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**Petrology and Mineralogy of Cu-Ni-PGE Ore, Totten Area, Worthington Offset,
Sudbury Igneous Complex, Ontario**

by

Matthew C. Stewart

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

Carleton University

Ottawa-Carleton Geoscience Centre

August, 2002

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The undersigned recommend to the Faculty of Graduate Studies and Research acceptance
of the thesis **Petrology and Mineralogy of Cu-Ni-PGE ore, Totten Area, Worthington
Offset, Sudbury Igneous Complex, Ontario.**

Submitted by Matthew C. Stewart, B.Sc.,

In partial fulfillment of the degree of Master of Science

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Chairman, Department of Earth Sciences

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August, 2002

Abstract

The Worthington offset, composed of quartz diorite, extends SW from the Sudbury Igneous Complex intruding foliated metavolcanic and metasedimentary rocks of the Huronian Supergroup as well as the Nipissing Intrusions. The QD can be further subdivided into inclusion-free and inclusion-bearing quartz diorite. The IQD is located in the centre of the QD offset and is host to the majority of the Ni-Cu sulfides and PGE.

The massive, semi-massive magmatic sulfide is spatially associated with large metagabbro inclusions within the IQD. Sheared IQD occurs locally. Veins of chalcopyrite-rich sulfide occur throughout the IQD. Arsenide and sulfarsenide-bearing veins crosscut foliation and chalcopyrite-rich veins.

Sulfide liquid accumulated mechanically around large metagabbro inclusions. Hydrothermal processes resulted in an increase in Fe and Cl in hydrosilicates with proximity to sulfide. A deformational event occurred after the first hydrothermal event. Nickeline bearing veins crosscut chalcopyrite veinlets suggesting multiple remobilization events, pre and post deformation.

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TABLE OF CONTENTS

	page
NOTICE OF ACCEPTANCE	ii
ABSTRACT	iii
ACKNOWLEDGEMENTS	iv
TABLE OF CONTENTS	v
LIST OF FIGURES	ix
LIST OF PLATES	xiv
LIST OF TABLES	xix
LIST OF MAPS	xx
 CHAPTER 1: INTRODUCTION	 1
1.1. INTRODUCTION	1
1.2. PURPOSE OF STUDY	1
1.3. METHODOLOGY	2
1.4. CONTEXT OF STUDY	2
 CHAPTER 2: REGIONAL GEOLOGY	 4
2.1. REGIONAL GEOLOGY	4
2.2. GEOLOGY OF THE WORTHINGTON OFFSET AREA	5
 CHAPTER 3: SURFACE GEOLOGY SOUTH EAST OF THE TOTTEN #2 SHAFT	 8
3.1. INTRODUCTION	8
3.2. PECORS FORMATION	8
3.3. NIPISSING DIABASE	9
3.4. QUARTZ DIORITE	9
3.5. INCLUSION QUARTZ DIORITE	9
3.6. DIABASE DYKES	11
3.7. DEFORMATION	12
3.8. SULFIDE DISTRIBUTION	12
3.9. LOCAL FIELD RELATIONS	13
 CHAPTER 4: PETROLOGY AND SILICATE MINERALOGY OF BARREN AND INCLUSION-BEARING QUARTZ DIORITE	 20
4.1. INTRODUCTION	20

4.2. TEXTURES	20
4.2.1. CONTACT QD	20
4.2.2. QUARTZ DIORITE	21
4.2.3. FOLIATED QD	21
4.2.4. GRANOPHYRE	22
4.3. MINERALOGY	22
4.3.1. AMPHIBOLE	22
4.3.2. BIOTITE	23
4.3.3. CHLORITE	24
4.3.4. EPIDOTE	24
4.3.5. APATITE	25
4.3.6. GARNET	25
4.4. MINERAL CHEMISTRY	25
4.4.1. AMPHIBOLE	26
4.4.2. BIOTITE	28
4.4.3. CHLORITE	30
4.4.4. APATITE	31
 CHAPTER 5: SULFIDES	 47
5.1. INTRODUCTION	47
5.2. ORE TEXTURES	47
5.2.1. MASSIVE/SEMI MASSIVE SULFIDE	48
5.2.2. VEINS	48
5.2.3. DISSEMINATED AND BLEBBY SULFIDE	49
5.3. MINERALOGY	50
5.3.1. PYRRHOTITE	50
5.3.2. PENTLANDITE	52
5.3.3. ARGENTOPENTLANDITE	53
5.3.4. CHALCOPYRITE	53
5.3.5. SPALERITE	54
5.3.6. GALENA	55
5.4. MINERAL CHEMISTRY	55
5.4.1. PYRRHOTITE	55
5.4.2. PENTLANDITE	56
5.4.3. ARGENTOPENTLANDITE	58
 CHAPTER 6: MINERALOGY AND COMPOSITION OF SULFARSENIDES AND ARSENIDES	 85
6.1. INTRODUCTION	85
6.2. TEXTURES	86
6.2.1. DISCRETE GRAINS	86
6.2.2. ZONATION	87
6.2.3. VEINS	88

6.2.4. SULFARSENIDE RIM	89
6.2.5. REPLACEMENT TEXTURES	89
6.2.6. NICKELINE BLEBS	89
6.3. MINERALOGY	89
6.3.1. COBALTITE-GERSDORFFITE	90
6.3.2. NICKELINE	90
6.3.3. MAUCHERITE	91
6.3.4. MINERAL ASSEMBLAGE	91
6.4. MINERAL CHEMISTRY	91
6.4.1. COBALTITE-GERSDORFFITE	91
6.4.2. NICKELINE	92
6.4.3. MAUCERITE	93
 CHAPTER 7: PRECIOUS METAL MINERALS, OXIDES AND TELLURIDES	 108
7.1. INTRODUCTION	108
7.2. TEXTURES	108
7.2.1. DISCRETE GRAINS	109
7.2.2. INCLUSIONS	109
7.2.3. ZONATION	110
7.2.4. REPLACEMENT TEXTURES	110
7.3. MINERALOGY	110
7.3.1. MICHENERITE	110
7.3.2. UNNAMED PGM	110
7.3.3. SPERRYLITE	111
7.3.4. FROODITE	111
7.3.5. ARGENTIAN GOLD	111
7.3.6. HESSITE	112
7.3.7. TSUMOITE	112
7.3.8. ALTAITE	112
7.3.9. MAGNETITE	113
7.3.10. ILMENITE	113
7.4. MINERAL CHEMISTRY	113
7.4.1. MICHENERITE	113
7.4.2. UNNAMED PGM	114
7.4.3. SPERRYLITE	114
7.4.4. FROODITE	115
7.4.5. ARGENTIAN GOLD	115
7.4.6. TSUMOITE	115
 CHAPTER 8: DISCUSSION	 126
8.1 FIELD RELATIONS	126

8.2 SECONDARY SULFIDES	130
8.3 DEFORMATION	135
8.4 SULFARSENIDES AND ARSENIDES	137
8.5 ALTERATION CONDITIONS	140
8.6 RELATIVE TIMING OF EVENTS	141
CHAPTER 9: CONCLUSIONS	148
REFERENCES	150
APPENDIX 1	160
APPENDIX 2	161
APPENDIX 3	162
APPENDIX 4	163

	List of Figures	Page
Figure 2.1.	Regional map of Sudbury Structure showing deposits mentioned in study	7
Figure 3.1.	Comparison of quartz diorite textures A) QD B) inclusion bearing quartz diorite (IQD) with amphibolite inclusions C) foliated IQD with elongate amphibolite inclusions and sulfide blebs	15
Figure 3.2.	Gabbro inclusions in IQD with sulfide A) medium sized gabbro inclusion with no deformation B) Medium and large gabbro inclusions with interstitial sulfide, moderate foliation throughout	16
Figure 3.3.	Schematic of 245 zone showing gabbro inclusions in relation to sulfide accumulation and to trenches	18
Figure 3.4.	Schematic of 260 zone showing gabbro inclusions in relation to sulfides and to open pit	19
Figure 4.1.	A) General classification of amphibole (apfu) B) Classification of calcic amphibole ($\text{Na}+\text{K} < 0.5$; $\text{Ti} < 0.5$)	32
Figure 4.2.	A) Classification of calcic amphibole $\text{Na}+\text{K} > 0.5$; B) Classification of Fe-Mg-Mn amphibole	33
Figure 4.3.	A) Binary plot of amphibole Mg vs Fe in relation to sulfide textural type B) Cl (apfu) vs Fe number of amphibole displays clear trend in relation to distance from MASU	34
Figure 4.4.	Amphibole mineral chemistry in relation to sulfide textural type A) Binary plot of Mg vs Si (apfu) B) Binary plot of $\text{Na}+\text{K}$ vs Mg (apfu)	35
Figure 4.5.	Amphibole mineral chemistry in relation to texture A) Binary plot of Ti (C site apfu) vs Al (T site apfu) B) Binary plot of Cr (C site apfu) vs Al (T site apfu)	36
Figure 4.6.	Amphibole mineral chemistry in relation to distance from MASU A) Binary plot of Cl (apfu) vs $\text{Na}+\text{K}$ B) Binary plot of Fe (apfu) vs AL (T site apfu)	37

Figure 4.7.	A) Classification of biotite B) Ternary plot of biotite in relation to sulfide texture	38
Figure 4.8.	Binary plots of biotite in relation to sulfide texture A) Cl (apfu) vs Fe number displays Cl-Fe-rich biotite from massive sulfide B) Ti (apfu) vs K (apfu) displays distinct composition of arsenide bearing veins	39
Figure 4.9.	Binary plots of biotite in proximity to MASU A) Ti (apfu) vs Mg (apfu) B) Na (apfu) vs Mg number	40
Figure 4.10.	A) Classification of chlorite B) Chlorite mineral chemistry binary plot of Fe vs Mg displaying marked increase in Fe content of massive sulfide and chalcopyrite veins	41
Figure 4.11.	A) Ternary plot of chlorite Cr-Mn-Ti demonstrating the distinct composition of the gabbroic country rock and gabbro inclusions B) Chlorite Ti vs Fe number with regression line through chlorite analyses in relation to distance from orebody	42
Figure 4.12.	Chlorite mineral chemistry A) Binary plot of NiO vs TiO ₂ : all chlorite contain some Ni B) Binary plot of Cl# vs NiO (wt%) displays distinction between Cu-rich veins and As-rich veins	43
Figure 4.13.	Apatite Mineral chemistry A) Binary plot of F vs Cl (apfu) displays no difference between quartz diorite and inclusion quartz diorite B) Binary plot of Na vs Ca (apfu) reflecting Ca-rich quartz diorite apatite	44
Figure 4.14.	Apatite mineral chemistry A) Minor elevated P values in the quartz diorite B) Nd bearing quartz diorite apatite in contrast to apatite from inclusion quartz diorite devoid of Nd	45
Figure 4.15.	Apatite mineral chemistry A) Ternary plot of Mn-S-Sr displays Sr bearing quartz diorite apatite and S bearing apatite from the inclusion quartz diorite	46
Figure 5.1.	Histogram of Ni wt% in pyrrhotite analyses related to monoclinic and hexagonal polytypes.	65

Figure 5.2.	Binary plots of pyrrhotite mineral chemistry in relation to textural type. A) Negative correlation between Fe and S B) No correlation between S and Ni C) No correlation between Fe and Ni	76
Figure 5.3.	Binary plot pyrrhotites in relation to pentlandite A) atomic % Fe vs S showing po slightly depleted in Fe when located away from pn B) atomic % Fe vs Ni displays moderate increase in Ni content when located away from pn	77
Figure 5.4.	A) Histogram of cobalt content of pentlandite B) Histogram of Ni content of pentlandite	78
Figure 5.5.	A) MASU1 - massive pentlandite and lesser pyrrhotite and chalcopyrite B) MASU2 predominantly pyrrhotite with pentlandite and lesser amounts of quartz	79
Figure 5.6.	Mineral chemistry of pentlandite. A) Ternary plot of Fe-Ni-Co (atomic %) displays wide variation in MASU1 composition as well as Co free pentlandite from an arsenide bearing vein B) Binary plot of Fe vs S (atomic %) displays the same variable MASU1 compositions and S-poor pentlandite from po vein	80
Figure 5.7.	Pentlandite mineral chemistry in relation to crystal habit A) Binary plot of Fe vs Co atomic % displays positive correlation between Co and Ni with rosettes being Ni -rich B) Binary plot of Co vs S atomic % displays a negative correlation where the rosettes are slightly elevated in Co and S poor.	81
Figure 5.8.	Pentlandite mineral chemistry in relation to crystal habit A) Binary plot of Fe vs Ni (atomic %) displays a positive correlation for rosettes and a negative correlation for flames B) Binary plot of Fe vs S (atomic %) displays a negative correlation for rosettes and a positive correlation for flames.	82
Figure 5.9.	A) Fe-Ni-Ag ternary plot of argentopentlandite (at %) displays argentopentlandite from an As-rich vein slightly elevated in Ag B) S-poor composition of argentopentlandite from RGDI texture	83

