INTERPRETATIONS: THE HISTORY AND ORIGIN OF THE SUDBURY ORES

This concluding part of the study of the Sudbury ores is largely inter-
pretative and represents our final "distillation" of the ideas presented by
earlier investigators, by those who have contributed to the research
reported herein, and ideas expressed verbally by many field geologists
currently working in the area.

Part III is divided into four sections. At first it is necessary to indicate
in summary form the geological events before and after the original
deposition of the ores and to classify the processes involved in their
entire history as magmatic and post-magmatic effects. This is followed
by a discussion of the magmatic ores, the different lines of evidence on
which they are so classified, and certain theoretical considerations and
comparisons. Post-magmatic ore effects are then considered and a final
summary of conclusions is given.

A. HISTORY OF EVENTS AND CLASSIFICATION OF PROCESSES INVOLVED IN FORMATION OF THE ORES (SUMMARY)

Before attempting to analyze and interpret the complexities of the
minerals in the ores, their textural relations and distribution, it is essential
that we examine first the important geological events which occurred
before, during and after their initial emplacement, and endeavour to
integrate with these the various processes which have played a greater
or lesser part in their development. The geological history of the region,
as emphasized above, has been long and intricate. Failure to recognize
that several different processes, varying greatly in intensity, have been
active, each leaving its own imprint on the ores, would lead only to
confusion. In fact it is very probable that this very failure accounts for
some of the divergencies in opinions expressed on their origin. This
procedure is only common sense, but to avoid the accusation that it is
not an objective approach, let us hasten to indicate that in the following

sections, evidence supporting each conclusion will be cited in the proper place.

Briefly it is very apparent that the nickel-copper ores as we see them today have resulted in the main by the segregation of immiscible sulphide liquids from the nickel irruptive, some 1700 m.y. ago. Superimposed on these ores are many other effects, some peculiar ones, perhaps only late stage, but others, in later epochs involved remobilization due to intrusives and low intensity hydrothermal mineralization and alterations ending with very minor results of supergene solutions. Seen in their proper perspective, however, the latter account for only a very minute fraction of the ores and are more of scientific than economic interest. Some have been "red herrings" for those attempting to unravel the problems.

The succession of pertinent geological events can be grouped under six main headings, each of which seems quite distinct and three of which are directly or indirectly dated. It may be, however, that one or two items have been slightly misplaced and further field evidence may indicate they should be moved up or down to the next division. The six divisions are:

1. Significant pre-ore events yielding the environment into which the irruptive was intruded.

2. Intrusion of the Sudbury irruptive as a single body and *formation of the primary magmatic sulphide ores* ($\sim$1700 m.y.).

3. Hypogene alterations and remobilization effect of post-ore granite intrusion (minor).

4. "Secondary hydrothermal "mineralization and alterations—deep faulting (1200±120 m.y.).

5. Remobilization by Keweenawan trap and diabase dykes ($\sim$1020 m.y.) minor.

6. Supergene alteration (minor).

A brief outline of these events is given here and subsequent sections will deal separately with the primary magmatic ores and then with secondary, post-ore effects.

1. SIGNIFICANT PRE-ORE EVENTS

As indicated earlier not only has the pre-ore geological history of the region been decidedly complicated, but still is the subject of much debate. Certain geological premises have, however, been accepted, and those bearing in one way or another on the ore deposits and the environment in which they were formed may be briefly outlined.

The earliest pre-Huronian formations of ancient volcanics and sedi-

ments as seen outside the Sudbury basin were steeply folded, intruded
by (Algoman) granites and extensively granitized on the north, west, and
eastern sides. These were followed by a great erosion interval after which
the Huronian sediments (Bruce and Cobalt), as we know them in
Ontario, were deposited over most of the region, with the possible
exception of the south side of the basin, and later were extensively
intruded by Nipissing gabbro, as were the underlying pre-Huronian
rocks. Further erosion would appear to have largely removed most of
the Huronian in the immediate vicinity, leaving only scattered outliers
of the basal uraniferous conglomerates and quartzites, and possibly the
quartzite at the base of the Whitewater Group. Next recorded is the
outstanding period of brecciation with the development by "diatreme"
activity of the widespread "common Sudbury breccia," most notable of
which is the great Frood breccia zone, breccias along the "offsets" and
around the outer rim of the Basin. This is believed to have culminated in
the extraordinary vulcanism of the Whitewater, with the formation of
great thicknesses of tuff-breccias of the Onaping formation, within the
basin, and probably much beyond their present limit, followed by the
initial and perhaps continuing subsidence of the basin, and deposition
of slates and greywackes (Onwatin and Chelmsford). This apparently
unique Whitewater assemblage lay then as a concentric, elongated
synclinal trough, unconformably above the pre-Huronian basement,
much of the latter in a thoroughly brecciated state. The unconformity,
like that below the (upper) Huronian or Animikean at Mesabi, Minne-
sota, may represent two periods or a very long period of erosion, thus
explaining the general absence of the Bruce and Cobalt. Further subsi-
dence and faulting probably continued to further depress the basin
formations, fractured underlying basement rocks and formed the channel
or channels along which the Sudbury irruptive was intruded.

2. INTRUSION OF SULPHIDE-BEARING IRRUPTIVE AND FORMATION
OF THE MAGMATIC ORES

Intruded along the moderately inward dipping and somewhat irregular
surface of the unconformity, and locally breaking into and along the
steeply dipping basement formations with contemporaneous faulting,
the Sudbury irruptive assumed very much its present form as one great
downward-sagged and curving sheet, the central, basal portion of which
is still a matter of conjecture. Where it came in contact with already
brecciated rocks it was able to disrupt these and acquired abundant
foreign inclusions to form "inclusion norite" or quartz diorite breccia.
Assimilation of the more acid fragments, in places, may have been one

of several factors in modifying its composition to quartz diorite, but if there is any of the original undifferentiated magma chilled against footwall rocks it is possibly represented by this phase. Perhaps not immediately, but while still molten, from the base of the irruptive, magma was able to penetrate many steeply dipping breccia zones, opened up rather peculiarly by tensional stresses, moving laterally into them and downward to considerable depths below the main mass, and also picking up abundant breccia fragments to form some of the offsets. Other fractures and faults appear to have developed along contacts before crystallization of the irruptive was complete.

The temperature of the magma was undoubtedly high (1100° C?) as evidenced both by the orthopyroxene which crystallized in the basal norite, and the conversion of basic volcanics and breccia matrices, nearby, to pyroxene-hornfels. Whether or not the original magma yielded early crystals of basic silicates is not known. If so, these must have settled below the present zone of observation. In any case it is suggested that the exposed part of the irruptive was saturated quite early with dissolved sulphides. On cooling, differentiation began in the portion of the irruptive now visible, first undoubtedly by liquation with the gravitative separation of the heavier sulphide fraction with minor dissolved silicates and a lighter silicate fraction with minor dissolved sulphides. This is a gradual process occurring over a range of temperatures leading, as will be detailed, to various products. In time, the dominant silicate fraction further differentiated by the process of crystallization, yielding the more basic basal norite, the overlying more siliceous micropegmatite and fluids which altered some of the overlying rocks to granophyre or feldspathized them. Local variations in grain size and in composition of the former are undoubtedly due to crystal settling. Some in part may be due to further injections of magma and in part to late deuteric or even subsequent alterations, portions of which may make up the so-called "hybrid" or transition zone.

The segregation of the immiscible sulphide fractions led eventually to a wide variety of primary ore types. These will be detailed in the next section. Some moved downward to the base of the offsets (Frood-Stobie), some gathered in hollows underlying the irruptive (embayments) collecting more on flatter dipping contacts than the steeper, and crystallized *in situ*; some were injected, essentially as dry melts, into immediate footwall rocks wherever favourable structures developed, while some *residual sulphides* were trapped in the crystallizing norite or quartz diorite above (some disseminated ores). That the hot sulphide fluids, however, were not completely anhydrous is shown by the amphibole, biotite, epidote and other hydrous silicates they contain and by relatively

local metamorphism they produced on wall rocks. Where able to crystallize slowly and differentiate, a more hydrous residue eventually formed as at the base of the Frood, but even here zoning of metamorphic minerals —amphibole to biotite, indicates water content was not high at the immediate contact. It seems probable the advancing and injected sulphides aided in expelling water vapor from adjacent rocks. Such metamorphic fluids may then in part have preceded injected ores to produce some of the silicified areas like the "jasperoid" at Falconbridge which would thus appear older than the ores. Wherever such fluids became incorporated in the sulphide liquid, they may have aided in replacement of invaded rocks, where this does occur as along faults, e.g. Garson. These seem to have been the major steps in the development of the primary magmatic ores, evidence for which is presented in Section B, below.

The remaining four groups of post-magmatic-ore effects will be outlined briefly and later authenticated.

3. Post-magmatic Ore Effects

(a) Hypogene Alterations and Local Remobilization by Post-ore Granite

Hypogene alterations, possibly late-stage, are represented by complex pseudo-eutectic intergrowths of nickel arsenides, pyrrhotite, and chalcopyrite with associated quartz. The actual time of their development and cause is not clear but the conditions under which they must have formed suggests this classification. Remobilized breccia ore of a peculiar pentlandite-pyrite composition is indicated at the McKim mine in the post-norite granite adjoining the older Murray granite but not yet clearly distinguished from it.

(b) "Secondary Hydrothermal" Mineralization and Alterations

"Secondary hydrothermal" mineralization consists of small but widespread deposition of crustified galena-sphalerite veins, barren of precious metals, locally with late pyrrhotite where they cut massive ore, elsewhere with pyrite, marcasite, quartz and carbonates in both "marcasite ore" and wall rocks. Dating of the galena gives an age about 1200 m.y. Possibly related in part at least to this very much younger epoch is the development of some "marcasite ore" from primary sulphides, in various places and to depths of 4000 feet or more, though opinions differ on this.

Similarly fine cube pyrite, massive, and coarse pyrite in pyrrhotite, always with carbonate, quartz and some marcasite, noted to depths of at least 1800 feet along deep faults, may well be attributed to solutions

extant at this time. Some such occurrences have also millerite and violarite with marcasite which may have been superimposed, or, on the other hand, all may be supergene.

Development of rare pink, nickeloan pyrite with colloform carbonates, quartz and, locally, marcasite, may also belong with this group.

(c) REMOBILIZATION BY KEWEENAWAN TRAP AND DIABASE DYKES

This includes effects quite minor in character yet confusing, if not clearly recognized for what they are. They consist of recrystallization of ores around broken fragments of trap dykes, and the engulfment or remobilization of ore by olivine diabase dykes, dated at 1050 m.y., as at Garson and McKim. They have not been studied in detail, but at Fecunis Lake the diabase has only slightly modified the distribution of silver and lead along its immediate contact with massive ore.

(d) SUPERGENE ALTERATIONS

Supergene alterations, also of a very minor nature include development of marcasite and violarite, locally with millerite, selectively formed at the expense of pentlandite and pyrrhotite. In places these extend to depths of 1800 feet near faults and may be responsible for most of the marcasite and pyrite of secondary deposits. Further details appear in Section C of this part.

B. THE MAGMATIC ORES

There is no reason to repeat here the many lines of geological evidence given particularly by Coleman and co-workers and later by Collins and field geologists in support of the magmatic origin of the Sudbury nickel-copper ores and their derivation from the Sudbury irruptive. The proof is in the dictum that "where there is no norite or quartz diorite there is no ore." Here we shall rest our case on the evidence of the disseminated ores in irruptive rocks and its counterpart, newly described, of disseminated quartz diorite blebs in the sulphides, the immiscible-silicate-sulphide ore. Details which will appear in interpretations of the character and textural relations of the ore minerals themselves, based in many cases on their physical chemistry, and of the distribution of the metals within the various types of ores, confirm this thesis, should further proof be required.

1. Evidence of Ore Formed in Situ

(a) disseminated ore in norite and quartz diorite[1]

Examination of thin sections of disseminated ore in both norite and quartz diorite, especially from Creighton and Frood shows very clearly that the sulphides have segregated in liquid droplets within the silicate magma. Where undisturbed these retain their original rounded form. Although not everywhere exposed such ores are readily recognized and highly significant. Details of their microscopic relations follow.

The sulphide blebs in these are generally considerably coarser than the prevailing grain size of the enclosing silicates, though the grain size of the sulphide within the blebs is not greatly different from that of the coarser silicate particles. In the more highly disseminated ores the blebs are completely separated from each other by areas of silicate; where the ores are richer the individual blebs are closer together with a correspondingly smaller proportion of silicate, such ores gradually merging into a more massive type with the touching and final coalescence of the blebs (Plates XIV–XV). In some cases the sulphide pellets have very even boundaries with smoothly curving embayments and protuberances. In other cases the outlines are rather spongy or frayed, with the peripheral sulphide spreading out between adjacent silicate grains, isolating and enclosing these. In some cases fairly large grains of silicate (up to about 2.0 mm. across) are enclosed well within the body of sulphide pellets, but most included silicate is confined to the peripheral zones. Where the sulphides are in fair concentration, the extremities of the outer spongy areas come together, forming a network between individual pellets, and this relationship seems to grade into one of more or less complete coalescence. Perhaps a rather significant point regarding the mode of emplacement of the sulphides is that the outlines of the silicates *within* the sulphides are not noticeably different from the outlines of these same minerals in the silicate areas. This is particularly striking in the case of some of the sulphide-bearing norite containing idiomorphic to subidiomorphic orthopyroxene; some of the sulphide blebs here contain beautifully idiomorphic orthopyroxene, precisely similar to that of the non-sulphide bearing areas, and show no sign of corrosion or veining by the enclosing sulphide.

An interesting relationship has been found in which idiomorphic feldspar projects into composite blebs of pyrrhotite, chalcopyrite, and pentlandite, while orthopyroxene projects into the feldspar just as the feldspar projects into the sulphide. That the sulphide merely moulded

[1]This subsection was prepared in part by Dr. R. L. Stanton and is an amplification of section C, Part II.

itself about the feldspar as the feldspar presumably did about the pyroxene seems, on the evidence, to be a reasonable explanation of the relationship. This type of texture seems to be quite typical of sulphide-silicate relationships in the disseminated ores. One common feature noted by others (Wandke & Hoffman, 1924) is the association of biotite with opaque minerals, including magnetite or ilmenite. Smaller particles of oxide or sulphide, often rounded to club shaped, are frequently completely enclosed by a single optically continuous grain of biotite. Larger areas of opaque minerals often show a discontinuous rim of randomly oriented biotite grains against sulphide. This relation is duplicated in specimens in which the silicates occur as isolated blebs in massive sulphide and in part may be due to reaction. It is doubtful, however, if such occurrences can be attributed to, say, hydrothermal emplacement of both black oxides and sulphide, as the oxides are certainly in part normal magmatic products.

Although the majority of (undeformed) disseminated ores do not show clear evidence of emplacement of sulphides at the expense of silicates, there are some in which the sulphides very definitely form veins exploiting cracks and cleavages in the associated rock minerals. It is noticeable, as pointed out by Coleman (1913) that this type of relationship is found for the most part in rocks which have suffered alteration and, in most cases, mechanical deformation. The sulphides still occur as blebs showing all degrees from sparse dissemination to coalescence, but they tend to be less equidimensional, there is some tendency to "stringing out" and they appear interstitial to the silicates. In many cases numbers of fine, filament-like veinlets emanate also from them. Such veinlets often form webs through fractured silicate crystals or through small granulated areas, and may link one or more of the parent sulphide pellets. In these rocks there has generally been some, and often quite extensive, uralitization and shearing, with the formation of blue-green amphibole, and even chloritization. The sulphides tend to penetrate along the cleavage of the fibrous amphiboles and chlorite, and to work their way along cracks and cleavages in the unaltered pyroxenes and feldspars as well. Such relations suggest the sulphides are entirely post-alteration, but this is not necessarily so if the alterations are the result of reactions between the ore fluids (with minor volatiles) and the silicates.

Mineralized quartz-diorite breccias (inclusion quartz diorite) and "granite" breccias (with a quartz-diorite or feldspathic matrix and foreign rock fragments) probably simply represent special cases of disseminated ores already described. Some of these may grade into massive ore or "massive breccia" ore (*i.e.* massive sulphides with foreign fragments) and it becomes a problem to distinguish just where the base or

lower contact of the original magma was located. Some such ores appear on the north range. They obviously need distinction from ores injected into breccias.

