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Sulfide Mineralization in the Huronian Sediments in the Cobalt Area, Ontario, Canada

캐나다 온타리오주 코발트 지역의 휴로니안 퇴적암에 발달한 황화물 광화작용에 관한 연구

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ABSTRACT: Base metal sulfides occur in the Huronian sedimentary rocks that cover the Archean volcanic rocks in the Cobalt area, Ontario, Canada. They are mostly concentrated in the basal conglomerate which was formed in the pre-Huronian basin structure. Sulfide occurrence can be grouped as massive sulfide clasts in the basal and Coleman conglomerate, disseminated sulfides throughout the sediments, and disseminated sulfides near Ag-Co-Ni-As carbonate veins. Detrital mechanism can explain features such as angularity of sulfide fragments and graded bedding of dissemnated sulfides. Sulfides concentrated near carbonate veins are probably of hydrothermal origin. Nearby strata-bound type massive sulfide ore deposits and mineralized interflow units are the most probable sources for syngenetic sulfides. This is supported by the angularity of sulfide fragments, presence of massive sulfide boulders which are identical in mineralogy and texture to the strata-bound type sulfide deposits in the Archean basement, and a similar composition of sphalerite in the Archean volcanic rocks and Huronian sedimentary rocks. Some sulfide grains, especially in sandstones and argillites, were undergone recrystallization during the intrusion of the Nipissing diabase.

Key words: cobalt, sulfide mineralization, archean volcanics, huronian sediments, coleman member

요약 : 캐나다 온타리오주 코발트지역에는 시생대의 화산암을 부정합으로 피복하고 있는 원생대의 휴로니안 퇴적암 내에는 황화물이 농집된 광화작용이 발달한다. 황화광물들은 원생대에 발달했던 퇴적분지에 쌓인 기저역암 내에 농집되어 있다. 황화광물은 기저역암과 Coleman 역암에서는 파편형태로, 퇴적암 전체에서는 광범위한 산점상 형태, 그리고 Ag-Co-Ni-As 탄산염맥 주변의 산점상 형태 등으로 산출된다. 황화광물 파편들의 형태가 모가 나있고 사암과 이질암에서 점이적 퇴적구조를 나타내고 있는 것으로 보아 황화광물들이 기계적 운반작용에 의해 이동된 후 퇴적암 내에서 광화작용을 이루었음으로 시사한다. 한편, 탄산염맥 근처에서 발견되는 산점상 광석광물들은 열수작용에 의해 형성된 것으로 추정된다. 기반암인 시생대 화산암에 발달한 대규모의 화산성 황화물 광상이 퇴적암에 존재하는 광석광물의 공급원이었음을 알 수 있다. 사암 및 이질암에 존재하던 광석광물들은 후기에 관입한 휘록암에 수반된 열에 의해 재결정작용을 받았다.

주요어 : 코발트, 황화광물 광화작용, 시생대 화산암, 휴로니안 퇴적암, 콜먼 멤버

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Introduction

The Cobalt mining district became famous as a result of the discovery of rich silver deposits in 1903 during the building of the Timiskaming (North Bay) and Northern Ontario (Haileybury) railway. Since then, significant amounts of Ag, Co, Ni, As, and Bi had been produced until 1972: 600,000,000 ounces of silver, 23,000,000 kg of cobalt, 8,000,000 kg of Ni, 2,500,000 kg of copper (Petruk *et al.*, 1971). Over one hundred mine shafts marked on the geological map of Cabalt (Thomson, 1964) record the prosperous days of full mining activities between 1904 and 1961 in the township of Cobalt. At present only a few mines are producing Ag, Co, and Cu in the Cobalt area. However, early workers showed little interest in the sulfide mieneralization which are observed widely in the Huronian sediments of the Cobalt area in their enthusiasm for developing the silver from the time of discovery of silver-bearing ore veins (Knight, 1942; Boyle, 1966; Goods and Watkinson, 1986; Andrew *et al.*, 1986).

The purpose of this study is to describe occurrence characteristics of sulfide mineralization in the Huronian sediments and their origin. To study the sulfide mineralization in the Cobalt area, an understanding of the structural relationship among the Archean volcanic basement, Hurinian sedimentary rocks, and Nipissing diabase is essential because deposition and sulfide mineralization of the Huronian sediments appear to have been largely controlled by the attitude of the pre-existing Archean basement rocks. Sedimentary work for the Huronian sediments was done by a few workers including Lindsey (1967). Unfortunately, no work has been done on the sulfide mineralization in the Huronian sediments in the Cobalt area, the main objective of this study is to describe the sulfide mineralization especially in the Keewatin volcanics and Huronian sedimentary units.

