is rarely intergrown with sphalerite. In contrast, a quite different mode of occurrence of galena is in late fracture-fillings, cutting massive normal ore and wall rocks where it is always associated with sphalerite, minor late pyrrhotite, and, in places, with marcasite and secondary pyrite, and is quite devoid of precious metals with the exception of traces of silver.

In the normal copper-nickel ores it is probably a relatively late mineral to crystallize along with chalcopyrite and rare sphalerite but no precise age relations can be discerned. In the siliceous ores of the Frood it is associated chiefly with chalcopyrite and pyrrhotite and occurs as stringers

in siliceous gangue. Particle size ranges up to at least a centimeter across, with an average of about 1 mm. in largest dimension. In chalcopyrite it occurs occasionally as partially developed cubic crystals (Pl. XII, 69), or as rounded grains within and at the border of chalcopyrite with gangue. In places bornite has developed in the chalcopyrite at the border with galena or with gangue. In other places galena very clearly corrodes chalcopyrite and thus is at least in part later than it in time of deposition. It also replaces and moulds itself around other earlier minerals such as magnetite, pyrite, sperrylite, pyrrhotite, pentlandite and even cubanite. It has essentially mutual relations with very rare sphalerite and stannite, though very occasionally it has been found including a little stannite. In places sphalerite and stannite locally rim galena and thus overlap it in time of deposition. The association of parkerite with this type of galena is very conspicuous as noted by Michener & Peacock (1943). Much of the parkerite is present within and at the borders of galena, as rounded grains (Pl. XII, 70) though galena has never been found forming veins in it. Both hessite and tetradymite though also occurring outside galena, are chiefly contained within it with round mutual boundaries. In one instance, native silver had been found replacing bornite and a grain of galena which is partially surrounded by chalcopyrite (Pl. XII, 69). In another section gold (electrum) appears moulded about a sharp edge of galena and between it and chalcopyrite (Pl. XIII, 73). Galena is also the only host for the rare mineral B, believed to be schapbachite. As noted above (p. 84) it also contains odd grains of bornite.

Galena in late veins cutting massive ore (Pl. XIII, 78) and in wall rocks contrasts sharply with the granular type described, in form, association and trace element assemblage. It is usually coarse, with vein widths up to 2–3 cm., and in places good crystal terminations have developed in open spaces. Gangue filling of some such veins, as at Falconbridge (Clarke 1946), is of quartz and carbonate and the composite veins may attain widths up to 5 cm.

In a galena-sphalerite vein cutting massive ore (Pl. XIII, 78), a selvage of sphalerite with some sharply terminated crystals projecting inward, lies next to the walls and in places is followed by the peculiar type of pyrrhotite which appears pseudomorphous after bent chlorite or biotite (Pl. XI, 62). Both sphalerite and pyrrhotite may be included in the galena, often with frayed boundaries suggesting some replacement. Clarke reports that in late veins at Falconbridge with which marcasite is also found, galena is commonly along the borders and sphalerite within. The order of deposition appears to have been marcasite, galena, sphalerite, quartz and carbonate.

Qualitative spectrographic analysis of galena from the two main types of occurrences are given in Table 12, and show very sharp differences

TABLE 12. QUALITATIVE SPECTROGRAPHIC ANALYSES OF GALENA

Elements:	Galena intergrown with sulphides				Late vein galena			
	Frood-1	Frood-7	Frood-8	Garson-3	Vein in Sulph.-2 in Carb.-4		Fbg-5	Creighton-6
As	S	—	—	—	—	—	—	—
Sb	W	—	—	M	M	Tr	S	—
Bi	E	E	E	—	VFTTr	—	—	—
Cd	S	—	—	S	M	Tr	—	Tr
Co	S	Tr	—	—	—	—	VS	—
Cr	—	M	S	—	—	—	W	—
Cu	VS	S	S	S	M	M	VS	W
In	—	—	—	—	—	—	S	—
Mo	—	—	—	—	—	—	Tr	—
Ni	S	S	M	—	M	—	VS	FTr
Au	Wtr	—	—	—	—	—	—	—
Ag	VS	E	E	VS	VS	W	VS	Tr
Pt	VS	VS	FTr	—	—	—	—	—
Pd	S	—	S	—	—	—	—	—
Te	S	S	S	—	—	—	—	—
Sn	VS	VS	S	—	VFTTr	—	—	—
Zn	W	—	—	—	M	—	VS	W
V	—	S	S	—	—	—	—	—

Symbols: E—extreme, VS—very strong, S—strong, M—medium, W—weak, Tr—trace, FTr—faint trace, VFTTr—very faint trace, Fbg. = Falconbridge, — = not detected.

indeed, though it must be recognized that these undoubtedly reflect mineral impurities rather than elements contained in the actual galena structure. Inclusions of hessite, tetradymite, and parkerite in galena intergrown with sulphides are for the most part so fine that they could not possibly be removed from it. Samples 1, 7, and 8 are of this type. These show bismuth (extreme), copper, nickel, platinum, silver, tellurium, and tin in all three, palladium in two, and gold in one. Silver is very strong to extreme but is also present in the late veins types represented by samples 2, to 6. Of these No. 2 is from the specimen illustrated in (Pl. XIII, 78); No. 3 (Garson) is associated with carbonates as is No. 4 from an unknown locality, and Nos. 5 and 6 are reported from Falconbridge and Creighton, respectively. No. 5 appears to have been contaminated somewhat with Co, Cu and Ni. All of these can be seen to be lacking in the precious metals (except silver), bismuth and tellurium and tin.

Parkerite

The properties of parkerite at Sudbury have been described in detail by Michener & Peacock (1943) in their paper on the re-definition of the species, following its initial recognition by Scholtz (1936) in the Insizwa ores. Only a brief description was given of its occurrence at Sudbury, although Michener (1940) describes it in more detail in his thesis.

The parkerite is readily recognized by the properties given by Michener & Peacock, particularly by its pale cream colour and by its striking lamellar twinning (Pl. XII, 70) revealed both by pleochroism and double refraction. Michener reports that cleavage fragments and grains, concentrated from galena-rich ores by means of a superpanner and a flotation cell, show orthorhombic symmetry. They are often elongated and striated, with prismatic cleavage. The mineral has a bronze colour on a fresh surface, tarnishing darker.

Its occurrence in the Sudbury ores is principally as irregular, equidimensional, rounded, and subhedral particles up to 3.0 mm. or so, in largest dimension; particle size is highly irregular with an approximate mean of about 0.1–0.2 mm. A less common occurrence is as veinlets or stringers up to about 2.0–3.0 mm. long and 0.1–0.2 mm. wide, near the contacts of massive ores. Most of the parkerite occurs within galena—a striking and persistent relationship. Within the galena it is also associated with hessite, tetradyomite, native bismuth, less commonly native gold, and occasionally with bismuthinite (?) In one case it has been found in contact with schapbachite, in turn within galena. A further notable feature of the occurrence of parkerite is its association with native bismuth and pyrrhotite in some of the galena-pyrrhotite-rich patches and also in rare bornite both in the siliceous mineral zone of the Froid (Pl. XII, 71, 72). In such cases the pyrrhotite frequently appears to have been attacked by the bismuth, which in turn often contains one or a number of particles of parkerite. In some instances such parkerite is enclosed, with just a ragged rim of native bismuth, in the pyrrhotite and a similar association of parkerite and native bismuth has been noted with the bornite. It is perhaps significant that in such parkerite-rich specimens pentlandite is seldom if ever present.

Tetradyomite

This has been detected by the writers principally in non-vein galena in which it is often closely associated with hessite. Michener noted three mineral associations.

- (1) as small grains in non-magnetic pyrrhotite
- (2) as an impure intergrowth with native bismuth in the galena-Ni-Bi-S type of mineralization.

(3) as small grains in galena. The last is by far the most common in our specimens and it is in fact quite a striking feature that it seldom occurs outside galena, and that almost every particle of galena (excluding that of the late-stage veins), if examined under sufficiently high magnification, contains at least a few small specks of it. A fourth association illustrated in Plate XII, 70, is as an inclusion in hessite.

Because of its fineness, and its intimate association with galena and hessite, it was not possible to collect sufficient suitable material for analysis. Although the general formula is $\text{Bi}_2\text{Te}_2\text{S}$, x -ray powder patterns obtained by Michener (1940) indicated higher tellurium and lower sulphur, and proximity to the variety wehrlite, Bi_2Te_3 . Spacings of the three strongest lines (cobalt radiation) obtained by Michener were (1) 3.24, (2) 2.36, (3) 2.21.

The mineral occurs as irregular and irregularly rounded flecks—as isolated individuals or as small groups of two or three. Maximum particle size is of the order of 0.05 mm. diameter, with a mean of the order of 0.01–0.03 mm. It is readily distinguished from its galena host by its very slightly creamy white colour, which is in sharp contrast with that of galena, and its high reflectivity. It shows no reflection pleochroism, but moderate double refraction with interference colours varying from pale pink to pale blue. Occasionally a very small lamellar twin occurs. Etch tests have had to be carried out always in contact with galena; reactions are: HNO_3 , 1:1, negative; conc., blackens; FeCl_3 ; stains brown to iridescent; KCN , HCl , KOH , HgCl_2 , all negative. Unfortunately no particles large enough for excavation could be found so that it has not been possible to make a positive identification by x -ray methods. Spectrographic determinations (carried out on five samples of galena enclosing substantial quantities of tetradymite) showed high bismuth and tellurium, but in view of the common occurrence of parkerite and hessite in the galena this is not of much significance.

Apart from galena the principal associates of tetradymite are hessite and parkerite—particularly the former. At least 10 per cent of all the tetradymite forms composite particles with hessite within the galena, and where they do not actually contact they are frequently in close proximity. In some cases all three of tetradymite, hessite and parkerite are grouped as composite particles, the tetradymite showing up distinctly whiter than the other two. The tetradymite may also be associated with native bismuth and with parkerite, within larger areas of galena.

Native Bismuth

Native bismuth is confined almost entirely to ores rich in galena (and pyrrhotite) or with parkerite and bornite, as at Frood. It is readily identified by its colour, double refraction and particularly by its softness and tarnish. Although it is only a minor constituent of the ores, it is noticeable that where it does appear it is quite common. It never shows any suggestion of sharp outlines and occurs simply as irregular particles or, most frequently, as irregular, ill-defined areas up to about 0.75 mm. across, intimately intergrown with pyrrhotite or galena and, occasionally,

with pentlandite, chalcopyrite and bornite. As noted elsewhere, its most consistent associate is parkerite, about which it frequently forms a rim (Pl. XII, 71, 72). Other minerals with which the native bismuth has been found are bismuthinite (?), schapbachite, and gold.

Mineral A—bismuthinite (?)

This occurs as a very rare constituent in some of the galena-rich ores. It has, so far, only been found within the galena, where it may form particles up to about 0.15 mm. largest dimension. The colour and reflectivity of the bismuthinite (?) are very similar to that of galena though it shows distinct reflection pleochroism from a creamy to a bluish white. Double refraction is strong—from slate grey to pinkish grey. Etch tests with HNO₃, HCl, KCN, FeCl₃, KOH and HgCl₂, although carried out in the presence of other minerals, gave the standard reactions. Little can be said concerning textural relationships. The mineral occurs simply as irregularly shaped particles (never as veins) and shows mutual boundaries with its host, galena, and with hessite which may accompany it. Where it has been seen in contact with parkerite, the bismuthinite (?) like native bismuth, tends to mould around crystal faces of parkerite.

(d) MINERAL SPECIES REPORTED BUT NOT CONFIRMED

In the early studies of the Sudbury ores a number of minerals have been reported from near surface deposits which we have been unable to confirm although we have no reason to question their identity. These include chalcocite, molybdenite, tetrahedrite, smaltite, danaite, native copper, graphite and cassiterite.

Chalcocite was reported by Barlow (1904) and later by Coleman (1913) from the Vermilion mine, along with bornite, but was not found in fresh workings in 1910. He suggests it was probably secondary and supergene from the weathering of chalcopyrite.

Molybdenite is recorded as occurring only in the Worthington offset by Coleman (1913 p. 27) but details of its association are lacking.

Tetrahedrite is noted as present in the ores of the Denison mine on the Worthington offset by Ellis Thomson (1938) where it is associated with pentlandite, silver, nickeliferous pyrite and chalcopyrite. In some specimens from the Frood we have noticed minute flecks of light grey mineral resembling tetrahedrite, but amounts are too small for positive identification. Antimony is a rare constituent of the Sudbury ore minerals and has been detected chiefly in the arsenides by spectrographic analyses.

Smaltite—Barlow (1904) records that E. B. Kenrick (1886) identified smaltite “in the form of minute octahedral crystals, with well marked octahedral cleavage (?) in association with chalcopyrite, from the town-

ship of McKim." It is possible that the material so identified was really gersdorffite, a not uncommon mineral in the ores.

Danaite—cobaltiferous arsenopyrite. This mineral is noted by Barlow (1904) as occurring in the north half of lot 6, con. III, Graham township on the Russel property. It was present in massive form along with quartz, pyrrhotite and a little galena and chalcopyrite. An analysis gave about 4 per cent cobalt, and appeared to confirm the species. It is also reported in considerable quantity from the old Century Copper Mine, N $\frac{1}{2}$ lot 4, con. IV Graham township "in intimate association with pyrrhotite, chalcopyrite and pyrite," disseminated in hornblende and biotite schists. These localities lie south of the Gertrude mine and south of the Creighton granite. They are thus 2 to 3 miles away from the norite contact.

Native Copper was reported by Barlow (1904) and also by Coleman (1913) was found in dendritic leaf-like form both at the Vermilion mine and on the 12th level of the Copper Cliff mine. In both cases it was considered a secondary product from the oxidation of chalcopyrite.

Graphite. A few flakes of graphite were reported by Coleman (1913) in country rock from the Lady McDonald mine.

Cassiterite was identified by Penfield and Wells, as reported by Coleman (1913) in concentrates of sperrylite from samples from the Vermilion mine. In view of the occurrence of primary stannite in some of the ores along with sphalerite and chalcopyrite, it is possible that some cassiterite, if not primary also, was formed by oxidation of stannite.

2. NON-METALLIC MINERALS

Non-metallic minerals associated with the Sudbury ores, on the whole are not of major quantitative importance, but none the less are at least of local significance and probably merit far more study than has yet been given them. The account given here is largely a review of available literature and private reports and such incidental studies we have been able to make on rather random specimens. They may be conveniently classed as (a) Gangue, inclusions and products of wall rock alteration and (b) Secondary oxidized supergene minerals developed in gossans. The first group obviously bear on the character of fluids which either preceded, accompanied or followed ore deposition, but the second is only of passing interest in such a severely glaciated area.

(a) GANGUE MINERALS, INCLUSIONS AND PRODUCTS OF WALL ROCK ALTERATION

Non-metallic minerals in the ore deposits vary greatly in quantities and character with type of ore. In both the disseminated and breccia-type ores they may attain very high proportions. In the former they consist

of quartz diorite, norite, and the silicates in these, such as pyroxenes, various amphiboles, epidote, feldspars, quartz and others. In the latter the enclosed rock fragments include fragments of various rock types bordering the irruptive and fine particles of their individual minerals. Other, epigenetic, non-metallic minerals in many of the deposits are notable by their absence, or relative scarcity, but in some, such as offset deposits at Worthington, Milnet and Froid, and in the marginal deposits at Garson, Falconbridge and occasionally elsewhere, quartz and carbonates appear in greater than average quantities—at least in certain portions of the deposits. Outstanding in this respect is the siliceous mineral zone in the lower levels of the Froid (Zurbrigg, 1957), the more than normal degree of (carbonate) alteration noted at the Garson (Yates, 1948) and the “jasperoid” and carbonates associated with hanging wall ore pods at Falconbridge (Lochhead, 1955).

In addition to varieties of quartz and carbonates, (pink calcite, and rare dolomite and siderite), other non-metallics noted as either developed within the ore or as distinct wall-rock alterations, consist particularly of brown biotite, a bluish to black amphibole (hastingsite), tremolite, actinolite, sericite, chlorite(s), rare talc, and garnets, (pink and red). Michener (1940) also reports in addition to the above at Froid, minor apatite, fluorite, zircon, titanite and prehnite. What has been considered by more than one author to be a rather widespread type of alteration is the development of quartz-diorite, consisting essentially of hornblende, oligoclase-andesine quartz and biotite, from the more mafic norite, as well as the alteration of pyroxene to amphibole, and development of quartz-rich and biotite-rich phases of the norite.

Descriptions of occurrences of quartz and carbonates particularly indicate their relations to the main sulphide mineralization are variable and confusing. Some appear to have preceded the main sulphides, (jasperoid and quartz fragments in both massive and breccia ore). Some, possibly a minor amount, are clearly associated with a late mineralization in fractures cross-cutting massive sulphides, associated in places with low temperature marcasite, sphalerite and galena. Still other occurrences appear more intimately related to the time of deposition of the main sulphides and in places seem pre-chalcopyrite in age. Such are found in offset deposits, and with some marginal ores as illustrated by Knight (1923) and Phemister (1925). Altogether, however, the latter form a very small proportion of the ores as a whole, and while they would not be expected in liquid sulphides segregated as immiscible liquids from a basic magma, they conceivably may have developed from adjacent wall rocks by the thermal effects of such hot liquids on any hydrous silicates, as is suggested by the “siliceous mineral zone” at the base of the great Froid

ore body. Some too may represent remobilized material as where part of the Murray granite seems post-norite and may have engulfed earlier formed ores (McKim).

Quartz

Quartz has been noted by Knight (1917) as a common constituent in such deposits in fissures and cracks associated with various sulphides and carbonates. At the Garson he describes a vein averaging 6' wide and up to 100' long with sulphide veinlets ramifying the quartz as if deposited a little later. In breccia ores such as at Crean Hill and others, quartz may make up a very considerable part of the ore but precise details as to its actual manner of occurrence are not given.

At the Murray mine, Phemister (1925) has described both quartz and quartz-feldspar-biotite veins in the footwall and in ore. Chalcopyrite, apparently continuous with massive sulphides, is found within the veins, but elsewhere the veins cut the massive sulphides. The possibility of the chalcopyrite having been re-mobilized was not considered but the veins are considered as a late, less intense stage in the mineralization. In the marginal sulphide breccia ore at the nearby McKim mine, Clarke & Potapoff (1959) describe fragments of quartz and carbonate in the breccia, but note also that in the footwall, pentlandite-rich breccia ores, contained in post-norite granite, these minerals replace the matrix.

In a specimen of our collections from the Creighton mine, a very fine-grained type of milky quartz, one-half inch wide borders chlorite schist and is followed inward by "dirty" fine-grained chalcopyrite with dark inclusions, which penetrates the quartz in exceedingly fine little stringers. This grades into normal appearing massive chalcopyrite which in turn encloses rounded bodies of fairly clear, glassy to greasy quartz which is also invaded by fine chalcopyrite stringers. In both cases the quartz seems intimately related to the chalcopyrite and to have been crystallized slightly before it.

In the lower part of the Frood, Michener describes quartz as common in stringer form in the contact rock or as a band, several feet wide, separating rock and ore. All three carbonates are associated with the quartz or occur as separate veins in the contact rocks.