(b) DISSEMINATED SILICATES IN SULPHIDE

Examination of the counterpart of disseminated ore, referred to above as "immiscible-silicate-sulphide" ore (*Frontispiece*) from the Frood, shows many features in common with the former. At first glance one might be inclined to the opinion that this is simply another example of a breccia ore on account of the variations in shape and size of the silicate aggregates, many of which depart widely from a round, drop-like form. Attention however, is directed to the rounded character and club-shape of the smaller ones, and to the bulbous protuberances extending from the larger body into adjacent sulphides. The rounded to ellipsoidal or pellet form of most of them is much more evident on the rough broken side of the specimen, and their present shapes may be explainable by movement of them within the sulphide liquid while they were perhaps in the form of a viscous fluid, and even during and following crystallization, as some are considerably fractured.

As noted earlier, thin sections show that all the silicate bodies have a similar composition which is essentially that of a rather fine-grained quartz gabbro or diorite, composed of much altered pyroxene, green hornblende, brown biotite, and laths of fresh feldspars, zones in which range from An_{25} to An_{65}, with an average in the labradorite range. Minor actinolite and tremolite appear to have developed from the pyroxene, and apatite and black oxides, consisting of ilmenite, magnetite and ilmeno-magnetite, are the chief accessories. Though orthopyroxenes have been reported from similar ores, in this specimen only clinopyroxene of a pale yellowish white type is present. It is often riddled with fine dusty inclusions, flakes of biotite and rimmed with green hornblende, and rods of either actinolite or tremolite. Within the larger plates of biotite, as in disseminated ore, are round to club-shaped inclusions of black oxides, and within some of the feldspars and quartz, as seen under high magnification, are numerous trains of fine "liquid inclusion"—like bodies of sulphides, clearly yellowish in reflected light. These trend across twin lamellae, fractures and even grain boundaries, and like the coarser rounded particles of sulphides, visible in the photograph (*Frontispiece*) must represent original immiscible sulphide droplets which separated from the silicate fraction and were trapped by the growing silicate crystals. Where the latter have been intensely shattered, the fine fractures (as in a glass) have been filled with thin seams of sulphides to give an intricate web pattern, also noted in some disseminated ores.

Around a considerable number of the silicate bodies are thin, usually discontinuous rims of fine biotite, often less than 0.1 mm. wide, flakes of which appear to parallel the border, in contrast to various orientations of biotite within. Intergrown with this and paralleling the biotite rim is usually a second rim of ilmenite, or mixtures of ilmenite and magnetite, in places made up of chains of small crystals. In many cases the rims of these minerals, as noted, are wrapped into and disappear within the silicates, resembling the snowball structure of some garnets. That the biotite rims developed by a reaction with early crystals and surrounding liquid is suggested by the evident replacement of ilmenomagnetite by rim type of biotite, the magnetite being replaced but not the ilmenite blades. It is not clear, however, that all the black oxides are early crystals. Their snow-ball structure may indicate a rotational movement of the globules before they were completely crystallized and discontinuities in the outer rims may be due to "rubbing off" of parts of them during such movements. As seen in a section cut at right angles to the surface photographed, many of the silicate bodies show a definite alignment which may also be related to their movement but such ore has not been examined in place to determine the actual direction—whether vertical or not.

In addition to such rounded aggregates, we have recently noted irregularly scattered clusters of well-formed lath shaped crystals of silicates (likely feldspar) embedded in the sulphide matrix, as if crystallized as individual grains and enclosed by later sulphide. The two textures displayed by the silicates are so different that they call for different explanations, as noted later.

Surrounding the silicate bodies, the pyrrhotite is quite as coarse grained as it is farther away, so there is no evidence of chilling of sulphide against them. Between some grains of pyrrhotite are fine seams of biotite, similar to the rims about the silicates. These lead into tiny clusters of silicates, chiefly quartz, feldspar and biotite and probably represent late silicates not completely segregated from the sulphide liquid fraction. Very fine branching fractures in the sulphides also are filled with fine biotite, deposition of which continued. Within the pyrrhotite grains are typical flames and "veinlets" of pentlandite and between the grains are coarser "interstitial" segregations of pentlandite and very rare whisps of chalcopyrite. From areal measurements the sulphides constitute 75 to 80 per cent of the specimen illustrated, silicates and oxides making up the balance. The proportions, however, are reported to vary from place to place.

From the foregoing it seems altogether likely that much of this ore represents the crystallized products of a mixture of immiscible liquids,

formed in one way or another as will be discussed later when we consider the theory involved (see below Theoretical Considerations and Comparisons, p. 160). One of these liquids was composed dominantly of silicates with minor sulphides in solution, the other, dominantly sulphide with minor silicates, each tending to further separate as they cooled and eventually crystallized. The presence of quartz, biotite, and amphibole with plagioclase and pyroxene in the silicate bodies indicates in this case surely that the magma from which they separated had already attained essentially the composition of a quartz gabbro at the time the liquids were separating and coalescing, and that sufficient water vapor was initially present to account for that in the biotite and amphibole. Volatiles would of course be somewhat enriched as final crystallization of the silicates ensued. In places fine individual laths of silicates in the sulphides indicate also that some crystallized directly rather than in globular bodies.

Ore of this type seems decidedly rare. It has been found only in the Frood-Stobie deposit where segregation and crystallization have occurred *in situ*, that is where movement of the two liquids has been slow and dominantly in a vertical direction. The specimen examined comes from near the base of the quartz diorite offset, a logical place for it, especially if the base of the still more massive ore below it represents the base of the original intrusive. Similar ore has also been observed, we are told, in the pit area, at considerably higher elevations where similar segregations of silicate and sulphide liquids must have formed from the overlying portion of the intrusive, now eroded away. Wherever forceful movement and injection of such mixed liquids took place into faults, more permeable contacts, or breccias, the silicates, crystallizing at higher temperatures, might well become separated one from the other as sparse individual grains of biotite, amphibole, quartz or feldspar, and be no longer recognizable as having formed from original immiscible liquid fractions. Delay in the onset of crystallization would also allow such liquids to separate more completely.

Further evidence for the development of some ores *in situ* is to be found in the excellently zoned Frood deposit and in the distribution of the metals, both of which are considered later.

2.   EVIDENCE OF INJECTED ORES

That many of the sulphide ores represent magmatic sulphides which have been moved from their original "gathering ground" and have been injected either laterally, vertically, or even in other directions into favourable structures, but never far from the norite, is indicated in various ways. A few outstanding examples will be given.

At the Creighton where there is abundant evidence of the segregation of sulphides in the pronounced norite "embayment" or trough, faulting occurred in such a way as to intersect the base of the norite–quartz diorite and contiguous footwall rocks, as described by Yates. *Massive* ore, practically the same as ore crystallized *in situ*, was introduced into the faults, and *disseminated sulphides*, into the adjacent wall rocks. Thus, taking the deposit as a whole the ores at Creighton consist of products formed both *in situ* and from injections.

The Falconbridge deposit is another excellent example, As shown so clearly by Lochhead, the ores here, largely of the breccia type, have been introduced along the faulted contact of norite and footwall rocks, a contact steeply inclined and rolling from a northward to southward dip. Taking off into the *hanging walls*, into norite on the upper levels, and into greenstones on the lower, are tangential shears along which the mineralization has extended, as well as an earlier siliceous alteration. Shear zones off in the "jasperoid" alteration were similarly mineralized in places and only an upward injection of the ore fluids can explain the deposits.

The relative restriction of injected ores to areas close to the contact of the norite is also well shown by the main ore zone at Falconbridge. To the west faulting along the contact passes into the norite (believed only partly solidified at the time), and to the east it leaves the contact and passes into footwall rocks, and in both cases ore ceases or dies out rapidly at either end. This suggests a thermal control, as the sulphide ore fluids would require a higher temperature to remain mobile compared, say, with more tenuous hydrothermal solutions.

Other examples of injected ores are numerous in which either massive, breccia or stringer ores lie next to norite, or, at times, at short distances off in the footwall rocks nearby, where the adjacent noritic intrusive now shows no evidence of disseminated or segregated immiscible sulphides. The absence of the latter would readily be accounted for if they had already "drained" out to other areas below.

The injected ores, as might be expected, show rather different sulphide-silicate textures compared with those crystallized *in situ* and it is in these that evidence of somewhat greater replacement is usually to be found.

Massive ores, whether of one or the other type, generally contain only scattered small flecks of silicates here and there in the sulphides so that no clear evidence is available as to whether they have been simply engulfed in the sulphides or largely replaced. An example of replacement by massive sulphide has been described at Falconbridge where massive gersdorffite along the outer border of pyrrhotite ore replaces chlorite-

biotite schist leaving undisturbed films and shreds of schist within it. Other examples are no doubt numerous, including the example given by Knight of the replacement of granite fragments in ore at Creighton. Massive stringer ores are recognizable of course as fracture fillings into which ore fluids passed from either nearby or more distant sources. That some of these fluids had become hydrothermal in character is suggested by both their metal and siliceous nature, as at Frood, but in other cases, they consist almost solely of chalcopyrite.

The mode of emplacement of injected ores in breccias presents interesting problems. The breccia ores have been recognized as of several different types though the ore minerals within them are very much the same, and, as far as we are aware, are essentially indistinguishable except for variations in coarseness of grain. (This is perhaps a subject for further study.) Major differences are in their form, location, composition and shape of included fragments, and in places, in the degree of actual replacement of host rocks. Some, like the common Sudbury breccias, contain fragments dominantly though not solely, of nearby host rocks, varying in composition as do these, and seem in fact to represent such breccias into which the ore minerals have been introduced. They never, however, appear to contain composite breccia fragments, suggesting complete disruption of the matrix. In places, as at Murray the fragments are all quite basic and well-rounded, in others they may be granitic or even gneissic and sub-angular (as at Creighton and north range) and it is difficult to decide which have arisen simply by infiltration of ore fluids and which are due to engulfment and some transport of pre-formed fragments. Many occur along the irruptive contact in sheet form where pene-contemporaneous faulting may have provided both the space for their ore fluids and many of the fragments from adjacent walls, including occasionally some norite as well as footwall rocks. At Garson, as noted, extensive breccia ores follow converging faults and highly altered shear zones and have replaced large areas between them, thus acquiring not only fragments of schist but also of quartz and carbonate. Still others have been injected or "wrapped into" the norite for considerable distances. Some may have formed by combinations of these processes. In practically all cases the sulphides appear to occupy the space one would suppose was originally filled with any pre-existing finer grained matrix. In many places this is entirely gone, while in others fine silicate particles are liberally scattered throughout. Here and there the sulphides, especially chalcopyrite, penetrate the larger fragments and clearly replace them along fractures or cleavage. Thin sections of the finer material, as from Falconbridge breccia ore, show inclusions of what were originally likely greenstones, now highly altered to epidote, zoisite, biotite, chlorite (peninnite) and quartz.

Most of them show rounded borders against sulphides though sharp angular crystals of epidote still preserve their form while shredded biotite and chlorite mixtures are partly replaced along cleavages. The obvious interpretation is that the sulphides *have* replaced the matrix and, in places, have completely disrupted it. This poses the problem as to the disposal of the replaced material for which there is no ready answer, if the ore fluids were largely magmatic. Molten sulphides can and do replace silicates but unless sufficient volatiles were present to remove them they must have been reconstituted and remain somewhere in the ore, probably as grains of silicates, amphiboles, biotite, quartz, *etc.*, now unidentifiable as to source. While minor amounts may have escaped by diffusion there is certainly no evidence of large scale alterations in adjacent wall rocks of a hydrothermal character. On the other hand it seems quite possible that the sulphide ore fluids in places were injected permissively into loosely consolidated breccias or into faulted contacts brought into a state of open-packing by accompanying dilational stresses. Some replacement of silicates still must have occurred, but perhaps not on the scale one might ordinarily envisage. By such a process, however, the problem of the replaced material would largely disappear.

What appears as a clear-cut case of extensive replacement by sulphides as in the highly sheared and altered zones at Garson requires explanation. Though not studied by us, Yates' account suggests the possibility that the alteration was largely pre-sulphide, so that this and shearing obscure rock contacts and relations. We can only suggest that perhaps, as in places at Falconbridge (jasperoid alteration), the alteration to quartz and carbonate resulted from more aqueous fluids driven upward ahead of the dryer sulphide liquids and that the greater degree of replacement by sulphides may have been aided by volatiles already present or by a mixture of such fluids.

A special but minor case of injected sulphides is the occurrence of mineralized breccias injected well into norite, as at the Gertrude, Murray, and Hardy. Two of these have been examined, but it is quite difficult to decide whether they represent rock fragments (1) caught up by early sulphide and injected along fractures or shear zones in the solidified norite, (2) mineralized breccia simply caught and "wrapped" into the border zone of the norite (some having an igneous matrix in parts), or (3) remobilized sulphide and breccia introduced at a later time. Of the three, the second seems most likely at the Gertrude and Murray.

In contrast to those deposits containing some pre-sulphide quartz and carbonate, we must note that where late, post-sulphide veins and alterations by these minerals have been reported, these may be due largely to a much later phase of hydrothermal activity, superimposed on the mag-

matic ores. Having established the magmatic character of the sulphides within and immediately adjacent to the irruptive rocks and crystallized in place, it should follow that those sulphide liquids which have been moved to other sites, still closely linked to the irruptive contact, and injected either into a dry or a more aqueous environment, must have been essentially the same to yield such similar deposits.

3. THEORETICAL CONSIDERATIONS AND COMPARISONS

At this point it will be well to examine available data based on experiment and theory as they affect the behavior of sulphide silicate systems on cooling. Here we shall deal only with processes leading to the separation of sulphide and oxide-silicate liquid fractions, *i.e.*, differentiation by liquation, leaving for later consideration (see section 4 and 6) factors affecting their mode of crystallization which bear on resulting textures of the ore minerals, their zonal relations and distribution.

