

## COPPER MINERALIZATION IN THE FOOTWALL COMPLEX, STRATHCONA MINE, SUDBURY, ONTARIO

M.K. ABEL<sup>1</sup>, R. BUCHAN<sup>2</sup>, C.J.A. COATS<sup>3</sup> AND M.E. PENSTONE<sup>1</sup>

<sup>1</sup>Falconbridge Nickel Mines Ltd., Falconbridge, Ontario P0M 1S0

<sup>2</sup>Falconbridge Metallurgical Laboratories, Thornhill, Ontario L3T 4A8

<sup>3</sup>Falconbridge Nickel Mines Ltd., Winnipeg, Manitoba R3J 0M1

### ABSTRACT

High-grade copper mineralization has been found in the footwall feldspathic gneiss complex at Strathcona mine, on the North Range of the Sudbury Basin. The mineralization occupies a system of fractures that strike N68°W and dip to the southwest at 45°. This zone, containing an estimated 910,000 metric tons with a grade of 9.09% Cu, 0.52% Ni and 34.3g/t Ag, is located from 150 to 350 m beneath the Irruptive contact. The fracture-filled veins range in thickness from a few mm to 6 m and are essentially massive sulfides composed of chalcopyrite and cubanite with lesser amounts of pentlandite and pyrrhotite. Minor components are magnetite and sphalerite; more rarely encountered in the ore are galena, violarite, pyrite, bornite, chalcocite, millerite, altaite, empressite, native bismuth, native silver and hauchecornite. Sulfide zonation is evident in most veins, with pentlandite and pyrrhotite concentrated on the footwall side. Wall-rock alteration adjacent to veins is restricted to selvages a few mm wide composed of hornblende, epidote, chlorite, magnetite and garnet. The introduction of a high-temperature, copper-rich liquid containing a crystallizing nickel-rich pyrrhotite phase into a system of open fractures in a dilatant zone is considered the most likely mode of genesis.

### SOMMAIRE

On a découvert une minéralisation riche en cuivre dans le complexe de gneiss feldspathique qui constitue l'éponte inférieure à la mine Strathcona, au flanc septentrional du bassin de Sudbury. La minéralisation est localisée dans un système de cassures orientées N68°W, à pendage de 45° vers le sud-ouest. Cette zone se trouve 150 à 350 m au-dessous du contact avec les gabbros du massif irruptif; elle contient environ 910,000 tonnes métriques de minerai à 9.09% Cu, 0.52% Ni et 34.3 g/t Ag. Les filons, dûs au remplissage des cassures, varient de quelques mm à 6 m de largeur, consistent surtout en sulfures massifs, chalcopyrite et cubanite, mais aussi en pentlandite, pyrrhotine et, accessoirement, magnétite et sphalérite. Le minerai contient aussi, en quantités minimes, les espèces

suivantes: galène, violarite, pyrite, bornite, chalcocite, millérite, altaïte, empressite, bismuth et argent natifs et hauchecornite. La plupart des filons montrent une zonation en sulfures, avec un enrichissement en pentlandite et pyrrhotine du côté de l'éponte inférieure. L'altération de la roche encaissante le long des filons se limite à une lisière, large de quelques mm, de hornblende, épidote, chlorite, magnétite et grenat. La minéralisation résulte probablement de l'introduction, à température élevée, dans un système de cassures béantes d'une zone en dilatation, d'un liquide cuprifère chargé de pyrrhotine nickelifère.

(Traduit par la Rédaction)

### INTRODUCTION

The Strathcona mine, owned and operated by Falconbridge Nickel Mines Limited, is located in Levack Township on the northwest rim of the Sudbury basin (Fig. 1). It is one of a group of nickel-copper sulfide ore deposits present along an 8.2 km section of the North Range of the Sudbury Irruptive. In the mines of the North Range, subunits of the Irruptive, going from hanging wall to footwall, include felsic norite, dark norite and dark norite breccia. The footwall complex at Strathcona includes the late granite breccia, which hosts a large proportion of the nickel-copper ores, and a compositionally variable group of brecciated and migmatized rocks, herein referred to as the feldspathic gneiss complex. It is within this latter group of rocks that the vein system of the Copper Zone occurs.

The Copper Zone was discovered by diamond drilling in 1976, by tracing the upward extension of narrow, subeconomic stringers of chalcopyrite and millerite, which had been intersected in mine openings on the 3050 level. Diamond drilling to date indicates probable ore reserves of 910,000 t grading 9.09% Cu, 0.52% Ni and almost 34.3 g/t Ag. The Copper Zone is presently being developed for production, scheduled to commence late in 1978.

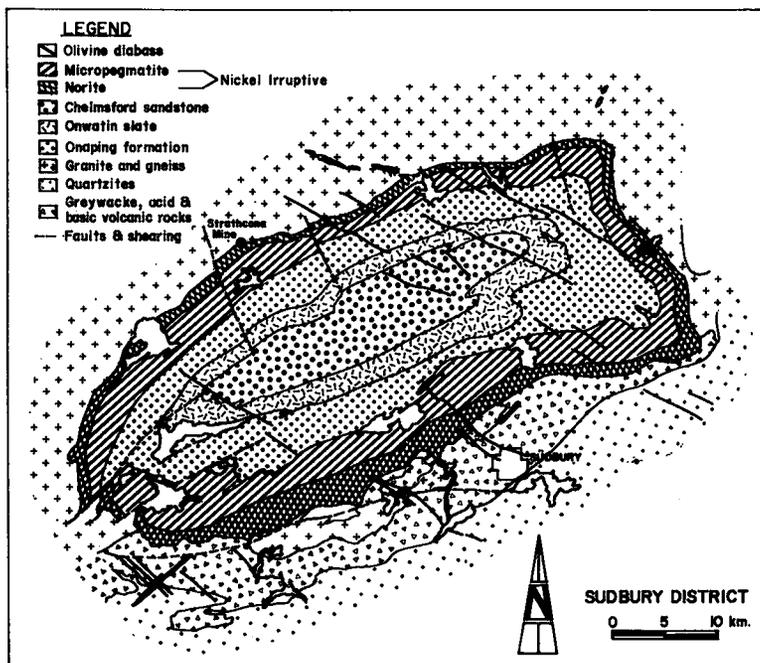


FIG. 1. Geological map of the Sudbury basin, showing the location of Strathcona mine.

