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**A SULPHUR ISOTOPE AND STRUCTURAL STUDY OF
THE SILVER VEIN HOST ROCKS
AT COBALT, ONTARIO**

by

BRADLEY STUART WILSON, B.Sc.

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of
the requirements for the degree of
Master of Science

Department of Geology

Carleton University

Ottawa, Ontario

December, 1986

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A SULPHUR ISOTOPE AND STRUCTURAL STUDY OF THE SILVER VEIN

HOST ROCKS AT COBALT, ONTARIO

submitted by Bradley Stuart Wilson, B.Sc.

in partial fulfilment of the requirements for
the degree of Master of Science

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ABSTRACT

Analysis of joint patterns in the Cobalt area, northern Ontario, was undertaken to help outline the structural setting of high-grade native silver-bearing veins and the structural history of the area. Similarities in orientation and certain physical features between joints and veins indicate that silver veins are located primarily within dilated joints. Joints, minor folds, and major reverse faults probably resulted from a compressive event that occurred prior to or during vein mineralization, about 2200 M.a. ago. Mineralogy, textures, and isotopic composition of heterogeneously distributed sulphide minerals within Huronian sedimentary rocks indicate that most of these sulphides, other than some of the pyrite, were deposited from vein-related fluids that permeated rocks adjacent to the silver veins. Blastic pyrite probably resulted from the mobilization of originally detrital sulphides during diagenesis or Nipissing diabase emplacement. These data reduce the possibility that Huronian sulphides were a major source of vein elements.

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CHAPTER I

INTRODUCTION

1.1 Introduction

In 1903, extremely high-grade native silver-bearing veins were found in the Cobalt area, Ontario (Figure 1.1). Since then, mining in the Cobalt camp and vicinity has produced over 17,000 metric tons of silver from native silver, Co-Ni-Fe arsenide-bearing veins (Mohide, 1985). Ore grades were impressively high, especially in the first eighteen years of mining (1904-1922), when the overall yearly ore grade never fell below 677 oz/ton. In 1915 the average ore grade for 24 companies was 2,359 oz/ton (almost 10% Ag) (Halls and Stumpfl, 1969). A colourful early history of the camp is outlined by Smith (1986).

Silver veins occur in relatively flat lying Proterozoic clastic sedimentary rocks, steeply dipping Archean volcanic and interflow sedimentary rocks and occasionally within a 300 metre-thick undulating sill-like intrusion of diabase (Nipissing diabase). The veins are never more than 215m away from the Nipissing diabase (Jambor, 1971b; Owsicki and Lovell, 1984). The silver veins are located in fractures and small faults, yet there have been only a few papers mentioning the structural aspects of the Cobalt camp (Moore, 1942; Halls and Stumpfl, 1969; Lowes, 1963; Thompson, 1957a; Knight, 1924).

To understand the origin of the silver veins at Cobalt, as in any vein-type deposit, it is necessary to understand the source of elements, source of transporting fluid, structural (physical), and chemical reasons for precipitation. Possible sources of vein elements

Figure 1.1 Location of the Cobalt mining camp.
(After Scammell 1984)

have been proposed recently by Goodz et al. (1986) (Archean rocks), Strong (1985) (Coleman member), Appleyard (1980) (Coleman member), and Jambor (1971e) (Nipissing diabase). A sulphur isotopic and mineralogical study was undertaken as part of this thesis to place constraints on these features.

Sulphide minerals occur sporadically throughout the area within the Proterozoic sedimentary rocks, Archean volcanic rocks and especially in the Archean interflow sedimentary rocks. Sulphides from the Archean volcanic and interflow sedimentary rocks, and the silver veins hosted within, were studied texturally and isotopically by Goodz et al. (1986). They concluded that sulphur and possibly the metals in the veins were derived from sulphides in the Archean basement. Previous studies suggest that Coleman member sulphides originated from detrital processes, hydrothermal processes, or both (Hartlein, 1972; Kim, 1979; Gebert, 1985). If the majority of Coleman member sulphides are detrital, then these sulphides, like those in the basement, may represent a viable source for the vein constituents.

1.2 Purpose of Thesis

This study was undertaken in an attempt to fill gaps in our overall geologic knowledge of the Cobalt area. One aspect of this study will investigate systematic joint patterns found throughout the Cobalt camp and relate this to the structural history of the area and the structural setting of the silver veins. The purpose of the second part of this study is to describe sulphides from the Coleman member, both texturally and isotopically, and to consider the mechanisms for their origin.

1.3 General Geology

The geology of the Cobalt camp has been described in detail by

Berry (1971), Knight (1924), Miller (1913), Mustard (1985), Goodz (1985), Thompson (1964a, 1964b, 1964c) and many others. The following description is based on these papers and field observations.

Table 1.1 is a chronologic summary of the geologic units exposed in the Cobalt area, and Figure 1.2 shows the general geology of the Cobalt camp investigated in this study.

Cobalt is located at the northeastern limit of the Southern Province where relatively thin, flat-lying Proterozoic sedimentary rocks of the Huronian Supergroup unconformably overlie a basement of steeply dipping Archean volcanic and minor interflow sedimentary rocks of the Superior Province. The lower members of the Huronian Supergroup, found in the Elliot Lake-Espanola area, are absent at Cobalt, and only the Cobalt Group occurs in the area. Figure 1.3 shows the relationship of the Huronian Supergroup to the Archean basement. Crosscutting both of these major units is the 300 metre-thick undulating sill-like intrusion of Nipissing diabase.

Archean Basement Rocks

The Archean basement rocks at Cobalt consist of predominantly intermediate to mafic volcanic flows ranging from massive to pillowed. Porphyritic and fine-grained felsic intrusions are present in some places. Beds of chert, tuff and fine-grained greywacke up to 15 metres thick (Jambor, 1971b) occur between the volcanic flows. Some of these interflow rocks are rich in various sulphide minerals. Hartlein (1972) reports that up to 30% by volume of some of the Archean interflow units are sulphide minerals. The interflow sedimentary rocks of the Cobalt camp are currently being studied by M. Smyk, M.Sc. student, Carleton University.

TABLE 1.1

STRATIGRAPHIC COLUMN, COBALT AREA

P H A N E R O Z O I C	Recent	† *	Fluvial and lacustrine deposits
	Pleistocene	*	Glacial sand, gravel and varved clay
	unconformity		
	Silurian	Thornloe Formation Wabi Formation	Dolomite, limestone Limestone, shale
	disconformity		
	Ordovician	Dawson Point Formation	Shale
		Farr Formation	Limestone
		Bucke Formation	Shale
		Guigues Formation	Sandstone
	unconformity		
P R O T E R O Z O I C	*Olivine and quartz diabase		
	intrusive contact		
	*Nipissing diabase		
	intrusive contact		
	Huronian	Cobalt Group	
	Supergroup	Lorrain Formation	Quartz arenite, arkose
		Gowganda Formation	
		Firstbrook Member	Laminated siltstone
		* Coleman Member	Conglomerate, sandstone, laminated siltstone
	unconformity		
A R C H E A N	*Diabase, minor lamprophyre		
	intrusive contact		
	Algoman	Granite, granodiorite, syenite	
	intrusive contact		
	*Dykes and sills of mafic and ultramafic rocks; lamprophyre		
	intrusive contact		
	Timiskaming	Lithic and feldspathic arenites and wackes; conglomerate	
	unconformity		
	Keewatin-type	*Mafic to intermediate mafic flows and tuffs; felsic flows and pyroclastics; minor interflow sediments (mainly black shale and chert); iron formation, volcanic rocks	
	Volcanic Rocks		

* indicates units and rock types found within the study area

Modified after Donaldson and Munro (1982)

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Figure 1.2 General geology map of part of the Cobalt mining camp.

Figure 1.3 Generalized stratigraphy of the Huronian Supergroup in relation to the Archean basement. (After Mustard, 1985).

The most common sulphides, although variably distributed, appear to be, in decreasing abundance, pyrrhotite, pyrite, sphalerite, chalcopyrite, galena, and traces of arsenopyrite and marcasite.

The sulphide minerals can occur as sulphide-rich beds, as disseminations throughout the rock, in nodular form or in small several millimetre-thick crosscutting veinlets. Nodular sulphides are composed of pyrite and/or pyrrhotite and can be as large as five centimetres in diameter. The crosscutting sulphides are sphalerite, pyrrhotite, chalcopyrite and galena.

The Archean volcanic pile was intruded by dykes of lamprophyre and small bodies of mafic and ultramafic rocks rarely wider than 150 metres. North of Cobalt a series of Archean conglomerates and greywackes occur called the "Timiskaming" sediments (Jambor, 1971b)(Table 1.1). These are both conformable and unconformable with the older Archean volcanic rocks.

The Archean rocks were folded and metamorphosed during the Kenoran orogeny, dated at about 2500 M.a. Coeval with this orogeny was the emplacement of several nearby granitic batholiths, locally termed the "Lorrain granite" or Algoman granites. Metamorphism during the Kenoran orogeny reached greenschist facies. The Archean rocks were tilted to near vertical attitudes and folded about axes striking west to northwest.

Proterozoic Sedimentary Rocks

Proterozoic sedimentary rocks were deposited unconformably upon an erosional surface having an estimated vertical relief of less than 100m (Mustard, 1985). This surface has been modified by gentle folding (Mustard, 1985; Knight, 1924). The Proterozoic sedimentary rocks in the Cobalt area and vicinity comprise the Cobalt Group of the larger Huronian Supergroup. The structural setting and stratigraphy of the

Cobalt Group and other groups of the Huronian Supergroup have been the subject of numerous papers (eg., Card et al., 1972; Stockwell et al. 1970; Roscoe, 1969). The Cobalt Group in this area is represented by the Lorrain and Gowganda Formations; the latter has been studied recently by Rosen (1985).

Gowganda Formation

The Gowganda Formation has been subdivided into two members, the Firstbrook and Coleman members (Rainbird, 1985), only the latter of which is found in the Cobalt camp.

Coleman Member in the Cobalt Camp

Detailed geology and descriptions of the Coleman member have been presented by Scammell (1984), Rainbird (1980), Mustard (1985), Kim (1979), and Hartlein (1972).

The Coleman member is composed of siliciclastic sedimentary rocks ranging in grain size from clay to large cobbles (as large as 13m across) and in the Cobalt camp is a maximum of 150 metres thick (Thompson, 1957b). Rock types consist of dropstone-bearing rhythmically layered silt and mudstone, or fine sand and siltstone, sandstone, and conglomerates or diamictites. The conglomerates range from matrix-supported paraconglomerates with as little as 5% pebble and boulder-sized clasts, to clast-supported orthoconglomerates with up to 75% clasts. They were deposited in a glacial environment where continental ice sheets and their associated melt waters carried sediment into a shallow marine setting (Mustard, 1985). The lowest part of the member consists of massive matrix supported diamictite deposited as a basal till, and above this a coarsening upward series of rocks were deposited as subaqueous outwash fans (Mustard, 1985).

Structurally these rocks have been folded slightly and offset by several faults. Metamorphic grade is very low to low greenschist facies (Card et al., 1972). Most rock types have a dark green colour due to a pervasive chloritic matrix.

Nipissing Diabase

The Nipissing diabase (Jambor, 1971d; Hriskevich, 1952) occurs as an undulating sill-like intrusion with a configuration of saucer-like broad basins and domes (Thompson, 1957a; Jambor, 1971b, 1971d) that have been accentuated to a small extent (a few degrees) by folding (Symons, 1970). Erosion has exposed the diabase such that it caps broad expanses and forms irregularly shaped outcrop patterns. Dips are, in general, shallow and the maximum thickness is about 330m (Jambor, 1971d). In most areas the diabase crosscuts the Huronian bedding and the Huronian-Archean unconformity at low angles, although it follows bedding and the unconformity in a few places.

Chlorite spotting in adjacent rocks forms a halo around the diabase and is probably a thermal metamorphic effect (Jambor, 1971d, 1971f; Dass, 1971; Appleyard, 1980). The 500°C ($\pm 75^\circ$) isotherm around the diabase is about 7.5m (25 ft) away as determined by paleomagnetic studies (Symons, 1967). Trace element geochemistry of the diabase reveals that Co, Ni, Cu, Ba, B, As, and Ag concentrations are not impressively high (Jambor, 1971a).

Nipissing diabase has recently been dated at 2217 ± 1.6 M.a. by Andrews et al. (1986).

Post-Nipissing Intrusions

Post-Nipissing intrusions are very uncommon and consist of narrow dykes of quartz or olivine diabase up to 80m wide. One of these dykes crosscuts a silver vein and has been dated at 1465 ± 168 M.a.

(Jambor, 1971b).

1.4 Structural Geology

Faults and Fractures

Three main sets of faults trending SE, NE, and ESE occur in the vicinity of Cobalt, each with different characteristics.

Faults trending SE are of regional extent with some over 160 km in length (Figure 1.4). Substantial movement on the McKenzie and Lake Timiskaming Faults has occurred during post-Silurian time and vertical displacements are as much as 305m, although additional periods of movement are possible (Jambor, 1971b). The ages of other SE faults are difficult to determine. Lovell and Caine (1970) related these faults to a rift valley system.

The second set of faults, which trend NE, are of local extent, occur mostly within the Cobalt camp and are shown in Figure 1.5. These are reverse faults, appear to be listric, and displacements and dips decrease progressively toward the NW.

These faults have had different names applied to them at different times, depending upon which property they cross and when referred to. For example, the Contact Fault (located in the NW corner of the camp) does not connect with the Trethewey or Coniagas Fault according to the maps of Thompson (1964a), but Knight (1924) called the southern end of the latter fault the "Contact Fault" and suggested that perhaps these two faults were connected (see Figure 1.5). It appears that these faults were defined mainly from isolated sites in mine exposures and perhaps the fine details, such as continuity and extent of these faults has been obscured.

Figure 1.4 Part of the Timiskaming rift valley system showing major southeast faults. (after Lovell and Caine, 1970)

Figure 1.5 Location map showing northeast reverse and thrust faults, and axes of minor folds.

According to Thompson (1957a) and his geology maps (1964a, 1964b) the largest NE-SW fault, the Cobalt Lake Fault, is about 7 km long. Its displacement varies along strike from presumably zero vertical displacement at both ends to documented values of 165m at the south end of Cobalt Lake, decreasing to 82m at the north end of the lake, and dips from 50 to 70° SE (Knight, 1924). The Valley or West Fault has a vertical displacement of about 23m and dips 45 to 65°. The Tréthewey or Coniagas Fault has less displacement and dips 10 to 30° (Knight, 1924). Knight's cross-sections reveal that some of the faults splay and are connected at depth (Figures 15 and 19, in Knight, 1924).

ESE faults are the third type and are summarized in Figure 1.6. These faults are dominantly vertical, normal (south side down) and several host silver veins. They have vertical displacements of less than 7.5m and are generally smaller than the NE faults. Horizontal displacements may exist but are probably small.

Joints and fractures are ubiquitous at Cobalt. A study of systematic joints is presented as part of the present study.

Folds

The Archean-Proterozoic unconformity surface and the Coleman member have been folded slightly, as indicated by the geologic cross-sections of Knight (1924) and Mustard (1985). Slight folding about NE-SW axes in the Nipissing diabase was interpreted from paleomagnetic studies (Symons, 1970) (Figure 1.5). Slight folding of the Coleman member and Nipissing diabase seemed evident to Thompson (1957a) but difficult to prove.

1.5 Silver Vein Deposits

Silver mineralization has been the target of economic

Figure 1.6 Location map showing east-southeast faults.

exploitation since the early 1900's and its genesis the focus of numerous studies, such as those by Petruk (1966, 1968, 1971d), Goods (1985), Berry (1971), Halls and Stumpfl (1969), Boyle and Daa (1971) and Daa (1970):

Silver mineralization at Cobalt and the surrounding satellite mining camps is of the native silver, Co-Ni-Fe arsenide type (Bastin, 1939), and occurs as steeply dipping discordant veins. Veins occur within 215m of the diabase (Jambor, 1971b) and are often within 30-60m of the Archean-Proterozoic unconformity (Knight, 1924).

Veins vary from less than a metre to about a kilometre in length, up to 120m in vertical extent, and pinch and swell from a hairline fracture to over a metre wide, but are commonly about 5cm in width (Jambor, 1971b; Petruk, 1971c). Veins or vein structures consist of smaller ore shoots, carrying ore minerals, separated by barren gangue. The percentage of ore shoot versus amount of barren vein varies greatly from place to place. Ore grades are impressively high in the veins (thousands of ounces per ton). Rarely, disseminated silver-bearing minerals around the vein, usually within the laminated siltstone, form a halo of lower-grade silver ore up to a maximum of 25m in width (Jambor, 1971b; Petruk et al., 1972; Owsicki and Lovell, 1984). In places this lower grade halo was mined after high-grade vein mining (Thompson, 1957a). In some places there is a halo of disseminated sulphide minerals around the vein that overlaps and extends beyond the halo of silver ore.

Native silver occurs intergrown with a complex assemblage of Co-Ni-Fe arsenides and sulpharsenides. These ore minerals, as well as less abundant sulphides and sulphosalts, occur in a gangue of predominantly calcite and dolomite. Antimony, mercury and bismuth are also enriched

2

3

in the veins and in general the veins richest in silver will have the highest Sb content and those ores poor in silver will contain the most bismuth (Petruk, 1966).

Elemental zoning and its associated mineralogic zoning in veins has been noted (Petruk, 1968; Petruk et al., 1972; Goodz, 1985). In general, areas richest in silver occur at the tops of veins or near vein junctions and contain an assemblage of Co-Ni arsenides; medium grade silver ore occurs with Co arsenides; and low to very low-grade silver occurs with either iron or nickel arsenides. Zoning in sulphide minerals peripheral to veins within Archean rocks at the Beaver-Temiskaming Mine has been documented by Goodz (1985).

Texturally the ore is complex, but generally silver occurs in the centres of zoned rosettes, dendrites, and tube-like growths of Co-Ni-Fe arsenides and sulpharsenides ~~several mm across~~ and as small veinlets throughout the vein material.

Fluid inclusion studies indicate that the ore fluids contained on the order of 25 wt.% equivalent NaCl and deposition temperatures were about 100-330°C (Strong, 1984; Scott and O'Connor, 1971; Strong, 1985). Sulphur isotope, oxygen isotope, and arsenopyrite studies by Goodz (1985) suggest mineral deposition temperatures were 130-227°C, 210-240°C, and 173-258°C, respectively at the Beaver-Temiskaming mine.

Thin alteration halos with bilateral symmetry about 5 cm on either side of veins have been investigated by Dass (1970). A dark chloritic band of chlorite-carbonate-albite grades into a light-grey bleached zone consisting of sericite-epidote-chlorite-carbonate which grades into fresh host rock.

By 1942, more than 80% of the ore at Cobalt had been produced

from veins hosted in the Coleman member (Moore, 1942). Silver production up to 1942 amounted to 385 million ounces. About 18 to 58 million ounces of the 75 million ounces of silver produced since 1942 have come from veins hosted in Archean volcanic rocks (Petruk, 1968; Goodz and Robinson, in press). Taking these figures into consideration, a recent estimate of 78% of the silver produced at Cobalt came from veins hosted in the Coleman member. These figures include production from the Archean-hosted New Lake basin, and it seems likely that within the study area the Coleman member hosted much greater than 78% of the silver production.

CHAPTER II

STRUCTURAL GEOLOGY

2.1 Introduction

During detailed field mapping (at a scale of 1:2000) observations were made which suggest that joints and small faults may follow a systematic pattern, especially within the Coleman member. Mapping revealed abundant, often intense, fracturing, most of which occurs in parallel to sub-parallel sets (systematic joints).

The silver veins at Cobalt occur in small faults and fractures, and some authors have suggested that the veins may follow joints and may have some kind of systematic structural control (Petruk, 1971b; 1971c; Jambor 1971b; Halls and Stumpfl, 1969; Knight, 1924). With the exception of the works of Halls and Stumpfl (1969), most previous observations were restricted to mineralized veins and mine workings.

A joint orientation study was initiated to investigate 1) joint patterns, 2) a possible connection between joints and mineralized veins, and 3) the overall relationship of veins and joints to the structural evolution of the camp. An understanding of joint and fracture mechanisms could yield valuable information about the structural controls of vein occurrence, and on possible pathways followed by mineralizing fluids.

2.2 Field Methods

Fieldwork covered an area extending from less than one kilometre north of the town of Cobalt, to the north end of Cart Lake, about 2.7 by 1.4 kms. (Figure 2.1). The area straddles the Archean-Proterozoic

Figure 2.1 Location of structural study area.

unconformity, but does not include the Nipissing diabase.