In other offset deposits, particularly the Worthington and Milnet, quartz is not an uncommon associate of the metallic minerals. Coleman (1913) notes it intergrown in ores of the Worthington offset along with marcasite, gersdorffite, and niccolite. In parts of the Milnet ores it forms irregular curving seams with carbonate and again is associated with the peculiar pink (nickeloan) pyrite, marcasite, and chalcopyrite, and appears more or less contemporaneous with them.

At the Falconbridge mine Lochhead (1955) notes that on either side of the ore, early silicification has occurred, forming a fine grained rock, termed "jasperoid." Where developed in greenstone footwall rocks this has a grey colour, and in norite, a bluish colour. A detailed study of the jasperoid in drill core from the south wall, 3502 west drift by A. R. Graham (1956), shows it occurs as large discontinuous lenticular bodies in or near the south wall of the drift throughout its entire length and attains widths equal to some of the larger ore bodies. It is apparently barren of sulphides of the type which formed in the contact zone (along the norite) but a large pod of ore is noted lying off the nose of the largest jasperoid body. In composition it contains from 60 to 90 per cent quartz, the remainder being made up of oligoclase, chlorite, sericite, epidote, minor microcline, carbonate, and leucoxene after ilmenite. The quartz varies from even grained and unsheared, to quartz with a highly strained mortar structure with porphyroblasts up to several millimeters in diameter. The minor constituents always show an alignment, the schistose structure of the wall rocks being preserved in the jasperoid though some plastic deformation is indicated since its emplacement. Contacts are largely gradational and rarely sharp. These bodies clearly show extensive silicification over a large area of footwall rocks, the irregular shape of the bodies being due to continued shearing after initial replacement of the footwall rocks. Such shearing is suggested by Lochhead as being greater at depth than nearer surface.

Although the jasperoid bodies are on the whole barren of sulphides, near the edges irregular masses of ore follow and replace the grain boundaries of coarse quartz, giving fretted boundaries, according to Graham. He also notes a coarsening of the quartz grains near the ore and the tendency of sulphides to form apophyses in the quartz. In nests of epidote grains, in some cases with biotite altering to chlorite, occasional small sulphide masses are found. Ore minerals also replace hornblende present in the jasperoid and this replacement possibly accounts for the development of tremolite needles in such places, the iron of the original hornblende contributing to that of the sulphides. The common occurrence of biotite adjacent to ore minerals is also noted by Graham and its partial conversion to chlorite. From such occurrences it seems clear that extensive silicification in this area preceded the deposition of sulphides, but the reason for this is not readily apparent.

Less widespread are minor occurrences of quartz of a later generation associated with carbonate, chiefly calcite, and galena and sphalerite which transect massive pyrrhotite-pentlandite-chalcopyrite ore. Similar veins also fill fractures in wall rocks and are reported in many of the major mines.

Carbonates

Carbonates on the whole are relatively rare constituents of the main sulphide ores but have been described in both the "offset" and "marginal" deposits. Calcite is probably the most common, but dolomite and siderite have been noted by Michener (1940), as occurring at Frood.

In early accounts (Knight, 1917), calcite commonly intergrown with quartz is noted as filling fractures along with the common sulphides as well as occurring in veinlets in adjacent wall rocks at Crean Hill, Victoria and Garson mines. In these cases the carbonates appear more or less contemporaneous with the early sulphide ores. In the Worthington and Milnet offset deposits, however, quartz and carbonates are associated with nickeliferous pyrite and curving colloform structures suggest they are secondary minerals, possibly emplaced after earlier massive sulphides. At Frood, in the siliceous zones the carbonates are recorded by Michener as associated with quartz stringers in the contact rocks, with a quartz band, several feet wide separating ore from rock, or as individual veins in the contact rocks.

What are termed late-stage calcite-pyrite veins, associated with aplite dykes are noted by Mitchell & Mutch, (1957), as occurring in fractures in aplite in a zone 50-500 feet from the norite contact at the Hardy mine. The dykes and apparently the calcite-pyrite veins dies out near the ore, but the main period of ore deposition is regarded as either at the same time or slightly later than the aplite dyke stage.

Carbonates, especially calcite, are also associated in several deposits, Falconbridge, Garson, Hardy and no doubt others, with post-massive sulphide fracture fillings in which occur varying amounts of sphalerite, galena and late marcasite and pyrite. Quartz is usually present with the calcite of these veins. These are commonly regarded as late stage and hypogene rather than supergene as many are found at considerable depth (Lochhead, 1955).

Carbonates are noted also as secondary developments with chlorite, epidote, actinolite and other minerals in rocks such as norite, gabbro and schistose greenstones, but carbonatization of wall rocks in general does not appear to be very extensive, with the possible exception of parts of the Garson deposit.

Biotite

Brown biotite along with "blue green hornblende" is described as a typical alteration developed near sulphide ores by Wandke & Hoffman (1924) at the Murray mine, and by Michener (1940), at the Frood. At the latter, siliceous wall rocks, especially, have been converted to biotite schists for at least three feet from ore contacts and beyond this, to sercite-quartz rocks. In one of our specimens, coarse biotite forms a half-inch

selvage along massive chalcopyrite, with the cleavages oriented more or less normal to the contact. The index of refraction of this mica ($\beta = 1.640$) indicates it is intermediate between the iron and magnesium-rich biotites in composition. Biotite has also been noted by Mitchell & Mutch (1957), as developed in the matrix of the Levack breccia at the Hardy mine, and more particularly in the norite. In the latter, they state "as the ore zone is approached the norite becomes darker, with a considerable increase in biotite, usually accompanied by sulphide spots, and gradually grades into biotitic norite."

Biotite is found in various stages of alteration to chlorite.

Amphiboles

Several varieties of amphibole occur with the ores in various places and in the adjacent rocks. Wandke & Hoffman (1924), classified them into three types, (1) a product of direct crystallization in the norite and quartz diorite, (2) actinolite formed by the alteration of pyroxene and (3) a blue-green amphibole associated with and replaced by sulphides. Graham (1956), has noted also the occurrence of both brown and green amphiboles as well as tremolite in fine needles embedded in the common sulphide ore, where it appears to have formed from other amphiboles, some of the iron of which, may have entered the sulphides. Actinolite-rich inclusions of greenstones and older gabbroic rocks are common "inclusions" in quartz diorite of the Worthington offset.

The "blue-green hornblende" described by Wandke & Hoffman (1924) as developing most abundantly just ahead of sulphides, according to E. Fairbanks, had the following characteristics:

Indices: α —1.679, β —1.685, γ —1.700

Pleochroism: α —pale yellow, β —deep greenish yellow, γ —deep greenish blue

According to Michener (1940), the secondary amphibole developing next to sulphides and dying out rapidly away from the contact as brown biotite increases, is a variety of hastingsite. A dark blackish blue sample of similar amphibole in laths an inch or more in length, and intergrown with maucherite, was studied in our laboratory. Optical properties are as follows:

Indices: α —1.670, β —1.678, γ —1.682; maximum extinction 15° , $2V$ large (—)

Pleochroism: β —bluish-green, γ —dark blue-green to blue.

Spectrographic analyses showed strong sodium as well as Ca, Mg, Fe, Al, V, Sn, K. The mineral is too intimately intergrown with biotite and sulphides to allow complete separation for chemical analysis. The above properties indicate an alkaline variety similar to hastingsite. Indices are not as high as some given for ferrohastingsite.

Garnets

Deep red almandine garnet is of rather rare occurrence, a few specimens from the Froid showing it developed along the contact of sulphides with biotite and/or "blue" hornblende. Its index of refraction was determined as 1.80–1.81. Qualitative spectrographic analysis confirmed it as a high Fe, Al garnet with very little Mn or Ca.

A second type of garnet has been noted by Michener (1940), as a cryptocrystalline, jasper-like, massive, pink garnet occurring in siliceous contact rocks at depth in the Froid deposit, but no data are available to indicate its composition.

Pyroxenes

Pyroxenes in noritic rocks include augite and hypersthene. In places these are found in contact with sulphides and remain quite fresh. Optic angle measurements⁸ of hypersthene in several such sections over X range from 48° to 57° , indicating a variation from 56 per cent to about 70 per cent FeSiO_3 , according to Winchell's diagrams. In some, the hypersthene is uralitized.

Chlorite

Chlorite is a not uncommon silicate in and near ore zones, especially in footwall rocks of old volcanics. Chlorite schist impregnated and partly replaced by massive gersdorffite at Falconbridge has been referred to above. This chlorite as shown in thin sections is clearly secondary after biotite and all gradations from brown to green biotite to almost isotropic green chlorite can be seen. Both Michener (1940) and Graham (1956), have noted chlorite as a frequent alteration product of biotite, suggestive of retrograde metamorphism in places.

It is also present in sheared rocks along late faults and fractures. On the other hand chlorite is a relatively rare constituent in quartz diorite or norite in proximity to major sulphides and in these both femic minerals and feldspars have remained surprisingly fresh in contrast to other types of sulphide deposits as at Noranda.

(b) SECONDARY SUPERGENE MINERALS (NON-METALLIC)

Secondary supergene sulphides such as violarite, millerite and in places marcasite and pyrite have already been described. Oxidation products developed on the weathered surface of various ore deposits have been described by Coleman (1913). He noted the presence of minor melanterite, chalcantite, morenosite and malachite in the predominant limonitic material.

⁸These were made by Mr. R. D. Stevens.

Barlow (1904) described morenosite on gersdorffite and niccolite at the Gersdorffite and Worthington mines and annabergite in the same offset deposits. Michener (1940) has recorded the local development of erythrite at Frood.

As Coleman observed, surface exposures though not deeply oxidized illustrate the ready leaching of both nickel and copper which do not accumulate to any extent in the oxide zone. If such were ever formed they were probably removed during Pleistocene glaciation.

C. RELATIONSHIPS OF ORE MINERALS TO ROCK FORMING MINERALS

The relationships of the ore minerals to the non-metallic minerals associated with them are very critical in assessing the theories of origin and for this reason many of the details revealed by microscopic study will be given in Part III along with our interpretation. Here we may note some of the general relationships, treating them as objectively as possible. Actually the textural relations of the two groups of minerals, and of aggregates of them, vary considerably in the different types of ores. These become understandable however, only when consideration is given to their complex history both as liquid concentrations and crystalline products, and the problem becomes one of determining which textures are most significant and which processes have been most important.

For this purpose the major primary ores may be divided into two main groups, those forming an integral part of one or other phases of the Sudbury irruptive (including offsets) and those which have been introduced in one way or another along the contacts and adjacent footwall rocks guided by fractures, faults or shear zones or into pre-existing breccias of the common Sudbury type. Many secondary effects have been superimposed on the primary ores, some of which postdate them by long periods of time. To avoid confusion, however, these will be left for later consideration.

Most illuminating are the ores which can be shown to be spatially an original part of the main irruptive or an offset. These include (1) disseminated sulphide ores in norite or quartz diorite concentrated in the lower part of the intrusions, (2) the counterpart of these, namely disseminated silicate (quartz diorite) aggregates or pellets in otherwise massive sulphides (the immiscible silicate sulphide ore), and (3) the purer, massive ores below and gradational from them.

In all of these the textural relations indicate generally that the bulk

of the sulphides crystallized *after* the silicates, iron oxides and quartz, as shown by their projection into fractures and cleavages, by their interstitial distribution and by some embayment and replacement features. This seems true whether the sulphides are in contact with fresh anhydrous silicates such as pyroxenes and feldspars, or with hydroxyl-bearing amphiboles, biotite or even locally chlorite or other similar silicates. A purely objective approach might thus lead one to assume the sulphides were in all cases later in age and were introduced from some other source.

That this was not the case is best shown by features indicating the separation of immiscible sulphide liquid from silicate liquid and suggestive evidence of the separation of silicate liquid globules from the sulphide fraction, in other words, features showing the role of liquation. That liquid droplets of sulphides formed in both norite and quartz diorite magmas is shown by the rounded forms of these in the so-called disseminated ores, especially at Creighton and Froid, respectively. They are best preserved in undeformed and less altered phases and may be traced from single isolated blebs of sulphides in contact with fresh orthopyroxene and plagioclase, into larger and more irregular aggregates formed by coalescence, as illustrated in Plates XIV–XV, clearly indicating the merging of liquid droplets as the silicates were crystallizing. Similar globular bodies of disseminated sulphides are present throughout much of the quartz diorite at Froid, and also appear in quartz diorite pellets and more irregular inclusions within massive sulphides below (*Frontis-piece*). In the latter ore these range from a millimeter or so in diameter, cross sections varying from circular to swirly club-shaped bodies, down to minute, "liquid-inclusion" like particles, noticeable particularly in clear feldspars and quartz, both in irregular clusters and trains, the orientations of which seem not limited by grain boundaries. These are still detectable as sulphides in reflected light and in polished sections show a distinct emulsoid texture.

Almost identical forms of most of the smaller silicate (quartz diorite) pellets in sulphides are strongly suggestive of a similar origin, that is the separation of liquid silicate globules from a dominantly sulphide liquid, though admittedly the more irregularly shaped inclusions may represent partly or wholly crystallized quartz diorite bodies "swimming" (after Grip, 1961) and eventually trapped in solidifying sulphides. Even on these are small rounded globular excrescences along the borders. In such ores the similarity of the sulphide forms in silicate (quartz diorite) rock and the (smaller) silicate forms in sulphide is further borne out by the occurrence around *whichever is the minor phase*, of rims or partial rims of black oxides (ilmenite, magnetite and even ilmeno-magnetite) and fine plates of biotite oriented in many cases parallel to the bordering

surface. In the silicate globules in sulphides, particularly, these "rims" frequently curve into the silicates and disappear, much like the "snow-ball" structure of some garnets. They appear to represent reaction products between the two phases, and if the analogy is correct, may indicate some movement of one in the other before final crystallization of each was complete.

Also in common in the two types of ore, but developed locally in the silicate portion, are multitudes of fine hair-like fractures filled with fine sulphides yielding a distinct web pattern. These, in addition to minor embayments of sulphides in silicate, typical of replacement, are in keeping with the later crystallization of the sulphide liquid. To a much smaller degree, fine branching and en echelon strings, chiefly of biotite, follow fractures, gashes or possibly some grain boundaries of the sulphides, suggesting a minor amount of silicate formed after the sulphides.

In the more deformed, sheared, or altered and amphibole-rich phases of the irruptive, the rounded globular forms are no longer evident, the sulphides become largely interstitial to the silicates, the rounded borders gradually disappear and eventually become so ragged as to resemble sulphides introduced between the silicates and *apparently* replacing them to a considerable degree.

Although there has been no opportunity to examine in the field the gradation from either the disseminated sulphides in silicate rocks or the disseminated silicates in sulphide to more massive and purer sulphide bodies, descriptions by others confirm this to be the case, as do such specimens as we have examined. Within more massive ore the non-metallic inclusions are sparse and consist usually of isolated grains and more rarely of intergrown grains of the same silicates composing the norite or quartz diorite. Here and there minor erratics of foreign rock particles or quartz may also appear. These have borders varying from sharp to rounded and embayed, and again simply attest to the later time of crystallization of the surrounding sulphides and minor replacement.

Other massive ores, as shown by their structural relations have been introduced along the irruptive contacts, in places where faulted, or into fractures or faults in both irruptive and footwall rocks. In some cases as noted by Yates (1948) at Creighton and elsewhere by Wilson & Anderson (1959) some disseminated ores of injection origin may also be present. Relations of sulphides to non-metallics are again those simply indicating the later solidification of sulphides and varying degrees of replacement. An excellent case of the latter is shown at Falconbridge by massive gersdorffite, fringing normal sulphides, which has clearly replaced adjacent chlorite-biotite schist and left fine shreds and films of schist in parallel orientation with the footwall rock.

In the abundant breccia ores which vary so much both in character and origin from place to place, the relations of sulphides to inclusions, both large and small, are such as to suggest introduction of sulphides, extensive replacement of any pre-existing matrix and varying degrees of impregnation and replacement of coarser material, especially by chalcopyrite. Composition of included fragments are as variable as the country rocks and include norite or quartz diorite in places, as well as quartz and carbonates. The presence of still fresh feldspars and the usual assemblage of amphiboles, biotite and less commonly of epidote, zoisite and chlorite and rarely garnet, and the general lack of any widespread or uniform alteration of a typical hydrothermal type are noteworthy. In contrast to these, however, are the exceptional breccia ores at Garson illustrated and described by Yates (1948) which have formed between intersecting faults in zones along which shattering and shearing and much more than normal alteration occurred both in irruptive and other rocks. The ores there contain abundant fragments of schists, quartz and carbonates and in extending from one fault to the other must have replaced a considerable volume of rock. With these, perhaps, may be compared the zones of jasperoid developed in footwall rocks at Falconbridge to the east, and siliceous and carbonate alteration along tangential shears even in norite, into both of which sulphides have been emplaced. Both such pre-sulphide alterations and the actual amount of replacement accomplished in all the different types of breccia ores are problems for later discussion. It seems clear, however, that some ores have formed as integral parts of the irruptive rocks and hence pose no question as to how space was made for them. Others have been injected into fractures and faults with varying degrees of replacement. Just how the latter was accomplished remains to be determined.

D. DISTRIBUTION OF METALS AND MINERALS IN THE ORES

Before considering the significance of the detailed mineralogy of the ores, their relations to the rocks and minerals in which they occur, and the textures of the ore minerals themselves, it is essential that additional factual data be presented on the general distribution of the important ore minerals and metals within single deposits and in one deposit compared with another. In this section we shall consider what information is available in the literature and has been secured in the present study, dealing with (1) ratios of copper, nickel, iron, their common sulphides

and such zonal relations as are known, (2) the distribution of cobalt and selenium, (3) distribution of the precious metals, the platinum metals, gold and silver, and (4) the distribution of minor lead, zinc, tin and bismuth. Facts which emerge from such a study have a direct bearing on the various processes involved in the formation of these complex ores and an explanation for them will be sought in a subsequent section. Reference should be made to the classification of the ores as given in section (A) of this part.

1. COPPER-NICKEL-IRON AND THEIR MINERAL RATIOS

Ratios for the three major metals in all the deposits are not readily available but it has been indicated in accounts by International Nickel Company (1946), by Yates (1940), Zurbrigg *et al.* (1957), and by Wilson (1956) and Wilson & Anderson (1959), that individual mines, drawing on the various types of ore in each, show characteristic copper-nickel ratios which range from 0.5:1 to 3:1 (Table 13). Where mineral ratios

TABLE 13. COPPER-NICKEL AND MINERAL RATIOS

Mine	Ore Type	Mineral Ratios			
		Cu/Ni	Po	Pn	Cp : Cb
Creighton	F. wall copper	3 : 1	2	1	
	Massive	0.5 : 1			
	Disseminated	0.7 : 1			
	Av. other than Cu.		3.4	1	
Garson	average	1 : 1	4.7	1	
Levack	average	1 : 2	5	1	
Murray	average	1 : 2	6.6	1	
Frood	average		5.4	1	
Frood (Zones)	Dissem.	0-500'	6.39	1	0.88
	Lr. dissem.	1800'-2700'	5.46	1	1.17
	Heavy dissem.	2000'-2700'	5.52	1	1.24
	Massive dissem.	2700'-3300'	3.87	1	1.97
	Cubanite zone		1.79	1	5.19 : 5.44
	South siliceous		0.30	1	2.10 : 1.60

Po—pyrrhotite, Pn—pentlandite, Cp—chalcopyrite, Cb—cubanite

are given, averages of pyrrhotite-pentlandite show differences from mine to mine and on the whole these appear to be gradational. Where zoning is recognized, as in the footwall copper-rich ore at Creighton, and on an even greater scale at Frood, the mineral ratios change very decidedly, chalcopyrite (and cubanite) increasing at the expense of pyrrhotite, relative to a constant pentlandite proportion.