Figure 5.10.	Argentopentlandite mineral chemistry. A) Binary plot of Ag vs Ni displays a negative trend B) Binary plot of Ag vs Fe also displays a negative trend	84
Figure 6.1.	Fe-Co-Ni variation due to zonation within gersdorffite A) Fe-Co-Ni Ternary plot displays Ni-rich rim and Co+Fe rich core B) Binary plot of As vs S displays little variation in the As/S ratio	96
Figure 6.2.	Relative abundance of Fe-Co-Ni in sulfarsenide grains from the Totten Mine	103
Figure 6.3.	Mineral chemistry of sulfarsenides A) Fe-Co-Ni ternary plot (At. %) displays solid solution between metals B) Binary plot of As vs S (At%) displays negative correlation	104
Figure 6.4.	Metals vs As/S in sulfarsenides. Ni, Fe, Co all have no correlation with the As:S ratio	105
Figure 6.5.	Fe-Ni-Co Ratios in sulfarsenides A) strong negative trend between Ni and Co B), C) weak negative and positive trends respectively	106
Figure 6.6.	Nickeline analyses display a negative correlation between Ni and As	107
Figure 7.1.	A) PGM plotted on Pd-Bi-Te ternary diagram (atomic %) B) Sperrylite plotted on Pt vs As binary (atomic %)	122
Figure 7.2.	A) Projection of PGM onto Bi-Sb-Te ternary diagram (at%) B) PGM projected onto Bi-Sb binary diagram (at %)	123
Figure 7.3.	A) Argentinian gold mineral composition plotted on Au-Ag-Ni ternary diagram (atomic %) B) Argentinian gold composition plotted on Au-Ag binary diagram	124
Figure 7.4.	Bismuth telluride analyses with ideal tsumoite and pilsenite compositions overlain.	125
Figure 8.1.	Comparison metal abundances from whole rock data, QD vs IQD (after Lightfoot, 1997a).	142
Figure 8.2.	Schematic of IQD velocity profile during intrusion. A) Decrease in velocity due to friction with country rock and temperature decrease	

	B) Highest velocity in centre of dike (carrying largest inclusions) C) Local velocity decreases due to choking effect of large inclusions resulting in mechanical accumualtion of sulfide	143
Figure 8.3.	Cl/(Cl+F) vs X _m g of biotite (after Farrow and Watkinson, 1999), Copper Cliff South (CCS). Data from this study in colour.	144
Figure 8.4.	a) foliated chalcopyrite cross-cut by pyrrhotite+nickeline blebs b) chlorite overgrowing foliated biotite at selvage of nickeline vein	145
Figure 8.5.	Comparison of Totten sulfarsenides with magmatic Mount General'Skaya data (Barkov, 1999). Phase diagram after Klemm (1965). Overlain is the crystallization trend for Mount General'Skaya, data and the Totten data.	146
Figure 8.6.	Schematic cross section through orebody. A) Blebby and disseminated sulfide in IQD with small gabbro inclusions. B) Ragged disseminated sulfide often Cu rich, increase in gabbro inclusion size and abundance. C) Massive and inclusion massive sulfide bounded by large gabbro inclusions D) Large gabbro inclusions.	147

	List of Plates	Page
Plate 5.1a	Nickel rich massive sulfide with visible pentlandite megacryst hosted in pyrrhotite displaying variable oxidation intensities. Sample tot-79	60
Plate 5.1b	Layered massive sulfide having a foliation defined by alternating layers of chalcopyrite and pyrrhotite. Pentlandite megacrysts are also present. Sample WP-2	60
Plate 5.1c	Chalcopyrite and quartz rich massive sulfide from the Worthington Pit. Galena visible at the hand sample scale. Lesser amounts of pyrrhotite present as well. Sample WP-1	60
Plate 5.1d	Pyrrhotite-rich inclusion massive sulfide, with abundant gabbro inclusions. Sample tot-41	60
Plate 5.2a	Pentlandite and pyrrhotite located in the center of a chalcopyrite vein in IQD. Sample tot-63	62
Plate 5.2b	Chalcopyrite vein with quartz inclusion and splintering chalcopyrite veinlet which terminates in carbonate. Argentinian gold located at sulfide carbonate transition. Sample tot-45	62
Plate 5.2c	Variably oxidizing pyrrhotite rich vein containing pentlandite in the center hosted, in IQD. Sample tot-55	62
Plate 5.2d	Pyrrhotite vein with finely disseminated pyrrhotite halo hosted in IQD. Pentlandite located in the center, and chalcopyrite replacing pyrrhotite. Sample tot-77	62
Plate 5.3a	Deformed (elongate) blebby sulfide hosted in IQD. Abundant amphibolite chips are also deformed. Sample tot-73b	64
Plate 5.3b	RGDI pyrrhotite rich sulfide in IQD. Chalcopyrite and pentlandite at edge of sulfide accumulation. Sample tot-87b	64
Plate 5.4a	5-10% monoclinic pyrrhotite, hosted in Ni-rich massive sulfide near pentlandite megacryst. Sample tot-84a, field of view ~1mm.	67

Plate 5.4b	50% monoclinic pyrrhotite in massive sulfide. No change in pyrrhotite ratio around tsumoite grain. Sample tot-83, field of view ~1mm.	67
Plate 5.4c	Increase in monoclinic pyrrhotite at contact of chalcopyrite. Pentlandite exsolutions in chalcopyrite. Intergrowths display minor boxwork texture near contact with chalcopyrite, and two sets of composite lamellae away from contact. Sample tot-83, field of view ~1mm.	67
Plate 5.4d	Boxwork texture in massive sulfide near pentlandite. Sample tot-80, field of view ~1mm.	67
Plate 5.5a	~50% monoclinic and hexagonal pyrrhotite in massive sulfide. Kink banding within ellipse. Sample tot-154-5c, field of view ~0.5mm.	69
Plate 5.5b	Aligned intergrowths of monoclinic pyrrhotite. Sample tot-49b, field of view ~1mm.	69
Plate 5.6a	Semi-rounded pentlandite megacryst (octahedral parting) hosted in pyrrhotite located within massive sulfide. Sample tot-84a, field of view ~4mm.	71
Plate 5.6b	Pentlandite rosette in center of chalcopyrite vein adjacent to pyrrhotite. Sample tot-83.	71
Plate 5.6c	Pentlandite rim around pyrrhotite grain in massive sulfide. Sample tot-84a, field of view ~4mm.	71
Plate 5.6d	Pentlandite flame hosted in pyrrhotite. Sample tot-84b, field of view ~1mm.	71
Plate 5.7a	BSE image of argentopentlandite and pyrrhotite exsolutions in chalcopyrite. Sample tot-16.	73
Plate 5.7b	BSE image of an argentopentlandite grain at the arsenide-sulfarsenide-sulfide interface. Sample tot-4188.	73
Plate 5.7c	Large chalcopyrite crystals in chalcopyrite vein hosted in IQD. Sample tot-45.	73
Plate 5.7d	Chalcopyrite rich disseminations and blebs hosted in fine grained IQD. Sample tot-87b.	73

Plate 5.8a	BSE image of sphalerite grain at arsenide-sulfarsenide contact, hosted in a nickeline rich vein, adjacent to an unnamed Pd-Sb-Bi-Te mineral (PGM1). Sample tot-154	75
Plate 5.8b	Photomicrograph of abundant sphalerite and galena associated with argentian gold grains, hosted in a chalcopyrite vein. Sample tot-45, field of view ~1mm.	75
Plate 6.1a	Photomicrograph of discrete gersdorffite grain hosted in chalcopyrite with magnetite attached. Sample tot-84b, field of view ~0.3mm.	95
Plate 6.1b	BSE image of a euhedral discrete grain of gersdorffite with sperrylite inclusion. Sample tot-83.	95
Plate 6.1c	BSE image of a euhedral cobaltite attached to chlorite hosted in chalcopyrite. Sample tot-77a	95
Plate 6.1d	BSE image of zoned cobaltite hosted in chalcopyrite. Sample tot-83.	95
Plate 6.2a	Photomicrograph of nickeline, chalcopyrite, pyrrhotite hosted in IQD.	98
Plate 6.2b	Quartz, and carbonate vein with minor nickeline and chalcopyrite hosted in IQD.	98
Plate 6.2c	Nickeline veinlet cross cutting chalcopyrite veinlet in IQD.	98
Plate 6.3a	Photomicrograph of nickeline replaced gersdorffite (center) and gersdorffite rim formed at contact of nickeline with chalcopyrite. Sample tot-154, field of view ~0.8mm	100
Plate 6.3b	Photomicrograph nickeline partially replaced cluster of gersdorffite grains (center-bottom), and completely replaced grains (center-top) with remnant crystal faces still distinguishable. Sample As4188, field of view ~2mm	100
Plate 6.3c	Photomicrograph nickeline partially replaced gersdorffite. Sample tot-154, field of view ~1mm	100
Plate 6.3d	Photomicrograph of nickeline blebs in pyrrhotite and chalcopyrite. Sample tot-154c, field of view ~1mm	100

Plate 6.4a	BSE image of gersdorffite hosted in chalcopyrite (discrete grain) and of gersdorffite riming nickeline. Sample tot-as88.	102
Plate 6.4b	BSE image of anhedral nickeline attached to chlorite and biotite. Sample tot-as88.	102
Plate 6.4c	Photomicrograph of maucherite and unnamed PGM at nickeline grain boundary (cross polars). Note lamellae visible in nickeline. Sample tot-5b, field of view ~1mm.	102
Plate 6.4d	BSE image of all three As bearing phases (cobaltite, nickeline and maucherite). Note cobaltite grain being replaced by nickeline. Sample tot-5b.	102
Plate 7.1a	Photomicrograph of a discrete grain of michenerite hosted in Ni-rich massive sulfide. Sample tot-79, field of view ~1.5mm.	117
Plate 7.1b	BSE image of a hessite and altaite attached to an amphibole hosted in chalcopyrite. Sample tot-73b.	117
Plate 7.1c	Photomicrograph of a sperrylite inclusion within a cobaltite grain, all hosted in chalcopyrite. Sample tot-83, field of view ~0.5mm	117
Plate 7.1d	BSE image of michenerite and tsumoite inclusions in quartz all hosted in amphibole. Sample tot-46.	117
Plate 7.2a	BSE image of a zoned michenerite grain attached to altaite. Sample tot-45.	119
Plate 7.2b	Photomicrograph of magnetite replacing silicates of an amphibolite inclusion, within a chalcopyrite vein. Sample tot-84b, field of view ~2mm, reflected light.	119
Plate 7.2c	Photomicrograph of magnetite replacing the silicate assemblage of an amphibolite inclusion, within a chalcopyrite vein. Sample tot-84b, field of view ~2mm PPL.	119
Plate 7.3a	BSE image of michenerite forming a late stage veinlet within nickeline. Sample tot-151.	121

Plate 7.3b	BSE image of unnamed Pd-Sb-Bi-Te-Ni PGM forming an elongate grain at the interface between gersdorffite and nickeline. Sample tot-5b.	121
Plate 7.3c	BSE image of the unnamed Pd-Sb-Bi-Te-Ni PGM attached to galena within a nickeline bearing vein. Sample tot-5b.	121
Plate 7.3d	BSE image of sperrylite, attached to gersdorffite, and hosted in chalcopyrite. Sample tot-73b.	121

	List of Tables	Page
Table 1.1.	List of abbreviations	3
Table 3.1.	Structural features in map area related to regional features	17

List of Maps

Map. Map of Worthington Offset, South East of Totten #2 Shaft, back pocket

Chapter 1: Introduction

1.1 General Statement

The Totten area (#1 shaft, #2 shaft, Worthington Pit) is located ~36 km WSW of Sudbury, Ontario, in Drury township. It is accessible by regional road 516 and by the C.P.R. railway. Ore grade material was first discovered in the Totten area during the construction of the railway in 1884. Since the first discovery, three shafts have been sunk to exploit the ore, of which the Totten #1 shaft was the last to be shut down in 1970. Renewed exploration in the Totten area by INCO Ltd. has delineated further resources at depth by diamond drilling from surface. The preexisting infrastructure has added to the feasibility of exploiting this newly discovered resource.

