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**The Relationship of Cu-Ni-PGE Veins in the Levack Gneiss Complex to Contact
Magmatic Ore at the McCreedy West Mine, Sudbury.**

by

John Owen Everest, 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 Earth Sciences

Carleton University
Ottawa-Carleton Geosciences Centre
May 26, 1999

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**The Relationship of Cu-Ni-PGE Veins in the Levack Gneiss Complex to Contact
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submitted by John Owen Everest, B.Sc.,

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

A handwritten signature in dark ink, appearing to read "D. H. Watkinson", written over a horizontal line.

Thesis Supervisor

A handwritten signature in dark ink, appearing to read "R. R. Taylor", written over a horizontal line.

Thesis Supervisor

A handwritten signature in dark ink, appearing to read "R. R. Taylor", written over a horizontal line.

Chairman, Department of Earth Sciences

Carleton University

May 26, 1999

ABSTRACT

At McCreedy West Mine, Sudbury, Ontario, petrographic and quantitative (SEM-EDS, electron microprobe, Laser Ablation ICP-MS) analysis has been completed on sulphides from contact magmatic ore and footwall vein ore. This study has characterized the footwall ore as consisting dominantly of chalcopyrite-pentlandite-millerite with minor Pt-Pd bismuth tellurides and native gold. Analysis of vein pentlandite has revealed higher Ni and Pd contents but lower Co compositions than contact ore pentlandite. The identification of numerous hydrous Cl - bearing Fe-Mg silicates (chlorite, greenalite and pyrosmalite) associated with these vein sulphides, and the occurrence of fluid inclusions within vein hosted quartz and chalcopyrite suggest that the footwall ore was formed by hydrothermal means.

Assay analysis of ~ 30,000 ore samples has revealed the Cu-PGE rich character of the footwall veins with respect to the Ni-Co rich contact ore. Significant trends have been identified within the contact ore through the use of Pearce Element Ratio diagrams, DataMine sections, and histograms. These methods have suggested that Pt and Pd content increases from the Sublayer ore, through the Footwall Breccia ore and into the footwall vein ore, and that Ni decreases from the Lower Main Ore Zone to the Middle Main Ore Zone. Comparison of this data with data from other North Range contact deposits may prove beneficial towards the discovery of other footwall vein ore bodies

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Commendations to Dr. Catherine Farrow of INCO Ltd. for her significant research on the formation of Cu-Ni-PGE - rich footwall veins at Sudbury. Her research has been a springboard upon which this thesis has been able to capitalize.

Although I will never attain the level of appreciation that Dr. Ferenc Molnar has for his micro-world of fluid inclusions, I wish to thank Feri for our shared research partnerships and for reaffirming my faith that good research methods are still alive and well.

Enlightening discussions were held with many of my colleagues, including Dr. Dan Marshall and Dr. Frank Santaguida. More often than not, these discussions included topics other than just geology, but once in while good geological banter did occur. All mineral analyses were performed in the SEM-EDS and micro-probe labs with the aid of the indispensable Mr. Peter Jones.

It is with deep gratitude that I acknowledge the contribution of my wife Rachel; her encouragement, love and patience have made this possible.

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CHAPTER 1: INTRODUCTION

1-1. GENERAL STATEMENT AND PURPOSE OF STUDY

The McCreedy West Mine (formerly Levack West Mine) is located 30 km NW of Sudbury, Ontario in the town of Onaping. Production was initiated at the mine in 1971 and was terminated in November 1997 due to low metal prices and the depletion of much of the ore. During its 28 years of operation, 14,980,139 tons of ore was produced from the mine with an average overall grade of 1.76% Cu, 1.42% Ni and 0.06 oz/ton total precious metals. Much of the Cu from the McCreedy West Mine was restricted to veins that extend into the footwall from the more Ni-rich Contact Sublayer and Footwall Breccia ore at the contact of the Archean Levack Gneiss and the Proterozoic Sudbury Igneous Complex. During the 1970s and the early 1980s most of the ore came from the contact deposits, but with the depletion of this ore by the late 1980s, the footwall ore became the chief producer until mine closure (C. Davis, Inco Ltd., personal communication).

In the past, most exploration dollars at INCO Ltd. have been directed towards locating the large, bulk mineable Ni-rich ore bodies, but more recently, the Mines Exploration Branch at INCO Limited has been funneling more money into locating the narrow Cu-Ni-platinum group elements (PGE) - rich footwall veins. The reasoning behind this shift of focus relates both to the relatively close proximity of these veins to the established infrastructure of the mines as well as to the high PGE concentrations within the veins. The occurrence of the footwall veins proximal to the Ni - rich ore bodies has led to the general interpretation that the veins are genetically linked to the Sublayer/Footwall Breccia ore. It has been suggested by Naldrett and Kullerud (1967),

Naldrett et al. (1982) and Naldrett et al. (1997) that the Cu-Ni-PGE veins at the Strathcona Mine were formed by the segregation of a residual sulphide liquid produced by the fractional crystallization of a sulphide melt. An alternative hypothesis by Farrow and Watkinson (1992) and Farrow (1995) proposed that Cu, Ni and PGE were remobilized from typical Ni ore in the Sublayer and Footwall Breccia as chloride complexes in late stage hydrothermal fluids. The presence of epidote - actinolite - quartz and chlorite alteration selvages mantling the veins, and the occurrence of fluid inclusions have been cited as evidence of the latter interpretation.

To better understand the geology and geochemistry of the McCreedy West Mine, INCO Limited has provided all assay data collected from drill hole samples, as well as access to the McCreedy West Mine and all the mine plans and sections. With these data it has been possible to model various geochemical trends at the mine. It has been the intention of this thesis to interpret the assay geochemistry, but to do so with an appreciation and understanding of the mineralogy, mineral textures and mineral chemistry. To properly understand the chemical variability of the different ore zones, this study involved sampling both the Ni-rich hangingwall (“contact”) ore and the footwall Cu-rich veins. A petrographic, and quantitative chemical (SEM-EDS, electron microprobe, Laser Ablation) examination of the sulphide minerals within the contact ore and the veins, as well as the silicate alteration assemblages which mantle the veins has been performed to properly classify the characteristics of the minerals with respect to their geological location. When incorporated within a geochemical model of the mine, an understanding of the mineralogy has helped to provide a better understanding of some of the controls on the geochemical trends.

This thesis has been undertaken with the support of INCO Limited, to provide a better understanding of the geology and geochemistry of the McCreedy West Mine, and forms part of a broader study on the genesis of footwall orebodies at Sudbury by the Mineral Deposits Group at Carleton University.

CHAPTER 2: REGIONAL GEOLOGICAL SETTING

2-1. INTRODUCTION

The Sudbury Structure is a collective term, defined by Giblin (1984), for the greater than 15000 km² area represented by the sedimentary and brecciated rocks of the Whitewater Group (Onaping, Chelmsford and Onwatin Formations), the elliptically shaped Sudbury Igneous Complex (SIC), and the surrounding brecciated country rocks of the Superior and Southern Provinces, all of which occur along a zone of Early Proterozoic faulting and dislocation known as the Murray Fault System (see Fig. 2 Deutsch et al., 1995, and Fig. 2-1).

2-2. REGIONAL GEOLOGY

The oldest of the regionally relevant Pre-Cambrian rocks are those that are locally referred to as the Levack Gneiss Complex (Fig. 2-1). This unit of upper amphibolite to granulite facies gneissic rock occurs in contact with the North and East Ranges of the Sudbury Igneous Complex and consists dominantly of a migmatitic tonalitic gneiss with abundant mafic layers and xenoliths (Card et al., 1984), with lesser foliated tonalitic to granodioritic intrusions, and mafic, ultramafic and anorthositic intrusions. U - Pb zircon chronology of samples from both the Levack Gneiss and the Onaping Formation (breccia

fragments) by Krogh et al. (1984) have defined a metamorphic age of 2711 ± 7 Ma for the gneiss. Later northerly trending diabase dikes, which do not display strong metamorphic or deformational features, cross - cut the Levack Gneiss and have been dated at 2485 to 2690 ± 93 Ma (Coats and Snajdr, 1984).

The Early Proterozoic assemblage in contact with the South Range of the Sudbury Igneous Complex is regionally referred to as the Huronian Supergroup. This sequence, which has a minimum age of $2450 \pm 25/-10$ Ma (Krogh et al., 1984), consists dominantly of clastic sedimentary rocks with basal volcanic accumulations. Subsequent to its emplacement, the Huronian Supergroup was intruded, along the future southern margin of the SIC, by three significant Early Proterozoic granitic plutons which yield a minimum age of $2333 \pm 32/-22$ Ma (Frarey et al., 1982) based on Creighton Granite zircons.

The 1850 ± 1 Ma. old (Krogh et al., 1984) Sudbury Igneous Complex, emplaced in the Late Archean and Early Proterozoic strata, may be subdivided into 3 phases: a Lower Zone consisting of felsic to mafic norite, a Middle Zone of quartz gabbro, and an Upper Zone of granophyre and plagioclase - rich granophyric rock (Dressler, 1984). A variety of models have been proposed to explain the nature and origin of the SIC. These models have attempted to account for both the highly siliceous character of the SIC as well as the distinct chemical composition of the two major rock types: the granophyre and the norite. Some of the models of origin have been summarized by Naldrett and Hewins (1984), and include: 1) a folded differentiated sill, 2) a separate intrusion of granophyre and norite as ring dikes and 3) a funnel - shaped differentiated intrusion. More recently, the origin of the SIC has been attributed to: a) a contaminated mantle magma (Walker et al., 1991), b) an exclusively crustal melt resulting from meteorite impact (Grieve et al.,

1991, Dickin et al., 1992 and Grieve, 1994), c) formation by the intrusion and mingling of two separate magmas (Chai and Eckstrand, 1993, 1994) and derivation from the upper crust, with a smaller contribution from a mantle source (Lightfoot et al., 1997)

At the base of the Sudbury Igneous Complex occurs the Sublayer, the structurally lowest unit of the Lower Zone. The Sublayer is a discontinuous unit of noritic, gabbroic and quartz dioritic rock which occurs either within embayments along the outer contact of the structure (Contact Sublayer) or as radial offset dykes that extend from the base of the SIC into the footwall rocks (Offset Sublayer). These rocks may be distinguished from the Main Mass Felsic Norite and Quartz Gabbro by: a) their lower quartz content in relation to pyroxene, b) their common incorporation of a suite of mafic to ultramafic inclusions (Naldrett, 1984), and c) the occurrence of Ni - Cu sulphides as either fine disseminations or as irregular blebs and stringers. Although its age relationship with respect to the SIC is controversial, many geologists including Pattison (1979), and Watkinson (1998) believe the Sublayer to have been intruded prior to the Main Mass norite.

The Footwall Breccia occurs between the Levack Gneiss of the North and East Ranges and the base of the SIC, and like the Sublayer, forms as discontinuous sheets and lenses within footwall embayments. This economically important unit consists dominantly of refractory mafic fragments derived from the footwall rocks and rare sulphidic and quartzo-feldspathic fragments in a fine to medium-grained quartzo-feldspathic matrix containing blebby and disseminated sulphides. Like many of the units of the Sudbury Structure, the Footwall Breccia's relative age and relationship with respect to the Sudbury Igneous Complex has still not been fully reconciled. Cowan (1968) interpreted the Footwall Breccia as being related to local recrystallization and metasomatism, whereas

Pattison (1979) and Farrow (1995) suggested an igneous origin, Greenman (1970) proposed a metamorphic origin, and Peredery and Dressler (1984) observed that it was likely formed as a result of impact related melting.

The unique elliptical character of the Sudbury Structure has provided fertile ground for the proffering of numerous interpretations on its mode of origin. In general terms these hypotheses fall under two main headings: endogenic (igneous related) or exogenic (meteorite impact related). French (1968) suggested that planar deformation features identified by French (1967) and later Peredery (1972) in quartz and feldspar grains within the Onaping Formation are the direct result of a meteorite impact and therefore the Onaping Formation represents an impact breccia. Dence (1972) recognized similar features in the Archean footwall gneisses to the north of the structure, which he also suggested were impact related. Dietz (1964) and Dressler (1984) have proposed that shatter cones, which have been observed around the Sudbury Igneous Complex in the PreCambrian footwall rocks, are also shock-related features. The basis of these arguments relates directly to the concept of uniformitarianism. Because similar features are found at proven meteorite impact crater locations (e.g., Meteor Crater, Arizona; Ries Structure, Germany), a similar origin should be inferred for the Sudbury Structure based upon this evidence. Opinions differ greatly on the meaning of these features; Muir (1984) has suggested reasons why these characteristics do not necessarily imply an exogenic origin.

In terms of this study, one of the most important shock-related units associated with the Sudbury Structure is the Sudbury Breccia. The Sudbury Breccia consists of numerous irregularly shaped pseudotachylite - like bodies, veins, and dikes which occur within 80 km of the contact with the Sudbury Igneous Complex. It is by far the most

widespread and abundant of the breccia types in the Sudbury area, although much of its volume occurs within a few kilometres of the contact. Consisting of fragments of locally derived wall rock in a finely comminuted matrix of the same material, the origin of this unit has been attributed to brittle fracture and comminution of footwall rocks related to an explosive event (Dressler, 1984). The significance of the Sudbury Breccia to this study is related to its role as a conduit in which Cu, Ni, PGE bearing ore was emplaced during the formation of veins in the footwall to the Ni-rich Sublayer and Footwall Breccia deposits.

Table 2-1. Glossary of terms specific to Sudbury geology.

Contact Ore	Ni - rich ore which occurs within the Footwall Breccia and the Sublayer. This ore is considered to be hangingwall mineralisation to the footwall Cu - rich veins.
DataMine	Software package used by the mining industry for mine planning and interpolation of data between drill holes. Data can be presented in either 2 dimensional or 3 dimensional form.
Footwall Breccia	A collective term for a heterolithologic breccia which occurs in the footwall of the Sudbury Igneous Complex. The breccia is characterized by abundant locally derived Footwall rock fragments within a granophyric matrix. This unit potentially formed by melting associated with the introduction of either the SIC or Sublayer, and is locally host to significant pyrrhotite, pentlandite, and chalcopyrite (typical of Sudbury N. Range ore).
Footwall Veins	Cu - Ni - PGE - rich veins which extend from the contact ore into the footwall (Levack Gneiss). Mode of origin related to either a magmatic pulse or transportation by Cl bearing hydrothermal solutions.
Levack Gneiss Complex	Belt of high grade metamorphic gneisses adjacent to parts of the Sudbury Igneous Complex on the North Range. This 2.7 Ga. unit is generally tonalitic in composition with bands and layers of variable mafic units.
Lower Main, Middle Main, and Upper Main Ore Bodies	Ni-rich (pyrrhotite-pentlandite) contact-type hangingwall ore. The Middle Main ore occurs within a footwall embayment, and is adjacent to the origin of the Cu-rich footwall veins. The Lower Main ore occurs down dip from the Middle Main ore, and the Upper Main ore occurs up dip.
North Range	The northern portion of the Sudbury Igneous Complex which is distinct from the southern SIC by a general lack of deformation.

Table 2-1. Glossary of terms specific to Sudbury geology. (continued)

Platinum Group Minerals (PGM)	Common in the Cu-rich footwall veins at McCreedy West Mine. These Pt-Pd tellurides are commonly less than 30 µm in size and are generally associated with chalcopyrite. Common PGM include michenerite, moncheite and merenskyite.
Sublayer	Two varieties 1) Contact Sublayer: gabbro-norite which occurs at the base of the Sudbury Igneous Complex, and 2) Offset Sublayer: quartz-diorite which occupies the offset dykes of the Sudbury Igneous Complex. Typically contains fragments derived from the footwall, as well as mafic and ultramafic fragments that have debatable origins. This unit is host to much of the Ni mineralisation at Sudbury.
Sudbury Breccia	A pseudotachylite unit which has formed in the footwall to the Sudbury Igneous Complex. Unit is composed of fragments of locally derived wallrock within a comminuted matrix of the same. Formed as the result of the passage of shock waves related to the formation of the Sudbury Structure. Sudbury Breccia at McCreedy West Mine was a conduit for Cu - rich fluids which formed the footwall veins.
Sudbury Event	An event, 1.85 Ga. ago, which led to the formation of the Sudbury Structure. This event may have been the result of endogenic (igneous related) or exogenic (meteorite impact related) processes.
Sudbury Structure	A collective term for a structure which is defined by various lithologic, structural and geographic characteristics, and is directly linked to the formation of the Whitewater Formation, the Sudbury Breccia, the Sudbury Igneous Complex, and the various Sudbury Ni-Cu-PGE ore bodies.
Sudbury Igneous Complex (SIC)	A large differentiated layered intrusion consisting of granophyre, quartz-gabbro and norite. This unit, which formed at the time of the Sudbury Event, is host to many of the Sudbury Ni-Cu-PGE deposits.

Fig. 2-1 Regional geological map of the Sudbury area, showing the location of McCreedy West Mine with respect to other North Range mines with Cu-rich footwall mineralization.

CHAPTER 3: LOCAL GEOLOGY OF THE McCREEDY WEST MINE

3-1 INTRODUCTION

The McCreedy West Mine (formerly the Levack West Mine) is located at the western end of the Onaping-Levack mineralized belt. The Main Ore Zone consists of mineralized Footwall Breccia within an embayment at the contact of the southerly dipping Sudbury Igneous Complex and the Levack Gneiss. Footwall ore, which is composed dominantly of Cu-rich veins, extend from the contact ore into permeable pathways developed by Sudbury Breccia (Fig. 3-1).

Local outcrop exposure is restricted to an area just south of McCreedy West Mine adjacent to the Hardy Open Pit. The Hardy deposit represented a near surface, upper extension of the McCreedy West Ni-rich Footwall Breccia. Although the excavation and reclamation of the pit area is now complete and there is little evidence of mineralized Footwall Breccia, highly deformed Levack Gneiss, crosscut by dykes and veinlets of Sudbury Breccia (Fig. 3-2a, 3-2b, 3-2c), occurs over a widespread area adjacent to the walls of the former pit. The excellent exposure and pristine nature of the footwall rocks at this location are unequaled in the area, and may be considered to be representative of similar units that are observed down dip in the underground workings at the McCreedy West Mine.

Although peak metamorphism of the Levack Gneiss was at granulite grade, all footwall rocks have been subjected to thermal recrystallization within the metamorphic aureole developed around the Sudbury Igneous Complex. The development of this zone has resulted in retrograde metamorphism which has destroyed the relict granulite - facies

mineralogy (Farrow, 1995). Coats and Snajdr (1984) and Dressler (1984) have defined this metamorphic aureole 1 km beyond the SIC contact, subdividing it as follows:

- 1) 0 to 250 m = pyroxene hornfels
- 2) 250 to 600 m = hornblende hornfels
- 3) 600 to 1000 m = albite +epidote hornfels

3-2. LEVACK GNEISS COMPLEX

The Levack Gneiss Complex is a well layered unit consisting of mafic to felsic components as thick as a metre. Although these bands are often consistent and parallel, it is not uncommon to observe convoluted banding and pod-like units of the mafic component isolated within the felsic gneiss. The mafic bands within the felsic gneiss are composed of various combinations of plagioclase-amphibole-biotite-quartz-chlorite and minor apatite, the variability of which may either relate to the gradational nature of some of the bands with respect to the felsic gneiss or to the protolith composition.