In addition to these results, Wilson (1953) has also noted that "the

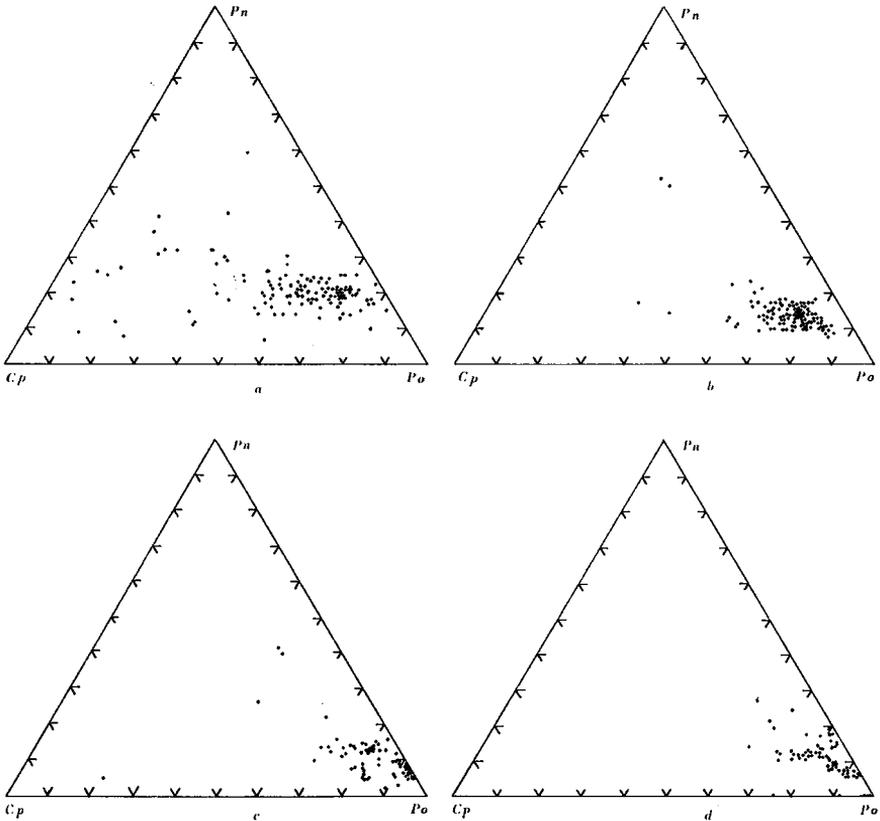


FIG. 4. Plots of pyrrhotite-pentlandite-chalcopyrite ratios of total sulphides in random samples from (a) Creighton mine; (b) Stobie mine; (c) Falconbridge mine; (d) Onaping Area mine.

sulphur:nickel ratio is constant in all types of ore at a single mine,"⁹ and in 1959, (Wilson & Anderson) that Cu/Cu+Ni ratios for Falconbridge ore are practically constant over a vertical range of 4000 feet.

These results are of course derived from a vast amount of data accumulated over many years. In order to see how well random sampling would agree with general averages, International Nickel Company of Canada, Ltd. and Falconbridge Nickel Mines, Limited, were kind enough to supply us with randomly selected analyses from the Creighton (150), the Stobie (150) and Falconbridge (78) and Onaping area (81) respectively. These are shown plotted in Figure 4 in terms of pyrrhotite, pentlandite

⁹An exception to this, however, is noted by Lochhead (1955) at Falconbridge where nickel to sulphides increases with depth and distance into the greenstone hanging wall. Copper also increases in hanging wall ore.

and chalcopyrite in 100 per cent sulphide. While there is a considerable spread of points in each case there is a marked concentration towards the pyrrhotite apex and a distinct tendency for 80–90 per cent of the samples to fall between lines drawn parallel to the pentlandite base on either side of the 10 to 20 per cent pentlandite composition, indicating again the tendency of chalcopyrite to increase chiefly at the expense of pyrrhotite, and of each deposit as a whole to have a somewhat different set of ratios, the pentlandite remaining rather constant. Plots of weight per cent and molecular per cent of Cu/Ni were also made from the same analyses but show a completely random distribution and no trends, which should be the case where copper varies more with iron. Figure 5 is a plot of analyses of random samples of low grade sulphides from Onaping area in terms of Fe, Ni, Cu, and S. It shows the dominance of iron and sulphur, a considerable spread in their ratios, and low amounts of nickel and copper which lie just above the Fe-S edge of the tetrahedron.

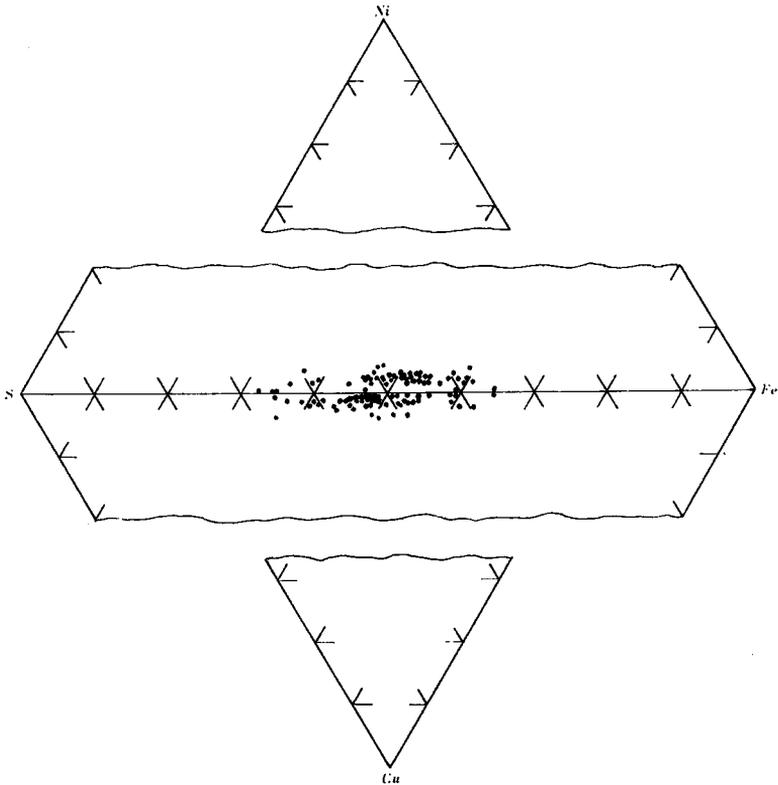


FIG. 5. Plot of Cu, Ni, Fe, S mol per cent in random samples from Onaping Area.

Precise data on the pyrrhotite-pentlandite-chalcopyrite ratios for all of the ores which have been mined are not available. Production of nickel and copper over the period 1947-1957, however, gives a ratio of Ni/Cu of 1.08. This agrees reasonably well with about equal quantities of pentlandite and chalcopyrite, which give a Ni/Cu ratio of 1.04. In terms of the three most common sulphides calculated to 100 per cent, the ratio of pyrrhotite: pentlandite: chalcopyrite is probably close to 70:15:15.

As will be shown later the relative constancy of metal and mineral ratios in individual deposits taken as a whole, the slight but distinct variations in ratios of different types of ore (disseminated, massive, zoned), and in one deposit compared with another, are all significant and call for explanation in any theory of origin.

2. COBALT AND SELENIUM

As neither of these elements occur alone in individual mineral compounds but are distributed in solid solution in many of the common minerals they require separate consideration.

(a) Cobalt

Determination of cobalt in the various minerals of the Sudbury ores is fraught with the difficulty of obtaining specimens free from inclusions of others. This is particularly true of both pyrrhotite and chalcopyrite which are usually "contaminated" with pentlandite. Table 14 shows the ranges of both cobalt and nickel found in various species, specially purified by Naldrett in so far as this was physically possible.

TABLE 14. COBALT-NICKEL CONTENT OF COMMON SUDBURY ORE MINERALS

Mineral	Per cent Cobalt	Per cent Nickel
Gersdorffite	1.38 - 12.00	15.90 - 27.70
Maucherite	0.39	
Niccolite	0.024 - 0.16	
Sperrylite	0.005	0.15
Pyrite (High Temp.)	0.15 - 1.41	0.021 - 0.070
Pyrite (Low Temp.)	0.011	0.024
Pentlandite	0.083 - 1.62	
Pyrrhotite*	0.012*	0.50
Chalcopyrite	0.005 - 0.014	0.052 - 0.33
Cubanite	0.013 - 0.015	0.36 - 0.47
Bornite	0.004	0.058
Marcasite (Replac.)	0.048 - 0.22	2.50 - 4.70
Marcasite (Late)	0.016	0.032 - 0.054

*Amount of Co based on arbitrary amount of Ni = 0.50%.

Gersdorffite, of all the Sudbury minerals, can take up the largest amount of cobalt which shows a reciprocal relation to nickel. In contrast iron in the gersdorffite tends to remain constant in any one deposit (Fig. 3). Other arsenides contain quite small amounts of cobalt.

Pyrite, as discussed earlier, shows a considerable range in cobalt (which varies with its time and mode of formation, Table 9), and, though not quantitatively important, shows several interesting features. That formed during the higher intensity stages of mineralization contains distinctly more cobalt than the lower temperature types. The former include early, pre-pyrrhotite pyrite, reaction pyrite formed from pyrrhotite and probably before pentlandite segregated, and certain later replacement types of pyrite. Reaction pyrite competes successfully for the cobalt contained in original pyrrhotite and may contain more cobalt than associated pentlandite. Pyrite replacing pentlandite, though not exceptionally high in cobalt (0.24–0.59 per cent), is enriched in this metal compared with adjacent pentlandite with 0.089 to 0.05 per cent, probably by diffusion of cobalt to the more favourable host.

Pentlandite of course accounts for the major amount of cobalt in the ores as a whole and averages close to 1 per cent (Table 6). As has been shown, the average Ni/Co ratio for samples from both north and south range deposits is quite constant (34.2–34.7). (Individual deposits may, however, show a greater variation, e.g. Hardy Ni/Co—31.9, Falconbridge—28.0.) Pentlandite with abnormally low cobalt may be attributed to either remobilization or loss by diffusion to replacing pyrite.

Pyrrhotite probably owes most of its cobalt content to contained pentlandite. The purest pyrrhotite that can be concentrated contains about 0.50 per cent nickel, which would correspond with only 0.012 per cent cobalt, based on Ni/Co ratios for the mineral. As noted in earlier descriptions (Table 4) pyrrhotite concentrates from the south range contain more nickel and nearly double the cobalt, in a less separable form, than samples from the north range.

The cobalt content of the copper minerals at Sudbury is quite low and where present much of it may be due to inclusions of other minerals. They differ in this respect from copper sulphides at Skaergaard, shown by Wager *et al.* to have separated early from the crystallizing magma and containing up to 2 per cent cobalt.

The distribution of cobalt is disseminated, compared with more massive ores at Sudbury is possibly of some significance. So far we have only been able to compare them with respect to pyrrhotite, the most easily separated mineral. As shown by results on both Hardy and Froid samples (Table 3, Part II) cobalt is identical and Ni/Co ratios are close in the two types of ore at the former. At Froid, however, the Ni/Co

ratio in disseminated pyrrhotite in the quartz diorite, above, is distinctly lower than that for massive pyrrhotite occurring below. The number of analyses is too small to allow any far reaching conclusion, but as will be shown later the results on the two deposits mentioned correspond with what would be expected under two somewhat different modes of formation.

(b) *Selenium*

Some data on the distribution of selenium in the Sudbury ores have been given elsewhere (Hawley & Nichol, 1959) and are summarized here for convenience. The study has not been exhaustive but gives some indication of the amounts present in the more common species. No selenide minerals have ever been recognized at Sudbury and it is regarded as substituting for sulphur in the sulphides (Table 15).

TABLE 15. SELENIUM CONTENT OF SUDBURY SULPHIDE MINERALS

	No. Samples	Range ppm Se	Average ppm Se
Pyrite	4	25-60	50
Pyrite (post-pentlandite)	1	130	130
Pyrrhotite			
N. Range	50	18-83	54
S. Range	51	17-230	72
Both Ranges	101		63
Pentlandite			
N. Range	17		45
S. Range	8		90
Both Ranges	25	30-160	85
Chalcopyrite			
N. Range	1		34
S. Range	21	33-165	100
Average	22	33-165	97

The above results show that all four sulphides contain rather similar and relatively low amounts of selenium. This limited range is probably more in keeping with ores crystallized from magmatic sulphides in contrast to non-nickeliferous hydrothermal deposits. Of the four minerals chalcopyrite is the better host, which is in agreement with other findings.

The consistent differences in selenium of the three most abundant sulphides in north and south range deposits may have some significance even if sampling is rather small. As suggested in the discussion of the geology of the area, the south range is believed to have been upthrust considerably, so that the present exposed levels represent a deeper

horizon than that on the north range. At Noranda, however, selenium appears in greater concentrations in the upper levels than at depth, so if this is common to other deposits, another reason for the observed difference at Sudbury must be sought. It may simply reflect original minor differences in the magma from which they were formed or differences in proximity to the conduit from which the irruptive magma came.

3. THE PRECIOUS METALS

Precious metal production from the Sudbury deposits include the platinum group, gold and silver. Data on the distribution of these in the ores as a whole and in individual deposits and ore types are fragmentary.

(a) *The Platinum Metals*

The platinum metals recovered consist chiefly of platinum and palladium with lesser quantities of rhodium, ruthenium and iridium. Osmium, though detected in the sulphides spectrographically, is not recovered, due no doubt to its volatility as an oxide. Actual production over the period 1947-1957 (Ontario Department of Mines) has ranged from over 200,000 to 400,000 oz. total platinum metals per year. In terms of total tons of ore treated, platinum metal ozs. per ton range from 0.019 to 0.26 (0.65-0.9 ppm.), but the actual tenor varies greatly from place to place and with type of ore. Production figures for the above period indicate that, in round numbers, platinum accounts for about 46 per cent, palladium 41 per cent, and combined rhodium, ruthenium and iridium for 13 per cent. In several of the common sulphides as will be seen, ratios of platinum metals depart from the above average with palladium in excess of platinum, and production from one group¹⁰ of deposits over a five year period has yielded the following percentages: Pt 36.6, Pd 40, Rh 8.8, Ru 9.9, and Ir 4.7. Ratio of ruthenium and iridium with respect to rhodium and the other two are of interest as reliable data on their occurrence in individual minerals are not yet available.

Sperrylite, michenerite and froodite, and possibly a third Pd-Bi compound are the only platinum metal minerals identified in the ores, even though many other minerals, alloys and synthetic compounds containing S, Te, Se, Sb, Bi, and Pb are known and have had their properties described. In view of this and the long lapse of time between the first recognition of the presence and the identification of the palladium bismuthides, it seems quite possible still other compounds of the platinumoids may yet be isolated, with the likely exception of any antimonides, as this element is decidedly rare in Sudbury.

¹⁰Courtesy of Falconbridge Nickel Mines, Limited.

With this in mind Groeneveld Meijer (1954–55) prepared eight different tellurides of the six platinoids to ascertain their physical properties and thus facilitate their recognition. Two phases of PdBi_2 were also made as well as an intermediate compound in the system PtAs_2 — PdAs_2 (50:50) which had a cubic structure and unit cell between that of the two end members proving such compounds can form even though Sudbury sperrylite carries only a small amount of palladium. None of these could be found in the ores.

Another mode of occurrence of the platinoids is in dilute solid solutions of the common sulphides and arsenides. This problem was examined in some detail by Groeneveld Meijer who reviewed existing data on the structural characteristics of the common sulphides, the co-ordination of the metal ions, nature of the bonding and the radii of both base and platinum metals in such compounds.

All but Pt form sulphides with the pyrite structure. PtS_2 has the cadmium iodide structure, and is not found in nature, but as an arsenide it too could enter pyrite. If bonding conditions are similar to the base metals, radii of the platinum metals are such as to allow the formation of pyrite solid solutions. Where Ir and Ru are trivalent, the more stable states, total valency balance might be achieved by substitution of As for S.

In chalcopyrite only Pt^4 and Pd^4 covalent bond lengths of 1.31 Å approach that of Cu (1.28 Å) while the other platinoids are larger. This, it is pointed out, may explain the common enrichment of Pt and Pd in chalcopyrite.

In pentlandite all the platinum metal radii are within 10 per cent of the octahedrally coordinated metal radius (1.44 Å) and might enter such positions. The radius of tetrahedrally co-ordinated metal ions in this mineral, however, is considerably smaller (1.11 Å).

Similar considerations for niccolite and pyrrhotite suggest all of the platinoids could substitute to some extent for either iron or nickel in them.

Furthermore, Groeneveld Meijer also indicated that it is mathematically very probable that if the platinum metals are present in amounts of 3 or more parts per million in ore samples they should be observable sooner or later, under the microscope. It has been found in our experience, however, that only when ores with 150 ppm. or more are encountered is it usual to see an actual platinum mineral. Also it has been evident that when the total concentration of Pt metals is low in individual species, analyses are quite reproducible. Such consistency favours a uniform distribution within them as would be present within a solid solution.

Analytical techniques for the platinum metals are time-consuming and call for highly skilled chemists. Quicker methods than the classical wet chemical have been tried, utilizing fire-assaying techniques and gold or silver as collectors and either spectrographic or ion-exchange methods of analyses for the dore beads. These have been critically reviewed by Beamish (1959) while Lewis (1957) earlier had noted the widely divergent results obtained on aliquots of a well homogenized ore sample by six commercial analysts, each using their own techniques. Methods used in our laboratory to determine the platinoids in various mineral concentrates and certain types of ore have been described elsewhere (Hawley, Lewis & Wark, 1951; Hawley, Rimsaite & Lord, 1953) while C. L. Lewis has kindly collaborated on some spectrographic determinations on gold beads, more recently supplied him. Probably the greatest single factor in the accuracy of such results is the efficiency of the fire-assaying, and actual recovery of all the Pt metals may vary considerably. The analyses of sulphides cited below, given in percentages of total Pt metals, are accordingly to be taken only as approximations. At least they may represent minima. All that are reported are of low grade material, as higher grade ore appears always to include actual platinum metal minerals.