1.2 Purpose of Study

The Sudbury Igneous Complex (SIC) is host to world class Ni-Cu-PGE deposits. The majority of deposits are located within the contact sublayer and within offset dikes. Extensive research has been conducted on all aspects of the SIC. When the SIC is viewed as a whole, differences amongst deposits located in the north range vs south range have been observed. Examples include; mineralogy (very few As, Sb-bearing minerals in the north range), textures (footwall vein deposits only found in the north range), lithology (footwall breccia only found in the north range). While these differences between north and south range deposits have helped in exploration guidelines and in more effective exploitation of known orebodies, it has become apparent that there are intra-range differences in mineralogy, composition and textures between deposits (Farrow and Watkinson, 1997). The purpose of this study is to further classify the Totten orebody that

includes detailed description of mineralogy (sulfides, PGM, arsenic bearing minerals, alteration minerals, quartz diorite mineralogy), mineral composition, monoclinic vs hexagonal pyrrhotite, structural features, and inclusion population. See table 1.1 for list of abbreviations.

1.3 Methodology

The classification of the Totten orebody will be accomplished by i) 1:200 scale field mapping at surface (access courtesy INCO Ltd.) ii) hand sample description and petrography of drill core samples (drill core courtesy INCO Ltd.) iii) microprobe and SEM analyses to document sulfide and silicate mineral chemistry as well as PMM mineralogy iv) magnetic colloid stain to qualitatively describe the abundance of monoclinic and hexagonal pyrrhotite.

1.4 Context of Study

This study is a small cog on the "Mineral Deposits Research Lab" wheel at Carleton University. As a result, this study has greatly benefited from access to previous and current graduate and postdoctoral students research on Sudbury. The work of Dr. Watkinson on mafic-ultramafic complexes is the foundation upon which this work is based. This study has been greatly advanced by work, past and present, of INCO Ltd. geologists who have done more research and exploration on this area than anyone else.

Table 1.1. List of Abbreviations

Amph	amphibole	PGM	platinum group mineral
BLBS	blebby sulfide	Pn	pentlandite
Bio	biotite	Po	pyrrhotite
Ccp	chalcopyrite	QD	quartz diorite
Chl	chlorite	Qdia	quartz diabase
Cob	cobaltite	RGDI	ragged disseminated
DIS	disseminated	SIC	Sudbury Igneous Complex
Ep	epidote	Sper	sperrylite
Gab	gabbro	STRS	stringers
Gers	gersdorffite		
Hpo	hexagonal pyrrhotite		
INMS	inclusion rich massive sulfide		
IQD	inclusion bearing quartz diorite		
Mag	magnetite		
MASU	massive sulfide		
Mau	maucherite		
Mich	michenerite		
Mpo	monoclinic pyrrhotite		
Nic	nickeline		
Odia	olivine diabase		
PGE	platinum group element		

Chapter 2: Regional Setting

2.1 Regional Geology

The Sudbury Structure is located at the contact of rocks from the Superior Province to the north, east and west and rocks from the Southern Province to the south (Fig. 2.1). The rocks of the Superior Province consist of upper amphibolite and granulite facies gneisses and migmatites (Card et al., 1984) which, stratigraphically below the SIC, are brecciated and termed footwall breccia. Rocks of the Southern Province belong to the 2500-2100 Ma Huronian Supergroup. This consists of clastic sedimentary rocks, basal volcanic rocks and associated sedimentary rocks, Nipissing Diabase, and intrusive granitic plutons. The Southern Province underwent a phase of ductile deformation during the Penokean orogeny (>2100 Ma – 1750 Ma) (Card et al., 1984).

The Sudbury Structure is composed of the sedimentary rocks of the Whitewater group, the SIC, and the brecciated country rocks (Giblin, 1984). The 1850 +/- 1 Ma SIC (Krogh et al., 1984) is an elliptical shaped mafic body consisting of 3 main units. The lower most unit consists of two sub-units; the Sublayer, and mafic norite. The discontinuous Sublayer is located at the base of the SIC and is economically significant hosting the majority of orebodies. It is composed of variable amounts of norite, gabbro, and quartz diorite as well as variable amounts of inclusions (both locally derived and ultra-mafic inclusions of unknown origin) and sulfides (Pattison, 1979). The Sublayer also extends into the country rock as radial and concentric dikes composed of quartz diorite. These dikes, termed "offset dikes", are also host to abundant sulfide and have several mines (e.g., Copper Cliff North Mine, Copper Cliff South Mine, Totten Mine). The mafic norite has very little sulfide and inclusions in comparison to the Sublayer.

Stratigraphically above the mafic norite lies the quartz gabbro (second unit) and above that lies the voluminous granophyre (third unit) both of which are devoid of sulfide and inclusions.

The origin and petrogenesis of the SIC is unresolved. Sudbury breccia (an "in situ" breccia of country rock which decreases in abundance away from the SIC), shatter cones, and shock metamorphic textures in quartz and plagioclase are interpreted by many (but not all; e.g.. Muir, 1984) as evidence for a meteor impact (e.g.. Dietz, 1964). The impact model and associated melt sheet does not discount the idea of intrusion related magmatism as part of the process that produced the SIC, and its mineral wealth (e.g.. Rousell et al., 1997).

Approximately 10 km SE of the Sudbury Structure lies the northern edge of the Grenville front. This 1000 Ma gneissic terrain underwent a major orogenesis. The effects of the Grenville orogenic events on the Sudbury Structure are disputed as these events and earlier events (Penokean orogeny) can not be distinguished (Card et al., 1984).

Major EW striking faults have deformed the Sudbury structure. This fault system is part of the Murray Fault Zone and can be traced into the Great Lakes Tectonic Zone with an overall distance of over 850 km from the SE corner of Lake Superior west to the Grenville front (Card et al., 1984).

2.2 Geology of the Worthington Offset Area

The Worthington Offset is located in the South Range of the SIC. It is a radial dyke that intrudes rocks of the Huronian Supergroup, Southern Province, that have been metamorphosed to lower greenschist facies (Magyarosi, 1998) and deformed during the

Penokean Orogeny (Barnes and Lalonde, 1973). These include volcanic and associated sedimentary rocks of the Elsie Mountain, Stobie and Copper Cliff formations, as well as sandstone and argillite of the McKim, Ramsay Lake and Pecors formations. Nipissing Gabbro (2.15 Ga; Card and Pattison, 1973) was intruded throughout the Huronian succession. All of these units are folded and dip to the south (Barnes and Lalonde, 1973). The Worthington Offset is cross cut by olivine and quartz diabase dykes (1.46 Ga; Gates and Hurley, 1973) and (1.25 Ga; Fahrig and Wanless, 1963).

Figure 2.1. Regional geology of the Sudbury area showing deposits mentioned in study

Chapter 3: Surface Geology South East of Totten #2 Shaft

3.1 Introduction

The Totten #2 shaft is located 50m north west of the Worthington Offset. The quartz diorite of the Worthington Offset at the Totten property intruded the Pecors formation, which is part of the Hough Lake group of the Huronian supergroup. The Offset itself is well exposed in the area in particular the eastern side. Detailed mapping was undertaken at a 1:200 scale in order to document the relationships amongst the contacts, textures, mineralogy, inclusion population, sulfide distribution and deformation (map in pocket). While there is no evidence of a surface expression of an ore body, these relationships are not easily interpreted from drill core.

3.2 Pecors Formation

Locally the Pecors formation is composed of interbedded sandstone, pebbly sandstone and argillite. Rare pebble to boulder sized clasts of granite gneiss are found within the sedimentary rocks. The latter are quartz-rich and have abundant quartz veins and veinlets throughout. The Pecors formation is quartz rich and has muscovite found throughout it. Beds composed of pelite are thin (2-4cm) and are biotite rich. Toward the south west, there is an increase in the quartz content. Along the eastern contact with the QD there are two locations that display Sudbury Breccia (map in pocket). The breccia has blocks up to 3m thick and as small as 1cm. The larger blocks are deformed.

3.3 Nipissing Gabbro

The QD has intruded into the Nipissing Gabbro north east of the Totten area. The Nipissing Gabbro is variably altered and varies in composition from melanogabbro to leucogabbro (Card and Pattison, 1973). Locally, blebby sulfides within the gabbro are pyrrhotite-rich. The gabbro is medium grained and equigranular, composed primarily of amphibole and variable amounts of plagioclase and chlorite with rare relict pyroxene.

3.4 Quartz Diorite (QD)

The Worthington Offset is well exposed south east of the Totten #2 shaft, in particular the eastern contact of the QD with the Pecors and the eastern QD/IQD contact (map in pocket). In two locations there is Sudbury Breccia at the contact with the QD and the Pecors formation. The thickness of the QD varies from 12m-6m. The QD is fine grained and biotite rich (up to 50%) along the contact with Pecors formation. It is relatively equigranular, and contains little to no sulfide. The QD contains rare metasedimentary inclusions in close proximity to the contact. Quartz carbonate veinlets occur throughout the QD, and are most abundant near the metasedimentary contact. The QD is generally coarser grained (Fig. 3.1a) than the IQD (<3mm).

3.5 Inclusion Quartz Diorite (IQD)

The IQD has a slightly darker colour on a fresh surface relative to the QD (Fig. 3.1b). The IQD in general has a more varied grain size from very fine grained to medium grained (3mm). It is host to abundant sulfides. Mineralogically it is similar to the QD,

with variable amounts (10-50%) of biotite. The IQD often has iron oxide staining both in areas containing sulfides and in sheared zones. In places the IQD is deformed (Fig. 3.1c)

The fine grained IQD contact with QD is well defined, and has good exposure at the eastern contact. As with the QD, the thickness of the IQD varies, and ranges from 14m-25m. At the QD contact the IQD is fine grained. Inclusions in IQD vary in size from millimeters to meters in size. The size of inclusions increases toward the center of the dike.

There are small (1mm-5cm) amphibole + biotite inclusions which are found laterally throughout the IQD. They are found from the contact with the QD through to the center of the IQD. The amphibolite inclusions are well rounded and in places elongate. These inclusions appear throughout the Worthington Offset in varying abundances (5-75%). In the Totten area the amphibolite inclusions are abundant, comprising up to 50% of the IQD.

There are gabbro inclusions as well, however they are not consistently found throughout the IQD. The gabbro inclusions range in size from 3cm-2.5m in the map area, and over 10m in other parts of the Worthington Offset. The larger gabbro inclusions are found in clusters (Fig. 3.2a). Interstitial to the larger (0.25-2m) gabbro inclusions is abundant sulfide (10-25% at surface) often accompanied with a foliation, non-penetrative to the inclusions (Fig. 3.2b). Some of the gabbro inclusions have an alteration selvage up to 1cm thick composed of fine grained chlorite. The amphibole in the gabbro inclusions ranges in size from <1mm – 3cm, occasionally in a radial shape.

The sedimentary inclusions range from 1-25 cm, averaging 3cm in size. They are well rounded, and elliptical. The inclusions are a well-bedded quartz arenite, similar in appearance to the Pecors formation.

Rare granite gneiss inclusions are found within the IQD. They are well rounded with an average size of 15cm.

Rare inclusions of QD are observed within the IQD. Also one inclusion of IQD was found within the IQD. The 30 cm thick inclusion of IQD only had one inclusion of amphibolite (5cm long) within it.

3.6 Diabase Dykes

There are two different diabase dykes that cross cut the Offset in the field area. There is a magnetic olivine diabase dyke with plagioclase phenocrysts and a non-magnetic quartz diabase dyke. The olivine diabase roughly strikes northwest-southeast and has a dip of 40° SW. It has a brownish colour on the weathered surface with several fractures and a dark grey colour on the fresh surface. The feldspar phenocrysts are up to 5cm long. The contact with the QD and IQD is sharp. The quartz diabase strikes east-west and is a dark grey on the weathered surface and a dark grey on the fresh surface. The contact of the quartz diabase with QD and the IQD is sharp. No sulfide is associated with either of the diabase dykes. Neither of the diabase dykes display any deformational features.