#### GEOLOGY OF THE STRATHCONA MINE

The geology of the Strathcona ore deposit has been documented by Cowan (1968). Principal geological features of the mine are illustrated on cross-section 22200E (Fig. 2). The orebody, associated with an embayment in the footwall of the Sudbury Irruptive, has a strike length of about 800 m and a dip of 20–60° south. Some mineralization occurs as irregular zones in dark norite and dark norite breccia and constitutes what is termed the Hanging Wall Ore Zones. Most of the Strathcona mineralization is present in the Main Ore Zone, which occurs in a zone of late granite breccia, between the Irruptive and the underlying feldspathic gneiss complex. This breccia varies from 10 to 60 m in thickness and is composed of fragments derived from both the Irruptive and gneiss complex in a quartz-rich breccia matrix (Cowan 1968, Hewins 1971). Mineralization of the Main Ore Zone consists of sulfide stringers and disseminations in the breccia matrix. Lenses and stringers of massive sulfides form the Deep Ore Zone, located up to 200 m below the base of the Irruptive in a system of dilation fractures in the footwall gneissic rocks.

The major sulfide minerals in these ore zones are pyrrhotite, pentlandite, chalcopyrite and lesser pyrite. Magnetite is an important accessory mineral. Differences in quantities of sulfide minerals and variations in metal ratios are important features of the ore zones. There is a pronounced zoning in the ratio of pentlandite to pyrrhotite. The Ni content in Fe–Ni sulfides is lowest in the Hanging Wall Zone and highest in the Deep Zone. The average Cu:Ni ratio in the orebodies also changes steadily: Hanging Wall Zone 1:3, Main Zone 1:2, Deep Zone 1:1. The Cu–Ni ratio increases markedly at the base of both the Main and Deep Zones, where stringers consisting almost wholly of chalcopyrite are common.

#### *Feldspathic gneiss complex*

The footwall rocks of the mines on the North Range consist of a brecciated volcanic and sedimentary sequence intruded by tonalite during regional metamorphism (Langford 1960, Greenman 1970). Commonly referred to as the Levack complex, this 3–5 km wide zone of brecciated rocks has a highly variable content of fragments in tonalite matrix, ranging between 20 and 80%. An increase in the content of fragments is evident towards the contact with

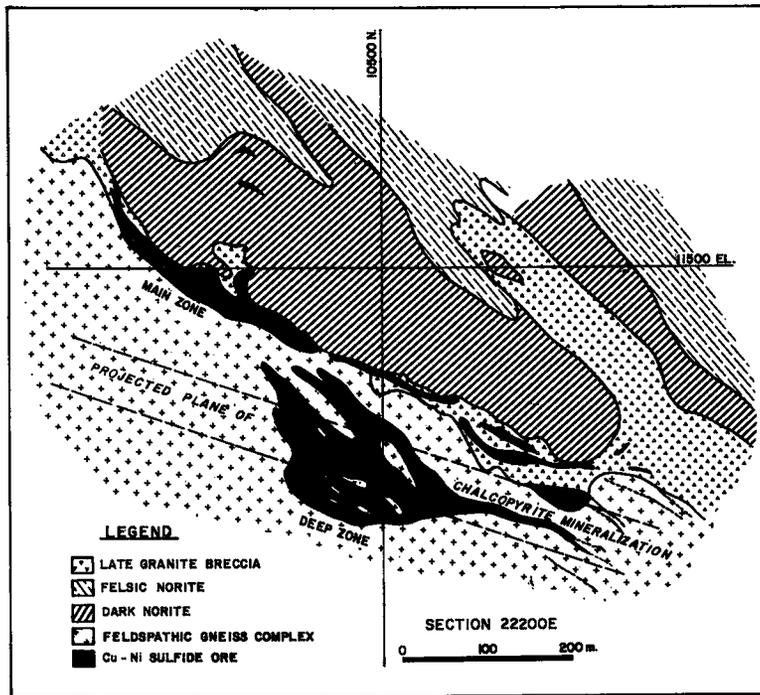


FIG. 2. Geological cross-section 22200E, Strathcona mine (looking E). Line of section is located in Figure 5.

the Irruptive. At Strathcona, the principal rock types in the complex are feldspathic gneiss of tonalitic composition, equigranular pyroxene hornfels, mafic pyroxene hornfels and Levack breccia. As the main component of this heterogeneous footwall assemblage is a medium-grained grey feldspathic gneiss, the preferred term for the whole unit is feldspathic gneiss complex. Modal compositions (in vol. %) for each rock type within the complex are given in Table 1.

Feldspathic gneiss has a well-developed gneissosity that commonly is intricately folded and disrupted by local brecciation (Fig. 3). Aggregates of subhedral to euhedral andesine laths about 0.10–0.15 mm long are predominant in this leucocratic rock. Gneissosity is defined by coarser-grained mosaic quartz and blocky subhedral grains of orthopyroxene forming light and dark layers with plagioclase. Other primary minerals include clinopyroxene, euhedral apatite, traces of zircon, blocky subhedral grains of titaniferous magnetite and ilmenite. The rock is very fresh, with only minor alteration of the ferromagnesian minerals to form traces of biotite, amphibole, chlorite, talc and carbonate.

