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**SPATIAL AND GENETIC RELATIONSHIP OF Cu-Ni-PGE ENRICHED
ORE TO QUARTZ DIORITE CONTACTS WITH THE METASEDIMENTARY
ROCKS OF THE McKIM FORMATION, COPPER CLIFF SOUTH MINE,
SUDBURY, ONTARIO**

Zsuzsanna Magyarosi (B.Sc., M.Sc.)

Thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of
the requirements for the degree of Doctor of Philosophy

Department of Earth Sciences

Carleton University

Ottawa, Ontario, Canada

August, 2002

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TO QUARTZ DIORITE CONTACTS WITH THE METASEDIMENTARY
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submitted by

Zsuzsanna Magyarosi (B.Sc., M.Sc.)

in partial fulfillment of the requirements
for the degree of Doctor of Philosophy

Chairman, Department of Earth Sciences

Thesis Supervisor

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ABSTRACT

Detailed field mapping, petrography, electron microprobe and Scanning Electron Microscope data, and assay data provided by Inco Ltd. were used to describe and explain the characteristics of the orebodies of the Copper Cliff South offset, concentrating on the origin of PGM (PGM: platinum group minerals). These orebodies are unusually enriched in Cu, Ni, PGE (PGE: platinum group elements) and Au compared to those in the Copper Cliff North mine. Most of the orebodies are located at the edges of the quartz diorite dike, whereas other orebodies in the offsets of the Sudbury Structure are located in the centre of the offset dikes.

The primary magmatic minerals in quartz diorite are plagioclase, quartz, amphibole and biotite. The major metallic minerals include monoclinic and hexagonal pyrrhotite, chalcopyrite, and pentlandite in variable proportion. The sulphides occur as massive, inclusion massive, net-textured, blebby, disseminated sulphides and as veins.

The Copper Cliff South area has been affected by the Sudbury Event (1.85 Ga), deformation and metamorphism of Penokean Orogeny (1.9 to 1.7 Ga), several hydrothermal events, and late deformation. Peak metamorphism of Penokean Orogeny occurred before the Sudbury Event; retrograde metamorphism and deformation postdated the Sudbury Event and outlasted the first hydrothermal event.

The first hydrothermal event was a major regional event that remobilized a large number of metals including PGE. The most common alteration minerals include biotite, chlorite, secondary amphibole, garnet, epidote, quartz, muscovite, stilpnomelane, ferropyrrosmalite, and calcite. PGM identified in this study are sperrylite, froodite, michenerite and hollingworthite.

The temperature at the time of this hydrothermal event was between 327 and 540° C, and the pressure was around 3-4 kbar. The fluids were Cl-rich and oxidizing. The source of heat was the Sudbury Igneous Complex and retrograde metamorphism of Penokean Orogeny.

Later hydrothermal events are genetically related to regional and local tectonic events such intrusion of dikes and faulting. Gold may be associated with one of these events.

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CHAPTER 1: INTRODUCTION

1.1. Purpose of study

The main goal of this study is to propose a genetic model that explains the unusual nature of the orebodies of the Copper Cliff South offset and helps in finding other ore rich zones in the Sudbury area. One of the models for the deposits of the Sudbury Structure proposed by Naldrett (1984, 1989) and Cochrane (1984) is the magmatic model that explains all of the characteristics of the orebodies by magmatic processes. However, some of the features cannot be explained only by magmatic processes and there is evidence for several hydrothermal events, in many locations in the Sudbury Structure, that remobilized some of the metals (Farrow and Watkinson, 1992, 1996; Farrow et al., 1994; Molnar et al., 1997, 2001; Watkinson, 1994). In order to determine which factors are prevalent for the orebodies of the Copper Cliff offset this project focuses on several objectives:

1. Determine the origin of zoning, both mineralogical and chemical, within and around the orebodies.
2. Determine what controls the location of orebodies with respect to the E-W contacts of the quartz diorite dike.
3. Detailed study and origin of the platinum group minerals.
4. Description and origin of sulphide bearing veins both in quartz diorite and country rocks.
5. Examine the nature of the contact of quartz diorite and country rocks, concentrating on the McKim metamorphic rocks.

Detailed mapping was undertaken to help in understanding the local geology, field relationships between sulphides and silicate rocks as well as structural aspects of vein ores. This was followed by petrography, microprobe and Scanning Electron Microscope (SEM) analysis, which revealed textural relationships between all minerals, helped identify the minerals, especially platinum group minerals, and detected zoning and chemical changes in minerals across and along the quartz diorite dike as well as the country rocks, which may be the key to understanding their origin. Assay data provided by INCO Ltd. was used to reveal metal zoning within the orebodies and any correlation among the analyzed elements. The composition and temperature of fluids may be revealed with fluid inclusion studies, but it was not possible to accomplish, because of the deformed nature of quartz in the Copper Cliff area (see chapter 4, quartz).

1.2. Location

The study area is located in the Copper Cliff South offset, situated approximately 5 km from downtown Sudbury, Ontario, Canada (at 81°00' longitude and 46°29'), in the South Range of the Sudbury Structure (Fig. 1.1). The orebodies studied in detail include the 865, 850, 800 and 810 orebodies of the Copper Cliff South mine, from north to south (Fig. 1.2).

1.3. Analytical methods

Detailed mapping at 1 to 200 scale was carried out at the surface exposure of 850 and 865 orebodies. Sampling has been accomplished from all 865, 850, 810 and 800 orebodies and host rocks. Forty-one samples were collected from both 800 and 810 orebodies at 3050, 3540, 3700 and 3930 ft levels of the Copper Cliff South mine and

polished thin sections were made. Sampling included every textural type of ore (massive, net-textured, disseminated and vein sulphide).

Minerals were identified petrographically, but many required confirmation by energy and wavelength dispersive spectrometry using a scanning electron microscope (SEM-EDS) and electron probe micro analyzer (EPMA). Pyrrhotite was also examined using a magnetic colloid (Craig and Vaughan, 1981). All mineral composition and most of the SEM-EDS data were collected at Carleton University using a Cameca Camebax MBX EPMA equipped with four WDS spectrometers, EDS detector, backscattered electron detector, and a 4 Pi EDS - X-ray and digital imaging system. Sulphides were analyzed at 20 kV with a 35 nA beam current and silicates at 15 kV with a 15 nA beam current. A suite of well-characterized metals, oxides, natural, and synthetic minerals were used as calibration standards. Raw X-ray data were converted to elemental weight percent using the Cameca PAP matrix correction program. The analyses of some minerals and some of the images were made with a JEOL 6400 digital SEM equipped with a Link System and XL EDS X-ray analyzer, Robinson and JEOL backscattered electron detector and a Semages PC based digital image capture system. The minerals were analyzed at 20 kV accelerating voltage and a 1.0 nA beam current. Spectral processing and matrix corrections were made with the Link ZAF4/FLS computer program using a similar set of calibration standards as in the electron microprobe analyses. Whole rock analysis was performed on samples along a traverse at the surface exposure of 850 orebody in order to detect changes in chemistry of the rocks across the dike.

1.4. Geologic Setting

1.4.1. Regional Geology

The Sudbury Structure is interpreted as an impact feature (Dietz, 1964; Golightly, 1994; Scott and Spray, 1999) consisting of the Sudbury Igneous Complex (SIC) and the Whitewater group that occupies the Sudbury Basin. The Sudbury Igneous Complex outcrops as an oval-shaped feature (Fig. 1.1), approximately 58 km long and 26 km wide that occupies the contact area between Archean rocks of the Superior Province and Proterozoic rocks of the Southern Province. The footwall rocks of the Sudbury Structure to the north consist of the Levack Gneiss Complex of the Superior Province, which is composed of migmatitic tonalitic gneiss with abundant mafic layers and xenoliths; metamorphosed to upper amphibolite and lower granulite facies (Card et al., 1984).

The footwall rocks to the south of the Sudbury Structure consist of metavolcanics and metasediments of the Huronian Supergroup (Table 1.1), which is part of the Southern Province (Card et al., 1972). The sediments were deposited between 2.5, youngest age of Archean rocks, and $2.217\text{Ga} \pm 4\text{ Ma}$ ago, the earliest age for the intrusion of Nipissing diabase (Van Schmus, 1965; Fairbairn et al., 1969; Corfu and Andrews, 1986, Noble and Lightfoot, 1992). The deposition was cyclical with four groups of formations, each of which proceeds from deposition in deep water environment to deposition in shallow water (Robertson et al., 1969; Roscoe, 1969). The Southern Province is bounded by the Grenville Province to the south, the zone of contact is called the Grenville Front (Easton, 1992).

The Main Mass of the Sudbury Igneous Complex is underlain by footwall breccia and can be subdivided into several units listed stratigraphically from bottom to top: contact sublayer (a discontinuous unit), mafic norite (North Range), quartz rich norite and

South Range norite (South Range), felsic norite, quartz gabbro and granophyre (Naldrett and Hewins, 1984). The offset dikes are either radial or concentric and composed of quartz diorite. The Whitewater Group consists of three formations: Onaping (oldest), Onwatin, and Chelmsford (youngest) (Dressler, 1984). The Sudbury Structure is the host of the largest amount of Cu-Ni-PGE ore in the world. Sulphide ore is typically found within the contact sublayer, footwall breccias, Sudbury Breccia, and offset dikes. Sulphides enriched in Cu and PGE are found in veins in the footwall rocks in deposits of the North Range (McCreedy West, Barnet, Coleman, Strathcona).

The Copper Cliff Offset is one of the radial offset dikes in the South Range of the Sudbury Structure. It is subdivided into the Copper Cliff North and Copper Cliff South segments, which are separated by the Creighton Fault. The Copper Cliff quartz diorite intrudes metavolcanic and metasedimentary rocks of the Huronian Supergroup, Creighton granite and Nipissing diabase. In the study area the quartz diorite intrudes metapelite of the McKim Formation, which typically consists of quartz, plagioclase, chlorite and biotite around the Copper Cliff South mine and Copper Cliff rhyolite, which is composed of quartz, K-feldspar and biotite. The orebodies in the Copper Cliff North segment are generally located in the centre of the quartz diorite dike (Cochrane, 1984; Rickard, 2000; Szentpeteri, 2001). The orebodies in the Copper Cliff South mine, however, are located at the edges of the dike. The most detailed description of the geology of the Copper Cliff offset is provided by Cochrane (1984).

1.4.2. Metamorphism and deformation

The Kenoran Orogeny affected the Levack gneiss of the Superior Province prior to the formation of the rocks of the Southern Province and the intrusion of the Sudbury

Igneous Complex; it also predates the intrusion of the Algoman Granite and Matachewan dikes (Table 1.1) (Card, 1971a, 1971b; Card et al., 1984).

Rocks of the Southern Province and Sudbury Structure have been modified during Proterozoic orogenic events (Penokean Orogeny) (Table 1.1). The grade of metamorphism ranges from diagenesis to lower amphibolite facies (Card, 1978; Jackson and Henderson, 1993). According to Card (1978), the rocks went through a "low pressure – intermediate temperature" metamorphism. The Southern Province south of the Sudbury Structure has been affected by two deformational events and repeated movements along major faults of the Murray System (Card, 1978; Card et al., 1972).

The whole area was affected by early deformation and low grade metamorphism (Bleazardian pulse of Penokean Orogeny) after the intrusion of Murray and Creighton Plutons (2.33 Ga ago) and before the intrusion of Nipissing diabase (2.219 Ga ago) (Card, 1978; Jackson and Henderson, 1993). It is generally agreed (Brocoum and Dalziel, 1974; Card, 1978; Jackson and Henderson, 1993; Blonde, 1996) that the main metamorphism and deformation (Penokean pulse of Penokean Orogeny) occurred after the intrusion of the Nipissing diabase and before the intrusion of the Sudbury dike swarm (1.26 Ga ago). The timing of this major event with respect to the development of the Sudbury Structure is still a matter of debate. Brocoum and Dalziel (1974), and Fleet et al. (1987) suggest that peak metamorphism occurred after the intrusion of the Sudbury Igneous Complex. According to Card (1978) and Riller and Schwerdtner (1997), the peak metamorphism predates the Sudbury Event. Deformation affected the area after 1.7 Ga; it is interpreted as the last phase of the Penokean Orogeny (Card, 1978), although the possibility cannot be ruled out that it was a separate and later event that followed the

Penokean Orogeny. The last event that affected the area was the Grenville Orogeny (1.0 to 1.3 Ga ago) involving deformation, high grade metamorphism and igneous activity south of the Grenville Front. The last movements along faults of the Murray System also occurred around 1.0 Ga (Riller and Schwerdtner, 1997).

1.5. Previous work

The amount of Cu-Ni ore and the unique geology of the Sudbury Structure attracted the attention of a large number of scientists. The most comprehensive work on the geology of the Sudbury Structure and surrounding area was published in 1984 (editors: Pye et al.). This OGS Special Volume contains a compilation of the work that has been accomplished since the discovery of the Cu-Ni ore in the Sudbury region.

Previous work on the Copper Cliff offset include a detailed description of the offset by Cochrane (1984) and mapping by Bite (1988). Stewart (1999) and Carter (2000) described the Copper Cliff South offset at the Kelly Lake orebody and also south of Kelly Lake. Szentpeteri (1999) and Rickard (2000) provided a detailed description of several orebodies (100, 120 and 900) in Copper Cliff North segment of the offset dike. Mourre (2000) studied the breaks in the quartz diorite dike along the offset.

Primary magmatic processes in magmatic sulphide deposits are discussed by Naldrett (1984, 1989). Hydrothermal remobilization of PGE is suggested in several world-class deposits including the Bushveld Complex (Schiffries, 1982; Ballhaus and Stumpfl, 1986; Boudreau et al., 1986; Johan and Watkinson, 1987; Schiffries and Skinner, 1987; Ballhaus, 1988; Ballhaus et al., 1988; Boudreau and Kruger, 1990; Harney et al., 1990), Two Duck Lake in Coldwell Complex (Watkinson et al., 1983; Dahl et al., 1986; Watkinson and Dahl, 1988; Good and Crocket, 1989; Mulja and Mitchell,

1989; Watkinson and Ohnenstetter, 1991; Ohnenstetter et al., 1992), Salt Chuck deposit in Alaska (Watkinson, 1990; Watkinson et al., 1991; Watkinson and Melling, 1992), Lac des Iles deposit (Watkinson and Dunning, 1979; MacDonald, 1988; Tellier et al., 1991), New Rambler, Wyoming (McCallum et al., 1976; Nyman et al, 1990), Stillwater Complex (Boudreau and McCallum, 1986; Dunn, 1986), and Rathbun Lake (Rowell and Edgar, 1986).

The presence of hydrothermal fluids in the deposits of the Sudbury Structure has been first suggested by Wandke and Hoffman (1924), Lausen (1930), and Lochhead (1955). Since then, the remobilization of PGE and base metals has been described both in the North Range (Farrow and Watkinson, 1992, 1996, 1999; Farrow, 1994; Farrow et al., 1994; Everest, 1999; Marshall et al., 1999; Watkinson, 1999; Molnar et al., 2001) and South Range (Watkinson, 1994; Molnar et al., 1997, 1999) of the Sudbury Structure, using several methods (field data, petrology, geochemistry, fluid inclusions, stable isotopes).

1.6. Nomenclature

Table 1.2 summarizes terms specific to Sudbury Geology.

MIDDLE PROTEROZOIC

Grenville Orogeny	1.0 Ga
Sudbury Swarm (Olivine Diabase)	1.24 Ga
Croker Complex	1.47 Ga
Hornblende (Quartz) Diabase dikes	?

EARLY PROTEROZOIC

Grenville Front and Cutler plutons	1.6 – 1.75 Ga
Retrograde metamorphism and deformation of Penokean Orogeny	~ 1.7 Ga
Sudbury Structure	1.85 Ga
Peak metamorphism and deformation of Penokean Orogeny	~ 1.9 Ga
Nipissing Diabase	2.15 Ga
Bleazardian Pulse of Penaokean Orogeny	2.2 – 2.4 Ga
Murray, Creighton, Skead plutons	2.2 Ga
Huronian Supergroup	2.2 – 2.5 Ga
Cobalt Group	
Bar River Formation	
Gordon Lake Formation	
Lorrain Formation	
Gowganda Formation	
Quirke Lake Group	
Serpent Formation	
Espanola Formation	
Bruce Formation	
Hough Lake Group	
Mississagi Formation	
Pecors Formation	
Ramsay Lake Formation	
Elliot Lake Group	
McKim Formation	
Matinenda Formation	
Copper Cliff Formation	
Elsie Mountain – Frood-Stobie Formations	

ARCHEAN

Matachewan dikes	
Algoman Granite	
Kenoran Orogeny	
Abitibi Subprovince volcanic rocks and sediments	2.7 – 2.75 Ga
Levack Gneiss	

Table 1.1: Geological column in the Sudbury area (after Card, 1971a, 1971b; Card et al., 1984)

Blebbly sulphide	an ore type, characterized by elliptical or rounded blebs of sulphide in silicate matrix
Contact Sublayer	the lowermost, discontinuous unit of the Sudbury Igneous Complex composed of inclusions in sulphide and norite matrix
Footwall breccia	located below the Sudbury Igneous Complex, composed of clasts of footwall in sulphide and igneous matrix
Inclusion massive sulphide	an ore type, characterized by massive sulphide containing inclusion of silicate rocks
Main Mass	the major part of the Sudbury Igneous Complex, excluding the offset dikes
North Range	the northern portion of the Sudbury Igneous Complex, separated from the southern portion by a zone of faulting (Chicago and Cameron Creek faults), called the South Range Shear Zone
Offset dike	a portion of the Sudbury Igneous Complex forming radial or concentric dikes, composed of quartz diorite
South Range	the southern portion of the Sudbury Igneous Complex, separated from the northern portion by a zone of faulting (Chicago and Cameron Creek faults)
Sudbury Basin	the area enclosed by the Sudbury Igneous Complex and occupied by the Whitewater Group
Sudbury Breccia	pseudotachylite consisting of locally derived angular to rounded clast and comminuted rocks and mineral fragments
Sudbury Event	catastrophic event leading to the formation of the Sudbury Structure
Sudbury Igneous Complex	large layered intrusion formed as a result of the Sudbury Event, consisting of the Main Mass and the offset dikes
Sudbury Structure	all rocks affected by the Sudbury Event

Table 1.2: Glossary of terms specific to Sudbury geology.