Typically, the felsic component of the Levack Gneiss is tonalitic in composition, consisting of 20 to 25% polycrystalline quartz grain aggregates in a matrix of 10 to 15 % finer grained quartz and plagioclase (60 %). The aggregates are generally 0.6 to 1.6 mm in size and consist of between 5 and 20 individual grains of recrystallized quartz (Fig. 3-3a) which are between 0.1 to 0.6 mm in size. Some of the grains contain relics of planar features in dusty centres that are surrounded by clear quartz (Fig. 3-3b). The inter - aggregate contacts occur frequently at triple point junctions whereas the outer contacts of the grains are defined by 0.05 to 0.1 mm sericitic alteration halos within plagioclase.

Amphibole, biotite, and ilmenite with lesser chlorite are the most common mafic minerals occurring within the tonalitic gneiss, generally representing 8 to 10 % of the rock. The amphibole grains are 0.05 to 0.1 mm in size, ragged and stringy looking with variable birefringence. Often the amphibole grains have been partially or wholly replaced by both biotite and chlorite with minor ilmenite blebs having developed during the reaction.

Although the mafic minerals define bands within the gneiss on a mm scale, mineral grains show no preferred direction of orientation, and are likely a result of the segregation of minerals during syn-tectonic recrystallization. The felsic component of the Levack Gneiss may display a pinkish colour in hand specimen. This characteristic may be related to localized hematization which occurs proximal to veining and fracturing within the gneiss. A strong albitic and sericitic alteration has also developed outwards from these fluid pathways resulting in the crystallization of albite within the pinkish zones, and the partial replacement of plagioclase by fine sericite grains (.02 to .05 mm). Despite the cloudy or dusty appearance of these feldspars in thin section, the primary plagioclase twinning is still visible. The quartz grain aggregates are not affected by this alteration, and retain their clear appearance. The mafic (Fe-Mg silicate) component of the rock becomes abundant locally within this zone of alteration, providing a patchy texture to the rock.

Ultramafic units occur locally within the footwall to the McCreedy West Mine. Compositions are variable but typically project along the pyroxenite to anorthosite edge of the IUGS (Igneous Rock) classification (plagioclase-pyroxene-olivine ternary) diagram. The variable proportions of primary pyroxene to plagioclase therefore define a rock of gabbroic composition. In least altered gabbroic units, the plagioclase grains (.04 to .4 mm) are clear, subhedral to euhedral and may represent between 20% and 55% of the

rock. In more altered specimens the plagioclase is strongly saussuritized and cloudy in appearance. In specimens where plagioclase dominates, grains typically occur in segregated clusters separated by chains of intergrown anhedral grains of clinopyroxene and orthopyroxene (.2 to 2 mm). The clinopyroxene grains are generally less altered than the orthopyroxene grains which may have been partially or wholly replaced by Fe-amphibole, biotite and lesser ilmenite and chlorite. The amphibole appears to have replaced the pyroxene along cleavage planes, resulting in the development of a stringy texture to the grains under crossed nicols. These grains have in turn been replaced by biotite which often contains relict fragments of the amphibole grains. The ilmenite occurs as cusped and wormy blebs (.05 to .5 mm) in the replaced pyroxene grains, and often contain inclusions of actinolite and exsolved blebs of rutile.

3-3. SUDBURY BRECCIA

The Sudbury Breccia occurs as narrow dikes, stringers and irregularly shaped bodies throughout the footwall at McCreedy West Mine (Fig. 3-2b, 3-2c, 4-3b). The fine-grained to aphanitic, dark green matrix of the Sudbury Breccia consists of finely comminuted rock flour with a composition similar to that of the host wall rock (Coats and Snajdr, 1984). The fragments themselves also appear to be of local derivation and therefore represent the various units of the Levack Gneiss Complex. Petrographic examination of representative samples from the Sudbury Breccia reveal a matrix consisting of randomly oriented plagioclase locally occurring as chadacrysts within recrystallized quartz and large (<2 mm) platy grains of biotite. Actinolite, epidote, chlorite, Fe-oxides, and lesser apatite are common throughout the matrix as grains no greater than .2 mm and

more commonly in the range of .05 to .1 mm. These grains are typically anhedral and randomly oriented in the matrix. Increasing proximity to veins tends to result in a greater proportion of mafic minerals at the expense of feldspar, and the disappearance of biotite in favour of chlorite.

3-4. FOOTWALL BRECCIA

Although Footwall Breccia is one of the more dominant units at McCreedy West Mine, access to areas where true Footwall Breccia has been recorded was limited due to cessation of mining operations. Semi-massive to massive sulphide samples with intra-sulphide/fragment granitic textures is the dominant variety of this rock observed at McCreedy West Mine. It is debatable though whether this rock is truly Footwall Breccia as suggested by INCO (personal communication with C. Davis) or is in fact fragmental Sublayer with a groundmass of semi-massive sulphide and granite. Unlike most Footwall Breccia, which is generally heterolithologic, the fragments in this rock are typically homogeneously noritic. To complicate matters more, the richness of the ore in the observed samples has made examination of host rock characteristics difficult to achieve. However, samples studied from other mines within the area (e.g., Coleman and Craig Mines) have provided the author with a good working knowledge of typical Footwall Breccia.

Footwall Breccia is a heterolithologic breccia, consisting of randomly oriented fragments that are representative of the lithology of the local footwall. These clasts may include diatexite, gneiss, diorite, gabbro, pyroxenite, anorthosite, diabase, granite, and Sudbury Breccia (Farrow, 1995). In ore-bearing sections of the breccia, the clasts tend to

be more numerous and more mafic in composition (Farrow, 1995), but as proximity to the norite contact decreases, the proportion of quartzo-feldspathic matrix to clasts increases. The rock at this point essentially is granophyric with scattered clasts and a variable sulphide content (Coats and Snajdr, 1984). The mafic inclusions within this footwall unit tend to have very sharp contacts with the matrix whereas the less abundant felsic clasts tend to have quite diffuse contacts. This incongruity is likely the result of the partial melting of the felsic clasts during intrusion of the magmatic matrix, leaving a felsic matrix containing sub-angular to rounded, variably sized mafic fragments.

The granophyric quartz-feldspar intergrowth (Fig. 3-3c) and the lack of significant deformation within the quartz may be indicative of an igneous origin. The matrix of the Footwall Breccia contains between 15 to 50 per cent quartz, which exists as anhedral, optically continuous oikocrysts containing subhedral to euhedral chadacrysts of plagioclase (Fig. 3-3d). In this fashion, quartz may also include epidote, chlorite, hornblende, and sulphide grains. K-feldspar is less common within the matrix of the Footwall Breccia, occurring with quartz as granophyric and micrographic intergrowths. It may also be found as isolated subhedral laths within the matrix, as well as a replacement of albite. In this latter case, K-feldspar has subsequently been altered to clay minerals.

Hornblende forms as intergranular, ragged anhedral grains within the dominantly felsic matrix. This hornblende is frequently altered to actinolite and chlorite which form along fractures and cleavage planes. Locally, alteration by these minerals is complete. In areas of intense sulphidation, well cleaved hornblende with epidote, biotite, and chlorite tends to be more highly concentrated, forming FeMg-silicate alteration halos around the sulphides. Locally, chlorite replaced hornblende has a poikiloblastic texture with dusty,

saussuritized feldspar inclusions. Accessory minerals in the Footwall Breccia are apatite, which forms as microscopic (< 15 µm) euhedral prisms dispersed throughout the matrix, and euhedral zircon crystals (< 1 µm).

3-5. CONTACT SUBLAYER

The Sublayer occurs as a thin layer between the Footwall Breccia and norite along most of the hangingwall/footwall contact at McCreedy West Mine. Typical Sublayer has not been observed at McCreedy West Mine due to access problems.

Two varieties of Sublayer have been distinguished along the outer margin of the Sudbury Igneous Complex: two pyroxene gabbro-norite of the marginal deposits such as at McCreedy West Mine, and hornblende-biotite quartz diorite which is traditionally associated with the offsets. Pattison (1979) has suggested that these two units are one and the same, with the latter representing a deuterically altered version of the former. The matrix of fresh igneous Sublayer consists of hypersthene, augite, zoned plagioclase laths with minor but variable amounts of quartz, lesser primary hornblende and biotite, micrographic quartz-feldspar intergrowths, iron oxides, and Fe-Ni-Cu sulphides. Rock texture ranges from intersertal to subophitic, with small randomly oriented plagioclase grains occurring interstitial to or partly enclosed by somewhat larger pyroxene. (Naldrett et al., 1984), (Pattison, 1979). Commonly, the Sublayer contains numerous inclusions, some of which are identifiable as originating from the country rock, others of ultramafic and mafic composition which have debatable origins (Lightfoot et al., 1997). A study of 264 inclusion samples from Strathcona Mine by Scribbins et al., (1984) has suggested that the dominant North Range inclusions vary from dunite through harzburgite, wehrlite, and

clinopyroxenite to norite and gabbro. Contact relationships between Sublayer and Footwall Breccia are inconclusive, but most evidence suggests that they are gradational over a few metres, with the Footwall Breccia representing a partial melt related to Sublayer intrusion.

Fig. 3-1. Generalized cross section of McCreedy West Mine geology (looking east), displaying the relationship between the Ni-rich hangingwall "contact" ore and the Cu-PGE-rich footwall veins.

Fig. 3-2a

Typical Levack Gneiss displaying convoluted banding defined by gabbroic layers within a tonalitic matrix. Pink colouration due to potassic and hematitic alteration associated with fracturing.

Levack Gneiss - Hardy Mine Area

Fig. 3-2b

Intense brecciation of Levack Gneiss related to Sudbury Event. Decimetre to metre scale, angular fragments of the Levack Gneiss occur within extremely fine grained, dark green, Sudbury Breccia matrix.

Sudbury Breccia - Hardy Mine Area

Fig. 3-2c

Dike of Sudbury Breccia in sharp contact with granitic part of the Levack Gneiss. Centimetre scale fragments occur within dark Sudbury Breccia matrix. Pink colour of gneiss related to potassic alteration and local hematization at fractures.

Sudbury Breccia - Hardy Mine Area

Fig. 3-3a

Polycrystalline grain of quartz within the Levack Gneiss. Grain occurs in strongly sericitized feldspar. Internal grain boundaries occur at triple point junctions. Crossed polars.

Sample MW-14348d

Fig. 3-3b

Quartz grains (from a polycrystalline grain) within Levack Gneiss are distinguished by central dusty planar features overgrown by clear recrystallized quartz. Plane polarized light.

Sample MW-14348d

Fig. 3-3c

Micrographic texture, within a sample from the Footwall Breccia, is formed by the intergrowth of quartz and plagioclase feldspar ($An=0$). Crossed polars.

Sample Craig - B, Craig Mine

Fig. 3-3d

Poikilitic texture, within a sample from the Footwall Breccia, is formed by a large oikocryst of quartz enclosing several plagioclase chadacrysts. Crossed polars.

Sample CR-94-04, Craig Mine

CHAPTER 4: MINERALOGY AND GEOCHEMISTRY OF THE McCREEDY WEST ORE ZONES

4-1. INTRODUCTION

Unlike the Strathcona Mine, McCreedy West Mine has a limited disseminated sulphide zone in the overhanging norite (Hoffman et al., 1979); instead, most of the ore occurs as disseminated sulphides within Footwall Breccia, semi-massive to massive sulphides within Footwall Breccia, and massive Cu-rich footwall vein sulphides (Fig. 3-1). The Footwall Breccia ore occurs in contact with the Levack Gneiss, with the disseminated variety overlying the semi-massive to massive sulphides. A thickening of this ore at ~12000' elevation (local elevation defined by INCO with 13000' occurring at approximate ground level) is related to an embayment into the footwall rocks. From this embayment, a Cu-rich vein system extends deeper into the footwall, subparallel to the contact of the SIC and the Levack Gneiss. Of these three ore types, only the semi - massive Footwall Breccia and footwall veins were observed. Access to the disseminated Footwall Breccia ore zones was impossible due to cessation of mining within these areas.

4-2. FOOTWALL BRECCIA ORE ZONES

Disseminated Footwall Breccia Ore

The sulphides in this disseminated variety of Footwall Breccia ore, frequently occur as spherical, subrounded blebs of pyrrhotite with lesser pentlandite, pyrite, and magnetite within a felsic igneous matrix. The similarity of these blebs to those which occur in Sublayer, lends support to the idea that the matrix of the Footwall Breccia is igneous in origin, and possibly related to the Sublayer matrix. An interesting feature of

these sulphide blebs is the fact that some of them are surrounded by a corona of mafic minerals, including epidote, actinolite, and chlorite. This halo feature is not present macroscopically on all blebs but the mafic minerals do seem to have an affinity for the sulphides and occur in greater concentration around the sulphides than in the matrix as a whole. In addition, when chalcopyrite occurs, it frequently forms as a late feature upon the blebs and within late fractures. Both of these relationships may be suggestive of a re-equilibration of the unit possibly related to the movement of late stage magmatic or hydrothermal fluids.

Semi-massive and Massive Footwall Breccia Ore

Semi-massive and massive sulphide mineralisation at the base of the Footwall Breccia, represents the dominant ore type at McCreedy West Mine; the main difference between the two varieties is their sulphide to igneous matrix ratios. In the semi-massive ore, mafic clasts are often shrouded in wispy sulphide blebs (Fig. 4-1c). These elongate strands of sulphides tend to armour some of these fragments in a manner that suggests either flow textures formed early in the development of the Footwall Breccia, or deformation of the sulphide at a latter date as a result of pressure-related flattening, stretching and distorting of the blebs and remobilization into newly formed fractures. Often these blebs appear to have been connected to adjacent sulphide blebs, but have become detached and separated from one another by narrow “veinlets” of Footwall Breccia matrix material. An increasing sulphide component at depth in the ore body has resulted in the disappearance of this igneous matrix in favour of massive pyrrhotite - pentlandite - pyrite - chalcopyrite - magnetite assemblages (Fig 4-1d).

4-3. FOOTWALL BRECCIA ORE MINERALOGY

Pyrrhotite dominates the massive sulphide component of the ore, forming anhedral, inter-connected grains which often display parallel fracturing along the 0001 parting direction. Although pyrrhotite has been documented as occurring in both its hexagonal and monoclinic forms on the North Range, the distinction between the two varieties was not observed at McCreedy West Mine. Other sulphide minerals, including pentlandite, pyrite, and chalcopyrite, developed late, and therefore tend to occur along pyrrhotite grain edges. Of these, pentlandite is the most important of the economic minerals in the Footwall Breccia. A familiar form of pentlandite is as flame-like lamellae (7 to 15 μm), which are in fact composites of even smaller elongate blebs (.7 to .15 μm) that extend perpendicularly away from hairline fractures along pyrrhotite parting directions. Pentlandite also tends to occur along the edges of the pyrrhotite grains as blocky textured grains 0.1 to 0.2 mm in width and locally as masses that are greater than 1 mm in width. Large euhedral grains of pyrite often occur adjacent to or overgrowing the pentlandite along the pyrrhotite grain boundaries. Inclusions of pyrrhotite and chalcopyrite within the grains and the euhedral habit of the grains suggest that this pyrite formed late in the development of the ore. Chalcopyrite also occurs frequently along grain boundaries, forming equigranular aggregates with pentlandite. In one sample chalcopyrite was observed within a late fracture cross-cutting a pyrrhotite grain. This suggests that after initial exsolution from the monosulphide solid solution (MSS), there was partial remobilization of Cu to local fractures. Magnetite, although not a major constituent of the ores, was present in most specimens examined. The grains are consistently subhedral with curved faces, often showing smoothly curving embayments, long club-shaped protuberances and beautifully

round inclusions of both sulphide and silicate.

Locally, pyrite and magnetite have formed narrow extensive bands (m scale) within the pyrrhotite. In these zones the pyrite forms the dominant component of the bands, and occurs as wispy strands which envelop subhedral magnetite grains. Minor chalcopyrite is also present as amorphous grains which drape the pyrite. Sample 1450-1 contains an example of this texture and has been interpreted as having formed within an oxidizing environment related to fluid passing through the pyrrhotite rich ore.

This fluid is interpreted as being instrumental in the formation of the Cu-rich footwall veins.

4-4. FOOTWALL VEINS

The Cu-Ni-PGE rich sulphides of the McCreedy West Mine footwall zone occur as massive veins, veinlets and disseminations structurally below the Fe-Ni-Cu-rich Footwall Breccia ore. The origin of these sulphides has been considered by some to be related to segregation of a Cu-rich residual magmatic sulphide liquid during crystallization of MSS (Hawley, 1962; Naldrett and Kullerud, 1967; Naldrett, 1982). More recent work on Sudbury deposits by Farrow and Watkinson (1992); Watkinson (1994); Farrow (1995); Farrow & Watkinson (1997) have suggested that the veins were formed by late stage hydrothermal fluids that remobilized some elements from the Sublayer and Footwall Breccia ore and utilized structures hosting the Sudbury Breccia as conduits of escape from the tremendous heat of the cooling Sudbury Igneous Complex. At McCreedy West Mine, many alteration features and fluid signatures are apparent which are compatible with the

latter hypothesis of vein formation

In this study, it has become apparent that footwall mineralisation occurred in a series of stages relating to varying fluid conditions. In the initial incursion, a minor nickel and iron rich fluid pulse was introduced into the footwall system, resulting in the formation of pentlandite, magnetite, and lesser pyrrhotite along the contact of Levack Gneiss with Sudbury Breccia. This was followed by the partial replacement of both the initial sulphide and oxide minerals and the silicates of the Sudbury Breccia by an increasingly more copper-rich solution, resulting in the development of chalcopyrite. An oxidizing pulse along the vein contacts then precipitated secondary magnetite which overgrew both the corroded early magnetite and the host minerals. Local replacement of sulphides at the distal extents of the vein system resulted in the formation of late millerite and bornite.

The footwall mineralisation event resulted in the formation of various alteration silicates. Assemblages involving chlorite-actinolite-epidote-biotite-stilpnomelane-pyroxmalite-talc occur within both the veins and their associated alteration halos. Generally, the Fe-Mg silicate replacement is restricted to halos which are only mm to cm in thickness, whereas sericitization-saussuritization, albitization, and hematization of the footwall silicates, typically extends several m from the vein contacts and provides a patchy pink colouration to the Levack Gneiss. Quartz has also been observed within the vein system, occurring towards the terminations of some of the veins.

4-5. VEIN SULFIDES AND OXIDES: PETROGRAPHY AND GEOCHEMISTRY

Chalcopyrite

Chalcopyrite [CuFeS_2] composes approximately 75% to 80% of the total vein mineral assemblage at McCreedy West Mine. Occurring as well twinned, anhedral mosaic grains (.4 mm to 3 mm), chalcopyrite appears to be the most continuously formed mineral phase within the footwall veins. Thin section examination has shown that chalcopyrite consistently replaces pentlandite along grain boundaries and fractures (Fig. 4-4a). This has resulted in the progressive break down of pentlandite into increasingly smaller subrounded islands as replacement by chalcopyrite has progressed. This micro-feature is mirrored in hand specimen, where chalcopyrite replaces wall rock fragments that have been included within the veins (Fig. 4-1b). Typically, the highly altered fragments display corroded margins and contain numerous cross cutting chalcopyrite bearing veinlets. The continuing corrosion of the margins has increasingly isolated pentlandite from its original location along the vein\wallrock interface.