Structural field work consisted of measuring the attitudes of systematic joints and small faults and estimating the spacing and relative strength of each joint set. For the purposes of this study a systematic joint set is defined as parallel to near-parallel fractures or joints, and at least three must be present on an outcrop scale in order to be recorded and presented here.

Several problems exist with recording data in this way. The number of systematic joint sets does not necessarily indicate the degree of fracturing in an outcrop. For example, an outcrop may be heavily fractured in a random fashion such that no systematic joints are produced, yet no data will be recorded, whereas the presence of only a few regular joints will produce recordable data. A second problem can occur when the outcrop is small and the joint spacing is large. If a systematic joint set has a spacing of one metre or more, an outcrop could be up to three metres wide and have only two joints present.

An estimate of joint strength was recorded at every site as strong, moderately strong, moderate, moderately weak, weak, or very weak. This estimate was based on the visual impact of the joint set and is a relative measure of a combination of joint spacing, length and straightness. For example, a "strong" joint set would consist of straight, very continuous joints usually 10m or more in length, spaced fairly close together (e.g., 0.5 m), while a "weak" set would consist of an irregular arrangement of short (0.1-1.0 m) joints with a varied spacing. Although estimating the strength of a joint set was based on visual impact and is affected by human subjectivity, joint strength is believed to be a valid parameter due to the large number of joint

-5

measurements and the apparent data consistency at repeated stations. When creating rose diagrams of joint orientation data, the joints are weighted according to their "strength" value. The following is a list of joint strengths and their corresponding weighted values: strong = 2; moderately strong = 1.5; moderate = 1.0; moderately weak = 0.75; weak = 0.5; and very weak = 0.25.

In areas of abundant outcrop, joints were measured at sites approximately 30-50 metres apart. Where jointing is weaker or the outcrop sparse, measurements were taken wherever conditions permitted. A total of 1585 joints were measured from 792 different sites.

2.3 Description of Systematic Joints

Systematic joints are described in more detail in Appendix A; a brief summary will be presented here.

Two types of systematic joints were noted, extensional and tight. Extensional joints are very rare, and are filled with 1-30 mm of fibrous quartz which grew perpendicular to the joint walls. Tight joints (<1 mm wide) are ubiquitous and abundant, although their intensity and orientation may vary locally. They are generally steeply dipping (70-90°) and occasionally have a thin coating of chlorite on their surface. Strike lengths vary from decimetres to decametres. Joints are for the most part planar and occur in parallel sets (systematic joints). Up to five joint sets can occur in a single outcrop, but commonly only 1-3 sets are present.

Host lithology can have an influence on joint spacing. In general, joint spacing is closest within the rhythmites or siltstones, wider in the conglomerate, and widest within the arenites.

Jointing in the Archean volcanic rocks is generally irregular,

inconsistent and much less intense than in either the Coleman member or the Archean interflow sedimentary rocks. This has also been noted by Lowes (1963) at the Old Casey Mine in nearby Casey Township, Ontario.

Joints often parallel silver veins (now mined out) and often their intensity increases adjacent to the vein.

2.4 Description of Small Faults

Small faults are generally gently dipping. Because of poor exposures and probably small displacements, these faults are usually only recognized where slickensides occur. They have slightly undulating surfaces and the largest exposures are tens of square metres. Slickensides are up to 1 cm thick and are composed of quartz and chlorite. Sense of motion could not be determined on about half the faults, but on the other half the motion was always reverse. For this reason all small faults are assumed to be reverse.

An excellent exposure on the West wall of the open pit in the Conlagas-Trethewey Mine shows a small listric fault offsetting bedding by about one metre. One end of the fault parallels bedding and the other end has a dip that gradually increases to about 30° as it cuts through and displaces the strata.

2.5 Small Fault Orientations

Small fault orientations are plotted and summarized in Figure 2.2. A total of 25 of the 27 small faults have shallow dips ranging from 0 to 40° . The poles to faults approximate a great circle trending 145° ; the average trend of these faults is perpendicular to this at 055° .

Slickensides, plotted on the edge of the stereonet, show that the last and possibly only movement on the small faults has a trend

Figure 2.2 Stereonet displaying attitudes of small faults and slickensides. Dots show positions of 27 poles to small, reverse faults. Plotted on the circumference are the projected azimuths of measured slickensides.

between 110° and 145° , with minor movements at about 010° .

2.6 Joint Orientations

Coleman Member

Orientation data are displayed using rose diagrams (radial histograms) because the majority of joints in the Coleman member have vertical to sub-vertical dips. Joints with dips of 70° or greater are plotted at 5° intervals for twelve geographic or structural areas within the Cobalt Camp.

The joint orientations from these areas are summarized in Figure 2.3. A rose diagram of all the Coleman member joint orientations is presented in Figure 2.4. These data appear to cluster about joint sets with orientations of approximately 030° , 060° , 085° , 110° , 130° , 150° , and 175° . These, plus a few other possible sets, are identified in Figure 2.5 and presented in Tables 2.1 and 2.2.

F, S_1 , and S_2 are the most abundant joint sets. F joints occur in all areas and are moderate to most abundant in 8 of 12 areas (I, II, III, IV, V, VII, VIII, and IX). They are best developed in most areas adjacent to and on the east side of the Cobalt Lake Fault.

F joints range widely in orientation from about 015° to 040° . At one site F joints appear to have a bimodal distribution with peaks at 015 and 035° . A bimodal distribution may be possible in the rest of the F joints but is not obvious because of the nearly continuous spread in orientations. F joints are approximately parallel to the Cobalt Lake Fault and to the folding in both the Coleman member and the Nipissing diabase (Figure 2.6).

S joints (S_1 , S_2 , and S_3) differ slightly in orientation and every area has at least one strong to moderate S joint set. S_2 joints

Figure 2.3 Map displaying joint orientation rose diagrams and their locations.

Figure 2.4 Rose diagram of all joints from the C Coleman member. (n= 1089).

TABLE 2.1

SUMMARY OF JOINT SETS AT COBALT

Joint Set	Trend	Range
F	030°	(015-040°)
K	060°	(055-070°)
X ₂	085°	(080-090°)
S ₂	110°	(105-115°)
S ₃	130°	(125-130°)
S ₁	150°	(140-155°)
X ₁	175°	(170-005°)

Figure 2.5 Joint orientation rose diagrams for the twelve
areas within the Coleman member.

I n=47

II n=67

III n=176

IV n=112

V n=216

VI n=76

VII $n=119$ VIII $n=117$ IX $n=58$ X $n=28$ XI $n=107$ XII $n=67$

TABLE 2.2**SUMMARY OF JOINT SETS FROM THE COLEMAN MEMBER**

Joint Set	Trend	Relative Strength
Area I		
F	040°	Strong
S ₂ (X ₂ ?)	100°	Moderate
S ₃ (S ₂ ?)	120°	Moderate
S ₁ (S ₃ ?)	140°	Moderate
Area II		
F	030°	Strong
S ₂	110°	Moderate
S ₃ (S ₁ ?)	130°	Moderate
Area III		
X ₁	000°	Very Weak
F	015°	Strong
S ₂ (X ₂ ?)	100°	Very Weak
S ₃ (S ₂ ?)	115°	Very Weak
Area IV		
F	015°	Strong
F	035°	Strong
K	065°	Very Weak
X ₂	085°	Very Weak
S ₂	110°	Moderate
S ₁	145°	Moderate
X ₁	170°	Very Weak
Area V		
F	025°	Strong
F (?)	040°	Weak
K	060°	Strong
X ₂	085°	Strong
S ₂	105°	Weak
S ₁ (?)	155°	Weak
X ₁	175°	Strong
Area VI		
F	040°	Very Weak
K	065°	Weak
S ₂ (X ₂ ?)	100°	Moderate
S ₃ (S ₂ ?)	120°	Strong
S ₁ (S ₃ ?)	140°	Moderate
X ₁	175°	Weak

Area VII

F	030°	Weak
K	070°	Weak
S ₂	110°	Strong
S ₃	125°	Moderate
S ₁	150°	Moderate

Area VIII

X ₁	000°	Weak
F	020°	Moderate
K	055°	Weak
(?)	075°	Very Weak
X ₂	090°	Moderate
S ₂	105°	Strong

Area IX

F	025°	Moderate
X ₂	080°	Weak
S ₂	115°	Strong
S ₃ (?)	130°	Strong
S ₁	140°	Strong

Area X

F	025°	Weak
K	070°	Weak
S ₂	105°	Strong
S ₃	125°	Moderate
S ₁	140°	Very Weak

Area XI

F	015°	Weak
K	055°	Weak
X ₂	085°	Moderate
S ₂	110°	Moderate
S ₁	145°	Strong

Area XII

X ₁	005°	Weak
F	040°	Weak
K	060°	Weak
X ₂	090°	Weak
S ₁	145°	Strong

Figure 2.6 Map showing the relationship of major faults and fold axes to the major joint sets.

are most abundant, being moderately developed in all but one area. S_1 joints are the next most abundant and occur in 8 areas; they are strongest on the west side of the Cobalt Lake Fault. S_3 joints lie between S_1 and S_2 joints, and occur in about half the areas. S joint sets occur singly, in pairs, or all three may occur together.

K joints are usually minor and occur in about half the sample areas. X_1 and X_2 joints are minor except in area V.

Archean Rocks

Joint orientations from the Archean rocks are presented and summarized in Figure 2.7 and Table 2.3. Peaks are identified and grouped similarly to the joints in the Coleman member.

F, K, S_1 , S_2 , S_3 , and X_2 joints have been identified (see Table 2.3 and Figure 2.7), but the peaks are not as well defined as those in the Coleman member. As shown in Figure 2.7 joints from area XIII form a rather random pattern, and identification of peaks matching those of the Coleman member may be wishful interpretation. Area XIV has a strong peak trending $100-125^\circ$ which is sub-parallel to a fault cutting across the area.

Joint orientations on the whole are somewhat more scattered and irregular than joint orientations in the Coleman member. This is not surprising since systematic joints in the Archean rocks are often scattered and harder to identify than those in the Huronian rocks.

2.7 Similarity Between Joint and Vein Orientations

Silver-vein orientations were measured directly from the geology map of the Cobalt area by Thompson (1964a). The vein orientation data were divided up and plotted using approximately the same areas as those

Figure 2.7 Joint orientation rose diagrams for the two areas within the Archean rocks.

TABLE 2.3

SUMMARY OF JOINT SETS FROM THE ARCHEAN ROCKS

Joint Set	Trend	Relative Strength
Area XIII		
F	025°	Moderate
K	055°	Moderate
X ₂	085°	Moderate
S ₃	125°	Moderate
S ₁	135-150°	Moderate
X ₁	175-010°	Moderate
Area XIV		
F	010-040°	Moderate
K	050-065°	Weak
S ₂	100-125°	Strong
S ₁ (?)	165°	Weak

used for the joint data, and are labelled similarly. Rose diagrams were generated by totalling the horizontal length of veins from each area and dividing their orientations into 5° intervals. Because of the inherent $5\text{--}15^\circ$ uncertainty in measuring vein orientations from the map, these rose diagrams should be considered an approximation only.

Vein orientations are, in general, similar to joint orientations as shown in Figure 2.8. Some areas, such as IV, V, VII, X, XI, and XIV, have joints in the same orientations as veins, although the relative abundance of veins and joints in each orientation may not match (i.e., a major peak orientation for veins may be a minor peak for joints and vice versa). Most vein peak directions conform to those of joint peaks from each area.

In a few areas, such as VI and VIII, vein peaks with orientations of 050° and 070° are dominant; corresponding joints sets are present, but weakly developed. On the scale of the study area trends of 050° and 070° are much more abundant in the veins than in the joints (Figure 2.8).

According to Thompson (1957a) the majority of the veins in the most productive part of the camp (areas X, XI, and XII) trend NW, which is the same as the trend of the dominant joint sets from those areas (Figures 2.3 and 2.5). This suggests that the majority of productive veins at this site are parallel to the dominant joint sets and are possibly joint hosted.

2.8 Veins vs. Joints

Silver veins from the study area occur predominantly within fractures in the Coleman member and occasionally in faults, such as Fault 64, Cobalt Lake Fault, and the Galena Fault (Jambor, 1971b; Moore,

Figure 2.8 Comparison of joint orientations with vein orientations. (Note; "n" is the number of joints that were measured to create that rose diagram, and "h" is the length, in metres, of silver veins used to create that rose diagram.) (This figure is 4 pages long.)

JOINTS

IV n=112

VEINS

IV h=1512 m

V n=216

V h=1884 m

VI n=78

VI h=1740 m

JOINTS

VII n=119

VEINS

VII h=834 m

VIII n=117

VIII h=1878 m

X n=28

X h=1206 m

2

MicroD

JOINTS

XI $n=107$

VEINS

XI $h=4518$ m XII $n=67$ XII $h=858$ m XIV $n=179$ XIV $h=2322$ m

1942; Petruk, 1971c).

Overall, the similarity between vein and systematic joint orientations suggests that the veins from this study are hosted predominantly in systematic joints. Veins that do not appear to follow systematic joints are probably following a random fracture, and do not necessarily weaken this relationship. Fluids responsible for silver deposition probably followed any available path and when fractures, whether random or systematic, were open, they became sites for mineralization. Differences in frequency between veins and joints of the same orientation probably reflect differences in the local and overall stress regimes between when the joints were formed and the time of mineralization.

Another line of evidence supports the hypothesis that most veins follow systematic joints: veins and joints show some similar physical characteristics in the field. Both joint and vein intensities vary with respect to host lithology. Within the Coleman member some major veins crosscut several rock units, whereas smaller branching veins are restricted to units that host the greatest degree of jointing (usually the rhythmites and siltstones). This relationship can be readily observed at the MacDonald Vein, Vein 64, and the open pit at the Coniagas-Trethewey Mine, and indicates that these veins are joint hosted. Vein-parallel joints, found in most surface vein-cuts, also strengthen this conclusion. Differences in joint patterns and intensities between the Coleman member and the Archean rocks are also duplicated in the vein patterns. Joints are far more abundant in the Coleman member than in the Archean volcanic rocks, probably due to competency differences, the Coleman member being more brittle. Veins in the Coleman member are also more abundant than those in the Archean

rocks, producing about 80% of the silver mined at Cobalt (Moore, 1942). Although many authors have noted that most ore veins occurring in the Coleman member pinch out at or just below the Archean-Proterozoic unconformity, some continue a short distance into the basement (Knight, 1924; Jambor, 1971e; Thompson, 1957a; Petruk et al., 1972). Where ore veins persist into the Archean basement, the vein-cuts are generally irregular and consist of many segments at different trends. The similarity to the irregular joints in the Archean rocks indicates that the veins followed pre-existing joints. This is best exposed on Nipissing Hill where the ore veins in Archean rocks are likely the roots of larger ore veins that extended into the overlying, now eroded, Coleman member.

In summary, the majority of ore veins are interpreted to be joint hosted, and most productive veins occur in the Coleman member, primarily because it was well jointed and provided a ready structural site for mineralization. It follows that if the veins are joint hosted, then the joints must be equivalent in age to, or older than the veins, and the age of mineralization is a minimum age for the formation of the systematic joints.

2.9 Similarity Between Joint Orientations and Other Structures

The Cobalt Lake Fault has an average trend of 043°, while other thrust or reverse faults (Contact, Valley, and Trethewey Faults) all have trends of about 025°. As shown in Figure 2.6, F joints are roughly parallel to these faults, while S₂ and S₃ joints are roughly perpendicular to these thrust faults.

Figure 2.2 shows that small reverse faults trend roughly 055°, K joints are nearly parallel to and S₁ joints are nearly perpendicular to

the trends of these small faults. Last movements on these faults (110° to 147°), as indicated by slickensides, coincide with the S_1 , S_2 and S_3 joints.

The two folds outlined during detailed stratigraphic work by Mustard (1985) trend 015° (syncline) and 030° (anticline) (Figure 2.6). These trends lie within the range of F joints. In areas where F joints are moderately to well developed these joints trend very close to parallel to that of the nearest fold axis. Areas I, II, V, VII, and IX are closest to the anticlinal axis (030°) and host F joints that trend 025 to 040° . Areas VII and XI are closest to the synclinal axis (015°) and have F joints that trend 015 to 020° . It is interesting to note that area IX, which lies between the two fold axes, has a bimodal array of F joints with peaks at 015 and 035° almost coincident with the two fold axes that flank that area.

2.10 Timing of Joints and Other Structures

Relative ages of systematic joints and other structures at Cobalt are summarized in Table 2.4. Based on section 2.7, joints are interpreted to have formed prior to vein mineralization. The maximum age of mineralization is that of crystallization of the Nipissing diabase, since the ore veins crosscut the diabase (Jambor, 1971b). The diabase has been dated at 2217 M.a. by Andrews et al. (1986). A quartz diabase dyke that crosscuts the veins, dated at 1465 M.a. (Jambor, 1971b) provides a minimum age of mineralization. Lead isotope studies indicate a model age of about 2200 M.a. for the silver veins (Thorpe et al., 1986; Thorpe, 1974). This is approximately equivalent in age to the diabase and indicates that mineralization occurred shortly after crystallization of the diabase. Based on paleomagnetic and U-Pb

TABLE 2.4

RELATIVE TIMING OF STRUCTURAL EVENTS AT COBALT

- (a) = Fairbairn et al., 1969.
 (b) = Andrews et al., 1986.
 (c) = Thorpe, 1974, and Thorpe et al., 1986.
 (d) = Jambor, 1971d.
- ← = most likely position
 ←- = possible position
 ←... = possible but less likely position

analyses, Andrews et al. (1986) concluded that silver mineralization occurred between 0.02 and 8.1 M.a. after crystallization of the Nipissing diabase. The evidence points to a minimum age for the joints roughly equivalent to that of post-dabase silver mineralization at about 2200 M.a.

The maximum age of jointing in the Coleman member is, obviously, that of consolidation of the sediments themselves, which has been dated by Fairbairn et al. (1969) at 2288 M.a. Symons (1967) has also suggested that sedimentation took place 10 to 100 M.a. prior to diabase emplacement.

Joint patterns within the Nipissing diabase were not examined in this study but were examined by Halls and Stumpf (1969). They found joints in the diabase that were coincident with S_1 , S_2 , F , X_2 and possibly X_1 joints. This suggests that these joint sets formed at the same time as the joints in the Coleman member, implying that the joints can be no older than the diabase. Contrary to this, the similarity between joint patterns in the two rock units could be due to the upward propagation of early formed Coleman member joints into the diabase by cyclic stresses related to semi-diurnal earth tides that resulted from gravitational effects of the moon (Hodgson, 1961; Price, 1966; Kendall and Briggs, 1933), and does not necessarily imply that jointing in both rock types occurred concurrently.

In summary, joints in the Coleman member are interpreted to have formed prior to silver mineralization, and may possibly be younger than the Nipissing diabase.

Major motion on the thrust faults is bracketed in time by the age of silver veins, which crosscut and are in part hosted within these faults (Knight, 1924), and by the depositional age of the Coleman

U

member, which these faults offset. The amount of offset on the Nipissing diabase by the Cobalt Lake Fault is unknown because its lower contact has been eroded everywhere along the fault except for one small area west of the fault at the north end of Cobalt Lake. Geologic cross-sections by Knight (1924) indicate that the Nipissing diabase is offset by the same amount as the Coleman member, indicating that the major movement on the thrust faults was post-diabase. These cross-sections are based on an extrapolated, assumed, gently undulating Nipissing diabase shape. If the shape were any different, the offset on the diabase would be less than on the Coleman member, although the major movement would still likely be post-diabase emplacement.

Thrust faults have also had some post-mineralization movement as indicated by minor brecciated and slickensided ore in the Cobalt Lake Fault (Knight, 1924). Although the amount of displacement is not known, it is suspected to be relatively small since Vein 490 in the Nipissing Mine crosscuts the Valley Fault with no offset and ore in the Cobalt Lake Fault is only rarely disrupted (Knight, 1924).

Small faults are younger than the Coleman member, which they crosscut. The similarity in trends of the small fault slickensides and the S joints indicates that the small faults may have developed at the same time as the joints.

The Coleman member has experienced minor folding of up to 10-20° on the limbs (Mustard, pers. comm. 1986). Some of this folding may be apparent and due to sediment compaction, but clearly some of the folding is tectonic as indicated by the continuity of the beds on the fold limbs. Slight folding in the diabase about NE-SW axes has been interpreted from paleomagnetic studies (Symons, 1970). Since the folding

event includes the diabase, its maximum age is that of the sill itself. It is not possible to detect folding in the silver veins, because single veins change dips from place to place and old records are not detailed enough to outline shifts of 10-20°. Joint dips may vary across a single outcrop, and often when field measurements were taken dips were only recorded when they were not steep; the data base is insufficient to determine if the joints have been folded by such a small amount. There is no clear cut minimum age for this folding. It could have occurred coincident in time with the faulting and jointing previously described, or possibly coincident with other younger events, such as the Penokean Orogeny (1850-1900 M.a., Van Schmus, 1976), and the Grenville Front (about 1200 M.a., Wynne-Edwards, 1972) which is about parallel to the fold axes at Cobalt.