F. G. Smith (1961) has recently reviewed and condensed the data available on artificial sulphide-oxide-silicate (FeS-FeO-SiO$_2$) liquids and applied them to the natural system, pyrrhotite-magnetite-gabbro (silicates), tracing out the cooling and crystallization history for liquids initially rich in silicates, some with a low and others with a higher magnetite-silicate ratio, in only the former of which liquid immisciblity plays an important role. Data are still far from complete and, although Smith indicates that projection to a two component plane, such as sulphide-silicate+oxide, leads to ambiguity, this has certain advantages, as used to some extent by Wager *et al.* (1957). These we shall attempt to show as in figure 6, before examining Smith's portrayal of the natural ternary system. Figure 6 is a simplified binary diagram, modified after Wager *et al.* on the supposition that the miscibility gap between silicates (plus some oxides) and sulphides (plus oxides and silicates) increases with lowering temperatures, as along the curves *eca* and *bfg*. Point *e*, as noted by Wager *et al.*, is very close to the left hand ordinate (.025–0.1) per cent sulphide) and *g* close to the 1 per cent silicate ordinate (after Vogt), though *f* may contain up to 10 per cent dissolved oxides in sulphides. It is probable the slope of the curve *ea* on the left is steeper and *bf* somewhat more gentle on the right. Smith has noted factors other than temperature affecting the miscibility gap, which appears to be reduced by oxides of iron, alkalies and hydrogen and increased by CaO, Al$_2$O$_3$ and Cu$_2$S. Provided there is some slope on either side of the curve, the point we wish to make is that once the solubility of sulphides in silicates has been exceeded two liquids will form, such as *a* and *b*, as at T_1, and begin to separate by gravity. With falling temperature and

SILICATE/
OXIDE
LIQUID

1100°

SULPHIDE RICH

a - b LIQUID   T1

1000°   c - d   T2

TWO   LIQUID   FIELD

f   T3

e

900°

800°

g   T4

0   50   100
%   SULPHIDE

SILICATES
OXIDES
WITH SULPHIDE
BLEBS

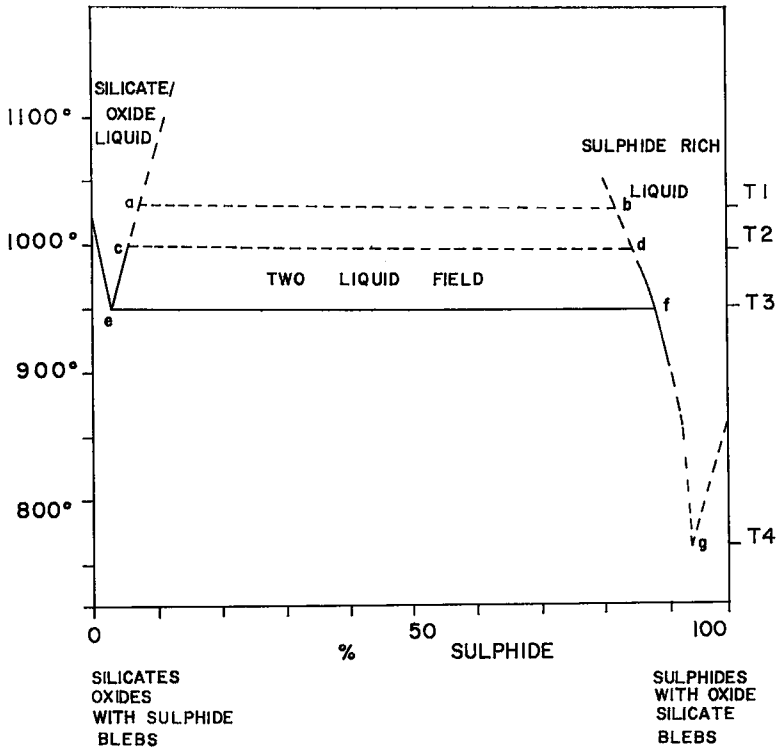SULPHIDES
WITH OXIDE
SILICATE
BLEBS

FIG. 6. Diagrammatic section illustrating cooling, separation of immiscible silicate-rich and sulphide-rich liquids and crystallization, treated as a binary system. Point *e* lies close to left ordinate. Crystallization starting at *e* or *g* would extend over a range of temperatures. Point *d* represents approximate composition of "immiscible-silicate-sulphide" ore from Frood. (In part after Wager, Vincent & Smales, 1957.)

decreasing solubility of one in the other, these will change to *c* and *d* respectively, as at T_2, and to *e* and *f* at T_3, the dominantly silicate liquid still containing some dissolved sulphide (and oxide) and the dominantly sulphide liquid containing both oxides and silicates. Depending on bulk composition of each, the silicate liquid will begin to crystallize, as at *e*, and continue to do so over a range of temperatures until it is used up, some "exsolved" sulphide (+oxide) liquid being trapped in the growing crystals, to yield fine globules of sulphide on crystallizing as "disseminated" ore. Adding to such sulphides may be droplets of sulphide liquid separated at higher temperatures, but which had not had time to segregate below the lighter silicate layer. In a similar manner sulphide rich liquids, such as *d*, on "exsolving" and separating by gravity, will further change

in composition to *f by exsolving silicate liquid droplets*, if above T_3, and thereafter, by crystallization of silicates, arriving eventually at composition *g*, at which temperature the sulphides and/or oxides begin to crystallize, yielding an ore dominantly of sulphides and some oxides, with rounded aggregates of silicates (quartz gabbro), probably not very different from the ore sample described from near the base of the Frood deposit (the immiscible silicate-sulphide ore).

As noted in this type of ore there are in addition to the more globular and smaller pellets of silicate material, larger and more irregular aggregates which, though of the same composition and grain size, depart very much from a drop form. For these a somewhat different explanation must be sought. This ore, as described, lies below disseminated sulphides of the quartz diorite offset and is followed below by still more massive ore and the siliceous mineral zone around its lower limit. There is no indication of any chilled margin at the base of the offset. A logical explanation for this would be that the lowermost part of the original "quartz diorite" magma was displaced while still molten or only partly crystallized, by the downward settling, heavier molten sulphide fraction. Just as some residual sulphide liquids become trapped in the main crystallizing silicate fraction above, so some silicate bodies (liquid or solid) rising from the base may have been trapped in the solidifying sulphides below. As indicated, the silicates in all cases appear to have crystallized before the sulphides, and also to have "unmixed" small liquid sulphide inclusions which were trapped within.

In contrast to the behaviour of such sulphide-silicate liquids as portrayed by Figure 6, Smith traces their cooling history in a somewhat different way. (See this journal, vol. 6, 555–575, 1961.) A gabbroic magma originally low in iron sulphides and magnetite, on cooling will crystallize silicates, the residual liquid moving to a two-liquid boundary at which time liquid sulphides will separate (and possibly begin to segregate) from the silicate liquid. Continued crystallization of silicates from the latter causes further separation of liquid sulphides, and, if we interpret his diagram correctly, the miscibility gap decreases rather than increases, with lowering temperature. Eventually the silicate liquid is used up by crystallization, and thereafter silicates continue to separate, not as liquids or droplets but as crystals, from the still molten sulphide fraction (as would be the case between *f* and *g* of figure 6). Eventually the remaining sulphide liquid moves across the silicate field to the magnetite boundary and with crystallization of iron oxides and minor silicates eventually solidifies at a ternary eutectic with final crystallization of all three types of minerals. Except for the absence of any textures in the ores suggestive of a ternary eutectic, this agrees with the observed

paragenesis of silicate crystals-magnetite-sulphides. It does not indicate a period during which silicate liquids would separate as liquids from the sulphide fraction, but this depends of course on the temperature of the latter and the solubility of silicates in it. As we have noted above, perfectly preserved laths of silicates (feldspars?) are also found embedded in sulphides of the ore under discussion, suggesting their direct crystallization. They are however, quite in contrast to the globular aggregates for which we favour separation by liquation. Any other explanation would have to involve rounding of crystallized silicate aggregates as they moved upward in the sinking heavier sulphide liquid, possibly with a rotational motion as inferred from the "snow-ball" structure of the biotite-oxide rims. This is a subject for further study.

Two remaining points should be noted. One is the presence within the silicate bodies of both ilmenite and magnetite and microscopic intergrowths of the two, whereas in the sulphides here, the black oxide is dominantly magnetite with very minor intergrown ilmenite. This is taken as indicating a definite partitioning of the titanium. In some other ores we have noted ilmenite occurring singly, in more irregular grains than magnetite, and such grains may well have been derived from original globular aggregates of silicates, liberated by their disintegration during flowage, and hence be a useful criteria for an injected ore. Of even greater importance, however, is the fact that in the presence of abundant sulphur, nickel will normally enter the liquid sulphides rather than the silicate fraction where some could have been readily accommodated in early crystals. Cobalt, copper, and many other metals, notably the platinum group, do likewise, but their partitioning depends on several factors which will be considered further below.

In summary then, differentiation of sulphide-silicate liquids by liquation, as shown more precisely by modern experiments, but long recognized from smelting practice, thus seems quite adequate to account for the segregation of great volumes of sulphide liquid towards the base of such an intrusion as the Sudbury irruptive and its offset dykes. The various types of ores which appear to have resulted are illustrated on the following page, some crystallizing in place, with or without further differentiation, some moving to other favourable sites (Table 20).

4. Evidence of the Textures and Paragenesis of the Magmatic Ores

The paragenesis of the primary nickel-copper ores as interpreted from textural relations of the ore minerals is based on a study of ores of the different types from all the important producing mines. Their general

TABLE 20. SCHEMATIC PRESENTATION OF CRYSTALLIZATION HISTORY OF THE SUDBURY IRRUPTIVE AND ASSOCIATED MAGMATIC ORES

Liquid fractions	Crystallized products	Examples In part at:
Silicate-rich fraction, minor sulphides — (Aplite?) Micropegmatite Norite-Quartz	gabbro and altered equivalents *Disseminated* Sulphides	Creighton
Quartz diorite	At base and in Offsets with residual sulphides in Q.D. and in Q.D. Breccia, irregular segregations and stringers of sulphides where fractured	*Disseminated Ore* in Q.D. — Frood-Stobie *Disseminated Ore* in Q.D. Breccias — Frood-Stobie *"Granite" Breccia Ore* — Hardy, Levack
Sulphides crystallized *in situ*	Non- or slightly differentiated. Common pyrrhotite-pentlandite-chalcopyrite ore with or without silicate blebs	*Massive Ore* *Breccia Ore* *Chalcopyrite Stringer Ore* — Creighton, Frood
Sulphide-rich fraction, minor silicates	Differentiated by crystallization with silicate blebs, grading from low copper to high copper	*Silicate-Sulphide Ore* *Massive* and *Breccia* Ore *Cubanite Zone* *Arsenide Zone* *Siliceous Mineral Zone* with high precious metals Bi, Te, Pb, (Sn) — Frood-Stobie
Injected Sulphides	Along faults, breccias, and contact zones (largely undifferentiated)	*Massive Ore* *Breccia Ore* *Disseminated Ore* in walls *Minor Stringer Ore* — Falconbridge, Murray, Garson, parts of Hardy, Levack (?) Creighton and others

Sudbury *Irruptive*

similarity warrants their consideration together as one group, particularly to avoid unnecessary repetition. It is not to be thought, however, that actual times of deposition of similar ore minerals in widely separated deposits or even in different types of ore in one deposit have necessarily been identical. What will be shown is that the ore fluids have, for the most part, crystallized in a very similar manner, but some distinctive differences are evident. These have resulted in the zoning of certain minerals and the greater enrichment of some deposits in arsenides, precious metals and the rarer exotic minerals, compared with others. In these the crystallization history has been drawn out and is more readily decipherable, compared with those where an opportunity for crystallization differentiation was not afforded. To avoid confusion we shall deal here only with the products arising directly from the magmatic sulphide fluids, leaving consideration of the secondary minerals to a later section.

As shown on Table 21 the primary minerals may be grouped into three divisions, early crystallates, the major minerals, and late minerals. In determining the paragenetic order, the various criteria commonly used have been carefully reviewed and are considered in conjunction with experimentally established chemical relations. These will be discussed in individual cases, so that the basis on which age relations are inferred is made clear.

(a) THE EARLY MINERALS

Of the minerals giving evidence of their early crystallization, the oxides and arsenides clearly precede the sulphides. Oxides and arsenides however, as shown by our collections, seem mutually exclusive. The reason for this is not clear; possibly the arsenides formed later and completely replaced them.

Magnetite, ilmenite, and rarer magnetite-ilmenite graphic intergrowths usually occur separately, magnetite being much the more common in the sulphide ores. In some deposits magnetite is visible in glistening octahedral crystals, in others it shows varying degrees of rounding. In some ores (Hardy) it forms bands up to a foot wide. Pyrite (Pl. I, 1) is moulded around it and in many sections pyrrhotite, pentlandite, cubanite and chalcopyrite can be found replacing it (Pl. I, 4). Chalcopyrite (Pl. I, 2) and gangue minerals fill fractures in magnetite more often than do other sulphides. Magnetite is accordingly one of the first formed metallic minerals in the ores. Much of it probably represents a product of direct crystallization from an oxide-sulphide melt (Smith, 1961); crystal settling may account for banded accumulations and smaller segregations (Pl. I, 3).

In some disseminated ores, notably from the McKim and Mount

TABLE 21. PARAGENESIS OF THE NICKEL–COPPER ORES

(Primary mineralization only, based chiefly on massive and differentiated or zoned ores)

I. EARLY CRYSTALLATES	Oxides	Magnetite I, ilmenite, and intergrowths
	Arsenides	Sperrylite ... continues with chalcopyrite
		Gersdorffite
		Niccolite
		Maucherite
	Sulphide	Pyrite (see later generations)
II. MAJOR MINERALS (iron, nickel, copper sulphides)		*Nickeliferous* pyrrhotite mix crystals
		"Reaction" Pyrite (minor)
		Magnetite II (minor)
		Pentlandite—segregation from pyrrhotite begins—coarse grained rims (net), veins, lamellae, interstitial—early; fine blades, flames—later
		Chalcopyrite (associated with crystals of sperrylite) Fe-rich-Cu-S mix crystals with minor Ni and Zn—unmix to form intergrowths of chalcopyrite with one or more of:
		Cubanite, valleriite, pyrrhotite, pentlandite and sphalerite
		(Sphalerite ± chalcopyrite of common ores, with traces of Sn, likely same as post-galena sphalerite with stannite—see below) (Minor)
III. LATE MINERALS (nickel, bismuth, lead, zinc, tin, copper, precious metals)		*Enriched only in zoned deposits:* probably disseminated or in solid solution in unzoned ores
		Heazlewoodite, sperrylite
		Bismuth—tellurium minerals:
		Parkerite, michenerite, froodite, schapbachite (?), bismuth, bismuthinite (?), tetradymite, hessite
		Bornite (I) with chalcopyrite and exsolved chalcopyrite
		Galena, minor sphalerite with stannite
		Native Silver (with Bornite II)
		Gold (electrum)
		(Possible late stage reactions developing pseudo-eutectic intergrowths of arsenides, pyrrhotite and chalcopyrite (?) See Secondary Minerals)

Nickel deposits, ilmenite is present rather than magnetite and differs from it in occurring in more irregular grains. In the "immiscible silicate-sulphide" ore (Frood) ilmenite forms thin rims along with other oxides and biotite in the silicate blebs; some grains in sulphides elsewhere, as in injected ores, may have had such an origin. In still other specimens, ilmenite intergrown with magnetite (Pl. II, 7–8) is not dissimilar from occurrences in un-mineralized norite or quartz diorite. Where sulphides are present they commonly replace magnetite more readily than ilmenite and in twinned ilmenite itself, replacement of alternate lamellae by pyrrhotite-pentlandite appears to have occurred, (Pl. II, 9). Chalcopyrite replacing magnetite to yield an embryo-shaped residual (Pl. I, 4) appears

to have taken up iron and exsolved a partial rim of cubanite. As shown below, a rare second generation of magnetite is clearly post-pyrrhotite and rather intimately associated with rims of pentlandite and with chalcopyrite, both of which it appears to precede.

Of the arsenides, sperrylite and gersdorffite are very definitely early in order of crystallization, but neither have been found in contact with the iron oxides nor pyrite. Rounded cubic, octahedral and pyritohedral grains of sperrylite occur as inclusions in pyrrhotite, pentlandite and chalcopyrite and in places where fractured, sperrylite is veined by the latter (Pl. IV, 19, 20, 21). Other minerals such as cubanite, galena, sphalerite and rare stannite either enclose it or are moulded about it. The reported occurrence of sperrylite in footwall rocks of the siliceous mineral zone at Frood has not been studied, but its common association here with chalcopyrite suggests it was concentrated also along with the copper-rich residual ore fluids and continued to crystallize with them and other rarer minerals. Inclusions noted in earlier descriptions, of chalcopyrite, pyrrhotite, sphalerite as well as those reported by Michener, namely palladium bismuthides, gold and hessite, may reflect simply contemporaneous crystallization or minor replacements by these minerals.

Gersdorffite found sparingly in south range and offset deposits, chiefly at the margins of the deposits, also seems in most cases an early product of crystallization. This is well shown by coarse to fine granular gersdorffite replacing chlorite-biotite wall rocks at Falconbridge, and by the occurrence of the normal sulphides, pyrrhotite-pentlandite-chalcopyrite moulded around well formed crystals (Pl. IV, 22). These along with niccolite and maucherite, embay and replace the gersdorffite. In places it has been host for the development of pseudo-eutectic intergrowths of niccolite, maucherite, pyrrhotite or chalcopyrite (Pl. V, 27, 28, 29). Lausen, however, recognized it as the earliest of the arsenides in the Worthington ores, but considered all of these as deposited after the common sulphides. It has not been possible to check this, but if true, it would suggest a later generation.

An interesting though minor occurrence which may bear on the age relations of gersdorffite is illustrated in Plate IV, 24. Here a gersdorffite crystal is enclosed by both pyrrhotite and niccolite. A narrow rim of gersdorffite follows the contact away from the crystal and would normally be interpreted as a remnant left by replacement. On the other hand such a rim could conceivably be due to a reaction between niccolite and pyrrhotite which together contain the necessary constituents to form ferroan gersdorffite. A. Y. Smith (1961), with this in mind, actually succeeded in bringing about such a reaction between these two minerals heated in a sealed tube at $750°$ C in an atmosphere of H_2S. It is likely

however, that only a minor portion, if any, of the gersdorffite in these deposits has had such an origin.