Occasionally the titaniferous magnetite is partly or wholly replaced by chlorite, leaving only the exsolved blades of ilmenite unaltered.

Equigranular pyroxene hornfels occurs as large blocks, bands or small inclusions in the feldspathic gneiss. In drill-core intersections it is quite distinctive, appearing as a medium- to fine-grained equigranular gabbroic rock. In thin

TABLE 1. MINERAL ASSEMBLAGES IN ROCK TYPES OF THE FELDSPATHIC GNEISS COMPLEX

Mineral	Feldspathic Gneiss	Equigranular Pyroxene Hornfels	Mafic Pyroxene Hornfels	Levack Breccia	
				Matrix (variable)	Inclusions (variable)
Plagioclase (An)	55-60 An <sub>25</sub>	35-45 An <sub>40-44</sub>	45-50 An <sub>40</sub>	50-60 An <sub>36-40</sub>	30-50 -
Albite	-	-	-	0-5	-
Quartz	20-25	-	-	5-10	25-40
Orthopyroxene	6-10	4-6	-	-	2-5
Clinopyroxene	1-4	15-25	40-45	0-10	10-20
Amphibole	Tr	10-20	1-2	0-2	0-2
Biotite	1-2	6-10	5-8	2-10	2-5
Magnetite	1-2	3-6	8-10	0-3	0-3
Ilmenite	1-2	<1	<1	0-1	Tr
Chlorite	Tr	Tr	Tr	0-10	1-2
Carbonate	Tr	Tr	<1	0-4	1-2
Apatite	Tr	-	-	-	-
Zircon	Tr	-	-	Tr	-
Talc	Tr	Tr	-	-	-
Epidote	-	-	-	-	0-2
Sulfides (Tr)	Cp,Py	Cp,Po,Pnt,Py	Cp,Po,Py	Po,Cp,Pnt,Bn,Sph,Gal	-

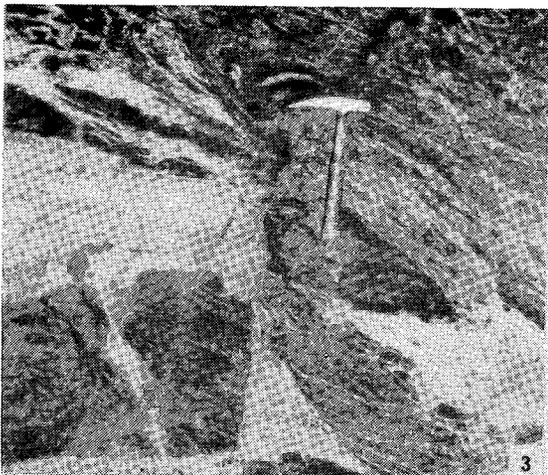


FIG. 3. Feldspathic gneiss complex with blocks of pyroxene hornfels, 2625 level, Strathcona mine.



FIG. 4. Levack breccia veining feldspathic gneiss, 2625 level, Strathcona mine.

section, blocky grains of clinopyroxene and pale brown hornblende are interspersed with fresh stubby laths of andesine. Other primary minerals include orthopyroxene, biotite, titaniferous magnetite and ilmenite. Partial or complete alteration of the hornblende to a mixture of granular magnetite and biotite is characteristic; orthopyroxene is commonly altered to talc, carbonate and chlorite.

Mafic pyroxene hornfels is the term applied to blocks that are much darker and lack the uniform texture of the equigranular pyroxene hornfels. These have a glassy appearance on a fractured surface and contain feldspathic patches. In thin section, however, texture is almost identical to that of the equigranular variety. Coarse-grained anhedral clinopyroxene and fresh granoblastic andesine laths form most of the rock. Patches of original hornblende have broken down to a granular mixture of biotite and magnetite. The latter is quite abundant and invariably carries exsolved blades of ilmenite.

Levack breccia is erratically distributed as veins, dykes and irregularly shaped masses with sharp contacts in the feldspathic gneiss complex (Fig. 4). As pointed out in previous descriptions of this unit (Speers 1957, Mitchell & Mutch 1956, Cowan 1968), it consists of small fragments of host rock set in a very fine-grained dark matrix. Both fragments and matrix vary in composition according to the local host rock; hence in the sections examined the Levack breccia varies considerably in mineralogy. Fragments noted in the breccia consist of pyroxene hornfels, mosaic quartz with or without recrystallized pyroxene, granular mosaic clino-

pyroxene, euhedral grains of fresh orthopyroxene and patches of clinopyroxene, amphibole and biotite. A prominent feature of the matrix is the development of coarse brown biotite porphyroblasts. They occur with very fine-grained plagioclase of indeterminate composition, granular clinopyroxene and variable amounts of chlorite, carbonate, quartz, magnetite and ilmenite. Minute grains of sulfides are widely disseminated throughout the breccia.

Numerous aplite veinlets and irregular patches and dykes of coarse-grained red pegmatite are present within the feldspathic gneiss complex. Joint planes commonly contain epidote and pyrite; these are flanked by a zone up to 10 cm wide of epidotized, pink-stained country rock.

TABLE 2. COMPOSITIONS OF MAIN ROCK TYPES IN FELDSPATHIC GNEISS COMPLEX

	Feldspathic Gneiss	Equigranular Pyroxene Hornfels	Mafic Pyroxene Hornfels
SiO <sub>2</sub>	61.8	48.8	48.5
Al <sub>2</sub> O <sub>3</sub>	21.5	14.8	15.3
MgO	1.5	7.0	5.9
CaO	5.9	10.7	11.8
FeO	2.2	7.5	6.8
Fe <sub>2</sub> O <sub>3</sub>	1.0	4.3	5.3
Na <sub>2</sub> O	5.0	2.9	3.1
K <sub>2</sub> O	1.1	0.8	0.5
TiO <sub>2</sub>	0.50	0.86	0.95
MnO	0.05	0.18	0.20
Ni	0.01	0.01	0.01
Cu	0.01	0.01	0.01
Zn	0.006	0.008	0.007
P <sub>2</sub> O <sub>5</sub>	0.17	0.14	0.16
L.O.I.	0.56	0.34	0.25
Total:	101.31	98.35	98.79

Analyses: Falconbridge Metallurgical Laboratories, Thornhill, Ont.  
Constituents reported in wt. %.