Figure 1.1: Regional geologic map of the Sudbury Structure (modified after Farrow and Watkinson, 1996). Dashed rectangle is enlarged in figure 1.2.

Figure 1.2: Surface geology map of the Copper Cliff Offset showing the study areas (modified after Cochrane, 1984 and Szentpeteri, 2001).

CHAPTER 2: FIELD RELATIONSHIPS

2.1. Introduction

In the study area the Copper Cliff offset is approximately 1.8 km long and averages in thickness around 40 m; there are several breaks in the dike one of which is located at the surface exposure of 850 and 865 orebodies, between the two ventilation shafts, where detailed mapping has been accomplished on the surface (Appendix 1). The major rock type is quartz diorite that intrudes Copper Cliff rhyolite on both sides north of this break and Copper Cliff rhyolite to the west and McKim pelite to the east, south of the break. At Copper Cliff South mine the quartz diorite is composed of silicate and Fe-Cu-Ni sulphide minerals and intrudes metapelite of McKim formation on both sides. Both country rocks are brecciated along the contact. The major orebodies in the study area include, from north to south, the 865 and 850 orebodies in the mapped area, and the 810 and 800 orebodies in the Copper Cliff South mine. Three types of later dikes intrude in the area: olivine diabase, hornblende diabase and aplite dikes.

2.2. Quartz diorite

The major primary minerals in the quartz diorite are quartz, plagioclase, amphibole and biotite, but the quartz diorite is variably altered in the whole area. The most common alteration minerals include biotite, chlorite, epidote, secondary amphibole, quartz, titanite, calcite, garnet, stilpnomelane.

In the study area the quartz diorite shows changes in grain size, degree of alteration, and the amount and type of inclusions enclosed. It ranges in grain size from fine (~ 0.2 mm) to medium grained (up to 1-2 mm), generally is finer grained towards the edges of the dike due to faster cooling.

The degree of alteration increases toward massive sulphide and is recognized by changes in mineralogy and modal abundance of alteration minerals. Biotite is the most common and spatially the most widespread alteration mineral. Chlorite, although very common, is spatially not as widespread as biotite; it is almost absent in barren quartz diorite, appears in disseminated and blebby sulphide enveloping the sulphide (Fig. 2.1, A and B) and is abundant in net-textured, massive and blebby sulphide beside massive sulphide. Garnet and stilpnomelane appear almost exclusively in massive sulphide. Figure 2.2 shows the change in biotite content of quartz diorite, which is the most useful in representing the change in the degree of alteration, at the surface exposure of 850 orebody, south of the break. The least altered quartz diorite consists of less than 5 vol. % biotite, approximately 30 to 40 vol. % amphibole, plagioclase and quartz (Fig. 2.3). Moderately altered quartz diorite consists of biotite between 5 and 30 vol. %, plagioclase, quartz, less than 30 vol. % amphibole, epidote (typically around 5 vol. %, but may be as much as 15 vol. %) and trace amounts of chlorite spatially associated with sulphide (Fig. 2.4). In strongly altered quartz diorite amphibole is entirely replaced by biotite, epidote and/or titanite, the amount of biotite is above 30 vol. %, but typically around 40 – 50 vol. % (Fig. 2.5, A and B). In very strongly altered quartz diorite chlorite, biotite and secondary amphibole are abundant and garnet (locally also abundant) and stilpnomelane appear. The amount of biotite generally increases to the eastern contact, where the surface exposure of the orebodies are, and to the north, where the break in the quartz diorite dike is located (Fig. 2.2). Strongly altered biotite zones also occur in one location at the contact with rhyolite and in the centre of the dike.

Most of the inclusions in the quartz diorite can be subdivided into three major types: the first and most common are inclusions containing quartz + plagioclase $\pm$ biotite $\pm$ chlorite $\pm$ muscovite in variable proportions; the source of them is most likely the McKim formation (Fig. 2.1, A and 2.4). Inclusions of Copper Cliff rhyolite are also common; they consist of quartz + feldspar (plagioclase and K-feldspar) $\pm$ biotite (Fig. 2.5, B). Two metavolcanic inclusions (the exact size of which could not be determined, but they are larger than 2.5 cm) have been described from a drill core through the quartz diorite dike in the Copper Cliff South mine; they consist of mainly amphibole and biotite (~80 vol. %). These metavolcanic inclusions were located in the centre of the dike. In this study ultramafic (exotic) inclusions have not been found. The size of most inclusions ranges from microscopic to 0.5 m in size, most commonly they are around 1 cm. The amount of inclusions is typically below 10 vol. % in the inclusion rich zones (Fig. 2.6, A and B). At the surface exposure of 865 orebody most of the inclusions were found in the centre around the massive sulphide and along both edges (see Appendix 1). South of the break inclusions were found only in the margins of the quartz diorite dike. The exact location of inclusion rich zones in quartz diorite in Copper Cliff South mine was not possible to determine, but based on the maps and drill cores of INCO Ltd. the quartz diorite is rich in inclusions in the centre of the dike; this inclusion rich zone locally extends towards the edges as shown in the cross section (Fig. 2.11). Smaller inclusion rich zones are found along the edges as well (other cross sections, samples 98-4, 97-8).

2.3. McKim formation

The McKim formation consists of pelite of variable composition (quartz-rich and quartz-poor layers). It is metamorphosed in the whole area but primary sedimentary

features such as bedding, cross-bedding and scouring have been preserved (Fig. 2.7, A). The mineralogy is a function of the grade of metamorphism. The most common minerals are quartz, plagioclase, K-feldspar, muscovite, biotite, chlorite, staurolite, and garnet. The highest grade of metamorphism is represented by the staurolite-biotite-muscovite-quartz-plagioclase assemblage (lower-amphibolite) found in the Agnew Lake area, approximately 5 km southwest of the Sudbury Structure (Fox, 1971). In the field area pseudomorphs after staurolite are present in some blocks in Sudbury Breccia in the break of the quartz diorite dike, between the two ventilation shafts, suggesting that the grade of metamorphism reached lower-amphibolite facies.

The McKim formation is brecciated in the whole area, especially close to where the quartz diorite intruded (Fig. 2.7, B). The size of clasts in the breccia ranges from very small (mm) to very large size (m). In the field area the contact of quartz diorite and McKim formation is very poorly defined. The change between quartz diorite and metapelite in the field is a 1-2 m wide zone where it is difficult to distinguish them. This zone is very rich in biotite (up to 60 vol.%) and both the quartz diorite and metapelite are richer in biotite with proximity to the contact (Fig. 2.2). Often, there are shear zones in metapelite close to the contact that contain sulphides, mainly chalcopyrite. The strike direction of these shear zones ranges between 5 and 30°, which is approximately 10 to 30° off the contact between the two rocks.

2.4. Copper Cliff formation

The rhyolite of the Copper Cliff formation consists of quartz, K-feldspar, plagioclase and variable amount of biotite; it is not as brecciated as the McKim formation (from 5 cm to m size clasts). It is more brecciated (size of clasts approximately 5-10 cm)

within 2 m of the contact with quartz diorite. Although most of the time there is no variation in composition of clasts and matrix of the Sudbury Breccia, the clasts of brecciated rhyolite close to the contact consist only of quartz and feldspar and the matrix consists of quartz, feldspar and up to 30 vol. % of biotite. This variation in the brecciated rhyolite is also present in the break of the quartz diorite, between the north and south segments. According to Mourre (2000), the matrix of this breccia is enriched in platinum group elements and gold; it contains 22.8 ppb Pt, 29.5 ppb Pd and 70.1 ppb Au on average.

South of the break the contact of quartz diorite and rhyolite is a very sharp intrusive contact. North of the break this contact is more diffuse. The quartz diorite contains more rhyolite fragments (up to 10 vol. %), some of which are angular to subrounded, but some are elongated and were probably partially melted by the heat of the dike (Fig. 2.6, B).

2.5. Break in the quartz diorite dike

The break in the quartz diorite is located in the middle of the mapped area, around the ventilation shafts (see Appendix 1). North of the break the quartz diorite is bounded by Copper Cliff rhyolite on both sides, south of the break the quartz diorite intrudes rhyolite to the west and McKim pelite to the east. Between the north and south segments of the dike the contact of rhyolite and pelite is exposed; both rocks are brecciated (cm to m size clasts). Also, there are pods of quartz diorite in this area, which are not attached to the rest of the quartz diorite dike. The size of these pods is less than 3 m and they have a close to horizontal contact with the country rocks. There is no evidence of faulting or shearing in the break (see Appendix 1). Drilling in the area suggests that the north and

south segments are connected below surface. Similar breaks occur along the strike and down-dip such as between the funnel and the northern tip of the dike at 400-ft level and in the Copper Cliff South mine at 1250-ft level (Cochrane, 1984; Mourre, 2000).

According to Cochrane (1984) and Mourre (2000), there is an increase in brecciation in these breaks and sulphides are concentrated south of these breaks; this is consistent with the observations in this study.

2.6. Later dikes

Dikes intruding the quartz diorite include hornblende (quartz) diabase dikes trending approximately east-west, similar in attitude to the Creighton and subsidiary faults that acted as conduits for magma (Grant et al., 1962, Rousell et al., 1997), olivine diabase dikes trending between 295 and 310° (Rousell et al., 1997) and aplite dikes with a northeast-southwest trend (Copper Cliff South mine geologists, personal communications). The thickness of the dikes in the field area never exceeds 4 m and the contacts of the dikes with the other rocks are always very sharp, chilled, intrusive contacts.

2.7. Orebodies

2.7.1. Location of orebodies

The four orebodies in the study area from north to south include the 865, 850, 810 and 800. In the mapped area massive sulphide is found in three locations (see detailed map). North of the break there is one massive sulphide body (surface exposure of 865 orebody), located approximately in the centre of the quartz diorite dike. The size of this orebody is approximately 6 by 3 m on the surface. The quartz diorite is rich in inclusions around the orebody (5 to 10 vol. %). There are two massive sulphide bodies south of the

break (surface exposure of 850 orebody), located along the quartz diorite and McKim contact. The size of these showings are 9 by 4 and 5 by 2.5 m, from north to south respectively. Most of these two orebodies are hosted in quartz diorite, but some sulphide is hosted in McKim formation.

In Copper Cliff South mine the 800 orebody is located at the western and the 810 orebody at the eastern edge of the quartz diorite dike (Fig. 2.9, 2.10 and 2.11). In several places the two orebodies are connected through the centre of the dike or there is another orebody in the centre of the dike, parallel to the contact of the quartz diorite and country rocks. The location of massive sulphide bodies in the Copper Cliff South mine does not always coincide with the location of inclusion rich zones (Fig. 2.11).

2.7.2. Description of orebodies

The most common ore minerals in the Copper Cliff South area are pyrrhotite, chalcopyrite, pentlandite and magnetite. Pyrite is also present in small amount in the 865 orebody, north of the break. Galena has been found in later quartz veins. Other minerals distinguished by microscope, microprobe and/or SEM include gerdorffite/cobaltite, bismuth tellurides, sphalerite, melonite, hessite, native Bi and Te, cubanite, hollingworthite, sperrylite (described in detail in chapter 3). The quartz diorite around the orebodies is very rich in biotite (~ 60 vol. %), especially around the orebodies south of the break (Fig. 2.2).

All orebodies in the mapped area show a mineralogical and a textural zoning; they contain a pyrrhotite-rich massive centre and increasing amount of chalcopyrite towards the edges. Locally, massive chalcopyrite occurs with small amount of pyrrhotite. Massive sulphide is surrounded by blebby chalcopyrite rich ore; around it the quartz diorite

contains several veinlets composed of mainly chalcopyrite and small amount of pyrrhotite. At the 800 and 810 orebodies in the levels studied in detail (below 3050 ft level from surface) the chalcopyrite content increases toward the edge of the dike: the orebodies in the centre of the dike are generally poorer in chalcopyrite content. However, a few chalcopyrite- and PGM-rich veins have been found in the centre of the dike. In the upper levels (above 1500 ft level) the centre of the dike is richer in chalcopyrite (Cochrane, 1984).

Sulphide occurs as massive, inclusion massive (Fig. 2.8, A), net-textured, blebby, finely disseminated sulphide and veins (Fig. 2.8, B). Usually the massive sulphide is surrounded by net-textured and blebby to finely disseminated sulphide. The inclusion massive sulphide contains inclusions of quartz diorite and country rocks (Fig. 2.8, A). The size of inclusions ranges up to several metres in size. Minor amount of sulphide is also present in shear zones in the McKim formation (see above). Detailed map (detailed map in the back) shows the approximate amount of sulphide in the rocks at the surface exposure of 850 and 865 orebodies.

2.7.3. Sulphide veins

Sulphide veins are fairly common in quartz diorite, but also found along contacts of the quartz diorite and in the country rocks (Fig. 2.8, B). Most of the sulphide-bearing veins are parallel to major regional and local features in the Copper Cliff South area (Fig. 2.13). A significant number of sulphide veins are located parallel to the strike of quartz diorite dike, which is N to NNE (Copper Cliff South mine level plans; Cochrane, 1984) and the contact of Main Mass of the Sudbury Igneous Complex with the footwall rocks in the South Range (Rousell, 1984). A few veins strike parallel to the average foliation of

the Penokean pulse in the Main Mass of the Sudbury Igneous Complex, which is 45° (Cowan et al., 1999). A large number of veins strike parallel to the Creighton Fault ($\sim 85^{\circ}$ / $70-75^{\circ}$, Cochrane, 1984; Rousell et al., 1997). There are also some sulphide containing veins that are parallel to shear zones in McKim formation (see detailed map) and in the mapped area sulphide veinlets are found along bedding in McKim formation (Fig. 2.7, A). The remaining veins strike parallel to later dikes such as hornblende diabase, olivine diabase and aplite dikes. A few veins may be related to the Evans Fault that strikes approximately 60° and dips 40° to the south and may have been the last tectonic event affecting the Copper Cliff South offset dike (Cochrane, 1984).

2.8. Discussion

2.8.1. Sudbury Event

Brecciation of country rocks (Fig. 2.7, B) and formation of shatter cones are the most common shock metamorphic features in the Copper Cliff South. This was followed by the intrusion of quartz diorite and crystallization of primary magmatic sulphide from an immiscible sulphide liquid.

2.8.1.1. Intrusion of quartz diorite

In the study area the quartz diorite dike is emplaced into Sudbury Breccia, suggesting that it intruded along fracture zones in highly brecciated areas created by meteorite impact (Hawley, 1962; Grant and Bite, 1984; Lightfoot et al., 1997). The lack of evidence of any lateral and/or vertical movement, such as faulting or shearing, in the break in the quartz diorite at the surface exposure of 850 and 865 orebodies (see Appendix 1) suggests that these fractures behaved like en echelon faults (Cochrane, 1984), following planes of weakness (highly brecciated zones). North of the break the

quartz diorite intruded rhyolite on both sides, south of the break it intruded along the contact of Copper Cliff rhyolite and McKim formations, which was probably a plane of weakness and more intensely brecciated. Also, the amount of brecciation is the highest in the break and it may represent either a continuation or a splay of the South Range Breccia Belt (Dressler, 1984; Johns, 1996; Scott and Spray, 1999), which would create an area of weakness. Chilled margins are fairly common in the mapped area, suggesting that the breccia was already cooled at the time of intrusion; this is in agreement with Lightfoot et al. (1997).

According to Lightfoot et al. (1997) two distinct phases of quartz diorite can be distinguished in the Worthington offset, one of which is inclusion and ore bearing and occupies the centre of the dike and the other with no inclusions and no sulphides occupying the edges of the dike. Golightly (1994) suggests that the first pulse of magma was injected during the initial stages of the formation of the Sudbury Igneous Complex and the second pulse was injected following the collapse of the crater caused by the impact. Pattison (1979), however, suggests that the magma intruded outward from the Main Mass. In the Copper Cliff offset Grant and Bite (1984) noted the presence of two phases of quartz diorite in a distal segment of the offset south of the Murray and Makada faults. Morris (1982) also suggests the presence of two pulses of magma based on paleomagnetic data. There is no evidence for more than one pulse of magma at the surface exposure of 850 and 865 orebodies, but it may have been overprinted by secondary events such as alteration and/or metamorphism.

The quartz diorite in the mapped area contains inclusions of only the country rocks that are concentrated along the edges of the dike (see Appendix 1). Some of the

rhyolite inclusions seem to have been partly melted by the heat of the dike, suggesting that mingling and assimilation may have occurred, but this is a matter of debate.

According to Lightfoot et al. (1997) and Murre (2000) the REE element signature across and along the offset dike does not suggest assimilation of country rocks. Changes in composition of quartz diorite across the dike are represented in Fig. 2.13. The quartz diorite is enriched in SiO_2 and K_2O at the edges. The McKim formation shows a sudden decrease in SiO_2 beside the contact, then an increase, suggesting that SiO_2 was removed from the McKim formation beside the contact. K_2O shows the same trend across both the eastern and western contact, but it is not as strong. Some of these changes, however, may have been caused by alteration, which is expected to be more intense in more permeable areas such as lithologic contacts, rather than assimilation of country rocks. Also, the variations in Al_2O_3 and SiO_2 in McKim formation may represent changes in stratigraphy.

2.8.1.2. Formation of primary magmatic sulphides

At the present time most scientists agree that the sulphides formed in the Main Mass of the Sudbury Igneous Complex and were carried into the offset dikes by the quartz dioritic magma (Cochrane, 1984; Golightly, 1994; Scott and Spray, 1999), although the possibility of formation of sulphides in the offset dike is not ruled out (Cochrane, 1984). According to Naldrett (1981) change in $f\text{O}_2$, $f\text{S}_2$ and/or water content due to the presence of brecciated footwall rocks may have triggered the crystallization of sulphides. Naldrett and MacDonald (1980) presented evidence that adding SiO_2 to the melt would also trigger the crystallization of sulphides by decreasing the solubility of sulphur as proposed by Irvine (1982). Golightly (1994) suggests that sulphide crystallization in the Main Mass occurred due to mixing of melted preexisting sulphide-

rich mafic rocks and felsic rocks. According to Golightly (1994) and Scott and Spray (1999) the sulphide and quartz diorite (2nd pulse) were injected from below during the collapse of the crater caused by the impact.