The similarities between joints and fold orientations described in section 2.9 indicate that the two probably share a similar origin, and it seems likely that the folds are related in age and origin to the joints and faults and are also about 2200 M.a. old. Van Schmus (1976) reported a tectonic event dated at 2100 $\pm$ 50 M.a. from the Huronian Supergroup in Ontario which appears to be coincident in time with the formation of the joints, faults and folding at Cobalt.

2.11 Mechanisms of Joint Formation

Table 2.4 shows that if joints formed after diabase emplacement, then jointing and fault development could have occurred over the same time interval; between diabase emplacement, and silver mineralization. In addition, the orientations of the thrust faults and joints are related, in that the prominent joint sets, F and S₂ joints, are nearly parallel and perpendicular to the thrust faults, which suggests that

joints did occur after diabase emplacement and are roughly coeval with thrust faulting. It seems likely, therefore, that the stress field responsible for the thrust faults could also have generated the joints. To develop thrust faults in their present orientation would have required a nearly horizontal major compression (σ_1) trending about NW-SE (previously suggested by Knight, 1924) and ideally the direction of the least compressive stress (σ_3) would be vertical. Unfortunately, in an ideal situation a vertical least compressive stress (σ_3) would result in at least one set of horizontal, not vertical joints.

Several authors have found that joints form nearly perpendicular to bedding regardless of stress direction or dip of bedding (Muecke and Charlsworth, 1966; Hodgson, 1961; Price, 1959, 1966). This could explain the vertical jointing in the flat-lying Coleman member, but does not explain the mostly vertical jointing in the underlying Archean volcanic rocks.

Another possible explanation of thrust faults and vertical joints is that these features developed at slightly different times in a changing stress regime, where σ_3 was either vertical or horizontal, at some time later $\sigma_2 = \sigma_3$ (uniaxial compression), and eventually σ_2 and σ_3 switched positions. σ_3 would be vertical during fault development, and horizontal during joint development. Since inspection of the thrust faults is not possible because of limited exposure, relative timing of these two events cannot be determined in the field. Prior to joint and fault development and when the least compressive stress (σ_3) was vertical, the near horizontal Nipissing diabase may have been emplaced.

Regardless of the orientation of the least principal stress (σ_3), observations made at Cobalt are similar to those from other

Mountain foothills in Alberta were parallel and perpendicular to the folds and thrust faults of the Rocky Mountains. Das Gupta and Currie (1983) found a similar relationship from within the Rocky Mountain fold belt. Nichelsen and Hough (1967) noted that joints in the very slightly folded area west of and adjacent to the Appalachian Mountains in Pennsylvania were again parallel and perpendicular to the trend of the fold belt. Ver Steeg (1944) reports that one set of joints in Ohio is perpendicular to and another set parallel to minor folds. This indicates that the structural events leading to the development of vertical joints which are perpendicular to and parallel to folds and thrust faults are not unique and may be expected in compressional tectonics.

Orthogonal sets of joints have been interpreted by some authors to be due to one structural event, and have been considered the basic unit of jointing (Babcock, 1973; Price, 1959, 1966; Nickelsen and Hough, 1967; Das Gupta and Currie, 1983; Lajtai, 1977). Das Gupta and Currie (1983) and Lajtai (1977) suggested that orthogonal joint sets are the result of one load-parallel tensile joint set due to compression, and a load-perpendicular joint set developed during relaxation, due to the release of residual stress within the rock. These residual stresses can be developed by processes such as diagenesis and dolomitization that occur under conditions of compression. Differential elastic and plastic responses to stress can also result in residual stress within rocks.

At Cobalt, several joint sets form nearly perpendicular pairs that may be genetically linked. The range in orientation of the S_2 and S_3 joints is nearly perpendicular to the range of the F joints. The S_2 and S_3 joints sometimes have overlapping trends and were difficult to

distinguish and define. This is similar to the range and possible bimodal split in orientation of the F joints. This and the overall predominance of these joint sets suggests that the S_2 and S_3 joints and the F joints may be related to a compressional event that probably changed orientation slightly during joint development. The X_1 and X_2 joints are perpendicular and both are poorly developed, which may imply a genetic similarity. The S_1 and K joints are also perpendicular to each other. Their trends also coincide with that of the small faults and the NW compression postulated as necessary for the development of the major thrust faults.

The overlapping range in orientation of the S joints with that of many of the small fault slickensides possibly implies that the small faults developed at the same time as the joints, and that the major NW compression may share a similar range in orientation from approximately $110-150^\circ$. Joints that developed perpendicular to this compression, probably during the release of residual stress, are represented by the F and K joints.

The S joints could also be explained as an example of a load-parallel joint set (S_3) flanked by shear joints (S_1 and S_2) as described by Price (1966). This would imply that the principal stress direction was stationary during joint development. However, the range in orientation of the small fault slickensides suggests that the principal stress direction shifted as small faults and possibly the major joints developed. The presence of joints perpendicular to the S_1 and S_2 sets, the K and F joints, suggests that these joints may be two orthogonal sets and that the S_1 and S_2 sets are not shear joints. Lajtai (1977), Das Gupta and Currie (1983), and Nichelsen and Hough (1967) suggested that shear joints do not exist. These arguments give credence to the

hypothesis of a changing principal stress orientation, rather than one joint set flanked by shear joints due to a single compression.

The development of the orthogonal X_1 and X_2 joints remains difficult to explain, unless the principal stress direction strayed as far away as the X_2 trend (085°) during joint development.

Joint formation may have been aided by a high pore-fluid pressure (Secor, 1965) such as may have existed below the diabase.

2.12 Structural Controls on Silver Mineralization

Obviously not all joints are mineralized, and vein orientation frequency does not always mimic joint trend frequency (Figure 2.8). Silver veins are fractures or joints that have preferentially opened to allow the movement of fluids and the deposition of vein minerals. There must be factors other than simply the presence of joints controlling which fractures open and at what orientation to become sites for mineralization. Minor movements between large faulted blocks may have created local stresses that dilated joints, or perhaps the presence of Archean interflow sedimentary rocks and Archean shears or faults in the underlying basement influenced which joints dilated and at what orientation. It has been mentioned by numerous authors (Knight, 1924; Jambor, 1971e; Thompson, 1957a; Petruk, 1968; 1971c) that some veins occur in the Coleman member directly above thin bands of Archean interflow sedimentary rocks, while some veins within the Coleman member of the Kerr Lake Arch occur above Archean shears and faults (Halls and Stumpf, 1969). This may be due to differential responses in the Archean rocks to the applied stress. It would seem reasonable to expect the massive lavas to act as large relatively competent blocks and much of the strain to be released by renewed movements along pre-

existing planes of weakness or taken up in the fractures of the interflow rocks by virtually undetectable micro-displacements. This would result in fracturing or widening of pre-existing joints in the overlying, laterally homogeneous Coleman member, which would yield sites favourable for mineralization, as suggested by Thompson (1957a).

Pre-existing fractures or joints may be "opened up" by high pore-fluid pressures (Secor, 1965). Prior to mineralization, intraformational fluids, presumably at hydrostatic pressure, may have been trapped between the relatively impervious Nipissing diabase and the Archean basement. Assuming that uplift and erosion took place, then lithostatic pressure would decrease, and the pressure of these "trapped" fluids would increase relative to the prevailing lithostatic pressure. The resulting pore-fluid overpressure may have been enough to cause pre-existing joints and fractures to "open up" as suggested by Secor (1965) or may have initiated joints beneath the diabase in the first place. Fluid inclusion studies by Strong (1985) suggest that mineralizing fluids were boiling during silver mineralization. If these overpressured "trapped" waters were released suddenly, the fluids may have boiled or exsolved a gas phase and rapidly deposited the vein minerals as suggested by Strong (1985) and Watkinson (1986).

A structural site for mineralization appears to be an important control of where veins will form. Other native silver Co, Ni arsenide type deposits from around the world are open space filling and are structurally controlled. Sites as simple as dilated faults are common, such as those at Sabinal, Chihuahua, Mexico (Krieger, 1935), the Black Hawk District, New Mexico (Gillerman and Whitebread, 1956; Gillerman, 1968), Silver Islet, Ontario (Oja, 1966; Franklin, 1970;

Tanton, 1931; Bruce, 1942), and possibly Jachymov, Czechoslovakia (Bejsgschlay et al., 1916; Mrna, 1963; Mrna et al., 1979). The deposits at Silver Islet are extremely rich (up to 75% Ag) and filled in the spaces between a fault breccia (Wilson, 1986). Mineralization occurring in faults and associated extension fractures is found at Great Bear Lake, N.W.T. (Badham, 1975, 1976; Badham et al., 1972; Cambell, 1957; Kidd, 1942; Robinson and Morton, 1972; Robinson and Ohmoto, 1973), and possibly at the Beaver-Temiskaming Mine at Cobalt, Ontario (Goodz, 1985). At Kongsberg, Norway, silver deposits, found in sulphide-rich, graphite-bearing schists called "fahlbands", occur in extension gashes spatially and structurally related to a series of en echelon faults (Neumann, 1944).

Silver ores from the satellite mining camps around Cobalt also occur in faults and joints. In Casey Township the veins are found primarily within the Coleman member and are located in systematic fractures, presumably joints, and faults very similar to that at Cobalt (Lowes, 1963; Thompson, 1965). In the Silver Centre area veins follow older faults mostly within Archean rocks (Petruk, 1971c). In the Miller Lake-Gowganda area, productive veins occurred almost exclusively in the Nipissing diabase and appear to follow cylindrical joints, which are most abundant in the area of the mines (Petruk, 1971c; Moore, 1957; Eakins, 1961; McIlwaine, 1979; Scott, 1964, 1972).

CHAPTER III

SULPHIDE MINERALS IN THE COLEMAN MEMBER, GOWGANDA FORMATION

3.1 Introduction

Sulphide minerals of the Cobalt area occur in three main environments; 1) within Archean interflow sedimentary rocks; 2) within the Coleman member of the Gowganda Formation; and 3) within native silver Co-Ni arsenide and sulpharsenide veins.

Sulphide minerals occur heterogeneously throughout the Coleman member within the Cobalt camp. Concentrations in hand specimens range from 0% to more than 4% and a wide variety of sulphide minerals were identified. Coleman member sulphide minerals have previously been described by Kim (1979), Hartlein (1972), Gebert (1985), Halls and Stumpfl (1969), Lovell (1978), Boyle et al. (1969), Owsicki and Lovell (1984), Donaldson et al. (1984), and others.

The purpose of this chapter is to provide a descriptive data base for the interpretation of sulphur-isotope ratios from these sulphide minerals and to attempt to resolve the origin of these sulphides.

3.2 Sample Locations and Site Descriptions

Samples were collected from the host rocks of Little Silver Vein, MacDonald Vein, ML Vein, Nipissing Hill, Silverfields Mine, Coniagas-Trethewey Mine, Kerr Lake Arch, and Vein 3 (Figure 3.1). These sites were chosen mainly for the availability of samples at the surface, and Coleman member sulphides from some sites were reported in previous

Figure 3.1 Location of sample sites.

studies. Detailed sample location maps and site descriptions are found in Appendix B.

3.3 Sulphide Descriptions and Mineralogy

Metallic minerals were identified primarily by standard reflected-light microscopy. Where minerals were very fine grained and intergrown, the electron microprobe was used to aid in the identification process. Owing to the small grain size of some of these minerals, X-ray diffraction could only be used for a few samples.

Qualitative microprobe analysis revealed the presence of a tiny Co-Ni-Fe-As-sulphide mineral, that usually occurred as irregular (Plate 1.A) to euhedral (Plate 1.B) inclusions within chalcopyrite, sphalerite, pyrrhotite, or galena. The iron content is usually lower than the Co and Ni contents; the Co:Ni ratios vary significantly. It seems likely that this mineral is either cobaltite (CoAsS), gersdorffite (NiAsS), or a partial solid solution. Petruk (1971a) and Watkinson and Goodz (1986) showed that cobaltite and gersdorffite from Cobalt can contain significant amounts of iron and that each mineral can accommodate Co and Ni to some degree. All samples of this mineral have tentatively been called gersdorffite, both for simplicity and because several near-Ni end members were identified.

In this study, sphalerite was found to be abundant at four sites and uncommon to absent at the other sites. Several minerals strongly resembling sphalerite in reflected light were identified using microprobe data. TiO_2 is abundant in virtually every sample and may be confused with sphalerite. Several samples of this mineral were identified as rutile using X-ray diffraction. Occasionally chalcopyrite is rimmed with a red oxyhydroxide of iron and some copper. This also

PLATE 1

- A) Reflected-light photomicrograph showing irregular gersdorffite (ger) occurring with sphalerite (sph) in conglomerate at Nipissing Hill. Scale bar is 0.1 mm long. (NIP).
- B) Reflected-light photomicrograph showing euhedral and subhedral gersdorffite (ger) occurring with chalcopyrite (cp) and pyrrhotite (po) within siltstone at Little Silver Vein. Scale bar is 0.2 mm long. LSV-2
- C) Reflected-light photomicrograph of euhedral pyrite within siltstone at Little Silver Vein. Scale bar is 0.2 mm long. (LSV-4).
- D) Reflected-light photomicrograph of pyrrhotite (po) and gersdorffite (ger) that have the form of euhedral pyrite, from siltstone at Little Silver Vein. Scale bar is 0.4 mm long. (LSV-B).
- E) Reflected-light photomicrograph of euhedral pyrite (py) with a core of chalcopyrite (cp), from siltstone at Little Silver Vein. Scale bar is 0.2 mm long. (LSV-A).
- F) Reflected-light photomicrograph of pyrrhotite that has the form of euhedral pyrite, from siltstone at Little Silver Vein. Scale bar is 0.8 mm long. (LSV-A).
- G) Transmitted-light photomicrograph showing two euhedral grains of pyrite from siltstone at Little Silver Vein. One grain is solid and the other is ring-shaped in cross-section. Scale bar is 0.4 mm long. LSV-3
- H) Reflected-light photomicrograph of a pyrite (py) grain from siltstone at Little Silver Vein. The pyrite has a core of intergrown allanite (Al) (light grey) and detritus (darker grey). Scale bar is 0.2 mm long. (LSV-18).

strongly resembles sphalerite in both reflected and transmitted light.

Sulphide Minerals from Little Silver Vein

Little Silver Vein (LSV) is one of the major sample sites in this study. Sulphide descriptions are broken down according to rock type.

Sulphides appear to display a mineralogic and elemental zoning about LSV as shown in Figure 3.2. Unfortunately sample density is insufficient to clearly define zones. The presence of the Ag-bearing minerals, acanthite and tetrahedrite, is restricted to three samples from one unit within 3m of the vein-cut. Galena occurs with the silver-bearing minerals and in a few samples close to the vein. Pyrrhotite is found at most of these sites and also occurs in samples just beyond the galena zone. Gersdorffite and/or arsenopyrite occurs in samples up to 4.5m from the vein. Samples with either pyrite ($\pm$ chalcopyrite), or without sulphide minerals occur farther from the vein. The different mineral zones are not at consistent distances from the vein (Figure 3.2) and may be influenced by stratigraphic horizons and rock types.

Laminated Siltstone

Sulphide minerals are often associated with rutile, chlorite spots and a rare earth silicate (identified on the basis of qualitative microprobe data as allanite). Grain size ranges from <0.1mm to 2.5mm, which is almost invariably many times larger than the grain size of the siltstone. Concentrations range from 0.2% to 2.0% (estimated from polished thin sections). The general characteristics of these sulphides (mineralogy, morphology, chlorite association, and host-rock grain-size association) are summarized in Table 3.1.

Pyrite morphology ranges from anhedral to euhedral (Plates 1.C

Figure 3.2 Sulphide mineralogy and zoning at Little
Silver Vein.

SULPHIDE MINERALOGY AND ZONING AT LITTLE SILVER VEIN

(Profile View)

and 1.E). Euhedral pyrite grains show prominent development of octahedral faces $\{111\}$, and smaller or equal-sized pyritohedron faces $\{102\}$. At some sites, pyrite with anhedral to euhedral outlines occur predominantly in the form of spherical shells that appear ring-like in section (Plate 1.G). The cores are commonly composed of chlorite-free silt-sized detritus, or chalcopyrite (Plate 1.E), or intergrown quartz (presumably detrital) and allanite (Plate 1.H). Most pyrite is to some degree poikiloblastic and contains inclusions of detrital material.

Pyrrhotite within 5 metres of the vein-cut appears to occur primarily as a pseudomorph after euhedral pyrite (Plates 1.C, 1.D, 1.E, and 1.F). Chalcopyrite and worm-like growths or tiny euhedra of gersdorffite are usually found with pyrrhotite in these pseudomorphed grains (Plate 1.B).

Within chlorite spots, pyrite is usually more abundant, sometimes has a larger grain-size and is subhedral. However, the pyrite morphology is not necessarily related to the chlorite spotting since most spots occur in coarser laminae where the pyrite tends to be less euhedral regardless of proximity to chlorite spots. Pyrite grains over 2 mm in diameter tend to occur where chlorite spots have grown outward into a finer grained mud-rich layer (Plate 2.A). These features imply that the chlorite spots and pyrite growth may be genetically linked.

Arenite

Sulphide minerals are very heterogeneously distributed and compose 0-2% of the arenites at LSV. The sulphide minerals identified are, in order of decreasing relative abundance, chalcopyrite, pyrrhotite, pyrite, arsenopyrite, galena, gersdorffite, tetrahedrite, covellite, sphalerite, acanthite, and boulangierite (Table 3.2).

PLATE 2

- A) Transmitted-light photomicrograph of a chlorite spot within siltstone at Little Silver Vein. Where the spot occurs in the finer grained layers is an opaque mass of intergrown chalcopryrite and pyrrhotite. Scale bar is 3.2 mm long. (LSV-2).
- B) Reflected-light photomicrograph of euhedral arsenopyrite within a volcanic clast in conglomerate at Little Silver Vein. Scale bar is 0.5 mm long. (LSV-36).
- C) Reflected-light photomicrograph showing pyrrhotite (po), tetrahedrite (tet), and chalcopryrite (cp) that occur between detrital grains in arenite at the Coniagas-Trethewey mine. Scale bar is 0.8 mm long. (CTM-D).
- D) Transmitted-light photomicrograph of opaque sulphides (chalcopryrite and pyrrhotite) occurring between detritus within arenite at Little Silver Vein. Scale bar is 0.8 mm long. (LSV-49).
- E) Transmitted-light photomicrograph showing the occurrence of opaque sulphides (chalcopryrite and pyrrhotite) within a clast at Little Silver Vein. Scale bar is 0.8 mm long. (LSV-49).
- F) Reflected-light photomicrograph showing chalcopryrite occurring around and within detritus at Coniagas-Trethewey mine. Scale bar is 0.8 mm long. (CTM-E).
- G) Reflected-light photomicrograph of native silver, chalcopryrite and tetrahedrite surrounding a detrital clast at the Coniagas-Trethewey mine. Scale bar is 0.8 mm long. (CTM-A).
- H) Transmitted-light photomicrograph of chalcopryrite surrounding a detrital grain at Little Silver Vein. Scale bar is 3.2 mm long. (LSV-35).