*Composition of rock types in feldspathic gneiss complex*

Compositions of the feldspathic gneiss and two varieties of pyroxene hornfels in the footwall complex are listed in Table 2. Feldspathic gneiss, previously referred to as tonalitic gneiss (Langford 1960) and quartz-plagioclase-augite gneiss (Naldrett & Kullerud 1967) have a composition close to that of the average tonalite (Nockolds 1954). The composition of both pyroxene hornfels units are essentially the same and probably have been derived from varieties of the same rock type. Pyroxene-rich inclusions in feldspathic gneisses of the footwall complex have been termed mafic granulite (Mitchell & Mutch 1956), mafic gneiss (Langford 1960), metagabbro (Greenman 1970), or simply recrystallized gabbro by other Sudbury workers. The analyses show that the inclusions are indeed close to the average gabbro in composition. Recrystallization has taken place at a grade of metamorphism in the pyroxene-granulite facies.

STRATHCONA COPPER ZONE

Copper mineralization in the feldspathic gneiss complex occurs as a series of fracture-filling veins that can be arbitrarily confined within a block having horizontal dimensions of 250 x 150 m and a dip-slope length of 215 m. The block strikes N68°W and dips to the southwest at 45°. This attitude reflects the principal strike direction of the veins within the block, but only represents an overall average dip of the vein system. Available information at the present time indicates two principal vein sets within the system, one dipping at 35° and the second at 60°, but both having an approximately identical strike of N68°W. The vein system is shown as it occurs in plan view on the 2625 level in Figure 5. If the plane of the vein system is projected through the Strathcona Deep Zone, its apparent position on section 22200E would appear as that indicated in Figure 2. The relative position of the Copper Zone to the Main Ore

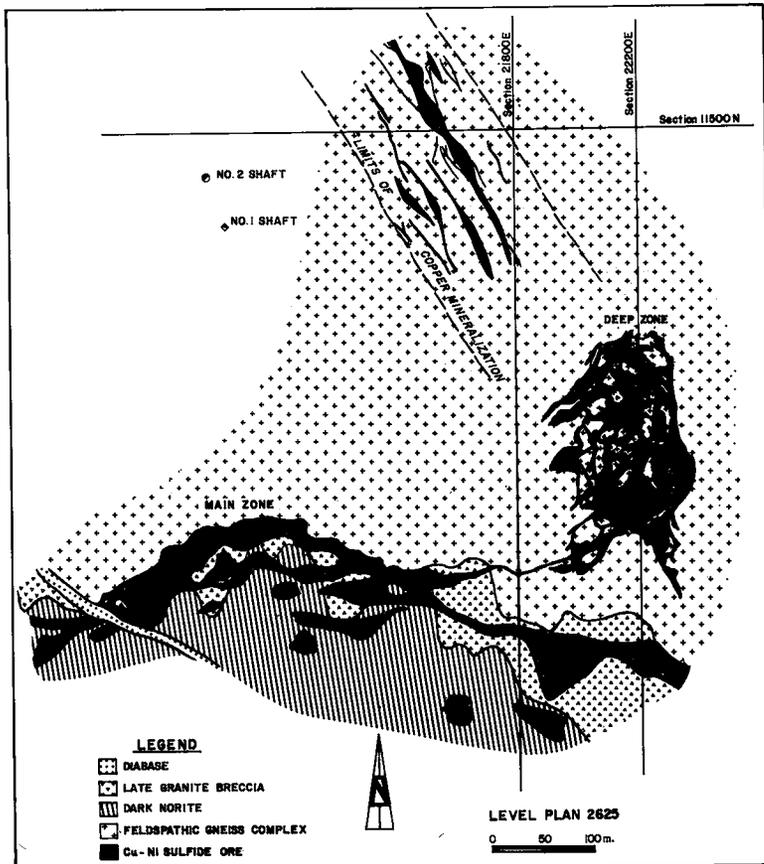


FIG. 5. Level plan 2625, Strathcona mine.

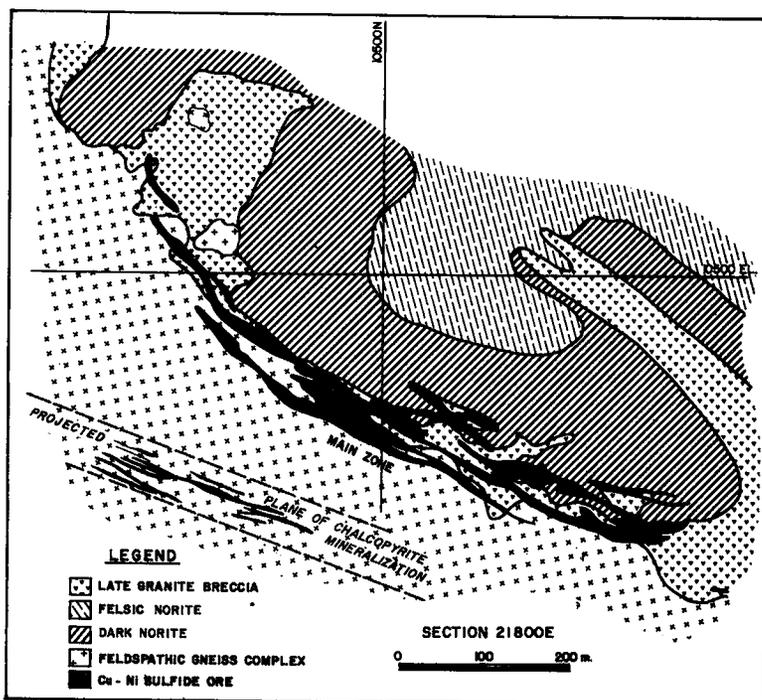


FIG. 6. Geological cross-section 21800E, Strathcona mine (looking E). Line of section is located in Figure 5.