3.7 Deformation

A foliation is pronounced within the IQD in areas that contain these large inclusions. The steeply dipping foliation (72-748) is defined by amphibole and biotite and trends sub-parallel to the Offset (map in pocket). This fabric does not penetrate the larger (> 30cm) inclusions. In these areas the IQD is biotite rich, and there is often chalcopyrite found along the foliation. The smaller inclusions (< 30cm) in areas that have a pronounced fabric are elongate, and in places blebs of sulfide are also elongate parallel to the foliation.

Ductile deformation is also observed in the zones of Sudbury breccia as folded bedding of some of the large folded blocks of the Pecors formation.

The quartz diabase appears to have intruded along a brittle fault (refer to map). This is interpreted by i) the sediment contact at the western edge of the diabase/QD contact is Offset to the east, ii) the width of both the QD and the IQD varies considerably on either side of the quartz diabase dyke, iii) previous regional mapping has demonstrated faulting that has the same strike as the dyke. See table 3.1 for list of local structural features related to regional features.

3.8 Sulfide Distribution

Very little sulfide is found within the QD. Very rare fine disseminations of pyrrhotite and occasional veinlets of quartz+carbonate+pyrrhotite±chalcopyrite (>1%). Close to the contact with the IQD there is an increase in the veins and veinlets which are quartz rich and occasionally contain pyrrhotite and lesser amounts of chalcopyrite (<1%).

Sulfides are found throughout the IQD as fine disseminations of pyrrhotite and as blebby sulfides of pyrrhotite and chalcopyrite. Occasionally there are chalcopyrite rich disseminations and veinlets close to the contact with the QD. The amount of sulfide increases toward the large gabbro inclusions as does the abundance of chalcopyrite. Texturally the sulfides occurs as blebs and disseminations approaching the inclusion clusters, and increase in abundance to form ragged disseminated textures along with veins and veinlets. These sulfide and inclusion rich clusters occur in the center of the IQD.

Along the foliation plane in areas of sheared IQD there are disseminations and veinlets of chalcopyrite. One vein of massive chalcopyrite (5cm thick) striking N60E occurs at the north east section of the map area (map in pocket).

3.9 Local Field Relations

The detailed mapping for this project focused on the area around the Totten #2 shaft. However the "245" zone and the "260" zone of the Worthington Offset were sketch mapped to document the field relations.

3.9.1 Worthington Offset: South of AER Mine Rd. Turn-off

The 245 zone (Fig. 3.3) is located approximately 1km NE from the Totten #2 shaft, within the Worthington Offset. There are moderate amounts of outcrop, relative to the area surrounding the #2 shaft, predominantly consisting of IQD. Amphibolite and gabbro inclusions are present, and similar trends in sulfide distribution relative to gabbro inclusions are observed.

3.9.2 Worthington Offset: North of AER Mine Rd. Turn-off

The 260 zone (Fig. 3.4) is located approximately 1.4km NE of the Totten #2 shaft. This area has been documented by Lightfoot et al. (1997a) prior to the reclamation of the open pit. This location displays the largest observed gabbro inclusions, and deformation similar to what was documented in the map area. The sulfide content increases within the large gabbro inclusion clusters and chalcopyrite veinlets and disseminations are prominent along the shear zones.

Figure 3.1 Comparison of quartz diorite (QD) textures A) QD B) inclusion bearing quartz diorite (IQD) with amphibolite inclusions C) foliated IQD with elongate amphibolite inclusions and sulfide blebs

Figure 3.2. Gabbro inclusions in IQD with sulfide A) medium sized gabbro inclusion with no deformation B) Medium and large gabbro inclusions with interstitial sulfide, moderate foliation throughout

Table 3.1. Description of veins, fractures and joints observed in the field area.

Feature	Strike and Dip	Mineralogy	Related to Regional Features
Offset dike	N45E, 70-80°	See chapter 4	Radial to SIC
Diabase dike	N315E 40	See chapter 3	Murray fault Zone
Shear zone, veins, inclusions elongated	N220-235E 72-74°	Biotite and amphibole in shear zone, ccp±po in veins	Sub-parallel to offset, faulting (younger than Murray fault zone)
Veins (rare)	N021E 58°	Pyrrhotite and quartz	
Fractures, joints	N345E 90°	NA	
Fractures, joints, rare veinlets	N280-290E 90°	Quartz and pyrrhotite in veinlets	Diabase dikes, ~Murray fault zone

Figure 3.3. Schematic of 245 zone showing gabbro inclusions in relation to sulfide accumulation and to trenches

Figure 3.4 Schematic of 260 zone showing gabbro inclusions in relation to sulfides and to open pit

Chapter 4: Petrology and Silicate Mineralogy of Barren and Inclusion-Bearing Quartz Diorite

4.1 Introduction

The Worthington Offset at the Totten property is composed of two different quartz diorites (QD and IQD). The mineralogy is the same for both; however modal abundances vary between them and within them. The variations within the QD are related to the contact phase (see 4.2.1), and the variations in the IQD are related to the proximity of sulfides. Using suggested nomenclature from Grant and Bite (1984), both the barren quartz diorite and the inclusion quartz diorite would be classified as amphibole-biotite quartz diorite.

4.2 Textures

Textures formed by silicates were not studied in detail relative to the sulfide textures (chapter 5.2). There is less diversity of textures observed within the silicates and there is no relationship between silicate texture and ore grade.

4.2.1 Contact QD

The QD at the contact with the sedimentary rocks is fine grained and biotite rich. It has a moderately developed foliation defined by the biotite. This texture is most pronounced at the sedimentary rock contact and gradually becomes less well defined into the QD proper. The QD has an increase in quartz content with respect to the IQD, and there is trace ($>>1\%$) chalcopyrite along the foliation.

The increased quartz content in the contact QD has been described at other Offset locations and was attributed to the assimilation of local quartz rich Huronian sedimentary rocks (Grant and Bite, 1984). This is not in agreement with the conclusions of Lightfoot et al. (1997a) who state that the quartz diorite's composition was not altered due to any local assimilation of country rock.

4.2.2 Quartz Diorite

The barren quartz diorite is composed of plagioclase, amphibole, biotite, quartz, chlorite, epidote, apatite & opagues. It is medium to coarse grained and is equigranular. Rare pseudomorphs of amphibole (1-1.5 cm) are visible at the hand sample scale, but are replaced with a later amphibole and biotite. Previous detailed work on the Worthington Offset (Grant and Bite, 1984), (Lightfoot et al., 1997) have described quartz diorite with pyroxene pseudomorphs closer to the contact with the SIC and infer that the amphibole and biotite from the amphibole biotite quartz diorite are pseudomorphs after pyroxene. No relict pyroxene was observed at the Totten property.

4.2.3 Foliated Quartz Diorite

The inclusion bearing quartz diorite has been affected by local shear zones. These deformed zones within the QD are either amphibole rich, or biotite rich. The amphibole found in the shear zones is petrographically unlike the amphibole found in the main dyke quartz diorite (see 4.3.1) in that it has a blue-green pleochroism.

4.2.4 Granophyre

The QD has a granophyric intergrowths composed of quartz and feldspar that forms interstitially to amphibole and plagioclase. Grant and Bite (1984) described this same texture and have deduced that the feldspar within the granophyre is orthoclase. The granophyric texture is spatially associated with apatite clusters. The QD has a much greater quantity of granophyre than the IQD.

4.3 Mineralogy

The silicate mineralogy is the same for the QD and the IQD. Plagioclase, amphibole, biotite and quartz are the primary components of the QD and IQD. Chlorite, epidote and apatite and garnet are minor minerals. The silicates associated with sulfides (amphibole, biotite, chlorite and epidote) were analyzed in detail.

Plagioclase is euhedral and has variable amounts of sericitic alteration. It has albite twins and Carlsbad twins.

Quartz is common throughout the QD and the IQD. It occurs as anhedral grains with undulose extinction in the silicate part of the dike as well as in sulfide bearing veins and veinlets, and as discrete grains within massive and semi-massive sulfides.

In locations proximal to vein and disseminated sulfides, amphibole, epidote and biotite occasionally contain sulfide inclusions.

4.3.1 Amphibole

The amphibole within the QD and the IQD is a major component of the quartz diorite, occurs within the sulfides, and is abundant at the margins of chalcopyrite veins.

The amphibole within the quartz diorite is variably altered to chlorite and biotite. It is euhedral to subhedral with a yellow-green to green pleochroism.

The amphibole within and adjacent to sulfides has little to no chlorite and biotite alteration. These amphiboles occur as discrete grains or in radial clusters. Amphibole is often host to precious metal minerals and bismuth telluride inclusions.

The inclusions of gabbro are predominantly composed of 1-10mm amphibole. Small xenocrysts of amphibole from these inclusions are found in the IQD. The amphibole within the gabbro inclusions are subhedral to anhedral and always display one good cleavage direction and often display a second cleavage direction. The grains are interlocking with variable alteration to chlorite and biotite. The fine-grained amphibolite inclusions contain smaller (<1mm-5mm) and less altered amphibole relative to the gabbro inclusions.

4.3.2 Biotite

Biotite is both a primary mineral and an alteration product of amphibole in the QD and IQD. The secondary biotite is the most abundant form of biotite found in both the QD and IQD. It forms anhedral grains with bird's eye extinction. It has variable concentrations throughout the dyke with moderate increase in abundances at the edge of inclusions. This is attributed to the inclusions not being in equilibrium with the melt and forming a reaction rim. This has been suggested for the inclusions found at the North Mine, Copper Cliff Offset (Rickard, 2000).

Biotite occurring within and adjacent to sulfides appears to be in equilibrium with the surrounding sulfide. The biotite found within MASU and INMS form euhedral radiating clusters associated with chlorite and stilpnomelane. The largest abundance of biotite associated with sulfides is in the foliated Cu rich sulfide and foliated nickeline rich veins. This biotite does not appear to be primary. Biotite occurs in association with sulfide of all textural types.

Minor amounts of biotite (5%) are found within the gabbro inclusions as an alteration after the amphibole along with minor quantities (>5%) chlorite, and biotite is also commonly found within the amphibolite inclusions.

4.3.3 Chlorite

Chlorite occurs in the QD and IQD with biotite as an alteration product of amphibole. Chlorite is also found within chalcopyrite and at the margins of chalcopyrite veins. The composition of chlorite hosted within sulfides plots in the ripidolite field, with very little compositional variation. Chlorite found at the margin, and within nickeline veins forms in radiating fans, even in nickeline veins bordered by foliated massive biotite.

4.3.4 Epidote

Epidote in the IQD is most abundant surrounding fine disseminations of sulfides and at the margin of veins and veinlets. The epidote also tends to be located at the rim of sulfide blebs as well as discrete grains within sulfide, where it may be zoned, and have

allanite cores. Grains enclosed by sulfide are euhedral to subhedral, and epidote located at the margins of veins and blebs forms anhedral masses.

4.3.5 Apatite

Apatite grains are found throughout both the QD and IQD. They are most abundant in granophyre found in QD, but are found throughout the silicate matrix of both the QD and IQD. They form euhedral translucent elongate crystals, sometimes with opaque inclusions. No apatite was recognized within the sulfides in the IQD.

4.3.6 Garnet

Garnet was identified in two thin sections of massive and semi-massive sulfide. They form euhedral and subhedral grains adjacent to amphibole and biotite, and hosted in anhedral quartz within sulfide.

4.4 Mineral Chemistry

Of the silicates present in the IQD, amphibole and biotite can be found in association with sulfides of all textural types, as well as within IQD devoid of sulfides. For this reason they were analyzed using the microprobe (see appendix 1 for methods) for comparison. Binary plots (two variables), and ternary plots (three variables) were used to depict the compositional differences between textural type and proximity to massive sulfide. The samples were categorized by sulfide textural type (MASU, veins, etc.) and by the proximity to the orebody. Texturally, the Ni-rich massive sulfide had abundant and diverse silicates but typical massive sulfide had little to no (primary) silicates present.

For samples labeled "IQD away from orebody" there was less than 5% sulfide as disseminations and blebs. Samples labeled "IQD approaching orebody" had 5-8% sulfide as blebs and disseminations. The proximity to the orebody was known from drill core intersections (BH97-152-5). Samples listed as away from orebody, are from surface, away from any known concentrations of sulfide. The foliated IQD sample is similar in distance from the orebody as the "IQD approaching orebody" samples, however there is less sulfide present.