Niccolite and maucherite both have a rather limited distribution and two modes of occurrence, one in more massive particles, the other in pseudo-eutectic intergrowths. The massive types appear earlier in age and are earlier than pyrrhotite, pentlandite, chalcopyrite or cubanite. The relations of niccolite to maucherite, according to other observers, is variable. Lausen places maucherite as earlier than niccolite in the Worthington as does Zurbrigg *et al.* for the Frood. We have noted maucherite adjacent to wall rocks with minor niccolite in intergranular spaces, but Michener notes niccolite in places occurs next to wall rocks and is followed inward by maucherite, then chalcopyrite. The two are clearly closely associated in time and it may well be that in various places their order of appearance is related to arsenic vapor pressure. Locally maucherite clearly replaces and encloses odd islands in optical continuity with larger areas of niccolite.

Recent investigations by Yund (1958–9, 1961), confirm the fact that in arsenic vapor maucherite melts incongruently to niccolite and liquid+vapor, or conversely that from an Ni-As liquid in the composition range between niccolite and (beyond) maucherite, niccolite crystals will form first and, by reacting with remaining (arsenic-deficient) liquid+vapor, will form maucherite, suggesting this is the normal order of forma-tion.

The pseudo-eutectic intergrowths containing niccolite and maucherite are replacements of original gersdorffite and of later development. These are discussed in their probable paragenetic order in a later section, (C, p. 188).

Pyrite of several different generations is in most cases a very minor constituent of the ores, and only in north range and some offset deposits is it present in appreciable amounts. An early generation occurs as clearly corroded crystals replaced by pyrrhotite, pentlandite, chalcopyrite and sphalerite (Pl. II, 10–12). This type encloses rounded grains of magnetite but has not been found in contact with the early crystals of arsenides. Other types are described later.

While early pyrite is typical of hydrothermal copper ores there is no indication it has formed from such liquids here. As shown by Kullerud & Yoder the reaction $FeS_2 = Fe_{1-x}S + L + V$ is univariant in character, pyrite being stable below 743° C at approximately 10 bars and pyrrhotite, above. With quite high pressures pyrite may be stable at over 800° C, but sulphur must have been present in sufficient concentration to allow some pyrite to form early in those deposits in which it appears. Its absence however in most of the pyrrhotite ores may indicate temperatures

of the iron-rich sulphide ore fluids were above the dissociation point of pyrite, or that bulk composition was such that pyrite could not form.

(b) THE MAJOR MINERALS

Pyrrhotite-pentlandite-chalcopyrite with minor sphalerite and intergrowths. The great bulk of the ore deposits of course consist of pyrrhotite, pentlandite and chalcopyrite and the intimate association of these three strongly indicates their introduction together in one ore fluid. From this it appears, as will be shown, nickeliferous pyrrhotite solid solutions crystallized early and chalcopyrite, or more locally chalcopyrite and cubanite, later. Most, if not all occurrences of pentlandite appear to be the result of progressive unmixing of the nickeliferous pyrrhotite up to and probably including the time of deposition of the chalcopyrite and possibly even longer during further cooling. A very minor amount of pentlandite may be due to unmixing from nickeliferous Cu-Fe-S solid solutions.

Pyrrhotite

Although more than one generation of pyrrhotite can be distinguished in these ores much the greater part of it appears of one age and, as shown by its textural relations, it replaces early magnetite, early pyrite (Pl. II, 11), sperrylite (Pl. IV, 19), gersdorffite (Pl. V, 25), some niccolite and maucherite (Pl. VI, 35). The relation of magnetic to rare, non-, or weakly-magnetic (one phase) pyrrhotite is not known, but since both contain identical intergrowths of pentlandite, they are presumed to have formed at much the same time though differing probably in Fe/S ratio, a feature explainable by local variations in partial pressure of sulphur at some time during their cooling history. A rare variety of pyrrhotite showing typical α and β lamellae, similar to that described by Scholtz in Insizwa ores, appears in rims bordering rounded magnetite grains. This type is replaced by intergrowths of cubanite and chalcopyrite. As Kullerud & Yoder (1959) imply the lamellae appear related to rapid inversion which, for iron-deficient pyrrhotites, takes place between 650° and 700° C. They also note that pyrrhotite quenched rapidly from above 700° C consist of two phases.

Developed within and around grain boundaries of pyrrhotites of some north range ores is considerable fine euhedral (cobalt-rich) pyrite, formed as a reaction product, as noted in Part II, B. This clearly forms at the expense of pyrrhotite, has pentlandite flames deposited on it, and is slightly corroded by later chalcopyrite. In a rare instance elsewhere, common pyrrhotite is followed by a second generation of magnetite (Pl. I, 5) as shown by its cross-cutting relations, and this too, like

"reaction" pyrite appears earlier than flames of pentlandite, and similarly may be a reaction product. In most ores, however, pyrrhotite is cut or replaced to varying degrees by chalcopyrite (Pl. XI, 61), chalcopyrite-cubanite, sphalerite (Pl. II, 11) and by a wide variety of later minerals including in places, a much later generation of pyrite. The later crystallization of chalcopyrite compared with pyrrhotite is clearly demonstrated by textural features illustrated, and only under exceptional circumstances has any reversal of this order been found. It is further confirmed in a way by the not uncommon segregation of fairly pure chalcopyrite in stringer zones, often in the footwalls of the major ore bodies and at the extremities and borders of fractures in brecciated rocks such as quartz diorite mineralized also with intergrown pyrrhotite and pentlandite. This relationship is best explained by the slightly earlier crystallization of pyrrhotite and the movement of the residual copper-rich fluid to nearby fractures.

Pentlandite Intergrowths

The pyrrhotite-pentlandite textures, detailed in an earlier section (Part II, B), as has been argued elsewhere (Hawley & Haw), indicate an ex-solution or unmixing origin for the pentlandite. Nowhere in these ores have we found any unequivocal proof of the existence of a pentlandite fluid after crystallization of the pyrrhotite, as would be indicated by veinlets of pentlandite cutting completely across individual grains of pyrrhotite,[2] as reported for instance, in Lynn Lake ores (Ruttan, 1955). Nor have any textures which can be clearly identified as due to simultaneous crystallization of pyrrhotite and pentlandite been noted, as would undoubtedly be the case had the ore fluids attained a eutectic composition, as demonstrated by Kullerud (1956) in his synthesis of minerals in the Fe-Ni-S-system (Figures 7, 8). Although the bulk composition of the Sudbury ores lies well to the left of the central cross-section, Figure 8, this may be used for illustration. Under equilibrium crystallization of liquids between D and C in composition, the remaining liquid will on cooling eventually attain the eutectic composition E, at which point pyrrhotite of D and pentlandite of C composition will crystallize together. Strong fractionation during crystallization might allow liquids on either side of these limits to also attain a eutectic composition. On the other hand it is equally clear that original liquids, richer in sulphur than D, and ranging from A to D in composition will yield, under equilibrium conditions (where early crystals can react with liquid) only crystals of a

[2]A rare exception consists of a *composite* veinlet, apparently transecting several small grains of pyrrhotite, the grain structure of the pentlandite being controlled by adjacent pyrrhotite.
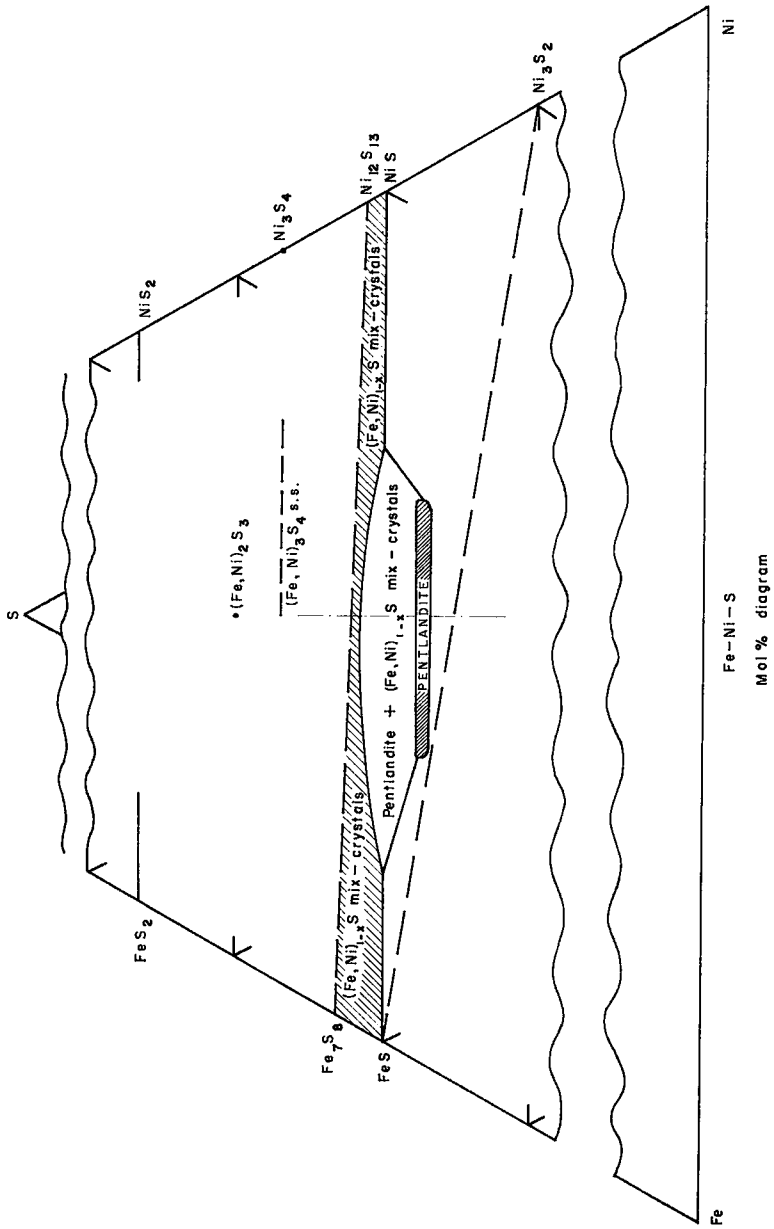
S

FeS₂

Fe₇S₈

FeS

NiS₂

Ni₃S₄

Ni₁₂S₁₃

NiS

Ni₃S₂

Ni

*(Fe,Ni)₂S₃

(Fe,Ni)₃S₄ s.s.

(Fe,Ni)₁₋ₓS mix-crystals

(Fe,Ni)₁₋ₓS mix-crystals

Pentlandite + (Fe,Ni)₁₋ₓS mix-crystals

PENTLANDITE

Fe

Fe–Ni–S

Mol % diagram

FIG. 7. Sub-solidus phase relationships at 500° C for part of the Fe-Ni-S system, after Kullerud (1955–6), showing fields of "nickeliferous pyrrhotite" mix-crystals and pentlandite.
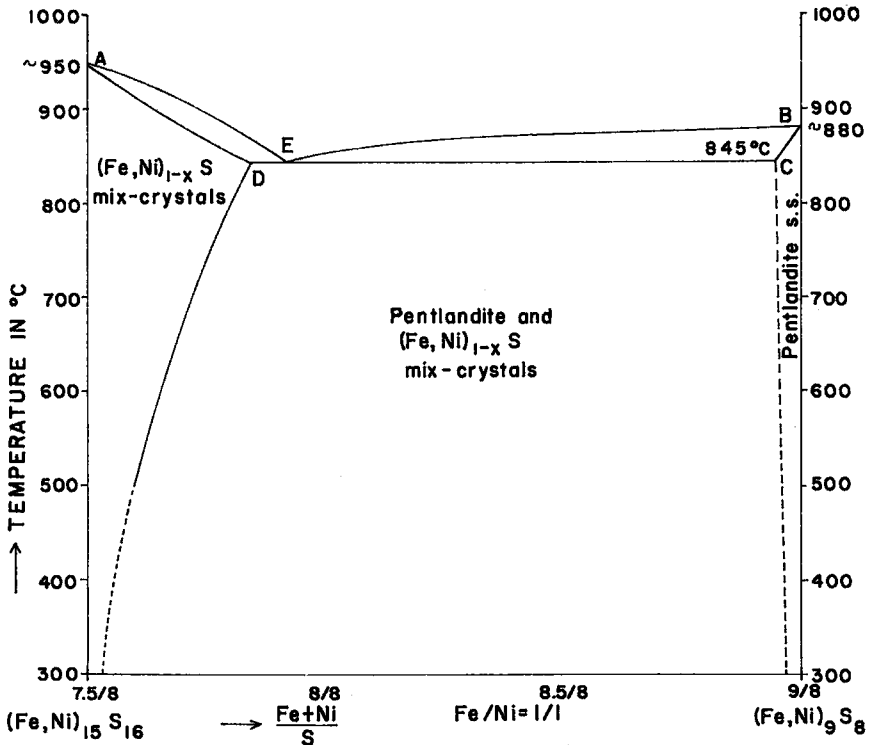
FIG. 8. A vertical section in the Fe-Ni-S system along central line, Fe/Ni = 1/1, (after Kullerud), showing eutectic relations of nickeliferous pyrrhotite mix crystals and pentlandite.

nickeliferous pyrrhotite solid solution of the same composition as the initial liquid, and pentlandite will only appear as an exsolved product when the composition line intersects the inclined solubility curve extending downward from D, as along the line GH.

A logical corollary which can be drawn from experimental data and the apparent absence of eutectic textures of pyrrhotite and pentlandite in these ores, is that crystallization of the ore fluid must have occurred originally under rather constant partial pressure of sulphur and a sufficiently high sulphur content to maintain the total composition within the limits shown (Figure 7) by the field of $(Fe, Ni)_{1-x}S$ mix crystals. A second, is that no very great amount of fractionation (separation of early pyrrhotite mix-crystals from liquid) took place, although a study of metal and mineral ratios (see p. 116) suggests this actually has occurred to some extent as shown by variations in bulk composition of widely separated ore bodies.

In connection with the sulphur content of such ore fluids it is interesting to note how McKinstry (1957) has shown that during progressive crystallization, as indicated by the successive mineral assemblages which appear stable under decreasing PT conditions, sulphur increases in general, in which case (nickeliferous) pyrite[3] might be expected to appear, mantling early crystals of pyrite and even replacing earlier pyrrhotite. Such a tendency for sulphur to increase in any case, would obviously favor crystallization of pyrrhotite mix crystals rather than of pyrrhotite and pentlandite at a eutectic.

On cooling of such mix-crystals, however, Kullerud has further shown that nickeliferous pyrrhotites take up more sulphur, and in a closed system of constant composition this can only be obtained by the ex-solution of the lower sulphur-bearing pentlandite $(Fe,Ni)_9S_8$. It has also been experimentally indicated (Hawley & Haw) that heat treatment of nickeliferous pyrrhotites under conditions whereby sulphur content of the solid could decrease, as in a vacuum or as might obtain in a restricted system during a prolonged period of mineralization by fracturing and crushing of already solidified material, the bulk composition would move to a lower sulphur level and pentlandite would exsolve, liberating some sulphur for the remaining pyrrhotite. The similarity of flames, lenses and even veinlets of pentlandite formed experimentally, in this way, to natural occurrences supports such an ex-solution origin for them.

Of the three modes of occurrence of pentlandite, as classified above (Part II, B) there can be no question as to the ex-solution origin of pentlandite lamellae, lenses or veinlets and flames or brushes contained *within* pyrrhotite grain boundaries. Their relation to twin planes in pyrrhotite is interpreted as due to post-twinning segregation, but there is no clear indication that such twinning is secondary rather than primary.