Table 16 shows the distribution found in samples of the more common sulphides at Sudbury. In pyrite and the majority of pyrrhotites, platinum is present in excess of palladium while in pyrrhotite from one mine, and in pentlandite and chalcopyrite, the reverse is true. In these samples total platinoids range from about 1 to 7 ppm., and any discrete platinoid minerals enclosed in them would have to be very small indeed. Rhodium was determined in all pyrrhotite except that from one mine, though it is

TABLE 16. APPROXIMATE AMOUNTS AND RATIOS OF PLATINUM METALS IN COMMON ORE MINERALS OF SUDBURY

Mineral	No. samples Type-loc.	Percentage Pt. metals			Total Average ppm in mineral
		Palladium	Platinum	Rhodium	
Pyrite	3-N. & S. ranges	41.4	56.4	2.5	1.90
Pyrrhotite	21-S. Rge. one mine	27.6	72.4	n.d.	0.99
	9-S. Rge. one mine	51.7	31.9	16.4	1.527
	3-Dissem.	24.2	73.5	2.3	1.01
	1-N. Rge.	23.0	76.0	1.0	1.53
	3-Offset	37.1	51.5	11.4	1.76
Pentlandite	3-S. Rge.	59.5	33.0	7.5	5.42
Chalcopyrite	7	81.4	17.7	0.9	7.69

n.d. = not determined.

known to be present there. It varies considerably in the different minerals showing greater concentrations in pyrrhotite and least in chalcopyrite. As rhodium is often difficult to collect in assaying, losses occurring in slags and cupels, the doubtful accuracy of the figures may well detract from any significance they might have.

Analyses of pyrrhotites in three concentrates made from disseminated ore give results very similar to 21 samples from a south range deposit and one from a deposit on the north range, all of which are from either massive or breccia ore. On this basis no distinction can be drawn between the different types.

Analyses of pyrrhotite, pentlandite and chalcopyrite of higher grade ore (not reported) in all cases gave very high platinum, indicating the probable inclusion of sperrylite in the samples. On the other hand a high grade nickel arsenide ore proved rich in palladium and bismuth, and undoubtedly contained michenerite, froodite or a third species of bismuthide. Other samples of arsenides, however, are also reported to contain sperrylite as well.

TABLE 17. PLATINUM METALS IN MINERALS AND ORE IN AN OFFSET DEPOSIT, SUDBURY

Minerals	Percentage of total Pt metals			Total Pt metals-ppm
	Palladium	Platinum	Rhodium	
Pyrite	42.2	50.3	7.5	4.714
Pyrrhotite	48.7	44.3	7.0	1.869
Pentlandite (Pyrite ¹)	64.6	25.1	10.3	10.52
Chalcopyrite	71.5	28.3	0.22	8.058
Mill Average— (6 months)	65.0	33.0	2.0	5.325
Magmatic Sulphides ²	63.5	31.7	4.8	—

¹Non-magnetic concentrate from pyrrhotite sample.

²After Noddack & Noddack (1931).

In Table 17 the distribution of the palladium, platinum and rhodium in the minerals of a minor "offset" deposit are given for comparison with a mill average for the mine and with results given earlier. Ratios for the metals in pyrite, pentlandite and chalcopyrite agree in general with earlier results, but pyrrhotite here shows slightly more palladium than platinum, and a consistent increase is noted in palladium with the normal paragenetic order of these minerals. In this case rhodium seems confined largely to the three earlier minerals compared with chalcopyrite. Ratios for the mill average are surprisingly close to those reported by Noddack & Noddack (1931) for magmatic sulphides.

The above data support the thesis that a certain proportion of the platinum metals occurs in dilute solid solution within the common sulphides, particularly in lower grade (as applied only to precious metals) ores, but the proportion of recoverable platinum metals occurring in this manner is not known. Higher grade ores are probably invariably accompanied by either sperrylite which is generally most common in chalcopyrite, or the bismuthides of palladium, found chiefly with the arsenides of nickel and in the siliceous mineral zone at Frood. Data bearing on the factors which lead to the concentration of the platinum metals are not too abundant and some are at first glance confusing.

The occurrences of outstandingly platinum-rich ores referred to in the literature are limited chiefly to the old mines of the Worthington offset where sperrylite was first identified, and to the lower levels of the Frood, though no doubt there are others. In general the offset deposits have thus been regarded as favourable for such accumulations, and we are reliably informed that copper (chalcopyrite) and/or arsenide rich ores, located usually in areas most remote from the edges of the norite or quartz diorite, have also provided a most suitable environment. Michener states further that the precious metals and arsenides also extend farther into siliceous wall rocks compared with basic rocks such as gabbro, where values stop abruptly.

It is of interest to examine how production figures for the platinum metals compare with the average ratios found by Noddack & Noddack in magmatic sulphides.

From the ratios given in Table 18 it appears that platinum metals produced from Sudbury ores are on the whole much richer in platinum and at least locally richer in rhodium, but have about the same relative amounts of palladium, ruthenium, and iridium, as found by Noddack & Noddack in magmatic sulphides. The relative enrichment in platinum over palladium is also evident in analyses of low grade pyrite and many pyrrhotite samples.

TABLE 18. COMPARISON OF RATIOS: PLATINUM METALS IN MAGMATIC SULPHIDE ORES WITH PRODUCTION FROM SUDBURY

Ore	Pd	:	Pt	:	Rh	:	Ru	:	Ir	:	Os
Magmatic sulphides (N & N)	4.	:	2.	:	0.3	:	1.	:	0.4	:	0.1
10 Yr. prodn., Sudbury	4.1	:	4.6	:	1.3						
5 Yr. prodn., one group, Sudbury	4.0	:	3.7	:	0.88	:	0.99	:	0.47		
One offset, mill average, 6 months' prodn.	4.0	:	2.03	:	0.12						

An explanation for the distribution and concentration of the platinum metals will be considered later as their behaviour is intimately related to the processes by which the primary ores were formed.

(b) *Gold and Silver*

Gold and silver recovered as by-products in the refining of Sudbury ores over a ten-year period (1947-1956) have averaged slightly over 41,000 oz. gold and 1.2 million oz. silver, giving a ratio of 1:31. As the native metals they are exceedingly rare, and in this study have been noted in only one deposit. Gold is usually quite silver-rich, while silver aside from its occurrence in the native state has been identified in hessite and schapbachite, and the rare argentian pentlandite has been noted by Michener. Both metals are undoubtedly also present in a state of solid solution in the more common sulphides. No information on the distribution of gold has been secured, but because of its spectral sensitivity it has been possible to obtain some data on the distribution of silver in pyrite, pyrrhotite, pentlandite and chalcopyrite.

Table 19 summarizes spectrographic determinations of silver in four of the common sulphides at Sudbury and shows the distribution in pyrite, pyrrhotite and chalcopyrite to vary as 1.3:1:100. Secondary pyrite, post-pentlandite in age has more silver than earlier types. The difference between silver content in north and south range pyrrhotites seems characteristic as is the difference in cobalt and selenium, Pentlandite is apparently a slightly better host for silver than pyrite, but may owe part of it to impurities of galena. Chalcopyrite as in other types of ore deposits is much the best host for silver, the ratio approaching that found in hydrothermal gold ores (Hawley & Nichol, 1961). Here this characteristic, as will be seen, probably indicates only the tendency for enrichment of silver in the later or last liquids to crystallize from such

TABLE 19. SILVER CONTENT OF SUDBURY SULPHIDES

Mineral	No. samples	Range ppm silver	Average ppm silver
Pyrite-misc.	5	2-3	2.4
Pyrite "Reaction"	5	2-3	2.4
Pyrite Post-Pent.	1		10.
Pyrrhotite—			
S. Range	43	0.6-4.2	2.70
N. Range	60	0.6-3.7	1.57
Average	103		1.80
Pentlandite	24	<1.-14	3.4
Chalcopyrite	28	91-340	180.

sulphide ore fluids, and the same tendency under favourable conditions probably led to the late crystallization of hessite, schapbachite and native silver in the lower levels of the Frood.

In addition to the above occurrences, traces of silver were detected by Lewis (1950) in many other ore minerals including the nickel and platinum arsenides, cubanite, in some galenas, and even in magnetite, specularite and marcasite.

4. LEAD, ZINC, TIN, BISMUTH, ANTIMONY AND TELLURIUM

As noted under descriptions of galena and sphalerite, these minerals, though nowhere of economic importance, have two distinctly different modes of occurrence and mineral associations. Both occur in quite insignificant amounts in the common ores but are locally in greater concentrations in the lower levels of the Frood in which the galena is associated with a wide variety of bismuth and precious metal minerals, and the somewhat rarer sphalerite has abundant chalcopyrite and stannite in ex-solution intergrowths. In the normal ore lead is found also in traces in pyrrhotite and pentlandite, while zinc has been detected in pyrite and all chalcopyrites but not in pyrrhotite nor the arsenides. (Lewis, 1950.)

Both galena and sphalerite are also present in small but widespread quartz-carbonate veins, usually with marcasite both in the nickel-copper ores of both ranges, and in adjacent wallrocks. These carry none of the precious metals, except traces of silver, and as will be shown, are of a much different origin and age than the main deposits.

Tin, though also of no economic importance, has been detected in spectrographic traces in chalcopyrite, cubanite, sperrylite and galena of the main ores, but is chiefly concentrated only in the minerals of the deeper levels of the Frood.

Bismuth with minor traces of antimony has been detected spectrographically especially in the arsenides, gersdorffite, niccolite and maucherite, and alone in sperrylite, in several deposits. The association of bismuth in these, along with palladium, and its concentration in several bismuth minerals intergrown with galena and bornite such as parkerite, tetradymite, native bismuth and bismuthinite have been noted in the siliceous mineral zone at the base of the Frood. No data are available on the distribution of tellurium except its rare occurrence in tetradymite and hessite at the Frood, though it may of course substitute for sulphur to some extent in the many sulphides.

Further consideration of the above data is given later.

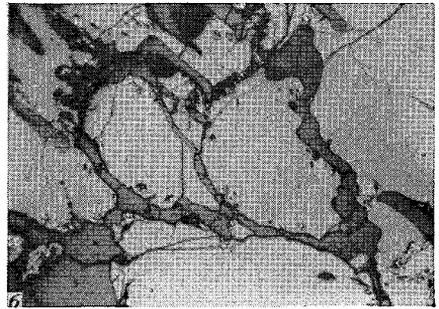
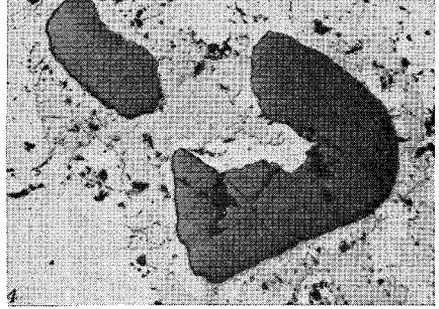
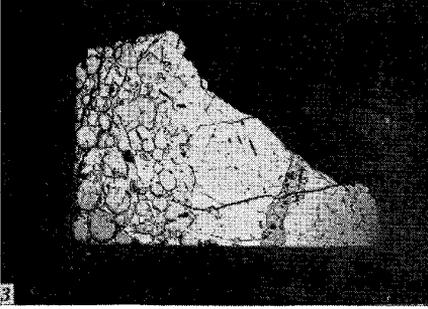
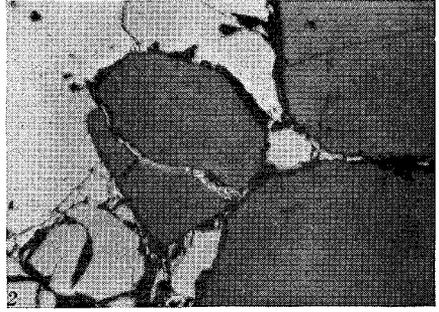
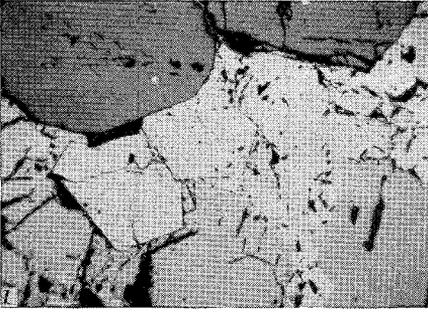


PLATE I

1. Rounded grains of magnetite (*dark grey*) surrounded by sharp crystals of pyrite (*white*), partly enclosed by pyrrhotite (*light grey*) and pentlandite (*speckled white*). Refl. light, in air, $\times 17$ (Ni58).
2. Magnetite (*black*) cut by vein of chalcopyrite (*white*). Pyrrhotite (*light grey*) is moulded on magnetite, lower left. Refl. light, in air, $\times 27$ (Ni1).
3. Granular magnetite (*left*) in pyrrhotite with pentlandite and chalcopyrite. Refl. light, in air, $\times 1.5$ (Ni1).
4. Magnetite (*black*) corroded and embayed by sulphides. White borders or rims around magnetite consist chiefly of intergrown chalcopyrite and cubanite with some fine fringes of "flame" pentlandite. Light grey pyrrhotite lies beyond the rims and replacing it is (*white*) chalcopyrite, lower left. Refl. light in air, $\times 16$ (Ni27).
5. Two coarse grains of pyrrhotite, one white, one dark grey, left, showing two generations of magnetite. Small crystal of magnetite (*grey, upper left*) enclosed in pyrrhotite, while a second generation of magnetite occurs in stringers following contact and transgressing both grains of pyrrhotite. Refl. light, X-nicols, in air, $\times 27$ (Ni19).
6. Late magnetite stringers, interstitial to and cross-cutting pyrrhotite. Fine (*white*) flames of pentlandite are developed along contacts. Refl. light, in air, $\times 17$ (Ni19).

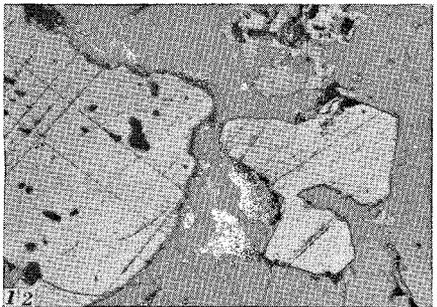
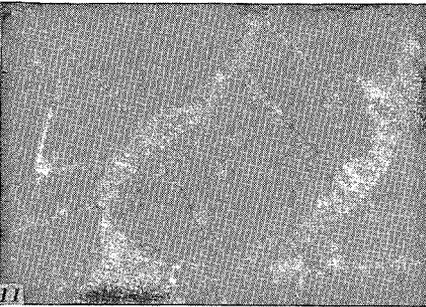
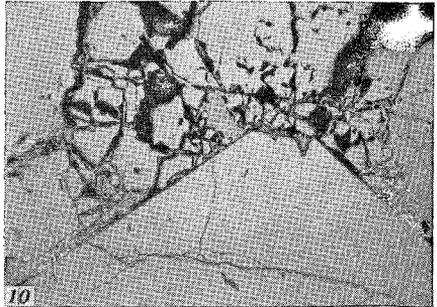
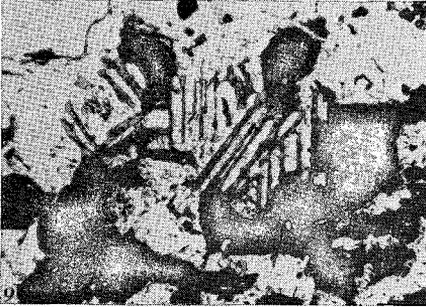
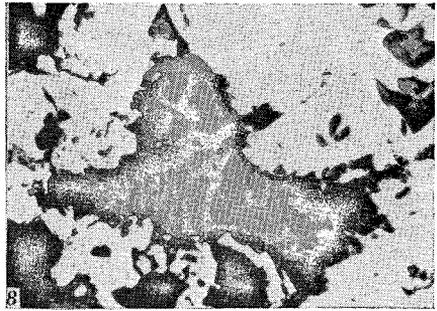
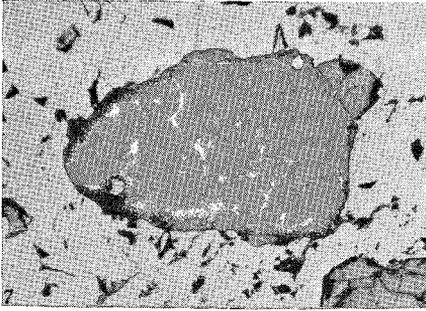


PLATE II

7. Magnetite grain (*centre*) with exsolved lamellae of ilmenite along (111) partings, surrounded and partly replaced by pentlandite (bottom) and pyrite (*top*). Refl. light, in oil, $\times 78$ (Ni 193).
8. Twinned ilmenite (*grey*) replaced gangue (*black*) and to lesser extent by pyrrhotite (*white*). Refl. light, in oil, $\times 156$. (Ni131).
9. Lamellae of ilmenite (*mottled grey*) now largely replaced by gangue. These are apparently remnants of an intergrowth with magnetite(?) which is wholly replaced by pyrrhotite-pentlandite and also by dark gangue. Refl. light, in oil, $\times 78$ (Ni133).
10. Large euhedral crystal of early pyrite (*lower half*) with pentlandite (with cleavage and pits) and pyrrhotite moulded about it. A little replacement of sphalerite and pyrrhotite occurs at the apex of the crystal. Refl. light, in air, $\times 17$ (Ni71).
11. Pyrite (*on left*), transected and replaced by pyrrhotite (*medium grey*) and sphalerite (*dark grey*). Sphalerite, carrying minute exsolution blebs of chalcopyrite, cuts the earlier formed pyrrhotite veinlets. Refl. light, in air, $\times 17$ (Ni71).
12. Pyrite (*white*) invaded and replaced by chalcopyrite (*grey, low relief*). Higher relief (*light grey*) pyrrhotite at top includes (*white*) pentlandite. Refl. light, in oil $\times 16$ (Ni115).