Methods

Using the Ontario Department of Mines Provisional maps P-96 and P-97, scale 1 inch to 400 feet (Thomson, 1964), approximately 60 mine shafts including three underground shafts were observed in addition to the outcrops of the Huronian sediments. Samples were collected from the ourcrops and undergrounds as well as from the mine dumps where mine shafts were closed and not accessible. Laboratory works included petrographic and ore microscopic observations of thin- and polished-sections, electron microprobe analysis, and X-ray fluorescence spectroscopy.

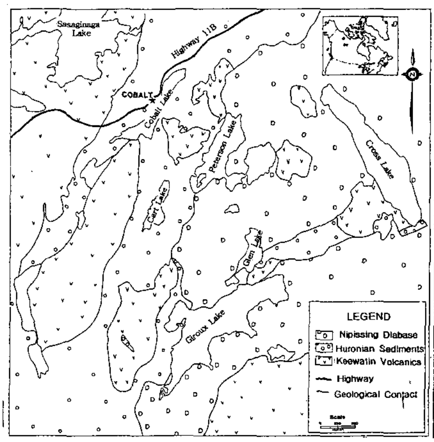

Fig. 1. Geological map of Cobalt area, Ontario, Canada.

Geology of Cobalt Area

Archean Rocks

The geology and geological column of Cobalt area are shown in Fig. 1 and Table 1, respectively. The Archean rocks are predominantly fine-grained, green flow rocks. These volcanic rocks are massive to pillowed flows and are silicified in some places. Pillowed volcanics are widely developed (Fig. 2), and sulfides, although minor in aboundance, are contained in the pollowed selvages as well as flows themselves. Well-layered interflow rocks consisting of chert, tuff, and slate are present locally (Fig. 3) and, in most cases, are mineralized heavily with pyrite, pyrrhotite, sphalerite, chalcopyrite, and galena. During Kenoran

Table 1. Geological column for the Cobalt area (after Jambor, 1971).

Eon	TIME AND ROCK UNITS			
	Keweenawan		Olivine and quartz diabase dykes	
			intrusive contact	
			Nipissing diabase sheets	
			intrusive contact	
PROTEROZOIC	Huronian	Cobalt Group	Lorrain Formation	Arkose, quartzite
			Gowganda Formation	
			Firstbrook Member	Mainly bedded argillite
			Coleman Member	Conglomerate, greywacke quartzite, arkose
			Kenoran Orogeny, 2490m.y.	
ARCHEAN	Matachewan		Dykes of diabase, minor lamprophyre	
			intrusive contact	
	Algoman		Large salic intrusions, Lorrain Granite, Round Lake Batholith	
			intrusive contact	
	Haileyburian		Minor dykes and sills of mafic rocks; lamprophyre, serpentinite	
			intrusive contact	
	Timiskaming		Mainly greywacke and conglomerat	
			unconformity	
	keewatin		Mainly intermediate to mafic flows; some pyroclastics and acid volcanics, minor interflow sediments with chert, sulfides; iron formation; schist.	

orogeny, dated at about 2.5 b.y. (Jambor, 1971), the Archean volcanics underwent regional metamorphism and deformation resulting in near-vertical dips.

Proterozoic Rocks

Huronian Sedimentary Rocks

In the study area, Huronian sedimentary rocks are represented by the Coleman Member, the lower unit of the Gowganda Formation, which rests directly on the Keewatin volcanic rocks. The Colemen Member consists largely of conglomerate with variable amounts of sandstone and argillite at several horizons. Its maximum thickness attains about 180m. The Gowganda Formation was dated to be 2288m.y. by the Rb/Sr method (Fairbairn *et al.*, 1969).

Nipissing Diabase

The Nippising diabase intruded both the Archean and Huronian rocks, and occurs as sill-like bodies that attain a maximum thickness of 400 meters in the Cobalt area. The dips of the diabase intrusions are generally gentle. The Nipissing diabase has an approximate composition of a tholeiite (Miller, 1911). The age of the Nipissing diabase was determined to be 2162m.y. (Fairbairn *et al.*, 1969) and 2155m.y. (Van Schmus, 1965) by the Rb/Sr method, and 2095 m.y. by the K/Ar method using biotite (Lowdon *et al.*, 1963). Hriskevich (1952) and Coldwell (1967) have described the petrographical variations of the diabase in the vicinity of the Colonial mine shaft where differentiation of the magmas resulted in a concentration of olivine- and hyperthene-bearing diabase in the basin part

Fig. 2. Pillowed volcanic rocks seen in some Archean volcanics.