The partial replacement of Ti-bearing magnetite grains by chalcopyrite (Fig. 4-5a to 4-5f) often results in the formation of embayed, kidney shaped magnetite grains isolated within a chalcopyrite matrix. These grains have been overgrown by a later, purer magnetite phase (Fig. 4-5d and 4-5e). This has resulted in chalcopyrite blebs being included as small grains within the overgrowth. Where replacement of the magnetite grains by chalcopyrite has moved to completion, the grain outline can often be discerned by the occurrence of fine blades of greenalite which have formed along the pseudomorphosed grain boundaries (Fig. 4-5b, 4-5c, 4-5f).

The alteration halos which surround the veins consist partially of finely

disseminated grains of chalcopyrite (Fig. 4-2a to 4-2d). Although much of the Fe-oxide and Fe-silicate alteration is restricted to a very narrow zone around the vein, chalcopyrite precipitation has extended beyond this halo. The distance that Cu - rich fluids have travelled from the vein is strongly influenced by the lithology of the host rock. For example: Samples 14348e and 14348d were samples of granitic gneiss which were taken 5 cm and 150 cm away respectively from a 50 cm wide chalcopyrite rich vein. A thin section of sample 14348e displayed only a few grains of chalcopyrite and sample 14348d revealed only 1 grain. However, sample 14348f which was taken within Sudbury Breccia 1 m away from the same vein on its opposite side, has many disseminated grains (.3 to .5%, 2 to 50 μm) of chalcopyrite. The permeability of the host rock therefore has a strong control over the distal extent of mineralisation. This character may be further recognized by examining the contact of the veins with the various wall rocks. Veins that occur adjacent to granitic gneiss or noritic fragments generally have very sharp contacts, whereas those that occur adjacent to Sudbury Breccia have poorly defined contacts consisting of finely disseminated chalcopyrite which grades into massive sulphides.

Pentlandite

Pentlandite $[(\text{Fe}, \text{Ni}, \text{Co})_9\text{S}_8]$ generally occurs as variably sized, anhedral, corroded blebs within a chalcopyrite matrix. Commonly these blebs have been invaded by chalcopyrite along parting cleavage planes and along fractures (Fig. 4-4a). This relationship is suggestive of pentlandite precipitation preceding chalcopyrite. Generally two varieties of pentlandite occur: 1. Violarite $[(\text{Ni}, \text{Fe}, \text{Co})_3\text{S}_4]$ bearing pentlandite, where violarite represents ~50% of the grain, and 2. violarite-free, 'clean', pentlandite. It is not obvious at the present time why some of the pentlandite contains violarite and other

pentlandite does not. There is no remarkable relationship among the various minerals which would suggest the presence of one over the other. Where violarite does occur with the pentlandite, it seems to represent a corrosion of the latter along intersections of cleavage or parting planes, forming triangular masses at these locations.

Commonly pentlandite is massive, and occurs paralleling vein edges or shrouding wall rock inclusions within the vein. It is suggested here that pentlandite was a mineral that formed early along the wallrock prior to invasion by the Cu - bearing fluids. These penetrating Cu-rich fluids resulted in intense alteration of the wallrock to chalcopyrite. This had the effect of separating the pentlandite from its contact with the wallrock (Fig. 4-1b). Continuing alteration and changing fluid conditions locally reduced the massive pentlandite to isolated pentlandite grains within a massive chalcopyrite matrix.

Pentlandite is commonly associated with Ti - magnetite bands which form along the vein contact where the wallrock is of a more mafic to ultramafic composition (Fig. 4-4g). In such an environment, pentlandite has a very close spatial association with magnetite and is considered to have precipitated contemporaneously or slightly prior to the oxide.

Narrow pentlandite veinlets (cm scale) also occur as offshoots from the main sulphide veins (Fig. 4-2b). Typically these are fracture fillings within the Levack Gneiss and may either consist of mono-mineralic pentlandite or may be a combination of pentlandite and chalcopyrite if the fractures were re-opened for the Cu-rich phase. The narrow nature of these veins relates directly to the relatively impermeable character of the gneissic wall rock when compared to Sudbury Breccia.

Electron-probe analysis of vein pentlandite (Appendix 4) shows a lower Co but

higher Ni content than Footwall Breccia pentlandite. The average vein pentlandite contains 0.10 ± 0.06 atomic % Co and 30.61 ± 1.72 atomic % Ni in comparison to 0.66 ± 0.15 atomic % Co and 27.55 ± 1.05 atomic % Ni in the Footwall Breccia. The Ni trend at McCreedy West is the opposite of what Abel et al. (1979) found for the pentlandite at Strathcona Mine, where Ni content was higher in the Main Ore Zone. An analysis of the histogram for McCreedy West Mine with respect to other North Range deposits (Appendix 2) reveals that veins at Whistle Mine display a similar Co trend as at McCreedy West, although the Sublayer pentlandite at Whistle appears to be even more enriched in Co than the Footwall Breccia at McCreedy West Mine. Another significant trend within the vein pentlandite is its Ni and Co composition with respect to the minerals with which it occurs. Pentlandite which contains violarite has very low Co and Ni compositions (0.04 ± 0.02 atomic % Co and 28.90 ± 0.80 atomic % Ni) when compared to the average vein pentlandite. The low values of Ni and Co in the pentlandite with associated violarite can be explained by a transfer of these elements to the parasitic violarite during its formation. Violarite typically contains 21.88 ± 0.93 atomic % Ni and 0.56 ± 0.05 atomic % Co. Other significant pentlandite geochemical trends include elevated Co compositions (0.21 ± 0.05 atomic %) where pentlandite is associated with millerite and decreased Ni compositions (28.40 ± 0.49) where pentlandite is associated with magnetite bands at the edge of the veins.

Laser ablation analysis has revealed that Pd and Te contents are elevated within footwall pentlandite veins. Analysis by laser ablation was performed on clean areas of the pentlandite grains showing no inclusions. These analyses revealed that gram level values of both Pd and Te may occur contemporaneously or individually (see Appendix 4). The

concurrent values may represent the analysis of micro – inclusions invisible either petrographically or with the aid of the SEM-EDS. The occurrence of elevated Pd without elevated Te (or vice versa) may represent the occurrence of these elements as distinct entities within a pentlandite solid solution.

Pyrrhotite

In contrast to the contact deposits, pyrrhotite $[(\text{Fe},\text{Ni})_{1-x}\text{S}]$ is one of the least dominant sulphides to occur within the footwall copper veins. Its most common mode of occurrence is in narrow veinlets (0.01 to 0.1 mm in width) which occur along chalcopyrite grain boundaries and represent a late exsolution from the chalcopyrite. Locally these veinlets are wider (0.2 to 0.8 mm), and take on more bleb-like characteristics. This characteristic is particularly evident where the veinlets have encroached upon magnetite grains (Fig. 4-4f)

Pyrrhotite occurs less commonly in a form similar to that of pentlandite: as large, elongate blebs (> 1 cm length, 2 to 3 mm width) which parallel the vein - wallrock contact. Pyrrhotite also occurs (sample MW-700-9165c) as 0.1 to 0.2 mm blebs within pentlandite grains (Fig. 4-4b). This latter form may represent an exsolution of pyrrhotite along pentlandite cleavage planes.

Analysis of pyrrhotite grains by the electron microprobe has revealed that Footwall Breccia pyrrhotite contains less Ni than the pyrrhotite within the footwall veins. The average vein pyrrhotite contains 0.64 ± 0.30 atomic % Ni, whereas the pyrrhotite from the Footwall Breccia contains only 0.39 ± 0.10 % Ni. An analysis of the histogram for McCreedy West Mine with respect to other North Range deposits (Appendix 2) reveals that this characteristic may be site specific.

Millerite

Millerite [(Ni,Fe,Co)S] occurs near the distal extents of the footwall vein system. It appears as optically (crystallographically) continuous bands along the vein/wallrock contact, frequently consisting of greater than 1 cm sized grains with excellent cleavage and exceptional lamellar twinning (Fig. 4-4h). Thin section observations have revealed that millerite has formed by the preferential replacement of pentlandite, often pseudomorphing the entire grain. Although this mineral has formed late in the development of the vein, chalcopyrite has been observed replacing the millerite along grain boundaries.

Microprobe analysis reveals that the composition of the millerite is close to stoichiometric, but with minor Fe (0.98 ± 0.17 atomic %) and trace Co (0.18 ± 0.09 atomic %).

Magnetite

In the footwall veins of the McCreedy West Mine, magnetite $[(\text{Fe}^{+3}, \text{Al}, \text{Ti})_2(\text{Fe}^{+2}, \text{Mg}, \text{Mn}, \text{Ni})\text{O}_4]$ occurs in a variety of habits. It occurs as bands along vein/mafic host contacts (Fig. 4-1a), as veinlets extending into the vein from the magnetite bands (Fig. 4-4g), as anhedral to euhedral porphyroblasts isolated within the vein (Fig. 4-5f), and as disseminated silicate replacement extending away from the veins (Fig. 4-5g). Typically the magnetite has two distinct chemical compositions; an early magnetite with variable amounts of Ti and Al (91.44% magnetite, 5.57% hercynite, 1.27% ulvospinel, 0.61% jacobsonite, 0.58% magnesoferrite, and 0.45% trevorspinel) and a very pure, late, euhedral magnetite (99.1% magnetite) (Fig. 4-5a to 4-5g).

Magnetite bands form along the vein edge where the host rock is more mafic in composition (Fig 4-4c to 4-4f). This texture is typified by closely-spaced, comb-like

grains of Ti^{2+} and Al^{3+} bearing magnetite that have grown elongate into the vein (Fig. 4-4g). A later, more pure magnetite, has formed along grain contacts as a rim on the early magnetite. This has resulted in the frequent incorporation of host sulphides by the magnetite grain. The contact between the early and late varieties of magnetite is easily recognized by this change from inclusion rich to inclusion free magnetite, as well as by a weak colour variation, and a lower contact relief.

Veinlets of late magnetite may extend away from the oxide - silicate contact, into the vein proper. These veinlets occur along chalcopyrite grain boundaries and transect all other minerals except for the latest sphalerite and galena bearing veins. Typically these veinlets consist of a central fracture along which subhedral to euhedral magnetite grains have grown outwards, absorbing and incorporating the host sulphides. The central part of this fracture is often defined by a narrow veinlet of the host sulphide.

Magnetite also occurs as distinct bleb-like and euhedral grains within the sulphides. The bleb-like textures displayed by the magnetite grains, represent resorption of original grains by a later Cu - rich solution. This process has resulted in the formation of magnetite grains that are distinctly cusped to amorphous in shape. Some of these resorbed grains have then been overgrown by the later magnetite, which has resulted in a more euhedral zoned grain containing an inclusion rich outer zone.

Replacement of all Fe-silicates and oxides by Al and Ti bearing magnetite in the fine-grained gabbroic wallrock adjacent to the sulphide veins, has resulted in the formation of poikiloblastic grains with inclusions of subrounded grains of quartz and feldspar (Fig. 4-5g). With increasing distance from the vein, the occurrence of magnetite has decreased as a result of less permeable conditions and/or a change in chemistry and temperature of this

continuously evolving fluid. As alteration of the wallrock by later Cu-rich fluids advanced, grains became isolated along the vein margins within chalcopyrite. This process would explain the lack of magnetite in the central regions of the vein. Because chalcopyrite replaced Sudbury Breccia represents most of the vein material, the less permeable gabbroic contact of the vein did not yield to replacement as easily, and therefore the magnetite which forms at this contact will not be as thoroughly enveloped by the vein. Along the Sudbury Breccia/vein boundaries, the occurrence of magnetite is limited, and therefore very little magnetite is incorporated into the vein as the host breccia is altered to sulfidic material.

Bornite

A rare mineral at McCreedy West Mine, bornite $[\text{Cu}_3(\text{Fe}, \text{Ag})\text{S}_4]$ is constrained to narrow fractures within the Levack Gneiss at the distal extents of the footwall vein system. The 1 to 3 mm wide sulphide part of these veins is typically enveloped by much wider chloritic alteration halos. Despite its apparent macroscopic solitary nature, thin section examination reveals that the bornite often occurs with millerite and minor quantities of PGM and native silver.

Microprobe analysis of 2 bornite grains reveals that there is minor substitution of Fe by Ag within the bornite structure.

Sphalerite

Sphalerite $[(\text{Zn}, \text{Fe}, \text{Cd})\text{S}]$ is present in the veins of the footwall as part of both an early and late phase of mineralisation. In its early phase, sphalerite occurs within chalcopyrite as 10 to 50 μm blebs associated with PGM and hessite (Ag_2Te). In its later phase, sphalerite occurs as amorphous grains (generally $< .4\text{mm}$) with galena and local

pyrite in late cross cutting veins. Local deformation has resulted in late fracture openings where quartz-sphalerite-galena vein systems cross cut entire Cu-rich veins. Within these veins, sphalerite and lesser galena have coated the fracture wall, while quartz has filled the central void.

Electron probe analysis has established that Cd values in sphalerite may vary between 0.5 and 2.0 atomic %, and Fe may vary between 1.15 and 8.3 atomic %, but there does not appear to be any characteristic which might distinguish early sphalerite from late sphalerite. The chemical variation may suggest that the composition of sphalerite is equally inconsistent through time and that its composition may be partially influenced by local geology.

Galena

Similar to sphalerite, galena [Pb(S,Se)] is representative of both an early and a late phase of mineralisation. As an early phase, galena occurs as isolated < 50 µm blebs within a chalcopyrite host. Identification of these blebs is made difficult by their similar appearance to some PGM. Careful examination in reflected light though reveals that a weak blue tint is indicative of these grains. The secondary galena may be distinguished from earlier galena by its larger, euhedral grain size (<.3mm), and its occurrence with sphalerite and local pyrite in late cross cutting veins.

Electron probe analysis reveals that as a function of Se and S, galena:clausthalite ratios vary between 1.3:1 to 10.5:1. As with sphalerite, there is no apparent chemical composition that distinguishes a late galena from an early galena. Both the early and late phases of galena show variable Se:S.

Pyrite

Pyrite [FeS₂] occurs sparingly within late fractures which cross cut the vein system. Where these grains have overgrown the fractures, they have reacted with the host sulphide and formed outer zones on the pyrite grains consisting of bravoite [(Ni,Fe)S₂].

Minor Sulfides

Ag-pentlandite [Fe_{4.9}Ni_{3.1}AgS₈] occurs within chalcopyrite as brownish (darker than pyrrhotite) grains that have formed directly adjacent to vein sulphides and silicates. Other less common sulphides include S-geffroyite [(Cu,Fe,Ag)₉(S,Se)₈], hauchecornite [Ni₉(Bi,Sb,As,Te)₂S₈] and acanthite [Ag₂S].

4-6. VEIN SILICATE ASSEMBLAGES

The footwall veins at McCreedy West Mine are host not only to the various ore minerals, but also to a wide array of Fe-silicate minerals. Assemblages consist of chlorite, actinolite, epidote, biotite, greenalite, stilpnomelane, pyrosmalite and garnet, and occur both within the vein proper and as 1 to 5 cm wide dark green to black halos along the vein - wall rock contacts (Fig. 4-2a to 4-2d). At the terminations of some of the veins, quartz occurs with chalcopyrite, millerite and large euhedral grains of epidote (samples 14387 & 14389).

Nearest the vein contact, whether it be Sudbury Breccia or Levack Gneiss, alteration of the host rock minerals to Fe-silicates is generally complete. This includes replacement of both the fine grained feldspathic matrix as well as the larger quartz grain mosaics. With increasing distance from this intense alteration at the contact, it becomes apparent that alteration of the wall rock progresses foremost along grain boundaries and

fractures. Outside of this most intense alteration zone, the quartz grain mosaics are the most resilient, displaying only minor biotite and chlorite along internal grain boundaries. This has resulted in the appearance of quartz grain mosaics as isolated 'clasts' within a replaced Fe-silicate host

Epidote

Epidote [$\text{Ca}_2\text{FeAl}_2(\text{Si}_2\text{O}_7)(\text{SiO}_4)(\text{O},\text{OH})_2$] is the most common Fe-silicate mineral in selvages that are hosted by Sudbury Breccia. It most often occurs as anhedral to subhedral grains (.02 to 5 mm) intermixed with sulphides at the immediate contact of the vein with the wallrock, and as halos on disseminated sulphides in the alteration selvage. These grains often have a spotted appearance under plane polarized light due to the inclusion of up to 40% sulphide blebs. The largest and most euhedral grains, are those that occur in veins containing a high concentration of hydrothermal quartz. These grains are inclusion free and occur randomly within the quartz or along the vein margins perpendicular to the contact. The occurrence of epidote is reduced along vein contacts where magnetite is dominant. Under these circumstances, chlorite and actinolite define the dominant alteration assemblage.

Chlorite

Chlorite [$(\text{Fe},\text{Mg},\text{Al},\text{Ni},\text{Mn})_6(\text{Si},\text{Al})_4\text{O}_{10}(\text{OH},\text{O})_8$] is the most widespread and penetrating of the Fe - silicate alteration minerals at McCreedy West. It occurs as fine mesh-like, micron-scale grains, and as larger platy grains (mm scale) throughout the altered zones of the Levack Gneiss and the Sudbury Breccia. In alteration halos where epidote is adjacent to the sulphide veins, chlorite occurs within distinct alteration fronts which extend beyond the epidote replacement zone. Often chlorite is observed as a

replacement of amphibole. In Fig 4-5h, the cleavage traces of an amphibole grain from Sample MW-700-9140 are still apparent after replacement by chlorite. In the same sample, the replacement of other amphibole grains has resulted in the development of round titanite grains within large plate-like grains of chlorite.

In some instances, amphiboles have first been overgrown by biotite and then replaced by chlorite. Chlorite replacement of biotite is common throughout the alteration assemblage, with chlorite frequently observed forming ragged margins on biotite grains.

In samples where the host rock is more gabbroic in composition (e.g.: MW-600-9411 and MW-700-9165-C), two forms of chlorite typically occur within the alteration halo: a golden-brown iron-rich chlorite ($\text{Fe}/\text{Fe}+\text{Mg} = \sim .68$) intergrown with a more magnesian greenish-yellow chlorite ($\text{Fe}/\text{Fe}+\text{Mg} = .53 \pm 0.05$). Their compositions likely reflect the variable iron content of the host rock pyroxenes. In another sample of gabbroic composition (MW-OC-570-9411-2), an iron-rich chlorite ($\text{Fe}/\text{Fe}+\text{Mg} = 0.83 \pm 0.02$) is observed as a replacement margin on talc after pyroxene.

In addition to reflecting the chemistry of the proto-minerals, the composition of the chlorite is strongly dependent upon location with respect to vein proximity. A typical vein chlorite may have an $\text{Fe}/\text{Fe}+\text{Mg}$ ratio of $0.93 \pm .05$, whereas chlorite which occurs within the alteration halo displays an $\text{Fe}/\text{Fe}+\text{Mg}$ ratio of $0.81 \pm .10$, and chlorite which occurs within relatively unaltered wall rock has an $\text{Fe}/\text{Fe}+\text{Mg}$ ratio of $0.67 \pm .08$. Cl variability is also significant in the context of these three environments. Chlorite which occurs within the sulphide veins may contain 0.26 ± 0.25 atomic % Cl, chlorite which occurs within the alteration halo may contain 0.20 ± 0.21 atomic % Cl, and chlorite which occurs within relatively unaltered wall rock may contain 0.08 ± 0.08 atomic % Cl.