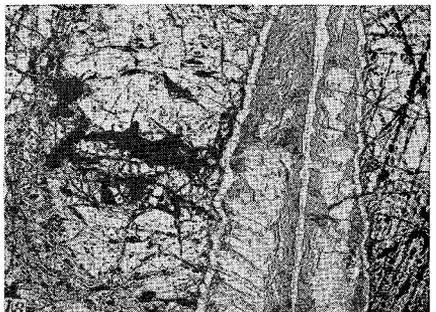
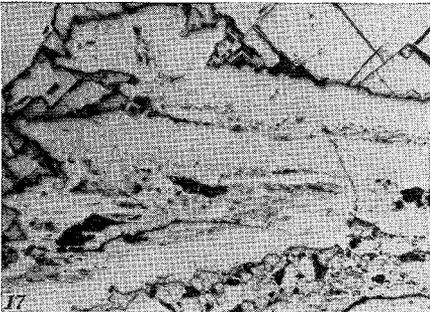
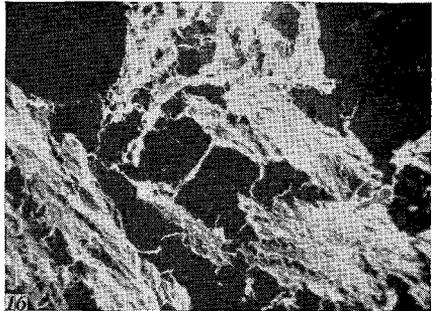
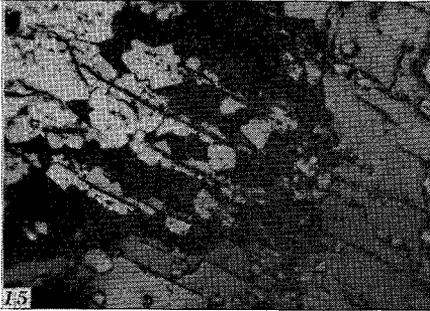
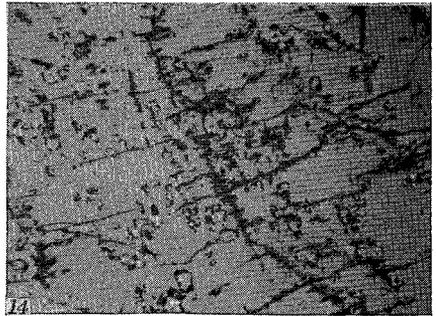
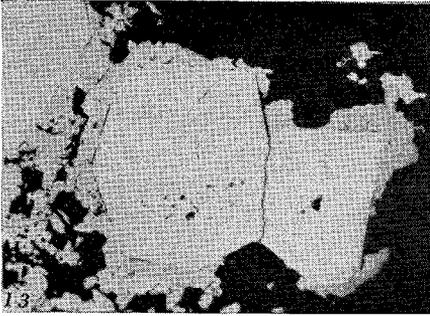


PLATE III

13. Nickeliferous pyrite (*light grey*) forming irregular rims about subhedral normal pyrite (*white*). Refl. light, in oil, $\times 38$ (Ni22) (Milnet).
14. Secondary pyrite (small light cubes with minor dark gangue) and feathery marcasite (tarnished dark, along cracks) in pyrrhotite. Refl. light, in air, $\times 17$ (Ni46) (Garson).
15. Late pyrite (*white*) in quartz (*black*) and pyrrhotite (*grey*). Pyrite within the pyrrhotite is a secondary product as in 14. Note continuity and parallelism of partings in both pyrrhotite, quartz and pyrite suggesting latter two are replacements of pyrrhotite. Part of the pyrite along with quartz likely introduced. Refl. light, in air, $\times 17$ (Ni52) (Creighton).
16. Feathery pyrite (*white*) within pentlandite, the latter stained black by chromic acid. The pyrite has been formed by late-stage alteration of pyrrhotite. Refl. light, in air, $\times 17$ (Ni183).
17. Late pyrite replacing coarse pentlandite with cleavage (*top*). The pyrite contains abundant wispy inclusions of (*greyish*) pentlandite. (McKim mine sample of pentlandite-rich ore from within Murray granite.) Refl. light, in oil, $\times 78$ (Ni193).
18. Spear or disc-shaped pyrite with clear medial seam and edges and lamellar structure within, cutting pyrrhotite-pentlandite ore. The pyrite contains numerous inclusions of low-cobalt pentlandite, is rich in nickel and has about twice selenium content of normal pyrite. Refl. light, in air, $\times 2$ (Creighton Mine).

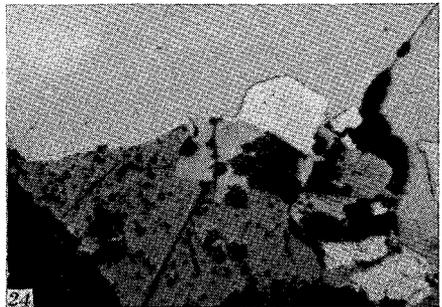
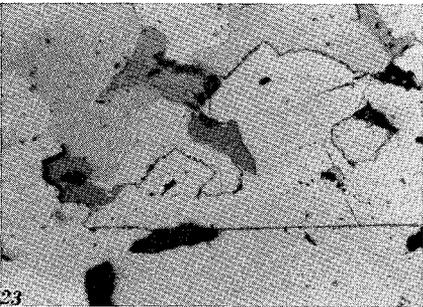
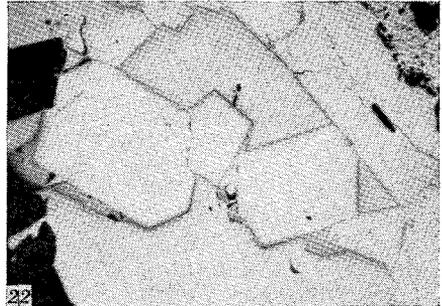
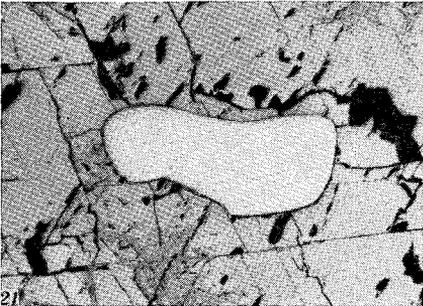
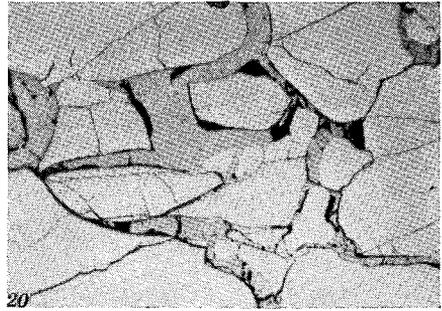
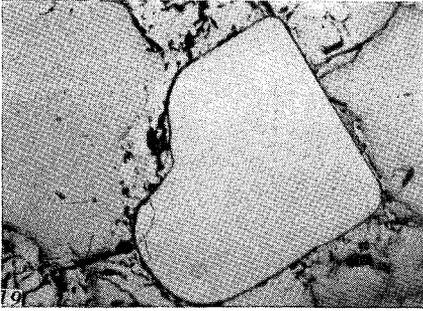


PLATE IV

19. Subhedral sperrylite (*white*) surrounded and partly corroded by pentlandite (*speckled white*) and pyrrhotite (*grey*). Refl. light, in air, $\times 17$ (Ni78).
20. Sperrylite (*white*) showing fracturing and veining by chalcopyrite (*grey*). Refl. light, in air, $\times 17$ (Ni77).
21. Rounded grain of sperrylite (*white*) in coarse pentlandite. Darker grey material following cleavages and replacing pentlandite is an intergrowth of cubanite and chalcopyrite. Refl. light, in air, $\times 78$ (Ni3).
22. Gersdorffite crystals (*white*) with sharp outlines showing little or no replacement except at grain of sperrylite, and about which are moulded chalcopyrite (*off-white*) and (*light grey*) pyrrhotite, centre. Refl. light, in air, $\times 17$ (Ni34).
23. Gersdorffite (*centre*) embayed and replaced by niccolite (*light grey*) and chalcopyrite (*dark grey*). Grain structure of niccolite apparent on upper left and top. Refl. light, in oil, $\times 78$ (Ni39).
24. White gersdorffite crystals bounded on top and right by niccolite and bottom by pyrrhotite. Note fine rim of gersdorffite between niccolite and pyrrhotite. (Black is gangue). Refl. light, in oil, $\times 156$ (Ni45).

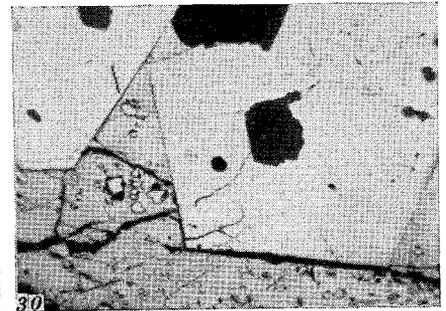
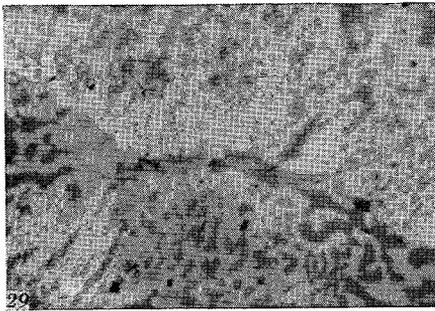
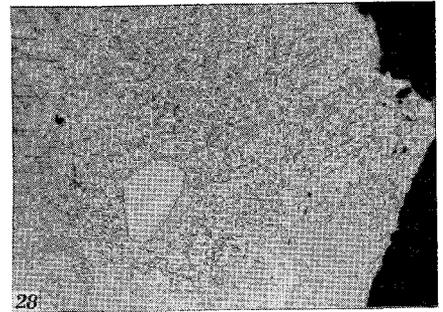
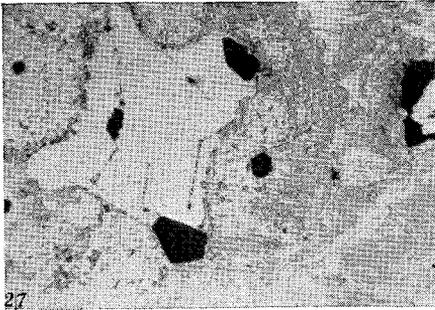
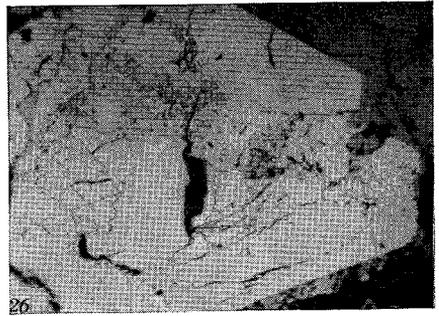
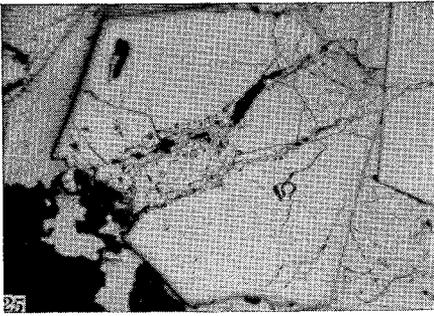


PLATE V

25. Crystal of gersdorffite broken, and partly replaced by chalcopyrite (*left and bottom*). Pentlandite containing fine pyrrhotite forms much of the groundmass on the right. Refl. light, in air, $\times 17$ (Ni34).
26. Gersdorffite crystal replaced by pyrrhotite (*upper right, containing fine secondary pyrite*), chalcopyrite (*lower left*) and intergrowth of niccolite and maucherite (*central areas*). Refl. light, in air, $\times 38$ (Ni10).
27. Residuals of gersdorffite (*white*) within fine gersdorffite-chalcopyrite-niccolite replacement intergrowth. Refl. light, in air, $\times 17$ (Ni34).
28. Gersdorffite relict (*white*), with much irregular, fine residual gersdorffite in the surrounding chalcopyrite-niccolite matrix. More clearly defined intergrowth of chalcopyrite, niccolite and maucherite is shown on the extreme upper right. Refl. light, in oil, $\times 60$ (Ni41).
29. Spongy gersdorffite (*white*) residuals in pseudoeutectic intergrowth of niccolite (*lighter grey*), chalcopyrite (*intermediate grey*) and maucherite, dark grey to almost black. Refl. Pol. light, in oil, $\times 156$ (Ni41).
30. Idiomorphic gersdorffite (*white*) surrounded by pyrrhotite containing fine secondary pyrite. A little chalcopyrite replacement at upper right. Refl. light, in air, $\times 17$ (Ni34).

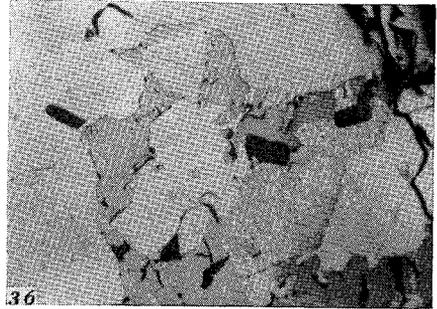
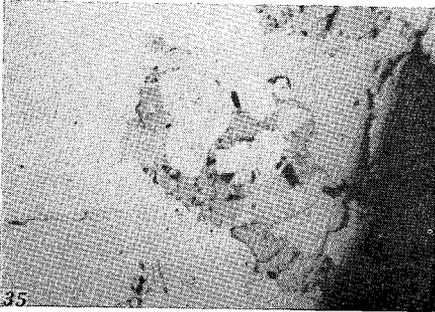
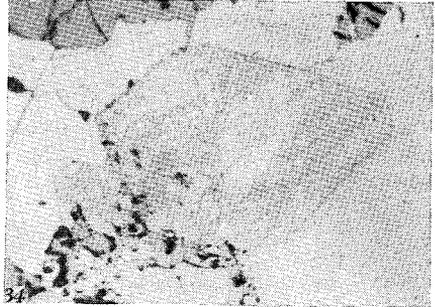
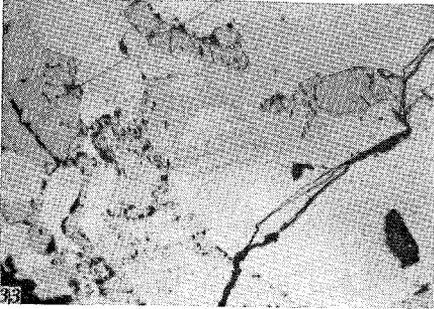
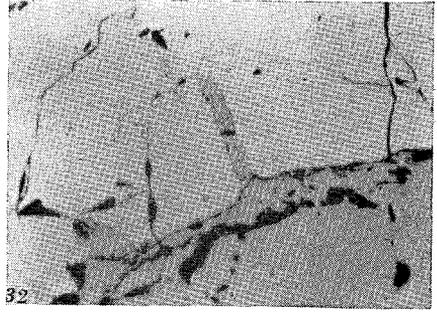
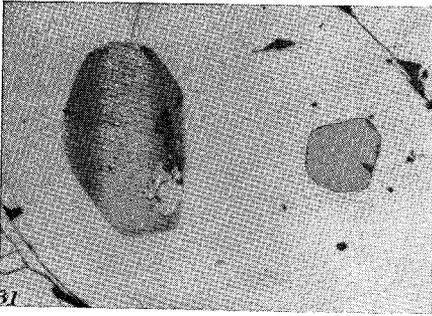


PLATE VI

31. Rounded (subhedral) grains of maucherite (*dark grey*) in niccolite (*light grey*). Rounded inclusion of chalcopyrite in maucherite grain on left. Form of maucherite grains suggests they may be pseudomorphous after gersdorffite, crystals of which are present in niccolite. Refl. pol. light, in oil, $\times 156$ (Ni44).
32. Massive maucherite (*white*) showing veining and replacement by pyrrhotite (*grey*). Refl. light, in air, $\times 17$ (Ni34/2).
33. Former subhedral crystal of gersdorffite (*centre*) enclosed in massive maucherite (*white*). Gersdorffite now largely replaced by fine pyrrhotite-maucherite intergrowth. Replacement veinlets and rounded bodies of pyrrhotite, containing pentlandite flames, also occur in the maucherite. Refl. light, in air, $\times 17$ (Ni184b).
34. Enlargement of above, showing detail of gersdorffite remnant, and pyrrhotite-maucherite intergrowth. Refl. light, in air, $\times 38$ (Ni184b).
35. Massive maucherite (*white, left*) veined by pyrrhotite (*grey, containing pentlandite flames*) and chalcopyrite (*intermediate grey*). The pyrrhotite contains two maucherite-pyrrhotite pseudomorphs of subhedral gersdorffite crystals (*right of centre*). Refl. light, in air, $\times 17$ (Ni184b).
36. Enlargement of central portion of above, showing detail of pentlandite flames (*white*) and fine pyrrhotite-maucherite intergrowth pseudomorphous after gersdorffite (*right and top centre*) in white maucherite. Refl. light, in air, $\times 38$ (Ni184b).

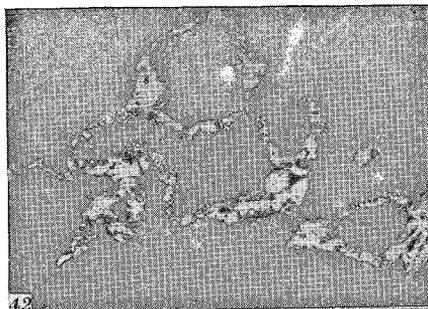
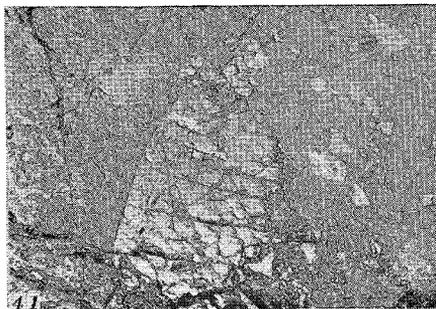
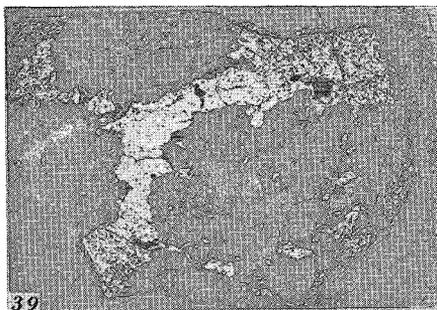
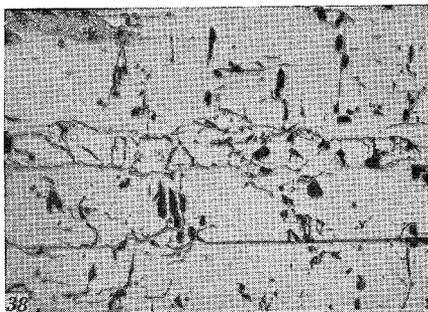
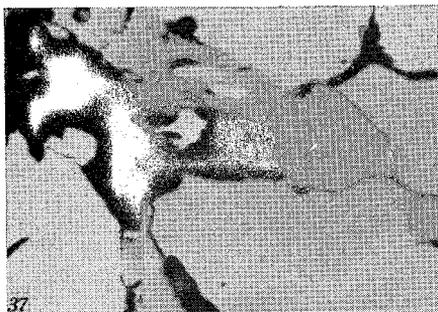


PLATE VII

37. Dark grey pyrrhotite invading and exploiting grain boundaries in niccolite (*lighter grey to white*). One of two niccolite inclusions in pyrrhotite (*upper centre*) is optically continuous with niccolite on top. Refl. light, in oil, $\times 156$ (Ni45).
38. Irregular lens or veinlet of pentlandite (*white centre*) paralleling basal parting of single grain of pyrrhotite (*light grey*). Many very fine blades of pentlandite also lie parallel to parting. Refl. light, in air, $\times 34$ (Tx16) Murray lamellar ore.
39. Coarse, rounded grains of pentlandite (stained dark grey with chromic acid), *apparently* cemented and replaced by pyrrhotite (*white*). Other sections indicate reverse relation. Refl. light, in air, $\times 1.5$.
40. Rounded mass of pentlandite (stained dark grey with chromic acid) in pyrrhotite which is fine grained close to pentlandite and coarser farther away. Under higher magnification and crossed nicols pentlandite is actually seen to replace individual pyrrhotite grains and is interpreted as a sub-solidus segregation. Refl. light, in air, $\times 1.5$ (Ni133).
41. Large ovoid of pentlandite in pyrrhotite. Outline of this pentlandite normal to this surface is irregular to step-like. Oblique light in air, $\times 3$.
42. Cell or net texture of pentlandite (*white*) in pyrrhotite (*gray*). Refl. light, crossed nicols, $\times 26$ (Ni70).