Zone is more evident on section 21800E (Fig. 6), where it can be seen to lie between 150 and 350 m below the dark norite-late granite breccia contact.

Individual veins within the system range in width from a few mm to approximately 6 m. The multiplicity of veins creates a problem in extrapolation and interpretation of diamond-drill hole results. A complete structural analysis of the vein system must await the availability of mine openings at some point in the future.

Veins consist almost entirely of massive sulfides and have extremely sharp contacts with the host rocks. Some veins are straight and maintain a consistent width for many metres, whereas others are more irregular and exhibit marginal apophyses extending short distances into the wall rock. The latter type gives the appearance of having fragments of wall rock enclosed within the vein. Minor disseminated sulfides in the wall rock are restricted to within a few cm of the veins. Sulfide migration seems to have been restricted during emplacement of the massive vein system. Some offset is commonly apparent between intersecting veins, and narrow veins may terminate against wider veins. The vein sulfides evidently occupy

a system of fractures in a zone of dilatancy in the feldspathic gneiss complex. The fractures postdate the brecciation and recrystallization of the complex.

TABLE 3. ELECTRON MICROPROBE ANALYSES<sup>†</sup> OF SELECTED SULFIDES

SAMPLE	SULFIDE	Cu	Ni	Fe	Co	S	TOTAL
5817	Chalcopyrite	34.6	0.16	30.4	-	35.02	100.2
	Atom. Prop.*	0.499	0.002	0.498		1	
5817	Cubanite	23.4	0.13	40.9	-	34.8	99.2
	Atom. Prop.*	0.339	0.002	0.675		1	
5086	Pentlandite	-	31.2	34.0	0.44	33.4	99.0
	Atom. Prop.*		0.510	0.584	0.007	1	
5817	Mackinawite	2.14	5.80	54.9	-	35.5	98.3
	Atom. Prop.*	0.030	0.089	0.888		1	
		Zn	Cd	Fe	Mn	S	TOTAL
5817	Sphalerite	54.9	1.43	8.93	0.22	33.49	99.0
	Atom. Prop.*	0.805	0.012	0.153	0.004	1	

<sup>†</sup>Analyses reported in wt. %; analyst: G. Springer, Falconbridge Metallurgical Laboratories.

\*Atom. Prop.: atomic proportions on basis of 1 sulfur atom.

#### MINERALOGY OF THE COPPER MINERALIZATION

Sulfide veins consist essentially of chalcopyrite and cubanite with an average ratio of about 3.7:1. Accessory vein minerals include coarsely crystalline pentlandite, blocky pyrrhotite commonly replaced by cubanite, sphalerite, nickel-

iferous mackinawite, primary and secondary magnetite, and traces of assorted sulfides, tellurides and native metals.

Chalcopyrite comprises approximately 67% of the total mineral assemblage. It is invariably twinned and occurs as coarse-grained mosaic patches averaging more than 1.5 mm in diameter; these enclose all of the other sulfide and oxide phases. A microprobe analysis of chalcopyrite (Table 3) shows it to be nearly stoichiometric.

Cubanite is the next most abundant sulfide mineral in the Copper Zone, comprising about 18% of the total sulfides. It occurs in chalcopyrite either as massive round patches that invariably enclose relict grains of pyrrhotite or pentlandite, or as coarse laths up to 5 mm long oriented parallel to the (112) planes of the host chalcopyrite (Fig. 7). Interpenetrating textures of cubanite blades following three (112) directions in chalcopyrite are not uncommon. These textures seem similar in occurrence to those in the cubanite-rich zone at the Froid-Stobie mine (Zurbrigg *et al.* 1957, Hawley 1962). The texture results from unmixing in an FeS-saturated  $\text{CuFeS}_2$  solid solution at approximately 590°C (Yund & Kullerud 1966). An electron microprobe analysis of cubanite shows it to have a composition of  $\text{Cu}_{1.02}\text{Fe}_{2.03}\text{S}_3$  (Table 3).

Pyrrhotite constitutes about 3.5% of the sulfides in the vein system. It is a nonmagnetic variety and occurs as very coarse-grained patches with diameters commonly exceeding 1 cm. Extensive replacement by chalcopyrite and cubanite is observed in most samples.

Although abundant in some narrow stringers and forming nickel-rich zones in some of the larger massive sulfide veins, pentlandite constitutes only an estimated 1.5% of the total sulfide assemblage. It is present as large blocky crystals up to 10 cm across, readily visible in hand specimen, and as fine-grained crystals resulting from exsolution. The larger grains are invariably replaced by chalcopyrite and cubanite along cleavage planes and shatter cracks (Fig. 8). Exsolution "flame" pentlandite occurs along the basal planes of pyrrhotite and at the junction of cubanite laths and chalcopyrite (Fig. 9). The electron-probe analysis of massive pentlandite listed in Table 3 shows it to have a lower nickel content than pentlandite from the Main Ore Zone, where it reaches 35.9%.