Greenalite

Greenalite $[(\text{Fe}, \text{Mg}, \text{Mn}, \text{Al})_{2-3}(\text{Si}, \text{Al})_2\text{O}_5(\text{OH})_4]$, a mineral chemically similar to chlorite but structurally characterized by serpentine-like layers (Deer et al., 1977), is a common alteration mineral within the veins and alteration selvages as a replacement of magnetite. Greenalite typically forms as elongate, blade-like grains which extend perpendicularly away from partially replaced magnetite grains (Fig. 4-5b, 4-5c, 4-5f). The nature of the replaced mineral is revealed in greenalite's high Fe/Fe+Mg ratio (0.97), whereas the nature of greenalite's origin is reflected by its high Cl content (3.16 ± 0.40 atomic % in the veins, 0.65 atomic % in the alteration halo). One greenalite grain, which was fully enclosed within a PGM, contained 8.72 atomic % Cl (sample 14385).

Amphibole

Amphibole is widespread along the margins and alteration selvages of the McCreedy West veins. Light to medium green coloured in plane polarized light, amphibole grains are typically well cleaved, subhedral to euhedral and variably sized from .1 to 2 mm. The majority of these grains are randomly oriented, but they have also been observed forming comb-like grains along the vein margins (e.g.: sample MW 14382a).

Chemically, most of the grains are Fe-actinolite $[\text{Ca}_2(\text{Fe}, \text{Mg})_5\text{Si}_8\text{O}_{22}]$ with very low contents of Cl. The occurrence, and Cl content of the actinolite is consistent with amphiboles reported by Farrow (1995), and Li and Naldrett (1993a) from the Deep Copper Zone at Strathcona. Only one amphibole from McCreedy West Mine contained significant Cl values. This ferro-edenitic-hornblende (1.05 weight % Cl) occurred within 100 μm of the vein contact in an alteration selvage which overprinted a gabbroic host

rock. Associated minerals with this hornblende were magnetite, garnet, pentlandite and native gold.

Biotite

Biotite $[K(Mg,Fe)_3(AlSi_3O_{10})(OH)_2]$ occurs as ragged and platy grains which occur within the Fe-Mg silicate alteration halo directly adjacent to the vein, as well as part of the more extensive alteration front which extends further into the wall rock and includes albitic, sericitic and hematitic alteration. These grains have formed as a replacement of pyroxene grains, which are in turn replaced by chlorite. Most grains of biotite contain between 0.1 and 0.3 atomic % Cl; however, one grain within the alteration halo to a chalcopyrite rich vein contained 2.8 atomic % Cl.

Stilpnomelane

Stilpnomelane $[(K,Ca,Na)(Fe,Mg,Al)_{12}(Si,Al)_{16}(O,OH)_{54}nH_2O]$ is a common mineral within the sulphide veins of McCreedy West Mine. Despite its similarity to biotite, this light to medium brown mineral is easily distinguished by its prismatic habit and its lack of the characteristic mottling effect of biotite. The most common form of stilpnomelane is as comb-like grains which have developed perpendicular to the vein contact but within the sulphide. The nature of their occurrence suggests that these grains initially formed at a vein contact which has subsequently been enveloped by the sulphide as it replaced the host wall rock.

Garnet

Garnet $[(Mn,Fe,Ca,Mg)_3(Al,Fe,Mn,Cr,Ti,V)_2(SiO_4)_3]$ has been observed only where the sulphide vein is in contact with gabbroic wall rock (Fig. 4-4e). At this location, a .05 to .15 mm wide band of massive garnet occurs as part of a zoned assemblage which

includes magnetite, Fe-actinolite and plagioclase, and the presence of pentlandite with native Au. Six analyses by microprobe have revealed the garnet to be a spessartine (27.68 ± 1.53 atomic % Mn).

Pyrosmalite

Pyrosmalite $[(\text{Fe}^{+2}, \text{Mn})_8\text{Si}_6\text{O}_{15}(\text{OH}, \text{Cl})_{10}]$ has been observed in several samples from McCreedy West Mine. The occurrence of this Fe-rich silicate is commonly as fine, mesh-like, grayish-green masses which sub-parallel the wallrock contact within the sulphide vein. The importance of this mineral relates to its tendency to incorporate chlorine in its structure. The analyses of 3 pyrosmalite grains by microprobe reveal a consistent Cl content of 6.61 ± 0.32 atomic %. The elevated levels of Cl in the pyrosmalite is suggestive of formation by a Cl rich hydrothermal solution.

4-7. PRECIOUS METAL MINERALS

The footwall veins at McCreedy West Mine are host to a wide variety of platinum group minerals (PGM) including: michenerite, moncheite, merenskyite, maslovite, froodite, altaite and sperrylite. All of these minerals, except for the relatively rare sperrylite and altaite, are palladium/platinum compounds with Bi and Te. Frequently associated with these PGM are the tellurides hessite and tsumoite. In addition, grains of argentian gold and native silver have been identified locally. Most of the platinum/palladium minerals are associated with sulphides (Table 4-5), either at sulphide - silicate interfaces or more commonly as inclusions within the sulphides; only one moncheite grain was observed within the gangue without an associated sulphide. These findings corroborate similar observations made by Farrow (1995) and Farrow and

Watkinson (1997) at McCreedy West Mine. With respect to other Sudbury area mines, the occurrence of vein hosted PGM appears to vary both within and between ore bodies. At the Strathcona Deep Copper Zone, PGM have been observed by Farrow (1995), and Farrow and Watkinson (1997) as occurring dominantly at grain boundaries of quartz and epidote whereas Li and Naldrett (1993) have described them as occurring at the sulphide grain boundaries. At the McCreedy East Mine, Molnar (personal communication, 1998) has stated that most PGM occur within the silicate assemblage associated with the veins. At the Barnet property, most PGM occur within chalcopyrite (Farrow, 1995; and Farrow and Watkinson, 1997), whereas at the Rathbun Lake Mine (near Lake Wanapitei) Rowell and Edgar have observed 'hydrothermally emplaced' PGM, similar to those associated with the Sudbury Structure, which occur dominantly with the silicates.

As outlined in Table 4-5, michenerite and moncheite are the dominant PGM to occur at McCreedy West Mine. Although quite similar in size (generally less than 40 μm) and shape (subround to subangular), moncheite is slightly brighter than the greyer michenerite. The only other physical characteristic which may aid in distinguishing between the two PGM at McCreedy West Mine is their preference of occurrence. As can be seen in Table 4-5 moncheite has a tendency to develop assemblages with hessite within chalcopyrite whereas michenerite tends to occur alone within chalcopyrite. On an individual basis though, both of these minerals have been observed as part of mineral aggregates with hessite, sphalerite and galena as well as the silicates actinolite and chlorite. Often PGM grains are revealed as composite grains only after examination with the Scanning Electron Microscope. This method of quantitatively/qualitatively examining the PGM reveals the composition of the grains by exposing contrasting atomic masses as

variable shades of grey in back scattered electron images (Figs. 4-11a to 4-11f).

Utilization of this method has revealed zoned PGM grains composed of moncheite - merenskyite, michenerite - merenskyite, and michenerite - merenskyite - moncheite.

Typically within these grains, one PGM has exsolved from the other or occurs as a later overgrowth of the other. An extreme example of PGM exsolution occurs in Fig. 4-12 where a host merenskyite has exsolved lamellae which are depleted in Te but enriched in Pd.

When plotted upon a ternary PdPtNi - TeSe - BiSb diagram (Fig. 4-10a), most of the PGM at McCreedy West Mine project as a solid solution between michenerite and merenskyite/moncheite. Grains which have end member compositions on this diagram may still contain significant substitution of Pt and Pd. As can be seen in Fig. 4-9b and Fig. 4-10b, michenerite at McCreedy West Mine may contain between 0 and 10.4 atomic % (0 and 13.16 weight %) Pt. This data compares favourably with data from Farrow (1995) who described McCreedy West michenerite with 5.4 to 13.6 weight % Pt. Moncheite at McCreedy West Mine has significant substitution of Pd for Pt (1.11 to 26.5 atomic%) (Fig. 4-9a and Fig. 4-10b) and merenskyite contains Pt (0.2 to 11.4 atomic %) and Ni (0 to 15.2 atomic %) as substitutions for Pd (Fig. 4-10b).

Au has only been observed where gabbroic host rocks are in contact with narrow oxide bands which frequently separate the Cu - rich sulphide vein from the country rock. These argentic gold grains (Ag: Au = 55:45) are quite small (< 30 μm) (Fig. 4-4e) and irregular, and commonly occur with small grains of pentlandite.

4-8. FLUID INCLUSIONS

In an attempt to better understand the composition of the fluids which transported the Cu-Ni-PGE to the footwall, daughter minerals within open fluid inclusions were qualitatively and semi-quantitatively analyzed with the SEM-EDS at Carleton University. The procedure for this technique involved physically splitting samples which contained significant quartz and/or chalcopyrite. Fragments of this material were immediately carbon coated, placed in the Jeol 6400 SEM-EDS, and analyzed using the Link eXL LZ4 instrument. Only semi-quantitative analysis of the grains was possible due to the small size of the grains, the irregular surfaces of the material, and the partly hidden nature of some of the grains within the inclusion cavity. The full details of analytical conditions have been described by Watkinson and Jones (1996), and Farrow et al. (1994),

Six samples from McCreedy West Mine were selected for fluid inclusion research. Qualitative examination by secondary electron imaging revealed numerous quartz and chalcopyrite hosted inclusions which appeared solitary within two dimensions. Daughter grains composed dominantly of NaCl, (Na,Ca) chloride and CaCl_2 (Fig. 4-14b, d, & e) and lesser Fe-Mn-rich chloride (Fig. 4-14a, & c) and quartz (Fig. 4-14f), occurred within both the inclusion cavities and as spatter on the edges of the inclusions. In some inclusion cavities, grains containing Zn, Pb, & Sn with Cl and S were detected. These grains were probably accidental sphalerite, galena and cassiterite (Fig. 4-14b, c, e, & f), covered in a thin film of Cl-rich material derived from the quenched liquid.

NaCl and (Na,Ca) chloride grains typically have a perfect cubic habit (Fig. 4-14b, d & e), whereas Fe-Mn rich chlorides have a variable morphology which ranges from acicular fibrous (Fig. 4-14a) to amorphous anhedral (Fig. 4-14c). Tetragonal cassiterite

occurs as elongate prismatic grains (Fig. 4-14c), and quartz is stubby and prismatic (Fig. 4-14f). Sphalerite occurs as wedge-like grains (Fig. 4-14b & c) whereas galena has a flat cubic morphology (Fig. 4-14f).

The daughter minerals which have been observed at McCreedy West Mine, are similar to those observed by Molnar et al. (1999), and Molnar et al. (1997) in the footwall of the South Range, and to North Range footwall occurrences which have been examined by Farrow (1995), Farrow et al. (1994), and Molnar (personal communication). Unlike other footwall occurrences, no Ba or Pb chlorides were observed at McCreedy West Mine.

Fluid inclusion evidence suggests that highly saline fluids were probably responsible for transporting the ore forming elements to the footwall. Molnar (personal communication) has observed that these ore bearing fluids represent one stage of a multigenerational sequence of fluids, which included carbonic fluids predating footwall ore formation and saline fluids postdating ore formation. Based upon fluid inclusion thermometry by Farrow (1995), and Molnar (personal communication), the ore forming fluids likely had a model composition of $\text{NaCl-CaCl}_2\text{-H}_2\text{O}$ and a temperature of approximately 300 to 350 °C.

Table 4-1 Mineralogy of vein samples from McCreehy West Mine.

Abbreviations: **act**-actinolite, **Au**-gold, **bi**-biotite, **bn**-bornite, **br**-bravoite, **ccp**-chalcopyrite, **chl**-chlorite, **ed**-edenite, **ep**-epidote, **fr**-froidite, **gar**-garnet, **gn**-galena, **grn**-greenalite, **hbl**-hornblende, **hes**-hessite, **mag**-magnetite, **mas**-maslovite, **mch**-michenerite, **mer**-merenskyite, **mln**-melonite, **moc**-moncheite, **mr**-millerite, **pn**-pentlandite, **po**-pyrrhotite, **py**-pyrite, **pys**-pyrosomalite, **ser**-sericite, **sp**-sphalerite, **spe**-sperryllite, **stl**-stilpnomelane, **te**-talc, **ti**-titanite, **tsu**-tsuomite, **vi**-violetite.

Sample	Host Rock	Sulfides	Oxides	PGM - Au - Rare Minerals	Fe-Mg Alteration Silicates	Comments
700-9140	Granitic Levack Gneiss	ccp	ti		chl	ti occurs as nodules in chl alteration halo
700-9092s	Granitic Levack Gneiss	ccp-po-pn	mag(1)-mag(2)		chl-ser-bi-grn	strongly brecciated (altered) associated wallrock
700-9165c	Gabbroic Levack Gneiss	ccp-po-pn-sp(2)-gn(2)	mag(1)-mag(2)	mch-moc-min-hes-Au	chl-grn-(Fe)act-gar-pys	greenalite & ccp replace mag, po replaced by pn
700-9165	Granitic Levack Gneiss	ccp-py-sp	mag(1)-mag(2)		(Fe)act-(Fe)hbl-chl-sp-ep	
700-9165t	Sudbury Breccia	ccp-pn-sp(2)-gn(1)		moc	(Fe)act-chl-stp	stp elongate perpendicular to vein boundaries
700-9163	Sudbury Breccia	ccp-pn-mr-sp(2)			ep-chl	large euhedral grains of ep (0.2 to 1.2 mm), mlr replacement of pn
570-9411a	Granitic Levack Gneiss	ccp-pn-sp(2)		moc	chl	narrow vein, ccp pn = 5.4
570-9411b	Granitic Levack Gneiss	ccp-pn-vi-sp(2)-po	mag(1)-mag(2)		chl-bi	mag(2) cross cuts pn grains, strongly contact with feldspar fragments
600-9411	Gabbroic Levack Gneiss	ccp-pn-po-sp(2)	mag(1)-mag(2)	Au-spe	chl-(Fe)act/hbl-gar-pys	gold with pn at oxide band/host rock contact, pyx partially replaced by bi-chl
600-9400-2	Granitic Levack Gneiss	ccp-mr-sp(2)-pn			chl-ep-stp-pys	mr occurs in vein & alt halo with ccp - after pn
700-9164	Granitic Levack Gneiss	ccp-pn-mr	mag(1)		(Fe)act-chl	mag partially replaced by ccp and act,
570-9411-1	Granitic Levack Gneiss	pn-ccp		moc	chl-(Fe)act-ep	narrow vein (<1 cm wide)
570-9411-2	Gabbroic Levack Gneiss	ccp-pn-sp-po-vi-gn(1)	mag(1)-mag(2)	mch-moc-Au	chl-tc-bi-pys	narrow vein, gold coloured chl,
650-9320	vein - massive	ccp	mag(1)-mag(2)		(Fe)act-stp	3% mag grains throughout
570-9430-2c	Granitic Levack Gneiss	ccp-sp(2)-gn(2)-(Ag)pn-gn(1)		hes	chl-ep	narrow ccp (99%) vein (< 1 cm wide), gn and sp at vein contact with quartz
570-9430-2b	vein - massive	ccp-pn-sp(1)-sp(2)-py-br-gn(2)-gn(1)		moc-mch-mer-tsu-hes	stp	euhedral growth of pyrite/bravoite late fractures
570-9430-2a	Sudbury Breccia	ccp-pn			ep-chl-stp	same sample as previous but at vein/wallrock contact
14348a	LG/SB	ccp-sp(2)	mag(1)		chl-ep-(Fe)act	strongly brecciated (altered) associated wallrock
14348b	vein-massive	ccp-po-pn-sp(2)-(Ag)pn	mag(1)	mch-moc-min-hes	NA	sample is from center of vein, pn grains partially replaced by po
14348c	LG/SB	ccp-pn-sp(2)	mag(1)-mag(2)		chl-ep-(Fe)act	strongly brecciated (altered) associated wallrock
14350a	Granitic Levack Gneiss	ccp-pn-sp(2)-gn(1)	mag(1)-mag(2)	mch		many large PGM (<50 um), pn & mag grains restricted to 1 cm wide zone along contact

Table 4-1 Mineralogy of vein samples from McCreedy West Mine (continued)

Sampl	Host Rock	Sulfides	Oxides	PGM - Au - Rare Minerals	Fe-Mg Alteration	Comments
14350	vein - massive	ccp-pn-vi-sp(2)-(Ag)pn-gn(1)	mag(1)	mch	NA	sample is from center of vein, pn occurs as large oblate grains
1437	Granitic Levack Gneiss	ccp-pn	mag(1)-mag(2)		(Fe)act-chl	strong K alteration (pink colouration to wallrock), 40% mag in vein
14378	Gabbroic Levack Gneiss	ccp-pn-po	mag(1)-mag(2)		(Fe)act-chl-grn	pn associated with mag band at contact, mag veinlets perpendicular/parallel to contact
14378	Gabbroic Levack Gneiss	ccp-pn-po-vi-Agpn-sp(1)-gn(1)	mag(1)-mag(2)	moc-hes-min	(Fe)act-chl-slp	mag band along contact, mag(1) separated from mag(2) by quartz grains
14379	Gabbroic Levack Gneiss	ccp-pn-sp(2)-sp(1)	mag(1)	moc-hes-min	(Fe)hbl	sharp contact with wallrock - no mag band
14379	Sudbury Breccia	pn-ccp-mr-sp(2)-sp(1)			chl-ep-(Fe)act	
14380	Gabbroic Levack Gneiss	ccp-pn-po-(Ag)pn	mag(1)-mag(2)	moc-mch-hes	chl-(Fe)act-grn	mag grains throughout (15%)
14380	Granitic Levack Gneiss	ccp-pn-sp(1)	mag(1)	mch-mas-hes-min	chl-(Fe)act-slp	stipnomelane defines alteration front in ccp
14381	Granitic Levack Gneiss	ccp-pn-sp(1)-gn(1)		moc-fro-hes	(Fe)act-chl	actinolite grains are perpendicular to vein contact
14381	Sudbury Breccia	ccp-pn		moc-mch-hes	ep-(Fe)act-chl	minor carbonate at vein edge
14382	Sudbury Breccia	ccp-po-pn-sp(2)-sp(1)		mch-moc-hes-min	chl-(Fe)act	2 to 3 mm long bleb of po, 2 mag bands along contact separated by ccp, po after mag(2)
14382	vein - massive	ccp-po-Agpn-sp(2)	mag(1)-mag(2)	mch-hes-min	NA	veinlets of po along parallel fractures in ccp and draping mag
14384	Granitic Levack Gneiss	bn-ccp-mr-gn(1)		Ag-PGM	ep-(Fe)act	unnamed PGM in bornite
14384	Granitic Levack Gneiss	mr-ccp-pn		mch-mer-tsu	chl-bi-ep-act	millerite contains rounded ccp inclusions (millerite after ccp)
1438	Sudbury Breccia	ccp-pn-sp(1)-gn(1)		mch-fro-tsu-hes	chl-(Fe)act-bi-slp-grn	pn blebs in vein near wall rock contact, minor quartz in vein
1438	Granitic Levack Gneiss	pn-ccp-sp(2)-gn(2)		moc-hes	ep-chl-Fe(act)	strongly brecciated (altered) associated wallrock
1438	Granitic Levack Gneiss					
1438	Sudbury Breccia	ccp-sp(2)-gn(2)-sp(1)		moc-mch-hes	ep-(Fe)act	excellent example of partial replacement of host rock by disseminated ccp
1438	Sudbury Breccia	ccp-mr-gn(1)		moc	ep-chl	hydrothermal q is dominant mineral with large ep (<4mm), mr partially absorbed by ccp
14390	Sudbury Breccia	mr-ccp-pn		mer-mch-hes	(Fe)act-ep-chl	merenskyite in millerite, michenerite in chalcopyrite
1439	Sudbury Breccia	ccp-mr-pn		moc-mch-mer-hes	ep-act-(Fe)act	partial replacement of pn by mr