The not uncommon occurrence in both chalcopyrite and cubanite of lenses and irregular grains of pentlandite (with or without pyrrhotite) particularly where they show signs of corrosion, suggest that most of these are in fact remnants of original pyrrhotite-pentlandite intergrowths. Two types of pentlandite-chalcopyrite intergrowths which differ from this type are the "collars" of pentlandite in chalcopyrite, plates or blades of the former extending inward from grain boundaries, and the fine composite spindles of valleriite-pentlandite arranged en echelon within chalcopyrite but usually not far from corroded remnants of pentlandite. It seems quite possible that both of these are the result of the breakdown

[3]Such a type of pyrite, associated with quartz, in offset ores has been noted but is believed to have formed under hydrothermal conditions, and is placed with Secondary Ore Minerals.

of unstable Cu-Fe-Ni-S solid solutions formed by reaction or solution of pyrrhotite-pentlandite by surrounding "chalcopyrite"–ore fluid. In the former, ex-solution may have occurred almost immediately on crystallization of the chalcopyrite, before nickel and iron had had an opportunity to diffuse far into the liquid. In the latter, somewhat greater diffusion may have occurred so that ex-solved valleriite and pentlandite strings or spindles are more widely distributed throughout chalcopyrite grains. Both, however, are quite rare and differ in abundance and form from pentlandite-chalcopyrite-cubanite intergrowths described in the pyrrhotite-free ores of the Mackinaw mine, Washington, (Milton & Milton, 1958) and from the peculiar pentlandite-chalcopyrite intergrowths in pyrrhotite of ores at Igdlukúnguaq, Greenland (Pauly 1958), both of which are ascribed to exsolution from nickeliferous copper-iron solid solutions for which Pauly suggested the name "chalcopentlandite."

In other cases, fringes or collars made up of flames of pentlandite project into pyrrhotite along its grain boundaries with chalcopyrite, as noted also by Scholtz (1936) in Insizwa ores. These may be simply the result of exsolution from original nickeliferous pyrrhotite, localized by the crystallizing chalcopyrite, under conditions which did not favour the diffusion of nickel into the encroaching chalcopyrite fluid.

The origin of interstitial pentlandite (Pl. VII, 42; VIII, 45) is perhaps on less certain ground, particularly as the amount of such pentlandite often seems too great to have had a local derivation from adjacent grains of pyrrhotite. The coarser interstitial pentlandite, however, passes into thin rims and partial rims about pyrrhotite grains, few of which now contain ex-solved pentlandite within their borders due to their depletion in nickel. As similar rims have been synthesized by ex-solution (Hawley & Haw) these and the coarser aggregates of interstitial pentlandite also are regarded as exsolved products formed under conditions allowing more distant diffusion and almost complete segregation of pentlandite.

It may be suggested that the different textures resulting—segregation *within* and to *without* the grain boundaries of pyrrhotite is a function of temperature, as the process indicated by Figure 8 clearly shows it to occur over a *range* of temperatures below 845° C. Undoubtedly also any inversions occurring in the pyrrhotite on cooling must be another factor. That the flame type forms after the interstitial pentlandite, at least in part, is indicated by its addition to the latter, giving in places, irregular boundaries. The occurrence of second generation magnetite in some places and of "reaction" pyrite in others, as partial rims about pyrrhotite allows an inference to be drawn as to the relative ages of associated rims or flames of pentlandite. Nowhere do veins of magnetite clearly cut the pentlandite as they do grains of pyrrhotite. Rather does pentlandite

enclose blebs of magnetite in such areas and occupies deep cusps within the magnetite. This suggests segregation of the pentlandite occurred after formation of second generation magnetite and "reaction" pyrite, and before or during deposition of chalcopyrite. There is of course no reason why long continued segregation of pentlandite might not occur until the temperature had declined considerably.[4]

Coarse rounded aggregates, particularly those with scalloped borders (Pl. VII, 40) as indicated above appear clearly as replacements of bordering pyrrhotite grains, cross-cutting the boundaries of one pyrrhotite grain after another. Near such segregations the adjacent pyrrhotite is largely devoid of fine flames of pentlandite which appear, however, farther away. The finer grain of the adjacent pyrrhotite may be due to recrystallization (possibly under stress) a process which would doubtless aid in exsolution of pentlandite. Coarse ovoids (Pl. VII, 41) have probably formed in a similar manner. As exsolution is in essence a replacement process in the solid state, evidence of replacement alone does not imply the presence of a liquid phase and these peculiar coarse segregations are believed to be just other examples of unmixing of nickeliferous pyrrhotites formed under optimum conditions for diffusion.

Within coarse grains of pentlandite in many cases ragged inclusions of pyrrhotite are found. Some of these can be shown to be in optical continuity with adjacent or nearby pyrrhotite, indicating they are remnants left by incomplete replacement. In some cases such inclusions however, appear as either flame-like or triangular shaped bodies, the edges of the latter paralleling octahedral cleavage of the host. Occasionally several such fine particles extinguish together. As these are confined to individual grains of pentlandite they may be again either remnants of original pyrrhotite or even ex-solution pyrrhotite formed by the breakdown of a somewhat iron-sulphur-rich-pentlandite, as would be expected from Kullerud's diagram (Figure 8) from the inclination of the line bounding the pentlandite field from C toward $(Fe,Ni)_9S_8$.

In summary, then, pentlandite in these ores is considered to be entirely the result of segregation from nickeliferous pyrrhotite (and rarely chalcopyrite) solid solutions. The many different forms these have taken suggest ex-solution occurred under varying conditions of temperature and pressure of sulphur and over a period of time. Indications are it began after development of twin lamellae in pyrrhotite and after the local develop-

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[4]It has been called to our attention by H. R. Wynne-Edwards that the indicated ages for the coarser, interstitial pentlandite as early and the finer flame type as later, is the reverse of what is found in perthitic feldspars. This may be due to the greater ease of diffusion of nickel in a sulphide such as pyrrhotite, compared with the sluggish diffusion in ionic crystals of feldspar where an increase in water vapor pressure may occur at a late stage with falling temperature and greatly aid in the unmixing.

ment of second generation magnetite and "reaction" pyrite. Some of the coarser segregations as interstitial pentlandite and ovoids or coarse rosettes appear to have developed under optimum conditions of diffusion, probably at higher temperatures, while the finer flames which add on to the coarser material are in part at least formed later and may represent products arising at somewhat lower temperatures. That segregation continued into the period of deposition of chalcopyrite is shown by fine rims of flames or blades, along the contacts of pyrrhotite and chalcopyrite extending into one or other of these minerals. Both chalcopyrite and cubanite clearly replace earlier formed pentlandite and the development of "collars" of pentlandite in chalcopyrite and of composite spindles of both valleriite and pentlandite suggest that the replacement of earlier nickeliferous pyrrhotite locally produced a nickel-iron-copper sulphide solid solution which exsolved pentlandite and in the latter case, valleriite. Where chalcopyrite replaced coarse pentlandite (Pl. XI, 63) fine-grained aggregates of cubanite appear to have developed along the cleavages as reaction products, but the behaviour of nickel in this case has not been determined.

As will be shown below, a second generation of pyrrhotite occurs locally with cubanite and a much later one has formed where massive normal ore is cut by late veins of galena and sphalerite.

Chalcopyrite and Intergrowths

Chalcopyrite of different generations can be recognized more by its associated minerals than by discernable differences in form or composition. By far the greatest part of it is intimately associated with the nickeliferous pyrrhotite and pentlandite, while later generations are probably relatively insignificant. In all cases it crystallized after pyrrhotite and other earlier minerals and was followed by sphalerite, bornite, galena, and other later minerals.

Several different types of ex-solution intergrowths are found in chalcopyrite, including cubanite, valleriite, pyrrhotite, pentlandite, and very rare sphalerite. It has participated in the development of pseudo-eutectic intergrowths with niccolite, maucherite and pyrrhotite, but in these it is not clear whether it represents primary or remobilized chalcopyrite. In addition, it encloses replacement residuals of earlier minerals, as well as small particles of many rarer species, many of which may be more or less contemporaneous with it or somewhat younger.

Where not complicated by the different types of intergrowths mentioned, it is quite clear that the bulk of the chalcopyrite crystallized from the same ore fluid as the pyrrhotite, after second generation magnetite and "reaction" type pyrite, and during, and also after the

segregation of pentlandite from pyrrhotite. Experimental work by Greig *et al.* (1955) on Cu-Fe-S liquids, covering the composition of the Sudbury ores, if we assume nickel behaves as iron, indicates that under equilibrium conditions copper-bearing pyrrhotite solid solutions should crystallize first at temperatures above 912° C, and later exsolve the copper as ex-solution chalcopyrite. This has clearly not occurred here. Rather has a low copper but nickeliferous pyrrhotite crystallized first, and the copper has been enriched in the residual liquid to crystallize as chalco-pyrite at somewhat lower temperatures. This process has clearly been important in the development of rich copper zones in many of the major ore deposits, particularly along their borders in areas usually more remote from the norite or quartz diorite.

Of the various intergrowths in and with chalcopyrite, that with cuban-ite is the most common and best displayed in ores from the cubanite zone of the Frood-Stobie. Though found sparingly in other deposits, it is nowhere else developed on the same scale. As noted above, the granular cubanite in interlocking crystals with similar sized grains of chalco-pyrite, may well represent a product of direct crystallization, somewhere below 950 °C. (see Greig), or otherwise must represent completely segre-gated grains from a former solid solution. As this ore contains replacement remnants of magnetite, pyrrhotite, and pentlandite, it is not possible to say how much the higher iron content of the liquid from which the cubanite formed was due to this replacement and how much to original segregation from its source. The evidence of replacement may be quite adequate to explain it. In any case it is important to note that the order of crystallization of these ores, save for the presence of cubanite, is the same as in those with no cubanite.

Oriented intergrowths in chalcopyrite which are probably more important in Frood ores than in others include:

1. Cubanite laths, often along three directions.
2. Valleriite rods or strings, with or without cubanite and present in both.
3. Composite spindles of valleriite and pentlandite.
4. Pyrrhotite cutting both intergrown cubanite and chalcopyrite.
5. Pentlandite as "collars" along grain boundaries.
6. Sphalerite as asterisks—very minor.

All of these are clearly products of unmixing of solid solutions which must have contained iron, nickel or zinc in excess of that which could be held by the chalcopyrite (or cubanite) on cooling. While each of these metals may have been present in the original copper-rich liquid from which such solid solutions crystallized it seems likely, except for zinc, they were acquired by replacement of earlier grains of pyrrhotite and

pentlandite as suggested above, illustrating as is so often the case, crystallization under non-equilibrium or changing conditions. This is particularly well shown by the localization of valleriite spindles around a pentlandite remnant (Pl. XI, 66), by "collars" of pentlandite within grain boundaries of chalcopyrite adjoining pyrrhotite (Pl. X, 57), and by probable reaction rims of cubanite and chalcopyrite around magnetite, and similar intergrowths replacing coarse pentlandite (Pl. I, 4; XI, 63). Zinc, on the other hand, though of very minor occurrence, has likely been locally concentrated along with the copper (and some tin) in the remaining ore fluid as nowhere has sphalerite or stannite been found to precede chalcopyrite.

Such exsolution intergrowths were undoubtedly formed while temperatures were still quite high. Schwartz (1927) notes the unmixing temperature of cubanite from chalcopyrite is between 400° and 450° C., temperatures confirmed by Michener on Sudbury material. As with temperatures of unmixing of pentlandite from pyrrhotite, however, this probably occurred over a range of temperatures rather than at a fixed point. Both the original nickel and copper-iron solid solutions and their unmixed products are typical of minerals formed from molten sulphides at high temperatures.

The significance of the foregoing in the zoning of the copper and other minerals at Frood and to a smaller extent elsewhere will be dealt with in section 5.

Sphalerite (Sphalerite-Stannite)

As noted in earlier descriptions sphalerite is nowhere abundant. At least three and possibly four generations have been indicated. As noted under chalcopyrite the first is exceedingly rare, occurring as ex-solution asterisks in chalcopyrite and cubanite. The second is post-chalcopyrite while the third belongs to a much later period of mineralization. The second is found in the common sulphide ores cutting pyrite and pyrrhotite (Pl. II, 11) and also as small irregular masses, which under crossed-nicols can be seen to exploit grain boundaries of chalcopyrite. In many ores it is only present as small flecks, usually in or next to chalcopyrite. In none of these ores has stannite been observed, but spectrographic analyses by Lewis (1950) show tin is usually present.

In the Frood, on the other hand, sphalerite in the deeper level ores, is almost invariably accompanied by stannite which shows typical exsolution relations to it. Here the mineral sequence is much more complex and stannite also is found in many species. The fact that the sphalerite overlaps galena in time of deposition, suggests that stannite does likewise. The presence of intervening species between chalcopyrite and galena

such as parkerite, tetradymite and others, simply allows this type of sphalerite to be placed in its correct paragenetic position, as noted below, rather than indicating that the two are distinctly different generations. Post-main-ore type of sphalerite is described later.

(c) THE LATE MINERALS—Cu-Ni-As-Bi-Te-Pb AND PRECIOUS METALS

There is of course no sharp division between the time of deposition of the preceding minerals and the rather complex group which follow, but an arbitrary line is drawn at this point because of the distinct change in their chemical character, although deposition of copper both as chalcopyrite and cubanite, and finally as bornite, continued.

This stage can only be illustrated at the present time by occurrences at the Frood-Stobie. It is not recognizable in many of the other deposits or parts of them, where it may, however, be represented by trace amounts of these rarer minerals and elements in the common ore minerals, where conditions for their greater concentration were not so favourable.

At the Frood-Stobie this type is largely confined to the outer and lower arsenide and sulphide zones and the sulphide-poor siliceous ore below, to which bornite seems confined, as described by Zurbrigg et al. (1957). As noted earlier, the arsenides give quite clear evidence of crystallizing early, ahead of the common sulphides, while many of this group show by their textural relations, a slightly younger age. In many places they occur only as fine grains, included in or moulded on the more common species, so age differences are by no means clear-cut. Some, such as sperrylite, may have continued to crystallize along with the sulphides, but there can be little doubt that here as in other ore deposits, particularly as shown by the precious metals, they are the products of concentrations effected in the last residual liquid of the original ore fluid, in part, drained downward into fracture zones, like roots. In this respect this deposit compared with others, is an "upside down" one.

Aside from the earlier common sulphides with which they are in part intermingled, metallic minerals of the group are characteristically low in iron, as indicated by bornite with only minor chalcopyrite. This may account for the presence of rare heazlewoodite in place of pentlandite. Bismuth is typically in relatively high concentrations and has combined with nickel, palladium and sulphur to form parkerite, michenerite, froodite, and bismuthinite; with silver to form schapbachite, and with tellurium, tetradymite. Excess bismuth formed the native metal. Tellurium has also combined with silver to produce hessite. In places grains of all of these are found in bornite with minor chalcopyrite, or in galena which appears to have formed still later. Native silver and electrum, found separately, appear to be the latest minerals of the group.

The basis of the above generalized paragenesis is given in the following summary. Heazlewoodite, enclosed as fine grains or strings in both chalcopyrite and bornite can only be placed as earlier than both. A definite order cannot be established for the various bismuth-bearing minerals, but of them parkerite is probably one of the earliest. That it formed by direct deposition is suggested by its deposition as fine veinlets near contacts with massive sulphides (Michener). It is enclosed in both bornite and galena and in both is often associated with native bismuth. In some pyrrhotite-rich galena samples, bismuth replaces pyrrhotite and encloses and rims parkerite, suggesting some of the latter might be a reaction product of bismuth and nickeliferous pyrrhotite or even pentlandite which is seldom if ever seen near it. As in bornite, however, the two may be simply the result of serial deposition.

No definite position can be given for the palladium bismuthides which at Frood are reported to occur below disseminated ores along with the nickel arsenides, electrum, hessite and galena. One grain tentatively identified as michenerite occurs with hessite along grain boundaries of massive maucherite. The unknown palladium-bismuthide (Mineral C) in niccolite in pseudo-eutectic intergrowth with chalcopyrite and maucherite, from Garson, is not incompatible with a late stage of formation.

Schapbachite (?) and bismuthinite (?) seem confined to galena. The former shows mutual boundaries with both parkerite and bismuth, while bismuthinite is moulded about the parkerite. Bismuth is also found in small particles intergrown with pyrrhotite, pentlandite, chalcopyrite and bornite. The tellurides, tetradymite and hessite, are found in galena-rich ores as composite and separate particles along with parkerite around which hessite moulds itself, as it does in places about some tetradymite. Hessite thus seems slightly later, as might be expected, as the bismuth became exhausted. The hessite, in turn, appears partly replaced by bornite.