Sphalerite is evenly distributed throughout the vein sulfides to a total estimated content of 0.5%. It occurs as irregular patches up to 0.35 mm in diameter, usually enclosed in chalcopy-

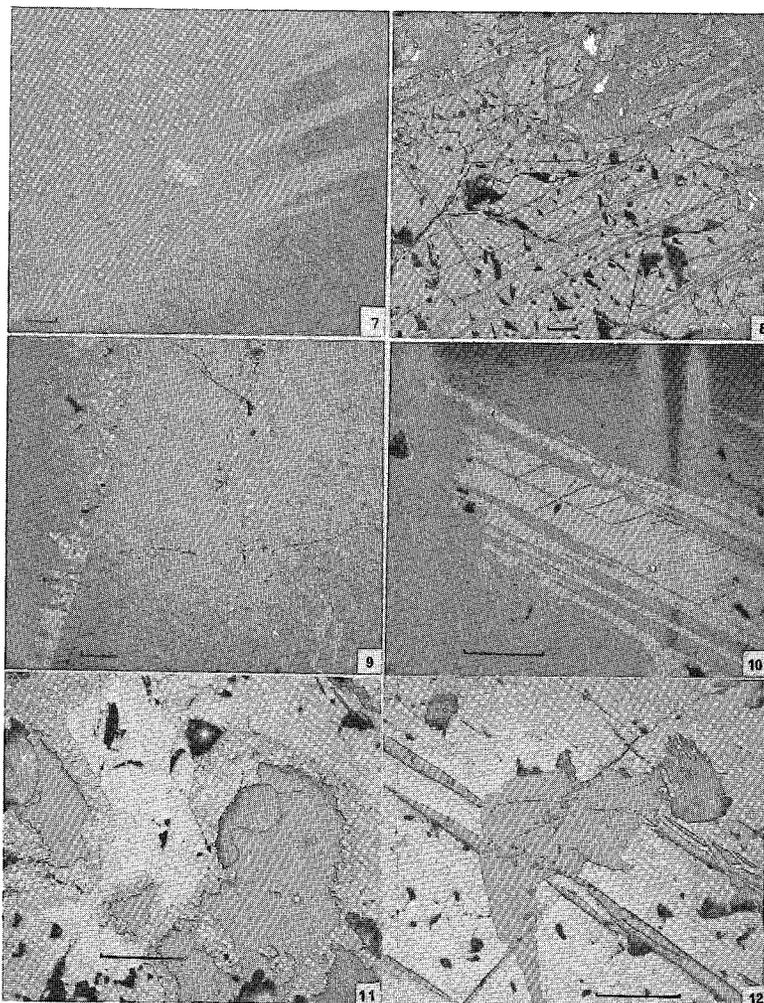
rite. Some sphalerite is inclusion-free, but the majority contains numerous blebs of exsolved chalcopyrite. An analysis of sphalerite (Table 3) shows a Cd content of 1.43% and 15.7 mol % FeS.

Mackinawite is a minor constituent of these ores, occurring as narrow spindly grains in chalcopyrite (Fig. 10). Their development is controlled by grain boundaries and crystallographic directions in the chalcopyrite. In this environment, mackinawite is believed to be the product of unmixing of solid solutions that contained nickel or iron in excess of that which can be held by chalcopyrite (or cubanite) on cooling (Hawley 1962). An electron-probe analysis of mackinawite (Table 3) shows it to contain 2.14% Cu and 5.80% Ni. Additional minor and rare minerals identified in the ore include galena, violarite, pyrite, bornite, chalcocite, millerite, altaite (PbTe), native silver, native bismuth, empressite (AgTe), and hauchecornite  $\text{Ni}_9(\text{Bi},\text{Sb},\text{Te})_2\text{S}_8$ .

Magnetite constitutes approximately 5% of the vein material and is present in two distinctive relationships. Prominent subrounded to euhedral grains up to several mm in diameter occur throughout the sulfide assemblage. A cell-edge measurement of 8.3985(15) Å for this magnetite compares closely with the lattice dimension of 8.396 Å for pure magnetite (Deer *et al.* 1962). Marginal replacement of magnetite crystals by chalcopyrite and cubanite is a common feature that preserves "ghosts" of the original euhedral crystal outline (Fig. 11). The second type of occurrence consists of bladed to vein-like magnetite of late formation that follows crystallographic directions in chalcopyrite and occasionally cross-cuts other sulfides (Fig. 12).

#### *Sulfide zoning and distribution of metals*

Although underground development of the Copper Zone has not yet reached the stage where meaningful conclusions about sulfide zoning within the veins can be made, it is evident that there is an irregular pattern of sulfide distribution and metal content across the widths of some veins. In Figure 13, the copper and nickel contents of two massive sulfide intersections from the same diamond drill hole are presented in histogram form, together with the percentages of the principal sulfide phases present, as calculated from a combination of chemical assays and an X-ray diffraction method. The latter determines relative proportions of the copper-bearing sulfides, chalcopyrite and cubanite.



- FIG. 7. Multiple lamellae of cubanite (dark) in chalcopyrite (light). The rectangular white grain is altaite (PbTe). Scale bar 0.01 mm.
- FIG. 8. Coarse grain of porous pentlandite (light) extensively replaced along cleavages and cracks by chalcopyrite and cubanite. Minor relict pyrrhotite occurs in the cubanite. Scale bar 0.1 mm.
- FIG. 9. Exsolution blades and patches of pentlandite within and along the sharp boundary of cubanite laths in chalcopyrite. The chalcopyrite is etched with  $\text{AgNO}_3$ . Scale bar 0.1 mm.
- FIG. 10. Multiple lamellae and irregular massive patches of cubanite (dark) with chalcopyrite (light grey). Pentlandite (white) present along the interface of chalcopyrite and cubanite is mostly contained within the chalcopyrite, but also projects into the adjacent cubanite. Mackinawite forms narrow dark stringers in chalcopyrite. A small grain of galena accompanied by gangue is enclosed in massive cubanite. Scale bar 0.1 mm.
- FIG. 11. Euhedral crystals of magnetite (dark grey) show peripheral replacement by chalcopyrite (white) and cubanite (light grey). Within replacement zones, relict specks and laths of oxide are aligned along crystallographic planes of the original magnetite. Scale bar 0.1 mm.
- FIG. 12. Late veins of magnetite (high relief) follow crystallographic directions in chalcopyrite (white) and transect a grain of sphalerite (grey). Narrow blades of cubanite and a partially replaced grain of amphibole are enclosed in the chalcopyrite. Scale bar 0.1 mm.