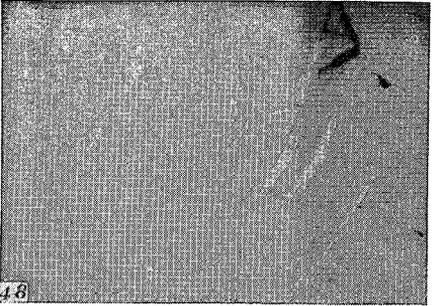
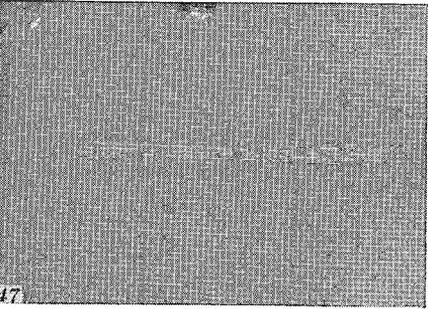
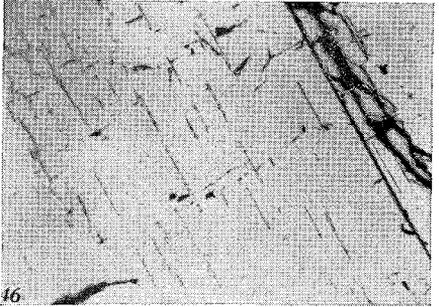
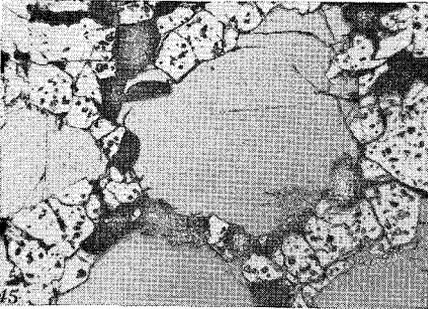
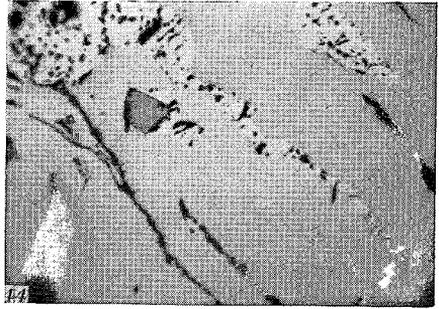
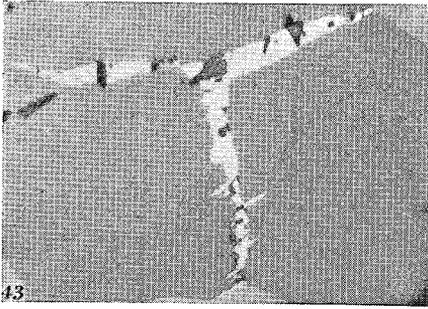


PLATE VIII

43. Pentlandite (*white*) following grain boundaries of pyrrhotite (*grey*). Flames of pentlandite (*lower centre*) protrude into pyrrhotite. Refl. light, in air, crossed nicols, $\times 54$ (Ni165).
44. Interstitial granular pentlandite (*white*; *upper left*) gradational into rim or type, following around pyrrhotite grain boundaries towards lower right. Refl. light, in air, $\times 17$ (Ni165).
45. Cell or net texture of granular pentlandite (*white*) around grains of pyrrhotite (*grey*) which is devoid of intergrown blades of pentlandite. Pentlandite contains many fine inclusions. Pits are black. Refl. light, in oil, $\times 78$ (Ni19).
46. Section perpendicular to (0001) plane of pyrrhotite, showing basal parting and orientation of pentlandite rods parallel to this. Refl. light, in air, $\times 17$ (Ni50).
47. Detail of blade or rod of pentlandite (*white*) in pyrrhotite (similar to No. 46), showing en echelon structure of pentlandite. Refl. light, in oil, $\times 315$ (Ni57A).
48. Flames of pentlandite in pyrrhotite; note slightly different orientation of flames on either side of pyrrhotite twin boundary. Refl. light, in oil, $\times 38$ (Ni71).

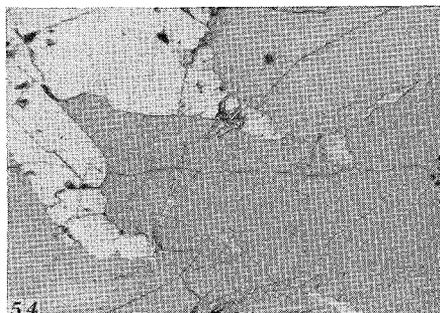
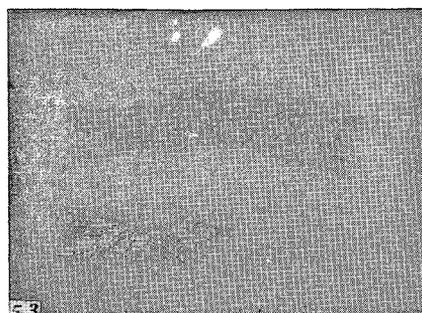
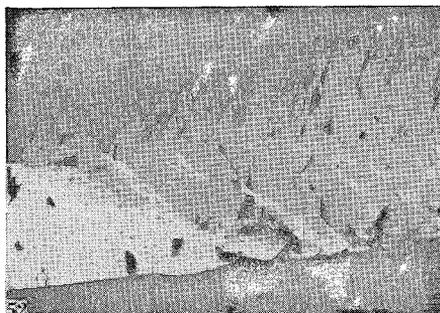
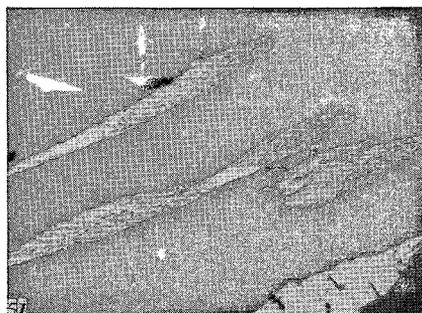
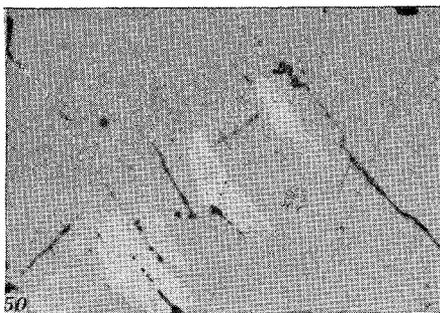
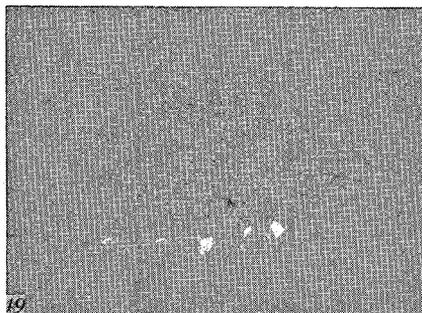


PLATE IX

49. Pentlandite rosette (*light grey*) in pyrrhotite (*dark grey*) polished along parting plane of pyrrhotite. Refl. light, in oil, X 252 (Ni1).
50. Enlargement of pentlandite flames, similar to those of Plate VIII, 48, showing spongy structure. Refl. light, in oil, X 75 (Ni71).
51. Spindle and wedge shaped aggregates of pentlandite (*light*) in pyrrhotite (*dark*). En echelon, flame character of upper segregations in contrast to solid pentlandite wedge at base. Refl. light, in air, crossed nicols, X 156 (Ni71).
52. Pentlandite (*light grey*) showing herring-bone structure in twinned pyrrhotite, one twin lamella of which is white, rest, dark grey. Refl. light, in air, crossed nicols, X 81 (Tx-7).
53. Fine arborescent blocky segregations of pentlandite (*white*) in pyrrhotite (*grey*) cut parallel to basal parting. These contrast with rosettes of No. 49. In oil X 156 (Ni50-2).
54. Coarse interstitial pentlandite (*white*) passing into finer rims and flames along grain boundaries of non-magnetic pyrrhotite (*grey*). Refl. light, in oil, X 78 (P16-2).

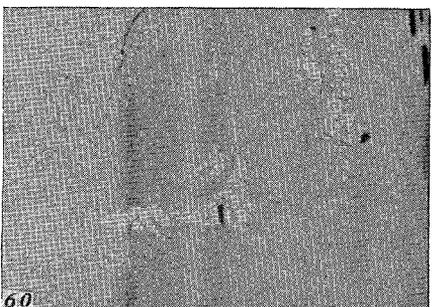
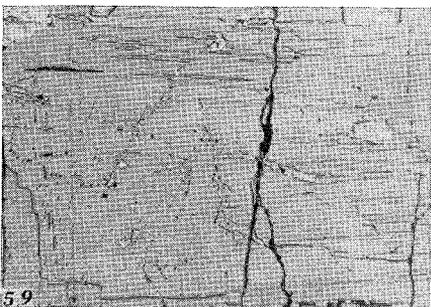
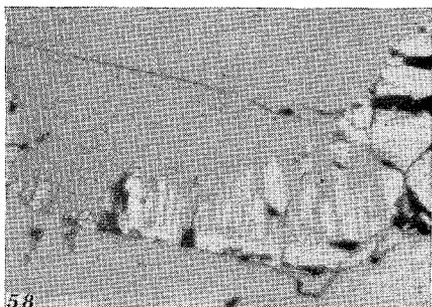
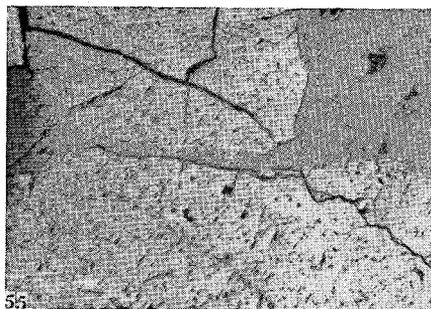


PLATE X

55. Coarse pentlandite grains (white) with abundant inclusions of fine pyrrhotite (*light grey*) surrounded by pyrrhotite (*darker grey*) which near the larger grains of pentlandite contains abundant flames of pentlandite, but farther away (*upper right*) is relatively free of them. A few small grains of fine secondary pyrite occur in pyrrhotite. Refl. light, in oil, $\times 16$ (Ni38).
56. Apparent two-phase body in coarse pentlandite (*white*) showing cleavage. Dark gray mottled mass in centre and in veinlets on left are composed of intergrown pyrrhotite of two orientations accounting for differences in colour. Refl. light, in oil, $\times 396$ (F.19) (section from Falconbridge Nickel Mines).
57. Dark grey pentlandite flames (stained dark with chromic acid) projecting outward from central core of pyrrhotite into chalcopyrite suggesting a reaction rim. Refl. light, in oil (Fa 17) (specimen Falconbridge Nickel Mines).
58. Enlargement of part of 57 showing pentlandite (*white*) rim paralleling contact between pyrrhotite (*on bottom*) and chalcopyrite on top. Blades of pentlandite project up into chalcopyrite. Refl. light, in oil, $\times 252$ (Fa 17).
59. Blades of cubanite (*running right and left, with slightly higher relief*) in chalcopyrite. Pentlandite grains (white) occur as "gash-like veins" and in clusters following curved fracture (?) (upper centre) and interrupt cubanite blades. Refl. light, in oil, $\times 78$ (Ni27).
60. Pentlandite (*light grey*) segregations in chalcopyrite and apparently partially replaced by it. Refl. light, in oil, $\times 252$ (Ni27).

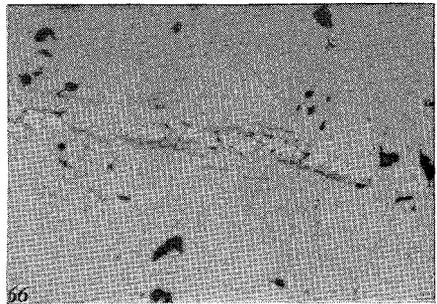
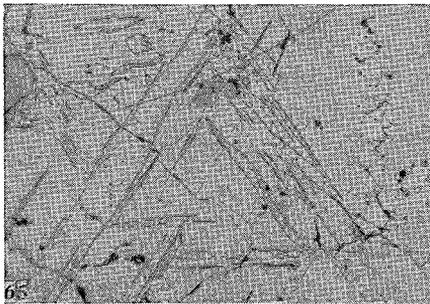
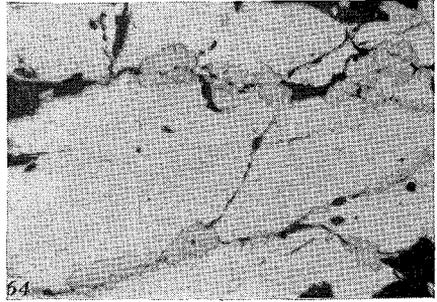
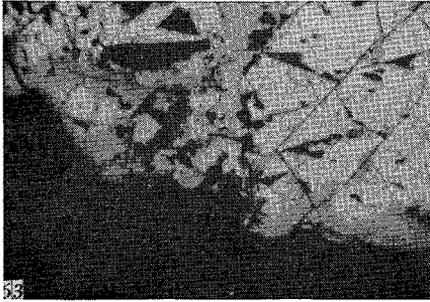
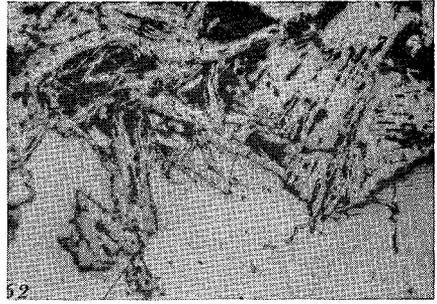
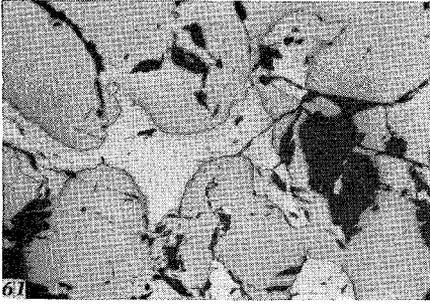


PLATE XI

61. Chalcopyrite (*white*) interstitial to pyrrhotite (*grey*) and clearly replacing it along grain boundaries. Refl. light, in air, X 38 (Ni176).
62. Pyrrhotite (*top*), pseudomorphous after bent chlorite (?), suffering some replacement by "vein-type" late galena (*white*). Refl. light, in air, X 17 (Ni176).
63. Light and darker grey mixture of cubanite and chalcopyrite replacing coarse pentlandite along periphery and cleavages, as in Plate IV, 21. Cubanite occurs as a fine selvage between pentlandite and chalcopyrite, and as ex-solution laths in the latter. Refl. light, in oil, X 60.
64. Late pyrrhotite (*grey*) localized in cracks in and along grain boundaries of earlier chalcopyrite (*white*). Refl. light, in oil, X 160 (Ni176) (same specimen as 62 & 78 with late vein of pyrrhotite, sphalerite and galena).
65. Blades and laths of cubanite following three (112) directions in chalcopyrite. Blocky pentlandite masses with cleavage, in chalcopyrite on right. Refl. light, in air, X 34 (Ni27).
66. Exsolution spindles of valleriite with en echelon arrangement (*dark grey—in maximum absorption position*) associated with lens of pentlandite (*white*) showing cleavage in chalcopyrite. Polarized reflected light, in air, X 73 (Ni160).

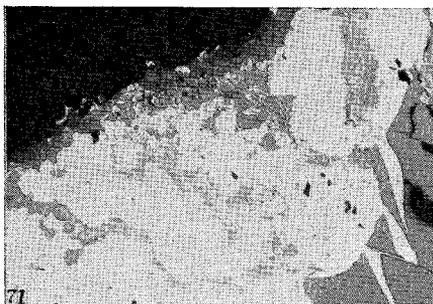
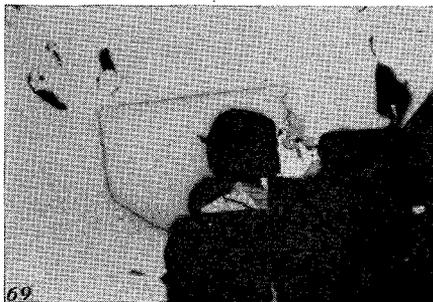
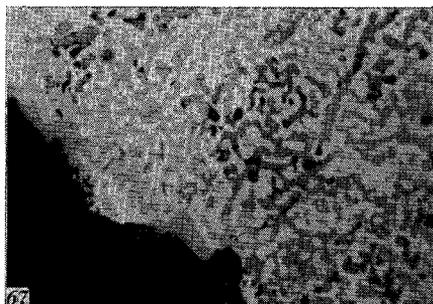


PLATE XII

67. Pseudoeutectic intergrowth of chalcopyrite (*lightest grey to white*), niccolite (*medium grey*) and maucherite (*darker grey*); black is gangue. Refl. light, in oil, $\times 60$ (Ni41).
68. Sphalerite (*dark grey*) with abundant oriented blebs of chalcopyrite (*white*), embaying and apparently replacing coarse chalcopyrite. Refl. light, in air, $\times 138$ (Ni56).
69. Subhedral crystal of galena (*centre*) largely surrounded by chalcopyrite (*top*), associated with native silver (*white*) partially rimmed by bornite (*dark grey*). Magnetite grains (*black*) in lower right. Refl. light, in oil, $\times 38$ (Ni16).
70. Gold (*white, lower right*), and hessite (*grey with scratched surface at top left*) moulded about parkerite centre, showing typical polysynthetic twinning. The white angular particle within the hessite is tetradymite. Galena (*smooth grey*) forms the lower portion of the photograph. Refl. light, in oil, $\times 38$ (Ni16).
71. Parkerite (*white*) rimmed by native bismuth, in bornite (*grey*). Note exsolution lamellae or lenses of chalcopyrite (*white*) in bornite at lower right, and spongy chalcopyrite between areas of parkerite-bismuth. Refl. light, in oil, $\times 38$ (Ni157).
72. Parkerite (*flat white*) and native bismuth (*white, high reflectivity and showing polishing imperfections*) in bornite (*grey*). The bismuth tends to sponge and filament form, and occurs as discontinuous rims round the parkerite. Refl. light, in oil, $\times 38$ (Ni157).