Bornite in the siliceous ore zone clearly replaced chalcopyrite, and has also ex-solved spindles of it. Later than the bismuth and tellurium-bearing minerals which it encloses, some appears enclosed in turn by galena. Some bornite replacing chalcopyrite shows such a close spatial relation to native silver (Pl. XII, 69) that it appears as an alteration produced by the silver depositing fluid. This may be a slightly later generation than bornite developed away from the silver.

Galena, aside from minute flecks noted occasionally in chalcopyrite of normal ores, and in post-main ore fractures, is well developed in both the lower massive ores of Frood and in the siliceous ore below, in both of which it is characterized by bismuth and precious metal mineral inclusions. In the massive sulphide ores it extensively replaces and

moulds itself around the common sulphides as well as magnetite, sperry-lite, pentlandite and cubanite. Sphalerite with stannite, or both in-dividually, appear to overlap the galena in time of deposition as both are found within and also as rims around it. In the siliceous ores galena encloses minor bornite and is thus placed as the later.

The very latest minerals believed to have crystallized from the main nickeliferous ore fluids are the native metals, silver and gold (electrum). As the two occur separately their relative age relations are unknown. Native silver appears to replace galena and in bornite-rich specimens forms veinlets with gangue traversing chalcopyrite and bornite, the latter seeming to develop as an alteration next to the silver, as noted. Pale yellow gold (electrum) occurs as small flecks within and at the margins of many of the previously described minerals. It has not been seen as veinlets in massive sulphides which it tends to plate, but Michener has noted its occurrence in fractures in the siliceous contact rocks adjoin-ing the siliceous ore, but not in more basic rocks. It thus appears to have travelled farthest and to the greatest depths of the complex assemblage found at the base of the Frood deposit. In the common ores low values in gold and silver are always present and probably represent metals which were unable to escape from the crystallizing sulphides.

If the above interpretation is correct, the residual liquids from which this late group crystallized would be expected to have had concentrated in it most of the volatiles (H_2O, F, etc.) originally present in the ore fluid, however small in amount these may have been. Some water was used up in biotite and amphibole crystallizing from immiscible silicates within the sulphides. Some must have contributed to the amphibole and biotite wall rock alterations noted, and to the formation of quartz and carbonate in the "siliceous mineral" zone. Neither the garnet alteration nor the amphibole however indicate a very high concentration of volatiles, and it seems possible that such volatiles as there were, may also in part have been derived from the wall rocks themselves.

The textures displayed by the ore minerals on the whole, the abundance of ex-solution intergrowths, their similarity to textures produced synthe-tically from dry melts, and their high temperature characteristics, all confirm the magmatic character of the sulphide ore fluids. That a more aqueous residual liquid should be formed at the close of their crystal-lization history is entirely expectable.

5. EVIDENCE OF THE DISTRIBUTION OF METALS AND ZONING

The distribution of metals in mineral deposits is the result of many different factors affecting their concentration in source fluids, however formed, and their crystallization from them. The general similarity of

the Sudbury ores indicates that for the most part these factors have operated to produce rather uniform ore fluids which crystallized under rather similar environmental conditions. It has been demonstrated that the *primary* ore fluids were essentially sulphide melts arising by liquation from the irruptive magma, some of which may have been later modified in places. Differences in the distribution of the metals have been indicated both in different types of ore within a single deposit, as well as in one deposit compared with another and especially in the strikingly zoned deposit at Frood-Stobie. On the other hand some deposits, containing different types of ore (disseminated, breccia, or massive) show very little, if any, variation. We shall now examine these to determine if suitable explanations can be found within the framework of the proposed magmatic hypothesis.

The most marked variations in metal and mineral ratios are exemplified by the Frood-Stoble deposit and factors which have produced the zoning here may well explain minor variations noted elsewhere.

Factors affecting the distribution of metals in deposits formed from magmatic sulphides fall into two main groups, those effective in partitioning the metals between silicate and sulphide liquids, and those which operate especially during the crystallization of the sulphide fraction. Wager *et al.* (1957) have recently given pertinent data on the former in their study of the layered intrusive at Skaergaard. The Skaergaard example, however, differs from the Sudbury in some very important respects; in it sulphur was a relatively scarce component and only copper and iron sulphides have been formed but no nickel ores. Wilson & Anderson (1959) have reviewed both groups of factors and suggested criteria which might be used to distinguish ores formed *in situ* from ores which have been injected to other sites.

Two factors which affect the partitioning of the above metals between the silicate and sulphide liquid fractions, are the concentration of sulphur and the relative affinity of the metals for sulphur, their chalcophile character. Copper is more chalcophile than nickel or iron, and at Skaergaard where sulphur was quite low, this led, after considerable crystallization of silicates, to the separation of a copper-rich liquid (with appreciable cobalt), crystallizing to bornite, digenite, and a little chalcopyrite, while nickel and most of the iron remained in the liquid, the nickel and some iron being taken up in growing silicate crystals. As crystallization of silicates continued, sulphur content increased, and eventually iron sulphides separated to crystallize as pyrrhotite with quite minor nickel and lower cobalt. This might suggest that the earliest sulphide liquids would always be relatively rich in copper and, if segregated out, would be the first to crystallize and give copper-rich ores,

the nickel and iron sulphides separating later. That this may have played some part in the Sudbury ores is suggested by the fact that what are regarded as residual disseminated ores in norite and quartz diorite are relatively impoverished in copper, compared with many underlying non-disseminated ores (Frood) which probably separated earlier. While unquestionably important at Skaergaard, it was clearly not so effective in the sulphur-rich norite at Sudbury where much nickel and iron must have separated along with copper, probably in both early and later stages. This in general is shown by the low nickel content of the basic silicates of the irruptive, in which much might have been lost. It seems also indicated by the copper-nickel ratios of some massive ores, as at Creighton (Table 13), by the presence of replacement remnants of pyrrhotite and pentlandite in the copper-rich (cubanite) zone at Frood, and by the composition of the sulphides in the "immiscible silicate-sulphide" ore of the same mine, now consisting dominantly of pyrrhotite with lesser pentlandite and minor chalcopyrite. As we shall see, other processes may aid in the separation and concentration of copper, even from early segregations, so it is not possible here to determine just how important its affinity for sulphur actually was.

Other differences between the early copper concentrations at Skaergaard and the copper-rich zone at Frood with which it has been compared (Wilson & Anderson, 1959) may be noted. One is in the cobalt content and the other, the association at Frood of the peculiar siliceous mineral zone rich in Pb, Bi, and precious and native metals. At Skaergaard cobalt has been shown to have been concentrated with the copper sulphides (2 per cent) to such an extent as to suggest there it was more chalcophile than nickel (Wager *et al.*, 1957) though generally the reverse is true (Rankama & Sahama, 1950). We have no data from Sudbury by which we can compare the cobalt content of the original magmas, but at Frood, deep bornite is quite low (0.004 per cent) in cobalt, while averages for cubanite are not much above that found in pyrrhotite (.013–.015 per cent), and some cobalt in both cubanite and chalcopyrite may be accounted for by impurities of pentlandite noted in polished sections. Moreover, in this deposit cobalt may be inferred as behaving in a more normal manner (less chalcophile than nickel) by virtue of its somewhat lower content in pyrrhotite of the deep copper zone, if segregated early, and its higher content in disseminated (residual) pyrrhotite trapped in the quartz diorite above (see Table 3, Part II, B). Data are few and differences slight and much more research is needed to clarify this point. At Hardy, on the other hand, Ni/Co ratios are closer and Co content identical in pyrrhotite of the two types of ore, a condition which might obtain if the ores were injected at the same time. The siliceous mineral

zone grading downward from the copper ore is a further complication. If the copper represents an early concentrate, this too, by virtue of its position, should be also, and yet it contains many elements and native gold and silver, not normally deposited early in the paragenetic sequence, and another explanation seems required.

In summary then, sulphides separating early from such magmas may be expected, according to their normal chalcophile properties, to be richer in copper than nickel and iron, and richer in nickel than cobalt and iron, in comparison with sulphides separating later. There are suggestions that in some of the Sudbury ores such partitioning has occurred, especially with respect to copper and cobalt, and further study may uncover other examples. As will be seen, however, other processes may work in the opposite manner for both nickel and copper.

The second group of factors affecting the partitioning of metals which may be equally or even more important than the first, are those which Bowen (1928) considered as playing a vital role in the crystallization differentiation of igneous rocks. As in silicate magmas the course of crystallization of sulphide liquids is largely controlled by the mode of crystallization of solid solutions, which in turn depends on whether this occurs under *equilibrium* or *non-equilibrium* conditions. Under equilibrium conditions growing crystals of solid solutions, initially richer in the higher melting substance, continuously *react* with the liquid and eventually attain the same composition as the original liquid. Under non-equilibrium conditions, early crystals fail to react for one reason or another, and thus have a different composition than those forming later—the process known as *fractionation*.

Applying this to the crystallization of a nickeliferous pyrrhotite solid solution, the most abundant constituent of the ores, in the former case, (under equilibrium conditions), uniform nickel:iron and eventually pentlandite:pyrrhotite ratios would be expected, as is the case in many of the deposits. Under conditions favouring fractionation, however, assuming the sulphide ore fluids were all much the same to start with, deposits with somewhat lower nickel[5] may represent relatively early crops of crystals, and those richer in nickel, crystals formed from the remaining liquid, thus accounting for such variations in nickel as noted in some deposits compared with others.

Sulphur concentration has also been indicated as important in determining whether nickel and iron will crystallize as a single nickeliferous solid solution, on the one hand, or as nickeliferous pyrrhotite *and* pentlandite at a eutectic, on the other. The mineralogy of the ores clearly

[5]Since iron-rich pyrrhotite would have a higher melting point than that richer in nickel.

show that sulphur was in sufficient concentration so that most of the nickel originally entered pyrrhotite which later exsolved the pentlandite.

Crystallization of copper-iron-nickel sulphide liquids is more complicated, but here too, the process of fractionation may lead to enrichment in residual liquids of copper (and some iron) by the earlier crystallization of nickeliferous pyrrhotite. Textural studies of the ore minerals confirm that little, if any, copper entered the pyrrhotite, as nowhere have exsolution intergrowths of copper minerals been found in it; paragenetically the copper sulphides are always later. Movement of such copper-rich liquids to cooler areas, more remote but never far from the irruptive contacts, and into footwall fractures would yield chalcopyrite-rich stringer zones, as at Creighton, and at Frood-Stobie, movement downward would account for the increasing copper ratios at depth and the rich cubanite-chalcopyrite zone. Temperature and perhaps the degree of replacement of earlier pyrrhotite by the copper fluid, likely controlled the deposition of cubanite (or a Cu-Fe-S solid solution) compared with chalcopyrite, the former likely requiring higher temperature conditions. The mobility of such copper fluids is also demonstrated time and again where chalcopyrite alone replaces fragments in breccia ores, or is concentrated at the ends and sides of composite stringers.

Solubility of other elements in copper-rich sulphide *liquids* compared with nickel-iron, is still another factor. From both chemical and mineralogical data both on these deposits and many others, elements such as lead, zinc, tin, bismuth, tellurium, arsenic, selenium and the precious metals under suitable fractionation conditions appear to be thus enriched in the copper fluids. Solubility in *crystals* of copper minerals, however, is low, so as cubanite and chalcopyrite crystallize the residual liquid should be still further enriched in these until their solubility products are reached, at which point they would crystallize, along with remaining copper sulphides to form the group of rare sulphides, arsenides, bismuthides, tellurides and native metals, as at the base of the Frood and in the siliceous mineral zone. The solubility factor both in early and late sulphide liquids and fractionation thus offer a simple explanation for the zoning of metals in this deposit. Reasons for their association with quartz and carbonates at the base of the deposit have already been given, p. 181.

The apparently anomalous behaviour of the arsenides is a problem. In unzoned deposits it has been shown that the arsenic-bearing minerals, especially gersdorffite and sperrylite crystallized in part before the common sulphides. On the lower levels of the Frood, the arsenides form a sheath around the sulphides, including the cubanite zone. They thus either must have arrived there ahead of the copper sulphides, in a (more

volatile?) fluid form, or have been expelled from the dominantly sulphide liquid as it advanced downward. Textures show clearly that both niccolite and maucherite here, are replaced by cubanite and chalcopyrite so the arsenides crystallized before crystallization of the copper sulphides was complete. Such occurrences suggest that arsenic concentration in the early, undifferentiated sulphide melt was sufficient to cause early crystallization of some arsenides before pyrrhotite. With crystallization of nickeliferous pyrrhotite, copper and sulphur then increased in the remaining liquid and may well have affected the solubility of the arsenide minerals so that further precipitation of them was delayed. By the time much of the remaining copper and iron sulphides crystallized, arsenic concentration may have risen to the point where arsenides would again be precipitated along with some remaining copper sulphides. Such a behaviour is not unique, but some experimental investigation of this phase of the problem would doubtless aid in its clarification.

The distribution of the platinum metals as a group calls for some further explanation. Whereas platinum, with apparently a great affinity for arsenic, crystallized chiefly as sperrylite, palladium is found as bismuthides associated both with nickel arsenides as well as lead and bismuth minerals in late differentiates. A certain amount of all the platinum metals also occurs in solid solution in the common sulphides. In general, Rankama & Sahama (1950) have noted that "the pronouncedly chalcophile" character of the Pt metals explains their concentration in sulphides as compared with metals, though they are recognized as having siderophile characteristics as well. The latter feature, affinity for metals, they suggest is responsible for the concentration of both Pd and Pt in ("hydrothermal") nickel-cobalt arsenides, since both *arsenides* and *bismuthides* are more metal-like than sulphides. The arsenides of course are not restricted to hydrothermal deposits, so this factor should apply equally well to the magmatic ores. It has also been shown elsewhere (Hawley & Ramsaite, 1953) that palladium is the one Pt metal found in minute amounts in sulphides of hydrothermal copper and gold ores, indicating its ability to persist even in the more siliceous residual liquids of crystallizing magmas. In the Sudbury sulphides palladium has been shown to increase in the sulphides of some deposits in the order of their paragenesis, and late differentiates would thus be expected to show an enrichment. In the case of the Frood, however, conditions seem to have been such that both platinum and palladium were concentrated in the lower copper-arsenic-bismuth-rich zones, but perhaps not for exactly the same reason for each.

Little can be said on the distribution of the other Pt metals for lack of data. The chalcophile character of Rh, Ru and Ir explains their

association with sulphides. Such analyses as we have, suggest somewhat more of these is present in earlier crystals of pyrite, pyrrhotite and pentlandite than the later chalcopyrite but much more information is needed before this can be accepted as a general rule.

The full significance of zoning in the Frood-Stobie deposit and to a much lesser extent in a few others, may now be shown. Here it is of a rather unique type compared with most other primary mineral deposits. This lies in the fact that the mineral zones are so arranged that what are interpreted as products of late crystallization underlie the earlier, and as late crystals normally form at lower temperatures, the lowest (siliceous mineral) zone would appear to be of this type. As shown and stated earlier the Frood-Stobie deposit was clearly formed *in situ* and is an "upside-down" deposit. The reason for this is not hard to find. The magmatic source of the deposit lies above, not at greater depth, as in so many other zoned deposits. The irruptive was the source also of heat. As the ore fluids migrated downward and outward into breccia and fractured wall rocks they passed into a cooler environment, but temperatures must have remained sufficiently high to permit fractionation to occur to such an extent. Somewhat peculiar structural conditions must have also obtained to permit the downward injection of the sulphide-rich quartz diorite magma from the former extension of the main irruptive above. One can only suppose this was caused by tensional fracturing, perhaps related to torsional warping, in the great Frood breccia formation, the fractures dying out only at considerable depth. The richness of the sulphide deposits may even indicate not only segregation of sulphides from the "offset" dyke but also from the up-dip portion of the main irruptive as well. The deposit as a whole thus testifies to the magmatic nature of the ore and to its immediate source in the Sudbury irruptive.

As noted by Wilson & Anderson, variations in metal ratios is a diagnostic feature of ores formed *in situ*, and uniformity, of injected deposits. This is not necessarily an inherent difference but is doubtless caused more by temperature differences in the environment of deposition, injected ores cooling more rapidly with less opportunity for fractionation to occur. In this case the elements characteristic of late differentiates would remain enmeshed in the common sulphides as is so well shown by spectrographic traces in them.