Table 4-2 Average composition of sulfides from the McCreedy West Mine (atomic %)

Footwall Vein Ore	No. of analyses	Fe avg stdev	Co avg stdev	Ni avg stdev	Cu avg stdev	Zn avg stdev	Pb avg stdev	S avg stdev	Se avg stdev	Cd avg stdev	Ag avg stdev
Chalcopyrite	18	24.68 ± 0.30			25.36 ± 0.31			49.96 ± 0.16			
Pentlandite	44	21.46 ± 1.12	0.10 ± 0.06	30.59 ± 1.72				47.00 ± 0.27			
Millerite	12	0.98 ± 0.17	0.08 ± 0.09	48.83 ± 0.68				50.11 ± 0.59			
Pyrrhotite	18	45.90 ± 0.43		0.64 ± 0.30				53.48 ± 0.33			
Bornite	2	9.61 ± 0.25			50.40 ± 0.28			39.54 ± 0.42			0.45 ± 0.44
Violarite	2	21.14 ± 0.10	1.30 ± 1.07	20.03 ± 1.00				57.40 ± 0.18			
Sphalerite (1)	12	3.87 ± 1.91				44.46 ± 1.70		50.08 ± 0.45		1.04 ± 0.62	
Sphalerite (2)	5	3.26 ± 1.92				45.57 ± 1.68		49.98 ± 0.54		1.14 ± 0.57	
Galena	12	1.83 ± 1.04			2.86 ± 1.90		48.30 ± 1.53	36.89 ± 5.57	10.08 ± 5.69		
Contact Ore	No. of analyses	Fe avg stdev	Co avg stdev	Ni avg stdev	Cu avg stdev	Zn avg stdev	Pb avg stdev	S avg stdev	Se avg stdev	Cd avg stdev	Ag avg stdev
Pyrrhotite	33	45.86 ± 0.52									
Pentlandite	21	24.52 ± 0.99	0.66 ± 0.15	0.39 ± 0.10				53.66 ± 0.46			
Chalcopyrite	3	24.72 ± 0.04		27.51 ± 1.05	25.11 ± 0.53			47.25 ± 0.37			
Pyrite	6	32.63 ± 0.45	0.68 ± 0.37					50.08 ± 0.49			
								66.63 ± 0.23			

Table 4-3 Average composition of oxides from the McCreedy West Mine (atomic %)

Footwall Vein Ore	No. of analyses	Fe ²⁺ avg stdev	Fe ³⁺ avg stdev	Mg avg stdev	Mn avg stdev	Ti avg stdev	Al avg stdev	Cr avg stdev	Ca avg stdev	Si avg stdev
Magnetite (1)	10	33.45 ± 0.98	61.68 ± 2.69	0.20 ± 0.29	0.20 ± 0.14	0.65 ± 0.85	3.66 ± 1.91			
Magnetite (2)	15	33.09 ± 0.31	66.54 ± 0.17	0.13 ± 0.22	0.03 ± 0.05		0.13 ± 0.17			
Mag in Contact Ore	6	33.38 ± 1.47	62.29 ± 4.47	0.87 ± 0.58	0.11 ± 0.17	1.23 ± 1.49	1.53 ± 1.57			
Ilmenite	8	41.26 ± 2.61	7.49 ± 4.28		4.90 ± 2.32	46.08 ± 2.07		0.05 ± 0.09		
Titanite	2	0.83 ± 0.16				30.37 ± 0.92	1.70 ± 0.97		32.69 ± 0.14	33.33 ± 0.02
Rutile	1	1.19			0.10	96.64	0.30	0.20	1.09	0.49

Table 4-4 Average composition of silicates from veins, alteration assemblages and contact ore, McCreedy West Mine (atomic %).

Footwall Vein Alteration Minerals	No of analyses	Si	Al 1	Al 2	Ti	Fe ²⁺	Fe ³⁺	Mn	Mg	Ca	K	a	Na	Cl
		avg	stdv	avg	stdv	avg	stdv	avg	stdv	avg	stdv	avg	stdv	avg
Chlorite (in vein)	6	27.97 ± 0.88	11.91 ± 1.02	12.95 ± 0.39		41.66 ± 2.84		0.41 ± 0.23	3.15 ± 2.01		1.08 ± 1.26			0.26 ± 0.15
Chlorite (in alt halo)	38	29.14 ± 2.49	10.89 ± 2.35	11.80 ± 1.78		37.19 ± 4.56		0.44 ± 0.38	9.09 ± 5.07		0.51 ± 0.51			0.20 ± 0.22
Amphibole (in vein)	17	51.69 ± 1.99	1.91 ± 1.89	0.69 ± 0.56		19.82 ± 3.85	2.38 ± 2.15	0.50 ± 0.32	10.06 ± 4.42			12.81 ± 0.67		
Amphibole (in alt halo)	8	50.51 ± 3.55	2.80 ± 2.82	0.83 ± 0.73		16.54 ± 2.17	2.84 ± 2.92	0.87 ± 0.77	12.18 ± 2.90			12.68 ± 0.90		
Epidote	8	37.50 ± 0.16	0.06 ± 0.09	27.30 ± 0.64		0.24 ± 0.19	10.07 ± 0.70		0.38 ± 0.42			24.41 ± 0.36		
Greenalite (in vein)	8	38.17 ± 1.18	1.29 ± 1.16	4.39 ± 1.70		49.62 ± 2.61		1.59 ± 1.22	1.47 ± 0.86					3.16 ± 0.40
Greenalite (in alt halo)	1	39.40	1.34	7.11		48.76		0.26	1.70					0.65
Stilpnomelane (in vein)	7	49.29 ± 1.16		8.78 ± 0.26		34.69 ± 1.51		0.17 ± 0.17	0.89 ± 0.47		3.32 ± 2.29		2.54 ± 0.64	
Pyroxmalite (in vein)	3	39.47 ± 0.93				36.97 ± 0.28		15.3 ± 0.60	1.64 ± 0.36					6.61 ± 0.32
Garnet (at vein contact)	6	36.63 ± 0.64	0.84 ± 0.62	22.81 ± 2.64		1.84 ± 2.02	2.92	27.68 ± 1.51	0.23 ± 0.26	7.04 ± 1.18				
Biotite (in alt halo)	4	36.46 ± 2.35	14.78 ± 2.27	1.53 ± 1.46	1.78 ± 1.84	30.08 ± 3.27			4.17 ± 1.68	0.08 ± 0.10	9.73 ± 2.25	0.41 ± 0.43	0.79 ± 1.34	
Other Occurrences of Silicates	No of analyses	Si	Al 1	Al 2		e		Mn	Mg		K	a	Na	Cl
		avg	stdv	avg	stdv	avg	stdv	avg	stdv	avg	stdv	avg	stdv	avg
Chlorite (in LGC)	10	28.93 ± 2.25	11.20 ± 2.13	12.10 ± 1.25		31.43 ± 3.89		0.29 ± 0.12	15.38 ± 3.82		0.07 ± 0.15	0.13 ± 0.09		0.08 ± 0.08
Amphibole (in LGC)	2	51.00 ± 0.75	2.99 ± 0.95	0.02 ± 0.02		5.78 ± 2.56	6.50 ± 3.15	0.20 ± 0.00	21.50 ± 0.06			11.88 ± 0.76		
Amphibole (in FW/BX)	1	51.30	2.60	0.01		2.40	5.11	0.60	25.56			12.22		
Greenalite (in PGM)	1	34.02	2.47	2.35		46.05		5.64	0.75					8.72
Biotite (in LGC)	3	36.01 ± 0.54	15.18 ± 0.62	1.40 ± 2.41	3.18 ± 1.02	22.00 ± 2.26			10.57 ± 2.86		10.89 ± 1.10	0.11 ± 0.09	0.27 ± 0.47	0.25 ± 0.12

Table 4-5 Occurrence of PGM with respect to other footwall mineralisation, and the atomic Pd/Pd+Pt ratios for the PGM.

Class	Class Description	michenerite		moncheite		merenskyite		maslovite	froodite	sperryite	? PGM	tsumoite	Total
		(n)	Pd/Pd+Pt	SiDev	(n)	Pd/Pd+Pt	SiDev	(n)	Pd/Pd+Pt	SiDev	(n)	(n)	of class
1	grains which occur wholly within ccp	48	0.89	± 0.04	5	0.13	± 0.08	2	0.95	± 0.03		1	56
2	grains which occur in ccp with hes	12	0.90	± 0.08	41	0.18	± 0.09					2	58
3	grains which occur in ccp with hes and sph	9	0.84	± 0.15	9	0.18	± 0.21	2	0.64	± 0.11			21
4	grains in pn	2	0.87	± 0.03	1	0.15							3
5	grains in po	1	0.87		1	0.07							2
6	grains in mlr	2	0.97	± 0.03				5	0.94	± 0.06	2	2	11
7	grains in ccp with sil	14	0.85	± 0.11	14	0.23	± 0.20				1		29
8	grains in sil alteration selvage				1	0.20							1
9	grains at the contact of Ni & Cu sulfide & sil	5	0.88	± 0.08	1	0.06							6
10	grains occurring with tsu	4	0.90	± 0.16									4
11	grains in ccp with gn	1	0.99						3				4
12	grains in ccp with sp	1	0.92		2	0.31	± 0.16						3
13	grains in silicate in vein				1	0.45		2	0.55	± 0.01			3
14	grains in bornite										2		2
Total Number of PGM		99			76			11			5	4	203

Mineral	Atomic % Pt	Atomic % Pd
Froodite	0 to 0.43 %	30.29 to 33.01 %
Maslovite	28.5 %	3.73 %
Merenskyite	0.2 to 12.87 %	11.61 to 30.4 %
Michenerite	0 to 10.92 %	20.1 to 31.9 %
Moncheite	5.0 to 31.7 %	1.17 to 26.5 %
Sperryite	95.3 %	0 %

Table 4-6 Mineralogy of the footwall veins.

Mineralogy	Formula	Description
Sulfides		
Chalcopyrite	CuFeS_2	most common sulfide, occurs throughout evolution of vein, (grains: .4 to 3 mm), frequently replaces pentlandite and magnetite, also occurs as disseminated grains within the alteration halo, major PGM host
Pentlandite	$(\text{Fe},\text{Ni})_9\text{S}_8$	variable grain size, often partially replaced by violarite & chalcopyrite, formed very early in evolution of vein
Pyrrhotite	Fe_{1-x}S	occurs as narrow veinlets (.01 to .1 mm) and elongate blebs along chalcopyrite grain boundaries (less than 1 cm) - often attached to magnetite grains, more nickeliferous in Footwall than Sublayer.
Millerite	NiS	occurs as large (>1cm) optically continuous grains within chalcopyrite, likely formed later in evolution of the veins but prior to complete formation of chalcopyrite
Violarite	FeNi_3S_4	occurs within the pentlandite as a very late, low temperature overgrowth, patchy texture
Bornite	Cu_5FeS_4	terminations of larger vein systems, associated with native silver
Sphalerite	ZnS	two variants: 1) occurs as blebs < 50 mm associated with PGM and hessite. 2) as reddish brown amorphous grains (.1 to 2mm) frequently associated with late galena and pyrite in late fractures
Galena	$\text{Pb}(\text{S},\text{Se})$	two variants: 1) occurs as isolated blebs in chalcopyrite (10 to 40 mm) sometimes associated with PGM. 2) occurs as euhedral grains in late fractures and associated with late sphalerite, Se=2.86 to 12.07%
Ag-pentlandite	$(\text{Fe},\text{Ni},\text{Ag})_9\text{S}_8$	occurs as brownish amorphous grains (darker than pyrrhotite) attached to other grains (silicate or sulfide) in chalcopyrite
Pyrite	FeS_2	occurs in late fractures as euhedral grains (.1 to .5 mm)
Bravoite	$(\text{Fe},\text{Ni})\text{S}_2$	associated with pyrite in late fractures, represents a zonation of the pyrite grain into the host sulfide
S-Geffroyite	$(\text{Cu},\text{Fe},\text{Ag})_9(\text{S},\text{Se})_8$	light blue - grey, irregular grains, partly skeletal grains (<.5 mm), observed with millerite and chalcopyrite
Hauchecornite	$\text{Ni}_6\text{BiSbS}_4$	forms as irregular, partly skeletal grains (30 to 80 mm) and aggregates up to 1.8 mm in size, strongly anisotropic, white with beige tint
Acanthite	Ag_2S	elongate, partly lobate grain (60 x 100 mm)

Table 4-6 Mineralogy of the footwall veins (continued).

Mineralogy	Formula	Description
Oxides		
Magnetite 1	$\text{Fe}^{2+}(\text{Fe}^{3+},\text{Al})_2\text{O}_4$	an early forming magnetite, occurs as corroded blebs (.1 to 2 mm) within chalcopyrite and as bands (1 to 4 mm wide) along the vein - mafic wallrock contact
Magnetite 2	$\text{Fe}^{2+}\text{Fe}^{3+}_2\text{O}_4$	a later forming euhedral magnetite which typically has corroded earlier formed magnetite and often contains blebs of the host sulfide, typically crosscuts all other mineralization except the late Zn-Pb veins
Tellurides Bismuthide & Arsenides		
Hessite	Ag_2Te	occurs as isolated amorphous blebs (<30 mm) within chalcopyrite and often associated with PGM and sphalerite.
Michenerite	$(\text{Pd,Pt})\text{BiTe}$	generally < 30 mm, blebby to subhedral grains, often occurs alone within chalcopyrite, sometimes associated with hessite and sphalerite
Moncheite	$(\text{Pt,Pd})(\text{Te,Bi})_2$	generally < 30 mm, blebby amorphous grains, frequently associated with hessite in chalcopyrite.
Merenskyite	$(\text{Pd,Pt})(\text{Te,Bi})_2$	frequently associated with millerite, blebby amorphous grains
Maslovite	$(\text{Pt,Pd})\text{BiTe}$	only one grain (10 mm) identified, occurs with hessite and melonite in chalcopyrite
Altaite	PbTe	only one grain (22 mm) identified, occurs enclosed within a hessite grain within chalcopyrite
Tsumoite	BiTe	occurs with michenerite in millerite or with hessite and michenerite in chalcopyrite, < 20 mm
Melonite	NiTe_2	occurs with maslovite and hessite in chalcopyrite, < 20 mm
Froodite	PdBi_2	small anhedral grains (< 5 mm) often associated with galena in chalcopyrite
Sperrylite	PtAs_2	one triangular grain (15 mm) identified in chalcopyrite

Table 4-6 Mineralogy of the footwall veins (continued).

Mineralogy	Formula	Description
Native Elements		
Gold - Silver Alloy	Au ₅₅ Ag ₄₅	identified along norite - vein contact where magnetite corona occurs, generally attached to pentlandite grains
Silver	Ag	occur in bornite veinlets towards the termination of large vein systems, light grey, cusped, (.5 mm)
Silicates		
Epidote	Ca ₂ FeAl ₂ (Si ₂ O ₇)(SiO ₄)(OH) ₂	subhedral to euhedral grains, after feldspar, occurs both within the vein and the alteration halo
Chlorite	(Fe,Mg,Al,Ni,Mn) ₈ (Si,Al) ₄ O ₁₀ (OH,O) ₈	green, patchy to mat like composites, occurs dominantly along the vein-wallrock contact, low Cl values but the chlorite in the vein on average contains twice the Cl as the chlorite in the 'unaltered' wallrock
Greenalite	(Fe,Mg,Mn,Al) ₂₋₃ (Si,Al) ₂ O ₄ (OH) ₄	occurs frequently within the chalcopryrite often associated with Fe-actinolite, and as halos around corroded magnetite grains, generally has a very high Cl content (1.37 to 1.78% Cl), one grain of greenalite fully enclosed within a PGM had a Cl content of 4.2%
Fe-Actinolite	Ca ₂ (Fe,Mg) ₅ Si ₈ O ₂₂	platy grains (.1 to 1 mm), md green, grains in veins are Fe-actinolite whereas grains in 'unaltered' wallrock are actinolite to hornblende, Si value above 7.1
Biotite	K(Mg,Fe) ₃ (AlSi ₃ O ₁₀)(OH) ₂	occur dominantly within the alteration halo as ragged, platy grains, may occur as a replacement of wallrock amphiboles
Stilpnomelane	(K,Ca,Na)(Fe,Mg,Al) ₁₂ (Si,Al) ₁₆ (O,OH) ₅₄ nH ₂ O	occurs as elongate, needle-like grains frequently growing comb-like away from a former fluid source (.1 to 1 mm in length) massive patches which occur close to the vein-wallrock contact but within vein, very Cl rich
Pyrosmalite	(Fe ²⁺ ,Mn) ₈ Si ₆ O ₁₅ (OH,Cl) ₁₀	massive patches which occur close to the vein-wallrock contact but within vein, very Cl rich
Albite	(Na,Ca)AlSi ₃ O ₈	occur as saussuritized grains within the vein and as an alteration zone in the alteration package which halos magnetite bands in contact with noritic host rocks, 20 mm in width
Garnet	(Mn,Fe,Ca,Mg) ₃ (Al,Fe,Mn,Cr,Ti,V) ₂ (SiO ₄) ₃	massive, occurs as an alteration zone in the alteration package which halos magnetite bands in contact with noritic host rocks, 50 mm in width

Fig. 4-1a

Chalcopyrite-rich vein in sharp contact with gabbroic host rock. 3 mm wide magnetite band at contact consisting of Al and Ti rich magnetite overgrown by pure magnetite. Pure magnetite also occurs as narrow stringers exiting at obtuse angles from the main magnetite band and cross-cutting pentlandite blebs. Gold is associated with pentlandite at magnetite/silicate contact.

Sample 14378a - 600 level

Fig. 4-1b

Chalcopyrite-rich sample with inclusion of gabbroic rock. Cu rich fluids have encroached upon the gabbroic inclusion resulting in the formation of a halo of partially altered silicates. Pentlandite, which was previously adjacent to the inclusion has since been isolated and partially replaced by the advancing chalcopyrite mineralization.

Sample MW-700-11 - 700 level

Fig. 4-1c

Typical sulfide rich Footwall Breccia sample. Pyrrhotite is dominant sulfide, occurring as elongate blebs and fragments. Pyrite occurs as subhedral grains overgrowing pyrrhotite. Subrounded clasts are composed dominantly of pyroxene rich gabbro. The silicate matrix is granophyric in texture.

Sample MW-1150 - 1150 level

Fig. 4-1d

Footwall Breccia sample from a zone with a higher sulfide to silicate matrix ratio than the previous sample, and with an increased gabbroic clast content. Although the sulfide mineralogy is similar to MW-1150, blebby and fragmental textures are not apparent.

Sample MW-1450 - 1450 level

4-1a

5 cm

4-1b

5 cm

4-1c

5 cm

4-1d

5 cm

Fig. 4-2a

Sulfide component consists of 60% highly corroded pentlandite fragments and blebs in a chalcopyrite matrix. Vein is unusual for its high content of pentlandite. 4 cm wide alteration halo within Levack Gneiss consists of 1 cm band of disseminated chalcopyrite nearest the contact, and epidote + chlorite + Fe-actinolite alteration throughout. Moncheite and hessite occur within the chalcopyrite.