The location of primary magmatic sulphides in the offset dikes was controlled by structural traps (Cochrane, 1984), flow differentiation (Bhattacharji and Smith, 1964; Cochrane, 1984) and/or gravitational settling (where the offset dike was not vertical) (Cochrane, 1984). According to Cochrane (1984) in every process the sulphide is located where the inclusions are, which may be either because the inclusions were affected by the same mechanical processes as the sulphides or due to chemical changes: the amount of country rock inclusions may have changed the composition of the quartz diorite enhancing the crystallization of sulphides (Naldrett, 1981; Naldrett and MacDonald, 1980; Golightly, 1994).

The location of the 850 and 865 orebodies may be explained by magmatic processes. Assuming that the direction of movement of the magma was outward from the Main Mass of the Sudbury Igneous Complex (Pattison, 1979) or up and outward (Golightly, 1994; Scott and Spray, 1999), the highest velocity of the flow would have been the centre of the dike north of the break and the eastern contact of the dike immediately south of the break (similar to a meandering river).

The location of the 800 and 810 orebodies is difficult to explain by magmatic processes only. At the present time the centre of the dike contains a large proportion of inclusions, but only a small proportion of the sulphide is found here (Fig. 2.11); this is not consistent with the proposed magmatic origin.

2.8.2. Evidence for a major hydrothermal event

The quartz diorite is weakly to strongly altered throughout the whole area. The most common alteration mineral is biotite that shows a spatial relationship with the sulphide and the contacts of quartz diorite (Fig. 2.2). The increase in biotite content may have been caused by assimilation of siliceous country rocks or alteration, or a combination of the two processes (Grant and Bite, 1984). Most of the veins and a significant number of sulphide blebs in the area are surrounded by biotite and other hydrous minerals such as chlorite, Fe-rich amphibole, epidote, suggesting that they were formed by hydrothermal fluids. The contact of quartz diorite with the country rocks acted as channels for the hydrothermal fluids, which explains the increased amount of biotite as the contacts are approached. Therefore, observations in the mapped area support the hydrothermal origin for the hydrous minerals, but the assimilation of country rocks may have also played a significant role in the enrichment of biotite.

The 800 and 810 orebodies originally may have formed in the centre of the dike and against the footwall, where most of the inclusions are and they were later remobilized toward the edges of the dike by hydrothermal fluids. This is also consistent with the increasing amount of chalcopyrite toward the edges of the dike. Other evidence for lower temperature remobilization of sulphides is the presence of muscovite in inclusions in massive sulphide. Muscovite is stable only below 650° C at pressures below 4 kbar (Yardley, 1989), therefore the temperature of sulphide at the time of its formation did not exceed this temperature. The enrichment in PGE of the matrix of brecciated Copper Cliff rhyolite is also consistent with the circulation of hydrothermal fluids in more permeable areas close to the quartz diorite. Ames et al. (1998) suggested that the impact triggered a regional hydrothermal event that lasted for a maximum 4 Ma after the impact; this event

may have remobilized the sulphides or precipitated them at the edges of the dike. The abundance and strike directions of sulphide veins (Fig. 2.7, B, 2.8, B and 2.12) suggest that more than one hydrothermal event affected the Copper Cliff South area.

2.8.3. Metamorphism and deformation

The presence of staurolite porphyroblasts in some of the clasts of Sudbury Breccia, but not in the matrix and neighbouring clasts suggests that peak metamorphism occurred before the brecciation, therefore before the Sudbury Event. Deformation affected the rocks after the impact as revealed by foliated quartz diorite with blebby sulphide (Fig. 2.1, A and 2.5, B).

Figure 2.1, A: Foliated biotite (brown) - chlorite (green) rich quartz diorite containing blebby sulphide (black areas) and a quartz-rich inclusion (sample 98-4). B: Chlorite (green) rich quartz diorite with blebby sulphide (black areas, sample 97-9).

Figure 2.2, A: Variations in the degree of alteration (the amount of biotite) of the quartz diorite at the surface exposure of 850 ore body, south of the break.

Rock types:

Olivine diabase	
Hornblende diabase	
Inclusion massive sulphide	
Quartz diorite (<5% biotite)	
Quartz diorite (5 - 30% biotite)	
Quartz diorite (> 30% biotite)	
Nipissing diabase	
McKim boulders	
McKim pelite	
Rhyolite boulders	
Copper Cliff rhyolite	

Symbols:

Vein with no sulphide	
Vein with sulphide	
Shear zone	
Estimated sulphide content:	
Inclusion massive	
> 20 %	
> 10 %	
> 5 %	
> 2 %	
Ventilation shaft	
Sudbury Breccia	
Inclusions of country rocks	

Figure 2.2, B: Legend for figure 2.2, A.

Figure 2.3: Weakly altered quartz diorite, biotite (brown) content is less than 5 vol. % (sample 98-18-2). The green mineral is amphibole.

Figure 2.4: Moderately altered quartz diorite containing blebby sulphide (black areas) and a chlorite-rich inclusion; biotite (brown) content is between 5 and 30 vol. % (sample 11). Most of the green minerals outside of the inclusion are amphibole.

Figure 2.5, A: Strongly altered quartz diorite with disseminated sulphide (black areas), biotite (brown) content is more than 30 vol. % (sample 98-19-2). B: Strongly altered, foliated quartz diorite with blebby sulphide (black areas) and a quartz-rich inclusion, biotite (brown) content is more than 30 vol. % (sample 98-41-9).

Figure 2.6, A: Fine-grained, inclusion-rich quartz diorite. B: Inclusion-rich quartz diorite at the contact with rhyolite.

Figure 2.7, A: Primary sedimentary features in McKim formation with a sulphide veinlet along the bedding. B: Moderately to strongly brecciated McKim metapelites close to quartz diorite (Sudbury Breccia).

Figure 2.8, A: Massive sulphide with inclusions of McKim metapelites containing muscovite (sample 97-8). B: Zoned, chalcopryite rich vein and disseminated sulphide in McKim pelite (sample 97-6).

Figure 2.9: Location of 800 and 810 ore bodies at 3050 ft level, Copper Cliff South mine. Distance between parallel lines closest to each other is 500 ft. Modified after underground maps at Copper Cliff South mine, Inco Ltd.

Figure 2.10: Location of 800 and 810 ore bodies at 3700 ft level, Copper Cliff South mine. Distance between parallel lines closest to each other is 500 ft. Modified after underground maps at Copper Cliff South mine, Inco Ltd.

Figure 2.11: Location of 800 and 810 ore bodies on the KL177500 cross section looking south, Copper Cliff South mine. Distance between vertical lines is 200 ft. Modified after underground maps at Copper Cliff South mine, Inco Ltd.

A. Barren veins in Copper Cliff South area

B. Sulphide veins in Copper Cliff South area

Figure 2.12: Strike directions of barren (A) and sulphide bearing veins (B) in Copper Cliff South area represented on rose diagrams. Other structural data from Cochrane (1984), Rousell (1984), Rousell et al. (1997), and Cowan et al. (1999).

Figure 2.13: Variations in major element compositions along the traverse across the quartz diorite dike (see detailed map attached in the back) for the location of traverse).

CHAPTER 3: METALLIC MINERALS – SULPHIDES, OXIDES, PRECIOUS METAL MINERALS (PMM) AND ASSOCIATED MINERALS

3.1. Introduction

The most common metallic minerals in Copper Cliff South area are pyrrhotite, chalcopyrite and pentlandite. Other metallic minerals include magnetite, cubanite and argentian pentlandite, sphalerite, galena, sulpharsenides (gerdorffite and cobaltite) and tellurides (bismuth, lead, silver and nickel tellurides). Precious metal minerals identified in the samples include sperrylite, froodite, michenerite, hollingworthite and argentian gold.

Sulphide occurs as massive, inclusion massive, net-textured, blebby, disseminated sulphide and in veins. In inclusion massive sulphide the inclusions are either quartz diorite or country rock inclusions.

3.2. Major metallic minerals

3.2.1 Pyrrhotite

Pyrrhotite is the most common sulphide in the orebodies at Copper Cliff South mine. It is abundant in massive and disseminated sulphide and commonly occupies the centre of veins with chalcopyrite at the edges, although the reverse has been observed as well. The average pyrrhotite content is approximately 25 volume percent in veins, 50 volume percent in massive sulphide and 80 volume percent in blebby sulphide considering data normalized to 100 volume percent sulphide. Two varieties have been identified in this study, ferromagnetic monoclinic pyrrhotite and diamagnetic hexagonal pyrrhotite. Most of the samples from Copper Cliff South mine contain both monoclinic and hexagonal pyrrhotite in approximately equal amounts. Distinguishing the two

varieties is important in the milling process of the sulphides, where magnetism is used to separate pyrrhotite from the ore. Magnetic data may also provide information in prospecting for these deposits.

Monoclinic pyrrhotite occurs in hexagonal pyrrhotite as lamellae (Fig. 3.1, A), composite lamellae (Fig. 3.1, B), and boxworks (Fig. 3.1, C). The thickness of lamellae ranges between 0.2 μm to 40 μm and changes within one grain. Where pentlandite flames are present, the orientation of lamellae is the same as the orientation of pentlandite flames (Fig. 3.1, A), which is parallel to the (0001) parting of pyrrhotite (Naldrett, 1984), and the lamellae appear as a continuation of pentlandite flames. Composite lamellae consist of both hexagonal and monoclinic pyrrhotite and form lenses in hexagonal pyrrhotite (Fig. 3.1, B). The thickness of composite lamellae is typically around 50 μm , but it varies. There are usually two sets of composite lamellae, that are oriented approximately at 60° angle to each other. The direction of lamellae within the composite lamellae is the same within one set. The boxwork texture consists of lamellae that are not continuous and are attached to the neighbouring lamellae, forming boxes. Composite lamellae and boxworks most commonly occur in the centre of pyrrhotite grains and grade into lamellae toward the edges (Fig. 3.1, B and C), creating a textural zoning in the pyrrhotite grains.

Although, most pyrrhotite grains are richer in monoclinic pyrrhotite toward the edges (Fig. 3.1, A and B), examination of two disseminated sulphide samples from Copper Cliff South mine revealed blebs of pyrrhotite consisting of hexagonal pyrrhotite rims and monoclinic pyrrhotite rich cores (Fig. 3.1, D). Samples from Copper Cliff South mine contain veinlets of quartz locally with chalcopyrite, pyrrhotite or galena that cut through these pyrrhotite blebs, resulting in brecciation of the pyrrhotite and chalcopyrite.

Along these veinlets only hexagonal pyrrhotite is present, indicating that in some areas monoclinic pyrrhotite was converted to hexagonal pyrrhotite probably by a fluid with low fS_2 and rich in Fe. One massive sulphide sample also shows an enrichment of hexagonal pyrrhotite and contains veinlets with sphalerite and galena.

The composition of pyrrhotite changes with respect to Ni, Fe and S content. Figure 3.2, A shows the distribution of monoclinic and hexagonal pyrrhotite and the location of analyses (larger black dots). The darker lamellae are monoclinic pyrrhotite and the lighter lamellae are hexagonal pyrrhotite. In this pyrrhotite grain the thickness of monoclinic pyrrhotite lamellae ranges between 1 and 40 μm . The Ni and Fe contents in hexagonal pyrrhotite are higher than in monoclinic pyrrhotite (Fig. 3.2, B and 3.3, A). The S content is higher in the monoclinic variety (Fig. 3.3, B). The Ni content of both pyrrhotite from a vein and disseminated sulphide in McKim metapelites is lower than in the blebby sulphide from quartz diorite, but the variation in Ni, Fe and S content in hexagonal and monoclinic variety shows the same trend.

3.2.2. Chalcopyrite

Chalcopyrite is the second most common sulphide in the Copper Cliff South mine. The average chalcopyrite content of the 810 orebody between 500 and 3000 ft levels is 18 weight percent (Cochrane, 1984), compared to an average ranging between 1.2 to 32.3 weight percent in most of the orebodies around the Sudbury Structure, including the Cu rich ores in the footwall rocks (Naldrett, 1984). Also, the chalcopyrite content increases along the Copper Cliff Offset to the south, with depth, and toward the edges of the quartz diorite dike (Cochrane, 1984). Chalcopyrite is common in every ore type, especially in veins, where it typically occurs at the edges. In disseminated sulphide,

chalcopyrite commonly envelopes blebs of pyrrhotite and pentlandite. Chalcopyrite contains more PGM than does any other sulphide (Table 3.1).

3.2.3. Pentlandite

Pentlandite is also present in all ore types, but it is more common in massive sulphide than in veins and disseminated sulphide. Pentlandite occurs as flames in or at grain boundaries in pyrrhotite or occupies the grain boundaries between pyrrhotite. It commonly forms megacrystic “eyes” or lenses in massive sulphide and in veins. The amount of Co in pentlandite is highest in veins, lower in disseminated sulphide, and lowest in massive sulphide (Fig. 3.4). The amount of Ni is higher in massive and disseminated sulphide and lower in veins.

3.3. Minor metallic minerals

Argentopentlandite ($(\text{Fe,Ni})_8 \text{Ag S}_8$) is often present in small amounts, forming light pink, pleochroic elongated grains in chalcopyrite. Ag replaces Ni in the pentlandite structure (Fig. 3.5).

Cubanite is more common in veins and disseminated sulphide, than in massive sulphide. It is brown-yellow, pleochroic and occurs as exsolution blades in chalcopyrite (Fig. 3.6). In most samples cubanite is probably hydrothermal in origin.

Magnetite is very common in most samples, forms euhedral to subhedral grains in major sulphides. Locally, magnetite is found with pyrite, Fe-rich violarite, gersdorffite replacing pyrrhotite surrounded by chlorite (Fig. 3.7).

Sphalerite occurs in minor amounts. It forms anhedral grains in chalcopyrite, but it is often present in veinlets, cutting through major sulphides as a product of later hydrothermal activity.

The most common Fe – S (- Ni) rich phase excluding pyrrhotite is pyrite. In one sample the Ni rich variety of pyrite (bravoite) forms euhedral, strongly zoned crystals at the boundary of pyrrhotite and silicates. The amount of Ni in bravoite ranges between 2.27 and 11.65 weight percent, the rim is richer in Ni. Bravoite is a secondary product replacing pyrrhotite at the edges. Right beside the pyrite the Ni content of pyrrhotite is lowest, then it increases and slightly decreases again. Pyrite also occurs as lenses in pyrrhotite, that are oriented parallel to the monoclinic pyrrhotite lamellae (Fig. 3.1, C). These pyrite lenses are surrounded by another Fe-S mineral, that contains ~ 20 wt. % Ni ($\text{Fe}_{0.296} \text{Ni}_{0.149} \text{S}_{0.555}$), which is probably Fe-rich violarite (Fig.3.7). Mackinawite is another fairly common Fe-S phase in the Copper Cliff South area. It is light brown, strongly pleochroic and occurs as thin blades in chalcopyrite. The average composition of mackinawite is $\text{Fe}_{0.443} \text{Ni}_{0.054} \text{S}_{0.503}$.

Galena is fairly common in every type of ore, often occurs in later veins (Fig. 3.8) and is spatially associated with PGM and bismuth tellurides (Fig. 3.8, A and B).

The two common sulpharsenides are gersdorffite (Fig. 3.7 and 3.9) and cobaltite. They typically form euhedral crystals that are distinctly zoned (Fig. 3.10, A). The PGM-bearing sulpharsenides are all zoned cobaltite with higher Co and Rh contents in the centre and higher Fe and Ni contents at the rim (Fig. 3.10, B). Sulpharsenides with no PGM are all gersdorffite. Most commonly they are located at the boundary between silicates and sulphides or in silicate inclusions in massive sulphides (Fig. 3.9) Those that are zoned have a Co-poor and Ni-rich centre. Locally, gersdorffite may contain inclusions of bismuth tellurides (tsumoite), magnetite and silicates (Fig. 3.7).

The most common tellurides in Copper Cliff South mine are bismuth tellurides (Fig. 3.11, A), observed in all ore types and commonly associated with PGM and galena. Most of the bismuth tellurides are tsumoite (BiTe) (Fig. 3.11, B). In one sample it appears as inclusions in sperrylite, but it may also contain native Te along fractures (Fig. 3.11, A). The other common tellurides are melonite (NiTe_2), altaite (PbTe) and hessite (Ag_2Te), all found together and/or with galena, gersdorffite - cobaltite and PGM.

3.4. Precious metal minerals

Precious-metal minerals (PMM: PGM and Au, Ag-bearing minerals) in the 800 and 810 orebodies are present in all types of ore, but most commonly in inclusion massive sulphide, and veins cutting both quartz diorite and metapelite. All PMM found in this study have been described in the mines around the Sudbury Structure (Cabri and Laflamme, 1974, 1976); Szentpeteri et al., 2001). Although, in one sample from Copper Cliff South mine Cabri and Laflamme (1974) found numerous, large grains of sudburyite; in this study of the 800 and 810 orebodies sudburyite has not been found. Some PMM are enclosed by chalcopyrite, pyrrhotite, and even pentlandite, but many occur in chlorite, amphibole, epidote, biotite, and quartz. In this study approximately 72 percent of PMM were enclosed by sulphides, 26 percent in silicates with the remainder being located at the contact of sulphides and silicates. These percentages do not include the Ag minerals. The most common trace minerals spatially associated with PMM are bismuth tellurides (usually tsumoite), galena, and gersdorffite or cobaltite.

3.4.1. Sperrylite

Sperrylite (PtAs_2) is by far the most abundant PMM in both orebodies. It occurs in all types of ore, and all parts of the orebodies. Four types of sperrylite were

recognized: homogeneous, zoned (Fig. 3.12, A and B), with hollingworthite and Rh-rich cobaltite (Fig. 3.12, C and D), and with inclusions of other minerals (Fig. 3.12, E).

Homogeneous sperrylite may also contain inclusions that were not intersected in the polished thin sections.

Homogeneous sperrylite is the most abundant type, occurring in massive sulphide, disseminated sulphide and veins. This type of sperrylite is most often enclosed by chalcopyrite, but has also been observed as inclusions in chlorite, amphibole, epidote, or at the contact of sulphide and silicates (including garnet, biotite and quartz).