Other hydrous silicates were analyzed that were found in association with either sulfides or with PGM. Apatite was analyzed (including rare earth elements) from both the QD and the IQD for comparison. (Microprobe analyses on cd in back pocket)

4.4.1 Amphibole

The majority of the amphibole analyzed has a calcic composition (Fig. 4.1a). The amphibole from gabbro inclusions and from the gabbro country rock plot in the Fe-Mg-Mn field. Of the calcic amphibole analyzed most have $\text{Na}+\text{K}<0.5$ and $\text{Ti}<0.5$ and are classified together (Fig. 4.1b). Of these, amphibole from gabbro inclusions are Mg rich and fall in the actinolite field. Most amphibole analyzed from the IQD silicate groundmass plots as ferro-hornblende and ferro-tschermakitic-hornblende. The amphibole within and adjacent to chalcopyrite veins tends to have higher Fe contents and fall in the ferro-tschermakitic-hornblende field.

The calcic amphibole where $\text{Na}+\text{K} > 0.5$ plot in the ferro-pargasitic-hornblende range. These amphiboles are from MASU and INMS along with amphibole from foliated IQD (Fig. 4.2a).

The Fe-Mg-Mn amphibole plot in the cummingtonite field. These analyses are composed of gabbro inclusions and from gabbro country rock except one amphibole that is within the INMS (Fig. 4.2b).

Figure 4.3a demonstrates the negative correlation between Fe and Mg amongst the amphibole. It clearly displays the tendency for amphibole associated with sulfide (>5%) to be Fe-rich. Some amphibole within sulfide appears zoned with ferro-actinolite cores. The exception to this is in the foliated IQD which has similar Mg-Fe contents to MASU and INMS, but little sulfide associated with it. This figure also shows the Mg-rich composition of amphibole from both gabbro country rock and gabbro inclusions.

There is a positive correlation between Cl content and the Fe number (Fig. 4.3b), which also demonstrates that not only is the amphibole from sulfide rich zones Fe rich it is also Cl rich relative to amphibole in sulfide poor (<5%) IQD. The increase in sulfide content within the IQD is correlative with this trend.

Figure 4.4a) shows that the inclusions of gabbro and the gabbro country rock have similar Mg and Si contents. Two analyses of sulfide poor IQD (<5%) and two INMS specimens also plotted in the same vicinity. The amphibole from sulfide rich textures plot together (Fig. 4.4b). In this case there is an association of Si depletion with increased sulfide content. The analyses from foliated IQD have similar Si contents to the textures with abundant sulfide. In general there is a positive correlation between Mg and Si within amphibole.

Figure 4.5a demonstrates distinctions between the gabbro (inclusions and country rock) with the rest of the analyses. In general there is a positive correlation between Ti and Al for amphibole. Figure 4.5b has distinct groupings similar to 4.5a for the gabbro

analyses vs the sulfide textures however there doesn't appear to be any trend between the amphibole analyses from the gabbro inclusions and country rock with the rest of the amphibole.

Figure 4.6a,b shows amphibole mineral chemistry in relation to the distance from the orebody and clearly there are trends between increased Cl content (Fig. 4.6a) and sulfide abundance. There is a marked increase in Na+K content when the amphibole is located within massive semi-massive textures. As well increased Fe content (Fig. 4.6b) and sulfide abundance have a positive correlation as well.

4.4.2 Biotite

The analyzed biotite plots in the annite field (Fig. 4.7a). The biotite within gabbro inclusions approaches the phlogopite field while the MASU biotite has compositions closest to the ideal annite composition.

In general there is a clear increase in the Fe content of the biotite with proximity to massive sulfide (Fig. 4.7b). The biotite from the silicate groundmass is texturally different from the biotite hosted in massive sulfide, however there is the same trend found between biotite from the silicate groundmass of samples collected away from any known orebody and those from IQD approaching ore. The metagabbro inclusions are Mg rich relative to the biotite from the IQD and sulfide. Biotite located within the foliated IQD has Fe-Mg contents most similar to the biotite hosted in massive sulfide. The biotite found adjacent to the arsenide veins has an intermediate Fe-Mg-K composition relative to those from other textural types examined.

The biotite within the MASU has elevated Cl contents, followed by biotite in foliated IQD. There is a positive correlation between biotite hosted in the IQD (away from orebody) and those within the MASU. There is no correlation between biotite found bordering the arsenide veins or between the foliated IQD analyses when looked at separately. Considering that the biotite adjacent to the arsenide bearing veins is strongly foliated, it can be interpreted that there is a positive correlation of Cl and Fe number between foliated textures (Fig. 4.8a).

Figure 4.8b demonstrates the relatively uniform potassic content of the biotite, with a marginal increase with increased proximity to the orebody. This plot also shows the unique grouping of the biotite found in association with nickeline, which is depleted in Ti.

When examining the biotite of the silicate matrix of the IQD in comparison to the proximity to the orebody there are some clear trends. Figure 4.9a provides an example of how the biotite mineral content changes with proximity to the MASU. The Mg content decreases (Fe increases), and the potassium content mildly increases (1.7- 2.1 apfu). The increase in K occurs in the IQD with 5-8% blebby and disseminated sulfide that is several meters from RGDI and MASU. Also of interest is the wide range of Mg content displayed from the samples that were taken at surface (away from any known orebody). Figure 4.9b also provides a clear trend in the biotite mineral chemistry in relation to the distance from the orebody. The samples approaching ore are less Mg rich and have an increase in Na content. The biotite within the MASU does have the same trend with respect to Mg content, but it does not follow the same trend of increased Na for all samples.

4.4.3 Chlorite

The majority of chlorite analyzed plot in the ripidolite field (Fig. 4.10a). The chlorite analyzed from MASU all plot in the daphinite field. Figure 4.10b demonstrates the negative correlation in the chlorite between Fe and Mg (apfu). As with other minerals, the mineral chemistry of chlorite shows an increase in Fe content (and decrease in Mg content) approaching the orebody. As well, the gabbro inclusions, and gabbro country rock are Mg rich relative to the other chlorite analyses. The arsenide bearing veins have an intermediate Fe-Mg composition.

Figure 4.11a is a ternary plot of trace metals found in chlorite. The gabbro inclusions and gabbro country rock have compositions distinct from the rest of the chlorite. The binary plot Ti (apfu) vs Fe number (Fig. 4.11b) demonstrates the distinct difference between the arsenide veins. It also displays the negative correlation ($m = -0.053$) between Ti and Fe number for chlorite away from the orebody, to chlorite approaching the orebody, to chlorite within MASU.

All chlorite contains Ni (Fig. 4.12a). Chlorite from one of the nickeline bearing veins has the widest range in Ni contents (0.59 - 0.21 wt%) and the smallest variation in Ti content (0.00 - 0.02 wt %). The other nickeline bearing vein does not have chlorite with the same variation in Ni and Ti contents. In general there is not a wide range in Ni content (0.33- 0.14) for the rest of the analyses, but there is some diversity in the Ti contents (0.00 - 0.19 wt %). Figure 4.12b displays the difference between Cu-rich veins and As-rich veins, where the chlorite within Cu-rich veins have higher Cl contents and than the As bearing veins. Also apparent is the Cl rich analyses of the massive sulfide

with large pentlandite megacrysts. See appendix 2 for entire trace metal comparison among chlorites.

4.4.4 Apatite

The apatite analyzed by the microprobe was from two different locations. From the barren QD located at surface and from IQD with 5% sulfide approaching the orebody. The apatites have similar Cl/F ratios (Fig. 4.13a), with the IQD apatites having less F (1.32-1.38 apfu) than the apatite from the QD (1.30-1.58 apfu). Figure 4.13b plotting Ca vs Na does show a clear difference in the mineral chemistry between apatite from QD and apatite from IQD. QD apatite has an increased Ca content (9.962- 9.995 apfu) relative to the IQD apatite (9.901- 9.960 apfu), while half of the IQD apatite analyses have a markedly enriched Na content (0.032 and 0.077 apfu). Other major elements that differ within the apatite mineral chemistry are Fe, Si, and P. These elements are plotted in figure 4.14a showing the QD apatite are phosphorous rich, and silica and iron poor in comparison with IQD apatite. Trace element data from the apatite analyses (Fig. 4.14b) demonstrates that Nd is present in all of the QD apatite, but is only detected in one IQD analysis. The IQD apatite are also void of Sr (fig 4.15), while all but one QD analyses detected Sr. This figure shows that the IQD apatites have S within their structure while all but one of the QD apatites have no S.

Figure 4.1. A) General classification of amphibole (apfu)
 B) Classification of calcic amphibole ($\text{Na}+\text{K} < 0.5$; $\text{Ti} < 0.5$), refer to text

Figure 4.2. A) Classification of calcic amphibole $\text{Na}+\text{K} > 0.5$; refer to text

B) Classification of Fe-Mg-Mn amphibole

Figure 4.3. A) Binary plot of amphibole Mg vs Fe in relation to sulfide textural type B) Cl (apfu) vs Fe number of amphibole displays clear trend in relation to distance from MASU

Figure 4.4. Amphibole mineral chemistry in relation to sulfide textural type A) Binary plot of Mg vs Si (apfu) B) Binary plot of Na+K vs Mg (apfu)

Figure 4.5. Amphibole mineral chemistry in relation to texture
 A) Binary plot of Ti (C site apfu) vs Al (T site apfu)
 B) Binary plot of Cr (C site apfu) vs Al (T site apfu)

Figure 4.6. Amphibole mineral chemistry in relation to distance from MASU A) Binary plot of Cl (apfu) vs Na+K B) Binary plot of Fe (apfu) vs AL (T site apfu)

Figure 4.8. Binary plots of biotite in relation to sulfide texture
 A) Cl (apfu) vs Fe number displays Cl-Fe-rich biotite from massive sulfide B) Ti (apfu) vs K (apfu) displays distinct composition of arsenide bearing veins

Figure 4.9. Binary plots of biotite in proximity to MASU

A) Ti (apfu) vs Mg (apfu) B) Na (apfu) vs Mg number

A)

B)

Figure 4.10. A) Classification of chlorite B) Chlorite mineral chemistry binary plot of Fe vs Mg displaying marked increase in Fe content of massive sulfide and chalcopyrite veins

A)

B)

Figure 4.11. A) Ternary plot of chlorite Cr-Mn-Ti demonstrating the distinct composition of the gabbroic country rock and gabbro inclusions B) Chlorite Ti vs Fe number with regression line through chlorite analyses in relation to distance from orebody

Figure 4.12. Chlorite mineral chemistry A) Binary plot of NiO vs TiO₂ all chlorite contain some Ni B) Binary plot of Cl# vs NiO (wt%) displays distinction between Cu-rich veins and As-rich veins

Figure 4.13. Apatite mineral chemistry A) Binary plot of F vs Cl (apfu) displays no difference between quartz diorite and inclusion quartz diorite B) Binary plot of Na vs Ca (apfu) reflecting Ca-rich quartz diorite apatite

Figure 4.14. Apatite mineral chemistry A) Minor elevated P values in the quartz diorite B) Nd bearing quartz diorite apatite in contrast to apatite from inclusion quartz diorite devoid of Nd

Chapter 5: Sulfides

5.1. Introduction

Sulfides from the Totten property have been sampled in two different areas: first from outcrop encountered during surface mapping as previously discussed, and from drill core obtained from INCO Ltd. Spatial relationships to the QD, IQD and inclusion population were documented in large part from the surface mapping and then compared with drill core intersections. While chapter 3 made brief mention of sulfide location, mineralogy and texture it was based all on field observations. This has limits due to the weathering and the surface exposure of any area. This chapter will include observations made from hand samples and thin sections from both surface and drill core samples as well as data collected using the microprobe (see appendix for methods).

5.2. Ore Textures

The sulfide textures described can be observed from the hand sample scale. There are 6 main groupings; massive sulfide (MASU), inclusion massive sulfide (INMS), ragged disseminated sulfide (RGDI), blebby sulfides (BLBS), disseminated sulfides (DIS), and sulfide veins and veinlets. In the map area DIS and sulfide veins are visible at surface. One hundred and fifty metres to the north east, the Worthington Pit has MASU, INMS, DIS, BLBS, and veins visible at surface. The majority of the samples studied composed of MASU, INMS, RGDI, BLBS, DIS, and veins are from drill core intersections of the Totten ore body at depth.

5.2.1. Massive Sulfide / Inclusion Massive Sulfide

The massive /semi-massive sulfide assemblage is predominantly pyrrhotite, with variable amounts of pentlandite and chalcopyrite. Some massive sulfide zones are Fe-Ni rich with pentlandite megacrysts up to 3cm in diameter (Plate 5.1a). Some of these large pentlandite “eyes” are found in banded massive sulfide (Plate 5.1b). There is 5-25% chalcopyrite present and little to no quartz in the banded massive sulfide. In contrast other massive sulfide zones contain large amounts of Cu (40-75% chalcopyrite). The copper rich massive sulfide also has abundant quartz (10-20%) and galena (0- 5%) (Plate 5.1c).