In this section the detailed relations of different types of primary ores to the various rocks and structures in which they are found show close agreement with experimental and theoretical considerations and indicate they represent magmatic sulphide liquids separated from the irruptive and offsets, some crystallizing *in situ*, others *injected* into favourable sites. The relations of the primary ore minerals to one another, uncluttered by

post-ore effects, their character and intergrowths support their high temperature magmatic origin. Processes active during their initial segregation as liquids and their later successive crystallization, especially *fractionation*, seem adequate to account for such differences as have been noted in the distribution of the common minerals and metals, and the zoning which characterizes a very few deposits.

C. POST-MAGMATIC ORE EFFECTS

Superimposed on the main magmatic sulphide deposits are four rather distinct groups or types of effects outlined in an earlier chapter. The subdivisions may be too few as they cover an interval in Precambrian time of about 700 m.y. as well as to the present. As several occur quite separately, age relations are not everywhere certain. Many are of local distribution, others more widespread. Quantitatively and economically they are for the most part of little moment and their chief claim to importance is the confusion they might cause or have caused, if not recognized as secondary and clearly later in age. A few are of scientific interest. They will be described in their probable order of development.

1. Hypogene Alterations and Local Remobilization by Post-ore Granite

These include two rather different effects, the development of peculiar pseudo-eutectic intergrowths of nickel arsenides with pyrrhotite and chalcopyrite in arsenical ores, and what seems clearly the result of remobilization of normal breccia ore by the post-norite and post-ore granite adjoining the pre-norite Murray granite, yielding the pentlandite-pyrite rich ore at the McKim mine. Both appear to have formed under hypogene conditions, but after the main ores had solidified. Temperatures were thus probably somewhat lower than earlier, and pressure conditions somewhat different. Grouping them together does not imply they were formed at the same time, although this is possible.

(a) PSEUDO-EUTECTIC INTERGROWTHS OF NICKEL ARSENIDES AND SULPHIDES

The several types of psuedo-eutectic intergrowths of niccolite, maucherite, chalcopyrite and pyrrhotite, peculiar to some of the Sudbury ores, as described in detail in Part II, B and elsewhere, are essentially replacements, in most cases at the expense of original gersdorffite. Four two-phase and two three-phase intergrowths have been noted, not counting residuals of gersdorffite, in all but one of which chalcopyrite,

most commonly, and pyrrhotite are involved. The one exception is the intergrowth of niccolite and maucherite, but even this is usually found close to chalcopyrite. The latter combination was once thought to result from the introduction of chalcopyrite into niccolite, before the important role of gersdorffite had been noticed. That this and the other intergrowths did not form during the early crystallization of gersdorffite, niccolite, pyrrhotite and chalcopyrite is suggested by two facts. One is that these minerals may be found in several ores in close contact showing no replacement, or where replacement is evident, it is often of the normal type of embayment and veining. The second is that recent experiments indicate that when gersdorffite and chalcopyrite are heated in an atmosphere of sulphur no reaction occurs, but in an arsenic atmosphere pseudoeutectic intergrowths of niccolite and maucherite, with chalcopyrite replacing maucherite, do form. In the normal ores it has been shown that pyrrhotite (pentlandite) and chalcopyrite crystallized after the earlier arsenides at which time sulphur vapor pressure must have been quite high. Accordingly it is suggested these replacement intergrowths were not formed at this time, but later, when pressure of sulphur at least had decreased and the system in which the minerals had originally formed became a more open one. Rather than being the result of introduction of a metasome, as in normal replacement, the various intergrowths are believed to have arisen from various reactions involving dissociation of gersdorffite, in places of niccolite, accompanied by diffusion of sulphur and arsenic, respectively out of these minerals, and in places of copper or chalcopyrite, inward, to form a part of such intergrowths with niccolite and maucherite. The pyrrhotite component conceivably may have resulted from ferroan gersdorffite along with niccolite or maucherite, or it may represent, in the absence of original gersdorffite, part of earlier grains of pyrrhotite into which niccolite has diffused. Experiments by A. Y. Smith (1961) confirm the mobility of nickel as well as of copper in heat treatment of such minerals.

The question then is, when did such intergrowths form? Experimental evidence supports the view that they would only develop when temperatures were still fairly high, and that a distinct change in vapor pressure was essential to upset earlier equilibrium conditions. It is therefore suggested these reactions occurred after deposition of the primary ores but before temperatures had declined to any great extent. It has been indicated that faulting occurred *during* the intrusion of the norite, and it is not improbable that this recurred after the ores were finally emplaced. Near such faults vapor pressures in the still hot arsenides and sulphides would be radically modified and affect such equilibrium conditions as had been attained. Though not prominent in specimens in which these

intergrowths occur, quartz (and possibly some carbonate) is present and both chalcopyrite and niccolite are found penentrating it. Both gangue minerals have been noted in two deposits from which such ores come, namely the Garson and Worthington. Further field studies may throw additional light on the origin of these occurrences.

(b) REMOBILIZED PENTLANDITE-PYRITE BRECCIA ORE

One of the most interesting of the post-main ore effects is the peculiar pentlandite-pyrite-rich and copper-poor breccia ore in the post-norite granite adjacent to the Murray mass, McKim mine. The sulphide composition of this differs considerably from that of subjacent normal-type breccia ores. Pentlandite relatively has increased while pyrrhotite had decreased and almost all chalcopyrite has disappeared, on the basis that the one was derived from the other by engulfment and remobilization in the granite, as suggested by Clarke & Potapoff (1959). This is well supported by the sudden ending of normal breccia ore which follows the contact between norite and greenstone, at the point where granite cuts out the greenstone and even invades the norite, as noted by Lochhead.[6] Here both types of ore contain considerable quartz and carbonates, but the pentlandite-rich breccia has a pegmatitic matrix. The change in character of the ore is exactly what would be expected. Under the temperatures and pressures under which granites normally form, as noted earlier (Kullerud & Yoder, 1959), pyrite becomes the stable phase of iron sulphide instead of pyrrhotite, provided enough sulphur is available. The pentlandite is quite coarse grained, has probably suffered some recrystallization and has apparently lost most of its normal cobalt content. It is replaced considerably by pyrite (Pl. III, 17) which, interestingly, contains more cobalt than the pentlandite. Minor pyrrhotite is still present so it is probable that equilibrium under these conditions was not fully reached throughout the zone.[7] Interestingly, too, disseminated sulphides in well identified norite fragments in this breccia are now, too, composed chiefly of pentlandite, replaced by pyrite, with minor pyrrhotite remaining. The dearth of chalcopyrite is of course understandable. Its mobility on heating has been demonstrated, and it may well have diffused upward to higher levels.

A minor occurrence of similar pyrite cutting normal pyrrhotite-pentlandite ore at Creighton (Pl. III, 18), and showing a similar cobalt

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[6]Personal communication.

[7]This is perhaps confirmed by the occurrence in the same granite, of lenses of breccia ore similar in all respects to contact breccia ore except for a low quartz-carbonate content and some granite replacing the matrix around the borders. Clarke & Potapoff feel that this difference in mineral composition may have been important in the reactions occurring during remobilization resulting in the pentlandite-pyrite-rich ore.

distribution to that in McKim ore, suggests it was formed under some-what similar conditions. At this locality, however, the Creighton granite adjoining the norite and ore seems largely pre-ore, but granitic breccia and granite-like dykes have been injected into the norite and may be in part products of granitization. Some fine pseudo-eutectic intergrowths of pyrite and pentlandite have also been reported from this deposit and may be related, though we have not encountered them in the present study.

2. "SECONDARY HYDROTHERMAL" MINERALIZATION AND ALTERATION

This subdivision includes the development of secondary pyrite of various types—peculiar pink nickeloan pyrite, confined to "offset" deposits, fine cube pyrite, coarse to massive pyrite replacing pyrrhotite, always with some gangue, considerable marcasite, in many cases with the above types of pyrite and in "marcasite ore," formed by alteration of common type ores. In all of these quartz and carbonate are commonly present as they are in late galena-sphalerite veins. The veins cut both massive magmatic ores, fill fractures and faults in footwall rocks, and are found in both north and south range deposits. They have a crustified structure; in some pyrrhotite replacing bent chlorite is present, minor and rare chalcopyrite has been seen in a few, while most carry some pyrite and/or marcasite. Most of the galenas from the Sudbury area on which age determinations have been made appear to be of this post-main ore type. As noted below, however, much of the marcasite mentioned above may prove to be supergene.

Pinkish, nickeloan pyrite found rimming early pyrite and associated with quartz and carbonate usually showing distinct colloform structures seems clearly a secondary development in the Worthington, Foy, and Milnet offsets. We have been unable to confirm its pre-chalcopyrite age reported by some, but have noted its intimate association with gangue minerals, and also, at Milnet with marcasite. The association suggests it may be hydrothermal, formed under different conditions than the other magmatic ores in such offsets. It differs from other types of second-ary pyrite, but has been placed in this group by virtue of its associated minerals.

Fine cube pyrite with marcasite, always with gangue, replacing pyrrhotite selectively along partings and fractures, as well as coarser pyrite with quartz and even some massive pyrite, as described by Michener & Yates (1944) occurs close to faults to depths of 1800 feet. In places, as shown by these authors and others, both pyrite and marcasite alterations of pyrrhotite and pentlandite are quite selective and chalcopy-rite is for the most part unaffected where present. The same seems to be

true for adjacent pseudo-eutectic intergrowths of nickel arsenides. In places, however, the alterations are accompanied by or seem to grade into violarite and millerite, both of which are regarded as supergene, and accordingly all might be so regarded. On the other hand the extension of the marcasite alteration in the nickel ores to depths of over 4000 feet, as at Falconbridge, where there is no indication of surface waters penetrating today, and the association of marcasite and/or pyrite with the late galena-sphalerite veins and of these with "marcasite ores" suggests a deep-seated though obviously low temperature origin.

Although the lead-zinc veins vary slightly in mineralogical make-up, their simple mineralogy, distinct lack of precious metals and crustified character suggests their classification with Schneiderhöhn's "secondary hydrothermal" type of deposit and their formation during a metamorphic epoch not immediately associated with recognizable igneous intrusives. Open space filling indicates pressures were low. Temperatures may have varied somewhat in the lower ranges with deposition of pyrrhotite locally, pyrite and quartz in some, and marcasite, quartz and carbonate in others. This variation suggests the pH of the solutions ranged from near neutral to acid.

Dating of galena of this type from the McKim, Falconbridge, Frood, Garson and Worthington mines by Russell et al. (1954) gives an average of 1200 m.y. ± 120 m.y. They were recognized as later than the main nickel-copper mineralization and were considered related to extensive faulting early in the Grenville orogeny. It thus seems clear that both the veins and probably the pyrite and marcasite alterations were formed long after the main ores. Former interpretations of hydrothermal features of these have been applied to the sulphide ores themselves and thus confused the issue. It seems not unreasonable however, that at a subsequent time meteoric waters may have penetrated some of the same deep fracture systems, giving rise to more marcasite, violarite and millerite. We have, of course, no way of estimating the amount of marcasite developed at either time.

3. LOCAL REMOBILIZATION EFFECTS NEAR KEWEENAWAN DYKES

Reference was made earlier to the problem of the pre- or post-ore age of numerous small trap dykes and the conclusion reached that they were post-ore. Although we have not had the opportunity to study these, it follows that where some such dykes occur as broken fragments encased in normal nickel ore, some recrystallization must have occurred in the ore minerals.

Similarly where olivine diabase dykes have been noted cutting massive

ore bodies, the common ore minerals and pyrite have been found within and along fractures in such dykes, as at Garson and McKim. In fact at one time this led to the suggestion the ores were post-diabase in age. There can, however, be no question but that these instances simply indicate local remobilization of the sulphides by the heat of the intrusives and redeposition within them.

Through the kindness of Falconbridge Nickel Mines we were able to examine samples of ore on either side of a small four foot olivine diabase dyke on the 3200 level, Fecunis Lake mine. This cuts quite sharply through the ore body and has not been mineralized to any noticeable extent. The results of spectrographic analyses of pyrrhotite concentrates on either side are given in Table 22 and illustrated in Figure 9 after Nichol (1958).

The dyke has had little if any effect of the distribution of Co, Ni, Cr, Ti, V or Se. The relative constancy of the Co/Ni ratio is quite striking. Cr, Ti and V, although more erratic, vary sympathetically, suggesting they are present in a similar form, probably as fine rock inclusions in the pyrrhotite. Silver, however, though also somewhat erratic, does appear to show a slight enrichment at the contact on either side of the dyke. Where highest, silver seems accompanied by higher than normal amounts of lead and it may be that the intrusive dyke, even though small, caused some redistribution of these elements.
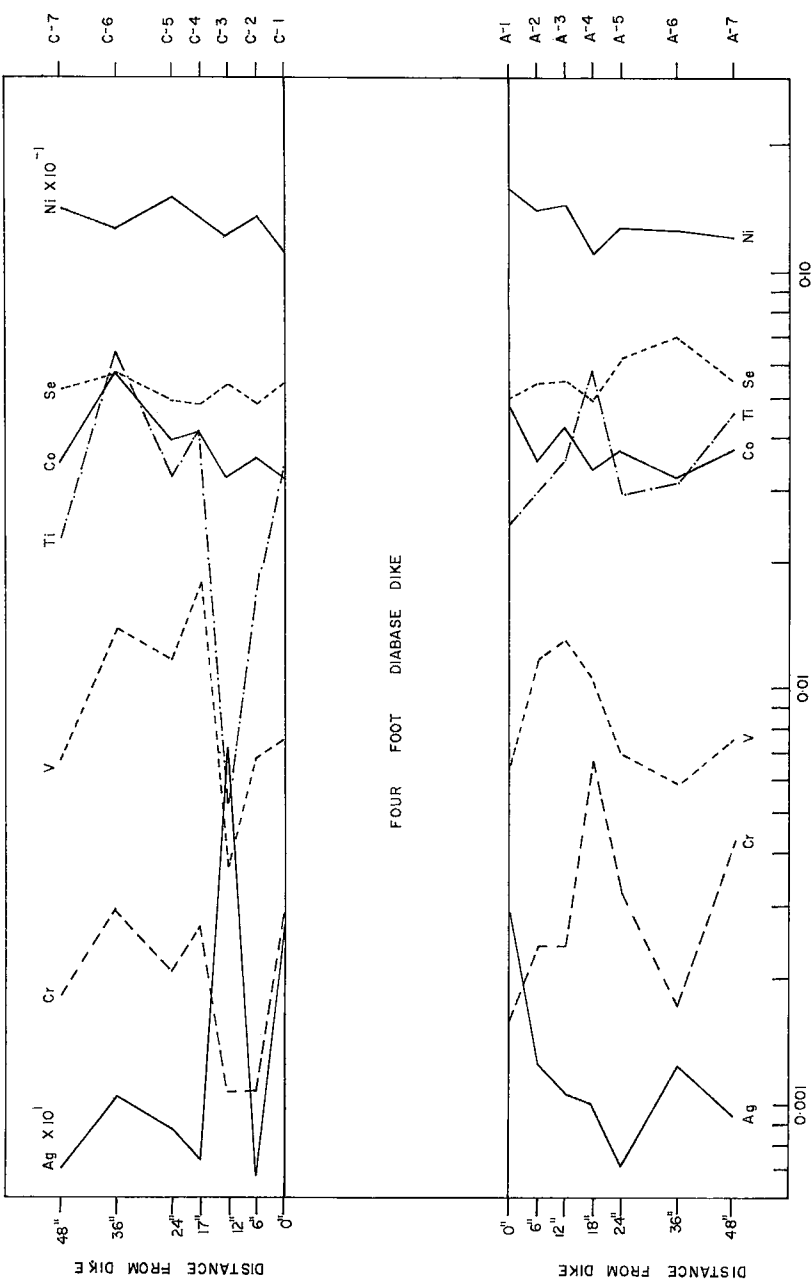
4. Supergene Alterations

Supergene alterations are of minor extent and consist of secondary sulphides and relatively shallow oxidized zones.

The secondary and supergene character of violarite and millerite and their marked selectivity in replacing pyrrhotite and pentlandite in preference to chalcopyrite have been well demonstrated by Michener & Yates. These are almost always accompanied by marcasite and possibly all such marcasite has formed in this way, but we have already noted the difficulty of distinguishing between such marcasite in the absence of the nickel sulphides, and that formed with the late Precambrian lead-zinc mineralization. Rare, secondary chalcocite, possibly covellite, and bornite have also been reported.