Zoned sperrylite has only been found in one large vein (approximately 1 - 2 m wide) in the centre of the quartz diorite dike, where it is relatively abundant. The vein consists of quartz and chalcopyrite at the edges, pyrrhotite with pentlandite lenses and minor chalcopyrite in the centre. The alteration selvage is composed of amphibole and quartz. Most of the zoned sperrylite is enclosed by both pyrrhotite and pentlandite. The grains have Sb rich centres and Sb poor rims (Fig. 3.12, A and B). Sperrylite containing Sb has been reported by Cabri and Laflamme (1976) from several mines around the Sudbury Structure. Sperrylite grains are often attached through the Sb poor rims, but may have been resorbed (Fig. 3.12, A and B). Sperrylite is locally in contact with galena and/or bismuth telluride and/or gersdorffite.

Two sperrylite grains were found in cobaltite, one in disseminated sulphide at the contact of pyrrhotite and chlorite, and one in a chalcopyrite-rich vein in metapelite. The former is located in the centre of a cobaltite crystal that also contains hollingworthite (Fig. 3.12, C). The other sperrylite is attached to zoned cobaltite (Fig. 3.12, D), that is Rh-rich toward the centre. This sperrylite is located in a vein in the country rock, and is

therefore of hydrothermal origin. In both cases sperrylite precipitated first, followed by hollingworthite or Rh-rich cobaltite and cobaltite.

Inclusion-bearing sperrylite was observed only in massive sulphide. One grain is euhedral and contains tiny (less than 5 μm long) inclusions of anhedral bismuth telluride, and the other contains numerous anhedral inclusions of michenerite up to 20 μm in diameter (Fig. 3.12, E). Both sperrylite and michenerite are anhedral and broken, probably due to deformation. They are enclosed by chalcopyrite, but adjacent to garnet and chlorite. In both cases sperrylite precipitated after bismuth telluride and after or synchronously with michenerite.

3.4.2. Froodite

Froodite (PdBi_2) is the second most common PMM in Copper Cliff South mine (Table 3.1). Most froodite is located in veins in quartz diorite or metapelite, but one was found in net-textured sulphide. The average composition is $(\text{Pd}_{0.87} \text{Au}_{0.13})(\text{Bi}_{1.93} \text{Te}_{0.07})$. Some froodite grains contain up to 6.9 weight percent Au and approximately the same amount of Te. The grains show variation in Te content. All froodite grains are enclosed by silicates (chlorite, biotite, quartz), except one that is enclosed by chalcopyrite at the edge of a large vein. Therefore, all froodite is interpreted to be of hydrothermal origin, having precipitated simultaneously with chlorite and biotite.

3.4.3. Michenerite

Michenerite (PdBiTe) is common, occurring in massive, disseminated and vein ore. The composition of michenerite is relatively constant $(\text{Pd}_{0.96} (\text{Bi}_{0.87} \text{Sb}_{0.09}) \text{Te})$ and is characterized by a small content of Pt (less than 0.11 weight %). The composition of michenerite is slightly different from those of the Copper Cliff South mine analyzed by

Cabri and Laflamme (1974), the latter being richer in Sb and Ni. Michenerite may be enclosed by silicates (chlorite and quartz), chalcopyrite, pyrrhotite and also sperrylite (Fig. 3.12, E); one grain was overgrown by bismuth telluride. Michenerite enclosed by silicates as well as those from veins enclosed by sulphides are interpreted to be of hydrothermal rather than magmatic origin. One michenerite grain was enclosed by chalcopyrite that was located between garnet and chlorite; this suggests that michenerite may have precipitated from hydrothermal fluids with the hydrous minerals.

3.4.4. Hollingworthite

Hollingworthite (RhAsS) is typically located in the centre of cobaltite grains (Fig. 3.10, A and 3.12, C). It occurs as subhedral grains, restricted to disseminated sulphide and veins. Cobaltite is generally euhedral and zoned, with more Rh and Co, and less Fe and Ni toward the centre. Hollingworthite is subhedral. One cobaltite grain contains sperrylite in the centre as well (Fig. 3.12, C).

3.4.5. Gold minerals

Argentinean gold occurs in the wall rock of a vein (approximately 0.5 to 2 cm from the vein) in the centre of the quartz diorite dike, that also contains sperrylite, froodite and michenerite. Gold appears as small blebs (approximately 0.5 mm across) in a larger chalcopyrite bleb and in a veinlet (Fig. 3.12, F) with calcite. In both cases Au is spatially associated with parkerite ($\text{Ni}_2\text{Bi}_3\text{S}_2$). Its composition is ($\text{Au}_{0.56}\text{Ag}_{0.44}$). Calcite veinlets cut through the large sulphide vein, revealing that this event postdates the first hydrothermal event following the primary magmatic process. However, the relationship between Au and the minerals within the large vein has not been observed directly.

3.4.6. Silver minerals

The most common Ag mineral in Copper Cliff South mine is hessite (Ag_2Te), present in all types of ore. It is usually spatially associated with bismuth telluride, galena, gersdorffite - cobaltite and PGM. In a pyrrhotite-rich massive sulphide sample, volynskite (AgBiTe_2) occurs as a zoned grain, with tsumoite in the centre, volynskite in the middle, and hessite at the rim. Volynskite was found with the same minerals in Copper Cliff North mine (Szentpeteri, 1999).

3.5. Discussion

Most scientists agree that the sulphides from most of the deposits in the Sudbury area are primary magmatic in origin, crystallized from an immiscible sulphide liquid. In the Copper Cliff South area there is evidence that the sulphides have been affected by several hydrothermal events, metamorphism and deformation.

3.5.1. Primary magmatic processes

The sulphides in the Copper Cliff South area are genetically associated with the quartz diorite. The metals concentrated in a sulphide liquid that was immiscible with the silicate liquid (Naldrett, 1989). In the Copper Cliff South rocks the crystallization of sulphides probably started due change in SiO_2 , $f\text{O}_2$, $f\text{S}_2$ or water (see chapter 2). The most common assemblage is monoclinic pyrrhotite + hexagonal pyrrhotite + pentlandite + chalcopyrite + magnetite, which is typical for magmatic sulphide deposits. Figure 3.13. shows this assemblage in an Fe – Ni – S ternary diagram. The MSS and magnetite were the first minerals to crystallize. Pentlandite started to exsolve around 250° C (Naldrett, 1989), followed by monoclinic pyrrhotite. Most pyrrhotite grains are richer in monoclinic pyrrhotite toward the edges (Fig. 3.1, A and B), which according to Naldrett and Kullerud (1967) may be explained by the exsolution of pentlandite that has a relatively

lower sulfur:metal ratio, thus increasing the S content of the host pyrrhotite and stabilizing monoclinic pyrrhotite. However, this could also result from interaction of fluid rich in S or poor in Fe (Naldrett and Kullerud, 1967).

Other evidence for primary magmatic origin of sulphides is the textural zoning in pyrrhotite grains: in hexagonal pyrrhotite composite lamellae and boxworks of monoclinic pyrrhotite most commonly occur in the centre of pyrrhotite grains and grade into lamellae toward the edges (Fig. 3.1, B and C). According to Yund et al. (1974), Yund and Davidson (1978) and Lianxing and Vokes (1996), slow cooling (below 254° C) will cause exsolution lamellae to increase in thickness and spacing, to be reduced in number and become irregular in shape. This explains the presence of composite lamellae in the centre of pyrrhotite grains where cooling was slower than at the edges. Lianxing and Vokes (1996) suggest that the boxwork texture appears as neighbouring lamellae try to form larger composite lamellae during slow cooling. This textural zoning may be caused by metamorphism, but according to Arnold (1962) and Yund and Hall (1970) during slow cooling following peak metamorphism (above 450° C for a long enough time for the pyrrhotite to anneal) hexagonal pyrrhotite exsolves pyrite rather than monoclinic pyrrhotite.

3.5.2. Evidence for hydrothermal processes

The sulphides have been affected by several hydrothermal events; one of the evidence for this is the presence of sulphide veins in quartz diorite and country rocks. These veins are usually richer in chalcopyrite and they are often zoned with chalcopyrite at the edges and pyrrhotite in the centre, although the opposite has been observed as well. Locally, the veins are monominerallic, consisting of only chalcopyrite; which is not

possible to form by fractionation of a sulphide liquid, because in a magmatic system the number of components must be the same as the number of phases. Pentlandite is also typically present in the veins. Rocks around the veins are rich in hydrous silicates such as chlorite, biotite, Fe-rich amphibole.

The assemblage chalcopyrite + hexagonal pyrrhotite + monoclinic pyrrhotite + cubanite (Fig. 3.6) is probably hydrothermal in origin and not a product of a Cu-rich magmatic liquid. Figure 3.14 shows this assemblage in the Cu – Fe – S ternary diagram, it must have formed below 300° C (the first appearance of cubanite). Both cubanite and pyrrhotite exsolved from chalcopyrite, cubanite exsolved before pyrrhotite, suggested by cross-cutting relationships.

Chalcopyrite replaced pyrrhotite in several areas resulting in the enrichment of the sulphide (Watkinson, 1999), which is commonly concentrated at the contacts of the quartz diorite dike and at the contacts of country rock inclusions within quartz diorite, where the rocks were probably more permeable. Figure 3.15 shows several stages of the replacement of pyrrhotite by chalcopyrite in blebby sulphide. The blebs are surrounded by hydrous silicates rich in Fe. Pentlandite is also enriched in some of these blebs (Fig. 3.16), suggesting that the sulphide was enriched in Ni through the same process as Cu. Figure 3.17 is an isocon diagram showing the enrichment of the sulphide taking figures 3.15 and 3.16 as examples. Massive chalcopyrite-rich ore is most likely the result of the same process, suggested by the abundance of hydrous silicates that have the same composition as the ones spatially associated with veins and blebs (see chapter 4).

Both in massive and blebby sulphide pyrrhotite is also often replaced by other minerals such as pyrite, bravoite and Fe-rich violarite that may be replacing pentlandite

as well. Pyrite replaces pyrrhotite along cleavage planes (0001 planes) parallel to monoclinic pyrrhotite lamellae (Fig. 3.20, A and B). In one sample violarite is located in the centre of the pyrite lenses, extending into pyrrhotite and/or pentlandite (Fig. 3.1, C and 3.7). Bravoite replaces pyrrhotite along the edges, forming euhedral grains zoned with respect to Ni content.

Monoclinic pyrrhotite is locally replaced by hexagonal pyrrhotite around veinlets containing galena and sphalerite (Fig. 3.8) and at the edges of pyrrhotite blebs (Fig. 3.1, D and 19, B). Lianxing and Vokes (1996) suggested that the absence of monoclinic pyrrhotite in the rim of pyrrhotite grains could be the result of interaction with Fe-rich fluids.

3.5.3. Evidence for hydrothermal origin of PGM

In the Copper Cliff South area there is several lines of evidence supporting the hydrothermal origin of PGM.

1. At present, 27 percent of PGM are enclosed by hydrous and Cl rich silicates or other alteration minerals such as chlorite (Fig. 3.18, A), amphibole (Fig. 3.18, B), epidote, biotite and also quartz or they are located at the contact of sulphides and silicates. This relationship suggests that they precipitated from a fluid in the same time as the hydrous silicates.

2. Of 46 PGM observed in this study 22 were found in massive sulphide, 20 in veins and 4 in disseminated sulphide.

3. Some of the PGM and PGE-bearing minerals have complicated growth histories that are difficult to explain by only magmatic processes; such as zoning in sperrylite with respect to Sb content and resorption of the zoned grains (Fig. 3.12, A and

B), the occurrence of sperrylite with zoned hollingworthite, Rh-rich and Rh-poor cobaltite (Fig. 3.12, C and D). These features may be explained by precipitation of these minerals from a fluid accompanied by changes in temperature, pressure and/or the composition of the fluid. Based on textural relationships michenerite precipitated before or in the same time as sperrylite (Fig. 3.12, E), which was followed by precipitation of galena and tsumoite (Fig. 3.12, A and B). Hollingworthite, then Rh-rich and Rh-poor cobaltite precipitated after sperrylite (Fig. 3.12, C and D). Gersdorffite precipitated after magnetite and tsumoite, as revealed by the occurrence of these minerals as inclusions in gersdorffite.

4. PGM are spatially and most likely genetically associated with minerals that are not typically found in magmatic sulphide deposits such as bismuth tellurides, galena, native Bi and Te, hessite, gersdorffite and cobaltite.

3.5.4. Deformation and metamorphism of sulphides

Sulphides are very sensitive to small changes in temperature and pressure, due to their crystal structure. They deform plastically at lower temperatures and pressures than most of the other minerals do. Therefore, they are useful indicators of the conditions that affected the rocks. In Copper Cliff South area sulphides display a variety of metamorphic and deformational features.

1. Sulphides are layered, which is most commonly defined by alternating pyrrhotite – chalcopyrite layers, often with eyes or lenses of pentlandite (Fig. 3.19, A).
2. Blebs of sulphides are elongated in the foliation plane.

3. Pyrrhotite grains are aligned (Fig. 3.19, B) - the c axis of pyrrhotite is perpendicular to the foliation. Monoclinic pyrrhotite lamellae in hexagonal pyrrhotite (0001 plane of pyrrhotite) are parallel to the foliation. This texture is seen in layered and disseminated sulphide, where the sulphide blebs are elongated in the foliation plane.
4. Pyrrhotite shows kink banding, displayed by monoclinic pyrrhotite lamellae (Fig. 3.19, C).
5. Twinning in pyrrhotite is also displayed by monoclinic pyrrhotite lamellae (Fig. 3.19, D).
6. Compositional differences in pyrite lenses are parallel to kink banding in pyrrhotite (Fig. 3.20).
7. Bismuth tellurides and galena are elongated in the foliation plane.
8. Sperrylite is broken up into smaller pieces forming elongated trails parallel to foliation (Fig. 3.21).

Most of these features are present in every type of ore, including sulphide veins, suggesting that the Copper Cliff South area was affected by both metamorphism and deformation after and during remobilization and precipitation of some of the sulphides. The relative timing of metamorphism and deformation is not certain in the Copper Cliff South area. In all layered sulphide samples pentlandite appears as megacrysts that are interpreted as porphyroblasts (McQueen, 1987). These megacrysts either overprint the layering or form elongated lenses that are parallel to layering. Some of these megacrysts contain pyrrhotite and/or chalcopyrite along the fractures, indicating that pentlandite was brittle and pyrrhotite and chalcopyrite were ductile at one time. These relationships

suggest that metamorphism happened in the same time as deformation, but in some areas the recrystallization of pentlandite continued after the deformation.

According to Barrett et al. (1977), McQueen (1979, 1981), Marston and Kay (1980), and Groves and Hudson (1981) layering of sulphides is a metamorphic fabric formed during exsolution of low-temperature sulphides from deforming high-temperature phases. Cowden and Archibald (1985) and McDonald (1970) concluded that the layering is the result of mechanical segregation of sulphides during ductile deformation. In the Copper Cliff South area there is evidence for both processes. The formation of alternating pyrrhotite – chalcopyrite layers is the result of mechanical segregation, although temperatures were also elevated (in some areas above 450° C, the annealing temperature of pyrrhotite). There is no evidence that at the time of deformation the temperature was high enough to take Cu into MSS and then exsolve chalcopyrite. In the same sample, however, monoclinic pyrrhotite forms lamellae in hexagonal pyrrhotite; these lamellae are parallel to the layering. Exsolution of monoclinic pyrrhotite must have occurred under pressure. Also, exsolution of pentlandite from deforming higher temperature phase may have happened in areas where pentlandite forms lenses parallel to foliation (Fig. 3.19, A).

The alignment of pyrrhotite grains (c axis perpendicular to the foliation) has been described by Ostwald and Lusk (1977) and McQueen (1987) in samples from Western Australia (Fig. 3.19, B). They interpreted this as annealing under anisotropic stress conditions. In the Copper Cliff South area this is apparent from the monoclinic pyrrhotite lamellae that are parallel to the foliation. Monoclinic pyrrhotite exsolves from pyrrhotite

along the (0001) plane, that is perpendicular to the c axis. This texture also suggests that annealing of pyrrhotite occurred in the rocks.

Kink banding (Fig. 3.19, C) and twinning (Fig. 3.19, D) are common in pyrrhotite in the Copper Cliff South mine. According to Clark and Kelly (1973) kinking is more abundant at temperatures lower than 300° C, twinning is more abundant above 300° C.

Pyrite also forms lenses in pyrrhotite in some of the samples. In some of these pyrite lenses there are compositional differences in pyrite (Ni and Co content) that are more or less parallel to kinking and twinning planes in pyrrhotite (Fig. 3.20). These differences may have been caused by deformation and metamorphism that affected the rocks.

In layered sulphides bismuth tellurides and galena form elongated lenses, rods in other sulphides, suggesting that these minerals were deformed and metamorphosed together with other sulphides. Sperrylite was also affected by these events, but was competent and brittle. Grains of sperrylite are broken up in smaller pieces; in one sample these pieces form an elongated trail parallel to foliation (Fig. 3.21).