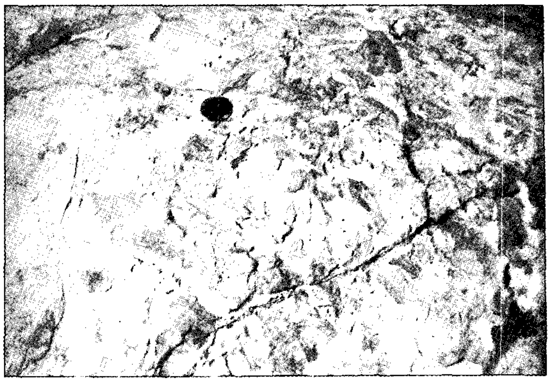

Fig. 4. Basal breccia developed directly on the Archean unconformity.

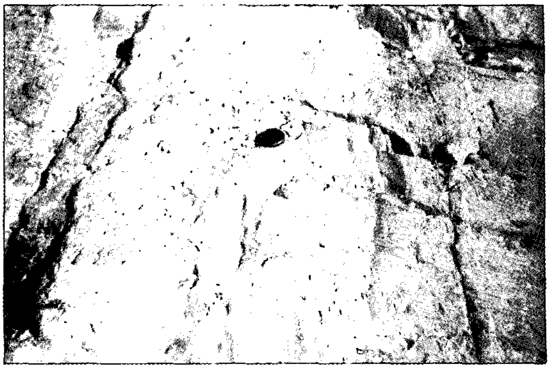

Fig. 3. Interflow rocks formed between the massive volcanic flows.

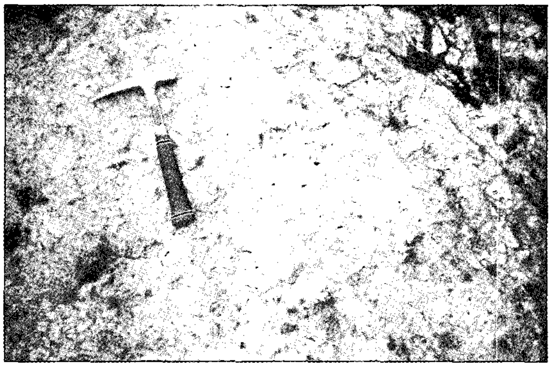

Fig. 5. Basal conglomerate outcrop. White clasts are completely silicified volcanics.

of the intrusion. The Nipissing diabase is most important from the economic point of view because the occurrence of Ag ores appears to be generally restricted to the diabase and to country rocks of all types within about 20m of the diabase contacts.

Lithology of the Huronian Sediments

Lithological study of the sulfide-bearing Huronian sediments (Coleman Member) will provide a basis for deducing the interrelationship between sedimentation and sulfide mineralization.

Conglomerates

The most wide spread unit of the Coleman Member is a conglomerate, which outcrops near the township of Cobalt. In general, the clasts of the conglomerate have a wide diversity of size, lithological composition, and roundness. The matrix is very poorly sorted and contains small angular grains of quartz and feldspar together with various lithic fragments resulting from physical breakdown of clasts less than 2 mm in size. The composition of clasts may be grouped into volcanic, plutonic, and sedimentary rocks. The conglomerates may be subdivided into three units on the basis of morphology and the composition of clasts: (1) basal breccia, (2) basal conglomerate, and (3) the typical conglomerate.

Basal Breccia

This unit is developed directly on the Archean unconformity, and consists mainly of angular frag-

Table 2. Electron microprobe analyses of sulfides in the Archean volcanic rocks

	1	2	3	4	5
Fe	30.5	46.6		59.4	11.6
Cu	35.1				63.6
Zn					
Pb			86.4		
S	35.4	53.9	13.3	40.2	26.5
Total	101.0	100.5	99.7	99.6	101.2

1: chalcopyrite, 2: pyrite, 3: galena, 4: pyrrhotite, 5: bornite. All values are average of five analyses.

ments of mafic to felsic volcanics, but does not contain granitic fragments (Fig. 4). The matrix is dark in color, and is composed of chlorite (85~90%) with minor amounts of quartz, plagoclase, sericite, and sphene. Basal breccia outcrop attains a maximum thickness of 1.5 m and a maximum lateral extent of about 10 m (Rainbird *et al.*, 1985). This unit is overlain by a thick unit of the conglomerate with general characteristics of common conglomerate, and their contact is sharp. Most breccia fragments are highly angular and vary from wedge-shaped to polygonal, indicating a minimum transportation distance. The breccia framents are mainly locally derived from underlying Keewatin volcanics.

Basal Conglomerate

This unit is composed of fairly well rounded clasts of felsic to mafic volcanics (Fig. 5). The basic criterion by which this unit is distinguished from the conglomerate unit is the absence of granitic clasts. As it occupies the lowermost part of the Coleman sedimentary sequence, thus the term 'basal' is used in this study. The apparent thickness of the basal conglomerate is about 13m. Subangular to well rounded, pebble-size rock fragments fill the interstices between some cobble-to boulder-sized clasts.