TABLE 3.2

MINERALOGY AND RELATIVE SULPHIDE ABUNDANCE FROM LITTLE SILVER VEIN

Sample #	Distance from Vein	Rock Type	Percent Sulphide	Sulphide Mineralogy (determined from polished thin sections)	(Determined from Heavy Mineral Separates)
LSV-01	4.0 m	CH cong		CP(65%), PO(30%), GAL(5%), PY(1%), GERS(r)	CP(95%), GAL(5%)
LSV-11	4.8 m	CH cong		PT(100%)	PT(100%)
LSV-12	4.5 m	CH cong		CP(79%), PO(20%), PY(1%), SPH(r)	PO(100%) / CP(98%), GAL or TET(2%)
LSV-13	3.7 m	CH aren		CP(96%), PO(2%), ARS(4%), PY(r)	CP(100%)
LSV-14	1.2 m	CH cong		CP(40%), GAL(40%), PO(20%), SPH(r), GERS(r)	PO(100%) / GAL(100%) / CP(100%)
LSV-16	1.8 m	CH cong	0.13%	ARS(70%), CP(20%), PO(10%)	ARS(85%), CP(15%)
LSV-17	2.7 m	CH cong	0.01%	----	----
LSV-18	4.1 m	CH aren		CP(70%), ARS(20%), PO(5%), GERS(5%)	CP(96%), ARS(4%)
LSV-19	4.6 m	CH aren		CP(96%), PO(2%), GERS(r)	CP(100%)
LSV-40	4.4 m	CH aren	0.01%	----	----
LSV-41	5.0 m	CH aren	0.02%	----	----
LSV-42	5.3 m	CH silt		ARS(98%), CP(2%)	ARS(95%), CP(5%)
LSV-43	4.5 m	Ch silt		ARS(90%), CP(5%), PO(5%)	ARS(99%), CP(1%)
LSV-44	3.0 m	CH silt	0.16%	CP(60%), ARS(40%)	ARS(99-100%), CP(0-1%)
LSV-45	7.2 m	CH silt	0.02%	----	----
LSV-46	10.5 m	CH silt	0.02%	----	----
LSV-47	3.4 m	CH aren	0.19%	TET(45%), GAL(30%), CP(20%), GERS(5%)	CP(40%), ARS(35%), TET(20%), GAL(5%), BOUL(2%)
LSV-48	0.2 m	CH aren		CP(65%), PO(10%), GAL(10%), TET(10%), GERS(3%), PY(2%)	PO(100%) / CP(85%), TET(10%), GAL(5%)
LSV-49	2.6 m	CH aren		CP(85%), PO(10%), GAL(5%), SPH(r), ACAM(r)	PO(100%) / CP(100%)
LSV-50	3.0 m	CH aren	0.15%	CP(70%), ARS(30%)	CP(90-95%), ARS(5-10%)
LSV-51	5.7 m	CH aren		CP(90%), PO(10%)	CP(99%), ARS(1%)
LSV-52	8.4 m	CH aren	0.01%	----	----
LSV-53	10.8 m	CH aren	0.08%	CP(70%), PY(30%)	PT(60%), CP(40%)
LSV-54	13.6 m	CH aren	0.01%	----	----
LSV-55	3.0 m	CH cong		PT(100%)	----
LSV-56	6.8 m	CH cong	0.42%	PT(95%), CP(5%)	PT(95%), CP(5%)
LSV-57	16.8 m	CH cong	0.26%	CP(60%), PT(40%)	CP(70%), PT(30%)
LSV-58	22.9 m	CH aren	0.001%	CP(100%)	----
LSV-59	0.9 m	CH aren		CP(94%), PT(5%), GERS(1%)	CP(40%), PT(40%), ARS(20%)
LSV-60	4.5 m	CH aren		CP(90%), COV(10%), GERS(r)	CP(100%), some COV coatings
LSV-61	4.8 m	CH aren	0.01%	----	----
LSV-62	6.1 m	CH aren	0.01%	----	----
LSV-63	5.1 m	CH aren		CP(100%)	CP(100%)
LSV-64	5.3 m	CH aren		CP(96%), GERS(2%)	CP(100%)
LSV-66	4.3 m	CH aren		PT(95%), CP(5%)	PT(98%), CP(2%)
LSV-67	4.3 m	CH aren	0.25%	PT(30%), CP(50%)	PT(95%), CP(5%)
LSV-7	?	CH cong	----	CP(74%), PO(20%), ARS(1%), SPH(r), AG(r), ACAM(r)	PO(100%) / CP(100%)
LSV-2	?	CH cong	----	PO(64%), GAL(15%), SPH(15%), CP(5%), TET(1%), GERS(r)	PO(100%) / CP(100%) / SPH(100%) / GAL(100%)

PT = pyrite
 PO = pyrrothite
 GAL = galena
 SPH = sphalerite
 CP = chalcopyrite
 BOR = bornite
 BOUL = boulangerite
 AG = native silver
 PENT = pentlandite
 PYRRAS = pyrrhotite
 TET = tetrahedrite
 GERS = gerodierite
 ARS = arsenopyrite

CH = Column number
 AR = Archaean
 silt = siltstone
 aren = arenite
 cong = conglomerate
 pag = porphyroclastic
 orth = orthoconglomerate
 chrt = bedded chert
 infil = interflow sedimentary rocks
 SUL = massive sulphides
 / = separation between hand picked or magnetically separated fractions
 r = rare

Sulphide minerals next to the vein were observed to be more abundant than farther away.

Chalcopyrite is the most abundant sulphide, with the exception of one sample which contains abundant blastic pyrite. Rocks bearing chalcopyrite can be divided into two broad groups; those containing pyrite and/or gersdorffite, and those containing pyrrhotite and/or other sulphides.

Pyrite, although dominant in only one sample, usually occurs as euhedral to subhedral poikiloblastic grains similar to those in the siltstones. Arsenopyrite, both from the arenite and a thin (15 cm) siltstone unit within the arenite, occurs as large (up to 5mm across) subhedra to euhedra (Plate 2.B) and in one place chalcopyrite is found surrounding closely spaced arsenopyrite euhedra. The remaining sulphides occur as irregular masses (up to several mm across) that infill the spaces between (Plates 2.C, 2.D, and 2.F), and sometimes occur within detrital grains (Plates 2.E, 2.F, and 3.H). Occasionally sulphides rim clastic grains (Plates 2.G and 2.H). In some places the sulphide masses have a poikiloblastic texture with numerous detrital inclusions (Plates 3.A and 3.B). Many samples contain chlorite and/or carbonate in association with the sulphide minerals.

Orthoconglomerate

The types of sulphide minerals and their relative abundances in the orthoconglomerate are summarized in Table 3.2, and are very similar to those in the arenite. On the scale of the outcrop, sulphide minerals do not appear to be as abundant as in the arenite, except at the arenite-orthoconglomerate contact.

Pyrite and arsenopyrite are characterized by euhedral to

PLATE 3

- A) Reflected-light photomicrograph of poikiloblastic chalcopyrite within arenite at Coniagas-Trethewey mine. Scale bar is 0.5 mm long. (CTM-C).
- B) Transmitted-light photomicrograph of poikiloblastic sulphides within arenite at Little Silver Vein. Sulphides are partially intergrown with chlorite. Scale bar is 3.2 mm long. (LSV-48).
- C) Transmitted-light photomicrograph of infilled pore space between conglomerate clasts at Little Silver Vein. Clasts have been coated with plagioclase (plag) crystals. Infilling after plagioclase is chlorite (chl), carbonate (carb), and sulphides (galena and chalcopyrite). Scale bar is 3.2 mm long. (LSV-35).
- D) Reflected-light photomicrograph showing galena intergrown with euhedral chlorite within conglomerate at Nipissing Hill. Scale bar is 0.5 mm long. (NIP-8402).
- E) Transmitted-light photomicrograph of a chlorite spot within siltstone at Silverfields mine. Opaque sulphides (sphalerite, galena, and chalcopyrite) are restricted to the chlorite spots. Scale bar is 3.2 mm long. (SFM-8421).
- F) Reflected-light photomicrograph of chalcopyrite (cp) microveining within pyrite (py), from Little Silver Vein. Scale bar is 0.2 mm long. (LSV-57).
- G) Reflected-light photomicrograph of pyrrhotite rimming detrital quartz from siltstone at MacDonald Vein. Scale bar is 3.2 mm long. (MCV-303).
- H) Transmitted-light photomicrograph of sulphides (sphalerite, arsenopyrite, galena, and chalcopyrite) within a dropstone at Coniagas-Trethewey mine. Scale bar is 3.2 mm long. (CTM-N).

subhedral blastic growth either in detrital clasts or in matrix, whereas the remaining sulphide minerals tend to occupy space between and within clasts similar to that in the arenite. The associated chlorite, carbonate, and less common plagioclase behave in a similar fashion. Some samples clearly show growth of plagioclase crystals around some clasts. This stage was followed by deposition of sulphides and associated chlorite and carbonate in the remaining pore spaces (Plate 2.C). Galena and chlorite occasionally are intimately intergrown (Plate 3.D). Chalcopyrite will sometimes occur partially surrounding or occupying fractures in pyrite (Plate 3.F).

Mineralogically Zoned Sulphide-Rich Clots

Zoned sulphide-rich clots were found in two samples from LSV and in one bedrock sample from the Langis Mine, Casey Township. The latter is 12 by 15 cm, has a core of chalcopyrite, an inner rim, consisting of about 5 mm of galena, and an outer 3 to 7 mm rim of sphalerite. Sphalerite is disseminated in a halo around this fragment. Another 2 by 3 cm fragment at LSV consists of a pyrrhotite core with a discontinuous layer of chalcopyrite up to 3 mm thick, a layer of galena 1 to 2 mm wide, and an outer 1 to 2 mm rim of sphalerite. Another clot, 2 by 3 cm, consists of a core of chalcopyrite and a partial rim of pyrrhotite up to 3 mm thick. The clots from Little Silver Vein have a discontinuous zone of carbonate and chlorite around them.

The cores and rims of these clots are not mineralogically pure and contain small amounts of the other sulphide minerals. The clots also have minor concentrations of gersdorffite, tetrahedrite, and native silver.

Sulphide Minerals From MacDonald Vein

Sulphide mineral species and their relative abundances at

the MacDonald Vein (MCV) are listed in Table 3.3. Sulphide mineral zoning about the vein is shown in Figure 3.3. Sulphide minerals were not found in the three samples collected in the arenite.

Paraconglomerate

Closest to the vein, pyrrhotite dominates, but between 2.6 and 3.5 metres from the vein-cut the pyrrhotite content diminishes and pyrite is the only iron sulphide present.

Pyrite tends to occur within detrital clasts (mostly volcanic rocks) associated with chlorite and possibly sericite. Rutile is also associated with chlorite throughout most of the MacDonald Vein area. Pyrrhotite occupies space between silt-sized detritus and occurs as rims around sand-sized grains (Plate 3.G).

Siltstone

Pyrite (95-99%), chalcopyrite (1-5%), and traces of pyrrhotite occur in the siltstones. Sulphide mineral zoning with respect to the silver vein is not apparent, and if it were present close to the vein the zones have been removed by mining. Sulphides occur mostly within chlorite spots (Plate 3.E), associated with chlorite and sometimes epidote. In some places pyrite occupies space between detritus in the coarser sand-sized beds. Occasionally, sulphides occur within dropstones (Plate 3.H), and usually have a higher chalcopyrite:pyrite ratio than that found in the rest of the rock.

Chalcopyrite usually occurs either as blebs within the pyrite or within clastic quartz grains (often associated with epidote). Closest to the vein, chalcopyrite occurs as microveinlets within pyrite.

Orthoconglomerate

Sulphide minerals in the orthoconglomerate are associated with

TABLE 3.3

MINERALOGY AND RELATIVE SULPHIDE ABUNDANCE FROM MACDONALD VEIN

Sample #	Distance from Vein	Rock Type	Percent Sulphide	Sulphide Mineralogy (determined from polished thin sections)	(Determined from Heavy Mineral Separates)
MCV-303	0.0 m	CH para	0.01	PO(100%)	PO(60%), PT(40%)
MCV-304	2.6 m	CH para	0.04	PT(80%), PO(10%), CP(10%)	PT(100%)
MCV-305	3.5 m	CH para	----	PT(92%), CP(8%)	PT(100%)
MCV-306	7.2 m	CH para	0.28	-----	PT(100%)
MCV-307	0.3 m	CH silt	0.08	PT(95%), CP(5%)	PT(100%)
MCV-308	1.2 m	CH silt	0.14	PT(99%), CP(1%)	PT(100%)
MCV-309	2.4 m	CH silt	0.14	PT(95%), CP(5%), PO(r)	PT(99%), CP(1%)
MCV-310	4.3 m	CH silt	0.20	PT(99%), CP(1%)	PT(99%), CP(1%)
MCV-311	4.6 m	CH silt	0.0	-----	-----
MCV-312	4.0 m	CH silt	0.11	-----	PT(100%)
MCV-313	10.2 m	CH silt	0.15	PT(99%), CP(1%)	PT(98%), CP(2%)
MCV-314	11.7 m	CH silt	0.15	PT(98%), CP(2%)	PT(100%)
MCV-315	0. m	CH orth	1%	CP(98%), OR(2%)	PO(100%) / CP(100%)
MCV-316	1.6 m	CH orth	1.17	PT(98%), PO(1%), CP(1%)	PT(100%), CP(r)
MCV-317	4.3 m	CH orth	0.05	PT(99%), CP(1%)	PT(74%), PO(24%), CP(2%)
MCV-318	6.8 m	CH orth	0.24	-----	PT(100%)
MCV-319	7.2 m	CH orth	4.05	PT(95%), PO(2%), CP(2%)	PT(85%), PO(10%), CP(5%)
MCV-320	10.8 m	CH orth	0.49	-----	PT(100%)
MCV-321	13.2 m	CH orth	0.08	PT(100%)	PT(100%)

See Table 3.2 for abbreviations.

TABLE 3.4

MINERALOGY AND RELATIVE SULPHIDE ABUNDANCE FROM VEIN 3

Sample #	Distance from Vein	Rock Type	Percent Sulphide	Sulphide Mineralogy (determined from polished thin sections)	(Determined from Heavy Mineral Separates)
VT-290	0.0 m	CH silt	0.02	CP(65%), PT(35%)	PT(80%), CP(18%), PO(2%)
VT-291	2.8 m	CH silt	0.09	-----	PT(99%), CP(1%)
VT-292	5.3 m	CH silt	0.08	PT(95%), CP(5%)	PT(98%), CP(2%)

See Table 3.2 for abbreviations.

SULPHIDE MINERALOGY AND ZONING AT MacDONALD VEIN

Figure 3.3 Sulphide mineralogy and zoning at MacDonald Vein.

chlorite and occur predominantly within lithic clasts, often only occurring on the clast rims. Subhedral pyrite often has crystal faces that are oriented toward the interior or exterior of the clast.

Close to the vein, chalcopyrite occurs as open space fillings, around chlorite euhedra, in fractured clasts, or occurs after an earlier stage of plagioclase growth similar to that in the conglomerate at LSV (Plate 3.C).

Pyrrhotite, although not observed in thin section, and chalcopyrite with euhedral inclusions of gersdorffite, occur within one metre of the vein-cut. Farther away, chalcopyrite and pyrrhotite decrease in abundance and pyrite becomes dominant. Pyrrhotite was observed in two heavy mineral separates and in trace amounts in several thin sections >1 m from the vein-cut.

Vein 3

Chalcopyrite and pyrite occur in the samples of siltstone collected at Vein 3. Table 3.4 lists the types and relative abundances of the sulphide minerals. Sulphide minerals tend to occur within chlorite spots and inbetween clastic grains in the coarser silt-sized beds associated with chlorite. Sulphide mineral zoning may be present since the sample closest to the vein contains much more chalcopyrite than pyrite and may contain minor pyrrhotite, whereas, the other two samples farther away from the vein contain mainly pyrite. Next to the vein, pyrite has many fractures and embayments that are filled with chalcopyrite.

Sulphide Minerals from the Coniagas-Trethewey Mine

Fine Sand-Siltstone Rhythmites

Samples collected in the sand-siltstone rhythmite unit at the

edge of the large open pit at the Coniagas-Trethewey Mine (CTM) (CTM-102 - CTM-106) contain pyrite, which commonly occurs in chlorite spots or in coarser beds between clastic grains associated with chlorite. Metallic minerals in a sample collected immediately adjacent to a silver vein in the same unit are composed of native silver, tetrahedrite, chalcopyrite and gersdorffite. These minerals occur in chlorite spots, between detritus and within some of the clastic material, associated with chlorite and carbonate. In a few places a euhedral mineral, probably pyrite, has been replaced by native silver, tetrahedrite, chalcopyrite, and gersdorffite.

Mine Dump Samples at the Coniagas-Trethewey Mine

A variety of sulphide minerals (Table 3.5) and textures occur in mine dump samples. Two samples include Co-arsenide veins (CTM-B, CTM-E) and their wallrocks contain chalcopyrite, gersdorffite, sphalerite, and abundant euhedral arsenopyrite. Metallic minerals from samples hosting native silver-bearing veins (CTM-A, CTM-E, CTM-130) are composed of native silver, tetrahedrite, chalcopyrite, gersdorffite, and occasionally pyrrhotite and pyrite.

Sulphide-rich clasts occur in two samples (CTM-O, CTM-PE). In one clast (CTM-O), early formed pyrite appears to be replaced by chalcopyrite and pyrrhotite. Discontinuous pyrite rims, outlining euhedral forms, occur around chalcopyrite-pyrrhotite grains (Plate 4.G), and some fractured and broken pyrite grains are infilled with chalcopyrite. Subhedral pyrite with some chalcopyrite infilling embayments occur in the other sample (CTM-PE). Molybdenite was found in the centre of a granitic clast in one sample.

Metallic spots, similar to chlorite spots, occur in one sample. Minerals in the spots comprise tetrahedrite, pyrargyrite, chalcopyrite,

TABLE 3.3

MINERALOGY AND RELATIVE SULPHIDE ABUNDANCE FROM ONIAGAS-TETHEMET RINE

Sample #	Distance from Vein	Rock Type	Percent Sulphide	Sulphide Mineralogy (determined from polished thin sections)	(Determined from Heavy Mineral Separates)
CTM-PP	??	CH cong	----	CP(75%), PO(20%), GAL(2%), PY(2%), GERS(1%)	----
CTM-A	??	CH cong	3.04	TET(38%), CP(35%), AG(20%), GERS(2%), ACAN(2%), PO(2%), PTRAR(2%)	CP(40%), ARS(30%), TET(30%)
CTM-B	??	CH cong	2.09	CP(63%), ARS(25%), SPK(10%), GERS(2%), TET(r)	CP(70%), ARS(30%), SPK(r)
CTM-C	??	CH aren	----	CP(63%), TET(15%), AG(10%), PY(10%), GERS(2%), PO(1%), PTRAR(r)	----
CTM-D	??	CH aren	----	CP(40%), PO(40%), TET(10%)	----
CTM-E	??	CH cong	2.92	CP(60%), ARS(35%), GERS(5%)	CP(60%), ARS(40%)
CTM-F	??	CH silt	----	GAL(30%), ARS(30%), CP(20%), SPK(20%)	SPK(1), ARS(9)
CTM-O	??	CH cong	1.02 3.42	CP(60%), PO(30%), PY(10%)	CP(50%), PO(40%), PY(10%)
CTM-W	??	CH cong	----	BOH(40%), CP(30%), ARS(25%), TET(5%), PY(r)	BOH(70%), ARS(25%), CP(5%)
CTM-PL	??	CH cong	----	PY(90%), CP(10%)	PY(60%), CP(40%)
CTM-102	1.0 m	CH silt	----	PY(100%)	PY(100%)
CTM-103	3.0 m	CH silt	----	PY(100%)	PY(100%)
CTM-104	4.6 m	CH silt	0.0	----	----
CTM-105	6.9 m	CH silt	----	PY(100%)	PY(100%)
CTM-106	9.3 m	CH silt	----	PY(100%)	----
CTM-107	13.2 m	CH silt	0.0	----	----
CTM-110	----	CH cong	----	PY(95%), CP(5%)	----
CTM-130A	3 cm	CH aren	----	Ag(95%), TET(5%)	----
CTM-130B	6.5 cm	CH aren	----	TET(60%), CP(20%), Ag(15%), GERS(5%)	----
CTM-130C	9.5 cm	CH aren	----	TET(70%), CP(20%), Ag(5%), GERS(5%)	----
CTM-130D	12.5 cm	CH aren	----	TET(80%), CP(18%), GERS(2%)	----
CTM-130F	16 cm	CH aren	----	CP(50%), Ag(30%), TET(20%), GERS(1%)	----
CTM-130F	9 cm	CH aren	----	CP(30%), Ag(30%), GERS(30%), TET(10%)	----
CTM-1500	??	CH silt	----	PY(60%), CP(40%)	----
CTM-JOINT	??	CH silt	----	PY(80%), CP(20%)	----
CTM-523	----	CH aren	----	PY(90%), SPK(5%), CP(5%)	----

See Table 3.2 for abbreviations.

PLATE 4

A + B) Reflected-light photomicrograph showing sphalerite (sph) and gersdorffite (ger) intergrown with euhedral chlorite within conglomerate at Nipissing Hill. A) Scale bar is 0.1 mm long. B) Scale bar is 0.5 mm long. (NIP).

C) Transmitted-light photomicrograph of a porphyritic volcanic clast (lower half) within conglomerate at Nipissing Hill. The matrix of this clast has been partially replaced by galena and tetrahedrite. The phenocrysts are unreplaced. Scale bar is 3.2 mm long. (NIP-8402).

D) Reflected-light photomicrograph showing feathery appearance of pyrrhotite that is altering to pyrite or marcasite. Scale bar is 0.2 mm long. (MLV-264).

E) Reflected-light photomicrograph showing epitaxial overgrowth of gersdorffite (ger) on pyrite (py) from ML Vein. Scale bar is 0.1 mm long. (MLV-265).