Samples	PMM:PGM+Au, Ag min.	Description	Associated minerals	Enclosed in
96-2	Sperrylite	massive sulphide, pyrrhotite: chalcopyrite=1	bismuth telluride	chalcopyrite, close to chlorite and garnet
96-6	Sperrylite	chalcopyrite rich massive to disseminated sulphide	bismuth telluride, pyrrhotite, pentlandite	chlorite and at the boundary of chlorite and pyrrhotite
96-7	Sperrylite [2 grains]	chalcopyrite rich vein in McKim	chalcopyrite, bismuth telluride	chlorite
97-8A	Sperrylite	chalcopyrite rich massive sulphide with McKim inclusion	containing bismuth telluride inclusions	silicates (biotite, muscovite, quartz), in McKim inclusion containing muscovite
98-1A	Sperrylite	chalcopyrite rich vein in McKim	pentlandite, pyrrhotite	chalcopyrite
98-2	Sperrylite, Rh-rich cob	chalcopyrite rich vein in McKim	cobaltite	chalcopyrite, close to chlorite-muscovite inclusion
98-5B	Sperrylite	net-textured sulphide in quartz diorite		epidote
	Froodite, with Au			small grains in silicates (chlorite, biotite, plagioclase, quartz)
98-7	Hollingworthite	quartz-chalcopyrite-pyrrhotite vein in McKim		gersdorffite
98-9B	Sperrylite	>1m wide quartz-chalcopyrite- pyrrhotite vein in quartz diorite		amphibole
98-10	Sperrylite	blebby sulphide in quartz diorite (pyrrhotite>chalcopyrite)	hollingworthite, cobaltite	gersdorffite, between pyrrhotite and chlorite
	Michenerite Hollingworthite		sperrylite	chlorite and quartz cobaltite
98-12	Froodite with Au and Te	chalcopyrite rich vein in McKim		silicates
99-1B	Sperrylite	chalcopyrite rich blebby sulphide in quartz diorite, 5 m from contact	cobaltite	at chalcopyrite-silicate contact
99-3	Sperrylite	layered pyrrhotite-chalcopyrite rich massive ore	galena, bismuth telluride	in chalcopyrite
			Te, bismuth telluride	
99-4	Sperrylite [3 grains]	layered pyrrhotite-chalcopyrite rich massive ore	bismuth telluride (1 with inclusion of bismuth telluride), galena	in chalcopyrite
99-5	Sperrylite [4 grains] Hessite	pyrrhotite rich massive ore	bismuth telluride, galena, hessite bismuth telluride, galena, sperrylite, Ag-Te-Bi bismuth telluride, hessite	in chalcopyrite and pyrrhotite
	Ag-Te-Bi (volynskite?)			
99-6	Hessite [4 grains]	pyrrhotite rich massive ore toward the centre of dike	melonite, bismuth telluride, galena	in pyrrhotite, chalcopyrite, pentlandite, beside magnetite
99-7	Sperrylite	chalcopyrite stringer in the centre of dike	galena	in chalcopyrite
	Hessite		bismuth telluride, galena	in chalcopyrite
99-8	Sperrylite [7-8 grains]	pyrrhotite-chalcopyrite rich massive sulfide in the centre of dike	magnetite	at the border of pyrrhotite- chalcopyrite, pentlandite
	Ag-Cl-Bi-Te min?		bismuth telluride	
99-9	Sperrylite	pyrrhotite-chalcopyrite rich massive sulfide in the centre of dike	michenerite, bismuth telluride	in chalcopyrite, between garnet and chlorite
	Michenerite		sperrylite, bismuth telluride	in chalcopyrite, between garnet and chlorite
	Hessite		bismuth telluride Te, bismuth telluride	
99-10a	Froodite	PGM rich vein in the centre of dike, edge of vein	bismuth telluride	in silicates
	AuAg		parkerite	small veinlet in silicates, in the wallrock of a large vein
99-10d	Sperrylite	PGM rich vein in the centre of dike, centre of vein	gersdorffite, bismuth telluride and galena	
	Froodite Michenerite		pyrrhotite	in pyrrhotite

Table 3.1: Precious metal minerals found in the 800 and 810 orebodies, Copper Cliff South mine.

Figure 3.1, A: Monoclinic pyrrhotite lamellae and pentlandite flames in hexagonal pyrrhotite (sample 96-2). B: Composite lamellae in the centre of pyrrhotite grain (sample 98-4). C: Boxworks of monoclinic pyrrhotite and lenses of pyrite with violarite in grain of pyrrhotite (sample 97-9). D: Pyrrhotite bleb with hexagonal pyrrhotite rim (sample 99-1).

Figure 3.2, A: Lamellae of monoclinic and hexagonal pyrrhotite (backscattered image, sample 99-1). B: Ni content of monoclinic and hexagonal pyrrhotite.

Figure 3.3, A; Fe content of monoclinic and hexagonal pyrrhotite. B: S content of monoclinic and hexagonal pyrrhotite.

Figure 3.4: Chemical composition of pentlandite (Fe, Ni, S in at. %).

Figure 3.5: Chemical composition of Ag-pentlandite, Ag occupies the Ni site in the structure (Ag, Fe and Ni in at. %).

Figure 3.6, Cubanite in chalcopyrite with monoclinic and hexagonal pyrrhotite (sample 96-3).

Figure 3.7, Violarite, pyrite, magnetite, gersdorffite and chlorite forming along the cleavage planes (0001) and at the edges of pyrrhotite bleb (sample 97-9).

Figure 3.8, Galena vein in pyrrhotite in blebby sulphide (sample 97-1).

Figure 3.9, Gerdorffite in a silicate inclusion in massive chalcopyrite (sample 97-2).

Figure 3.10, A: Zoned cobaltite with hollingworthite in the centre (sample 98-7). B: Chemical composition of sulpharsenides (Fe, Co and Ni in at. %).

Figure 3.11, A: Bismuth telluride with native Te in the fractures (sample 99-9). B: Chemical composition of bismuth tellurides (elements in at. %).

Figure 3.12, A and B: Zoned sperrylite (sample 99-10). C and D: Sperrylite with hollingworthite and cobaltite (sample 98-10 and 98-2). E: Sperrylite with michenerite (sample 99-9). F: Gold veinlet in silicates, with parkerite ($\text{Ni}_2\text{Bi}_3\text{S}_2$, sample 99-10). All figures are back scattered electron images, except F that is reflected light photomicrograph).

Figure 3.13: The mpo+hpo+pn assemblage (shaded area) in the Fe-Ni-S ternary diagram.

Figure 3.14: The assemblage ccp+mpo+hpo+cub (grey shaded area) projected on the Cu-Fe-S ternary diagram from Fe-Ni-Cu-S quaternary system. Intermediate solid solution (ISS) is shown in striped areas.

Figure 3.15: Replacement of pyrrhotite by chalcopyrite. The amount of pyrrhotite decreases with increasing degree of alteration from 90 vol. % (A, sample 96-1), 80 vol. % (B, sample DC-11), 50 vol. % (C, sample 96-1), and 10 vol. % (D, sample DC-11) pyrrhotite.

Figure 3.16: Sulphide bleb enriched in Cu and Ni, surrounded by epidote and chlorite (sample DC-11).

- ◇ Least altered sulphide (Fig. 3.15, A)
- Slightly altered sulphide (Fig. 3.15, B)
- △ Moderately altered sulphide (Fig. 3.15, C)
- ⊗ Strongly altered sulphide (Fig. 3.15, D)
- Cu and Ni enriched sulphide (Fig. 3.16)

Figure 3.17: Alteration of sulphide (replacement of pyrrhotite by chalcopyrite) plotted on an isocon diagram assuming no change in volume (after Grant, 1986).

Figure 3.18, A: Sperrylite with bismuth telluride (tsumoite) in chlorite in chalcopyrite rich massive sulphide (reflected light, sample 96-6). B: Sperrylite in Fe-rich amphibole in chalcopyrite rich massive sulphide (reflected light, sample 98-9).

Figure 3.19, A: Layering of sulphides defined by lenses of pentlandite aggregates (sample 99-9). B: Alignment of monoclinic pyrrhotite lamellae in hexagonal pyrrhotite parallel to elongation of sulphide bleb (sample 97-1). C: Kink banding in pyrrhotite defined by monoclinic pyrrhotite lamellae (sample 98-1). D: Twinning in pyrrhotite defined by monoclinic pyrrhotite lamellae (sample 99-3).

Figure 3.20: Compositional differences in pyrite (A) developed parallel to kink banding in pyrrhotite (B) in sample 97-8.

Figure 3.21: Grains of sperrylite broken up due to deformation, forming an elongated trail parallel to layering (sample 99-8).

CHAPTER 4: SILICATES – PETROGRAPHY AND MINERAL CHEMISTRY

4.1. Introduction

The primary minerals in quartz diorite include plagioclase, quartz, amphibole, biotite and apatite. Pyroxene, often present in quartz diorite north of the Creighton Fault (Rickard, 2000; Szentpeteri, 2000), has not been found. Relict pyroxene has been described by other geologists working in the area (Bite, 1988). In the study area pyroxene was probably present, but has been replaced entirely by amphibole and biotite. The quartz diorite is weakly to strongly altered in the whole area. The degree of alteration increases with increasing amount of sulphide and toward the contacts (see chapter 2). In all samples primary amphibole is partially or entirely replaced by biotite, epidote and/or titanite. The alteration minerals include Fe-rich amphibole, biotite, epidote, titanite, chlorite, garnet, quartz, muscovite, stilpnomelane, ferropyrrosmalite, calcite, and K-feldspar.

4.2. Plagioclase

The anorthite content of plagioclase ($\text{CaAlSi}_2\text{O}_8$) ranges between 1 and 35 %. Plagioclase closer to or in massive sulphide tends to be richer in Na, which could be secondary. Zoning in plagioclase has not been investigated, but according to Cochrane (1984) the core of plagioclase from Copper Cliff offset is richer in Ca and the rim becomes rich in Na.

4.3. Quartz

Quartz (SiO_2) is both a primary and a secondary mineral in the quartz diorite. It is locally intergrown with plagioclase, forming granophyric texture. Quartz is fairly common in massive sulphide and almost always present in veins. All quartz in veins from

Copper Cliff South show deformational features such as undulatory extinctions, highly serrated crystal boundaries, presence of subgrains in larger grains (recrystallization), annealing (120°C angles at the grain boundaries), which are all evidence for dislocation creep mechanisms in quartz (Twiss and Moores, 1992). Fluid inclusion work was being proposed in this study, but was not accomplished because according to Kerrich (1976) temperature data from tectonic vein quartz exhibiting evidence for dislocation creep mechanisms is not reliable: it yields no unique maximum, has a wide variance and displays a significantly higher mean temperature than the undeformed quartz. The reason for the unreliable data is that the dislocation arrays are spatially associated with fluid inclusions (Birkeland and Carstens, 1969; White, 1973) and leakage of fluid inclusions occurs along them (Kerrich, 1976). The growth layers that typically contain primary fluid inclusions are destroyed by the deformation in most quartz grains in Copper Cliff South; and the fluid inclusions present in the quartz are typically smaller than 5 µm and are located along some of the healed fractures.

4.4. Amphibole

Amphibole (formula unit: $(\text{Ca}, \text{K}, \text{Na})_2 (\text{Fe}, \text{Mg}, \text{Al}, \text{Ti})_5 (\text{Si}, \text{Al})_8 \text{O}_{22} (\text{OH})_2$) occurs both as a primary magmatic and as a secondary mineral. It has been observed in silicate inclusions in sulphide veins and in massive sulphide with other hydrous silicates, quartz and garnet (Fig. 4.1, A and B). Locally amphibole contains sperrylite. It varies in composition from actinolite to ferro-tschermakite and ferro-pargasite (Fig. 4.2). The composition of primary amphibole is probably Mg-rich hornblende, as revealed by zoned amphibole in barren quartz diorite: the core is rich in Mg and the rim is rich in Fe (similar in composition to secondary amphiboles in massive sulphide and veins). This is in

agreement with the primary amphibole composition from the North Range of the Sudbury Structure (Everest, 1999). The composition of secondary amphibole in massive sulphide and in veins ranges between Fe-rich hornblende and ferro-tschermakite. Some of the amphiboles in massive sulphides may also be zoned with Fe-poor actinolite core and Fe-rich ferro-tschermakitic-hornblende, ferro-tschermakite or ferro-pargasitic rim (Fig. 4.3, sample 96-2). The Fe content in amphiboles is the highest in veins and massive sulphide and lowest in disseminated sulphide and barren quartz diorite. The Fe content shows a strong positive correlation with K+Na, suggesting a potassic and weak sodic alteration; and a negative correlation with Mn (Fig. 4.4). Secondary amphiboles from Kelly Lake orebody, Copper Cliff North mine and McCreedy West mine are also rich in Fe, K and Na (Everest, 1999; Rickard, 2000; Carter et al., 2002). The K content is generally the highest in amphiboles from Copper Cliff North mine. The Fe content of amphiboles also shows a dependence on distance from the orebody (Fig. 4.5). Amphiboles closest to an orebody are generally richest in Fe. Although, this is not true for the core of most amphiboles (Fig. 4.5: lower trend), that is probably primary in origin.

The Cl content of amphiboles from Copper Cliff South mine is generally highest in ferro-tschermakitic hornblende, ferro-tschermakite, and ferro-pargasite, but never exceeds 0.047 atoms per formula unit; in the other amphiboles the Cl content is less than 0.02 atoms per formula unit. The Cl content shows a positive correlation with the Fe and K+Na, but the slope of these trends changes as a function of the sulphide texture that hosts the amphibole (Fig. 4.6). The Cl content of amphiboles from veins and some amphiboles from massive sulphide shows a strong negative correlation with Ni. The Cl content of amphiboles from Copper Cliff North mine is the highest (Rickard, 2000),

except one amphibole from McCreedy West mine (Everest, 1999). Amphiboles richest in Cl are also enriched in K (Volfinger et al., 1985, Morrison, 1991, McCormick and McDonald, 1999).

4.5. Biotite

Biotite (formula unit: $(K, Na, Ca)_2 (Fe, Mg, Al, Mn, Ti)_6 (Si, Al)_8 O_{20} (OH)_4$) in Copper Cliff South mine is dominantly a secondary mineral, although primary magmatic biotite is also present. Mg-rich biotite from quartz diorite with disseminated sulphide is probably the closest to primary magmatic composition. Biotite may replace amphibole in quartz diorite, but it is also very common in inclusions in massive sulphide, along veins and around sulphide blebs (Fig. 4.1, A and B). It is commonly intergrown with chlorite along cleavage planes. Locally biotite contains froodite.

All biotite in the Copper Cliff South area is annite (Fig. 4.7). Biotite from massive sulphide has the highest Fe, K and Mn and the lowest Si contents, followed by biotite from veins, and biotite from disseminated sulphide and barren quartz diorite has the lowest Fe, K and Mn and the highest Si contents (Fig. 4.8). Biotite from Copper Cliff South is richer in Fe than metamorphic biotite from McKim metapelites ~ 10 km southwest of the Sudbury Structure and biotite from Onaping formation (Magyarosi, 1998). The Mn content is highest in Onaping biotite, followed by biotite from Kelly Lake orebody, Copper Cliff South biotite and lowest in McKim biotite (Carter et al., 2002). The Fe content in biotite also shows a strong dependence on distance from the orebody (Fig. 4.9). Similar to amphibole, biotite closest to an orebody is richest in Fe.

The Cl content in biotite from Copper Cliff South mine never exceeds 0.072 atoms per formula unit. The Cl content is the highest in the veins. There is a positive

correlation between Cl and Fe and a negative correlation between Cl and Ni (Fig. 4.10). Biotite from massive sulphide shows a different, but still positive trend between Cl and Fe. The Cl content of biotite from Kelly Lake orebody is in the same range and shows the same trend (Carter et al., 2002). Biotite from McCreedy West orebody has slightly higher Cl content and also shows the same trend (Everest, 1999).

4.6. Chlorite

Chlorite (formula unit: $(\text{Fe, Mg, Al, Mn, Ti, K, Ca, Na})_{12} (\text{Si, Al})_8 \text{O}_{20} (\text{OH})_{16}$) is the most common alteration mineral in the Copper Cliff South area. It is found in inclusions in massive sulphide with amphibole, biotite, garnet, epidote and quartz; in veins and in disseminated sulphide where it often envelopes sulphide blebs with biotite (Fig. 4.1 and 4.13). In barren quartz diorite it is not as common as biotite and epidote. Chlorite locally contains sperrylite. In some samples it is an alteration product after amphibole and biotite, it may be intergrown with biotite along cleavage planes.

No significant variations have been detected in the composition of chlorite from the whole area; most are Fe-rich ripidolite, whereas a few fall in the daphnite, pseudothuringite and brunsvigite field (Fig. 4.11), using nomenclature of Hey (1954). Similar to amphibole and biotite, the Fe content of chlorite shows strong dependence on the distance from the orebody; the Fe content is highest in chlorite closest to the orebody (Fig. 4.12). The Mn content increases with the Fe content. Chlorite from Copper Cliff South mine is also richer in Fe than chlorite from McKim metapelites from ~ 10 km southwest of the Sudbury Structure and chlorite from Onaping formation which is richest in Mn (Magyarosi, 1998). Chlorite along the whole Copper Cliff offset (Copper Cliff North and Kelly Lake orebody) has the same composition, but chlorite from McCreedy

West deposit is richer in Si (Everest, 1999; Rickard, 2000; Carter et al., 2002). The Cl content of chlorite ranges between 0 and 0.038 atoms per formula unit, but this variation does not appear to correlate with specific ore types or other elements within the chlorite. Chlorite from the study area contains up to 0.7 wt% NiO, an indication that the fluids from which it precipitated were also able to remobilize Ni.

4.7. Garnet

Garnet (formula unit: $(\text{Al, Ti, Cr})_4 (\text{Fe, Mg, Mn, Ca})_6 (\text{Si, Al})_6 \text{O}_8$) is relatively common in inclusion massive sulphide and veins with hydrous silicates and quartz (Fig. 4.1, B, 4.13, A and B). It has been found in one disseminated sulphide sample. All garnet from Copper Cliff South mine is rich in Fe, with Ca content between 0.2 and 0.98 atoms per formula unit and Mn content between 0.19 and 0.71 atoms per formula unit. Around the Sudbury Structure garnets from Copper Cliff South mine (massive sulphide and veins) are the richest in Fe (Fig. 4.14). Garnets from Copper Cliff North mine and Kelly Lake orebody and disseminated sulphide from Copper Cliff South contain less Fe, but slightly more Mn (Rickard, 2000; Carter et al, 2002). Onaping garnets are richer in both Mn and Ca, compared to Copper Cliff South garnets. McCreedy West garnets contain up to 30 weight percent Mn, the highest in the Sudbury area (Everest, 1999). Metamorphic garnets from McKim formation southwest of the Sudbury Structure contain more Mg, but the same amount of Fe, Mn and Ca as Copper Cliff South garnets (Magyarosi, 1998).

4.8. Apatite

Apatite ($\text{Ca}_{10} \text{P}_6\text{O}_4 (\text{OH, F, Cl})_2$) is fairly common in quartz diorite; forms elongated, euhedral to subhedral crystals in quartz and plagioclase, often in granophyric texture. Apatite from Copper Cliff South is very poor in Cl, less than 0.05 weight percent,

and rich in F, between 2.51 and 3.45 weight percent. The Cl and F contents of all analyzed apatite fall in the same field as the apatite from the footwall vein deposits in the North Range of the Sudbury Structure (McCreedy West, Barnet, Coleman) (Watkinson and Carter, unpublished data) (Fig. 4.15).

4.9. Less common alteration minerals

Epidote $((\text{Ca}, \text{Na})_4 (\text{Fe}, \text{Al}, \text{Ti})_6 (\text{Si}, \text{Al})_6 \text{O}_{24} (\text{OH})_2)$ is characteristically observed in or around sulphides, in massive sulphide and veins, and around sulphide blebs (Fig. 4.16, A). Epidote is also common in barren quartz diorite replacing amphibole, with biotite. The Fe content of epidote ranges between 0.82 and 1.54 atoms per formula unit.