Both Fe-Ni and Cu rich massive sulfides may contain up to 50% inclusions forming the texture inclusion massive sulfide (INMS) (Plate 5.1d). These inclusions range in size from millimeters to tens of centimeters. While there are larger inclusions adjacent to accumulations of massive sulfide, the inclusion massive sulfide texture implies inclusions hosted within massive sulfide. The inclusion types are similar in composition to the inclusions found in the IQD, with fewer metasedimentary inclusions and no granitic gneiss inclusions. Massive and semi-massive sulfides are spatially associated with gabbro inclusions between 25cm and 2m in diameter. INMS most often displays the association of the chalcopyrite with the inclusions (see chapter 5.3.4).

5.2.2. Veins

The sulfide veins are predominantly composed of chalcopyrite. The Cu rich veins may be further subdivided into two groups: chalcopyrite rich veins that contain pyrrhotite and pentlandite, generally located in the center of the vein (Plate 5.2a), and a group of

chalcopyrite veins that does not contain significant pyrrhotite or pentlandite but contains abundant quartz (Plate 5.2b). These veins contain sphalerite and galena as well as argentian gold. Both types of Cu rich sulfide veins host abundant PMM and cobaltite/gersdorffite. These chalcopyrite veins cross cut IQD and gabbro inclusions. These Cu rich veins have primary hydrous silicates throughout and are particularly abundant at the margins of the veins.

Pyrrhotite veins are much less common, but are found in close proximity to large accumulations of sulfide. These veins tend to have pentlandite in the center (Plate 5.2c). In some instances these veins have a halo of finely disseminated pyrrhotite surrounding the vein up to two centimeters thick (Plate 5.2d).

Sulfides also occur in quartz carbonate veins and veinlets throughout the IQD, QD, and sedimentary country rock. However, they are most prominent where they cross cut the QD-sedimentary rock contact. These veins and veinlets contain chalcopyrite and pyrrhotite.

5.2.3. Disseminated and Blebby Sulfides

The disseminated (DIS) and blebby (BLBS) sulfide is most often located around a massive/semi-massive sulfide zone, within IQD. The blebs are spherical and average 0.5-2cm in diameter. They can compose up to 25% of the rock, but tend to only account for 10% on average. They are pyrrhotite rich with occasional pentlandite flames. In some instances the pyrrhotite rich blebs have a chalcopyrite rim, or are composed entirely of chalcopyrite. The blebby texture can also be deformed demonstrated by elongate blebs of both pyrrhotite and chalcopyrite composition alongside elongate inclusions, hosted in

foliated IQD (Plate 5.3a). Rare chalcopyrite rich disseminations are found in the QD. These disseminations are often accompanied by quartz & carbonate and never exceed 5%.

Disseminated sulfide is the most common sulfide texture found throughout the IQD. Its composition varies from Fe rich to Cu rich. As with the blebby texture the disseminations increase in abundance toward the massive sulfide accumulations.

In close proximity to the massive inclusion/inclusion clusters the disseminated texture grades into a ragged disseminated texture (RGDI) with increasing abundance of sulfide. (Plate 5.3b) The term ragged disseminated texture is used here to describe sulfide abundances greater than 10% with abundant disseminations and in places interconnecting anhedral sulfide masses by veinlets of sulfide. Compositionally this texture can vary from close to 100% chalcopyrite through to a strict pyrrhotite + pentlandite assemblage.

5.3. Mineralogy

The petrography of the sulfides and type of textures were determined using polished slabs, a reflected light microscope, and in certain cases the electron microprobe.

5.3.1. Pyrrhotite

Pyrrhotite (Fe_{1-x}S) is the most abundant sulfide mineral present in the Totten ore. It occurs in all texture types. It is the predominant sulfide in MASU, INMS, RGDI, BLBS, and DIS. Pyrrhotite is host to the majority of the pentlandite as well as host to significant amounts of chalcopyrite.

Previous studies of the Sudbury ores (Rickard, 2000; Magyarosi, 2002) have revealed the presence of both polytypes of pyrrhotite (hexagonal and monoclinic). Batt (1972) described the variation in the nickel content according to the crystallography of the pyrrhotite from Sudbury ores. Batt showed that the hexagonal pyrrhotite contained 0.3-0.5wt% more Ni than the monoclinic pyrrhotite. Of 25 microprobe analyses from Totten, 7 display Ni content of monoclinic pyrrhotite and 6 display a Ni content of hexagonal pyrrhotite. The rest of the analyses have a Ni content intermediate to both polytypes (Fig. 5.1).

Qualitative observation of the pyrrhotite polytypes was performed on massive sulfide, Ni-rich massive sulfide, pyrrhotite in chalcopyrite veins, blebs, pyrrhotite associated with nickeline veins, and deformed RGDI pyrrhotite-rich sulfide using a magnetic colloid (see Craig and Vaughan, 1981). The Ni-rich massive sulfide had a marked decrease in the amount of monoclinic pyrrhotite (10-20%) compared to the average massive sulfide (~50%) (Plate 5.4a,b). Pyrrhotite from blebs, chalcopyrite veins and from typical massive sulfide had increases in the abundance of monoclinic pyrrhotite at the contact of pentlandite megacrysts, and near chalcopyrite grains (Plate 5.4c). There was an increase in the monoclinic pyrrhotite adjacent to a cobaltite grain, but no increase around a tsumoite grain (Plate 5.4b). The intergrowths of pyrrhotite display boxwork texture (Plate 5.4d) and composite lamellae, as seen in the aligned intergrowths.

The intergrowths of the monoclinic and hexagonal pyrrhotite display deformational textures (Clark and Kelly, 1973; Lianxing and Vokes, 1996). In the Ni-rich massive sulfide there is kink banding and in deformed RGDI there are aligned

intergrowths (Plate 5.5a,b). These deformational features have been documented in Sudbury by Magyarosi et al. (2002) from Copper Cliff South mine ore.

5.3.2. Pentlandite

Pentlandite (Fe_9S_8) is the most abundant Ni mineral in the Sudbury ores, and is the predominant ore mineral in the South Range of the SIC. Pentlandite occurs in all of the textures including Cu rich stringers. Pentlandite is found in two habits. Anhedral masses or semi rounded rosettes within pyrrhotite and lesser amounts in chalcopyrite, and also as exsolution "flames" within pyrrhotite and chalcopyrite.

Large grains of pentlandite were first reported from the Worthington mine by Barlow (1901). The anhedral masses are most common in pyrrhotite and in some cases are found in pyrrhotite rich layered sulfide. These grains of pentlandite (1mm-3cm) display distinctive octahedral parting (Plate 5.6a). The pentlandite found within the layered sulfide commonly has chalcopyrite at the edges and within fractures of the pentlandite. Less common are pentlandite rosettes within chalcopyrite rich veins, which most often occur in the center of the vein and in contact with pyrrhotite (Plate 5.6b).

In some massive sulfide textures, pentlandite is found as a continuous rim around pyrrhotite grains (Plate 5.6c). These rims often terminate or originate at larger rosettes of pentlandite. Naldrett (1984) described this texture from Sudbury ore and stated that it was hexagonal pyrrhotite that the pentlandite exsolved from and now rims.

Pentlandite flames (<1mm-3mm) are found throughout the pyrrhotite rich sulfides. They most often extend from fractures and grain boundaries within the

pyrrhotite, or at the boundary of chalcopyrite with pyrrhotite. The flames are also common within chalcopyrite but take on a more dendritic appearance. (Plate 5.6d)

5.3.3. Argentopentlandite

Argentopentlandite $\text{Ag}(\text{FeNi})_8\text{S}_8$ is common, though much less abundant than the pentlandite. Argentopentlandite is most commonly hosted in chalcopyrite and appears as small irregular exsolutions and as lamellae, often associated with pentlandite. When hosted in chalcopyrite, the argentopentlandite is found adjacent to similar lamellae of pyrrhotite (Plate 5.7a). It is also found in pyrrhotite and within nickeline bearing veins. The rare argentopentlandite observed within the nickeline bearing veins is small ($50\mu\text{m}$) anhedral masses at grain boundaries of chalcopyrite, pyrrhotite, cobaltite/gersdorffite and nickeline (Plate 5.7b).

5.3.4. Chalcopyrite

Chalcopyrite (CuFeS_2) is the most abundant copper mineral in the Totten sulfides, and occurs in all types of ore textures. It is most often found in vein and veinlet textures, both cross cutting sulfides and silicate assemblages. These textures that suggest the chalcopyrite was a late stage (last to crystallize or remobilized after crystallization) have been reported throughout the SIC eg. (Farrow and Watkinson, 1992; Everest, 1999; Magyarosi et al., 2002). In the Totten ore chalcopyrite frequently forms large crystals (1-2cm) that are recognizable by their twinning (Plate 5.7c). Not only does the chalcopyrite form in textures that cross cut sulfide assemblages, but it occurs in textures which indicate that it has replaced other sulfides. The chalcopyrite blebs are interpreted to have

formed by pyrrhotite rich blebs forming and then later being replaced by reacting with a Cu rich fluid. (Plate 5.7d)

Chalcopyrite is host to the majority of PGM (see chapter 7 for detailed description of PGM) as well as host to most sphalerite and galena. In pyrrhotite rich sulfides chalcopyrite often partially rims pentlandite eyes. It is also commonly found within fractures of inclusions. Rickard (2000) observed this relationship and suggested the affinity to the inclusions is due to hydrothermal remobilization of Cu and that brecciated/fractured inclusions provide permeability for this fluid. Another explanation for the association with inclusions is the difference in strength of the chalcopyrite relative to the other sulfides and surrounding silicates. Because it is ductile at lower P and T than the surrounding minerals it can flow into regions of less strain if a stress is applied, such as fractures within an inclusion or develop in a pressure shadow created by an inclusion in massive sulfide (McQueen, 1987).

Chalcopyrite occurs with hydrous silicates (amphibole, chlorite, epidote and biotite) in veins and in RGDI textures. These silicates are distributed throughout the chalcopyrite, but are most abundant at the edge of the veins.

5.3.5. Sphalerite

Sphalerite (ZnS) is not an abundant sulfide mineral in the Totten ore (<1%). It is most common as an accessory mineral in the Cu rich veins and veinlets. It is associated with galena and quartz. The small anhedral grains of sphalerite are also in close proximity to the argentian gold grains in the chalcopyrite veins. Unlike sphalerite from the Copper Cliff North Mine, no exsolution stars of sphalerite in chalcopyrite have been

observed (Rickard, 2000), nor has sphalerite been observed as late stage veins as in other Sudbury deposits (Owen and Coats, 1984; Everest, 1999).

Sphalerite also occurs (>1%) in nickeline bearing veins. It is often located at the arsenide-sulfarsenide-sulfide contacts (Plate 5.8a).

5.3.6. Galena

Galena (PbS) is similar in occurrence and in concentrations to sphalerite. It is an accessory mineral located in chalcopyrite + quartz veins and semi-massive sulfide. Macroscopically visible concentrations of galena were only observed from samples collected at the edge of the Worthington Pit. Galena has been observed in association with tsumoite and hessite within chalcopyrite veins. It is also attached to, and near, Au found in chalcopyrite veinlets along with above average concentrations of sphalerite (Plate 5.8b).

5.4. Mineral Chemistry

This section will concentrate on data collected using the electron microprobe (see appendix 1 for methods, data on cd in back pocket). The results will be compared amongst different textural types as well as being related spatially to the ore body.

5.4.1 Pyrrhotite

The abundance and spatial distribution of pyrrhotite allows its compositional variation to be compared and contrasted amongst all textural types. While the Fe and S contents display a negative correlation (Fig. 5.2a) there is no correlation evident between

Ni and S (Fig. 5.2b) or Ni and Fe (Fig. 5.2c). MASU and Fe rich veins vary in Ni content from 0.2- 0.8 atomic %. This variation in Ni content may be attributed to the different polytypes of pyrrhotite (see chapter 5.2.1.). Blebby and disseminated pyrrhotite has only one analysis of 0.5 atomic % and the rest of the analyses having a Ni content of 0.4 atomic %. While the blebby sulfides have a consistent Ni content, they have the largest variation in Fe content (46.2- 47.7 atomic %). Pyrrhotite analyzed from a nickeline vein has the highest sulfur content (53.7 atomic %) and the lowest Fe content (45.9 atomic %).