Conglomerate

Coleman conglomerates, the most widespread unit in the area, are characterized by a great diversity of clasts in size, composition, and texture. The most frequently observed clast materials are mafic to felsic volcanics, granitic materials, lamprophyre, argillites, chert, tuff, sandstone, vein quartz, and feldspar porphyry. Most clasts are smaller that 10 cm in diameter, although some are exceedingly large, up to 1.8 m. The roundness of the clasts varies from subangular to well rounded. Matrix of this unit is composed mainly of angular to subangular sand- to mud-sized grains of plagioclase, quartz, chlorite, muscovite, and carbonates together with sand-sized lithic fragments.

Sandstone

Sandstone occurs at several different horizons. This sandstone unit has numerous primary sedimentary and deformation structures such as cross-bedding, ripple-lamination, and convolute laminations. Quartz, plagioclase, chlorite, and sericite are the common components.

Argillite

Argillite occurs less than conglomerate and sandstone units in the study area. They are characterized by well-banded layers of alternating silt- and clay-sized grains. The maximum thickness of argillites are found to be about 4.5 m. Although argillites are made up of alternate layers of different thickness, each layer has an extensive uniform thickness, less than 1 cm.

Sulfide Occurrences

Base metal sulfide occurrences in the Cobalt area may be divided into three groups on the basis of the age of mineralization and accompanying host rock types: (1) sulfides that occur in the Archean rocks and are the oldest in age, (2) younger sulfides that occur in the the Coleman sediments, and (3) sulfides that occur with Ag-Ni-Co-As carbonate veins developed in the Archean and Proterozoic rocks, and are the youngest in age. The common sulfide minerals in each group are chalcopyrite, pyrite, pyrrhotite, sphalerite, bornite, and galena.

Table 3. Chemical compositions of sphalerite from Cobalt area

Location	Mode of occurrence	Wt.%					
		Fe	Zn	Cd	Mn	S	Total
Drummond shaft 4	Basal conglomerate	6.52	59.63	0.32	0.09	34.36	100.91
		7.21	59.47	0.28	0.08	34.01	101.06
		7.31	58.80	0.81	0.06	34.51	100.85
		6.85	59.86	0.33	0.05	34.80	101.89
		7.23	59.69	0.18	0.07	34.62	100.81
		6.35	59.55	0.22	0.08	34.15	100.34
Drummond cairn	Basal conglomerate	6.82	60.63	0.24	0.01	33.23	100.93
		7.01	61.12	0.22	0.01	33.54	101.89
		6.36	60.90	0.20	0.01	33.56	101.01
Drummond cairn	Basal conglomerate	6.22	61.76	0.25	0.05	33.39	101.68
		6.90	60.37	0.18	0.03	33.33	100.81
		6.54	60.55	0.20	0.07	33.32	100.66
		6.61	60.47	0.23	0.06	33.00	100.36
Drummond shaft 4	Sandstone	6.34	60.97	0.20	0.06	33.92	101.48
		6.55	60.28	0.18	0.10	33.64	100.75
		6.76	60.55	0.22	0.10	32.75	100.37
		7.57	59.16	0.20	0.08	34.75	101.22
Cross Lake O' Brien	Massive sulfide	6.87	58.44	0.26	0.09	33.20	98.85
		6.96	59.11	0.30	0.08	33.45	99.91
		7.19	57.88	0.26	0.09	33.66	99.07
		6.18	56.88	0.25	0.11	32.41	95.83
Cobalt Lake shaft 4	Interflow rock	6.16	60.06	0.27	0.09	32.99	99.57
		6.20	59.61	0.17	0.07	33.21	99.25
		7.24	56.38	0.28	0.05	32.83	96.79

Keewatin Rocks

Sulfide minerals of the Archean rocks occur in the graphitic schists, tuff, massive volcanics, and pillow selvages of volcanic flows. They occur as thick massive sulfide bodies in the volcanic flows (Fig. 6), lenses, bands, or stringers in the interflow rocks (Fig. 7), and disseminations in the volcanic flows, as well as in pillow selvages.

Electron microprobe analyses were carried out on these sulfides (Table 2). Sphalerite compositions (Table 3) from the Archean rocks, basal conglomerates, and other Coleman sediments are important because sphalerite is commonly found throughout all the units, Fe-content in sphalerite is dependant upon the temperature of formation, acting as a tracer (Barton and Tourmin, 1966).