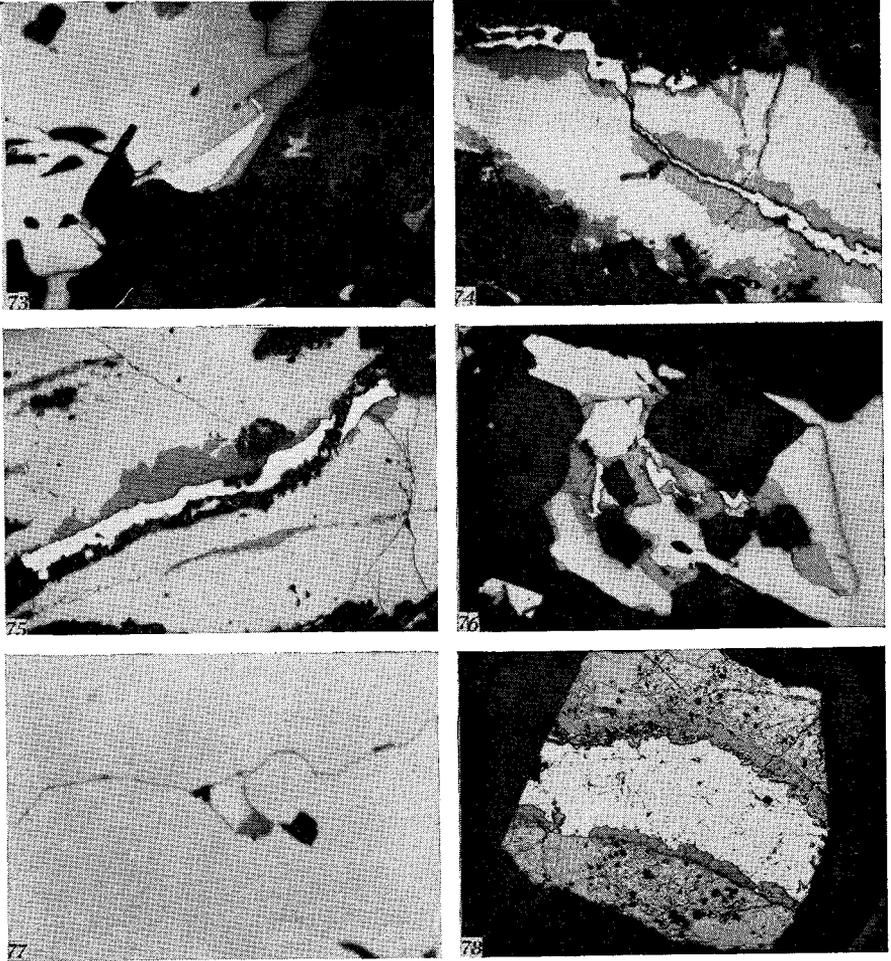


PLATE XIII

73. Native gold (*centre*) within galena (*upper left*), and moulded about chalcopyrite (*grey with higher relief*). A little bornite also present (*top centre*). Refl. light, in oil, $\times 38$ (Ni16).
74. Vein of native silver (*white*) cutting chalcopyrite (*intermediate white*) and bornite (*darker grey*). Note that silver and chalcopyrite are separated by a rim of bornite, and that where the silver vein pinches there is no bornite developed. (Black is gangue). Refl. light, in air, $\times 17$ (Ni157).
75. Chalcopyrite cut by a composite vein of silver (*white*) and gangue (*black*). Note development of bornite along vein wall only as a rim between silver and chalcopyrite. Refl. light, in air, $\times 17$ (Ni157).
76. Native silver (*bright white*) rimmed by bornite (*grey*), in association with parkerite (*lower centre*) chalcopyrite (*with high relief, right*) and galena (*extreme right*). Refl. light, in oil, $\times 38$ (Ni16).
77. Massive maucherite (boundary between two grains runs irregularly across photograph) enclosing a composite particle of michenerite? (*speckled white*) and hessite (*dark grey*). Black is gangue. Refl. light, in air, $\times 99$ (Ni34/2).
78. Vein of late galena (*white*) with selvage (*grey*) of sphalerite with minor pyrrhotite (*higher relief*) between, cutting massive sulphide ore of pyrrhotite, pentlandite and chalcopyrite. Refl. light, in air, $\times 1.5$ (Ni176).

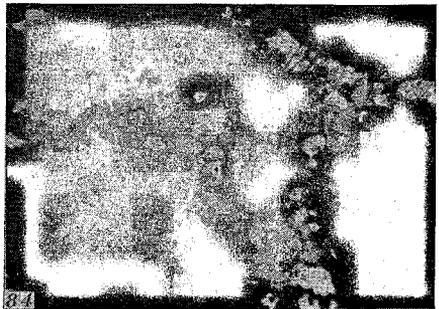
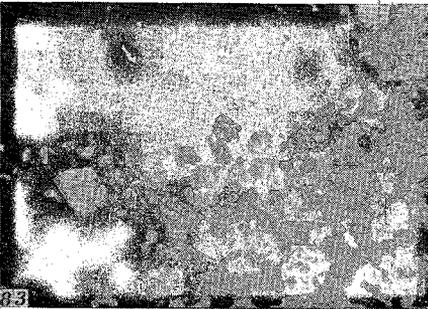
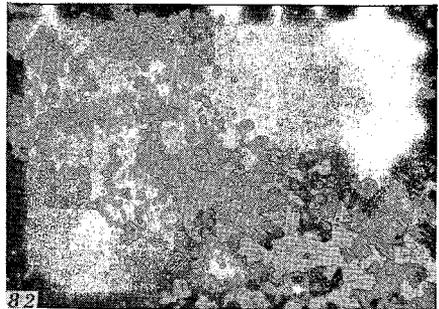
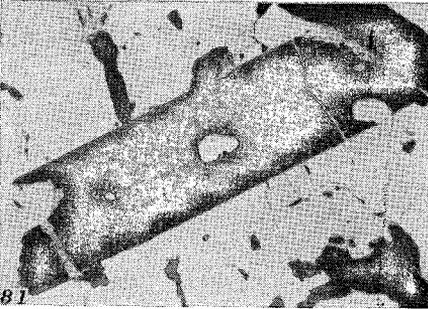
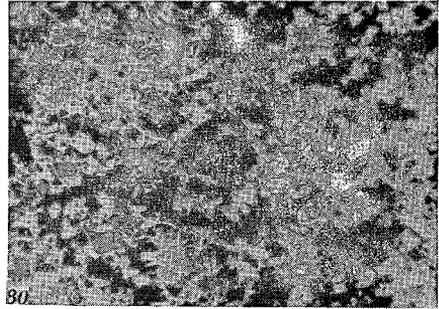


PLATE XIV

79. Millerite (*light, lower half*) and violarite (*dark, spongy*), adjacent to chalcopyrite (*light grey, upper right*). The millerite and violarite are late-stage alteration products of pentlandite, formerly adjacent to the chalcopyrite. Refl. light, in air, $\times 17$ (Ni5).
80. Marcasite (*white*) and interstitial, feathery nickeloan pyrite (*off-white*), with dark grey grains of primary magnetite. Black is gangue. Refl. light, in oil, $\times 38$ (Ni22).
81. Subhedral hornblende set in massive maucherite (*white*), and showing corrosion and veining by maucherite, pyrrhotite (*lower left, grey*) and chalcopyrite (*upper right*). Refl. light, in air, $\times 17$ (Ni34/1).
82. Thin section showing two sulphide blebs (*black, lower left and upper right*) separated by silicates. Margins are clearly irregular and spongy. Transmitted light, $\times 15$.
83. Thin section showing two sulphide blebs (*black, top and lower left*) at coalescing stage. Note marginal inclusions of subhedral pyroxene and feldspar, both of which are somewhat rounded. Transmitted light, $\times 15$.
84. Thin section showing almost complete coalescence of sulphide blebs (*black*). Transmitted light, $\times 15$.

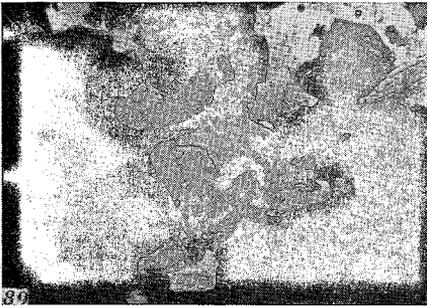
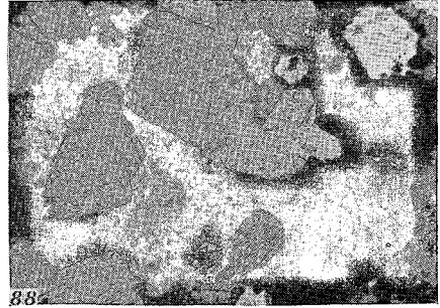
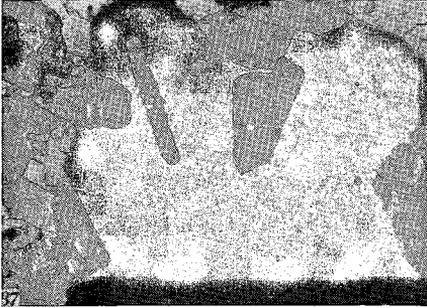
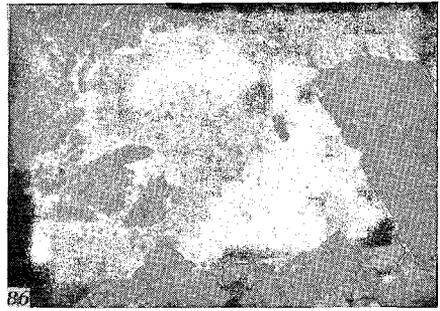
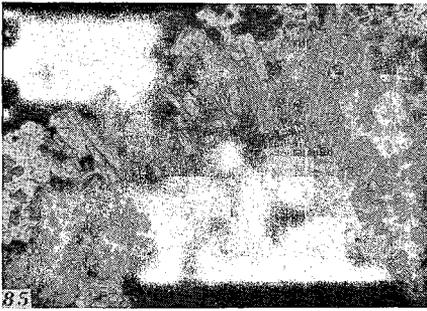


PLATE XV

85. Thin section showing minor veining of silicate by sulphide (*black*), developed around margins of sulphide blebs. Transmitted light, X 15.
- 86, 87, 88. Sulphide blebs (*black*) in coarse "Norite." Note that the feldspars (*light grey*) tend to show sharp edges against sulphide, with the latter an interstitial constituent. Corrosion of silicates evident in places. Transmitted plain light, X 15.
89. Corrosion of silicates (*light and darker grey*) by sulphide (*black*). Transmitted plain light, X 15.
90. Inclusion of subhedral to slightly rounded orthopyroxene, in sulphide (*black*). Transmitted plain light, X 15.

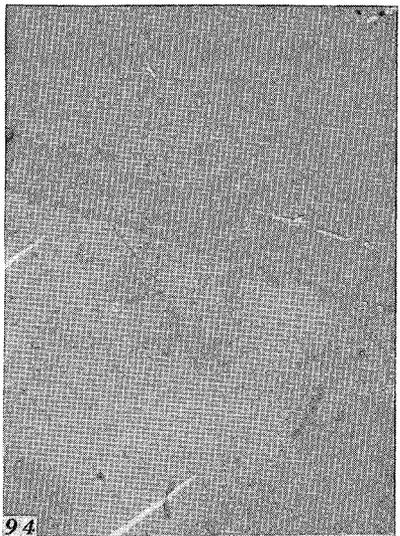
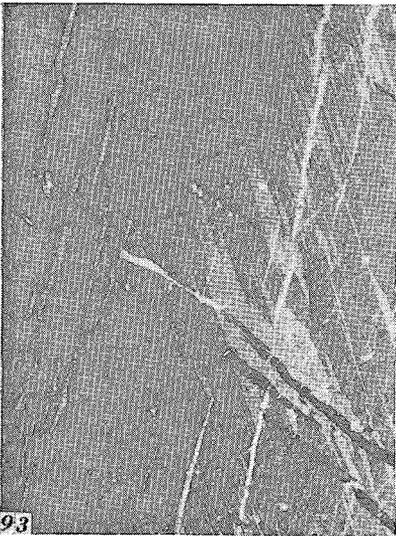
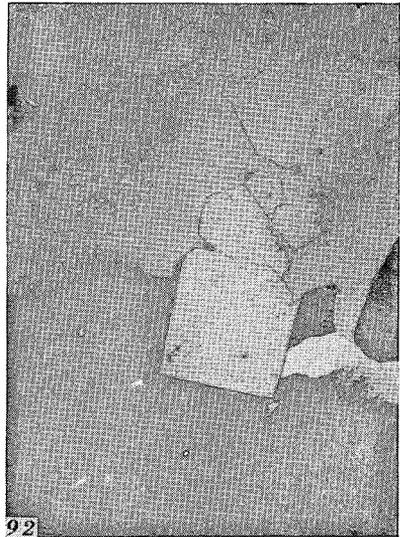


PLATE XVI

91. Fine "reaction" pyrite crystals (*white, centre*) forming at boundary between two pyrrhotite grains. Small segregations and flames of pentlandite (*light grey to white*) are developed in pyrrhotite. Crossed nicols, X 42. (photo by A. J. Naldrett).
92. Coarser "reaction" pyrite showing sharp crystal edges against pyrrhotite (*dark grey, bottom*), but corroded boundaries against chalcopyrite (*light grey, top*). Crossed nicols, X 42 (photo by A. J. Naldrett).
93. Two prominent sets of stringers or blades of ex-solution pyrrhotite, one, white, the other black (at extinction) in intergrowth of cubanite (*light grey*) and chalcopyrite (*dark grey*). Angle between pyrrhotite stringers is bisected by cubanite lamellae. Crossed nicols, X 119. (Specimen courtesy M.I.T. No. 1697).
94. Cubanite lath (*darker grey*) in chalcopyrite with fine strings of valleriite (*white*) oriented in chalcopyrite, and paralleling border of cubanite. With partially crossed nicols, X 119. (Specimen courtesy M.I.T. No. 1435).

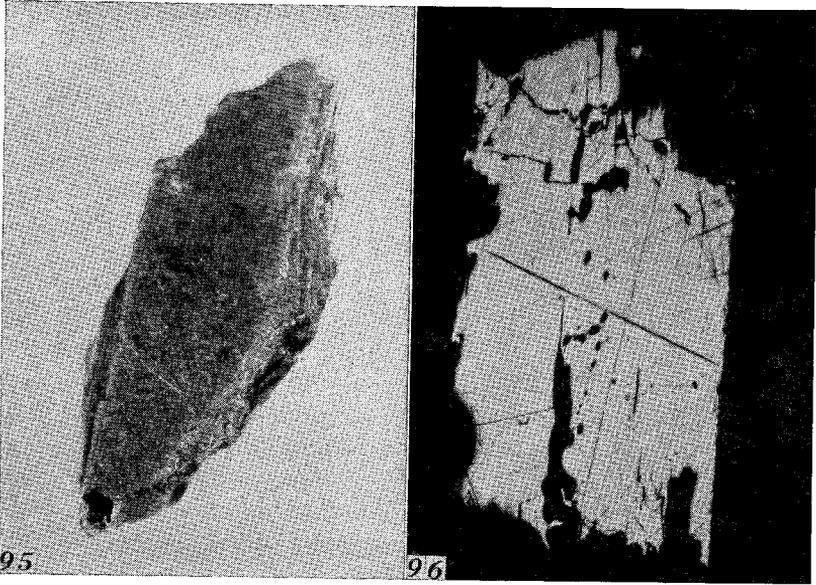


PLATE XVII

95. Froodite-PdBi₂, Frood Mine, Sudbury. Crystal fragment showing (100) cleavage, $\times 14$. Photo by C. E. Michener.
96. Froodite-PdBi₂, Frood Mine Sudbury. Polished surface in bakelite mount $\times 43$. Photo by C. E. Michener.

effects of two or more orogenies and many periods of intrusive activity. Finally, from a more practical standpoint, though by no means new and perhaps hardly required, we may emphasize what has long been common practice, that the search for ore in this area continue along the norite contact, particularly where changes in dip occur. There seems no reason why ores should not continue in suitable structures to depths well below mining limits, nor for that matter, why other offsets may not be present in footwall rocks, difficult though they would be to find beneath the irruptive cover.

REFERENCES

- ARNOLD, R. G. (1957-8): The Fe-S system. *Ann. Report. Director Geophysical Laboratory, Carnegie Inst. Washington*, **57**, 218-222.
- BARLOW, A. E. (1904, 1907): Origin, geological relations and composition of the nickel and copper deposits of the Sudbury mining District, Ontario. *Geol. Surv. Canada, Ann. Report 14* (for 1901) 1-236 (no. 873). Revised and reprinted 1907, *Geol. Surv. Canada, Ann. Report* (for 1908) 1-244 (no. 961).
- BEAMISH, F. E. (1959): A critical evaluation of spectrographic fluorescent x-ray polarographic methods for the determination of the platinum metals. *Talanta*, **2**, 244-265.
- BOWEN, N. L. (1928): *The Evolution of the Igneous Rocks*. Princeton Univ. Press.
- BROWNE, D. H. (1893): The composition of nickeliferous pyrrhotite. *Eng. Min. Jour.* **56**, 565-566, (Dec. 2).
- BUERGER, M. J. (1937): The unit cell and space group of cubanite. *Am. Mineral.* **22**, 1117.
- BURR, S. V. & PEACOCK, M. A. (1942): A preliminary study of the alloys of palladium and bismuth. *Univ. Toronto Studies, Geol. Series*, **47**, 19-20.
- BURROWS, A. G. & RICKABY, H. C. (1929): Sudbury Basin area. *Ontario Dept. Mines Ann. Rept.* **38**, pt. 3.
- (1934): Sudbury nickel field restudied. *Ontario Dept. Mines Ann. Rept.* **43**, pt. 2.
- CHIRKOV, I. N. (1940): Pentlandite from the copper-nickel deposit of Monche-Tundra. *Comptes. Rend. de L'Acad. des Sce. de L' U.S.S.R.*, **29**.
- CLARKE, A. M. (1946): Occurrence of marcasite at Falconbridge Nickel Mines. *Unpub. master's thesis. Queen's University*.
- & POTAPOFF, P. (1959): Geology of McKim mine. *Proc. Geol. Assoc. Can.* **11**, 67-80.
- COLEMAN, A. P. (1905): The Sudbury nickel field. *Ontario Bur. Mines, Ann. Rept.* **14**, pt. 3.
- (1913): The nickel industry. *Dept. of Mines Canada No.* 170.
- , MOORE, E. S., & WALKER, T. L. (1929): The Sudbury nickel intrusive, *Univ. Toronto Studies, Geol. Ser.* **28**, 1-54.
- COLGROVE, G. L. (1942): The system Fe-Ni-S. *Unpub. doctorate thesis, University of Wisconsin*.
- COLLINS, W. H. (1925): North shore of Lake Huron. *Geol. Survey Canada. Mem.* **143**.
- (1934): Life history of the Sudbury nickel irruptive (I). *Trans. Roy. Soc. Canada*, **28** (IV), 123-177.
- (1935): (II) *Trans. Roy. Soc. Canada* **29** (IV), 27-47.
- (1936): (III) *Trans. Roy. Soc. Canada* **30** (IV), 29-53.
- (1937): (IV) *Trans. Roy. Soc. Canada* **31** (IV), 15-43.
- COOKE, H. C. (1946): Problems of Sudbury geology. *Geol. Survey Canada, Bull.* **3**, 77.
- DANA, J. D. & E. S. (1944, 1951): *System of mineralogy* **1**, 2 ed. 7, by C. Palache, H. Berman & C. Frondel, New York.