The pyrrhotite grains which occur near pentlandite have a slight increase in Fe content relative to grains away from pentlandite and grains hosted within pentlandite (Fig. 5.3). The pyrrhotite grain hosted in pentlandite is enriched in nickel, whereas pyrrhotite adjacent to pentlandite has a range in Ni content from 0.2 – 0.6 atomic % (Fig. 5.3).

5.4.2. Pentlandite

Similar to pyrrhotite in spatial distribution and abundance, pentlandite compositions can be compared amongst textural types. Pentlandite most frequently contains 6.0-6.2 atomic % Co (Fig. 5.4a) and 27.4-27.8 atomic % Ni (Fig. 5.4b).

Two different massive sulfide types were compared. MASU1 (Fig. 5.5a) has 20-30% pentlandite associated with biotite + chlorite 6 stilpnomelane, 5-8% chalcopyrite, > 5% inclusions and the remainder pyrrhotite. The second MASU2 (Fig. 5.5b) has 15% pentlandite, 5% inclusions, 5% chalcopyrite and the remainder is pyrrhotite. As well, pentlandite compositions from BLBS, DIS, RGDI and from a nickeline bearing vein have been compared.

Figure 5.6a displays the variation in the pentlandite composition. MASU1 has a wide range in composition relative to MASU2, in particular the Fe-Ni content. Pentlandite from BLBS also has a wide range of Fe and Ni. The pentlandite analyzed from the nickeline bearing vein has a similar Fe-Ni content to that from other textural types, but it has no Co.

Figure 5.6b) shows the RGDI (Po vein) analyses are slightly depleted in S in comparison with most textural types. Again this binary plot shows that the MASU1 samples have the widest array of compositions, both in Fe content and in S content. The pentlandite analyzed from the nickeline bearing vein does not have an extreme composition relative to the other textures, but it does not plot within any of the groupings seen with the other textures.

The pentlandite composition also has variation relative to its own texture (rosette, flame, veinlet). Figure 5.7a displays the increased Co and Ni content of pentlandite rosettes, as well the variation in the Co and Ni composition of the flames. Figure 5.7b displays a similar distribution of mineral chemistry but also shows the pentlandite veinlet has less S than most of the flames analyzed, and less Co than the rosettes analyzed. Figure 5.8a displays a negative correlation between Fe and Ni for the flame texture and a positive correlation with the rosette texture. Figure 5.8b has a negative correlation between Fe and S for the rosette textured pentlandites and a positive correlation for the flame textured pentlandites.

5.4.3. Argentopentlandite

The composition of argentopentlandite from RDGI sulfides and from a nickeline bearing vein were analyzed. Both have the same general composition, with the argentopentlandite from the arsenic vein slightly enriched in Ag relative to the other analyses (Fig. 5.9a). The RDGI argentopentlandites have a depleted sulfur content relative to the nickeline bearing vein analyses (Fig. 5.9b). Both groups of argentopentlandites have a negative correlation with Ni and Ag (Fig. 5.10a) and a positive correlation between Fe and Ag (Fig. 5.10b). This trend has been observed in sulfides from the Copper Cliff South mine (Magyarosi, 2002).

The general composition of argentopentlandite is similar to grains analyzed at the Copper Cliff South Mine and the North Mine. In comparison with the grains analyzed by Magyarosi (2002) there is not as wide a range in compositions.

Plate 5.1 Photomicrographs of sulfide textures.

Plate 5.1a Nickel rich massive sulfide with visible pentlandite megacryst hosted in pyrrhotite displaying variable oxidation intensities. Sample tot-79

Plate 5.1b Layered massive sulfide having a foliation defined by alternating layers of chalcopyrite and pyrrhotite. Pentlandite megacrysts are also present. Sample WP-2

Plate 5.1c Chalcopyrite and quartz rich massive sulfide from the Worthington Pit. Galena visible at the hand sample scale. Lesser amounts of pyrrhotite present as well. Sample WP-1

Plate 5.1d Pyrrhotite-rich inclusion massive sulfide, with abundant gabbro inclusions. Sample tot-41

Plate 5.2 Photos of sulfide textures.

Plate 5.2a Pentlandite and pyrrhotite located in the center of a chalcopyrite vein in IQD. Sample tot-63

Plate 5.2b Chalcopyrite vein with quartz inclusion and splintering chalcopyrite veinlet which terminates in carbonate. Argentian gold located at sulfide carbonate transition. Sample tot-45

Plate 5.2c Variably oxidizing pyrrhotite rich vein containing pentlandite in the center hosted, in IQD. Sample tot-55

Plate 5.2d Pyrrhotite vein with finely disseminated pyrrhotite halo hosted in IQD. Pentlandite located in the center, and chalcopyrite replacing pyrrhotite. Sample tot-77

Plate 5.3 Photos of sulfide textures.

Plate 5.3a Deformed (elongate) blebby sulfide hosted in IQD. Abundant amphibolite chips are also deformed. Sample tot-73b

Plate 5.3b RGDI pyrrhotite rich sulfide in IQD. Chalcopyrite and pentlandite at edge of sulfide accumulation. Sample tot-87b

Figure 5.1. Histogram of Ni wt% in pyrrhotite analyses related to monoclinic and hexagonal polytypes.

Plate 5.4 Photomicrographs of pyrrhotite intergrowths.

Plate 5.4a 5-10% monoclinic pyrrhotite, hosted in Ni-rich massive sulfide near pentlandite megacryst. Sample tot-84a, field of view ~1mm.

Plate 5.4b 50% monoclinic pyrrhotite in massive sulfide. No change in pyrrhotite ratio around tsumoite grain. Sample tot-83, field of view ~1mm.

Plate 5.4c Increase in monoclinic pyrrhotite at contact of chalcopyrite. Pentlandite exsolutions in chalcopyrite. Intergrowths display minor boxwork texture near contact with chalcopyrite, and two sets of composite lamellae away from contact. Sample tot-83, field of view ~1mm.

Plate 5.4d Boxwork texture in massive sulfide near pentlandite. Sample tot-80, field of view ~1mm.

Plate 5.5 Photomicrographs of pyrrhotite intergrowths.

Plate 5.5a ~50% monoclinic and hexagonal pyrrhotite in massive sulfide. Kink banding within ellipse. Sample tot-154-5c. field of view ~0.5mm.

Plate 5.5b Aligned intergrowths of monoclinic pyrrhotite. Sample tot-49b, field of view ~1mm.

- Plate 5.6** Photomicrographs and photo of sulfide mineralogy.
- Plate 5.6a Semi-rounded pentlandite megacryst (octahedral parting) hosted in pyrrhotite located within massive sulfide. Sample tot-84a, field of view ~4mm.
- Plate 5.6b Pentlandite rosette in center of chalcopyrite vein adjacent to pyrrhotite. Sample tot-83.
- Plate 5.6c Pentlandite rim around pyrrhotite grain in massive sulfide. Sample tot-84a, field of view ~4mm.
- Plate 5.6d Pentlandite flame hosted in pyrrhotite. Sample tot-84b, field of view ~1mm.

- Plate 5.7** Photomicrograph and BSE images of sulfide mineralogy.
- Plate 5.7a** BSE image of argentopentlandite and pyrrhotite exsolutions in chalcopyrite. Sample tot-16.
- Plate 5.7b** BSE image of an argentopentlandite grain at the arsenide-sulfarsenide-sulfide interface. Sample tot-4188.
- Plate 5.7c** Large chalcopyrite crystals in chalcopyrite vein hosted in IQD. Sample tot-45.
- Plate 5.7d** Chalcopyrite rich disseminations and blebs hosted in fine grained IQD. Sample tot-87b.

Plate 5.8 BSE image and photomicrograph of sulfide mineralogy.

Plate 5.8a BSE image of sphalerite grain at arsenide-sulfarsenide contact, hosted in a nickeline rich vein, adjacent to an unnamed Pd-Sb-Bi-Te mineral (PGM1). Sample tot-154

Plate 5.8b Photomicrograph of abundant sphalerite and galena associated with argentian gold grains, hosted in a chalcopyrite vein. Sample tot-45, field of view ~1mm.

Figure 5.2. Binary plots of pyrrhotite mineral chemistry in relation to textural type.
 A) Negative correlation between Fe and S B) No correlation between S and Ni
 C) No correlation between Fe and Ni

Figure 5.3. Binary plot pyrrhotites in relation to pentlandite A) atomic % Fe vs S showing po slightly depleted in Fe when located away from pn B) atomic % Fe vs Ni displays moderate increase in Ni content when located away from pn

Figure 5.4. A) Histogram of cobalt content of pentlandite
B) Histogram of Ni content of pentlandite

Figure 5.5. A) MASU1 - massive pentlandite and lesser pyrrhotite and chalcopyrite
 B) MASU2 predominantly pyrrhotite with pentlandite and lesser amounts of quartz

Figure 5.6. Mineral chemistry of pentlandite. A) Ternary plot of Fe-Ni-Co (atomic %) displays wide variation in MASU1 composition as well as Co free pentlandite from an arsenide bearing vein B) Binary plot of Fe vs S (atomic %) displays the same variable MASU1 compositions and S-poor pentlandite from po vein

Figure 5.7. Pentlandite mineral chemistry in relation to crystal habit
 A) Binary plot of Fe vs Co atomic % displays positive correlation between Co and Ni with rosettes being Ni -rich B) Binary plot of Co vs S atomic % displays a negative correlation where the rosettes are slightly elevated in Co and S poor.

Figure 5.8. Pentlandite mineral chemistry in relation to crystal habit
 A) Binary plot of Fe vs Ni (atomic %) displays a positive correlation for rosettes and a negative correlation for flames B) Binary plot of Fe vs S (atomic %) displays a negative correlation for rosettes and a positive correlation for flames.

Figure 5.9. A) Fe-Ni-Ag ternary plot of argentopentlandite (at %) displays argentopentlandite from an As-rich vein slightly elevated in Ag
 B) S-poor composition of argentopentlandite from RGDI texture

Figure 5.10. Argentopentlandite mineral chemistry. A) Binary plot of Ag vs Ni displays a negative trend B) Binary plot of Ag vs Fe also displays a negative trend

Chapter 6: Mineralogy and Composition of Sulfarsenides and Arsenides

6.1 Introduction

Sulfarsenides and arsenides have been found in association with ore deposits world wide. Examples include nickeline and maucherite from Fe-Ni-Cu ores hosted in lherzolite massifs of Morocco and Spain (Gervilla et al., 1996), gersdorffite, nickeline, maucherite in the Hitura nickel deposit Finland (Hakli et al., 1976), sulfarsenides and arsenides associated with the silver deposits of the Cobalt/Gowganda region (Misra and Fleet, 1975), zoned gersdorffite (Ixer et al., 1979), and nickeline has been found at the Lady's Rake Mine in the North Pennines, England (Young et al., 1985), cobaltite-gersdorffite associated with rhodium and osmium from the Lakkulaisvaara layered intrusion Russia (Barkov et al., 1996), cobaltite occurs in the Mount Isa lead-zinc ores in Australia (Croxford, 1974), cobaltite-gersdorffite associated with pyrrhotite and pentlandite in spessartite sills from southern France (Beziat et al., 1996), cobaltite-gersdorffite within a chromite vein in the Outokumpu deposit, Finland (Klemm and Weiser, 1965), PGM are associated with sulfarsenides in the Las Aguilas Ni-Cu-PGE deposit of Argentina (Gervilla et al., 1997), and gersdorffite associated with uranium mineralization in the Zimmer Lake area of northern Saskatchewan, Canada (Watkinson et al., 1975). Clearly the sulfarsenide/arsenide minerals can be found in several different geologic environments and deposit types.

Within the SIC, arsenic is found in ores from the south range but has not been reported in the north range (Hawley and Stanton, 1962) apart from sperrylite. Gersdorffite (NiAsS), cobaltite (CoAsS), nickeline (NiAs) and maucherite ($\text{Ni}_{11}\text{As}_8$) are

the arsenic bearing minerals observed in this study as well as the PGM sperrylite, which will be discussed in detail in chapter 7.

Arsenic bearing minerals have been previously reported in the Totten area by Barlow (1901), Walker (1915), Lausen (1930), and Hawley et al. (1961). Walker and Lausen interpreted the arsenide/sulfarsenide minerals to have formed in late stage processes. Hawley disagreed and placed the formation of the arsenic bearing assemblages as part of the earliest primary magmatic stage of ore formation (Hawley, 1962).