Volcanic Flows

Massive sulfide deposits, similar to strta-bound types associated with Archean volcanism, are present between the volcanic flows. On many mine dumps, blocks of massive sulfides (Fig. 6) are abundantly found in the study area. Chalcopyrite (45%) and sphalerite (40%) are the principal constituents of massive sulfides with lesser amounts of galena (10%), phyrrhotite (3%), pyrite (2%), and bornite (less than 1%). Electron microprobe

Fig. 6. Massive sulfide boulder, rich in chalcopyrite and sphalerite, recovered from strata-bound type mineralized volcanics.

Fig. 7. Mineralized interflow alternating chert (black) and pyrrhotite layer (dark grey).

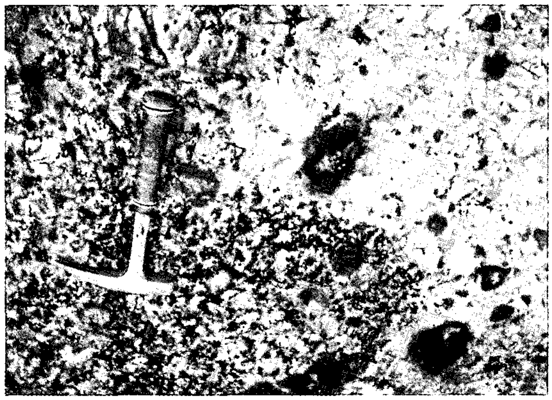

Fig. 8. Sulfide fragments (tarnished to dark brown) shown on the surface of the basal conglomerate.

Fig. 9. Massive chalcopyrite clasts in the Coleman conglomerate.

analyses have shown that Fe content in Fe-poor and Fe-rich sphalerites varies from 6.18 to 7.19 wt.% (Table 3). Cadmiun (0.25 ~ 0.30 wt.%) and manganese (0.08 ~ 0.11wt.%) contents are fairly uniform.

Interflow Rocks

Discontinuous lenses of nearly vertical interflow rocks between volcanic flows are composed chiefly of chert, graphitic schist, and minor amounts of argillaceous or tuffaceous materials. Most cases interflow rocks carry abundant sulfides in bands, lenses, pods, stringers, or disseminations. Some pyrite lenses are brecciated and exhibit remobilization texture. Electron microprobe analyses (Table 3) have shown that Fe wt.% of Fe-poor and Fe-rich sphalerite is in the range of 6.16 to 7.24 (Table 3). Cd (0.17 ~ 0.28) and Mn (0.05 ~ 0.09) contents are slightly lower but still similar to those of massive sulfides.

Pillowed Volcanic Rocks

Sulfides are sparsely disseminated throughout most volcanic flows. Pillow selvages are also mineralized with pyrrohtite, chalcopyrite, pyrite, and sphalerite although extremely minor in abundance.

Huronian Sediments

Basal Conglomerate

The most concentrated sulfide mineralization

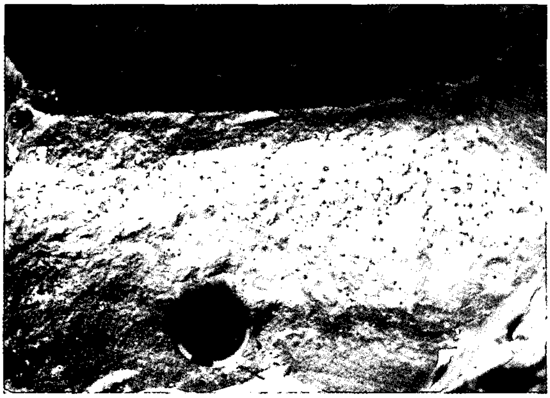

Fig. 10. Disseminated sulfides in the Coleman sandstone.

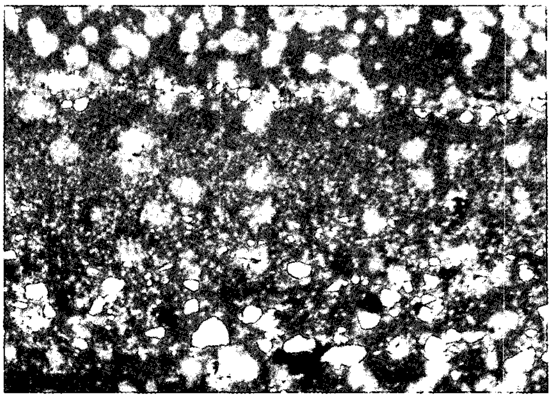

Fig. 11. Sulfides in the clastic horizon of the Coleman argillite. Sulfide grains (black) and quartz (white) show graded bedding. Transmitted light.