Sample 14386 - 810 level

Fig. 4-2b

Narrow (1 cm) vein of pentlandite (60%) corroded by late chalcopyrite within Levack Gneiss. Alteration halo is 3 to 5 mm wide and consists dominantly of chlorite. PGM (moncheite) occurs within chalcopyrite.

Sample MW-OC-570-9411a - 570 level

Fig. 4-2c

Chalcopyrite and pentlandite vein in contact with Sudbury Breccia. Alteration zone is defined by gradational contact with the Sudbury Breccia and replacement of all silicate mineralisation within 2 to 3 cm of the contact. Alteration consists of Fe-hornblende. Moncheite, hessite and melonite occur within the chalcopyrite. Pentlandite grains have formed sub-perpendicular to contact. Minor millerite has locally replaced pentlandite.

Sample 14379a - 590 level

Fig. 4-2d

Chalcopyrite, millerite and pentlandite vein in contact with tonalitic Levack Gneiss. Millerite has formed as a late partial replacement of both pentlandite and chalcopyrite. Alteration halo is 3 to 4 cm wide and consists of chlorite + biotite + epidote + actinolite. Michenerite, merenskyite and tsumoite occur within the millerite.

Sample 14384b - 590 level

4-2a

4-2b

4-2c

4-2d

Fig. 4-3a

0.5 m wide footwall vein within the Levack Gneiss. Pink colouration of Levack Gneiss related to hematitization associated with footwall vein alteration. A narrow pentlandite vein extends from the right side of the main vein.

570 level (9411 drift)

Fig. 4-3b

Narrow chalcopyrite - rich vein along the contact of the Levack Gneiss and the Sudbury Breccia. The structures hosting the Sudbury Breccia are also common hosts for the footwall veins.

600 level (9280 drift)

Fig. 4-3c

Narrow branching chalcopyrite - rich vein with dark Fe silicate alteration selvages overprinting the pervasive potassic alteration within the Levack Gneiss.

570 level (9430 drift)

Fig. 4-3d

Sub-rounded to sub-angular clasts of gabbroic to peridotitic composition occur within a massive sulfide (dominantly pyrrhotite) matrix.

1450 level - Contact Ore - Lower Main Ore Zone

4-3a

4-3b

4-3c

4-3d

Fig. 4-4a

Pentlandite replaced along cleavage planes by chalcopyrite. Millerite in the upper left corner has overgrown both the pentlandite and chalcopyrite. Reflected light.

Sample MW-1030-14

Fig. 4-4b

Triangular pyrrhotite exsolution occurring at intersections of cleavage planes within pentlandite grains. Reflected light.

Sample MW-700-9165C

Fig. 4-4c

Thin section of chalcopyrite vein in contact with a gabbroic host rock. Narrow magnetite band separates the silicates from the sulfides. Direct light.

Sample MW-700-9165C

Fig. 4-4d

Close - up of Fig. 4-4c showing the locations of Au grains with respect to the magnetite band. SEM back scatter image.

Sample MW-700-9165C

Fig. 4-4e

Close up of Fig. 4-4d showing individual Au grain attached to pentlandite grain. Fe actinolite occurs with albite and garnet at the contact. Reflected light.

Sample MW-700-9165C

Fig. 4-4f

Close up of magnetite band in contact with chalcopyrite. Pyrrhotite is draped along a subhedral grain of magnetite and displays a volume increase with respect to where it occurs isolated within the chalcopyrite. Reflected light.

Sample MW-700-9165C

Fig. 4-4g

Al - Ti magnetite grain (right side of image) intergrown with pentlandite. A later, pure magnetite has transgressed the pentlandite and enveloped the early magnetite. Reflected light.

Sample MW-14378a

Fig. 4-4h

Well twinned millerite adjacent to chalcopyrite. Pentlandite has formed along a fracture which defines the chalcopyrite/millerite contact. Reflected light.

Sample MW-9400-2

Fig. 4-5a

Al - Ti magnetite partially replaced along fractures by chalcopyrite. Chalcopyrite has totally replaced magnetite grain in upper left corner of photo. Reflected light.

Sample MW-700-9092Sa

Fig. 4-5b

Partially resorbed grain of Al - Ti magnetite replaced by chalcopyrite and elongate blades of greenalite. Reflected light.

Sample MW-650-9320

Fig. 4-5c

Partially resorbed grain of Al - Ti magnetite replaced by chalcopyrite and massive and blade - like grains of greenalite. Reflected light.

Sample MW-700-9092Sa

Fig. 4-5d

Secondary pure magnetite has formed along a fracture in the chalcopyrite. Chalcopyrite has been included within the magnetite grains. Reflected light.

Sample MW-700-9092Sa

Fig. 4-5e

Euhedral grain of pure magnetite has overgrown both a partially resorbed Al - Ti magnetite and the chalcopyrite that had been in the process of altering this mineral. Reflected light.

Sample MW-650-9320

Fig. 4-5f

Replacement of magnetite by chalcopyrite and greenalite has moved to completion, leaving only the form of the magnetite grain to suggest that it had previously existed. Reflected light.

Sample MW-700-9092Sa

Fig. 4-5g

Al - Ti magnetite has overgrown the Fe - Mg - rich silicates in the vein alteration halo, and included more resistant grains of plagioclase and quartz. Reflected light.

Sample MW-570-9411

Fig. 4-5h

Chlorite grains intergrown with quartz, display grain edges at 56 and 125 °. These two minerals have replaced an amphibole within the vein alteration halo. The amphibole may also have been a replacement of pyroxene. Plane polarized light.

Sample MW-700-9140

Fig. 4-6a: Histogram of various footwall chlorites showing the increase in Fe content with increasing proximity to the footwall Cu-rich veins.

Fig. 4-6b: Fe - Cl diagram which shows the variable chlorine content of chlorite with respect to its Fe composition and its proximity to the footwall Cu - rich veins. Chlorites within the vein and directly adjacent to the vein contain higher average Cl and Fe values.

Fig. 4-7a: Histogram of Co within pentlandite in the contact ore and the footwall vein ore. Contact ore pentlandite contains significantly more Co than footwall vein ore pentlandite.

Fig. 4-7b: Histogram of Ni within pentlandite in the contact ore and the footwall vein ore. Contact ore pentlandite contains less Ni than footwall vein ore pentlandite.

Fig. 4-8a. Ternary diagram displaying the variable composition of McCree West pentlandite as defined by the minerals with which pentlandite is associated.

Fig. 4-8b. Log - linear diagram of Co and Ni in McCree West pentlandite. The various symbols represent the minerals with which pentlandite is associated. Fe is displayed as anomalous where the size of the symbols deviate from the mean.

Fig. 4-9a: Histogram of Pd within McCreedy West Mine moncheite.

Fig. 4-9b: Histogram of Pt within McCreedy West Mine michenerite

Fig. 4-10a: A ternary diagram of (Bi+Sb) - (Pd+Pt+Ni) - (Te+Se) which displays the composition of all analysed McCreedy West Mine PGM.

Fig. 4-10b: A ternary diagram of Pd - Pt - Ni which displays the significant replacement of Pt for Pd in the michenerites, and the Pd replacement of Pt in the moncheites.

Fig. 4-11a

Pd depleted michenerite occurring with sphalerite, hessite and tsumoite within chalcopyrite. SEM backscattered image.

Sample MW-570-9430-2b

Fig. 4-11b

Merenskyite grain partially overgrown by moncheite. PGM occur within chalcopyrite and are associated with sphalerite and hessite. SEM backscattered image.

Sample MW-570-9430-2b

Fig. 4-11c

Pd rich and Pd depleted michenerite grains with exsolution of Pd depleted merenskyite. PGM occur within chalcopyrite and are associated with sphalerite and hessite. SEM backscattered image.

Sample MW-570-9430-2b

Fig. 4-11d

Pd depleted michenerite grain with overgrowth (exsolution?) of merenskyite and moncheite. PGM occur within chalcopyrite and are associated with sphalerite and hessite. SEM backscattered image.

Sample MW-570-9430-2b

Fig. 4-11e

Composite grain of altaite and hessite within chalcopyrite. SEM backscattered image.

Sample 14380b-2

Fig. 4-11f

Maslovite grain surrounded by intergrowth of melonite and hessite. These tellurides occur within chalcopyrite and are associated with sphalerite. SEM backscattered image.

Sample 14380b-2

alt=altaite, hes=hessite, ccp=chalcopyrite, sp=sphalerite, tsu=tsumoite, mas=maslovite, mch=michenerite, mer=merenskyite, mln=melonite, moc=moncheite

Fig. 4-12: SEM backscattered image of a composite grain of merenskyite and michenerite with an exsolution of an unknown PGM within the merenskyite. The composition of the merenskyite plus the unknown are plotted on the ternary diagram.
Sample MW-1030-1

Fig. 4-13: Sulfide-Oxide-PGM Assemblage Paragenetic Sequence in Cu-rich footwall veins.

Fig. 4-14a

Secondary electron image of fibrous Fe-Mn chloride grains (1) within an opened fluid inclusion in chalcopyrite (2).

Sample MW-14385

Fig. 4-14b

Secondary electron image of a euhedral Na chloride grain (1) with sphalerite (2) within an opened fluid inclusion in chalcopyrite.

Sample MW-14389

Fig. 4-14c

Secondary electron image of a euhedral cassiterite grain (1) with a Fe-Mn chloride (2) and sphalerite (3) within an opened fluid inclusion in chalcopyrite (4).

Sample MW-14378

Fig. 4-14d

Secondary electron image of a euhedral Na chloride grain (1) within an opened fluid inclusion in quartz (2).

Sample MW-14389

Fig. 4-14e

Secondary electron image of a euhedral Na - Ca chloride grain (1) with sphalerite (2) within an opened fluid inclusion in chalcopyrite (3).

Sample MW-14387

Fig. 4-14f

Secondary electron image of a euhedral quartz grain (1) with galena (2) within chalcopyrite (3).

Sample MW-14387

CHAPTER 5: ASSAY GEOCHEMISTRY

5-1. INTRODUCTION

Inco Limited has provided access to assay data compiled for more than 25,000 samples from McCreedy West Mine. This data has been provided for the purpose of creating a model of all significant geochemical trends within the ore zones at McCreedy West Mine. This geochemical interpretation can then be applied to other deposits on the North Range to see if they display similar geochemical characteristics. The underlying motivation for this model is to decrease footwall exploration costs by gaining a better understanding of the geochemistry of the contact deposits. This should allow the geologist to make a better determination of the probability of the occurrence of Cu-Ni-PGE footwall mineralisation.

At the McCreedy West Mine, compositional variability exists between the ore of the Sublayer norite, the Footwall Breccia and the footwall copper veins. Naldrett (1979) noted that the footwall veins are enriched in Pd, Pt and Cu and depleted in Os, Ru, Ir, Rh and Ni with respect to the Footwall Breccia. Standard assay data from INCO includes the elements Cu, Ni, Co, S, As, Pt, Pd, Rh, Au, Ag, and locally Fe. Through the application of various software packages, it has been possible to diagrammatically display some of this data in formats which exhibit the variability that occurs across the various ore zones.

5-2. INTRODUCTION TO PEARCE ELEMENT RATIOS

In igneous petrology, Pearce element ratio (PER) diagrams have been used to portray variations in chemical composition within and between rock suites. Specifically, equations are derived which relate changes in the composition of a system to the

stoichiometry of the material transfer process affecting the system. The axis coefficients of the diagrams are chosen so that the numerator represents those elements that affect the material quantities, and are active participants in the chemical evolution of the system. The denominator constituent represents an element that is not directly related to the fractionation of the system and therefore is conserved within the liquid component. Utilizing the forementioned constraints, the generation of a Pearce element ratio diagram will display a unique and predictable trend which represents the sorting of a mineral or a combination of minerals in an evolved system.

At the request of INCO Ltd; the same Pearce element ratio principles that have been used successfully for igneous rocks, have now been applied to the sulphide mineralisation in the hangingwall and footwall of the McCreedy West Mine. The basis for using Pearce element ratio diagrams relies on the assumption that the copper rich zones are in fact the fractionated end product of a sulphide melt. In this scenario, Cu is the conserved constituent and Ni and S are the active participants in the chemical evolution of the system. Regardless of whether the formation of the footwall copper veins is related to magmatic segregation or hydrothermal processes, the Pearce element ratio diagram should display unique trends which depict the compositional variability between the various ore bodies.

5-3. PEARCE ELEMENT RATIO DIAGRAMS

Utilizing data provided by INCO, it has been possible to determine compositional trends at the McCreedy West Mine with the aid of Pearce element ratio diagrams. Figs. 5-1a, 5-1b, 5-1c, represent the Ni, Cu and S values from 2030 data points culled from the

original data on a basis of a 1% Ni or Cu cutoff. All three of these diagrams present the same data but at differing scales. In a X-Y plot of the data (Fig. 5-1a), it may be observed that there exists one very strong linear trend with a slope of ~ 0.06 . In a properly proportioned Pearce element ratio diagram, this slope should relate to the mineral which has fractionated from the sulphide melt. In the Sublayer and Footwall Breccia ore at McCreedy West Mine, this mineral should be pyrrhotite with lesser pentlandite and magnetite. Based on this mineralogy, it quickly becomes apparent that Fe should be included within the Pearce Element Ratio in order to properly display the fractionating mineralogy. Unfortunately, Fe data is lacking for most of the ore analysed at McCreedy West Mine. The limited Fe data that is available does have some usefulness and will be discussed later. Despite its shortcomings, the diagram does display a significant trend when it is scaled in a manner that highlights data closer to the origin (Fig. 5-1b). At this scale a secondary trend is revealed which represents the Cu - rich character of the footwall veins. Two problems exist with this diagram though:

- 1) it is still difficult to determine the trend for a very tight cluster of data points which occur close to the origin of Fig. 5-1b at a S/Cu ratio of ~ 2 , and

- 2) in order to view the two distinct linear trends, it is necessary to rescale the diagram to such a degree that much of the data representing the Ni-rich Sublayer and Footwall Breccia is no longer visible.

One way of rectifying these problems is to view all of the data on a logarithmic plot (Fig. 5-1c). This method of presenting the data allows both the complete data set, and the two trends to be viewed at the same time. The near vertical trend represents the Cu - rich footwall veins and the sloping trend represents the Ni - rich footwall breccia and Sublayer norite ore deposits.

Although the development of these two trends is significant, a more meaningful use of the data is to interpret the variation along the individual trends with respect to the spatial arrangement of the ore bodies. For this to occur, a cull of the original data was performed using the 1% Ni or Cu cutoff. The next step was to examine each level of the McCreedy West Mine and determine the approximate center of the ore body on that level (Table 5-1). A three dimensional volume was then created for each level with an E-W width and N-S length of 100 feet centered on the ore body axis, and a height determined by a plane half way to the level above and below the level in question. This had the effect of creating a series of blocks encompassing the central portion of the ore body for each level, as well as providing a means of grouping data into meaningful three dimensional zones. Any data which did not have a northing, easting and elevation which was encompassed by the north, east and elevation coordinates of the individual zones was discarded. By culling the data in this manner, it became possible to examine the data step by step, from the bottom of the Lower Main ore zone, through the Middle Main ore zone and into the upper reaches of the Footwall Copper ore zone. The logarithmic plots in Figs. 5-2a, 5-2b, and 5-2c, represent a further refinement of the data within the individual zones. A lower cut-off of 15% S has been applied to the data to increase the likelihood that only ore grade material has been analyzed. This lower limit has restricted the data subset to 91 samples.

An examination of the data in Fig. 5-2a shows a strong linear trend of decreased Ni/Cu and S/Cu values within the Middle Main ore zone with respect to the Lower Main ore zone. Fig. 5-2b and 5-2c suggest that this may be related to a decreased Ni component in the Footwall Breccia ore rather than an increased Cu component. Also

there is a weak tendency towards an increased Ni/Cu ratio in the upper extremities of the footwall Cu veins with respect to the veins that occur lower in the deposit. Fig. 5-2b and 5-2c suggest that this is the result of an increased Ni component higher in the vein package rather than a decreased Cu component with respect to nickel. The nickel may be in the form of millerite bearing veins which are common at the distal extents of the vein system in the McCreedy West Mine.

A significant interruption occurs in the data between the S/Cu ratio of 4 and the S/Cu ratio of 9.5. This break represents the change from the nickeliferous semi - massive to massive sulphide of the Footwall Breccia to the Cu - rich veins of the footwall.

As previously mentioned, the most appropriate method of using Pearce Element Ratios for modelling fractionating pyrrhotite, is to define ratios which include Fe with Ni in the numerator and Cu as the conserved element denominator. In this fashion, a ratio of (Ni+Fe)/Cu vs. S/Cu should give a slope of 1, if indeed pyrrhotite has fractionated from a melt. An examination of Fig 5-3a and 5-3b reveals that Pearce Element Ratios do in fact define a trend which approximates the stoichiometric chemistry of pyrrhotite. Pyrrhotite composition is defined by a 1:1 ratio between (Fe,Ni) and S. The slope defined by the McCreedy West Mine data for the Lower Main to Middle Main samples is 1.03 ± 0.14 . This data has been culled on a 1% Cu or Ni cutoff and a S/Cu ratio of 8 to 300. This latter limit has been applied so that only the data which falls within the previously defined limits (see Fig. 5-2a) of the Lower Main and Middle Main ore bodies is considered.

It becomes readily apparent from an examination of the data that Pearce Element Ratios are successful in defining mineralogical trends in the magmatic contact ore where Cu may have been conserved in the magma, or alternatively, removed from the system at a

later time. These ratios are not as effective in discriminating trends in the footwall veins where Cu is more dominant than Ni and does not represent a conserved element. For this reason, the most important application of Pearce Element Ratios in the North Range is as a tool for distinguishing between various ore types. In this respect, homogeneous Ni-Cu deposits which have not witnessed a copper remobilization to the footwall should display more of a shotgun-like pattern on a Pearce Element Ratio Diagram with an approximate centre of gravity which has a lower Ni+Fe/Cu ratio than the trend defined by Ni-rich Footwall Breccia and Sublayer Norite. This point should reflect an undepleted Cu, Fe, and S component in the form of chalcopyrite in the contact ore. An examination of the composition of chalcopyrite (the dominant footwall Cu mineral at McCreedy West Mine) reveals that for every atom of Cu and Fe, there are 2 atoms of S. The atomic weight of S though is approximately half that of Cu and therefore a remobilization of these two elements to the footwall in an amount required to form chalcopyrite should not be reflected as a significant S/Cu ratio shift in the contact ore portion of the Pearce Element Ratio (PER) Diagram. The only ratio which should display a significant shift is the (Ni+Fe)/Cu ratio as discussed above. This ratio will be affected by an approximately proportional increase in Cu and Fe in an undepleted contact ore unit with very little change in Ni concentrations. The result of this would be a decrease in the ratio outcome as displayed by a lower centre of gravity on the PER logarithmic diagram.

An examination of the Upper Main ore body utilizing the same limits as were applied to the Lower Main and Middle Main ore bodies, reveals a (Ni+Fe)/Cu : S/Cu ratio of 1.03 ± 0.09 . The similarity of this ratio to that of the Lower Main and Middle Main, may reflect a semblance of the processes that operated on both ore bodies. This fact may

suggest that although the McCreedy West vein system appears to be physically connected to the Middle Main ore body, the Upper Main ore body should not be discounted as representing a partial influence on the footwall mineralisation. If the Upper Main was undepleted in chalcopyrite forming elements, the Pearce Element Diagram should reflect this characteristic as discussed above. A similar circumstance exists at the Strathcona Mine where the Copper Zones and Deep Copper Zones show no physical continuity with the contact ore but have been interpreted as having been derived from it.