F) Transmitted-light photomicrograph showing the discontinuous linear pattern of some of the sulphides (galena, sphalerite, and chalcopryite) at Nipissing Hill. Scale bar is 3.2 mm long. (NIP-8402).

G) Reflected-light photomicrograph of a grain of chalcopryite (cp) and pyrrhotite (po) that display a euhedral form and have a partial rim of pyrite (py). Sulphides occur in a conglomerate clast at Coniagas-Trethewey mine. Scale bar is 0.4 mm long. (CTM-0).

H) Reflected-light photomicrograph showing a sponge-like intergrowth of native silver (Ag) and pyrite (py) within a poikiloblastic mass of sulphides (chalcopryite and tetrahedrite [tet]) at the Coniagas-Trethewey mine. Scale bar is 0.3 mm long. (CTM-C).

gersdorffite, and a spongy intergrowth of pyrite and native silver (Plate 4.H). Other spots are composed predominantly of poikiloblastic chalcopyrite.

Bornite, arsenopyrite and chalcopyrite are the dominant sulphides in another sample of conglomerate (CTM-W).

Sulphide Minerals from the Silverfields Mine

Sphalerite and/or galena are the dominant sulphides in the samples collected from the Silverfields Mine (SFM); pyrrhotite and chalcopyrite are less abundant. Gersdorffite occurs as tiny euhedra or worm-like growths within chalcopyrite in all samples. Pyrite is present in only one sample and pentlandite has been tentatively identified by qualitative microprobe data in another sample. Sulphide mineralogy and their relative abundances are presented in Table 3.6. Mineralogic zoning with respect to silver veins is not apparent.

Within the siltstones, sulphide minerals are associated with chlorite and carbonate and are usually restricted to chlorite spots (Plate 3.E), like those at the MCV. Sulphide minerals within the conglomerates are texturally very similar to those at the MLV or LSV, where they occur associated with chlorite and carbonate between and within clastic grains, or infilling open spaces intergrown with chlorite after earlier formed plagioclase.

— In one sample hosting a silver vein, tetrahedrite occurs as disseminations and grains up to 13 mm across in a conglomerate host.

Sulphide Minerals from ML Vein

Although the types and relative abundances of sulphide minerals at the ML Vein (MLV), shown in Table 3.7, are varied, chalcopyrite appears to be dominant in most samples. Sulphide mineral distribution

TABLE 3.6

MINERALOGY AND RELATIVE SULPHIDE ABUNDANCE FROM SILVERFIELD MINE

Sample #	Distance from Vein	Rock Type	Percent Sulphide	Sulphide Mineralogy (determined from polished thin sections)	(Determined from Heavy Mineral Separates)
SFM-A	??	CH cong	----	SPH(85%), GALL(5%), CP(5%), PO(4%), CERS(1%)	SPH(96%), CP(2%), GALL(2%)
SFM-B	??	CH cong	----	SPH(85%), PO(10%), CP(3%), CERS(2%), GALL(r)	PO(100%) / SPM(96%), CP(2%), PY(1%), T(1%)
SFM-B421	20 m	CH silt	0.36	SPH(50%), GALL(20%), CP(20%), PO(10%), CERS(r), PY(1%)	CP(?), SPM(?)
SFM-B422	22 m	CH silt	0.14 0.62	SPH(80%), CP(10%), PO(10%), GALL(r)	SPH(97%), CP(2%), PO(1%)
SFM-B424	20 m	CH cong	0.42 0.43	SPH(90%), CP(5%), GALL(3%), PO(2%), CERS(r)	SPH(85%), CP(13%), GALL(2%)
SFM-B427	16 m	CH cong	0.71	SPH(48%), GALL(48%), CP(4%), CERS(r)	SPH(88%), GALL(10%), CP(2%)
SFM-B429	13 m	CH cong	0.26	SPH(45%), GALL(45%), CP(5%), PY(4%), PO(1%), CERS(r)	SPH(55%), GALL(40%), CP(5%)
SFM-B430	11 m	CH cong	0.23	GALL(65%), CP(29%), SPM(5%), CERS(1%)	GALL(93%), CP(5%), SPM(2%)
SFM-B5001	0.1 m	CH cong	----	----	TET(100%)

See Table 3.2 for abbreviations.

TABLE 3.7

MINERALOGY AND RELATIVE SULPHIDE ABUNDANCE FROM ML VEIN

Sample #	Distance from Vein	Rock Type	Percent Sulphide	Sulphide Mineralogy (determined from polished thin sections)	(Determined from Heavy Mineral Separates)
MLV-252	4.9 m	CH cong	----	CP(99%), CERS(1%)	----
MLV-256	8.9 m	CH cong	----	CP(80%), PY(15%), PO(5%), CERS(r)	PO(100%) / CP(80%), PY(20%)
MLV-261	0.0 m	CH cong	0.24	CP(90%), PY(10%)	PY(54%), SPM(25%), CP(3%), GALL(1%)
MLV-262	2.2 m	CH cong	0.20	CP(80%), PY(20%), CERS(r), COV(r)	PY(90%), PO(5%), CP(3%), GALL(2%)
MLV-263	4.5 m	CH cong	0.15	CP(65%), PY(34%), PO(3%), GALL(2%), CERS(1%), SPM(r)	PY(55%), CP(35%), PO(10%), SPM(r)
MLV-264	5.9 m	CH cong	----	CP(70%), PO(30%), PY(7%), SPM(2%), CERS(1%)	----
MLV-265	6.8 m	CH cong	0.04	PY(45%), PO(30%), CP(20%), CERS(5%)	PY(35%), PO(30%), CP(30%), SPM(5%)
MLV-266	9.1 m	CH cong	0.03	SPH(30%), GALL(20%), PO(20%), PY(20%), CP(10%)	PY(40%), GALL(25%), CP(20%), SPM(15%)
MLV-267	10.2 m	CH cong	0.55	CP(43%), PO(25%), GALL(15%), PY(10%), SPM(5%), CERS(2%)	SPH(35%), PY(30%), CP(20%), PO(10%), GALL(5%)
CV-25	10.2 m	CH cong	0.25	GALL(70%), SPM(25%), CP(2%), PY(2%), PO(1%), COV(r), YET(r)	GALL(50%), PY(25%), CP(10%), SPM(10%), PO(2%)
MLV-268	11.2 m	CH cong	0.02	PY(40%), SPM(25%), CP(25%), PO(10%)	PY(60%), CP(15%), SPM(15%), PO(5%), GALL(5%)
MLV-269	14.3 m	CH cong	----	CP(100%) (very low sulphide content)	----
MLV-270	16.9 m	CH cong	0.002	CP(?), PY(?)	PY(50%), CP(50%)

See Table 3.2 for abbreviations.

is extremely heterogeneous. Sulphides are composed of chalcopyrite, pyrite, pyrrhotite, galena, sphalerite, gersdorffite, tetrahedrite, and covellite.

Sulphide mineral zoning about MLV is not apparent, but may be complicated by the presence of a nearby subsurface vein, 5-20 metres from the sample line (Figure B.6).

Most sulphides appear either to occupy space between detrital pebbles or to occur within clasts, in association with chlorite with or without carbonate and plagioclase, which occur in a manner similar to the sulphides. Occasionally sulphides occur around euhedral blades of chlorite (Plates 4.A and 4.B), or in open spaces rimmed by plagioclase crystals (similar to that at LSV).

Sphalerite often occurs with rutile. Galena is usually intimately intergrown with chlorite. Gersdorffite almost always occurs as tiny euhedra within chalcopyrite or pyrrhotite, and in one place occurs as epitaxial overgrowths on pyrite (Plate 4.E). Pyrrhotite often has a feathery appearance and qualitative microprobe data indicate that it is altering to either pyrite or marcasite (Plate 4.D). In most places pyrite occurs as poikiloblastic grains with numerous fractures and embayments that are filled with chalcopyrite and sometimes pyrrhotite, suggesting that these sulphides occurred after pyrite formation.

Sulphide Minerals from the Kerr Lake Arch

Sampling of the Kerr Lake Arch (KLA) included sites at the Fleming Vein, Drummond Cairn, and isolated samples from around the area. Sulphide mineralogy and their relative abundances are listed in Table 3.8. Sulphide mineral textures are similar to those from other

TABLE 3.2

MINERALOGY AND RELATIVE SULPHIDE ABUNDANCE FROM NEPESING HILL

Sample #	Distance from Vein	Rock Type	Percent Sulphide	Sulphide Mineralogy (determined from polished thin sections)	(Determined from Heavy Mineral Separates)
NIP	35m	CH cong	----	SPH(65%), CP(20%), GAL(10%), OERS(3%)	GAL(100%) / SPH(96%), CP(3%), GAL(1%)
NIP-8401	8m	AR volc	----	SPH(60%), GAL(20%), PO(10%), CP(10%), ARS(r)	PO(100%) / GAL(100%) / SPH(100%)
NIP-8402	7m	CH cong	0.25	SPH(42%), GAL(42%), CP(6%), ARS(5%), TET(5%), OERS(1%), PO(r)	SPH(80%), GAL(15%), CP(5%)
NIP-8403	5m	CH cong	----	CP(90%), ARS(6%), TET(4%), OERS(0%)	CP(98%), TET or ARS (2%)
NIP-8404	3m	CH cong	----	CP(90%), SPH(5%), OERS(4%), PT(1%)	CP(85%), ARS(15%), GAL(r)
NIP-8405	30m	CH cong	----	PO(95%), CP(5%), SPH(r)	----
M-760	15m	CH cong	----	SPH(85%), GAL(5%), PO(5%), CP(5%), OERS(r)	SPH(99%), CP(1%)
M-711	130m	CH	----	PT(100%)	PT(98%), CP(2%)
M-741	25m	CH	0.04	CP(60%), PT(40%)	PT(95%), CP(5%), PO(r)

See Table 3.1 for abbreviations.

TABLE 3.3

MINERALOGY AND RELATIVE SULPHIDE ABUNDANCE FROM THE KERR LAKE AREA

Sample #	Distance from Vein	Rock Type	Percent Sulphide	Sulphide Mineralogy (determined from polished thin sections)	(Determined from Heavy Mineral Separates)
FV-340	0 m	CH cong	several	SPH(60%), PO(30%), CP(5%), GAL(5%)	PO(100%) / SPH(95%), CP(4%), GAL(1%)
FV-341	0 m	CH cong	----	PO(90%), CP(4%), GAL(3%), SPH(3%), ACAN(0.5%)	PO(100%) / SPH(90%), CP(10%)
FV-342	2-5 m	CH cong	----	CP(70%), PO(20%), ARS(5%), GAL(2%), OERS(2%), ACAN(0.5%), SPH(r)	PO(100%) / GAL(100%) / CP(97%), ARS(2%), GAL(1%), SPH(0%)
DC-TOP	10-30+ m	CH cong	----	GAL(40%), PT(35%), CP(23%), SPH(2%), OERS(r), PO(r)	GAL(40%), CP(30%), PT(30%)
DC-MID	10-30 m	CH cong	0.85	PT(95%), CP(5%), SPH(1%), GAL(1%)	PT(75%), SPH(20%), CP(5%)
DC-BOT	10-30 m	CH cong	----	SPH(75%), GAL(20%), PT(3%), CP(2%)	PT(45%), SPH(40%), GAL(10%), CP(5%)
KLA		CH cong	----	----	PO(100%) / CP(44%), TET or ARS(30%), GAL(2%), SPH(2%)
KLA-353	10-20 m	CH cong	----	PT(50%), CP(40%), SPH(10%)	PT(50%), CP(40%), SPH(10%)
KLA-354	5-10 m?	CH cong	----	PO(48%), GAL(15%), SPH(5%), CP(5%), PT(5%), OERS(2%)	PO(100%) / CP(94%), GAL(2%), SPH(2%)
KLA-850	1-3 m	CH cong	----	PT(80%), CP(10%), GAL(10%)	PT(90%), CP(10%)
IS-350		AR LNPL	0.31	?	SPH(81%), GAL(15%), CP(2%), PO(2%)
IS-351		AR LNPL	0.19	?	PO(60%), SPH(35%), CP(5%)

See Table 3.2 for abbreviations.

areas; they occur within and between detritus, and are associated with chlorite and sometimes plagioclase. Some euhedral pyrite (DC-TOP, KLA-353, KLA-354, KLA-650) have many fractures that are filled with chalcopyrite with or without galena and pyrrhotite.

Sampling at the Fleming Vein was not sufficient to properly establish any zoning about the vein.

Sulphide Minerals from Nipissing Hill

Sphalerite, galena, pyrrhotite, chalcopyrite, gersdorffite, arsenopyrite, tetrahedrite, and possibly pyrite occur in the Coleman member conglomerates and Archean rocks at Nipissing Hill (NIP). Table 3.9 lists the types and relative abundances of the sulphide minerals.

Sulphides are usually associated with chlorite and sometimes with epidote, plagioclase, carbonate or rutile, and often occur between clastic grains. This texture is most common in samples where chalcopyrite or pyrrhotite are dominant, whereas in sphalerite or galena dominant samples, sulphides commonly occur within clasts. In one sample, the fine-grained matrix on the periphery of a clast of porphyritic volcanic rock has been altered to galena and tetrahedrite (Plate 4.C); the phenocrysts are unaltered. In samples where sphalerite or galena are dominant, sulphides also occur around chlorite euhedra (Plates 4.A and 4.B) and in discontinuous linear patterns (Plate 4.F).

A sample of Archean volcanic rock, NIP-8401, contains predominantly sphalerite in areas of intense chlorite spotting and sphalerite, galena, pyrrhotite, and chalcopyrite in narrow (<1 cm thick) quartz veins.

3.4 Discussion

Textural evidence suggests that most of the sulphide minerals

occurring within detrital clasts originated by replacing rock-forming minerals, and were not original components of the clasts. The remaining sulphide minerals, other than blastic pyrite and euhedral arsenopyrite, occupy space between clasts with some associated partial replacements of adjacent grains (Plates 2.C, 2.D, 2.E, 2.F, and 3.E). Clearly these textures indicate that this sulphide in its present form is not detrital in origin as suggested by Kim (1979). Several models could explain the origin of these sulphides; 1) all sulphides were originally detrital and subsequently mobilized either during diagenesis, during thermal metamorphism peripheral to the Nipissing diabase, or by fluids related to silver mineralization; 2) all sulphides were introduced into the Coleman member from an outside source, probably deposited from vein-related fluids; or 3) a combination of 1 and 2.

Chlorite spot development is interpreted to have accompanied the thermal metamorphism related to diabase emplacement (Jambor 1971f) and the presence of sulphides within chlorite spots in siltstone indicate that sulphides, presumably detrital, may have been mobilized during spot development. This suggests that some sulphides may have originally been detrital since sulphides would have to be present prior to chlorite spot development in order for them to be mobilized. Contrary to this, the following evidence suggests that most of the Coleman member sulphides were not originally detrital. Sulphides from the Archean basement, the detrital source, are dominated by pyrite and pyrrhotite (Boyle et al., 1969; Goodz et al., 1986), whereas the most abundant Coleman member sulphide is chalcopyrite. As well, detrital sulphides are not likely to have survived the high energy sedimentary environments of the arenite and orthoconglomerate which host much of the sulphide found in this

study.

The second and most likely origin for the sulphide is introduction to the Coleman member from an outside source. Sulphide mineral zoning about MCV and LSV, the associated increase in sulphide abundance proximal to these veins, and the presence of arsenopyrite, gersdorffite and the silver-bearing minerals in many samples suggest that these sulphides were deposited from the same fluids responsible for native silver Co-Ni-arsenide and sulpharsenide mineralization.

Goodz et al. (1986) and Watkinson (1986) suggested that vein fluids derived their sulphur from a desulphurization reaction within the Archean basement rocks where pyrite has been altered to pyrrhotite. Presumably this fluid would have a low sulphur fugacity and if it came in contact with pyrite within the Coleman member it would probably be capable of altering pyrite to pyrrhotite. Replacement of pyrite by pyrrhotite within the siltstone at LSV confirms the possibility that the fluids which altered these sulphides could be vein-related. The presence of pyrrhotite rather than pyrite in other areas could possibly be an indicator of vein-fluid interaction.

It seems likely that fluids moving in Cobalt vein systems could migrate laterally through slightly permeable Coleman member wallrocks along clastic grain boundaries, and either partially replace clasts or deposit sulphides in the matrix, between detrital grains, possibly replacing the matrix and adjacent grains in the process. Consistent with this are the sulphide textures observed in the Coleman member. Perhaps certain types of clasts are preferentially replaced because of the internal chemistry of the mineral(s) in the partially replaced clasts. Fluids either moving outward from a vein, or migrating towards a vein fracture would presumably be affected by the differential

porosity and permeability of the individual beds. This may explain the irregular sulphide mineral zoning at both LSV and MCV (Figures 3.2 and 3.3).

Abundant sphalerite and galena and/or pyrrhotite in samples distant from veins at NIP, SFM, and KLA (up to 30 metres away) is difficult to explain by simple models of sulphide emplacement adjacent to silver veins. The presence of gersdorffite, arsenopyrite, and tetrahedrite found in this study and of acanthite at Drummond Cairn reported by Gebert (1985), however, suggests that these sulphides are most likely related to the fluids responsible for vein mineralization. Perhaps vein-related fluids permeated the Coleman member over a much wider area at SFM, NIP, and KLA than at LSV, MCV, and CTM. Thorpe et al. (1986) found that lead isotope ratios for galena from a number of geologic settings, including the Archean interflow rocks, are consistent with a Proterozoic model age. Their homogeneous composition, suggests that galena was either mobilized or introduced by a single widespread event. Perhaps this event could be responsible for depositing the widespread sulphide minerals found at KLA, NIP, and SFM.

Commonly associated with the sulphide minerals are chlorite, carbonate, plagioclase, and rutile. Deposition of carbonate, chlorite and plagioclase by a vein-related fluid might be expected since carbonate is the most common gangue mineral in the veins (Jambor, 1971c), and plagioclase and chlorite are common constituents of the alteration bordering the veins (Dass, 1970). Plagioclase occasionally replaces clasts and matrix, and occurs as crystals on the outside of clastic pebbles. Chlorite, carbonate and sulphide often infill pore space left after the plagioclase crystals have grown, indicating that at least in some places, the plagioclase formed prior to sulphide

deposition. Sulphide minerals occur around euhedral blades of chlorite at some sites, indicating that sulphide deposition occurred after or contemporaneously with chlorite in these places. Rutile is often intergrown with sphalerite and almost always associated with chlorite. The interrelationship of plagioclase, chlorite, rutile and the sulphide minerals is complex and should be the focus of another more detailed study.

Although most of the Coleman member sulphides appear to have a vein-related origin it seems likely that in many places blastic pyrite formed prior to these vein-related sulphides, based on the following evidence. Pyrrhotite pseudomorphs (with chalcopryrite, and gersdorffite) after euhedral pyrite occur within 5m of the vein-cut at LSV, and euhedral to subhedral pyrite from numerous other places have fractures and embayments that are filled with chalcopryrite, pyrrhotite, and galena indicating that these sulphides occurred after pyrite formation. Blastic pyrite is most abundant within siltstone units and perhaps formed during diagenesis or thermal metamorphism related to diabase emplacement from mobilization of very fine-grained detrital sulphide associated with the fine-grained sediment.

Clasts composed of nearly 100% sulphides (predominantly chalcopryrite), reported by Kim (1979) and Hartlein (1972), were not found in this study. These clasts were described as being very angular and may be truly detrital in origin. All of the sulphide-bearing clasts examined in this study appear to have derived their sulphide content in situ by partial replacement.

Zoned sulphide clots may possibly have been detrital sulphide pebbles that have partially reacted with vein-related fluids on the

CHAPTER IV

SULPHUR-ISOTOPE GEOCHEMISTRY

4.1 Introduction

Sulphur-isotopic variations in sulphide minerals from the Cobalt area have been the subject of studies by Petruk (1971d) and Goodz et al. (1986). Several analyses have also been reported by Hartlein (1972). The study by Goodz et al. (1986) was conducted at a site within the Archean volcanic rocks and was far removed from the Coleman member of the Gowganda Formation.

The present study was initiated in part to investigate the sulphur-isotope variations of sulphides in the Coleman member, as a complement to the study by Goodz et al. (1986), and to shed light on the possible source of the Coleman member sulphides. Originally it was hoped that sulphur-isotope values from sulphide pairs could possibly identify temperatures of sulphide deposition, and perhaps the existence of temperature zoning about the veins.

Sulphur-isotope ratios were determined on most of the samples described in the previous chapter. The results and interpretations presented in this chapter complement the sulphide descriptions.

4.2 Samples and Analytical Methods

Samples were collected from nine principal sites, described in Appendix B. Samples were taken primarily from Coleman member rocks collected adjacent to abandoned mines, but also include several specimens of Archean basement rocks.