In the thin gossans remaining on older deposits and along fracture zones in shallow workings, the various secondary oxidation products (Table 2) are now of only passing interest. It is probable the cassiterite reported with sperrylite in gossan from the old Worthington may have been secondary from original stannite. Much oxidized material was probably removed in glacial times.

FIG. 9. Diagram showing trace element distribution in pyrrhotite of massive ore cut by diabase dyke, Fecunis Lake mine (after Nichol, 1958).

TABLE 22. TRACE ELEMENT CONTENT OF PYRRHOTITE IN RELATION TO DISTANCE FROM DIABASE DYKE (AFTER IAN NICHOL.)
(Fecunis Lake—Sudbury Area)

Sample	Distance from Dyke	Ag ppm	Co %	Ni %	Co : Ni	Cr%	Pb%	Ti%	V%	Se ppm
C7	4′ E	.70	0.035	1.40	0.025	0.00180	—	0.023	0.0066	52
C6	3′	1.07	0.057	1.25	0.045	0.00295	0.0094	0.064	0.0140	57
C5	2′	.88	0.040	1.50	0.027	0.00210	—	0.032	0.0117	49
C4	1′ 5″	.74	0.041	1.35	0.030	0.00270	—	0.043	0.0185	47
C3	1′	7.30	0.032	1.22	0.026	0.00107	0.1	0.005	0.0047	53
C2	6″	.68	0.036	1.37	0.026	0.00105	0.013	0.016	0.0070	48
C1	0′	2.80	0.032	1.12	0.029	0.00290	0.059	0.034	0.0076	54
Average		2.02	0.039	1.34	0.029	0.00208		0.031	0.010	51
DIABASE DYKE	4′ wide									
A1	0′ W	3.00	0.047	1.60	0.029	0.00157	—	0.025	0.0064	49
A2	6″	1.25	0.035	1.40	0.025	0.0024	0.0152	0.029	0.0115	53
A3	1′ 0″	1.07	0.042	1.45	0.029	0.0024	0.011	0.036	0.0132	54
A4	1′ 6″	1.00	0.033	1.10	0.030	0.0068	0.0098	0.057	0.0105	48
A5	2′ 0″	.74	0.037	1.27	0.029	0.0032	0.0112	0.029	0.0069	61
A6	3′ 0″	1.25	0.032	1.25	0.026	0.0017	0.0130	0.031	0.0058	68
A7	4′ 0″ W	.94	0.037	1.22	0.030	0.0043	—	0.046	0.0074	53
Average		1.32	0.038	1.32	0.029	0.0032		0.033	0.0088	55

D. SUMMARY AND CONCLUSIONS

In this volume the attempt has been made to give a fairly complete and modern account of the mineralogy of the world's most famous nickel-copper ores of the Sudbury district and to apply it where possible to the problem of their origin.

After most of our mineralogical and chemical studies had been completed, it became apparent that, while these pointed very clearly to a magmatic origin of the ores, in order to understand the many different generations and other features of the minerals and their intergrowths, it was essential to integrate the results with as accurate an interpretation of the geological history of the region as could be arrived at from our limited field studies and a review of both the older and more recent literature which contains many confusing contradictions. This has been aided both by recent mapping and by publications by field geologists and by the Ontario Department of Mines, by several theses studies on critical areas, and particularly by the relatively recent dating of many of the formations, so that the pre- and post-ore history of the area may now be brought into proper perspective.

A review of the geological problems has thus been presented first to give the geological setting and the premises on which the conclusions are based. While we have accepted a somewhat modified view of the classical theories of Coleman and his associates and adhere fairly closely to the succession of events as expressed by field geologists in publications made within the last decade, it is probable that some divergent views may continue. These have served and will continue to serve a very useful purpose in calling for even more critical examination and appraisal of all the evidence.

Before describing the mineralogy the various classifications of the ores, physical, chemical and genetic, are reviewed, a new contribution to which is the description of what is termed an "immiscible-silicate-sulphide" ore in which silicate (quartz diorite) blebs are dispersed in a continuous sulphide phase. This is regarded as the counterpart of certain disseminated ores in which blebs of sulphides are dispersed in silicate (quartz diorite or norite). Both are interpreted as products of immiscible silicate and sulphide liquids and bear directly on the magmatic character of the ores, as opposed to suggestions of a hydrothermal origin.

Only a general summary of the mineralogical data will be given here as they are rather voluminous and the reader is referred to accounts in Part II where the physical and chemical characteristics of over 60 metallic and non-metallic minerals and their intergrowths are described in detail. These include the ubiquitous pyrrhotite, pentlandite and chalco-

pyrite of the common ores and the rather common oxides, magnetite, ilmenite and their intergrowths. Rarer sulphides of iron include pyrite of at least five different types and marcasite; of nickel-heazlewoodite, millerite and violarite; of copper-cubanite, valleriite and bornite; probably three generations of sphalerite, one closely associated with stannite and two distinct types of galena, one rich in precious metals, the other not. Arsenides present in some ores include gersdorffite, niccolite, maucherite and sperrylite, while bismuth is present in rare types of ore with nickel as parkerite, with palladium in froodite, michenerite and a third unnamed species, with silver as schapbachite (?) and as native bismuth and bismuthinite. Two tellurides include tetradymite and hessite and native metals consist of gold (electrum) and silver, the latter in close association with bornite. Elements not found as distinct mineral species but present in solid solution both in common sulphides and other metallic minerals include the rare platinum group metals, rhodium, iridium and ruthenium, as well as cobalt and selenium.

Pyrrhotite of the normal ores appears to vary from $Fe_{0.88}S$ to $Fe_{0.90}S$. A rare non-magnetic variety is noted. While most appears to consist microscopically of one phase, rare two-phase aggregates are present and x-ray studies suggest the latter are quite common. The non-magnetic type is hexagonal and a monoclinic variety has been reported. Two rare, but insignificant, later generations have been found. As the most common host for intergrowths with pentlandite these two minerals account for most of the nickel and probably cobalt, but alone pyrrhotite contains not over 0.4–0.5 per cent nickel. Ni/Co ratios in many pyrrhotites are close to 40 but in some ores decrease to 25. Our data indicate south range pyrrhotites on the whole contain more Ni, Co, Ag and Se than those on the north range, for which no ready explanation can be offered.

As is well known pentlandite of the Sudbury deposits is remarkably constant in composition, agreeing well with the formula $(Fe,Ni)_9S_8$, the atomic ratio of $Ni+Co/Fe$ averaging 1.11/1. and Ni/Co, 34/1. Average cobalt content is close to 1 per cent but peculiar cobalt-rich (2+ per cent) and silver-rich varieties have been noted by Michener, while our studies have shown that when replaced by hypogene pyrite cobalt preferentially moves into the pyrite structure. The many types of pentlandite intergrowths, chiefly in pyrrhotite and more rarely in chalcopyrite, have been classified and all are interpreted as ex-solution products.

Both chalcopyrite and associated cubanite are of normal composition, the former being especially noteworthy as a common host for sperrylite.

Mineralogical evidence indicates quite clearly that the widespread intergrowths of pentlandite and pyrrhotite, and the more restricted ones of chalcopyrite with cubanite, valleriite, pyrrhotite and rarely pentlan-

dite, are products of unmixing of former solid solutions formed ordinarily at high temperatures and typical of sulphide melts, as confirmed by experiments. Support for such magmatic ore fluids is also found in the relations of the sulphides to early magnetite, ilmenite, pyrite and arsenides, by reaction type pyrite developed from pyrrhotite, as on annealing from high temperatures, and even by peculiar pseudo-eutectic intergrowths of arsenides and sulphides, synthesized only at high temperatures. The relative dearth of typical hydrothermal alteration adds to this evidence although the limited development of amphiboles and biotite in wall rocks attests to a minor water content in either the ore fluids or the wall rocks themselves, and in a few places more extensive silicification and carbonate alteration appear to have preceded ore deposition.

Contrary to some opinion a very definite though complex paragenetic sequence can be discerned in the various types of ores which is best displayed in those showing some zoning. The mineralographic studies in conjunction with geological considerations have resulted in a dual classification of the ore minerals as *magmatic* on the one hand, and *post-magmatic* on the other, separate parageneses being given for each group. For the former, data available on silicate-sulphide systems have been used in tracing their concentration or segregation and crystallization.

Integrating both our mineralogical data and geological interpretations we may now present our conclusions by summarily detailing the succession of events leading up to and following the deposition of the major ores, noting the various processes involved.

Most important has been the confirmation of the mode of emplacement of the great Sudbury irruptive, the proof that it was the source of the bulk of the ores, that they represent primary magmatic sulphides segregated as immiscible liquids, some differentiated and crystallized *in situ*, and others injected and deposited in not too distant favourable structures, always in close proximity to the irruptive contact. Superimposed on the primary ores throughout the long period of subsequent Precambrian time has been the development of many secondary minerals resulting from reactions between primary ore minerals, alterations, late hydrothermal mineralization and even local re-mobilization by both granitic and basic intrusives. None of the latter are quantitatively or economically important, but heretofore they have been considered by some to be an integral part of the main mineralization, and thus may have contributed to the view that the deposits were entirely hydrothermal.

The Sudbury irruptive is believed to have been intruded essentially as a single sheet-like mass into an already partly down-sagged basin structure, above the underlying pre-Huronian formations and below the

unconformably overlying Whitewater group of peculiar tuff-breccias and sediments and a basal quartzite of undetermined age. The basement rocks had previously been extensively granitized, intruded by granite, in places, and highly brecciated, yielding a structural environment well prepared for the ores to come. By far the major part of the irruptive dips moderately into the Sudbury basin on all sides, the layering dipping more gently than the contacts, but locally it has cut abruptly into steeply dipping and probably contemporaneously faulted, footwall rocks, and has also been intruded in some cases, downward and outward into cross-cutting breccia zones, forming important "offset" dykes. The quartz diorite along the lower margin of the irruptive and in the (originally) underlying offsets seems the only phase which can possibly represent the composition of the original magma. Otherwise it may be explained as noritic magma, modified perhaps by assimilation of more siliceous foot-wall rocks and/or by the effects of ore fluids which accumulated in it.

At the horizons of the irruptive now exposed there is no evidence of an early period of crystallization of ultrabasic silicates and it appears that the magma as intruded, or very soon afterward, was already about saturated with sulphides. On cooling it began to differentiate, first by liquation, with the separation of the heavier immiscible sulphide liquid and a lighter silicate-rich, sulphide-poor fraction. The sulphide liquid, still with some dissolved silicates, settled rapidly and in places almost completely along more steeply dipping contacts, leaving in places relatively barren norite along the contact, but accumulating along the more gently dipping surfaces, especially in favourable troughs or embayments and engulfing and disrupting adjacent breccias to form (in situ) breccias ore, or where breccias were missing, fairly pure massive ores. In places, as at Frood-Stobie what must have been relatively early segregations, further separated into globules of silicate magma in a dominantly sulphide melt, eventually crystallizing as rounded blebs or particles of quartz diorite rimmed with biotite, ilmenite, and magnetite in a sulphide matrix. Trapped also in the sulphides were larger, more irregular bodies of silicates of about the same composition, some of which may represent material in the process of rising from the original base of the offset, at first perhaps as liquids but crystallizing before the sulphides. Alignment of many of the silicate inclusions and "wrapped in" rims of biotite and oxides, with a snowball structure, are taken as indicating the likely upward motion of the inclusions in the sulphide liquid. This is the "immiscible-silicate-sulphide" ore.

Within the steeply dipping offset dykes, settling of such liquid sulphides would be largely vertical, explaining perhaps the pipe-like character of ores in the Copper Cliff offset. At Frood-Stobie ideal conditions were

available for differentiation of the ore fluids to occur by fractionation or other processes to yield this remarkably zoned deposit.

In the meantime, the overlying irruptive, still containing some dissolved sulphides which continued to separate as the magma cooled, differentiated by crystallization into the lower, more basic norite, and the upper, more siliceous micropegmatite, residual sulphides being trapped in the norite, quartz diorite or gabbro phases to give, here and there, disseminated ores with globular forms or only sparsely scattered sulphides. Various later alterations, in part deuteric, took place in the norite, but details of these have not been traced.

The evidence is quite clear, especially at Creighton and Falconbridge that contemporaneous fracturing and faulting accompanied the intrusion of the irruptive. Into such structures and any others available such as contacts and breccias, sulphides were injected from sulphide pools already segregated, to give *injected* deposits of various types. These may have travelled in almost any direction, in places thousands of feet, but never far from the thermal influence of the irruptive rocks. This and the presence of *in situ* deposits, in turn, suggest a more local rather than a very distant source for such injected fluids, and it seems quite unnecessary to call on the more deeply-seated parent magma of the irruptive, wherever this may have been.

The most striking and indisputable evidence of the magmatic nature of the primary ores is to be found in the various *in situ*, disseminated, breccia, massive, and "immiscible-silicate-sulphide" ores at or near the base of the irruptive and in the offsets, in the relations of the sulphides to silicates in these, in the high temperature character of the ore minerals themselves, their textures, paragenesis and distribution, and especially in the peculiar "up-side down" zoning at Frood-Stobie. Here disseminated ores and immiscible-silicate-sulphide ores in the quartz diorite are followed downward by massive ores which become increasingly rich in chalcopyrite and cubanite, the cubanite zone, which in turn is succeeded by the siliceous mineral zone, rich in arsenides, bismuthides, platinum metals, native gold and silver along with other rare species such as parkerite, sphalerite with stannite, galena and bornite, and characterized by the rather striking alteration of wall rocks to soda amphibole, biotite, other hydrous silicates, quartz and carbonates as detailed by Michener. This zoning may have partly arisen by partitioning of metals in the sulphide and silicate liquids, but is considered as largely the result of fractionation of the magmatic sulphides, nickeliferous pyrrhotite crystallizing early, followed by chalcopyrite and cubanite while the other lower melting and more volatile end products, including some water, moved downward or farthest from the hot irruptive above.

For such *in situ* deposits there is no great space problem, the ores representing segregated portions of the original magma, though in places they have extended into adjacent fracture and brecca zones, exhibiting expectable but minor degrees of replacement of silicate and other wall rock minerals. For the *injected* deposits it is suggested that dilation of the ore zones may account for much of the space now occupied by sulphides and that much of the apparent replacement may not be real. That replacement occurred is not denied, but it is noted that the environments into which such ores were introduced may have ranged from essentially anhydrous to highly sheared and previously altered zones where quartz and carbonates were formed. In the latter, evidence of replacement is greater, and it may be that earlier alteration products modified the sulphide fluids and contributed to what now appear as hydrothermal characteristics. On the whole, however, the marked lack of hydrothermal alterations in the majority of the ore deposits, associated *in time* with them, rules out such processes as important factors.

Still other deposits are a combination of the two main types (*e.g.* Creighton), but the problem of sorting out all of them in this way is beyond the scope of this study. Criteria for such a distinction, include not only geological features, particularly structural, but also consideration of the distribution of metals and minerals within the deposits themselves, and the degree of replacement which can be shown to have occurred.

Much as an anticlimax, are the various changes which have taken place in the ores in their subsequent history. These pale into insignificance when compared to the primary ores, yet include such interesting features as a much later epoch of "secondary" hydrothermal mineralization and alteration, and the actual remobilization of ores by later intrusives.

Only a few corollaries need be drawn. In this day when the role of magmatism in the development of ores has been questioned, it is worthy of note that in addition to the nickel-copper sulphides with associated platinum metals, admitted by most as usually magmatic, a wide variety of other metals including lead, zinc, tin, gold and silver along with bismuth, arsenic, tellurium, sulphur, silica and carbonates have also been concentrated from a moderately basic magma where conditions were such as to promote differentiation of the ore fluids, and it requires no stretch of the imagination to envisage these grading into hydrothermal deposits of magmatic derivation.

A second corollary is that much useful research remains to be done, the fruits of which should contribute greatly to our knowledge of the origin of ore deposits. Especially may be noted further studies on the partitioning of metals in such deposits and the need for a detailed structural synthesis, utilizing modern methods, in this region which has felt the

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.

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