5-4. DATA ANALYSIS USING DATAMINE, HISTOGRAMS AND CORRELATION CO-EFFICIENTS

One method of visually presenting the geochemical data from McCreedy West Mine is through the application of 3D rendering software such as DataMine from DataMine Software Ltd.

Although not used at McCreedy West Mine, DataMine is used by INCO Ltd. for modelling ore grades within some of their other mining operations. In order to gain an understanding of the uses and operation of DataMine, a 5 day course was required at INCO Ltd., Copper Cliff. This course provided the necessary background to complete a block model of McCreedy West Mine. The parameters used in the creation of the model are outlined in Fig. 5-13. Upon creation of this model, it became possible to view the variability of the elements in three dimensions, 'slice' the model along North - South lines, and recognize various geochemical trends.

In models where individual elements were considered, it was possible to use the whole data set from McCreedy West Mine. This allowed high grade areas such as vein

sets in the footwall and massive sulphide in the contact ore to be distinguished from lower grade barren rock. In models where ratios were considered (i.e. $\text{Cu}/\text{Cu}+\text{Ni}$), it became necessary to set a minimum ore grade criterion so that trace occurrences of an element being considered within otherwise barren rock would not overly influence the ratio. In the footwall, the ore is defined by relatively narrow veins. To properly model the geochemistry of these veins, the ratios must reflect the composition of the massive sulphides within the veins and not within the relatively barren wallrock, otherwise a rock with a grade of .01% Cu and .01% Ni in the wallrock will give the same Cu/Ni ratio as 5% Cu and 5% Ni within the veins. Therefore, by setting a lower limit of 0.5 weight % Ni or Cu, the only data that is taken into account is that which is considered to be potentially worth mining.

For the purpose of this thesis, block models were created which display the elements Cu, Ni, S, Co, and Pt+Pd, and the element ratios, $\text{Cu}/\text{Cu}+\text{Ni}$, $\text{Cu}/\text{Cu}+\text{Pt}+\text{Pd}$ and $\text{Au}/\text{Au}+\text{Pt}+\text{Pd}$. Unfortunately, Fe could not be included within any of the models of the ore zones at McCreedy West Mine because collection of Fe as part of the geochemical package at McCreedy West Mine has only been a relatively recent endeavour, and therefore most samples have not been analysed for this element.

The Ni, Cu, and $\text{Cu}/\text{Cu}+\text{Ni}$ diagrams (Figs. 5-5, 5-6, 5-7) display the most significant geochemical trends at McCreedy West Mine. The division between contact ore and footwall ore is made very clear on the DataMine diagrams by the distinct chemical compositions of each of these zones. The 2% to 4% Ni values which are observed in the diagrams, reflect the intense massive to semi-massive pyrrhotite with pentlandite mineralisation in the Sublayer and Footwall Breccia. In contrast, Cu mineralisation is

insignificant within this zone, but increases substantially within the footwall, where it occurs within sub-parallel zones which define footwall veins. Within these veins, up to 30% Cu is represented by chalcopyrite and minor bornite, whereas lesser Ni is defined predominantly by pentlandite and millerite.

From the DataMine sections, a significant depletion of Ni appears to occur in the Middle Main orebody with respect to the Lower Main orebody, yet over the extent of both of these ore bodies Cu remains relatively constant. This variable chemistry is also reflected in the Cu/Cu+Ni diagram which highlights the depleted Ni component. Although the diagrams suggest that there is a gradation in Ni from the Lower Main to the footwall veins, one should not immediately assume this to be correct. A more faithful interpretation of the data may relate to the method of block model creation. The computer interpretation of the data between the drill holes was based upon Inverse Distance². This method of block filling may have resulted in a gradation of data between drill holes where there was limited data to influence the defined search radius of the blocks. Where there was no data within the search radius of individual blocks, these blocks have remained empty and appear white on the diagrams.

To rectify the question of whether the gradational nature of the Ni data in the Middle Main is a function of real contained data or related to a computer defined interpretation, it becomes necessary to look at some of the other analysed elements to see if they display significant variation within the Middle Main. An examination of the S data reveals several 'hotspots' throughout the zone. This suggests that significant drill hole data occurs within the Middle Main and has been used as part of the block model interpretation. In addition, the lack of any empty blocks on the diagrams, suggests that

data must be occurring within the defined 60 foot search radius of the block model. The lower Ni content of the Middle Main ore body therefore is real and may either reflect the hydrothermal transport of some of the Ni from this zone to the footwall or alternatively it may represent the late stages of a sulphide magma which had already fractionated out most of its Ni.

In order to better validate the data, histograms have been created from data which was culled on a 1% Ni or Cu and 10 % S cutoff. This cutoff was selected so as to minimize both the amount of data being used, and the risk of examining data that is not considered to be at least ore grade. An examination of the Ni histogram (Fig. 5-4b), reveals that the footwall vein ore contains only slightly less Ni (2.27 ± 2.53 weight %) than what is contained within the Footwall Breccia (2.34 ± 0.98 weight %) ore. The low Ni content of the Sublayer (1.51 ± 0.56 weight % Ni) with respect to the Footwall Breccia potentially suggests that most of the Ni was conserved until the formation of the Footwall Breccia. The Cu histogram (Fig. 5-4a) suggests that the dominant Cu grade of footwall ore is between 6.4 and 25.6 weight % (average = 9.23 ± 6.98 weight % Cu) whereas Footwall Breccia and Sublayer ore is generally less than 1.6 weight % (average = 0.80 ± 0.78 and 0.35 ± 0.96 weight % Cu respectively). In addition, the histogram suggests that more Cu occurs in the Footwall Breccia than the overlying Sublayer. This data is supported by correlation coefficients (Table 5-2) which show no correlation between Cu and Ni within the Sublayer, a positive correlation in the Footwall Breccia and a negative correlation in the footwall veins.

The Co sections produced by DataMine (Fig. 5-8), display the affinity that this particular element has for the magmatic ore in the hangingwall. The processes which

mobilised the Cu and lesser Ni to the footwall, did not have the same affect on the Co.

Despite this, Co correlates positively with Ni in all ore environments (Table 5-2).

However it has a negative correlation with Cu in the footwall, a neutral correlation with Cu in the Sublayer and a slightly positive correlation with Cu in the Footwall Breccia ore.

In a magmatic model, the segregation of Co to the contact ore would be the result of Co precipitating with Ni early in the formation of the magmatic sulphide ore and therefore not participating in the late Cu-rich residue which was injected into the footwall. In a hydrothermal model, Co would remain in the hangingwall due to its relative immobility in saline solutions.

In Fig. 5-11, Pt and Pd have been considered together. Examination of the data reveals the affinity that both of these elements have for the footwall veins. A direct comparison of Cu with Pt + Pd (Fig. 5-12) (PGE values have been multiplied by 50x) however reveals that the PGE appear to be enriched in the lower veins instead of the upper veins where Cu is more dominant. This occurs despite the fact that Pt and Pd minerals are consistently associated with chalcopyrite when analyzed by petrographic means. An explanation for this apparent contradiction may arise when consideration is given to the locally depressed Cu/Cu+Ni ratio in the lower veins of the footwall. The lower ratio may reflect proportionally more pentlandite with respect to chalcopyrite in the lower veins. Pentlandite within the footwall potentially contains more PGE in solid solution than other footwall sulphides (see mineral geochemistry - Chapter 4), therefore, the more concentrated the pentlandite in the vein, the higher the PGE values should be in the assay. An examination of the correlation coefficients, however, may refute this idea. In Table 5-1, Pt and Pd show strong positive correlations with each other and with Cu in

all ore zones. However, both Pt and Pd show absolutely no correlation with Ni in the footwall. The only explanation for this situation is that millerite is unduly influencing the Ni concentration in the footwall. This Ni - rich sulphide contains minimal PGE in solid solution and therefore it would tend to skew the correlation coefficient results towards a null or negative correlation. Pentlandite bearing PGE would still influence local zones of mineralisation such as those which occur in the lower veins of the footwall, but in the overall scheme it would probably not account for nearly as much Ni as the millerite.

An alternative way of looking at the spatial distribution of Pt and Pd is on a histogram utilizing the same data constraints which were placed on the previous histograms. In Fig. 5-5a and 5-5b, it may be observed that both Pt and Pd are more highly concentrated in the footwall ore than in the contact ore. In the footwall vein ore, the average Pt and Pd values are 0.11 ± 0.46 oz/ton and 0.15 ± 0.18 oz/ton respectively, whereas in the Footwall Breccia ore the average Pt and Pd values are 0.009 ± 0.007 oz/ton and 0.008 ± 0.007 oz/ton respectively, and 0.003 ± 0.005 oz/ton Pt and 0.003 ± 0.005 oz/ton Pd in the Sublayer. The inferred bimodal distribution of this footwall ore in the histogram is a manifestation of the 'x' scale, which doubles the weight % at equal spacings. When viewed on a linear scale, the distribution of the data is much smoother.

Assay geochemistry from McCreedy West Mine therefore displays various geochemical trends which could be useful as indicators of footwall ore. To utilize this data to its fullest extents, one must be prepared to compare the data acquired here with data from other Sudbury ore bodies. This comparison may display geochemical similarities which are consistent among ore bodies with footwall ore and could therefore influence future exploration programs.

Table 5-1 Limits used in the creation of ore blocks from the bottom of the Ni - rich Lower Main contact zone to the top of the Cu - rich footwall veins. Data has been used in the Pearce Element Ratio Diagrams which model the chemical variability of the ore zones at McCreedy West Mine.

Level	Elevation (feet)	Ore Body Limits				Ore Body Midpoint		Limits of Ore Block [100' X 100' X (Level Thickness)]					
		N (from) (feet)	N (to) (feet)	E (from) (feet)	E (to) (feet)	mean N (feet)	mean E (feet)	Level Elevation - (feet)	Level Elevation + (feet)	mean N-50 (from) (feet)	mean N+50 (to) (feet)	mean E-50 (from) (feet)	Mean E+50 (to) (feet)
570	12475	9100	9700	1200	1800	9400	1500	12457	12525	9350	9450	1450	1550
600	12440	9100	9700	1000	1950	9400	1475	12395	12457	9350	9450	1425	1525
700	12350	9000	9630	1250	1900	9315	1575	12333	12395	9265	9365	1525	1625
800	12315	9000	9610	1000	1900	9305	1450	12293	12333	9255	9355	1400	1500
810	12270	8920	9610	1000	1975	9265	1487.5	12240	12293	9215	9315	1437.5	1537.5
900-1	12210	8800	9550	1070	1800	9175	1435	12175	12240	9125	9225	1385	1485
900-2	12210	8280	8515	1230	1400	8397.5	1315	12175	12240	8347.5	8447.5	1265	1365
950-1	12140	8660	9535	1060	2015	9097.5	1537.5	12120	12175	9047.5	9147.5	1487.5	1587.5
950-2	12140	8185	8525	1200	1715	8355	1457.5	12120	12175	8305	8405	1407.5	1507.5
980	12100	8125	9192	1100	1830	8658.5	1465	12050	12120	8608.5	8708.5	1415	1515
1080	12000	7935	9180	1100	1705	8557.5	1402.5	11965	12050	8507.5	8607.5	1352.5	1452.5
1150-3	11930	7925	8275	1915	2315	8100	2115	11903	11965	8050	8150	2065	2165
1200-1	11875	8100	8625	1150	1470	8362.5	1310	11853	11903	8312.5	8412.5	1260	1360
1200-2	11875	7835	8100	1290	2100	7967.5	1695	11853	11903	7917.5	8017.5	1645	1745
1250-1	11830	8240	8475	1185	1440	8357.5	1312.5	11815	11853	8307.5	8407.5	1262.5	1362.5
1250-2	11830	7775	8140	1200	1620	7957.5	1410	11815	11853	7907.5	8007.5	1360	1460
1250-3	11830	7785	7970	1620	2135	7877.5	1877.5	11815	11853	7827.5	7927.5	1827.5	1927.5
1300-1	11800	8220	8555	1200	1565	8387.5	1382.5	11765	11815	8337.5	8437.5	1332.5	1432.5
1300-2	11800	7630	7925	1430	2165	7777.5	1797.5	11765	11815	7727.5	7827.5	1747.5	1847.5
1350	11730	7660	7820	1665	2140	7740	1902.5	11710	11765	7690	7790	1852.5	1952.5
1400	11690	7640	7950	1825	2340	7795	2082.5	11660	11710	7745	7845	2032.5	2132.5
1450-1	11630	7360	7660	1700	2270	7510	1985	11585	11660	7460	7560	1935	2035
1450-2	11630	7735	7980	2625	3120	7857.5	2872.5	11585	11660	7807.5	7907.5	2822.5	2922.5
1500	11540	7510	7600	1760	2260	7555	2010	11490	11565	7505	7605	1960	2060

Table 5-2 Correlation coefficients of various elements within the three main ore zones at McCreedy West Mine. The ✓ represents those elements which correlate either in a negative or positive mode. This data has been used to support and explain the outcome of the data which has been used in the histograms, DataMine sections and Pearce Element Ratio Diagrams.

FOOTWALL VEINS						
	CU	NI	CO	S	PT	PD AU
CU	1.00					
NI	-0.21	1.00				
CO	-0.58	0.40	1.00			
S	0.20	0.26	0.40	1.00		
PT	0.20	-0.04	-0.11	0.06	1.00	
PD	0.57	-0.05	-0.35	0.07	0.36	1.00
AU	0.27	-0.04	-0.19	-0.03	0.18	0.37 1.00
SHADED CELLS n = 968 NON SHADED CELLS n = 791						
FOOTWALL BRECCIA						
	CU	NI	CO	S	PT	PD AU
CU	1.00					
NI	0.36	1.00				
CO	0.16	0.68	1.00			
S	0.20	0.83	0.60	1.00		
PT	0.54	0.52	0.40	0.32	1.00	
PD	0.57	0.42	0.32	0.18	0.85	1.00
AU	0.23	0.18	0.11	0.13	0.36	0.33 1.00
SHADED CELLS n = 1395 NON SHADED CELLS n = 765						
SUBLAYER						
	CU	NI	CO	S	PT	PD AU
CU	1.00					
NI	0.17	1.00				
CO	-0.04	0.62	1.00			
S	0.13	0.71	0.61	1.00		
PT	0.38	0.30	0.22	0.29	1.00	
PD	0.52	0.22	0.16	0.28	0.91	1.00
AU	0.51	-0.23	-0.20	-0.08	0.13	0.28 1.00
SHADED CELLS n = 383 NON SHADED CELLS n = 131						

Footwall Veins	rPt:Pd	sig	rPd:Cu	sig	rPt:Cu	sig	rPd:Ni	sig
Footwall BX	0.36	✓	0.57	✓	0.20	✓	-0.05	✓
Sublayer	0.85	✓	0.57	✓	0.54	✓	0.42	✓
	0.91	✓	0.52	✓	0.38	✓	0.22	✓
Footwall Veins	rPt:Ni	sig	rPd:Co	sig	rPt:Co	sig	rCu:Ni	sig
Footwall BX	-0.04	✓	-0.35	✓	-0.11	✓	-0.21	✓
Sublayer	0.52	✓	0.32	✓	0.40	✓	0.36	✓
	0.30	✓	0.16	✓	0.22	✓	-0.04	✓
Footwall Veins	rNi:Co	sig	rCu:Co	sig	rCu:Cu	sig	rNi:Cu	sig
Footwall BX	0.40	✓	-0.58	✓	0.27	✓	-0.04	✓
Sublayer	0.68	✓	0.16	✓	0.23	✓	0.18	✓
	0.62	✓	-0.04	✓	0.51	✓	-0.23	✓
1	large values in one set correlate with large values in the other set							
0	values in both sets are unrelated							
-1	small values in one set correlate with large values in the other set							
✓	good correlation

Fig. 5-1a: Standard Pearce Element Ratio Diagram, with data constraints as detailed in the text.

Fig. 5-1b: Re-scaled Pearce Element Ratio Diagram, showing only data at low ratios.

Fig. 5-1c: Logarithmic version of Pearce Element Ratio Diagram, showing all data.

Fig. 5-2: Data within Figs. 5-2a to 5-2c have all been culled on the basis of a Ni or Cu value $\geq 1\%$ and a S value $\geq 15\%$. In addition, data has been defined by block limits as described within the text. Fig. 5-2a displays all of the data as culled. Fig. 5-2b displays the data with Ni anomalies highlighted. Fig. 5-2c displays the data with Cu anomalies highlighted. Ni increases from the Lower Main to the Middle Main ore zones. Footwall ore is compositionally distinct from contact ore.

Fig. 5-3a: Standard Pearce Element Ratio Diagram with the magmatic fractionation defined by Fe-Ni-S in the form of pyrrhotite in the contact ore..

Fig. 5-3b: Logarithmic Pearce Element Ratio Diagram with the magmatic fractionation of pyrrhotite defined by the slope of 1.02 in the contact ore. Footwall ore is defined by a much steeper slope relating to the influence of Cu.

Fig. 5-4a: Histogram which displays the variability of Cu within the 3 main ore types at McCreedy West Mine. Cu enrichment within the ore decreases from the footwall veins to the Footwall Breccia to the Sublayer.

Fig. 5-4b: Histogram which displays the variability of Ni within the 3 main ore types at McCreedy West Mine. Footwall vein ore and Footwall Breccia ore contain similar concentrations of Ni but the Sublayer ore is Ni depleted.

Fig. 5-5a: Histogram which displays the variability of Pt within the 3 main ore types at McCreedy West Mine. Footwall vein ore shows Pt enrichment with respect to Footwall Breccia and Sublayer ore.

Fig. 5-5b: Histogram which displays the variability of Pd within the 3 main ore types at McCreedy West Mine. Footwall vein ore shows Pd enrichment with respect to Footwall Breccia and Sublayer ore.

Fig. 5-6 DataMine cross sections showing Cu variability in the various ore zones at McCreehy West Mine. The upper diagram displays 1850 and 1950 sections, with Cu enrichment in the footwall. The lower diagram displays 1500, 1800, 2100, and 2400 sections viewed from an angle of 29.5° from the vertical, with Cu enrichment in the footwall.

Fig. 5-7 DataMine cross sections showing Ni variability in the various ore zones at McCreedy West Mine. The upper diagram displays 1850 and 1950 sections, with Ni enrichment in the contact (hangingwall) ore. The lower diagram displays 1500, 1800, 2100, and 2400 sections viewed from an angle of 29.5° from the vertical, with Ni enrichment in the contact (hangingwall) ore.

Fig. 5-8 DataMine cross sections showing Co variability in the various ore zones at McCreehy West Mine. The upper diagram displays 1850 and 1950 sections, with Co enrichment in the contact (hangingwall) ore. The lower diagram displays 1500, 1800, 2100, and 2400 sections viewed from an angle of 29.5° from the vertical, with Co enrichment in the contact (hangingwall) ore.

Fig. 5-9 DataMine cross sections showing S variability in the various ore zones at McCreech West Mine. The upper diagram displays 1850 and 1950 sections, with S enrichment in the contact ore.. The lower diagram displays 1500, 1800, 2100, and 2400 sections viewed from an angle of 29.5° from the vertical, with S enrichment in the contact ore..