Uncommonly, sulphide minerals were coarse grained enough to be

separated by hand picking. Usually sulphides were fine grained and required heavy mineral separation to isolate the sulphides. Samples were crushed, sieved (usually from -115 to +230 mesh), washed and the heavy minerals separated using the heavy liquid, methylene iodide.

Numerous sulphide species were isolated from heavy mineral separates by careful hand picking, magnetic methods (for pyrrhotite), and occasionally by chemical methods (described by Halls et al., 1983). Many heavy mineral separates were not isolated into different sulphide species because they were either mono-mineralic or too complex to separate.

A total of 186 analyses were performed on 171 separates from 132 samples. Fourteen mineral separates are from Archean rocks, two are from a silver vein, and the remaining samples are from the Coleman member. Analyses were performed at the OCCGS/GSC Stable Isotope Laboratory at the University of Ottawa. Sulphur was extracted as SO_2 by oxidation with Cu_2O at 1000°C and analyzed on a VG-Isogas Micromass 602E spectrometer. Two internal standards with $\delta^{34}\text{S}$ values of 1.13 and 30.5 per mil, were analyzed before and after each run of about 12 samples. Analytical precision was ± 0.2 per mil.

4.3 Previous Studies

In order to interpret the sulphur-isotopic values from the Coleman member, the data will be compared to previous sulphur-isotope studies conducted on vein and Archean basement sulphides. Petruk (1971e) reported $\delta^{34}\text{S}$ values for silver vein and Archean basement sulphides from a number of different sites in the Cobalt camp; a variety of sulphide species and mixtures were analyzed. Goods et al. (1986)

sulphides to date. Their data are summarized in Figure 4.1. This figure shows that Petruk's data are consistent with and overlaps those of Goodz et al. (1986).

$\delta^{34}\text{S}$ values for Archean basement pyrite ranges from 1.7 to 7.5 per mil, and values for pyrrhotite, galena, sphalerite and chalcopyrite vary less but lie within the range of pyrite values. Pyrite samples from the Beaver-Temiskaming Mine (BTM) have the lowest $\delta^{34}\text{S}$ values whereas pyrite from the Deerhorn Mine (DHM) have higher values, indicating that average isotopic compositions from pyrites vary from place to place in the Archean basement. Sulphur-isotopic ratios are also lowest at BTM and highest at DHM for pyrrhotite and galena (Figure 4.1).

$\delta^{34}\text{S}$ values for vein-hosted galena range from -0.7 to 6.2 per mil, although all but one value range from -0.7 to 4.0 per mil. Isotopic values for the other vein sulphides fall within the larger range for galena (Figure 4.1). $\delta^{34}\text{S}$ ratios for sphalerite and galena may vary from mine to mine since values from Vein 65 are consistently higher than those from the BTM.

$\delta^{34}\text{S}$ values are generally lower for vein-hosted galena than for Archean basement galena, although overlap is present. Sulphur-isotopic compositions for vein-hosted sphalerite and chalcopyrite have range that extend slightly beyond the ranges of those from the Archean basement (Figure 4.1). Goodz et al. (1986) reported that the average $\delta^{34}\text{S}$ values for vein sulphides (2.3 per mil) is lower than the average for Archean basement sulphides (4.0 per mil) at the BTM. The data shown in Figure 4.1 show that based on sulphur-isotopic compositions, distinguishing between vein-hosted and Archean basement sulphides is difficult to

Source of Data

impossible, except for galena.

4.4 Results

Archean Sulphur Isotopes

Sulphur-isotopic ratios from 13 of 14 Archean basement sulphides fall within the ranges reported by Goodz et al. (1986) and Petruk, (1971e) (Figure 4.1). In general, the Archean basement sulphides are isotopically heavier than sulphides in the Coleman member.

Coleman Member Sulphur Isotopes

Sulphur-isotopic data from this study are listed in Appendix C and illustrated in Figure 4.1. Pyrite data from the Coleman member range between -1.6 and +4.1 per mil, with all but two between -1.6 and 2.0 per mil; ratios are moderately evenly distributed across this range. Pyrite data from LSV range between -1.6 and +1.6 per mil, whereas MCV pyrite is heavier, ranging from 0.0 to 2.0 per mil. Pyrrhotite values are slightly heavier, ranging from 0.1 to 4.1 per mil. Some pyrrhotite data from LSV clusters around 0.2 per mil and the heaviest value (3.0 per mil) is slightly lower than the range of values from KLA (3.1 to 4.0 per mil). The range in $\delta^{34}\text{S}$ values for chalcopyrite is -0.1 to 3.5 per mil and again samples from LSV are at the lighter end of the range. Galena values are evenly distributed from -0.9 to +2.4 per mil. Sphalerite values range from 1.1 to 4.6 per mil with the majority between 2.0 and 3.5 per mil. Three arsenopyrite values are generally the heaviest of the sulphide analyses, with values of 3.9, 4.5 and 4.6 per mil.

Samples of composite sulphides fall into three broad categories. The $\delta^{34}\text{S}$ values for samples of pyrite with or without pyrrhotite and chalcopyrite range between -1.1 and 3.5 per mil. Samples of

arsenopyrite + chalcopryrite $\pm$ other sulphides fall between 0.8 and 3.6 per mil. Samples with significant sphalerite or galena have a smaller range of $\delta^{34}\text{S}$ values, between 1.5 and 3.1 per mil.

One sample with three mineral separates, from a zoned sulphide-rich clot from the Langis Mine, Casey Township, has $\delta^{34}\text{S}$ values much lower than those from the main Cobalt camp (Appendix C).

4.5 Site by Site Discussion

Little Silver Vein

LSV is the best site in this investigation and one of the best sites at Cobalt for studying sulphur-isotope variations within the Coleman member because LSV is fairly far away from the potential influence of the unconformity, the Nipissing diabase, and other silver-bearing veins. LSV is the only known vein in the immediate area, is about 50 metres vertically from the unconformity and at least 100 metres below the diabase.

Based on observations and interpretations presented in Chapter III, the siltstone at LSV was host to blastic pyrite that formed prior to vein mineralization. Euhedral pyrite in a 5 to 8 metre wide halo adjacent to the vein has been replaced by pyrrhotite and lesser amounts of chalcopryrite and gersdorffite, which is interpreted to have resulted from interaction with low sulphur fugacity vein-related fluids. Several percent chalcopryrite inclusions are present in pyrite from samples within 3 metres of the pseudomorphed zone.

Figure 4.2 displays the sulphur-isotopic compositions of sulphide minerals from the siltstone with respect to distance from the vein at LSV. Pyrite values distant from the vein are fairly constant.

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Microl

Figure 4.2 Sulphur isotopic variations within siltstone
at Little Silver Vein.

increase; adjacent to the vein the pyrrhotite and chalcopyrite values are in general higher or comparable to values in the pyrite.

Pyrite from samples >10 metres from the vein have an average $\delta^{34}\text{S}$ composition of -0.9 per mil (range; -1.6 to -0.5 per mil). This is much lower than any value reported for vein or Archean sulphides and probably represents sulphur derived from another source. As previously suggested in Chapter III, blastic pyrite may have been detrital sulphide that was mobilized during diagenesis or diabase-related thermal metamorphism. The $\delta^{34}\text{S}$ value of this blastic pyrite is much lower than the probable detrital source, the Archean basement, and may indicate that fractionation occurred during detrital sulphide mobilization, or that there is an unknown source for this sulphur. The relatively consistent $\delta^{34}\text{S}$ values at distances >10 metres from the vein suggest that these values were unaffected by vein fluids and remain at background isotopic levels.

Within 5 metres of the vein-cut, pseudomorphic pyrrhotite and chalcopyrite possess $\delta^{34}\text{S}$ values that are higher than the interpreted background levels for pyrite distant from the vein. If pyrite were in isotopic equilibrium with the pyrrhotite and chalcopyrite at a temperature of 250°C, the $\delta^{34}\text{S}$ value of the corresponding pyrite would be higher than that observed; 1.1 and 1.6 per mil higher, respectively. The average sulphur-isotopic compositions of chalcopyrite are lower than that of the vein chalcopyrite reported by Goodz et al. (1986). This does not mean that these sulphides have been unaffected by vein-fluids, but rather, that there has probably been mixing of lighter background sulphur with the heavier vein sulphur.

Pyrite, between 5 and 10 metres of the vein-cut, has numerous inclusions of chalcopyrite, and has higher-than-background $\delta^{34}\text{S}$ values

(Figure 4.2 and Table 3.1). This is probably due to an interaction with vein fluids, that altered the pyrite's original isotopic signature without altering its mineralogy.

In summary, vein-related fluids probably migrated laterally through the siltstone, reacted with the early-formed pyrite, altered it mineralogically to pyrrhotite, and altered the original isotopic composition of the pyrite by the addition of isotopically heavier vein sulphur.

Unfortunately, the sulphur-isotopic patterns found in the arenite and conglomerate are not as well defined as those in the underlying siltstone, nor was the sampling as systematic. The increase in sulphide abundance next to the vein, the presence of Ag, Sb, Co, Ni, and As sulphides, and the sulphide zoning about the vein in the rocks described in Chapter III implies that these sulphides share a vein-related origin. Chalcopyrite and pyrrhotite are the most abundant sulphides in the arenite and conglomerate. Isotopically their origin is not clear-cut since their $\delta^{34}\text{S}$ compositions are lower than those of the Archean sulphides and lower than most vein chalcopyrite reported by Goodz et al. (1986).

Most chalcopyrite data cluster around 1.0 per mil (Figure 4.1) and are between 3 and 6 metres from the vein (Figure 4.3). The few samples collected closer than 3 metres from the vein have $\delta^{34}\text{S}$ values both higher and lower than 1.0 per mil.

Arsenopyrite and arsenopyrite-rich samples have higher sulphur-isotopic compositions than those of vein arsenopyrite reported by Goodz et al. (1986) and are higher than almost all other sulphides sampled during this study.

Chalcopyrite veinlets within some of the blastic pyrite suggest that the pyrite formed prior to the influx of the other probably vein-related sulphides. This is consistent with observations in the siltstone, except that pyrite in the arenite and conglomerate is less abundant than in the siltstone. The difference in pyrite abundance is probably related to how detrital sulphides behave in different sedimentary environments. In the high energy environments of the arenite and conglomerate, sulphides are likely to break down quickly into very tiny grains due to their brittle and friable nature, and despite their high density, be carried into a lower energy environment. It seems likely then, that the arenite and conglomerate should have only small amounts of detrital sulphide, whereas the siltstone (at least where deposition first occurs) should have a higher sulphide content and possibly be more evenly distributed.

Isotopically, most pyrite-rich samples from the arenite and conglomerate are similar to those of the background levels in siltstone (Figure 4.1). One sample close to the vein has a higher $\delta^{34}\text{S}$ value and probably resulted from interaction with vein-related fluids carrying isotopically heavier sulphur.

The highest $\delta^{34}\text{S}$ values for pyrrhotite and chalcopyrite at LSV come from a weakly zoned and an unzoned sulphide-rich clot within the conglomerates (LSV-P, LSV-FP). Their $\delta^{34}\text{S}$ compositions lie at or below the lower range for Archean basement sulphides (Goodz et al., 1986). It seems likely that these clots could have been detrital in origin and that their slightly lower-than-Archean basement values could be due to interaction and isotopic exchange with an isotopically lighter vein-fluid. A strongly zoned sulphide-rich clot (LSV-Z) has $\delta^{34}\text{S}$ values similar to the other vein-related wall-rock sulphides and may have

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originally been detrital but has probably interacted with vein-related fluids that altered it isotopically, as well as imparted a zoned pattern to the different sulphide minerals.

Sulphide minerals within the siltstone have higher-than-background $\delta^{34}\text{S}$ values as much as 10 metres from the vein-out, but in the arenite and conglomerate this distance is less and varies somewhat depending upon stratigraphic level (Figures 4.2 and 4.3). This is probably due to the differential permeabilities of the wall-rocks. The siltstones are characterized by fine laminations and are fractured to a much greater degree than the arenites and conglomerates (Chapter II). This probably permitted vein-related fluids to migrate farther in the siltstones than in the other rocks, thus affecting a wider area on either side of the vein adjacent to the siltstones. The difference in grain-size and porosity between arenite beds would affect permeability and fluid flow, and is probably responsible for the variations in sulphide content and zoning with respect to the vein (Figure 3.2).

MacDonald Vein

Sulphur isotopes from the siltstone and paraconglomerate at MCV are similar to that in the siltstone at LSV, but data from the orthoconglomerate does not follow the same trend and is difficult to explain.

Sulphide mineralogy and sulphur-isotopic compositions with respect to distance from MCV are summarized in Figure 4.4. Pyrite in the siltstone at MCV occurs primarily associated with chlorite spots, like that at LSV, which suggests that pyrite from both sites probably share a similar origin, although the higher $\delta^{34}\text{S}$ values at MCV have to be accounted for. Background $\delta^{34}\text{S}$ values for pyrite at LSV average about

Figure 4.4 Sulphur isotopic composition of various sulphide minerals versus distance from the vein-cut at MacDonald Vein.

-0.9 per mil, whereas the pyrite from the siltstone at MCV averages 0.4 per mil (range; 0.0 to 0.7 per mil)(Figure 4.1). This ratio is within the range of $\delta^{34}\text{S}$ values interpreted to be affected by vein-fluids at LSV. For vein-related fluids to have isotopically altered pyrite as far as 12 metres from the vein-cut, this rock would have to be at least as permeable as the siltstone at LSV. This is probably unlikely because the siltstone at MCV is massive, finer-grained and not as well laminated as that at LSV. If a zone of pyrrhotite and/or chalcopyrite and a zone of isotopically heavier pyrite existed around the vein it was probably closer to the vein because of limited permeability and was removed during silver mining. Chalcopyrite veinlets within pyrite from the sample next to the vein may be a remnant of the mineralogic and isotopic zoning that may have existed around the vein. Although the sulphur-isotope ratios at MCV are higher than the "background" $\delta^{34}\text{S}$ values at LSV, the ratios at MCV are fairly consistent throughout the unit, like those at LSV. The sulphur-isotope values are still lower than vein sulphides and neither mineralogic nor isotopic zoning exist in the remaining wall rocks. This indicates that these are probably "background" $\delta^{34}\text{S}$ values.

Mineralogic and isotopic zoning does occur within the paraconglomerate. At distances >3 metres from the vein-cut, the $\delta^{34}\text{S}$ values are similar to those of "background" level pyrite in the siltstone. Adjacent to the vein the sulphides are isotopically heavier. This, in combination with the presence of abundant pyrrhotite next to the vein-cut, suggests an interaction with vein-related fluids.

The sample next to the vein in the orthoconglomerate contains gersdorffite as well as chalcopyrite and pyrrhotite, which suggests an

origin related to vein-forming fluids. The $\delta^{34}\text{S}$ values of these sulphides are as high as reported vein sulphides, and are similar to those of the pyrite in the other orthoconglomerate samples at this site. The sulphur-isotopic composition of this pyrite is much higher than that of the interpreted background level of the siltstone pyrite and implies that all of these samples have interacted with vein-related fluids. The sulphide mineral zoning extends much farther from the vein than in the other rock types (the pyrrhotite-pyrite zone extends about 9 metres from the vein-cut), and implies that the orthoconglomerate may have been more permeable. Pyrite beyond the pyrrhotite-pyrite zone has a high isotopic value. It seems unlikely that the pyrite in the orthoconglomerate shares a similar origin to the "background" level pyrite in the siltstone because of the increased abundance and mode of occurrence of the former. Pyrite concentrations are low ($<0.2\%$) and occur mostly within chlorite spots in the siltstone, whereas in the orthoconglomerate, concentrations are higher (up to 4.05%), and pyrite occurs predominantly as partial replacements of clasts; usually replacing the rims. This suggests that this pyrite may have been deposited from vein-related fluids that permeated this unit.

In summary, pyrite from the siltstone and paraconglomerate have isotopic compositions which are lower than vein sulphides but higher than "background" pyrite at LSV. This pyrite probably formed prior to vein mineralization, possibly during diagenesis or chlorite spotting. A zone of chalcopyrite-pyrrhotite, a zone of pyrrhotite-pyrite, and a zone of isotopically altered pyrite exists in the orthoconglomerate on either side of the MCV and probably existed in the other units but were removed by silver mining operations. These zones were superimposed upon the earlier-formed pervasive "background" level pyrite, and would have had

different widths depending upon the permeability of the host lithology.

Sulphur-isotopic data from the remaining sites do not necessarily follow the same trends shown at LSV and MCV and appear to be complicated by various processes. Some of the other sites occur in areas with many silver veins and vein-related fluids were probably more abundant and more pervasive. $\delta^{34}\text{S}$ values from vein sulphides appear to vary somewhat between different vein systems (Goodz et al., 1986). In addition, background pyrite values appear to vary from site to site. This will probably influence the sulphur isotopic compositions of the Coleman member sulphides, making site to site comparisons difficult.

Vein 3

Pyrite from the sample closest to Vein 3 appears to have formed prior to the chalcopyrite, which occurs as tiny veinlets within the pyrite. This suggests that the chalcopyrite may have a silver-vein related origin. Consistent with this is the sulphur-isotopic trend, which shows that the sample closest to the vein has the highest sulphur-isotope value (Figure 4.5) (Appendix C). The other two samples of pyrite may be too close to the vein to be unaffected by vein fluids, so their lower $\delta^{34}\text{S}$ values cannot be assumed to be at "background" levels.

Coniagas-Trethewey Mine

Pyrite from the laminated sand-silt rhythmites at the CTM occur primarily within chlorite spots and in low concentrations similar to LSV and MCV, which suggests that this pyrite might share a common pre-silver mineralization origin. The sulphur-isotope values, however, are much higher than interpreted background $\delta^{34}\text{S}$ values for MCV and LSV; averaging about 0.9 per mil (Figure 4.1 and 4.6). Although these samples (CTM-102 - CTM-106) were collected at the edge of a wide open-

Figure 4.5 Sulphur isotopic composition of pyrite within siltstone versus distance from the vein-cut at Vein 3.

Figure 4.6 Sulphur isotopic composition of pyrite within siltstone versus distance from the edge of the open pit at Coniagas-Trethewey mine.

cut (estimated to be 40 metres wide), they cannot necessarily be taken as having a "background" sulphur isotope value because these pyrite samples could have interacted with vein-related fluids that may have permeated the area. This area was the most productive in the Cobalt camp; dozens of veins occurred in the immediate area, and the large open-cut was made to remove low-grade ore, which presumably had been affected by ore-forming fluids. Fluids probably affected a much wider area than at LSV or MCV, and hence may have isotopically altered these pyrites.

Sulphides from samples hosting Ag or Co-As veins (CTM-A, CTM-B, CTM-E) possess $\delta^{34}\text{S}$ values compatible with a vein-related origin (see Appendix C).

Silverfields

$\delta^{34}\text{S}$ values from sphalerite-rich samples at SFM range from 2.1 to 2.6 per mil and average 2.3 per mil, which is comparable to the values of both Archean basement and vein sulphides. This, and the presence of ubiquitous gersdorffite in nearly all of the samples examined, indicates that these sulphides share a vein-related origin. The drill-core samples are within 11 to 22 metres of known veins, which implies that vein-related fluids may have permeated these rocks and deposited sulphides at least 22 metres from mineralized veins or that closer unknown veins exist.

Texturally, the sulphides in the conglomerates replace clasts, but in the siltstones the sulphides occur primarily within chlorite spots. Jambor (1971f) implied that chlorite spots developed prior to silver mineralization. If this is the case, the sulphides either developed coeval with the spots prior to mineralization, or were preferentially deposited in the pre-existing spots probably by vein-

related fluids. Chlorite spots may have provided a favourable site for sulphide deposition or perhaps early formed pyrite was replaced by other sulphides with an isotopic composition that reflects deposition by vein-related fluids.

ML Vein

Pyrite is one of the most abundant sulphides at MLV and in many places contains veinlets of sulphides, such as chalcopyrite; pyrite is interpreted to have formed prior to the other sulphides (Chapter III).

Although these samples were collected at different distances from MLV, a non-outcropping vein parallels the sampling lines at a distance of 5 to 20 metres. This could complicate potential zoning, both mineralogically and isotopically. Sulphur-isotope data for composite sulphide samples at the MLV range from 1.4 to 2.8 per mil and average 2.0 per mil. Considering the possibility of mixing lighter sulphur from early-formed pyrite with heavier vein sulphur, these data are consistent with a vein related-origin.

Kerr Lake Arch

The presence of gersdorffite and acanthite (Table 3.8), coupled with high sulphur-isotopic compositions (Appendix C) in the samples from KLA suggest a vein-related origin. Fluids probably permeated the Coleman member at least 30 metres or more from the veins, since this is the maximum distance from veins that samples were collected. Texturally, pyrite appears to have formed prior to the other sulphides as indicated by microveining of the other sulphides within the often euhedral pyrite.