Table 4. Elemental content of the sulfide-rich part of the Coleman Member around Little Silver Vein Mine

Rock type	Cu (ppm)	Zn (ppm)	Ag (oz/ton)	Co (ppm)
Conglomerate	1150	36	0.26	780
	1720	83	0.40	22
Sandstone	590	nd	0.10	nd
	960	nd	tr	nd
	4000	30	0.76	100
	5200	30	tr	100
	600	nd	0.60	nd
	4000	44	0.13	24
	3500	18	0.11	54
Argillite	30	50	tr	120
	175	35	0.70	162
	600	400	tr	nd
	78	24	tr	44

nd: not determined, tr: trace

among the sediments in the study area is found in the basal conglomerate. Sulfides in the basal conglomerate occur as massive sulfide fragments, disseminations in a matrix and clasts. Sulfide fragments up to 5 by 3 cm in size are abundantly observed on the surface of the basal conglomerate outcrop (Fig. 8). Sulfides occasionally enclose the grains of the matrix, preserving the euhedral crystal outlines. This means that some degree of mobilization of sulfides took place after the emplacement of both minerals in the conglomerate.

Variation of sulfide assemblages with distance from the base of the basal conglomerates is observed: amounts of galena and pyrite decrease, and those of sphalerite and pyrrhotite increase towards the bottom of the outcrop. Electron microprobe analyses of sphalerites from different locations (Table 3) show that sphalerite from the Drummond cairn varies from 6.22 to 7.01 wt.% Fe, whereas that from Drummond shaft 6.35 to 7.31 wt.%. They contain 0.18~0.25 wt.% Cd, and 0.01~0.10 wt.% Mn. The compositionally similarity of sphalerite is striking, despite the fact that sample locations are up to 2.5 m apart, and that there is a difference in the mode of occurrence.

Conglomerate

Massive sulfide fragments, fine disseminations, and sulfide-bearing clasts occur in the Coleman conglomerate. Massive sulfide fragments, mostly chalcopyrite, up to 10 cm in diameter are found in the basal portion of the Coleman conglomerate (Fig. 9). Coleman conglomerates occur at different stratigraphic horizons and one that belongs to a higher stratigraphic horizon contains far less sulfides than that at the base (Table 4). Cu content varies from 1,150 to 1,700 ppm, whereas Zn content is considerably low, ranging from 36 to 83 ppm.

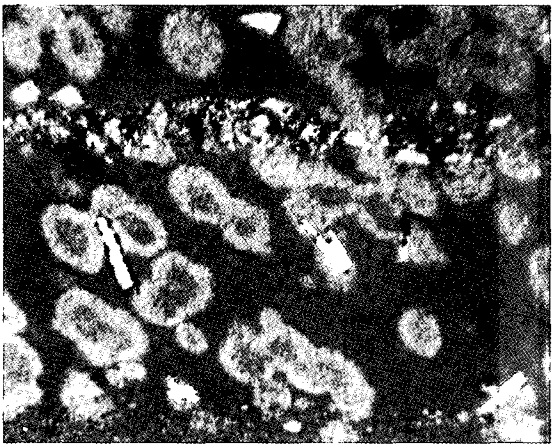

Fig. 12. Elongate pyrrhotite grains (a) are oriented obliquely to the laminations in Coleman argillite. Inequidimensional galena (b) are also seen. Transmitted and reflected light.

Sandstone

Sulfides mineralization occurs primarily as fine disseminations in the sandstone unit, although much less hen compared with that in the basal and Coleman conglomerate. Numerous spots consisting of chalcopyrite and calcite are developed (Fig. 10). Some chalcopyrite are rimmed with sphalerite. Sphalerite are often associated with chlorite, which is partly replaced by sphalerite. Chemical analyses of sphalerite from Drummond shaft 4 reveals that Fe wt.% is in the range of 6.34 to 7.57. Cd and Mn contents are in the range 0.18 to 0.22 and 0.06 to 0.10 wt.%, respectively (Table 3).

Argillite

Sulfide grains are finely disseminated conformably to the horizontal laminae in the well-laminated argillite unit. Fine sulfide grains are distinctly concentrated at the basal portion of each layer where clastic grains have graded bedding (Fig. 11). A few elongate pyrrhotite grains which are believed to be recrystallized are oriented obliquely to the horizontal laminations at about 10 to 45 degrees (Fig. 12). Cu content show 30 to 600 ppm, and Zn content attains 400 ppm.

Genesis of the Sulfide Mineralization

Two hypotheses that deserve to be considered to explain the sulfide mineralization of the Coleman sediments:

(1) Syngenetic origin
  (a) deposition of detrital sulfides
  (b) chemical precipitation from the hydrous depositional medium
(2) Epigenetic origin involving hydrothermal solutions

Syngenetic Origin

Detritus

The detrital origin requires that once sulfide grains are removed from the parent sulfide source, they behave in a similar manner to the clastic silicate grains. The most probable mechanism of their transport is that sulfides were mixed and transported by the current carrying clastic sediments from a local or remote source.