Stilpnomelane forms aggregates in massive sulphide and coexists with Fe-rich chlorite, epidote and biotite (Fig. 4.16, A). It is very rich in Fe and Cl (0.26 atoms per formula unit). Ferropyrosmalite, $(\text{Fe}, \text{Mn})_8 \text{Si}_6 \text{O}_{16} (\text{OH}, \text{Cl})_{10}$, also observed in massive sulphide, is rich in Fe and contains 4 weight percent Cl.

Calcite is rare in massive sulphide and in veins (Fig. 4.16, B). It is associated with Au. Calcite veinlets cut through larger veins of the first hydrothermal event, suggesting that some of the calcite precipitated during a second, later hydrothermal event.

4.10. Alteration assemblages

The most common assemblages of hydrous minerals in barren quartz diorite and in quartz diorite with disseminated sulphide are Amph+Bt+Ep and Amph+Bt+Tit (Fig. 4.17, A). Chlorite replaces amphibole, especially along smaller veinlets and around inclusions of McKim pelite; and the assemblages Bt+Chl+Ep and Gnt+Chl+Ep appear in the same samples (Fig. 4.17, A). These assemblages are very common in massive

sulphide as well, only here more Fe is present. Also, the compositions of minerals become richer in Fe with increasing amount of sulphide.

Gnt+Bt+Chl is the most abundant assemblage in veins and massive sulphide. It coexists with Amph+Bt+Ep and Gnt+Ep+Bt (Fig 4.17, B). These assemblages probably formed at different temperature and pressure conditions. The reaction $Ep + Chl = Gnt + Bt$ had to take place to stabilize them. Figure 4.18 represents the composition of coexisting garnet, biotite and chlorite on an AFM diagram. These garnet and biotite pairs were used to estimate the temperature at the time of precipitation of the minerals (327 to 540° C).

Another common assemblage is Calc+Chl+Bt, with Calc+Chl+Gnt that is present in only one sample (98-12, Fig. 4.17, C). These assemblages are found mainly along veins and may represent a later event (2nd hydrothermal event).

4.11. Discussion

4.11.1. Hydrothermal origin of secondary silicates

Most of the secondary silicates are hydrous, suggesting that a fluid must have been present at the time of their formation. Cl-rich minerals such as stilpnomelane, ferropyrrosmalite and bismoclite suggest that the fluids were rich in Cl, although the Cl content of most common hydrous silicates is not as high as in some other areas around the Sudbury Structure (McCreedy West, Everest, 1999). The reason for this may be their high Ni content (Volfinger, 1985; Farrow and Watkinson, 1999). According to Volfinger et al. (1985) in a Cl-rich environment the Cl content of hydrous silicates (amphibole and biotite) is controlled structurally; the higher the Fe and the lower the Mg and Ni content of the hydrous silicates, the more Cl the structure of the hydrous silicate can incorporate

(Mg-Cl and Ni-Cl avoidance rule). In Copper Cliff South there is a positive correlation between the Cl and Fe and a negative correlation between Cl and Ni in most samples, suggesting that the fluid precipitating amphibole and biotite was rich in Cl. This correlation is very weak or absent in some samples, especially massive sulphides. The lack of correlation and also the change in the slope of the trends (Cl versus Fe and Ni) is probably caused by change in temperature, pressure and/or fluid composition (Zhu and Sverjensky, 1992).

Fluids from which the hydrous silicates precipitated were rich in Fe, and probably Ca, K, Na and Mn, also suggested by fluid inclusion studies around the whole Sudbury Structure (Molnar et al., 1997, 1999, 2001). The high Fe content of hydrous silicates close to the sulphides may have also been partially caused by diffusion of Fe from sulphides into the silicates. Although, the presence of widespread Fe-rich hydrous silicates cannot be explained by only diffusion.

The secondary silicates are spatially associated with sulphides of every textural type and the composition of all secondary silicates is very similar, suggesting that all sulphides were affected by similar fluids at similar pressures and temperatures. Even barren quartz diorite is weakly to moderately altered in the whole area. Textural relationship suggests that some of the sulphides and hydrous silicates formed in the same time. Hydrous silicates are euhedral and locally contain sulphides and PGM (sperryllite, michenerite).

The temperature of precipitation of hydrous silicates was between 327 and 540 °C, estimated from coexisting garnet and biotite (Table 4.1 and 4.2, Ferry and Spear, 1978). Only garnet and biotite with low Ca, Mn and Ti contents were used for the

calculation, and according to Ferry and Spear the error is ± 50 °C. Garnet is spatially and genetically associated with hydrous silicates (chlorite, biotite, amphibole and epidote) that locally enclose PGM. Therefore, the estimated temperature should represent the temperature at the time of precipitation of PGM.

Amphibole composition was used to estimate the pressure at the time of its formation. According to Raase (1974) the pressure may be estimated from the Al in the tetrahedral Si position. Data that fall on the diagonal line (Fig. 4.19) reflect crystallization at 5 kbar pressure. Most secondary amphiboles from the Copper Cliff South mine plot just below the line where amphiboles from low-pressure regional metamorphic terrains plot, but they are comparable to amphiboles from Adirondack Mountains, where the pressure was around 3-4 kbar (Engel and Engel, 1962; Turner, 1968). Blonde (1996) estimated the pressure to be between 2 and 6.9 kbar during metamorphism of the rocks approximately 60 km west of the Sudbury Structure (May Township), which is in good agreement with the pressure estimation in Copper Cliff South mine.

4.11.2. Metamorphic origin of secondary silicates

The rocks in the Copper Cliff South area have been affected by at least two hydrothermal events, deformation and metamorphism. The area was affected by regional metamorphism of the Penokean Orogeny, but the timing of the metamorphism is controversial. Pseudomorphs after staurolite were found just north of the 850 orebody in some blocks in the pseudotachylite whereas the matrix and other blocks in the vicinity do not contain staurolite. Pseudomorphs after staurolite are also common in Elsie Mountain and Stobie formations just north of the Copper Cliff North mine. This relationship

suggests that staurolite grew before the brecciation occurred. Pseudomorphs of staurolite also occur as xenocrysts in quartz diorite and massive sulfide from Copper Cliff South mine (Fig. 4.20, A). Now, the xenocrysts are composed of mainly chlorite and muscovite. Since the composition of the quartz diorite and massive sulfide is not rich enough in Al and the quartz diorite is also too rich in Ca to produce staurolite (Yardley, 1989), they must have grown in the McKim Formation before the intrusion of the Sudbury Igneous Complex. Since staurolite-bearing assemblages represent the highest grade of metamorphism in the area, peak metamorphism of the Penokean Orogeny must have occurred before the Sudbury Event (Morrison, 1978; Golightly, 1994). The presence of chlorite porphyroblasts in the matrix and clasts and at the boundary of the matrix and clasts in the Sudbury Breccia from the Agnew Lake area (~ 5 km south west of the Sudbury Structure) suggest the retrograde metamorphism affected the rocks after the Sudbury Event (Fig. 4.20, B). Deformational and metamorphic features of sulphides in every ore type, including veins (see chapter 3) reveal that retrograde metamorphism lasted longer than the first hydrothermal event. Therefore, hydrous silicates and garnet precipitated during the first hydrothermal event are hydrothermal in origin, but they grew under retrograde metamorphic conditions. All common secondary silicates (biotite, chlorite, amphibole, garnet) are compared to metamorphic silicates from either metamorphosed McKim formation ~ 10 km southwest of the Sudbury Structure (chlorite, biotite, garnet) or metamorphosed Nipissing Diabase ~ 60 km west of the Sudbury Structure (amphibole, biotite). Amphiboles from Copper Cliff South mine are very close in composition to amphiboles from metamorphosed Nipissing Diabase and they show the same compositional trends. The only difference is the high Fe content of amphiboles

from Copper Cliff South mine that is due to hydrothermal nature of these amphiboles and shows a strong dependence on the proximity of sulphides and also because amphibole equilibrated with the sulphides during retrograde metamorphism (Froese, 1971). Some of the amphiboles (sample 99-10a) are strongly foliated. Biotite, chlorite and garnet from Copper Cliff South area are also very similar in composition to biotite from McKim metapelites and they show the same compositional trends. Again, the difference is the higher Fe content of the Copper Cliff South secondary silicates.

According to Kretz (1977) and Samson et al. (1999) the distribution of Fe and Mg between minerals formed at the same pressure and temperature should be the same. Fig. 4.21 shows the distribution of Fe and Mg between biotite and chlorite from Copper Cliff South area, McKim metapelites and Onaping formation (to the south of the main axis of the Sudbury Structure), suggesting that these minerals grew under the same pressure and temperature during retrograde metamorphism of Penokean Orogeny.

4.11.3. Estimating the proximity to orebodies with hydrous silicates

The most common alteration minerals in Copper Cliff South are biotite, Fe-rich amphibole and chlorite. Chlorite and other less common alteration minerals such as garnet, stilpnomelane, ferropyrrosmalite are rare in barren quartz diorite and common only with sulphides. Therefore, the presence of these minerals in larger amounts indicates the presence of an orebody within approximately 0.5 m.

Amphibole, biotite and chlorite, if it is present, show an increase in Fe content with decreasing distance from the orebody (Fig. 4.5, 4.9. and 4.12.). This variation may be used to estimate the proximity to an orebody, but caution must be taken. The best minerals for this estimation are biotite and amphibole. The composition of primary

amphibole, the core of the amphiboles, does not depend on the distance from the sulphide (Fig. 4.5), therefore it is necessary to distinguish the two generations of amphibole. The Fe content of secondary amphibole shows a moderate negative trend with the distance from an orebody. If the Fe content of the secondary amphibole is known, the equation for the slope of the trend (Fig. 4.5) may be used to estimate the distance from an orebody. Similar to amphibole, the Fe content of biotite may also be used to estimate the distance from an orebody, although this correlation is slightly weaker (Fig. 4.9), therefore larger errors are expected. The slope of the trend for biotite and amphibole is almost the same.

Sample		X alm	X prp	X sps	X grs	X ann	X phl
96-6	core	0.8994	0.0410	0.0226	0.0360	0.6075	0.1581
96-6	halfway	0.8943	0.0369	0.0313	0.0329	0.6075	0.1581
96-6	rim	0.8708	0.0333	0.0551	0.0392	0.6075	0.1581
97-5	core	0.8100	0.0140	0.0800	0.0960	0.6737	0.1685
97-5	rim	0.8020	0.0200	0.0770	0.1010	0.6737	0.1685
97-5	core	0.8300	0.0160	0.0780	0.0760	0.6737	0.1685
97-5	rim	0.8340	0.0000	0.0810	0.0850	0.6737	0.1685
97-7	core	0.8160	0.0350	0.0820	0.0670	0.6255	0.1777
97-7	rim	0.8410	0.0320	0.0850	0.0420	0.6255	0.1777

Table 4.1: Composition of garnet and biotite in equilibrium used for estimating the temperature.

Sample		p=500b	p=1000b	p=2000b	p=4000b	p=5000b	p=6000b	p=8000b	p=10000b
96-6	core	538.83	539.31	540.29	542.23	543.21	544.18	546.13	548.07
96-6	halfway	525.28	525.74	526.67	528.52	529.44	530.37	532.22	534.07
96-6	rim	517.30	517.74	518.63	520.42	521.31	522.20	523.99	525.77
97-5	core	460.31	460.64	461.30	462.61	463.26	463.92	465.23	466.54
97-5	rim	488.37	488.74	489.49	490.99	491.74	492.49	494.00	495.50
97-5	core	465.08	465.42	466.10	467.46	468.15	468.83	470.19	471.56
97-5	rim	325.77	325.86	326.05	326.42	326.61	326.79	327.16	327.54
97-7	core	525.30	525.75	526.65	528.45	529.35	530.26	532.06	533.86
97-7	rim	507.61	508.04	508.89	510.60	511.46	512.31	514.02	515.73

Table 4.2: Temperatures estimated with garnet and biotite in equilibrium (Ferry and Spear, 1978)

Figure 4.1, A: Altered quartz diorite in inclusion massive sulphide consisting of Fe-rich amphibole, biotite, chlorite, plagioclase and quartz (sample 96-6). B: Silicate inclusion in massive sulphide consisting of amphibole, garnet, chlorite, and biotite (sample 98-9).

Figure 4.2: Types of amphiboles from Copper Cliff South area.

Figure 4.3: Zoned amphibole in massive sulphide. The core is Fe-poor and the rim is Fe-rich (sample 96-2).

Figure 4.4: Composition of amphiboles from Copper Cliff South mine. The lines are regression lines and the numbers beside the lines are the correlation coefficients.

Figure 4.5: Change in the Fe content of amphibole as a function of distance from the ore body.

Figure 4.6: Cl content of amphiboles from Copper Cliff South area. Lines represent the regression lines for each type of ore, numbers beside the lines represent correlation coefficients.

Figure 4.7: Types of biotite from Copper Cliff South.

Figure 4.8: Compositional trends in biotite from Copper Cliff South area. Lines are regression lines, numbers are correlation coefficients.

Figure 4.10: Cl content of biotite from Copper Cliff South area. The line in the first diagram is the regression line for all samples except massive sulphide samples, the line in the second diagram is the regression line and the numbers beside the lines are correlation coefficients.

Figure 4.11: Composition of chlorite from Copper Cliff South area. The line in the second diagram is the regression line and the number is the correlation coefficient.

Figure 4.12: Change in the Fe content of chlorite as a function of distance from ore body.

Figure 4.13, A: Garnet, biotite and chlorite in massive sulphide (sample 96-2). B: Altered quartz diorite in massive sulphide consisting of garnet, biotite and chlorite (sample 96-2). Black areas are sulphides.

Figure 4.14: Composition of garnets in the Sudbury area (data from Magyarosi, 1998; Everest, 1999; Rickard, 2000; Carter et al., 2002). CCS = Copper Cliff South mine.

Figure 4.15: Comparison of F and Cl contents of apatite from Copper Cliff South mine to apatite from deposits in the North Range of the Sudbury Igneous Complex (contact sublayer and footwall) (data from Watkinson and Carter, unpublished data).

Figure 4.16, A: Stilpnomelane, chlorite and epidote in massive sulphide (sample 96-5).
B: Carbonate and chlorite along sulphide vein in McKim formation (sample 98-12).

Figure 4.17, A: The most common assemblages in barren quartz diorite represented on an ACF diagram, also present in massive sulphide. B: The most abundant assemblage in veins and massive sulphide represented on an ACF diagram. C: Calcite-bearing assemblages represented on an ACF diagram. Abbreviations: Amph=amphibole, Bt=biotite, Calc=calcite, Chl=chlorite, Ep=epidote, Gnt=garnet, kfp=K-feldspar, ms=muscovite, pl=plagioclase, q=quartz.

Figure 4.18: The composition of minerals in samples containing garnet, biotite and chlorite in equilibrium, shown on an AFM diagram.

Figure 4.19: Pressure estimated using the Al content in amphibole.

Figure 4.20, A: Staurolite xenocrysts in massive sulphide. B: Chlorite porphyroblasts in Sudbury Breccia ~5 km southwest of the Sudbury Structure. Chlorite porphyroblasts crosscut the boundary between clasts and matrix.

Figure 4.21: Distribution of Mg and Fe between biotite and chlorite from Copper Cliff South area and McKim metapelites from Agnew Lake area approximately 5 km southwest of the Sudbury Structure (Magyarosi, 1998).

CHAPTER 5: VARIATIONS IN THE METAL CONTENT OF THE OREBODIES

5.1. Introduction

Assay data from nine bore holes was provided by INCO Ltd; six of these bore holes have been analyzed for Cu, Ni, Co, Fe, As, Au, Ag, Pt and Pd, three of them have not been analyzed for PGE, Au and Ag. The location of bore holes is shown on Table 5.1. Additional data for the metal content of orebodies at Copper Cliff south mine was obtained from underground drilling and processed with Datamine program, which is a 3D program used by INCO Ltd. for modeling the orebodies in the Sudbury mining camp. Figures 5.5, 5.6, 5.7 and 5.8 represent the distribution of Cu, Ni, Pt and Pd, respectively, at 3050, 3540, 3700 and 3930 foot levels in Copper Cliff South mine.

5.2. Assay data, correlation matrices

The average Cu, Ni, Co, Au, Pd and Pt in every ore type is represented in table 5.2 and figures 5.1, A and B. The Cu and Ni contents are the highest in massive sulphide (12.401 and 7.496 wt %, respectively), followed by inclusion massive sulphide (6.437 and 6.178 wt %, respectively). The inclusion massive sulphide contains the highest amount of Au (0.353 oz/ton), followed by disseminated sulphide in quartz diorite (0.157 oz/ton). The Pd content is the highest in veins (0.227 oz/ton) and in disseminated sulphide (0.195 oz/ton) in McKim formation and the Pt content is highest in massive (0.592 oz/ton) and inclusion massive sulphide (0.250 oz/ton).

Correlation matrices were constructed for all data and for massive, inclusion massive, vein and blebby sulphide in order to detect any significant correlation among the analyzed elements (Tables 5.3 and 5.4). The lower limit of correlation coefficient that is statistically valid is shown below the tables. For tables with no numbers the lower limit of

correlation coefficient that is statistically valid and also significant is assumed to be 0.305. Numbers in bold characters represent strong correlations between the two elements. Some of the correlation coefficients are high, but they still do not represent a strong correlation. This is either because the trend line is nearly vertical or horizontal, or most of the analyses fall very close to each other with no apparent correlation and a few outliers determine the trend line.

Fe, Ni, S, and Co have a strong positive correlation with each other in every ore type. Cu is very variable; it has a strong positive correlation with Fe, Ni, S, and Co in blebby sulphide, veins and overall, but a significant negative correlation with Fe and Ni, and a moderate negative correlation with Co and S in massive and inclusion massive sulphide. Figure 5.2 shows the trend line of Fe versus Cu, which is similar to the trends of Ni, Co and S versus Cu.

Pt, similar to Cu, shows a strong positive correlation with Fe, Ni, S, Co, and Cu in blebby sulphide, veins and overall, but a strong negative correlation with Fe and S in massive sulphide. The variation of $Pt/(Pt+Pd)$ versus $Cu/(Cu+Ni)$ is shown on figure 5.3; there are two trends in massive and inclusion massive sulphide, but there is no correlation evident in other ore types. Pt has a positive correlation with Pd and Au in blebby sulphide. Pd and Au have a strong positive correlation with all elements in blebby sulphide.