Nipissing Hill

Samples of the Coleman member from NIP contain sulphides including arsenopyrite, gersdorffite, and tetrahedrite with high $\delta^{34}\text{S}$

values (Appendix C). This, in combination with the presence of dozens of silver veins in the vicinity (Figure B.8), suggests that these sulphides were deposited from vein-related fluids, consistent with findings elsewhere in this study.

Several samples of sulphide from narrow (>1 cm wide) veins in the underlying Archean basement possess sulphur-isotope values similar to those in the overlying Coleman member (compare NIP-8401, SMK-2, and MCK-017, with NIP-8402, W-760, and NIP), which suggests a common source. Sample MCK-017 is an Archean conglomerate (described by Donaldson et al., 1986) that contains chalcopyrite which is interpreted to occur as matrix and clast replacements, similar to that in the Coleman member above. Textural similarities and the nearly identical $\delta^{34}\text{S}$ values of sulphides in the Archean and Coleman member conglomerates suggest a common origin. This implies that fluids, probably vein related, permeated both the Coleman member and the Archean rocks to some extent, depositing isotopically similar sulphides in both rock units.

4.6 Discussion

Archean sulphides from this study tend to have the highest $\delta^{34}\text{S}$ values and most fall within the range of values reported by Goodz et al. (1986).

The mineralogy, texture and isotopic composition of sulphide minerals from the Coleman member suggest that most of the sulphides, other than some of the pyrite, were deposited from silver vein-related fluids that permeated rocks adjacent to the veins. The distance from the vein that these fluids permeated probably depended on a combination of host rock permeability and the number of open pathways for fluid to flow through the system. The effect of host rock permeability can be

seen at LSV and MCV (Figures 3.2 and 3.3), where vein-related sulphides occur in the wall rocks at varying distances from the vein, ranging from <2 to about 10 metres. At sites such as SFM, KLA, and NIP, where numerous ore-veins occur in close proximity, a wide variety of sulphides are found at distances of up to 30 metres from known veins. The difference in distance-from-the-vein that the vein-related sulphides occur is probably due to the numerous closely spaced ore-veins and the more abundant vein fluids that presumably were present at the last three sites.

On average, $\delta^{34}\text{S}$ values from LSV are the lowest, whereas values from KLA are the highest, suggesting that the isotopic composition of vein sulphides may vary somewhat between different vein systems at Cobalt. Based on the assumption that most of these sulphides originated from vein-related fluids, there may have been site to site variation in the fluid chemistry (fO_2 , fS , pH, and $\delta^{34}\text{S}$ composition of the fluid) to account for the slight site to site variations in sulphur-isotopic compositions.

Pyrite

Some pyrite, such as that intergrown with native silver at CTM (CTM-C) and perhaps that from the orthoconglomerate at MCV, may have been deposited from vein-related fluids, however, most of the blastic pyrite appears to have formed prior to most of the other sulphides. This is based on three lines of evidence; 1/ pyrite next to LSV has been pseudomorphed to pyrrhotite; 2/ pyrite in many places is riddled with tiny veinlets of other sulphides, usually chalcopyrite; and 3/ blastic pyrite distant from veins at MCV and LSV possesses unique isotopic compositions. It is not clear, however, when this pyrite formed. Pyrite probably formed either during diagenesis, during chlorite spot

development (pyrite and the spots are often associated), or were deposited from an early phase of the vein-related fluids.

The last possibility seems least likely since isotopic compositions would be expected to be higher, fluids would have had to affect a very large area and pyrrhotite in most places appears to be the stable iron sulphide deposited by the vein-related fluids.

Sulphide minerals tend to be friable and are not likely to survive the high energy sedimentary environments that occurred during arenite or orthoconglomerate deposition. Very fine-grained sulphides are likely to be carried into a calmer environment, such as that of the siltstones. Clastic sulphide, in the form of very fine-grained detritus in the fine-grained rocks (siltstone and paraconglomerate), is likely the source of pyrite which was mobilized into blastic, often euhedral grains during diagenesis or chlorite spotting. To account for the low $\delta^{34}\text{S}$ composition of early-formed blastic pyrite, as compared to the probable detrital source of isotopically heavier Archean basement sulphides, fractionation during sulphide mobilization is postulated.

Sulphur Isotope Thermometry

Under equilibrium conditions ^{34}S will partition itself among different sulphide minerals in the following order of enrichment: pyrite > pyrrhotite = sphalerite > chalcopyrite > galena (Kajiwara and Krouse, 1971). The difference in $\delta^{34}\text{S}$ values between different sulphide minerals is related by isotopic fractionation constants and is a function of temperature only (Ohmoto and Rye, 1979). This allows the use of sulphide mineral pairs as a geothermometer, assuming that isotopic equilibrium has been attained. The sulphur-isotopic fractionation constants used in the present study are those of Kajiwara

and Krouse (1971).

Goodz et al. (1986) suggested that vein fluids at the BTM evolved during mineralization. Early vein fluids had a low sulphur fugacity and deposited silicates and arsenides at temperatures near 250°C. As mineralization progressed, the sulphur fugacity of the fluids increased, temperatures dropped to about 150°C, and sulphides were precipitated. This suggests that if sulphides were deposited in the Coleman member from late stage vein fluids, then they should yield sulphur-isotopic temperatures of less than 200°C.

Temperatures calculated using sulphide pairs from the Coleman member show a high degree of scatter (Figure 4.7). Eleven of the 38 sulphide pairs analyzed display reverse fractionation, four calculated temperatures are above 796° C, which geologically is unreasonably high, and one temperature is calculated at 1° C. Three out of five pyrrhotite - sphalerite pairs appear to be in equilibrium, and only three of the remaining 19 calculated temperatures lie within the range of vein temperatures reported by Goodz et al. (1986). The 16 remaining calculated temperatures fall between 394° and 593° C (Figure 4.8), which is higher than temperatures found from fluid inclusions, oxygen isotopes, or arsenopyrite geothermometry (summarized in Goodz et al., 1986). Since nearly half of the sulphide pairs are obviously in disequilibrium, and most of the calculated temperatures are higher than expected for a vein-related origin, the sulphides may have been deposited rapidly enough that isotopic equilibrium was not attained, or in some instances approached but not attained. Perhaps as the sulphides replaced clasts they could have been isolated from further interaction with vein-related fluids, preserving a disequilibrium isotopic composition.

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Figure 4.7 Calculated temperatures for sulphide pairs showing experimental range in temperatures. Sulphur isotopic equilibrium fractionation factors used are those of Kajiwara and Krouse, 1971.

Figure 4.8 Histogram of calculated temperatures for sulphide pairs.

It is possible that the 16 higher-than-expected temperatures are true equilibrium temperatures and that these sulphides were deposited between 394° and 593° C, and not from cooler vein-related fluids. Perhaps these sulphides were deposited from warmer very early phase vein-related fluids. This fluid would have been capable of carrying and depositing Ag, Co, Ni, and As-bearing minerals, since these minerals occur in the Coleman member. Unfortunately this hypothesis is inconsistent with the conclusions of Goodz et al. (1986). Goodz et al. (1986) suggested that the sulphur fugacity of early vein fluids was low enough that sulphides would not be deposited. As mineralization progressed and the temperatures dropped, the sulphur fugacity of the vein fluids increased to the point where sulphides were able to precipitate.

Another consideration is the possible influence of contamination by small amounts of other sulphides and sulpharsenides. Many separates contain additional sulphide species in concentrations ranging up to 15%. Gersdorffite is present as tiny grains within sulphides in many samples, and acanthite or tetrahedrite may be present in others.

Overall, the high degree of disequilibrium among the sulphur-isotope pairs and the possible effects of contamination indicates that many of the temperature data probably cannot be relied upon for consistent or accurate results.

CHAPTER V

CONCLUSIONS

5.1 Introduction

In an attempt to fill gaps in our overall geologic knowledge of the Cobalt mining camp and to improve genetic models of silver-vein formation, this thesis investigated sulphide mineralization primarily from the Coleman member host-rocks of some silver veins, and structural aspects of these rocks. The mineralogical, textural and sulphur-isotopic composition of sulphides were examined in order to help determine their origin and to place constraints on various ore-forming parameters. A study of systematic joint patterns helped to determine the structural setting of the ore-veins and part of the structural history of the area. The conclusions of these various investigations are presented in the following sections.

5.2 Structural Geology and Structural Controls on Vein Mineralization;

The following are conclusions concerning the joints in the Cobalt area;

- 1) Systematic joints occur mainly in seven sets with orientations of 030° , 060° , 085° , 110° , 130° , 150° , 175° and nearly vertical dips.
- 2) Joints trending 030° , 110° , and 150° are most abundant (Figures 2.5 and 2.10).
- 3) Vein orientations are, in general, similar to those of the joints (Figure 2.8), and have several features in common, which indicate that most of the ore veins occupied and filled pre-existing joints. Since joints are most abundant in the Coleman member,

veins are more common in the Huronian rocks, but irregular and uncommon in the Archean rocks.

- 4) Joints probably occurred in response to a nearly horizontal, roughly NW-SE compressive event that also generated thrust faults (Cobalt Lake, Valley, Coniagas, and Trethewey Faults), minor folds and small, low angle, reverse faults. The compression may have varied in orientation by 40 or 50° during the development of the brittle structures.
- 5) Joints, faults and minor folds appear to be bracketed in time by Nipissing diabase emplacement and vein mineralization, and are probably about 2200 M.a. old (Table 2.4).

5.3 Coleman Member Sulphide Minerals;

The following are conclusions concerning the mineralogy and textures of the sulphide minerals within the Coleman member;

- 1) Sulphide minerals occurring within the Coleman member rocks are;
 - chalcopyrite, pyrrhotite, pyrite, sphalerite, galena, tetrahedrite, acanthite, gersdorffite, arsenopyrite, boulangerite, pyrargyrite, covellite, bornite, and possibly pentlandite.
- 2) Pyrite is often blastic in texture, arsenopyrite is usually euhedral, and the other sulphides usually occupy space between detrital material or partially replace clasts in association with chlorite, with or without carbonate and plagioclase. Within siltstones, sulphides are often restricted to or preferentially located within chlorite spots. Sulphides within arenites usually occupy space between clastic grains and partially replace adjacent clasts. Within the orthoconglomerates,

sulphides occur in a manner similar to that in the arenites; as well, the sulphides and chlorite partially replace clasts.

- 3) At some sites sulphides are more abundant and mineralogically zoned proximal to veins, indicating a vein-related origin, whereas at other sites a variety of sulphides are dispersed throughout the rock regardless of proximity to veins. However, the presence of Co, Ni and Ag-bearing sulphide minerals in these latter rocks suggests a vein-related origin for all of these non-zoned sulphides.
- 4) In general, pyrite is the only sulphide to occur distant from silver-veins, and a more complex sulphide mineralogy occurs proximal to veins.
- 5) Blastitic pyrite, common in the siltstones, is often cut by microveins of other sulphides. Thus, it is interpreted to have formed prior to vein-related sulphide deposition, perhaps during diagenesis or chlorite spot development.

5.4 Sulphur Isotope Geochemistry;

The following conclusions result from the interpretation of sulphur-isotope data in conjunction with sulphide mineral textures;

- 1) The mineralogy, texture, and isotopic composition of sulphide minerals from the Coleman member indicate that most of the sulphides, other than some of the pyrite, were deposited from vein-related fluids that permeated rocks adjacent to the veins.
- 2) The extent to which vein-related fluids permeated the Coleman member is probably a combined function of host rock permeability and fracture intensity.
- 3) Sulphur-isotopic compositions and textures of the sulphides in

limited samples of the Archean rocks at Nipissing Hill, as shown by Goodz et al. (1986), suggest that vein-related fluids permeated and deposited sulphides in parts of the Archean basement.

- 4) Most pyrite formed prior to vein emplacement, probably during diagenesis or chlorite spot development, by mobilization and recrystallization of low concentrations of detrital sulphide in the fine-grained sedimentary rocks.
- 5) Pyrites distant from the vein at Little Silver Vein and MacDonald Vein have low $\delta^{34}\text{S}$ compositions (-0.9 and 0.4 per mil, respectively), which are probably characteristic of the $\delta^{34}\text{S}$ composition of sulphides present prior to vein mineralization.
- 6) Pyrite close to the veins at Little Silver Vein and MacDonald Vein was altered either isotopically or mineralogically by vein-related fluids. The $\delta^{34}\text{S}$ value of pyrite has increased to levels similar to those of vein sulphides. Pyrite adjacent to the veins has been altered to ~~pyrrhotite~~, chalcopyrite and gersdorffite, or contains veinlets of other sulphides (usually chalcopyrite).
- 7) Arsenopyrite and an arsenopyrite-rich mineral separate have the highest $\delta^{34}\text{S}$ values at Little Silver Vein and are among the highest from this study, although Goodz et al. (1986) found that the isotopic composition of arsenopyrite was commonly lower than this in volcanic rocks at the Beaver-Temiskaming Mine.
- 8) Many sulphide pairs are not in isotopic equilibrium, and most yield temperatures too high to be consistent with a vein-related origin. Because of abundant and obvious disequilibrium, and possible contamination from other sulphides within a sample,

calculated equilibrium temperatures are assumed to be mostly unreliable.

5.5 Ore Forming Models

The structural data presented suggest that joints, faults and folds may be roughly coeval and occurred during or just prior to silver mineralization. Thus, brittle fracturing of rocks permeated with fluid may have induced boiling or phase separation by a sudden drop in fluid pressure below the diabase, and may have initiated vein-mineral deposition as proposed by Strong (1985) and Watkinson (1986).

Most Archean volcanic terrains contain local concentrations of sulphide minerals. Since the Coleman member is derived from eroded Archean granitic and volcanic rocks, it must contain some detrital sulphides. However, evidence presented in this study suggests that most sulphides in the Coleman member other than some of the pyrite, have a vein-related origin. Most pyrite appears to be derived by mobilization of probably original detrital sulphide.

Ore forming models developed for the Cobalt silver veins differ widely in their interpretation of the source of the vein elements. Proposed sources include the Nipissing diabase or its parental magma (Jambor, 1971e), deep-seated unknown sources (Halls and Stumpfl, 1969), the Archean basement sulphides (Goodz et al., 1986; Boyle and Dass, 1971), or the Coleman member (Appleyard, 1980; Strong, 1985). The data presented in this study do not necessarily help to define the source of the vein elements but they do help outline some of the characteristics of the vein fluids.

Within the fine-grained sedimentary rocks, the recrystallization of minor amounts of detrital sulphide to blastic pyrite may have been

capable of releasing some of the vein elements to formational fluids as proposed by Watkinson (1986). An electron-microprobe study of the siltstone-hosted blastic pyrite may reveal if this is possible. The low sulphur-isotopic values for this pyrite suggest that sulphur remaining in the mobilizing fluids would probably be higher than that of the detrital source, the Archean basement sulphides. This is consistent with the suggestion by Goodz et al. (1986) that vein-fluid sulphur is isotopically much heavier (about 7.9 per mil) than Archean basement sulphides (about 4.0 per mil). However, since most of the Coleman member sulphides are interpreted to have originated from vein-related fluids, the Coleman member should be viewed as a potentially minor source for the vein elements.

Most sulphides in the Coleman member were probably deposited by vein-related fluids circulating through the wall rocks during or close to the time of silver mineralization. This is consistent with most ore genesis models in that ore fluids, regardless of source, would probably be capable of depositing a halo of sulphide minerals peripheral to the vein deposits. Thus, this study leaves the problem of vein-element source unresolved.

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APPENDIX A

Description of Systematic Joints

Two types of joints were noted, extensional and tight.

Extension Joints

One type of joint found at Cobalt is clearly extensional and is very rare. It occurs as swarms of veinlets covering a few square metres. Their maximum length is about two metres, and are for the most part planar and sub-parallel with a spacing of centimetres to decimetres.

Extension joints range in thickness from 1-30 mm and are filled predominantly with fibrous quartz which grew perpendicular to the joint walls. There may also be minor amounts of calcite, chlorite or potassic feldspar present.

Tight Joints

Tight joints (<1 mm thick), the most abundant type of systematic joints, occur throughout the Cobalt camp. They are generally steeply dipping (70-90°), however, their intensity and orientation may vary locally.

Tight joints are for the most part planar, but some curve slightly and oscillate between two orientations five to twenty degrees apart, somewhat like a wave. In order to obtain the strike of the enveloping surface a range of orientations was recorded and the average value plotted. Joints rarely appear to be arcuate. East of Cobalt, a 25 square metre area hosts intense arcuate jointing, the centres of which have a common tangential trend of 110° and if extended would scribe a circle with a one metre radius. At a site east of Nipissing Hill and

west of Peterson Lake, immediately below the diabase, joints occur in an oval pattern about 5 by 10m. These may be related to circular cooling joints in the overlying diabase, which is only a few metres above this site, such as those noted by Jambor (1971d).

Most outcrops display more than one systematic joint set. In many cases joints of different sets are superimposed upon each other. In a few outcrops, one joint set is dominant in one small area and another set dominant in another area. Occasionally joints of one set change orientation and become a new set. This results in a patchy distribution of orientations and intensities. As many as five different systematic joint sets can occur in one outcrop, but generally only two or three sets occur together.

Although no consistent attempt was made to measure the strike length or dip length of the joints, the former appears to vary from centimetres to decametres. These variations in length can occur within a single outcrop. At one locality just south of the MacDonald Vein, a joint set having strike lengths in the order of decimetres displays an en echelon pattern. At the Coniagas-Trethewey Mine, two vertical exposures show a similar en echelon pattern on the dip lengths. Since en echelon patterns are only found at these sites, it is not considered an important aspect to the overall joint pattern at Cobalt.

Joints with offsets are rare, but have been observed at four sites. Displacements range from 0.5 to 5 mm. Three poorly exposed sites at the Coniagas-Trethewey Mine show a strike-slip component, with both right and left-handed movements. Well-exposed silt and mud rhythmites along the south-east side of Nipissing Hill show vertical displacements on one of two prominent joint sets. About 50% of the joints show movement and

about 80-90% of those are displaced southeast side down.

The distance between joints range from less than a centimetre to two metres or more. At several sites short, discontinuous and closely spaced joints occur between longer continuous joints of the same orientation that have a wider spacing.

In most places minerals occupying joint surfaces were not visible. In well exposed areas, where mineral infillings may be found, the most abundant mineral occurring on the joint surfaces is chlorite less than 0.5 mm thick. In fresh exposures at the Coniagas-Trethewey Mine, calcite up to 1mm thick, calcite and chalcopryrite, or calcite and chlorite are rarely found. Erythrite also occurs on some joint surfaces. This ~~could~~ be due to the weathering of cobalt arsenide minerals contained on the joint face or could possibly be due to erythrite, derived from a nearby silver vein, being deposited on the fracture surface.

Joints with mineral infillings were only found on fresh exposures such as mine workings and road cuts where the minerals are not likely to have weathered away. No mineral infillings were found in the rounded outcrops where most joints were observed. It seems likely that infilling minerals are more abundant than observed (although probably not ubiquitous), because infilling minerals would weather recessively on weathered outcrops and remain undetected.

Alteration halos occur along some joints at 12 of the 792 sites in the Cobalt area, mostly at the Coniagas-Trethewey Mine and the southeast side of Nipissing Hill. These halos have a bilateral symmetry and consist of continuous dark green bands or spots and white or bleached bands. This is similar to the alteration halos around silver veins described by Dass (1970). Halos observed at the Coniagas-

Trethewey Mine all have chlorite on their associated joint faces.

Host lithology can have an influence on the joint spacing and intensity. The most striking example of this is exposed on the cliffs in the vicinity of the MacDonald Vein. Massive siltstone is overlain by a condensed framework-supported orthoconglomerate forming a knife-sharp contact. Joint spacing in the siltstone is about 10 cm, whereas in the conglomerate it is about one metre. Most joints in the siltstone end abruptly at the contact or extend a few decimetres into the conglomerate before ending. Only about 10% of the joints pass through both rock types. Similar relationships can be observed at the vein cuts on Fault 64, and at the Little Silver Vein. Just south of Vein 3, joint spacing in orthoconglomerate (clasts >50%) is wider than that in the overlying paraconglomerate (clasts 5-10%), while a bed of sandstone has no visible joints. Joints in a sand-silt rhythmite at the Coniagas-Trethewey Mine are spaced closer than those in the overlying paraconglomerate. Systematic joints are often more abundant in large (.5-1m) granitic clasts than within a paraconglomerate host. At the Little Silver Vein, joints are abundant in the siltstones and poorly developed to nearly absent in the overlying arenite. In general, joint intensity is greatest within the rhythmites, less intense in the conglomerates, and poorly developed within the arenites.