Massive sulfide clasts of pebble- to cobble-size are occasionally found in the basal conglomerate and lower Coleman conglomerate. They are mainly composed of massive chalcopyrite or sphalerite. The clasts are angular, and their dimension is generally smaller than that of enclosing clasts, although some are exceedingly larger than other clasts. They are likely to be found in places where paleo-depression structures were developed. It seems that massive sulfide cobbles were derived from parent sulfide bodies presumably located on the valley flanks or crests nearby. It may imply that massive sulfide cobbles were mixed with the clastic sediments and were subjected to collision with more physically stable silicate clasts during the period of transport, resulting in brecciation. Considering the high angularity of these massive sulfide clasts, their transported distance would be minimal. Abundant massive sulfide boulders were found on many mine dumps, and some are exactly identical to the massive sulfide cobbles and pebbles in the Coleman conglomerate in mineralogy and texture.

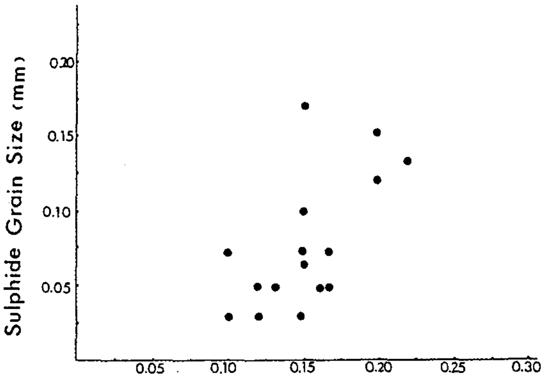

Fig. 13. Plot of clastic grain-size versus sulfide grain-size in the Coleman sandstone.

Sulfides conformable to the cross-beds, are graphically represented in Fig. 13. The size of both clastic and coexisting sulfide grains represents their maximum dimension in certain laminae, because the maximum competence of the transporting medium is represented by the largest silicate grains in the liminae. As shown in Fig. 13, the size of the clastic grains is in the range of 0.1 to 0.22 mm; on the other hand, that of the bedded sulfide grains lies within the range from 0.03 to 0.17 mm. The measure of sulfide grains may be exaggerated resulted from recrystallization associated with the intrusion of the Nipissing diabase. It is significant that the finer the clastic grains, the finer and the less concentrated the sulfides.

Specific gravities of sulfides are galena (7.5), pyrite (5.0), pyrrhotite (4.6), chalcopyrite (4.2), and sphalerite (4.0), and these are all heavier than quartz (2.65). Therefore it is expected that sulfide grains were transported by currents that could carry clastic grains greater than sulfide grains. Coarser sulfide grains were subsequently deposited at the bottom of each layer resulting from gravitational sinking. Some of the fine-grained sulfides could still remain in suspension in the quiescent depositional water body. These facts may suggest that competence of currents and gravitational precipitation were both important factors.

In the well-laminated argillites, very fine grains of sulfides are dispersed throughout the layers. Similar to the sulfides in sandstones, sulfide grains show graded bedding with silicates. Grain size of most sulfides is much smaller than that of enclosing clastics. Pyrrhotite grains probably of detrital origin, up to 0.35 by 0.05 mm, are oriented obliquely to the horizontal silty layer at about 10 to 45 degrees, probably resulting from penetration of pyrrhotite grains after deposition of this later (Fig. 12).

Detrital origin for the sulfides in the Coleman Member is again strongly supported by the observation of sphalerite compositions and probable sulfide sources. As shown in Table 3, Fe wt.% of sphalerite of the basal conglomerate and sandstone is in the range of 6.22 to 7.57. That of Keewatin rocks ranges from 6.16 to 7.24. Cd and Mn contents are mostly in narrow range of 0.15 to 0.30 and 0.01 to 0.10 wt.%, respectively. The similarity of sphalerite composition between the Coleman Member and the mineralized Keewatin rocks is striking compared with sphalerite values from Ag-Co-Ni-As and carbonate vein of 1.61 and 0.67~3.04 wt.%Fe, respectively. It suggests that sphalerite of the Keewatin rocks, basal conglomerate, and Coleman sediments can be grouped together, and may be from the common source, while sphalerite in the Ag-Co-Ni-As and carbonate veins is obviously of different origin.

Sources of sulfides in the basal conglomerate and Coleman Member are most probably strata-bound type massive sulfides and mineralized Keewatin interflow rocks. Field observation indicates that mineralized Keewatin interflow rocks and massive sulfide were extensively eroded before and during deposition of the basal conglomerate and Coleman sediments (Table 2). Keewatin volcanic flows themselves are also mineralized with sulfides, although sulfide content is much less than those of the afore-mentioned two major sulfide sources. Archean volcanic rocks were strongly deformed during the Kenoran orogeny, therefore sulfide bodies occurring between volcanic flows were also expected to be deformed;

hence, sulfides could have been readily eroded. Frost activity could have contributed to the minor amounts of fracturing the Archean rocks and associated sulfide bodies.