Pd also has a positive correlation with As in all types of ore, which is also apparent on figure 5.4 that shows the change in composition of the quartz diorite across the dike along two of the bore holes. The As content is high (up to 3.093 wt %) along bore hole 94562 (level 3320) compared to other bore holes; it is the highest in McKim

formation along the edges of the quartz diorite dike. Arsenides are very common in veins, also rich in Pd, in the Worthington offset, where they are related to a later event that postdated the first hydrothermal event (Stewart, 2002). The Copper Cliff South area was probably affected by the same event.

5.3. Metal distribution

In the Copper Cliff South mine the Cu, Ni, Pt and Pd contents increase toward the edges of the dike and to the south (Fig. 5.5, 5.6, 5.7 and 5.8). The location of high Cu values coincides with high Ni, Pt and Pd values, which is also apparent in the correlation matrices; there is an overall positive correlation between these elements. High-grade zones (zones rich in Cu, Ni, Pt and Pd) are generally located at the edges of the dike, but they also occur in the centre of the dike, generally separated by barren quartz diorite from the edges. This is also apparent from assay data along the bore holes (Fig. 5.4).

5.4. Comparison to Copper Cliff North mine

The two major orebodies in the Copper Cliff North mine are the 100 and 900 orebodies, from north to south. The Copper Cliff South mine is enriched in Cu, Ni, Pt and Pd compared to the 100 orebody in Copper Cliff North mine (Rickard, 2000). The massive sulphide contains four times more Cu and twice as much Ni in Copper Cliff South mine than the 100 orebody in Copper Cliff North mine (Rickard, 2000). The amount of Pt, Pd and Au is 10 to 20 times higher in the massive and inclusion massive sulphide in the Copper Cliff South mine than in 100 orebody. The Co content is the same.

The correlation coefficients among the elements are also very different in the two mines. Generally, the signs of correlations are the same, but the correlations are weaker in 100 orebody (Rickard, 2000).

In both Copper Cliff South and North mines the ore is richer in Cu, Pt and Pd toward south. In the North mine the 900 orebody is south of the 100 orebody and it is enriched in Cu, Pt and Pd compared to the 100 orebody (Rickard, 2000), but not as rich as the 800 and 810 orebodies in the South mine.

5.5. Discussion

According to Naldrett (1984, 1989) all the ore in the Sudbury area was formed by a major magmatic process and the metal zoning in the orebodies was produced by fractional crystallization. Although, the positive correlation among Fe, Ni, Co and S is consistent with fractional crystallization, the variable correlation coefficients and changing trends of Cu, Pt, Pd, Au and As with each other and other elements suggest that the rocks have been affected by more than one process (Tables 5.3 and 5.4 and Fig. 5.2 and 5.3). Evidence from this study points toward a major hydrothermal event that remobilized these elements and redeposited them along the edges of the dike, where the rocks tend to be more permeable, and a small amount in the centre of the dike, where the rocks were also more permeable due to the presence of country rock inclusions (Cochrane, 1984). This is also consistent with the zoning of Cu, Ni, Pt and Pd within the quartz diorite dike, which is typically richer in these elements toward the edges of the dike (Fig. 5.5, 5.6, 5.7 and 5.8). The source of Cu, Ni, Pt and Pd may have been a "100 type" orebody that is depleted in these elements and is located toward the Main Mass of the Sudbury Igneous Complex, a possible heat source for a hydrothermal event at that time (Farrow and Watkinson, 1992, 1999; Ames et al., 1998).

Borehole number	Level	Section	Angle	Ore body
96279	3930	177600	-0.2	810
98159	3700	177600	38.15	810
97311	3700	177550	0	810
98157	3700	177600	-16.15	810
98971	3700	177350	-17	810
94562	3320	177375	-51.15	810
101053	3540	177450	-24	810
93570	3320	177450	-27.45	810
94102	3320	177325	-30.15	810

Table 5.1: Location of bore holes used for assay data. The last 3 bore holes have not been analysed for PGE, Au and Ag. The angle represents the dip of the bore hole; positive sign is upward and negative sign is downward from horizontal. The last column is the number of the orebody at the start of the bore hole.

Ore type	Cu	Ni	Co	Au	Pd	Pt
Blebs in QD	1.026	0.334	0.008	0.041	0.034	0.034
Diss in QD	1.349	0.918	0.019	0.175	0.067	0.054
Specks in QD	0.278	0.076	0.003	0.023	0.021	0.036
Blebs in McK	1.508	0.588	0.008	0.070	0.195	0.005
Specks in McK	0.109	0.043	0.000	0.003	0.005	0.001
Veins in QD	3.488	0.725	0.010	0.076	0.150	0.175
Veins in McK	2.167	0.665	0.012	0.064	0.227	0.014
INMS	6.437	6.178	0.086	0.353	0.108	0.250
MASU	12.401	7.496	0.118	0.022	0.143	0.592

Table 5.2: The average Cu, Ni, Co, Pt, Pd, and Au content in different types of ore from Copper Cliff South. Cu, Ni, Co values are in wt. %, Pt, Pd and Au values are in oz/ton.

All data

	Cu	Ni	Co	Fe	S	Pt	Pd	Au	As
Cu	1.000								
Ni	0.693	1.000							
Co	0.623	0.850	1.000						
Fe	0.621	0.360	0.832	1.000					
S	0.883	0.043	0.821	0.985	1.000				
Pt	0.805	0.813	0.702	0.850	0.856	1.000			
Pd	0.377	0.340	0.420	0.313	0.319	0.263	1.000		
Au	0.175	0.237	0.171	0.237	0.223	0.053	0.246	1.000	
As	0.007	0.022	0.024	0.023	0.002	-0.061	0.762	0.045	1.000

shaded cells n=154

unshaded cells n=102

Massive sulphide

	Cu	Ni	Co	Fe	S	Pt	Pd	Au	As
Cu	1.000								
Ni	0.109	1.000							
Co	0.353	0.389	1.000						
Fe	0.738	0.816	0.354	1.000					
S	0.820	0.543	0.216	0.801	1.000				
Pt	-0.291	-0.013	-0.162	-0.839	-0.860	1.000			
Pd	-0.152	0.259	0.918	-0.113	-0.117	0.028	1.000		
Au	-0.381	0.054	-0.326	-0.743	-0.942	0.819	-0.084	1.000	
As	0.314	0.513	0.123	0.624	0.324	-0.033	0.836	-0.323	1.000

shaded cells n=17 (0.412)

unshaded cells n=9 (0.600)

Inclusion massive sulphide

	Cu	Ni	Co	Fe	S	Pt	Pd	Au	As
Cu	1.000								
Ni	0.332	1.000							
Co	0.569	0.920	1.000						
Fe	0.294	0.885	0.904	1.000					
S	0.305	0.378	0.187	0.843	1.000				
Pt	0.410	0.021	0.377	0.194	0.444	1.000			
Pd	-0.324	0.092	-0.176	-0.272	-0.296	0.026	1.000		
Au	-0.249	0.260	0.389	-0.052	0.057	-0.612	-0.347	1.000	
As	0.563	0.105	0.224	0.237	0.583	0.694	-0.227	-0.341	1.000

shaded cells n=13 (0.475)

unshaded cells n=7 (0.714)

Table 5.3: Correlation matrices for all data combined, massive and inclusion massive ore from Copper Cliff South mine. Numbers in parentheses under the table are the lower limits of the correlation coefficient that is statistically significant at the 95 % confidence level. See text for explanation where there is no number.

Veins in quartz diorite and McKim

	Cu	Ni	Co	Fe	S	Pt	Pd	Au	As
Cu	1.000								
Ni	0.807	1.000							
Co	0.379	0.708	1.000						
Fe	0.843	0.750	0.612	1.000					
S	0.928	0.776	0.558	0.955	1.000				
Pt	0.647	0.613	0.442	0.873	0.851	1.000			
Pd	0.333	0.669	0.381	0.240	0.298	-0.047	1.000		
Au	0.347	0.165	0.115	0.314	0.342	0.314	0.332	1.000	
As	0.208	0.661	0.401	0.139	0.191	-0.212	0.863	-0.072	1.000

shaded cells n=22 (0.359)

unshaded cells n=12 (0.497)

Blebbly sulphide in quartz diorite

	Cu	Ni	Co	Fe	S	Pt	Pd	Au	As
Cu	1.000								
Ni	0.864	1.000							
Co	0.848	0.900	1.000						
Fe	0.925	0.947	0.884	1.000					
S	0.955	0.969	0.896	0.968	1.000				
Pt	0.696	0.660	0.717	0.737	0.712	1.000			
Pd	0.746	0.525	0.692	0.675	0.634	0.842	1.000		
Au	0.725	0.583	0.731	0.714	0.670	0.875	0.976	1.000	
As	0.748	0.159	0.380	0.307	0.276	0.471	0.836	0.747	1.000

shaded cells n=53

unshaded cells n=44

Table 5.4: Correlation matrices for veins and blebbly sulphide from Copper Cliff South mine. Numbers in parentheses under the table are the lower limit of the correlation coefficient that is statistically significant. See text for explanation where there is no number.

Figure 5.1, A: The average Cu, Ni and Co content in different types of ore. B: The average Pt, Pd and Au content in different types of ore.

Figure 5.2: Fe versus Cu in different ore types from Copper Cliff South mine and trends for each type of ore.

Figure 5.3: Pt/(Pt+Pd) versus Cu/(Cu+Ni) in different types of ore from Copper Cliff South mine.

Figure 5.4: Variation in the composition of the rocks across the quartz diorite dike, along boreholes 98157 and 94562. Cu, Ni, S, Fe, As and Co are in wt. %, Au, Pd, Pt and Ag are in oz/ton.

Figure 5.7: Variation in Pt content at several levels at Copper Cliff South mine. Numbers in the legend are in oz/ton. Black boxes represent areas with no data.

Figure 5.8: Variation in Pd content at several levels at Copper Cliff South mine. Numbers in legend are in oz/ton. Black boxes represent areas with no data.

CHAPTER 6: DISCUSSION

6.1. Introduction

Rocks of the Copper Cliff South area have been affected by the Penokean Orogeny, which started before and ended after the Sudbury Event. Primary magmatic sulphides formed as a result of the Sudbury Event. The first hydrothermal event occurred shortly after the Sudbury Event in the same time as retrograde metamorphism and deformation of the Penokean Orogeny. It remobilized a large number of metals including PGE and resulted in the enrichment of primary magmatic sulphides. Later hydrothermal events also affected the rocks, but they were not as widespread as the first hydrothermal event. Table 6.1 summarizes all of these events in chronological order and the effects of them on the rocks in the study area. This chapter describes the events, provides an explanation for the enrichment of the orebodies and evidence for the proposed chronology.

6.2. Sudbury Event

The Sudbury Event occurred 1849 Ma ago (Krogh et al., 1984) and affected rocks of the Superior, Southern and Grenville provinces. In the Copper Cliff South area these rocks include the Copper Cliff rhyolite and the McKim Formation of the Huronian Supergroup and Nipissing diabase. Shock metamorphic features, caused by the passage of high-pressure shock waves, were the first to form due to the impact. In this study shatter cones have been found in the McKim formation just east of the quartz diorite dike at the surface exposure of the 850 orebody.

In the Copper Cliff South area the most common evidence for the meteorite impact is the formation of Sudbury Breccia. The brecciation of country rocks is more

intense in the vicinity of the quartz diorite. The size of clasts ranges from millimeter up to several meter large blocks. Some of the clasts are more rounded and show evidence for movement due to partial melting of the rocks at the time of the impact (Thompson and Spray, 1996). Metapelites of the McKim formation are generally more brecciated than the rhyolite and Nipissing diabase, which is probably due to their softer and less resistant nature.

The quartz diorite dike intruded along fracture zones in highly brecciated areas (Hawley, 1962; Grant and Bite, 1984; Lightfoot, 1997), as suggested by mapping at the surface exposure of 850 and 865 orebodies (chapter 2). Contact metamorphism probably occurred at the vicinity of quartz diorite dike, but it is overprinted by later events (circulation of hydrothermal fluids, metamorphism).

The Sudbury Event was the first ore-forming event in the Copper Cliff South area, when the sulphides crystallized from an immiscible sulphide liquid (Naldrett, 1984, 1989). Primary magmatic sulphides formed in the Main Mass and were carried into the offset dikes by the quartz dioritic magma (Cochrane, 1984; Golightly, 1994; Scott and Spray, 1999) and/or formed within the quartz diorite (Cochrane, 1984). The blebby appearance of some of the least altered sulphides suggest that in Copper Cliff South sulphides crystallized before silicates (Naldrett, 1984, 1989). The pyrrhotite-rich ore that is located typically in the centre of the offset dike and locally at the edges of the dike is considered primary.

6.3. Metamorphism and deformation of Penokean Orogeny

The Penokean Orogeny affected all rocks of the Superior and Southern provinces and the Sudbury Structure, but the timing of the metamorphism and deformation of the

Penokean Orogeny is controversial. The mode of occurrence of staurolite (in some of the blocks of Sudbury Breccia, in quartz diorite and massive sulphide) in the Copper Cliff South area suggests that the peak of metamorphism occurred prior to the intrusion of quartz diorite and therefore prior to the Sudbury Event. This conclusion is not compatible with the conclusions of Fleet et al. (1987), Rousell (1975), or Easton (1996), who suggested that the peak of metamorphism occurred after the emplacement of the Sudbury Igneous Complex. However, it is in agreement with the conclusions of Card (1978), who described a change in metamorphic grade at the contact of the SIC and Huronian country rocks. Card et al. (1984) attributed this to the Penokean pulse of Penokean Orogeny (1.9 to 1.7 Ga ago). This data is also compatible with conclusions of Riller and Schwerdtner (1997), who showed that amphibolite facies metamorphism accompanied by penetrative deformation affected the area before the Sudbury Event. According to Riller and Schwerdtner (1997), this metamorphism happened during the Blezardian pulse of Penokean Orogeny (2.4 to 2.2 Ga ago). Nipissing Diabase intruded the rocks of the Huronian Supergroup 2.219 Ga ago (Card, 1978; Jackson and Henderson, 1993). Blondé (1996) described amphibolite facies metamorphism in the Nipissing Diabase from May Township, west of the Sudbury Structure. Therefore, it is more likely that the amphibolite facies metamorphism occurred after the intrusion of Nipissing Diabase during the Penokean pulse (1.9 and 1.7 Ga ago).

The regional temperature was probably still elevated at the time of the impact and some retrograde metamorphism affected the area after impact, as revealed by the presence of chlorite porphyroblasts that occur in blocks and matrix of the Sudbury Breccia and also crosscut the contact of blocks and matrix, indicating that this chlorite

formed after impact (Magyarosi, 1998). Metamorphic and deformational features in sulphides were caused by retrograde metamorphism and deformation during the Penokean Orogeny.

6.4. First hydrothermal event

6.4.1. Characteristics of the first hydrothermal event

The first hydrothermal event was a large-scale regional event that followed the Sudbury Event and is responsible for the enrichment of the ore bodies in the Copper Cliff South mine, therefore economically very significant. It remobilized a large number of elements including PGE and redeposited them in veins in quartz diorite and country rocks, and in highly permeable areas such as the contact of quartz diorite and country rocks and locally the centre of the dike where the quartz diorite is rich in inclusions. It altered the quartz diorite and country rocks along the contact weakly to strongly in the whole area. Evidence for the presence of fluids is the abundance of alteration minerals (chlorite, biotite, amphibole, epidote, calcite, garnet, quartz, Fe-rich amphibole, stilpnomelane and ferropyrrosmalite) rich in water and Cl spatially associated with the sulphides. The chemistry and compositional trends of alteration minerals is very similar in every ore type suggesting that the same event affected all the rocks in the area.

6.4.2. Enrichment of the orebodies

One of the major processes in the enrichment of the orebodies was the replacement of pyrrhotite by chalcopyrite and pentlandite (chapter 3). Cu and Ni were introduced in the system by hydrothermal fluids and Fe was removed from sulphides and entered the hydrous minerals enriching them in Fe (Fig. 6.1). This process is also suggested by the variations in the Fe content of hydrous silicates spatially associated with

sulphides (chapter 4). The Fe content of hydrous silicates is proportional to the amount of sulphides (Fig. 4.2) and increases with decreasing distance from the orebodies (Fig. 4.5, 4.9 and 4.12).

The fluids that transported Cu also transported other elements including PGE, Au and Ag. PGM found as inclusions in hydrous silicates and chalcopyrite, the complicated growth history of some of the zoned PGM, and the common occurrence of PGM in veins suggests that the first hydrothermal event remobilized PGE and caused the enrichment of the orebodies of Copper Cliff South in PGE (also Au and Ag) compared to 100 and 900 orebodies of the Copper Cliff North mine (Rickard, 2000).

The effect of hydrothermal fluids on the primary pyrrhotite-rich sulphide is interpreted to be the replacement of pyrrhotite and locally pentlandite by chalcopyrite, bravoite, pyrite, Fe-rich violarite and magnetite. Also, monoclinic pyrrhotite is replaced by hexagonal pyrrhotite. The amount of secondary minerals increases closer to country rock inclusions in quartz diorite due to higher permeability along these contacts.

6.4.3. Composition of fluids and conditions during the first hydrothermal event

Fluids responsible for the transportation of metals were rich in Cl, as suggested by the presence of minerals such as ferropyrrosmalite and stilpnomelane. The fluids were also oxidizing as suggested by the presence of magnetite, pyrite and ferric iron in epidote (Fig. 6.2). The occurrence of bismoclite (BiOCl) also suggests a Cl-rich and oxidizing environment (Shaller, 1941), but it was observed in only one sample and may not have formed during the first hydrothermal event. Elements transported by the fluid include S, Cl, Cu, Ni, Fe, Pt, Pd, Ag, Au, Bi, Te, As, Sb, Pb, Ca, Mn and Rh.

The temperature was between 327 and 540 °C during the first hydrothermal event, estimated from coexisting garnet and biotite (Table 4.1 and 4.2). The pressure was around 3–4 kbar, suggested by the composition of secondary amphibole (Fig. 4.19).