Fig. 5-10 DataMine cross sections showing variable Cu/Cu+Ni ratios in the various ore zones at McCreehy West Mine. The upper diagram displays 1850 and 1950 sections, with Cu enrichment in the footwall. The lower diagram displays 1500, 1800, 2100, and 2400 sections viewed from an angle of 29.5° from the vertical, with Cu enrichment in the footwall.

Fig. 5-11 DataMine cross sections showing Pt+Pd variability in the various ore zones at McCreehy West Mine. The upper diagram displays 1850 and 1950 sections, with Pt+Pd enrichment in the lower vein sets of the footwall. The lower diagram displays 1500, 1800, 2100, and 2400 sections viewed from an angle of 29.5° from the vertical, with Pt+Pd enrichment in the lower vein sets of the footwall.

Fig. 5-12 DataMine cross sections showing variable C/Cu+Pt+Pd ratios in the various ore zones at McCreedy West Mine. The upper diagram displays 1850 and 1950 sections, with Cu enrichment in the upper veins of the footwall. The lower diagram displays 1500, 1800, 2100, and 2400 sections viewed from an angle of 29.5° from the vertical, with Cu enrichment in the upper veins of the footwall.

DataMine Modelling Criteria - McCreedy West Mine

Block Model Space: X (Eastings) = 1418.75 to 2581.25
 Y (Northings) = -2410 to 200
 Z (Elevation) = 11390 to 12790 (surface is 13000)

Cell Dimensions: X (Eastings) = 12.5 feet
 Y (Northings) = 10 feet
 Z (Elevation) = 10 feet

Number of Cells: X (Easting) = 93
 Y (Northing) = 261
 Z (Elevation) = 140

Elliptical Search Radius: X (Easting) = 60 feet
 Y(Northing) = 60 feet
 Z (Elevation) = 20 feet

Dip of Search Ellipse: 45° S

Data Used in Creation of Model: Samples were culled from data based upon a Cu or Ni cutoff of **0.5%**.

Fig. 5-13: Criteria used in the creation of the block model sectional diagrams (Fig. 5-6 to Fig5-12) of McCreedy West Mine ore zones.

CHAPTER 6: DISCUSSION

6-1. INTRODUCTION

The Sudbury Structure has always been the subject of controversy; whether it be for its mode of formation (endogenic vs. exogenic) or for the nature of origin of its ore. Mineralization at McCreedy West Mine occurs within two distinct environments: 1) Ni - rich disseminated and massive contact ore (Footwall Breccia and Sublayer) at the base of the Sudbury Igneous Complex, and 2) Cu - rich footwall ore within veins commonly associated with the Sudbury Breccia. The acceptance of a magmatic origin for the formation of the contact ore is fairly universal; however the origin of the footwall ore is much more contentious. Naldrett et al. (1982) have suggested that the vein ore was injected into the footwall after having been magmatically segregated by fractionation of monosulphide solid solution. Alternatively, Farrow and Watkinson (1997) and Farrow (1995) have suggested an origin related to the occurrence of contact convective cells which moved metal laden Cl solutions into the footwall from the contact area. In the preceeding chapters, data has been presented which has described the geological, mineralogical and geochemical makeup of the ore and orezones at McCreedy West Mine. Although both theories of formation are plausible, the data (textural, mineral and chemical) does not support footwall vein formation by a Cu-rich fraction of magmatic sulfide liquid. All evidence suggests that the footwall veins formed under the influence of hydrothermal solutions. An examination of all of the data will be presented in this chapter with particular emphasis directed at the hydrothermal aspects of the footwall ore. Factors which may prove important in the discovery of similar footwall ore will also be discussed.

6-2. SIGNIFICANCE OF MCCREEDY WEST MINERALOGY AND MINERAL GEOCHEMISTRY

The mineralogy of the McCreedy West Mine ore bodies is highly complex - more so in the footwall veins than the contact ore of the hangingwall. Most of the contact ore which was observed at McCreedy West Mine occurred as semi-massive to massive pyrrhotite with lesser pentlandite, chalcopyrite, magnetite and pyrite, and formed as a matrix to sub-rounded to sub-angular lithic fragments of gabbroic to peridotitic composition. On the other hand, the footwall ore is composed of at least 14 sulphides (dominated by chalcopyrite, pentlandite, millerite and pyrrhotite), 2 varieties of magnetite (a pure magnetite and an Al, Ti bearing magnetite), numerous tellurides (michenerite, moncheite and hessite are the most common), and native gold and silver. In addition, the vein mineralogy is characterized by distinctive hydrous Fe-silicate assemblages which include chlorite, epidote, Fe-amphibole, greenalite, stilpnomelane, biotite and pyrosmalite. Typically this set of alteration minerals has formed both within the sulphide rich veins and as narrow (cm scale) alteration zones along the edges of the veins. Where the host rock consists of Sudbury Breccia instead of Levack Gneiss, these alteration halos may extend outwards by many decimetres. Sericitization-saussuritization and lesser biotitization, with associated albitization and hematization, extends several m from the vein contacts and provides a patchy pink colouration to the Levack Gneiss. Quartz has also been observed within the vein system, occurring towards the terminations of some of the veins.

Significant geochemical trends have been indicated within some of the vein associated silicates. A typical vein chlorite may have an Fe/Fe+Mg ratio of $0.93 \pm .05$, whereas chlorite which occurs within the alteration halo displays an Fe/Fe+Mg ratio of

0.81 $\pm$.10, and chlorite which occurs within relatively unaltered wall rock has an Fe/Fe+Mg ratio of 0.67 $\pm$.08. Cl variability is also significant in the context of these three environments. Chlorite which occurs within the sulphide veins may contain 0.26 $\pm$ 0.25 atomic % Cl, chlorite which occurs within the alteration halo may contain 0.20 $\pm$ 0.21 atomic % Cl, and chlorite which occurs within relatively unaltered wall rock may contain 0.08 $\pm$ 0.08 atomic % Cl. Other silicates of geochemical importance include greenalite, which contains 3.16 $\pm$ 0.40 atomic % Cl in the veins and 0.65 atomic % Cl in the alteration halo, and pyrosmalite which contains a consistent Cl content of 6.61 $\pm$ 0.32 atomic % within the veins.

The fact that Fe silicates are occurring in such abundance within the veins and vein halos is quite significant. The fact that these same silicates are bearing high concentrations of Cl which tends to decrease away from the vein, is even more significant. These mineral assemblages can only be explained by the influence of Cl bearing hydrothermal solutions upon the wallrock. The close relationship between the silicates, sulphides and oxides within the veins suggest that this relationship extends to the formation of the veins by hydrothermal means. Excellent examples of these relationships have been presented within this thesis, the most notable of which is the formation of greenalite and chlorite around resorbed grains of Al-Ti bearing magnetite within chalcopyrite, and the later formation of pure magnetite around these same grains. Relationships such as these are suggestive of the presence of solutions which may have evolved from oxidizing to reducing and back to oxidizing during vein formation. Pyrite and magnetite bands within the pyrrhotite of the contact ore may define the fluid pathways of oxidizing solutions as they moved throughout the contact ore package on their way to the footwall. Based upon

work by Wood (1987), Mountain and Wood (1988a), Wood et al. (1989, 1994), Gammons et al. (1992), Farrow and Watkinson (1997) have suggested that highly acidic and oxidizing Cl-rich aqueous fluids are required to attain significant Pt and Pd solubility at 350 °C. These same Cl and S - rich fluids which dissolved and remobilized Pt and Pd, also formed the Cu rich veins of the footwall. Within the footwall environment, the PGE became 1) locked in solid solution with pentlandite, 2) associated with Te to form micro - inclusions within the pentlandite or 3) associated with Te $\pm$ Bi to form various tellurides within the chalcopyrite or millerite. This may in fact have been a two step process with the early formed pentlandite dissolved by later Cu (+ Bi) bearing solutions, thereby unlocking the PGE to form the micron - scale bismuth - tellurides.

Another key piece of evidence that reflects the influence of hydrothermal solutions is the occurrence of solitary fluid inclusions with polyphase chloride daughter minerals within both quartz and chalcopyrite within the veins. These inclusions which bear Fe+Mn+Cl, Na+Ca+Cl and Na+Cl crystals are similar to those observed within other footwall vein occurrences by Molnar et al. (1999), Farrow (1995), and Farrow and Watkinson (1992). Temperature data attained from some of these inclusions suggest that vein formation occurred at temperatures near 300 °C.

Geochemical examination of the various ore associated minerals has also revealed some startling anomalies. Electron-probe analysis of footwall vein pentlandite shows a lower Co but higher Ni content than hangingwall magmatic pentlandite. The average vein pentlandite contains 0.10 ± 0.06 atomic % Co and 30.59 ± 1.72 atomic % Ni in comparison to 0.66 ± 0.15 atomic % Co and 27.55 ± 1.05 atomic % Ni in the magmatic ore. Laser ablation studies have revealed that vein pentlandite harbours a high content

(gram level) of Pd in solid solution. Vein pyrrhotite appears to be a late exsolution from the chalcopyrite, and displays a distinct Ni composition with respect to the contact ore. The average vein pyrrhotite contains 0.64 ± 0.30 atomic % Ni, whereas pyrrhotite from the contact ore contains only 0.39 ± 0.10 atomic % Ni.

Although not significant from a formational aspect, the chemical composition of the aforementioned sulphides is important because it reflects characteristics unique to each zone of ore occurrence. A further examination of the variability of Ni and Co concentration within vein pentlandite with respect to its distance from the hangingwall/footwall contact though has not revealed any remarkable trends. The occurrence of Pd within pentlandite is highly significant from a metallurgical point of view, but not enough samples were analyzed by laser ablation to define any significant trends within the footwall ore. Simple calculations based upon a knowledge of the concentration of Pd in pentlandite, the assay of the sample, and an estimate of the percentage of each sulphide within the sample should provide a quick estimate of whether all of the Pd has been won through the milling and processing of the ore. A follow up of this information should be completed to ensure that processing procedures are adequate to ensure that all of the Pd is recovered from the ore.

6-3. SIGNIFICANCE OF MCCREEDY WEST BULK ROCK GEOCHEMISTRY

INCO Ltd. provided assays for more than 25000 diamond drilling samples at McCreedy West Mine. The intention of working with this data was to attempt to define any significant geochemical trends which may be used during exploration to indicate the potential occurrence of footwall ore. The standard assay by INCO included the analysis of

Cu, Ni, Co, S, As, Pt, Pd, Rh, Au, Ag, and locally Fe. Using some of this data, the initial emphasis was to test whether Pearce Element Ratio Diagrams might define any significant geochemical trends within the various ore bodies. The secondary goal was to utilize 3D rendering software (DATAMINE) to distinguish geochemical trends by interpolating data between drill holes. In addition, histograms and correlation coefficients were compiled to confirm or deny the existence of any significant trends.

Pearce Element Ratio diagrams have been used by igneous petrologists to portray variations in chemical composition within and between rock suites. By selecting data based upon location and ore grade, and by utilizing Ni and S as the active participants in the chemical evolution of the system and Cu as the conserved element, it was possible to utilize Pearce Element Ratio (PER) principles to define geochemical trends within the ore at McCreedy West Mine. These ratios defined ore which displayed a decrease in Ni content from the Lower Main Ore Zone to the Middle Main Ore Zone. This data was supported by histograms and DataMine sectional diagrams which also suggested this trend. The PER diagrams also displayed the distinct composition of the contact ore with respect to the footwall ore. The contact ore was shown to have a Ni/Cu ratio above 0.6 and a S/Cu ratio above 8, whereas the footwall ore had a Ni/Cu ratio below 0.6 and a S/Cu ratio below 4.0. In addition the footwall ore was defined by a much steeper slope which was related to its increased Cu component. According to the Pearce Element Ratio diagrams, Cu was distributed fairly consistently throughout each of the ore zones. This data compared favourably with the sectional DataMine diagrams and histograms of contact ore, but the histogram of Cu for the footwall ore suggested a bimodal distribution of Cu. This distribution may be explained by the DataMine sections which suggest zones

of higher grade Cu mineralisation in the upper veins of the footwall and lower grade zones in the lower veins.

Based upon a knowledge of the ore mineralogy, it became apparent that the implementation of only Ni, Cu and S in the PER diagrams was not maximizing all of the faculties of this diagram. Because pyrrhotite is the most dominant contact ore mineral, Fe must be considered as an active participant in any chemical evolution of a sulfidic magma. The application of the new ratios with Fe and Ni in the numerator and Cu in the denominator led to the development of a PER diagram which displayed a slope of approximately 1 for the contact ore data. This slope represents the dominant sulphide mineralogy of the contact ore (i.e. pyrrhotite), and what may be considered in a magmatic model as the mineral which has fractionated from the melt. The Cu - rich vein data still defines a much steeper slope on this diagram due to the strong influence of Cu. To properly define the mineralogy of the footwall would require a PER diagram which has Cu, Ni, Fe and S as active participants in the formation of the ore system. Unfortunately, there is no other element in the McCreedy West database which could be used as a conserved element in a PER diagram of the footwall veins, therefore this exercise has not been performed.

Pd and Pt data have been examined by the use of DataMine sections, histograms and correlation coefficients. The DataMine sections and histograms suggest a trend of increasing Pt and Pd values from the Sublayer ore, through the Footwall Breccia ore and into the footwall vein ore. Within the footwall veins, Pt and Pd appear to be more highly enriched within the lower part of the ore system where Cu mineralisation is less intense. Despite the data which suggests that there is no correlation between Ni and Pt + Pd, it is

now known that the Pd content within pentlandite is quite high (gram level). The negative correlation that exists between Ni and Pt + Pd may be attributed to overweighting by PGE depleted millerite within the footwall vein ore. The local concentrations of high PGE may therefore be attributed to an increased concentration of pentlandite. Further studies on the mode of occurrence of PGE within the various ore minerals is warranted to better evaluate the role individual sulphides play in the development of the overall precious metal pool.

6-4. CONCLUSION

Mineralization within the footwall veins at McCreedy West Mine appears to have occurred in a series of stages:

1st stage: (Al, Ti) magnetite - pentlandite formation. Gold precipitates at the contact of magnetite - pentlandite and mafic bands within the Levack Gneiss.

2nd stage: chalcopyrite - millerite formation with partial to full destruction of the 1st stage magnetite and pentlandite. PGE are released from pentlandite to form blebby micron - scale platinum - palladium bismuth tellurides (dominantly michenerite, moncheite and merenskyite) in the chalcopyrite and millerite. Micron - scale sphalerite, hessite and galena are associated with the PGM. Bornite forms at the distal extents of the vein system.

3rd stage: euhedral magnetite overgrowth of 1st stage magnetite remnants.

Blebs of chalcopyrite occur as inclusions within the euhedral magnetite.

4th stage: narrow veinlets of pyrrhotite are exsolved along chalcopyrite grain boundaries.

5th stage: sphalerite, galena and pyrite form in fractures which cross - cut all

earlier mineralization.

Sulphide formation within the footwall ore zones has been interpreted as resulting from hydrothermal emplacement during the cooling stages of the Sudbury Igneous Complex. Evidence for a hydrothermal emplacement relies firmly on observations made of mineral associations and mineral chemistries within the veins and the surrounding host rocks. The numerous Fe - Mg hydrous silicates associated with the sulphide, oxides and precious metal minerals, including Cl - bearing chlorite, Fe - actinolite, epidote, Cl - bearing greenalite, biotite, stilpnomelane, Cl - bearing pyrosmalite and talc, suggest a hydrothermal origin. In addition, fluid inclusion evidence from vein hosted quartz and chalcopyrite suggest that the fluid likely had a model composition of NaCl-CaCl₂-H₂O.

With the exception of pentlandite, and to a lesser extent pyrrhotite, sulphide mineral chemistries were generally unremarkable. Pentlandite within the footwall veins was shown to contain significantly more Ni but less Co than the pentlandite within the contact ore zones. Early evidence suggests that similar trends exist at other North Range mines. This chemical notability may prove useful for determining ore zone affinity, as well as for potentially helping to determine the mode of ore zone formation.

Assay geochemistry at McCreedy West Mine suggests that the footwall ore zone is the dominant repository of Cu, Pt and Pd, and the contact ore zone accommodates most of the Ni and the Co. Zonal geochemical variability may often be explained by analysing the minerals with which the individual elements are associated. The occurrence of high Pt + Pd values occurring in zones of low Cu in the lower veins of the footwall may be attributed to an increase in pentlandite. Laser ablation geochemistry of vein pentlandite has revealed that it contains gram level concentrations of Pd as either micro-inclusions

(with Te) or as part of a pentlandite solid solution. Other geochemical trends have been recognized through the application of Pearce Element Ratio diagrams, DataMine sections and histograms. These methods have described a trend of increasing Pt and Pd from the Sublayer ore, through the Footwall Breccia ore and into the footwall vein ore, and a decrease in Ni content from the Lower Main Ore Zone to the Middle Main Ore Zone.

This project has defined the geochemical and mineralogical characteristics of the McCreedy West Mine, however, the data compiled for McCreedy West Mine may be site specific and not useful on a larger scale. In order to develop an exploration model for the determination of Cu-Ni-PGE veins in the footwall to other contact ore bodies, these characteristics must be compared to other North Range mines to determine the usefulness of the data.

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Appendix 1A: 510 to 600 level plan with sample locations.

Appendix 1B: 700 level plan with sample locations.

Appendix 1C: 810 level plan with sample locations.

Appendix 1D 1000 level plan with sample locations.

Appendix 2a. Histogram of atomic % Co in pentlandite from various Sudbury ore deposits.

Appendix 2b. Histogram of atomic % Ni in pyrrhotite from various Sudbury ore deposits.

APPENDIX 3: METHODOLOGY - LASER ABLATION OF SULPHIDES

Polished thick sections were created (at least 150 μm) of specimens to be used in laser ablation analysis. These sections were then analysed petrographically for sulphides which were free of any mineral inclusions or oxidization. Suitable sulphides (including pentlandite, chalcopyrite, millerite and pyrrhotite) were circled and suggested for analysis.

The prepped sections were sent to Memorial University of Newfoundland where they were analysed by laser ablation microprobe-inductively coupled plasma-mass spectrometry. A complete synopsis of analytical techniques may be found in Taylor et al. (1997). Specifically relating to the data collected for this study, the following parameters were used:

- incident pulse energy: 0.10 - 0.25 mJ
- carrier gas: argon
- diameter of ablation pit: $\sim 100 \mu\text{m}$
- standards used: 1) synthetic millerite (NiS)
 2) MUN PGE reference standard, containing ~ 200 ppm PGE plus other metals (Cu, Zn, Co, Fe, Ag, Au, Te, As, Se, Cd, Sn, Pb, Bi)

Data used within this thesis refers only to analyses performed on pentlandite grains. Owing to potential Cu and Zn interferences of Pd data (refer to Table Appendix 3-1), only those analyses displaying no determinable Cu and Zn (checked using background corrected count rates), have been used in this study.

Table Appendix 3-1 Potential problems with the collection of Pd data due to the cumulative interference of Cu and Zn isotopes with Ar gas. In the three cases displayed, the sum of the Cu or Zn isotope with the Ar isotope would mask the Pd isotope.

Pd Isotope	Potential Interference Elements		Carrier Gas		Sum of Isotopes
Pd 105	Cu 65	+	Ar 40	=	105
Pd 106	Zn 66	+	Ar 40	=	106
Pd 108	Zn 68	+	Ar 40	=	108