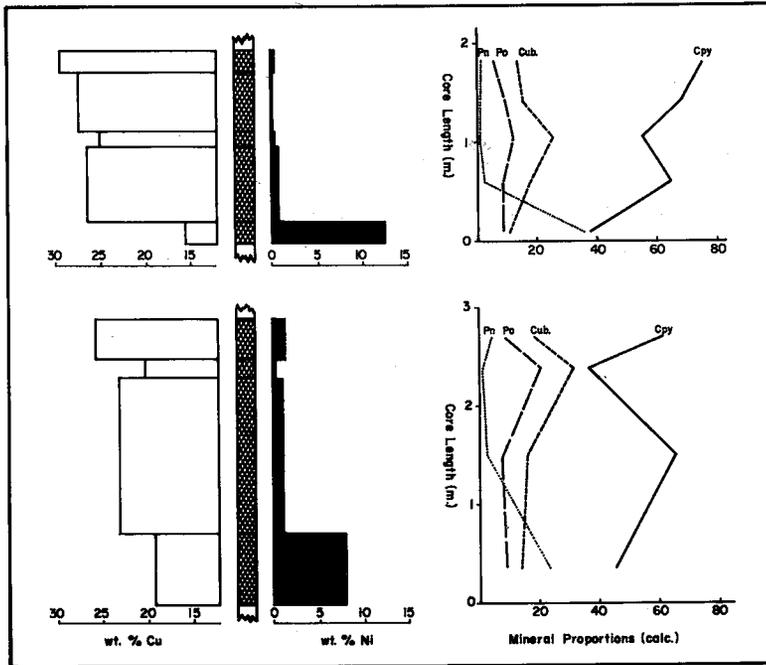


FIG. 13. Histogram plot of copper and nickel content of two massive sulfide veins intersected by DH 23-239 on 2375 level, Strathcona mine. Mineral proportions are calculated for chalcopyrite (cpy), cubanite (cub), pyrrhotite (po) and pentlandite (pn) from chemical analyses and X-ray diffraction results.

Although the sample lengths along the core are not uniform, the relations illustrated by Figure 13 seem to be valid. Nickel content of the sulfides increases substantially towards the lower or footwall side of each vein, and is accompanied by a corresponding decrease in copper content. This is reflected in the calculated proportions of pentlandite and chalcopyrite present in the massive sulfides. The proportions of pyrrhotite and cubanite vary sympathetically with each other and an increase in these two sulfides is accompanied by a decrease in chalcopyrite content. Stated another way, an inverse relationship exists between the amount of pyrrhotite present and the chalcopyrite/cubanite ratio. This is in agreement with the replacement textures observed in polished section, which indicate that the granular variety of cubanite has formed from the breakdown of chalcopyrite and pyrrhotite. Sphalerite is not plotted in Figure 13, but is very evenly distributed throughout each sulfide intersection, occurring in the same absolute amounts (0.5%).

#### Wall-rock alteration

Narrow selvages of dark alteration up to 5 mm in width are observed in the wall rock

adjacent to sulfide veins (Fig. 14). These are principally composed of green hornblende, epidote and chlorite. Euhedral grains of hornblende and porous anhedral epidote are also usually enclosed in and partly replaced by the adjacent sulfides. Chlorite commonly forms narrow veinlets parallel to the sulfide/host rock contact. Coarse patches of recrystallized albite enclose stubby laths of andesine, and round sieve-textured magnetite grains with entrained feldspar laths are also generally present in this zone. Of more restricted occurrence are round garnets in which Mn, Ca and Al are the dominant components, *i.e.*, a spessartine-grossularite type. These are porous in texture and generally contain abundant sulfide disseminations. Rarely associated with garnet is the mineral pyrosmalite  $(\text{Mn,Fe})_8\text{Si}_6\text{O}_{15}(\text{OH,Cl})_{10}$ .

#### DISCUSSION AND CONCLUSIONS

Massive stringer ores consisting almost solely of chalcopyrite are common to many of the ore deposits of the Sudbury basin, particularly along their margins and in areas remote from

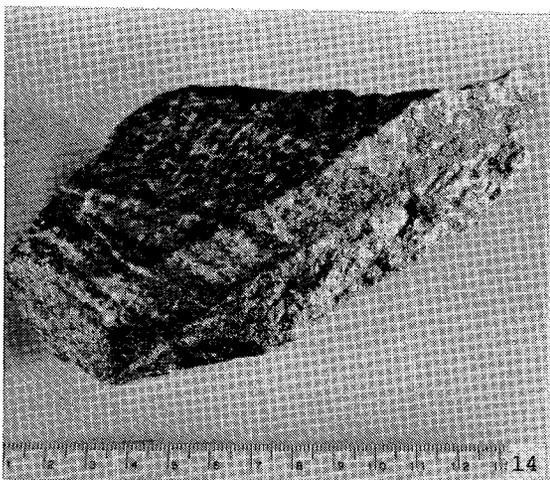


FIG. 14. Hand sample showing the sharp contact of massive sulfide (lower half) and feldspathic gneiss wallrock. The fracture occupied by the sulfides is essentially normal to the well-developed gneissosity of the wall rock. A thin septum of wall-rock alteration is visible adjacent to the sulfide vein.

the Irruptive contact. This led Hawley (1962) to postulate the separation of a highly mobile Cu-rich liquid by fractionation of a Ni-Cu-Fe sulfide magma and its introduction into fractures and dilatant breccia zones. Experimental work on phase relations in the Cu-Fe-Ni-S system (Craig & Kullerud 1969) has verified the coexistence of a Cu-rich liquid with crystallizing pyrrhotite above 850°C. Separation of this liquid can result in the formation of chalcopyrite-rich veins and segregations.