6.4.4. Relative timing

The first hydrothermal event occurred simultaneously with retrograde metamorphism and deformation of Penokean Orogeny that most likely outlasted this hydrothermal event. This is revealed by the metamorphic and deformational features displayed by sulphides of every textural type including veins precipitated by fluids of the first hydrothermal event (Table 1 and chapter 3). The quartz diorite shows a weak foliation in some samples. The foliation is more strongly developed around the contact of sulphide (massive and large veins) and silicates, where the rocks were more susceptible to strain.

The distribution of Mg and Fe in coexisting chlorite and biotite, which is the same in metamorphosed McKim formation, suggests that these silicates formed under retrograde metamorphic conditions (chapter 4).

6.4.5. Source of heat

Farrow and Watkinson (1992, 1999), Molnar et al. (1997, 1999, 2001), Ames et al. (1998), and Watkinson (1999) suggest that there was a major hydrothermal event that followed the Sudbury Event and remobilized a large number of metals. According to these scientists the source of heat for this hydrothermal event was the Sudbury Igneous Complex.

One of the major heat sources for the hydrothermal activity in the Copper Cliff South area was the quartz diorite dike, the closest cooling intrusive rock at that time. This

is also suggested by the veins that strike parallel to the offset dike. However, the metal zoning within the orebodies and along the whole offset dike: increasing Cu, Ni, Pt, Pd and Au to the south and upward, which is away from the Main Mass of the Sudbury Igneous Complex, suggests that the Main Mass may have provided significant amount of heat during the hydrothermal event.

According to Cowan and Schwerdtner (1994), Golightly (1994) and Grieve (1994) the Sudbury Igneous Complex was originally horizontal. Also, the Sudbury Igneous Complex may have been superheated, if it was a melt sheet. The location of the offset dikes at that time is not certain, but considering the estimated original size (approximately 200 km impact ring structure, Grieve, 1994), folding and uplift of the Sudbury Structure (Cowan and Schwerdtner, 1994) the Copper Cliff South mine was most likely under the Main Mass. In Cathles et al. (1997) model for the development of a hydrothermal system underneath a cooling ultramafic body, the Copper Cliff North and South mine area would have been in the path of the convective hydrothermal system of the cooling Main Mass. Also, according to Cathles et al. (1997) the convection is greatest below and near the contacts. Therefore, it is likely that it did provide significant amount of heat for the hydrothermal system and a thermal gradient away from the Main Mass is not surprising. The quartz diorite, which was also hot at the time and the contact of the dike with the abundance of breccia was probably a very good conduit for the fluids.

The ongoing retrograde metamorphism of Penokean Orogeny may have provided some heat as well, although it is difficult to prove.

6.4.6. Source of metals

The Copper Cliff South mine is enriched in some metals compared to other orebodies in the Sudbury area and that raises the question of the origin of these metals. The primary magmatic ore at the Copper Cliff South mine, typically located in the centre of the dike, provided some of the metals enriched in remobilized ore. The closest orebody that is depleted in these metals is the 100 orebody at Copper Cliff North mine (Rickard, 2000). If the Sudbury Igneous Complex (Main Mass and quartz diorite) was the source of heat for the hydrothermal event, it is also expected that the source of some of the metals for the enriched ore at Copper Cliff South mine may have been located toward the Main Mass of the Sudbury Igneous Complex, to the north, where the 100 orebody is located at the present. This is also in agreement with the increase of Cu, Ni, Pt and Pd in the Copper Cliff South mine upward and to the south. Therefore, an additional source for the metals that are enriched in the orebodies of the Copper Cliff South mine is a "100 type" orebody that is located toward the Main Mass of the Sudbury Igneous Complex and may have been since removed by erosion. Although, more geochemical data is needed to prove this hypothesis. Also, whether it was the 100 orebody or another similar orebody remains a question that is difficult to answer.

6.5. Later hydrothermal events

Later hydrothermal events in the Copper Cliff area are not as widespread as the first hydrothermal event. They are represented by minor chalcopyrite-rich veins and calcite veinlets, that cut through larger veins formed during the first hydrothermal event and foliation developed in silicates and sulphides. Au may have been remobilized during one of these events. The strike direction of these later veins (barren and sulphide bearing) suggests that they are genetically linked to later regional or local tectonic events. The

offset dike is cut by east-west trending hornblende (formerly quartz) diabase dikes that locally remobilize small amount of sulphides and create a weak foliation in the offset dike (Fig. 2.12). The hornblende diabase dikes have been correlated with lamprophyre dikes in Massey area (Cochrane, 1983), which are 1.415 ± 40 Ma old (Van Schmus, 1971). The Sudbury dike swarm (olivine diabase), intruded 1.238 ± 4 Ma (Krogh et al., 1987, Rousell et al., 1997), also locally remobilized small amount of sulphide. The spatial relationship between the later dikes and sulphide veins suggest that the dikes provided the heat for the remobilization of some sulphides. The Creighton Fault is part of the Murray Fault system, which was reactivated several times during the history of these rocks. It displaces the Sudbury dikes and the last movement along the fault was probably related to the Grenville Orogeny that was 1.0 Ga (Riller et al., 1997). Several barren and sulphide containing veins are recorded that strike parallel to the Creighton Fault. In the Copper Cliff South area the last event was the Evans Fault that separates the 800 and 810 orebodies in the upper levels. The faults were probably used as a conduit for the fluids that remobilized sulphides. The relative age of the aplite dikes is not known; the strike of the aplite dikes is very variable, but the average strike is around 45° . Barren and sulphide bearing veins are related to these events, but it is difficult to distinguish the effects of individual events, because the strike directions of some of them are the same (Creighton Fault and hornblende diabase dikes, Evans Fault and aplite dikes) and the directions of the veins sampled underground are not all known due to difficulties measuring directions underground. However, none of these events was as important economically and widespread as the first hydrothermal event. The Creighton Fault seems to have a larger number of veins associated with it, which is expected because it was the longest and most

regional brittle deformation that affected the area after the Sudbury Event and Penokean Orogeny. Veins striking parallel to the regional foliation are most likely posttectonic and the foliation planes were used as conduits for hydrothermal fluids.

6.6. Comparison to other studies

According to Naldrett (1981, 1984) and Naldrett et al. (1994, 1999), the ores of the Sudbury Structure formed as a result of one major magmatic event; differences and variations between the orebodies are explained by fractional crystallization. This study and other studies around the Sudbury Structure (Farrow and Watkinson, 1992; Farrow, 1994; Watkinson, 1994; Farrow and Watkinson, 1996, Molnar et al., 1997, 2001) prove that later hydrothermal events played a major role in the location and characteristics of the ore following the primary magmatic process. According to Farrow and Watkinson (1992), Farrow (1994) and Molnar et al. (2001) a highly saline, Cl-rich fluid affected the sulphides in the North Range deposits and carried a large number of metals including Cu and precious metals into the footwall rocks of the Sudbury Structure. Highly saline, Cl-rich fluids affected some of the sulphides in the Lindsley deposit (Watkinson, 1994; Molnar et al., 1997) and the Little Stobie deposit (Molnar et al., 1999) in the South Range. The range in temperature of hydrothermal activity in the Copper Cliff South area is similar to that estimated by other studies around the Sudbury Structure. According to Molnar et al. (1997, 2001) the minimum temperature of PGM precipitation ranged between 230 and 340° C in the Lindsey 4b deposit and around 480° C in the North Range footwall veins, determined from homogenization of fluid inclusions in quartz. In the Little Stobie deposit the minimum trapping temperature of fluid inclusions associated with the first hydrothermal event was between 180 and 350° C (Molnar et al., 1999).

From North Range deposits, Farrow and Watkinson (1992) suggested a minimum temperature of 130 - 440° C during the precipitation of platinum group minerals in the footwall rocks. Souch and Podolsky (1969) and Hoffman et al. (1979) suggested a minimum pressure of approximately 2.3 kbar at the time of formation of primary magmatic ores in the South Range. The minimum pressure of entrapment of fluid inclusions associated with early fluids was 1.8 - 2.2 kbar at the Little Stobie deposit (Molnar et al., 1999). According to Farrow (1994), Marshall et al. (1999), Watkinson (1999), Molnar et al. (1999), and Farrow and Watkinson (1999) the fluids responsible for the remobilization of base metals and platinum group elements were mixtures of formational brines, magmatic and metamorphic fluids, based on stable isotopic and fluid inclusion data. Farrow and Watkinson (1992, 1999) described this large-scale hydrothermal event as a late magmatic system, with the Sudbury Igneous Complex (SIC) as the major heat source driving the hydrothermal activity. Ames et al. (1998) also showed that large scale hydrothermal activity took place in the Whitewater Group after emplacement of the Sudbury Igneous Complex.

Later hydrothermal events have also been described by Molnar et al. (1997, 2001) both in the South and North Ranges. Morris (1982), based on paleomagnetic data, also suggests that there were at least three ore forming events in the offset dikes. According to Molnar et al. (2001), second stage of hydrothermal activity is related to thrusting and faulting in the late stages of Penokean Orogeny and the third stage of hydrothermal activity is related to the emplacement of northwesterly oriented Sudbury dikes that also has veins associated with it in the Copper Cliff South area. In the South Range, brittle deformation in the late stages of the Penokean Orogeny occurred along the Murray Fault

system (Creighton Fault) and that was associated with barren and sulphide bearing veins, similar to the North Range.

	Quartz Diorite	Sulphides	McKim metapelites	Copper Cliff rhyolite
Later hydrothermal events	<ul style="list-style-type: none"> - carbonate veinlets, sometimes with gold - small amount of ccp rich veins in QD 	<ul style="list-style-type: none"> - carbonate veinlets - small amount of ccp rich veins 	<ul style="list-style-type: none"> - carbonate veinlets - small amount of ccp rich veins 	
Retrograde metamorphism and deformation	<ul style="list-style-type: none"> - minerals are foliated in planes of weakness (along sulph veins, at lithological contacts, etc.) - foliation is defined by chlorite, biotite, amphibole - growth of low grade metamorphic minerals: chlorite, biotite, Fe-rich garnet 	<ul style="list-style-type: none"> - massive po and ccp are layered with lenses or eyes of pn - sulphide blebs are elongated in the foliation plane - mpo lamellae are aligned parallel to layering or elongation of blebs - kink banding and twinning in po - py lenses show compositional differences parallel to kink banding in po - bite, gal are elongated in foliation plane - sperr and mich are broken due to brittle deformation 	<ul style="list-style-type: none"> - formation of low grade minerals (chlorite, biotite) replacing staurolite, garnet and chloritoid - chlorite growing in Sudbury/Breccia (both matrix and clasts and across) 	
1st hydrothermal event	<ul style="list-style-type: none"> - sulphide veins in the QD - alteration of QD by fluids: gnt, chl, bt, ep, amph, stilpnomelane, ferropyrrosalite, quartz, etc. 	<ul style="list-style-type: none"> - zoned and monomineralic sulphide veins rich in ccp, PGM, tellurides, gal, gers-cob, etc. - ccp replacing po in massive sulphide and blebs - py, brav, viol, magn replacing po and pn - lpo replacing mpo - gal veinlet in brecciated po 	<ul style="list-style-type: none"> - sulphide veins (McKim inclusion in sulphides and disseminated sulphide - alteration of McKim close to veins and sulphides mainly chl, calc and bt 	<ul style="list-style-type: none"> - sulphide veins - alteration of rhyolite close to veins and sulphides - matrix of Sudbury Breccia becomes enriched with PGE
Sudbury Event 1849 Ma ago	<ul style="list-style-type: none"> - intrusion of QD 	<ul style="list-style-type: none"> - crystallization of primary sulphides from immiscible sulphide liquid 	<ul style="list-style-type: none"> - brecciation - shatter cones 	<ul style="list-style-type: none"> - brecciation - shatter cones
Peak of Penokean metamorphism			<ul style="list-style-type: none"> - growth of staurolite and chloritoid porphyroblasts - peak metamorphic assemblage: q+pl+ms+chl+st+bt 	

Table 6.1: List of events in the Copper Cliff South area in chronological order (oldest on the bottom) and the characteristics of them as shown by the rocks in the area.

Figure 6.1: The process of forming enriched orebodies by the replacement of pyrrhotite by chalcopyrite and pentlandite, accompanied by the formation of Fe-rich, hydrous silicates.

Figure 6.2, A: Oxide and sulphide stabilities at 300° C and 2 kbar represented on a $\log f\text{O}_2$ versus $\log \Sigma\text{S}$ (A) diagram for the H-O-C-Fe-Ni system and a $\log f\text{O}_2$ versus pH (B) diagram for the Fe-S-O-H system, after Frost (1985) and Mountain and Wood (1988a) respectively. Shaded areas represent the assemblages found in the Copper Cliff South area.

CHAPTER 7: CONCLUSIONS

The Copper Cliff South area was affected by metamorphism and deformation of Penokean Orogeny (1.9 to 1.7 Ga), the Sudbury Event (1.85 Ga), and several hydrothermal events one of which was a large-scale regional event.

In the Copper Cliff South area the Sudbury Event, caused by the impact of a meteorite, is responsible for the brecciation of country rocks and creation of shatter cones, which was followed by the intrusion of the quartz diorite dike and formation of primary magmatic sulphides from an immiscible sulphide liquid.

Peak metamorphism of Penokean Orogeny occurred before the Sudbury Event, but retrograde metamorphism and deformation affected the rocks after the Sudbury Event and outlasted the first hydrothermal event.

The first hydrothermal event was a large-scale regional event that followed the Sudbury Event and is responsible for the enrichment of the orebodies in the Copper Cliff South mine. It remobilized a large number of elements including PGE and redeposited them in veins in quartz diorite and country rocks, and in highly permeable areas such as the contact of quartz diorite and country rocks and locally the centre of the dike where the quartz diorite is rich in inclusions.

The fluids of the first hydrothermal event altered the quartz diorite in the whole area; the degree of alteration increases toward the sulphide and the contacts of quartz diorite with the country rocks. The alteration minerals are rich in water and Cl; they include chlorite, biotite, Fe-rich amphibole, quartz, garnet, epidote, stilpnomelane, ferropyrrosmalite, muscovite and calcite. The fluids were Cl-rich and oxidizing. The elements transported by the fluids include Cl, Cu, Ni, Fe, Co, S, Bi, Te, Pb, Zn, Pt, Pd,

Au, Ag, Rh, K, Na, Ca, Mn, As and Sb. The source of metals was primary magmatic sulphide in the Copper Cliff South area and partly a “100 type” orebody that is depleted in Cu, Ni, Pt, Pd and Au compared to the 800 and 810 orebodies.

The temperature was between 375 and 540° C ($\pm 50^\circ$ C) and the pressure was around 3-4 kbar. The source of heat was the Sudbury Igneous Complex and probably partially the retrograde metamorphism of Penokean Orogeny that happened simultaneously.

Later hydrothermal events are related to intrusions of hornblende diabase, olivine diabase and aplite dikes; and later brittle deformation such as repeated movement along the Creighton and its subsidiary faults, and Evans Fault. These later hydrothermal events were local and economically not as significant as the first hydrothermal event.

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APPENDIX 1: MINERAL ABBREVIATIONS

alm = almandine

amph = amphibole

ann = annite

bn = bornite

bt = biotite

calc = calcite

cc = chalcocite

ccp = chalcopyrite

chl = chlorite

cub = cubanite

cv = covellite

dg = digenite

ep = epidote

gal = galena

gers = gersdorffite

god = godlevskite

gnt = garnet

grs = grossular

hz = heazlewoodite

hm = hematite

kfp = potassic feldspar

magn = magnetite

mill = millerite

ms = muscovite

mt = magnetite

pent = pentlandite

phl = phlogopite

pl = plagioclase

pn = pentlandite

po = pyrrhotite

prp = pyrope

py = pyrite

sil = silicate

sper = sperrylite

sps = spessartine

st = staurolite

tal = talnakhite

tr = troilite

viol = violarite

vs = vaesite

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Oversize maps and charts are microfilmed in sections in the following manner:

LEFT TO RIGHT, TOP TO BOTTOM, WITH SMALL OVERLAPS

This reproduction is the best copy available.

UMI[®]

**Copper C
Surfa
of 850 an**

**Copper Cliff South Offset,
Surface exposure
of 850 and 865 orebodies**

Leg

Rock units:

Olivine diabc

Hornblende c

Inclusion ma

Quartz diorite

Nipissing dial

McKim l

McKim pelite

Copper C

Copper Cliff

Symbols:

Defined cont

Assumed cor

Vein with no

Vein with sul

Legend

Rock units:

Olivine diabase	
Hornblende diabase	
Inclusion massive sulphide	
Quartz diorite	
Nipissing diabase	
McKim boulders	
McKim pelite	
Copper Cliff boulders	
Copper Cliff rhyolite	

Symbols:

Defined contact	
Assumed contact	
Vein with no sulphide	
Vein with sulphide

Lege

Rock units:

Olivine diabase

Hornblende di

Inclusion massi

Quartz diorite

Nipissing diaba

McKim bo

McKim pelite

Copper Cliff

Copper Cliff rh

Symbols:

Defined contac

Assumed conta

Vein with no su

Vein with sulph

Shear zone

Estimated sulp

Inclusion n

> 20 %

> 10 %

> 5 %

> 2 %

Breccia

Foliation

Legend

Rock units:

Olivine diabase	
Hornblende diabase	
Inclusion massive sulphide	
Quartz diorite	
Nipissing diabase	
McKim boulders	
McKim pelite	
Copper Cliff boulders	
Copper Cliff rhyolite	

Symbols:

Defined contact	
Assumed contact	
Vein with no sulphide	
Vein with sulphide	
Shear zone	
Estimated sulphide content:	
Inclusion massive	
> 20 %	
> 10 %	
> 5 %	
> 2 %	

Breccia

Copper
Copper
Symbol
Defined
Assumed
Vein with
Vein with
Shear zone
Estimate

Included
> 2
> 1
> 5
> 2

Breccia
Foliation
Ventilation
Sample
Traverse

0

- Mckim boulders
- Mckim pelite
- Copper Cliff boulders
- Copper Cliff rhyolite

Symbols:

- Defined contact
- Assumed contact
- Vein with no sulphide
- Vein with sulphide
- Shear zone
- Estimated sulphide content:
 - Inclusion massive
 - > 20 %
 - > 10 %
 - > 5 %
 - > 2 %
- Breccia
- Foliation
- Ventilation shaft
- Sample locations
- Traverse

0 5 10 m