- DAVIDSON, S. C. (1946): Structural aspects of the geology of Falconbridge nickel mine, Sudbury District, Ontario. *Trans. Can. Inst. Min. Met.* **49**, 496-504.
- (1948): Falconbridge Mine. *Structural Geology Canadian Ore Deposits—Jubilee Volume*. 618-626. (*Can. Inst. Min. & Met.*)
- DE BRUYN, P. L. (1944): A new occurrence of nickeliferous ore in the Bushveld Complex. *Annals. Univ. Stellenbosch*, **22**, Sec. A, 63-96.
- DICKSON, C. W. (1904): The ore deposits of Sudbury. *Trans. Amer. Inst. Min. Eng.* **34**, 1-67.
- EDWARDS, A. B. (1952): The ore minerals and their textures. *Jour. Proc. Roy. Soc. New South Wales*, **85**, 26-46.
- (1954): Textures of the ore minerals: *Australian Inst. Mining & Met.* (Melbourne).
- FAIRBAIRN, H. W. & ROBSON, G. M. (1941): Breccia at Sudbury. *Ontario Dept. Mines. Rept.* **50**, pt. 6.
- , HURLEY, P. M. & PINSON, W. H. (1960): Mineral and rock ages at Sudbury—Blind River, Ontario. *Proc. Geol. Assoc. Canada*, **12**, 41-66.
- GINN, R. M. (1958): A study of granitic rocks of the Sudbury area: *Unpub. master's thesis, Queen's University*.
- (1960): The relationship of the Bruce series to the granites in the Espanola area. *Unpub. doctorate thesis, University of Toronto*.
- GOLDICH, S. S., NIER, A. O., BAADSGAARD, H., HOFFMAN, J. H. & KRAEGER, H. W., (1961): The Precambrian geology and geochronology of Minnesota. *Bull.* **41**, *Univ. Minnesota Press, Minneapolis*.
- GRAHAM, A. R. & KALMAN, S. (1952): Aurostibite AuSb_2 a new mineral in the pyrite group. *Am. Mineral.* **37**, 461.
- (1956): *Personal communication*.
- GREGORY, J. W. (1907-8): *Geol. Mag.*, **4**, 454; **5**, 139.
- GREIG, J. W., JENSEN, E., & MERWIN, H. E. (1955): The system Cu-Fe-S. *Ann. Rept. Director Geophys. Lab. Carnegie Inst. Washington*, **54**, 129-134.
- GRIP, E. (1961): Geology of the nickel deposit at Lainijaur in northern Sweden. *Sveriges Geol. Undersök.*, **55**, no. 1, 1-79.
- GROENEVELD MEIJER, W. O. J. (1954): Geochemistry of the platinum metals with respect to their occurrence in the nickeliferous sulphide deposits. *Unpub. doctorate thesis, Queen's University*.
- (1955): Synthesis, structures and properties of the platinum metal tellurides. *Am. Mineral.* **40**, 646-7.
- GUIDE BOOK for Field Trip No. 7, (1953): Sudbury Area, in conjunction with joint annual meeting in Toronto, Ontario, of *Geol. Soc. of Am.* and *Geol. Assoc. Canada* (by Sudbury geologists).
- GUIDE BOOK for Field Trip, Sudbury Area (1957): *Sixth Commonwealth Mining and Metallurgical Congress* (by Sudbury geologists).
- HAW, V. A. (1948): Further studies of nickel ores of the Sudbury type: *Unpub. master's thesis, Queen's University*.
- HAWLEY, J. E., COLGROVE, G. L., & ZURBRIGG, H. F. (1943): The Fe-Ni-S system. *Econ. Geol.* **38**, 335-388.
- & HEWITT, D. F. (1948): Pseudo-eutectic and pseudo-exsolution intergrowths of nickel arsenides due to heat effects: *Econ. Geol.* **43**, 273-279.
- , LEWIS, C. L. & WARK, W. J. (1951): Spectrographic study of platinum and palladium in common sulphides and arsenides of the Sudbury district Ontario. *Econ. Geol.* **46**, 149-162.
- , RIMSAITE, Y. & LORD, T. V. (1953): Lead bead method of spectrographic analysis of platinum metals, etc. *Trans. Canadian Inst. Mining & Met.* **56**, 19-26.
- & RIMSAITE, Y. (1953): Platinum metals of some Canadian uranium and sulphide ores: *Am. Mineral.* **38**, 463-475.

- & HAW, V. A. (1957): Intergrowths of pentlandite and pyrrhotite. *Econ. Geol.* **52**, 132-139.
- & BERRY, L. G. (1958): Michenerite and froodite, palladium bismuthide minerals. *Canadian Mineral.* **6**, 200-209.
- & NICHOL, I. (1959): Selenium in some Canadian sulphides. *Econ. Geol.* **54**, 608-628.
- & NICHOL, I. (1951): Trace elements in pyrite, pyrrhotite and chalcopyrite of different ores. *Econ. Geol.* **56**, 467-487.
- , STANTON, R. L. & SMITH, A. Y. (1961): Pseudo-eutectic intergrowths in arsenical ores from Sudbury. *Canadian Mineral.* **6**, 555-575.
- HARCOURT, G. A. (1933): The distribution of nickel in the Sudbury norite micropegmatite. *Unpub. master's thesis, Queen's University.*
- HORWOOD, H. C. (1936): Geology and mineral deposits of the mine of British Columbia Nickel Mines Ltd. Yale District. B.C. *Geol. Survey. Canada. Summ. Rept.* Pt. A, 66.
- HOWE, E. (1914): Petrographical notes on the Sudbury nickel deposits. *Econ. Geol.* **9**, 505-522.
- IBRAHIM, M. A. (1959): Ternary phase in the M_9S_8 section of the system Fe-Co-Ni-S. *Unpub. master's thesis, Nova Scotia Tech. College.*
- INTERNATIONAL NICKEL CO. OF CANADA, Staff (1946): Operations and plants International Nickel Co. of Canada. Chapt. III—Geology. *Can. Mining Jour.* **65**, No. 5, 322-331.
- JAMES, H. L. (1958): Stratigraphy of pre-Keweenaw rocks in parts of northern Michigan. *U.S. Geol. Survey. Prof. Paper* **314C**.
- JENSEN, E. (1942): Pyrrhotite melting relations and composition. *Am. Jour. Sci.* **240**, 695-709.
- KENRICK, E. B. (1886): Chemical contributions to the geology of Canada. *Geol. Surv. Canada, Ann. Report* **2**, pt. T, 11.
- KNIGHT, C. W. (1917): *Report of the Royal Ontario Nickel Commission, Toronto*, 105-211.
- (1923): The chemical composition of the norite-micropegmatite, Sudbury, Ontario. *Econ. Geol.* **18**, 592-594.
- KOUVO, O., HUHMA, M. & VUORELAINEN, Y. (1959): A natural cobalt analogue of pentlandite. *Am. Mineral.* **44**, 897-900.
- KULLERUD, G. (1956): Subsolidus phase relations in the Fe-Ni-S system. *Ann. Rept. Director Geophys. Lab. Carnegie Inst. Washington*, **55**, 175-177.
- & YODER, H. S. (1959): Pyrite stability relations in the Fe-S system. *Econ. Geol.* **54**, 533-572.
- & YUND, R. A. (1958-9): The Ni-S system. *Ann. Rept. Director Geophys. Lab. Carnegie Inst. Washington*. **58**, 139-153.
- LAUSEN, CARL (1930): Graphic intergrowth of niccolite and chalcopyrite, Worthington mine, Sudbury. *Econ. Geol.* **25**, 356-364.
- LEWIS, C. L. (1950): The minor elements of the Sudbury Ore minerals. *Unpub. master's thesis, Queen's University.*
- (1957): The determination of precious metals in ores. *Bull. Can. Inst. Mining Met.* **50**, (March, no. 539) 163-167.
- LINDGREN, W. & DAVY, W. M. (1924): Nickel ores from Key West mine, Nevada. *Econ. Geol.* **19**, 309-319.
- LINDQVIST, M., LUNDQVIST, D. & WESTGREN, A. (1936): The crystal structure of Co_9S_8 and of pentlandite. $(Ni, Fe)_9S_8$. *Kemisk Tidskrift*, **48**, 156-160.
- LOWDON, J. A. (1961): Age determinations by the Geological Survey of Canada, Report 2, Isotopic ages. *Geol. Surv. Canada, paper* **61-17**, p. 117.
- LUNDQVIST, DICK (1947): X-ray studies on the ternary system Fe-Ni-S. *Arkiv. Kemi. Min. Geol.* **24**, no. 22, 1-12.
- LOCHHEAD, D. R. (1955): A review of the Falconbridge ore deposit. *Econ. Geol.* **50**, 42-50.

- McKINSTRY, H. E. (1959): Mineral assemblages in the sulphide ores, the system Cu-Fe-S-O. *Econ. Geol.*, **54**, 975-1001.
- & KENNEDY, G. C. (1957): Some suggestions concerning the sequence of certain ore minerals. *Econ. Geol.* **52**, 379-390.
- MICHENER, C. E. (1940): Minerals associated with larger sulphide bodies of the Sudbury type. *Unpub. doctorate thesis, University of Toronto.*
- & PEACOCK, M. A. (1943): Parkerite ($Ni_3Bi_2S_2$) from Sudbury. *Am. Mineral.* **28**, 343.
- & YATES, A. B. (1944): Oxidation of primary nickel sulphides. *Econ. Geol.* **39**, 506-514.
- MILTON, C. & MILTON, D. J. (1958): Nickel-gold ores of the Mackinaw mine, Snohomish County, Washington. *Econ. Geol.* **53**, 426-447.
- MITCHELL, G. P. & MUTCH, A. D. (1957): Hardy Mine, *Structural Geol. Canadian Ore Deposits*, **2**, Congress Volume, 350-363. (*Can. Inst. Min. Met.*).
- NALDRETT, A. J. (1961): The geochemistry of cobalt in the ores of the Sudbury district. *Unpub. master's thesis, Queen's University.*
- NEWHOUSE, W. H. (1931): A pyrrhotite-cubanite-chalcopyrite intergrowth from the Frood mine, Sudbury. *Am. Mineral.* **16**, 334-337.
- NICHOL, I. (1958): A trace element study of contemporaneous sulphides, pyrite, pyrrhotite and chalcopyrite. *Unpub. master's thesis, Queen's University.*
- NICOL, W., & GOLDSCHMIDT, V. (1903): Über sperrylith. *Zeit. Kryst.* **38**, 1, 2, 58.
- NODDACK, IDA & NODDACK, W. (1931): Die geochemie des rheniums: *Zeit. Physik. Chem. A.* 154-207.
- PAULY, HANS (1958): Igdlukunguaq nickeliferous pyrrhotite: *Medd. om Grønland*, **157**, Nr. 3, 169.
- PEACOCK, M. A. (1940): On maucherite. *Mineral. Mag.* **25**, 557-572.
- (1946): On heazelwoodite and the artificial compound Ni_3S_2 . *Univ. Toronto Studies. Geol. Ser.* **51**, 59.
- & SMITH, F. G. (1941): Precise measurements of the cube edge of common pyrite and nickeliferous pyrite: *Univ. Toronto Studies. Geol. Ser.* **46**, 107-117.
- & YATSEVITCH, G. M. (1936): Cubanite from Sudbury, Ontario. *Am. Mineral.* **21**, 55.
- PENFIELD, S. L. (1889): On the crystalline form of sperrylite. *Am. Jour. Sci.* **37**, 71-73.
- (1893): On pentlandite from Sudbury, Ontario. *Am. Jour. Sci.* **45**, 492-497.
- PHEMISTER, T. C. (1925): Igneous rocks of Sudbury and their relation to the ore deposits. *Ontario Dept. Mines. Ann. Rept.* **34**, pt. 8.
- (1937): A review of the problems of the Sudbury irruptive. *Jour. Geol.* **65**, 91-116.
- (1956): The Copper Cliff rhyolite in McKim township, District of Sudbury. *Ontario Dept. Mines. Ann. Rept.* **65**, pt. 3, 91-116.
- (1961): The nature of the contact between the Grenville and Temiskaming sub-provinces in the Sudbury district of Ontario. *Canada. Rept. 21st. Inter. Geol. Cong.* pt. **14**, 108-119.
- RANKAMA, K. & SAHAMA, TH. G. (1950): *Geochemistry*. Univ. Chicago Press.
- REYNOLDS, DORIS (1954): Fluidization as a geological process and its bearing on the problem of intrusive granites. *Am. Jour. Sci.*, **252**, 585-587.
- RUSSELL, R. D., FARQUAHAR, R. M., CUMMING, G. L. & WILSON, J. T. (1945): Dating galenas by means of their isotopic constitutions. *Trans. Am. Geoph. Union*, **35**, 301-309.
- RUTTAN, G. D. (1955): Geology of Lynn Lake, *Trans. Can. Inst. Min. Met.* **58**, 191-200.
- *Structural Geol. Canadian Ore Deposits*, **2**, Congress Volume 275-291 (1957) (*Can. Inst. Min. Met.*).
- SADLER, J. F. (1958): A detailed study of the Onwatin formation. *Unpub. master's thesis, Queen's University.*
- SCHNEIDERHÖHN, HANS (1954): La position génétique des gîtes métallifères post-

- Triassic de l'Afrique du Nord Francaise. *Int. Geol. Congress, Algiers, 1952*, Sec. XII 73-90 (Translation by J. S. Brown).
- SCHOLTZ, D. L. (1936): The magmatic nickeliferous ore deposits of East Griqualand and Pondoland. *Trans. Geol. Soc. S.A.* **39**, 81-210. *Univ. of Pretoria*, **2**. *Nat. Sci. No. 1*. (reprint).
- SCHWARTZ, G. M. (1927): Chalcopyrite and cubanite. *Econ. Geol.* **22**, 44-61.
- (1931): The intergrowth of bornite and chalcopyrite. *Econ. Geol.* **26**, 186.
- SHORT, M. N. & SHANNON, E. V. (1930): Violarite and other rare nickel sulphides. *Am. Mineral.* **15**, 1-22.
- SMITH, A. Y. (1961): Experimental investigation of some textures of massive sulphide ores. *Unpub. master's thesis, Queen's University*.
- SMITH, F. G. (1961): Metallic sulphide melts as igneous differentiates. *Canadian Mineral.* **6**, 663-669.
- SPEERS, E. C. (1956): The age relations and origin of the Sudbury breccia. *Unpub. doctorate thesis. Queen's University*.
- (1957): The age relation and origin of common Sudbury breccia. *Jour. Geol.* **65**, 5, 497-514.
- STEVENSON, J. S. (1961): Recognition of the quartzite breccia in the Whitewater series. Sudbury Basin, Ontario. *Roy. Soc. Canada Abst.* June 1961, (in press), *Trans. Roy. Soc. Canada* sec. IV).
- STONEHOUSE, H. (1954): An association of trace elements and mineralization at Sudbury. *Am. Mineral.* **39**, 452-474.
- SUDBURY GEOLOGISTS (1953, 1957)—see GUIDE BOOKS above.
- SULLIVAN, C. J. (1957): Heat and temperature in ore deposition. *Econ. Geol.* **52**, 5-24.
- THOMSON, ELLIS (1938): Some ore minerals of the Denison mine. *Univ. Toronto Studies, Geol. Series.* **41**, 71.
- & ALLEN, J. S. (1939): Nickeliferous pyrite from the Denison mine. Sudbury district, Ontario. *Univ. Toronto Studies. Geol. Series.* **42**, 135.
- THOMSON, J. E. (1956): Geology of the Sudbury basin. *Ontario Dept. Mines Ann. Rept.* **65**, pt. 3, 1-56.
- (1957): Geology of Falconbridge township. *Ontario Dept. Mines Ann. Rept.* **66**, pt. 6.
- (1957): Recent geological studies in the Sudbury camp. *Canadian Mining Jour.* **78**, no. 4.
- (1957): The questionable Proterozoic rocks of the Sudbury-Espanola area. *Royal Soc. Canada, Special Pub.* no. **2**.
- (1960): Uranium and thorium deposits at the base of the Huronian system in the District of Sudbury. *Ontario Dept. Mines. Geol. Rept.* no. **1**, 1-40.
- (1961): Geology of MacLennan and Scadding townships. *Ontario Dept. Mines. Geol. Rept.* no. **2**, 1-34.
- (1961): Extent of the Huronian system between Lake Timagami and Blind River, Ontario. *Roy. Soc. Can. Abst.* June 1961, (in press, *Trans. Roy. Soc. Canada*, sec. IV).
- TOLMAN JR., C. F. & ROGERS, A. F. (1917): The origin of the Sudbury nickel ores. *Engineering and Mining Jour.* **103**, 226-229.
- UYTENBOGAARDT, W. (1951): *Tables for the microscopic identification of the ore minerals.* Princeton Univ. Press.
- WAGER, L. R., VINCENT, E. A., SMALES, A. A. & BARTHOLOMÉ, P. (1957): Sulphides in the Skaergaard intrusion, East Greenland. *Econ. Geol.* **52**, 855-903.
- WALKER, T. L. (1894): Notes on nickeliferous pyrite from Murray mine, Sudbury, Ontario. *Am. Jour. Sci.* **47**, 312.
- (1897): Geological and petrographical studies of the Sudbury nickel district, Canada. *Quart. Jour. Geol. Soc.* **53**, 40-66.
- (1915): Certain mineral occurrences in the Worthington mine, Sudbury Ontario, and their significance. *Econ. Geol.* **10**, 536.

- WALLBAUM (1943): *Zeits. Metallkunde*, **35**, 200.
- WANDKE, A. & HOFFMAN, R. (1924): A study of the Sudbury ore deposits. *Econ. Geol.* **19**, 169-204.
- WELLS, H. L. (1889): Sperrylite, a new mineral. *Am. Jour. Sci.* **37**, 67-70.
- WILLIAMS, HOWELL (1957): Glowing avalanche deposits of the Sudbury basin. *Ontario Dept. Mines. Ann. Rept.* **65**, pt. 3.
- WILLIAMS, K. L. (1958): Nickel mineralization in western Tasmania. *Australian Inst. Mining & Met. Stillwell. Anniv. vol.* **283**.
- WILSON, H. D. B. (1953): Geology and geochemistry of base metal deposits. *Econ. Geol.* **48**, 370-407.
- (1956): Structure of lopoliths. *Bull. Geol. Soc. Am.* **67**, 289-300.
- & ANDERSON, D. T. (1959): The composition of Canadian sulphide ore deposits. *Trans. Can. Inst. Min. Met.* **62**, 327-339.
- YATES, A. B. (1938): The Sudbury Intrusive, *Trans. Royal Soc. Canada.* **32**, (IV), 151-172.
- (1948): Properties of International Nickel Company of Canada. *Structural Geology of Canadian ore deposits. Jubilee volume* 596-617 (*Can. Inst. Min. & Met.*).
- YUND, R. A. (1958-9): The Ni-As-S system: *Ann. report Director Geoph. Lab. Carnegie Inst. Washington*, **58**, 148-153.
- (1961): Phase relations in the system Ni-As, *Econ. Geol.* **56**, 1273-1296.
- ZURBRIGG, H. F. (1933): A study of nickeliferous pyrrhotites. *Unpub. master's thesis, Queen's University*.
- , & GEOLOGICAL STAFF (1957): The Frood Stobie Mine: *Structural Geology of Canadian Ore Deposits*, **2**, (Congress volume) 341-350. (*Can. Inst. Mining & Met.*).