Jointing in the Archean volcanic rocks is generally irregular, inconsistent and much less intense than in either the Coleman member or the Archean interflow sedimentary rocks. This has also been noted by Lowes (1963) at the Old Casey Mine in nearby Casey Township, Ontario.

Systematic joints were generally hard to find in the volcanic rocks, hence orientations were recorded wherever joints could be found

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instead of at regular intervals. Upon passing from the Coleman member through the unconformity into the Archean volcanic rocks, joints were observed to both weaken and strengthen; most often joints either weakened or ended in the volcanic rocks.

Joints sometimes parallel silver veins (now mined out) and often their intensities increase adjacent to the vein. This is well developed in the vicinity of the MacDonald Vein and the Coniagas-Trethewey Mine. Strong joints in an outcrop in Cobalt, when projected, line up with major vein cuts at the Coniagas-Trethewey Mine.

APPENDIX B

Sample Locations and Site Descriptions

During the course of this study, hundreds of samples were collected, mainly from old surface mine workings, not all of which were examined in detail. Only those specimens examined, either isotopically, petrographically, or both are described here.

Little Silver Vein

At Little Silver Vein (LSV), a prominent cliff exposes a coarsening upwards succession of Coleman member rocks ranging from laminated siltstones at the base through arenite and orthoconglomerate at the top. A stratigraphic column by Mustard (1985) summarizes the rock types and geology (Figure B.1a). The base of the cliff is approximately 50m above the Archean-Coleman unconformity (Thompson, 1967) and at least 110 metres below the Nipissing Diabase.

Twenty samples were collected from a single 30 cm-thick bed of laminated siltstone at different distances from the vein. The remaining samples were collected at different stratigraphic levels and various distances from the vein in the arenite and orthoconglomerate (Figure B.2). In addition, three specimens with sulphide-rich clasts from the mine dumps were examined and analysed.

MacDonald Vein

The rock types of the MacDonald Vein (MCV) are summarized in a geologic section by Mustard (1985) (Figure B.1b). The base of the exposed cliff is about 5-15m above the unconformity and between 90 and 120m below the bottom of the Nipissing Diabase.

Samples were collected from the arenite at the vein-cut wall and

Figure B.1 Stratigraphic column of the

A; Little Silver Vein area.
B; MacDonald Vein. area.
C; Nipissing Hill area.
(after Mustard, 1985).

A **B** **C**

Figure B.2 Sample locations at Little Silver Vein. (Note; all sample numbers are preceded by the letters "LSV").

at intervals away from the vein in the upper siltstone, paraconglomerate, and orthoconglomerate exposed in a prominent cliff face (Figure B.3). Unfortunately awkward exposures made it impossible to continuously sample any single unit, hence samples from different rock types do not follow specific beds, as they do in the siltstones at LSV.

Coniagas-Trethewey Mine

Specimens from the Coniagas-Trethewey Mine (CTM) were taken from both outcrops and mine dumps. Dump material comprised samples with high sulphide content or specimens hosting mineralized veins. Figure B.4 shows outcrop sample locations. Five samples were collected along one sand-siltstone rhythmite at different distances from the vein-cut. These samples are about 40m above the Archean-Coleman unconformity and an unknown distance below the diabase.

Silverfield Mine

Two samples collected at Silverfields Mine (SPM) come from waste-rock piles near the headframe. The remaining specimens are diamond drill core from the fifth level of the mine collected at intervals between two veins (Figure B.5). The core is composed of two samples of siltstone and four of orthoconglomerate. Drill core is approximately 18m above the unconformity and about 55m below the diabase as determined from maps by Petruk (1968).

ML Vein

Samples from the ML Vein (MLV) are within 5m of the Archean-Coleman unconformity and about 80m below the diabase (based on cross-sections by Kim, 1979). All samples consist of orthoconglomerate taken from surface exposures at various distances from the MLV (Figure B.6).

SAMPLE LOCATIONS AT MacDONALD VEIN

Figure B.3 Sample locations at MacDonald Vein. (Note; all sample numbers are preceded by the letters "MCV").

Figure 8.4 Sample locations at Coniagas-Trethewey mine.

Figure B.5 Sample locations at the Silverfields mine.

Figure B.6 Sample locations at the ML Vein.

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influence on the samples is unknown.

The MLV, hosted mainly in the Coleman member, is unnamed on Thompsons' (1964a) geology map, but appears to be the northern extension of Vein 65, which occurs in Archean rocks.

Kerr Lake Arch

Samples from Kerr Lake Arch (KLA) are located in Figure B.7. Three samples adjacent to the Fleming Vein, five samples from Drummond Cairn and vicinity, and one sample at the west end of the KLA comprise the Coleman member specimens. An additional three samples were collected from Archean rocks at the eastern end of the arch. Except for the Fleming Vein specimens, the Coleman member samples were collected within 10m or less of the Archean-Coleman contact. Distance from the Nipissing diabase is unknown.

Nipissing Hill

Nipissing Hill (NIP) is the name of a broad hill east of and overlooking the town of Cobalt. Samples include both Archean and Coleman member rocks (Figure B.8) and are probably about 100 to 120m below the diabase. Coleman member samples range from 0-10m above the Archean-Coleman unconformity. Four samples collected at 1-2m intervals straddle the unconformity in close proximity to a mined out vein. Figure B.1c, a stratigraphic column, summarizes the rock types of the Nipissing Hill area.

Several Archean interflow samples were collected on the western flank of the hill (Figure B.8) by M. Smyk (SMK-2, MCK-017, and SMK-22).

Figure B.7 Sample locations at the Kerr Lake Arch.

Figure B.8 Sample locations at Nipissing Hill

APPENDIX C

LIST OF SULPHUR-ISOTOPIC RATIOS

<u>SAMPLE #</u>	<u>ROCK TYPE</u>	<u>CONTENTS</u>	<u>TYPE</u>	<u>S³⁴</u>	<u>VALUE</u>
Little Silver Vein Samples					
LSV-A	CM Silt	PO 100%	PO		1.4
		CP 95%, (GERS 5%)	CP		0.5
LSV-B	CM Silt	PO 100%	PO		1.4
		CP 95%, (GERS 5%)	CP		6.6
LSV-1	CM Silt	PO 100%	PO		2.4
		CP 95%, (GERS 5%)	CP		1.8
LSV-2	CM Silt	PO 100%	PO		0.2
		CP 95%, (GERS 5%)	CP		1.5
LSV-3	CM Silt	PY 97%, (CP 3%)	PY		0.6
LSV-4	CM Silt	PY 99%, (CP 1%)	PY		0.0
LSV-5	CM Silt	PY 99%, (CP 1%)	PY		1.6
LSV-6	CM Silt	PY 100%, (CP (R))	PY		1.0
					0.3
LSV-7	CM Silt	PY 100%	PY		0.0
LSV-8	CM Silt	PY 100%, (CP (R))	PY		-0.7
LSV-9	CM Silt	PY 100%	PY		-1.6
LSV-10	CM Silt	PY 100%, (CP (R))	PY		-1.3
LSV-12	CM Silt	PY 100%, (CP (R))	PY		-0.7
LSV-14	CM Silt	PY 100%, (CP (R))	PY		-0.9
LSV-16	CM Silt	PY 98%, (CP 2%)	PY		-1.1
LSV-18	CM Silt	PY 100%, (CP (R))	PY		-1.0
LSV-20	CM Silt	PY 99%, (CP 1%)	PY		-0.7
LSV-24	CM Silt	PY 100%	PY		-0.8
LSV-26	CM Silt	PY 100%	PY		-0.9
LSV-28	CM Silt	PY 100%	PY		-0.5

Little Silver Vein Samples (cont.)

LSV-30	CM Cong	CP 95%, GAL 5%, PY ?	CP	1.2
LSV-31	CM Cong		PY	-0.8
LSV-32	CM Cong	PO 100% CP 98%, GAL or TET 2%	PO CP	0.3 1.0
LSV-33	CM Aren	CP 100%	CP	1.0
LSV-35	CM Cong	PO 100% (MAG) CP 100% (HP) CP 95%, (GAL, PY?, ARS 5%)(HCl rejects) GAL 100% (HP) GAL 100% (Ag ₂ S)	PO CP GAL	1.1 2.6 2.1 -0.9 -0.8
LSV-36	CM Cong	ARS 85%, CP 15%	ARS+CP	3.6
LSV-38	CM Aren	CP 96%, ARS 4%	CP	0.9
LSV-39	CM Aren	CP 100%	CP	1.3
LSV-42	CM Silt	ARS 95%, CP 5%	ARS	4.6
LSV-43	CM Silt	ARS 99%, CP 1%	ARS	4.5
LSV-44	CM Silt	ARS 99-100%, CP 0-1%	ARS	3.9
LSV-47	CM Aren	CP 40%, ARS 35%, TET? 20%, GAL 5%, BOUL 2%	S	0.8
LSV-48	CM Aren	PO 100% (MAG) CP 85%, GAL 5%, TET? 10%	PO CP	0.1 -0.1
LSV-49	CM Aren	PO 100% (MAG) CP 100%	PO CP	0.3 0.5
LSV-50	CM Aren	CP 90-95%, ARS 5-10%	CP	0.9
LSV-51	CM Aren	CP 99%, ARS 1%	CP	0.9
LSV-53	CM Aren	PY 60%, CP 40%	PY+CP	0.5
LSV-55	CM Cong		PY	0.2
LSV-56	CM Cong	PY 95%, CP 5% (OR LESS)	PY	-0.5
LSV-57	CM Cong	CP 70%, PY 30%	PY+CP	-1.1
LSV-58	CM Aren		CP	0.2
LSV-59	CM Aren	CP 40%?, PY 40%?, ARS? 20%?	S	1.6
LSV-60	CM Aren	CP 100% (some COV coatings)	CP	1.1

Little Silver Vein Samples (cont.)

LSV-63	CM Aren	CP 100% (some COV coatings)	CP	0.8
LSV-64	CM Aren	CP 100% CP 100%	CP	1.1 1.1
LSV-66	CM Aren	PY 98%, CP 2%	PY	-1.4
LSV-67	CM Silt	PY 95%, CP 5%	PY	-0.6
LSV-FP	CM Cong	PO 100% (MAG) CP 100% (HP)	PO CP	3.0 2.7
LSV-P	CM Cong	PO 100% (MAG) CP 100% (HP)	PO CP	1.9 1.8
LSV-Z	CM Cong	PO 100% (Ag ₂ S) CP 100% (HP) SPH 100% (HP) GAL 100% (HP)	PO CP SPH GAL	0.1 0.9 1.1 -0.2

MacDonald Vein Samples

MCV-303	CM Cong	PO 60%, PY 40%	PY+PO	1.5
MCV-304	CM Cong	PY 100%	PY	1.5
MCV-305	CM Cong	PY 100% (HP)	PY	0.8
MCV-306	CM Cong	PY 100%	PY	0.7
MCV-307	CM Silt	PY 100%	PY	0.0
MCV-308	CM Silt	PY 100%	PY	0.4
MCV-309	CM Silt	PY 99%, CP 1%	PY	0.4
MCV-310	CM Silt	PY 99%, CP 1%	PY	0.5
MCV-312	CM Silt	PY 100%	PY	0.5
MCV-313	CM Silt	PY 98%, CP 2%	PY	0.3
MCV-314	CM Silt	PY 100%	PY	0.7
MCV-315	CM Cong	PO 100% (MAG) CP 100%	PO CP	2.1 1.9
MCV-316	CM Cong	PY 100%, CP (R)	PY	1.8
MCV-317	CM Cong	PY 74%, PO 24%, CP 2%	PY+PO	1.0
MCV-318	CM Cong	PY 100%	PY	1.8

MacDonald Vein Samples (cont.)

MCV-319	CM Cong	PY 85%, PO 10%, CP 5%	PY+PO	2.7
MCV-320	CM Cong	PY 100%	PY	2.0
MCV-321	CM Cong	PY 100%	PY	2.0

Vein 3 Samples

VT-290	CM Silt	PY 80%, CP 18%, PO? 2%	PY+CP	0.3
VT-291	CM Silt	PY 99%, CP 1%	PY	-0.1
VT-292	CM Silt	PY 98%, CP? 2%	PY	-0.2

Coniagas-Trethewey Mine Samples

CTM-A	CM	CP 40%, ARS 30%?, TET 30%?	CP+ARS+TET	1.5
CTM-B	CM	CP 70%, ARS 30%, SPH (R)	CP+ARS	2.5
CTM-E	CM	CP 60%, ARS 40%	CP+ARS	3.2
CTM-N	CM Silt		SPH+ARS	2.4
CTM-O	CM PEBBLE	CP 50%, PO 40%, PY 10%	CP+PO+PY	1.0
CTM-PE	CM PEBBLE	PY 60%, CP 40%	CP+PY	1.1
CTM-W	CM Cong	BOR 70%, ARS 25%, CP 5%	BOR+ARS	2.2
CTM-102	CM Silt	PY 100%	PY	1.1
CTM-103	CM Silt	PY 100%	PY	0.5
CTM-104-a	CM Silt	PY 100%	PY	1.0
CTM-104-b	CM Silt	PY 100%	PY	1.1
CTM-105	CM Silt	PY 100%	PY	0.7
CTM-523	CM Aren	PY 100%, CP ?	PY	0.1

Silverfields Mine Samples

SF-A	CM Cong	SPH 96%, CP 2%, GAL 2%	SPH	2.3
SF-B	CM Cong	PO 100% (MAG) SPH 96%, CP 2%, PY? 1%, ? 1%	PO SPH	4.1 2.6
SFM-8421	CM Silt		CP+SPH	2.2
SFM-8422	CM Silt	SPH 97%, CP 2%, PO 1%	SPH	2.1

Silverfields Mine Samples (cont.)

SFM-8424	CM Cong	SPH 85%, CP 13%, GAL 2%	SPH	2.3
SFM-8427	CM Cong	SPH 88%, GAL 10%, CP 2%	S	2.4
SFM-8429	CM Cong	SPH 55%, GAL 40%, CP 5%	S	2.1
SFM-8430	CM Cong	GAL 93%, CP 5%, SPH 2%	GAL	0.9
SFM-85001	CM Aren	TET 100% (HP)	TET	1.6

ML Vein Samples

MLV-256	CM Cong	PO 100% (Ag ₂ S)	PO	1.3
		CP 80%, PY 20%	CP+PY	1.7
MLV-261	CM Cong	PY 54%, SPH 25%, CP 3%, GAL 1%	S	1.9
MLV-262	CM Cong	PY 90%, PO 5%, CP 3%, GAL 2%	PY	1.4
MLV-263	CM Cong	PY 55%, CP 35%, PO 10%, SPH (R)	PY+CP+PO	1.8
MLV-265	CM Cong	PY 35%, PO 30%, CP 30%, SPH 5%	PY+CP+PO	1.9
MLV-266	CM Cong	SPH 100% (HP)	SPH	1.1
		SPH 100% (HP)		2.3
		GAL 100% (HP)	GAL	0.5
		PY 40%, GAL 25%, CP 20%, SPH 15%	S	1.9
MLV-267	CM Cong	SPH 15%, PY 30%, CP 20%, PO 10%, GAL 5%	S	2.0
MLV-268	CM Cong	PY 60%, CP 15%, SPH 15%, PO 5%, GAL 5%	S	2.8
MLV-270	CM Cong	PY 50%, CP 50%	CP+PY	2.6
CW-25	CM Cong	PO ? (Ag ₂ S) (contamination)	PO	5.3 (reject)
		GAL 50%, PY 25%, CP 10%, SPH 10%, PO 2%	S	1.5
CW-30	AR SUPH	PY 100%	PY	7.1

Kerr Lake Arch Samples

FV-340	CM Aren	PO 100% (MAG)	PO	3.3
		SPH 95%, CP 4%, GAL 1%	SPH	3.2
FV-341	CM Aren	PO 100% (MAG)	PO	3.5
		PO 100% (MAG)	PO	3.1
		PO 100% (Ag ₂ S)		2.8
		PO 100% (Ag ₂ S)		3.0
		SPH 90%, CP 10% or less	SPH	3.2
FV-342	CM Aren	PO 100% (MAG)	PO	3.1
		GAL 100% (HP)	GAL	2.4

CP 97%, ARS 2%, GAL 1%, SPH (R)
(HCl rejects)

CP 3.4
3.5

Kerr Lake Arch Samples (cont.)

IS-350	AR INFL	SPH 81%, GAL 15%, CP 2%, PO 2%	SPH	1.1
IS-351	AR INFL	PO 60%, SPH 35%, CP 5%	S	2.9
DC-TOP	CM Cong	GAL 100% (HP)	GAL	1.3
		GAL 100% (Ag ₂ S)		1.4
		GAL 100% (Ag ₂ S)		1.5
		GAL 40%, CP 30%, PY 30%	S	3.1
		PY 50%, CP 50%	PY+CP	3.5
DC-MID	CM Cong	PY 75%, SPH 20%, CP 5%	S	3.0
DC-BOT	CM Cong	PY 45%, SPH 40%, GAL 10%, CP 5%	S	2.4
KLA	CM Cong	PO 100% (MAG)	PO	4.0
		CP 66%, TET?, ARS? 30%, GAL 2%, SPH 2%	S	3.0
KLA-353	CM Cong	PY 50%, CP 40%, SPH 10%	S	2.8
KLA-354	CM Cong	PO 100% (MAG)	PO	3.1
		CP 96%, GAL 2%, SPH 2%	CP	3.3
KLA-650	CM Cong	PY 90%, CP 10%	PY	2.6

Nipissing Hill Samples

NIP	CM Cong	SPH 100% (HP) (possibly GERS)	SPH	2.0
		SPH 100% (Ag ₂ S)		2.2
		GAL 100% (Ag ₂ S)	GAL	0.7
		SPH 96%, CP 3%, GAL 1%	SPH	2.1
NIP-8401	AR VOLC	PO 100% (MAG)	PO	3.6
		GAL 100% (HP)	GAL	2.4
		SPH 100% (HP)	SPH	3.5
NIP-8402	CM PEBBLE	GAL 98%, TET 2%	GAL	1.5
NIP-8402	CM Cong	GAL 99%, CP 1%	GAL	1.9
		GAL 100% (Ag ₂ S)		2.2
		SPH 80%, GAL 15%, CP 5%	SPH	3.5
NIP-8403	CM Cong	CP 98%, TET or ARS 2%	CP	2.9
NIP-8404	CM Cong	CP 85%, ARS 15%, GAL (R)	CP+ARS	2.6
W-731	CM	PY 98%, CP 2%	PY	4.1
W-741	CM	PY 95%, CP 5%, PO (R?)	PY	1.9

Nipissing Hill Samples (cont)

W-760	CM Cong	SPH 100% (HP)	SPH	4.6
		SPH 99%, CP 1%		3.3
		SPH 100% (Ag ₂ S)		4.3
SMK-2	AR VEIN	CP 75%, PO 15%, SPH 5%, GAL 5%	S	3.6
	AR Chrt	PO 100% (MAG)	PO	3.0
MCK-017	AR Cong	CP 100% (HP)	CP	3.4
	AR VEIN	CP 100% (HP)	CP	3.2
SMK-22	AR VEIN	SPH 60%, GAL 40%	SPH+GAL	4.5

Langis Mine, Casey Township, Samples

LM-17	CM Cong	CP 100% (HP) (possibly ARS+GERS)	CP	-2.1
		GAL 100% (HP) (possibly some TET)	GAL	-1.9
		SPH 100% (HP) (possibly some GAL)	SPH	-0.1
LM-5000	AG VEIN	CP 100% (HP)	CP	2.1
		GAL 100% (HP)	GAL	0.8

Isolated Samples

MS-1	AR SUL	PO 100% (HP)	PO	5.1
SMK-1	AR SUL	PO 100% (MAG)	PO	3.6
		PY 100% (HP)	PY	5.0

(HP) = Hand Picked

(MAG) = Magnetic Separate

(Ag₂S) = Chemically converted to Silver Sulphide before isotopic analysis

(CP 2%) = Sulphide percentage estimated from thin section data as opposed to direct observation

(R) = rare

AR = Archean

CM = Coleman member

Silt = siltstone

Cong = conglomerate

PY = pyrite

PO = pyrrhotite

SPH = sphalerite

TET = tetrahedrite

BOR = bornite

BOUL = boulangerite

132 samples

171 separates

186 analyses

Aren = arenite

Chrt = bedded chert

Infl = interflow sedimentary rocks

SUL = massive sulphides

AG = native silver

CP = chalcopyrite

GAL = galena

ARS = arsenopyrite

ACAN = acanthite

GERS = gersdorffite

COV = covelite

PYRAR = pyrrargyrite

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