It is not known at the present time whether there is a physical connection between the Copper Zone and the mineralization of the Deep Zone (Fig. 5). As a unit, the latter ore deposit plunges S35°W at 48°, which is close to the calculated dip of the Copper Zone S23°W at 45°. The two deposits most probably have the same structural control, the Copper Zone representing distal mineralization for which the primary source must have been both the Deep and Main Zones of the Strathcona orebody.

Many features of the Copper Zone are consistent with an interpreted origin by introduction of a copper-rich sulfide-oxide liquid. Sharp contacts of veins with adjacent wall rock, uniform vein widths for considerable distances and intersecting and offsetting veins indicate the infilling of a dilatant fracture system. Frac-

tures developed subsequent to the deformation and high-grade metamorphism of the feldspathic gneiss complex, but presumably prior to or during the intrusion of the Irruptive.

A high-temperature copper-rich liquid and a crystallizing nickel-rich pyrrhotite phase seem to have invaded the fractures of the dilatant zone. Whether by a flow mechanism or gravitational settling, the homogeneous pyrrhotite phase became concentrated at the lower side of larger veins. This well-developed zonation suggests a relatively unrestricted movement of crystallizing pyrrhotite in its surrounding liquid. As chalcopyrite appears as a phase on the liquidus at about 970°C, the temperature of the vein fluid was probably at least 1000°C. By analogy with the experiments of Craig & Kullerud (1969), the presence of 5% magnetite in the system presumably lowered somewhat the initial melting temperature. The temperature at the contact of footwall rocks with the Irruptive during its intrusion is estimated to have been about 700°C (Naldrett & Kullerud 1967). As the Copper Zone mineralization extends to at least 350 m from the contact, the thermal gradient between veins and wall rock must have been relatively high. The coarse grain-size of the vein sulfides indicates that this high gradient was maintained over a long period of time.

At lower temperatures, subsolidus transformations in the vein sulfides included the separation of pentlandite from pyrrhotite and the breakdown of chalcopyrite solid solution to chalcopyrite and cubanite. The relatively large crystals (up to 10 cm) of pentlandite and pyrrhotite invariably display textures indicative of extensive replacement by chalcopyrite and cubanite. Feathery zones of exsolved pentlandite commonly occur at the mutual boundary of these two minerals. The separation of mackinawite in chalcopyrite occurred at some low, but indeterminate temperature. Magnetite crystallized as euhedral grains, evenly dispersed throughout the sulfides and as a second generation of fine veinlets. Although quantitatively minor, such minerals as galena, altaite, native silver, native bismuth, empressite and hauchecornite indicate an enrichment of Ag, Bi, Pb and Te in these ores. There is no accompanying enrichment in platinum-group elements.

#### ACKNOWLEDGEMENTS

The geological staff thank the senior management of Falconbridge Nickel Mines Limited for permission to publish this paper. The authors

received considerable assistance from other members of the geological staff at Falconbridge with respect to geological observations, constructive criticism and photography. Diagrams were prepared by Miss Giselle Coté.

## REFERENCES

- COWAN, J.C. (1968): Geology of the Strathcona ore deposit. *Can. Mining Met. Bull.* 61, 38-54.
- CRAIG, J.R. & KULLERUD, G. (1969): Phase relations in the Cu-Fe-Ni-S system and their application to magmatic ore deposits. In *Magmatic Ore Deposits* (H.D.B. Wilson, ed.), *Econ. Geol. Mon.* 4, 344-358.
- DEER, W.A., HOWIE, R.A. & ZUSSMAN, J. (1962): *Rock-Forming Minerals. 5. Non-silicates*. Longmans, London.
- GREENMAN, L. (1970): *The Petrology of the Footwall Breccias in the Vicinity of the Strathcona Mine, Levack, Ontario*. Ph.D. thesis, Univ. Toronto.
- HAWLEY, J.E. (1962): The Sudbury ores: their mineralogy and origin. *Can. Mineral.* 7, 1-207.
- HEWINS, R.H. (1971): *The Petrology of some Marginal Mafic Rocks along the North Range of the Sudbury Irruptive*. Ph.D. thesis, Univ. Toronto.
- LANGFORD, F.F. (1960): Geology of Levack Township and the northern part of Dowling Township, District of Sudbury. *Ont. Dep. Mines Prelim. Rep.* 5.
- MITCHELL, G.P. & MUTCH, A.D. (1956): Geology of the Hardy mine, Sudbury district, Ontario. *Can. Inst. Mining Met. Trans.* 59, 37-43.
- NALDRETT, A.J. & KULLERUD, G. (1967): A study of the Strathcona mine and its bearing on the origin of the nickel-copper ores of the Sudbury district, Ontario. *J. Petrology* 8, 453-531.
- NOCKOLDS, S.R. (1954): Average chemical compositions of some igneous rocks. *Geol. Soc. Amer. Bull.* 65, 1007-1032.
- SPEERS, E.C. (1957): The age relation and origin of common Sudbury breccia. *J. Geol.* 65, 497-514.
- YUND, R.A. & KULLERUD, G. (1966): Thermal stability of assemblages in the Cu-Fe-S system. *J. Petrology* 7, 454-488.
- ZURBRIGG, H.F. & GEOLOGICAL STAFF (1957): The Frood-Stobie mine. In *Structural Geology of Canadian Ore Deposits, 2*. *Can. Inst. Mining Met., Congress Vol.* 341-350.

Received July 1978, revised manuscript accepted December 1978.