Chemical Precipitation

Chemical precipitation of the sulfides could be another possible mechanism for some sulfide mineralization of the Coleman Member. This mechanism requires that solution with dissolved metals was introduced into the depositional system, followed by the precipitation of sulfides simultaneously with sedimentation or diagenesis. The solubility of Zn, Pb, and Cu in pure water at all temperatures up to 350 °C is extremely low (Barnes and Czamansky, 1967). Considering the Coleman Member would have been deposited in lakes, etc., then the solution source would have to be deep geothermal waters.

Chalcopyrite grains are more concentrated in the middle portion of sand beds rather than the base at Little Siver Vein Mine. If sulfides were carried by currents, then, they would settle to the basal portion of the bed. This may suggest that there might have been a distinct chemical event that occurred during or after the sedimentation. Sulfides enclosing silicate grains might be formed by two processes. One is the process of precipitation by nucleation around the clastic grains, and the second is a limited degree of mobilization of sulfides around silicate grains after they have emplaced in the sandstone as detritus.

Epigenetic Origin

An epigenetic origin for the sulfides in the Coleman sediments implies that sulfide mineralization took place in the rocks after lithification, and the loci of deposition were controlled primarily by the physical or chemical properties of the host rocks. Hydrothermal solutions would have mineralized the host rocks by diffusing laterally along the beds or upward from the base. Although there is nothing known, at present, to indicate whether they were leached from the sulfide deposits, the most likely channel ways for a hydrothermal introduction of sulfides are highly sheared Keewatin interflow rocks and massive sulfide deposits that are located nearby and have near-vertical attitude.

It was shown that sulfide grains are most likely concentrated in the lowermost portion of each bed, and this is conspicuous if graded bedding is recognized. A weakness in the upward diffusion model is that the grade of sulfide mineralization of the basal portion of each bed with coarse-grains in sandstones is richer than the upper portion with fine-grains. It is improbable that upward diffusion of hydrothermal solutions, passing through the silty-grained beds overlying more coarse-grained and permeable bed, is expected to act as a membrane that would capture the metals either physically or chemically from upward coursing solutions.

Mineralizing solutions would likely diffuse along coarse-grained beds favorable to lateral diffusion. In this case, permeability of the bed might be a primarily factor that controls the present distribution of sulfides in the sandstone and argillite, because more mineralization follows the coarser-grained portion of a given bed. Sulfide mineral concentration occurs heavily near the Archean unconformity. This may be partially explained by the fact that the unconformity might have provided a favorable site for the sulfide precipitation from hydrothermal solution.

Summary and Conclusions

There was pre-Huronian erosion surface which showed undulating topograph (Kim, 1980). The present difference between the highest crest and the deepest part of the valleys or basin is about 600 feet. However, the original difference would have been greater than 600 feet because the present crest of Archean volcanics are remnants of an erosion process since the intrusion of the Nipissing diabase. The fact that the Coleman Member dips towards the depressions and that paleo-current directons of the Coleman sandstones point to these structures strongly supports the existence of these depressions. These apparent depressions could have provided favorable sites for the deposition of the Coleman sediments and any accompanying detrital sulfides. In addition, the depressions might have provided a quiescent water system, allowing the transported clastic sediments and accompanying sulfides to form bedded sulfides in the evenly laminated layers.

Strata-bound type massive sulfide deposits and mineralized interflow rocks would have been deformed during the Kenoran orogeny, resulting in present near-vertical attitudes. Field observation indicates that Keewatin volcanic rocks carry enormous strata-bound type massive sulfide ores and mineralized interflow rocks. And significant amounts of sulfides had deposited on the pre-Huronian erosion surface in the Cobalt area. There is a similarity in mineralogy between the probable sulfide bodies and sulfides in the basal conglomerate and Coleman sediments. The more conclusive evidence that the interflow rock and massive sulfide deposits are the most prominent sulfide source is the relatively uniform chemical composition of sphalerites. The sphalerite in the carbonate or Ag-Co-Ni-As veins are to be of different origin from those of the basal conglomerate and the Coleman sediments. It is unlikely that sphalerite precipitation from hydrothermal solution would have a composition coincident with those of the massive sulfide deposits. The most likely source for the sulfides contained in the basal conglomerate and other Coleman sediments are locally but abundantly distributed strata-bound type massive sulfide deposits and mineralized interflow rocks. A possibility still remains that, except the basal conglomerate, some sulfides contained in the Coleman sediments might have been derived from a remote source as are some of the silicate clasts.

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