6.2 Textures

Arsenic minerals occur in two different textural types: discrete grains of cobaltite and gersdorffite hosted within sulfides, and as veins and veinlets of nickeline +cobaltite /gersdorffite $\pm$ maucherite with minor silicates (quartz, chlorite, biotite, $\pm$ carbonate).

6.2.1 Discrete Grains

Only sulfarsenides were found (no arsenides) as discrete grains within sulfides and at sulfide/silicate contacts. The discrete grains of cobaltite and gersdorffite are most abundant in chalcopyrite veins (Plate 6.1a), but have been observed in pyrrhotite rich sulfides as well. Cobaltite (CoAsS) and gersdorffite (NiAsS) form euhedral to subhedral grains; in some instances these grains contain sperrylite near their centers (Plate 6.1b). (See chapter 7 for detailed PGM description)

The cobaltite/gersdorffite grains are often attached to hydrous silicates, quartz, tellurides, and oxides when hosted in sulfides (Plate 6.1c). The silicates that are found attached to the sulfarsenides include chlorite, amphibole, epidote, and biotite.

6.2.2 Zonation

Zoned cobaltite/gersdorffite grains have been observed in South range deposits of the SIC previously by (Cabri and Laflamme, 1976), (Cabri, 1988) from 6 south range deposits. Stewart (1999), Szentpeteri (1999), Carter (2000), Rickard (2000), and Magyarosi (2002) all observed zoned grains from the Copper Cliff Offset. The grains tend to have a Ni rich core and Co rich rim (Stewart, 1999; Carter, 2000; Rickard, 2000). However Magyarosi (2002) noted that the sulfarsenide grains from the Copper Cliff South Mine had a Ni rich core and Co rich rim if they were barren of any PGM and that PGM bearing grains had Co rich cores and Ni rich rims.

PGM bearing sulfarsenides from the Mount General'Skaya Layered intrusion have compositional zoning as well (Barkov, 1999). Two distinct types of zones were documented. Type 1 zones have varying amounts of PGE, As/S and Co-Ni. Type 2 zones have varying compositions of Co-Ni with a distinct PGM in the core of the grains. Barkov also noted an intermediate zonation of both type 1 and type 2 patterns. These zonations within sulfarsenides are interpreted to be primary and not a product of alteration. In comparison, the recent work on sulfarsenides from the SIC, Szentpeteri (1999) documented intermediate type 1-type 2 zones, while Stewart (1999), Carter (2000), Rickard (2000) found type 2 zones and Magyarosi (2002) found type 2 zones and rare intermediate type 1/type 2 zones.

The discrete grains from the Totten property can be zoned with respect to their Co-Ni content. The zones have well defined contacts that appear to follow crystal faces (Plate 6.1d). As previously described the cobaltite-gersdorffite grains can also contain PGM in the core, but no PGE zonation within cobaltite-gersdorffite grains was observed. From quantitative microprobe analyses, the zonation results in the following changes in mineral chemistry: Co rich core to Co poor (Ni rich) rim of the grain fig. 6.1a. Unlike grains from the (Barkov, 1999) study, there does not appear to be a correlation between As/S with Co/Ni (Fig. 6.1b).

6.2.3 Veins

The arsenide and sulfarsenides found within veins are predominantly composed of nickeline with varying abundances of cobaltite, gersdorffite, $\pm$ maucherite.

Nickeline occurs as veins and veinlets in both QD and IQD. The veins and veinlets are most abundant in close proximity to large accumulations of sulfide. The veins range up to 3cm thick. These veins and veinlets are primarily composed of nickeline with minor pyrrhotite and chalcopryrite (Plate 6.2a), but some veinlets are primarily composed of quartz and carbonate with minor amounts of nickeline (Plate 6.2b). The latter is the most common occurrence, and in places these arsenide-bearing veins and veinlets cross cut chalcopryrite veins (Plate 6.2c).

The veins of arsenides and sulfarsenides display similar mineral associations. Often the sulfarsenides are associated with silicates (quartz, chlorite, $\pm$ biotite, $\pm$ epidote). These sulfarsenides are surrounded, or adjacent to the nickeline $\pm$ maucherite.

6.2.4 Sulfarsenide Rim

The nickeline that is in contact with sulfide (pyrrhotite, chalcopyrite) often has a rim of gersdorffite (~10µm thick) (Plate 6.3a). At the contact between the gersdorffite rim and the nickeline is often where the unnamed PGM is located. The gersdorffite is anhedral-subhedral with no inclusions or visible zoning.

6.2.5 Replacement Textures

The cobaltite-gersdorffite grains are often replaced by nickeline or maucherite within the nickeline veins (Plate 6.3b,c). The grains that are replaced are distinct grains, and not sulfarsenide that forms the "rim texture" at the contact of the arsenides with the sulfides.

6.2.6 Nickeline Blebs

In two of the nickeline veins (composed of chalcopyrite, nickeline, and pyrrhotite) the nickeline displays a rounded "bleb" like texture (Plate 6.3d). These round grains of nickeline are found in association with pyrrhotite. Due to the nickeline's weak pleochroism these spherical blebs are also visible within larger anhedral masses of nickeline, and are also visible due to preferential weathering of the anhedral masses of nickeline.

6.3 Mineralogy

There are five arsenic bearing minerals that have been identified at the Totten property in this study: cobaltite, gersdorffite, nickeline, maucherite and sperrylite.

Cobaltite and gersdorffite are considered together due to the apparent solid solution between them. The cobaltite-gersdorffite grains are more widespread than the nickeline (with minor maucherite), but nickeline is locally more abundant, forming veins.

6.3.1 Cobaltite-Gersdorffite

Cobaltite and gersdorffite occur as discrete grains and as rims around the nickeline (Plate 6.4a). The discrete grains are euhedral, and are bright white in reflected light. They occasionally contain inclusions of chalcopyrite, pyrrhotite and nickeline. Some discrete grains contain PGM in the centers and some have compositional zoning with respect to their Fe-Ni-Co content.

Cobaltite and gersdorffite found as a rim around nickeline, is anhedral to subhedral. It has the same white colour in reflected light as the discrete grains, but it does not contain any inclusions or zonation.

6.3.2 Nickeline

Nickeline is only found in the vein textures as previously described in chapter 6.2.3. The nickeline is pinkish brown in reflected light and has well polished surfaces. It is most commonly found as anhedral masses with no distinct cleavage or parting (Plate 6.4b). Occasionally it forms round blebs within the host sulfide (see chapter 6.2.6).

Under crossed-polars there are thin lamellae visible that display strong extinction. These lamellae were not visible under plane reflected light.

6.3.3 Maucherite

Maucherite forms irregular anhedral masses within the nickeline. It has a dull white colour under reflected light (compared to the cobaltite-gersdorffite grains). It has well polished surfaces similar to the nickeline. The maucherite often occurs between nickeline grain boundaries (Plate 6.4c).

6.3.4 Mineral Assemblage

All of the arsenide and sulfarsenide minerals were observed together in only one slide (Plate 6.4d). The sulfarsenides are attached to silicates (amphibole, chlorite), and are partially replaced by the nickeline in places.

6.4 Mineral Chemistry

All quantitative analyses were obtained using the Camebax electron microprobe (see appendix 1 for methods, data on cd in back pocket).

6.4.1 Cobaltite-Gersdorffite

The average composition of all sulfarsenide analyses are as follows; Ni - 0.498 apfu, Co - 0.351 apfu, Fe - 0.150 apfu. Figure 6.2 gives the Ni, Co, Fe contents in atomic % for all analyses. The average anion content for all analyses are as follows; S - 0.328 atomic %, As - 0.335 atomic %. No PGE were detected within the sulfarsenides.

Cobaltite (CoAsS) - gersdorffite (NiAsS) solid solution has been documented in natural settings (Beziat et al., 1996) where the primary substitution is Co for Ni+Fe. The solid solution between cobaltite and gersdorffite has also been established in the Copper Cliff Offset ores, Sudbury (Szentpeteri, 1999; Stewart, 1999; Carter, 2000; Magyarosi,

2002). From the analyses on sulfarsenides from the Totten ores, there is apparent solid solution between cobaltite and gersdorffite (Fig. 6.3a). There is a negative correlation between As and S (fig 6.3b) indicative of mutual substitution. The variation in the As/S ratio has been previously observed by Barkov (1999) in cobaltite-gersdorffite from the Mount General'Skaya layered intrusion.

Unlike the sulfarsenides observed by Barkov these grains do not have a positive correlation between As/S and Ni apfu, nor do they have a negative correlation between As/S and Co apfu. Both of these plots along with As/S vs Fe produce no clear trend (Fig.6.4 a,b,c). When comparing the metal ratios Ni and Co have a clear negative correlation (Fig.6.5a) indicating that one substitutes for the other. It also appears that Ni and Fe have a weak negative correlation (Fig.6.5b) and Fe and Co have a weak positive correlation (Fig.6.5c) which would suggest that the substitution amongst metals is Co+Fe for Ni. This is not in agreement with the observations of Beziat et al. (1996), who observed a Ni+Fe for Co substitution amongst primary magmatic sulfarsenides in Montagne Noire area France. Correlation coefficients for all elements analyzed appear in appendix 3.

Sulfarsenides from both the discrete grains and from nickeline veins have similar compositions.

6.4.2 Nickeline

Nickeline was analyzed for Ag, Pd, Rh, Pt, Os, Ir, Au, Sb, Te, Bi, Se, Fe, Co, Ni, Zn, Pb, As, and S using the electron microprobe. There were no PGE detected within the nickeline structure. The average Sb content is 0.002 (atomic %), 0.001 (atomic %) Co,

0.001 (atomic %) Fe, and 0.003 (atomic %) S. Apart from Ni and As, no other elements were detected. There is a clear negative correlation between Ni and As (Fig. 6.6).

6.4.3 Maucherite

The maucherite grains showed almost no other elements present other than Ni and As.

Plate 6.1 Photomicrograph and BSE images of sulfarsenide textures.

Plate 6.1a Photomicrograph of discrete gersdorffite grain hosted in chalcopyrite with magnetite attached. Sample tot-84b, field of view ~0.3mm.

Plate 6.1b BSE image of a euhedral discrete grain of gersdorffite with sperrylite inclusion. Sample tot-83.

Plate 6.1c BSE image of a euhedral cobaltite attached to chlorite hosted in chalcopyrite. Sample tot-77a

Plate 6.1d BSE image of zoned cobaltite hosted in chalcopyrite. Sample tot-83.

A)

B)

Figure 6.1. Fe-Co-Ni variation due to zonation within gersdorffite
 A) Fe-Co-Ni Ternary plot displays Ni-rich rim and Co+Fe rich core
 B) Binary plot of As vs S displays little variation in the As/S ratio

- Plate 6.2** Photomicrographs of nickeline bearing vein textures
- Plate 6.2a Photomicrograph of nickeline, chalcopyrite, pyrrhotite hosted in IQD.
- Plate 6.2b Quartz, and carbonate vein with minor nickeline and chalcopyrite hosted in IQD.
- Plate 6.2c Nickeline veinlet cross cutting chalcopyrite veinlet in IQD.

- Plate 6.3** Photomicrographs of nickeline bearing vein textures
- Plate 6.3a Photomicrograph of nickeline replaced gersdorffite (center) and gersdorffite rim formed at contact of nickeline with chalcopyrite. Sample tot-154, field of view ~0.8mm
- Plate 6.3b Photomicrograph nickeline partially replaced cluster of gersdorffite grains (center-bottom), and completely replaced grains (center-top) with remnant crystal faces still distinguishable. Sample As4188, field of view ~2mm
- Plate 6.3c Photomicrograph nickeline partially replaced gersdorffite. Sample tot-154, field of view ~1mm
- Plate 6.3d Photomicrograph of nickeline blebs in pyrrhotite and chalcopyrite. Sample tot-154c, field of view ~1mm

- Plate 6.4** BSE images and photomicrograph of sulfarsenide and arsenide minerals
- Plate 6.4a** BSE image of gersdorffite hosted in chalcopyrite (discrete grain) and of gersdorffite rimming nickeline. Sample tot-as88.
- Plate 6.4b** BSE image of anhedral nickeline attached to chlorite and biotite. Sample tot-as88.
- Plate 6.4c** Photomicrograph of maucherite and unnamed PGM at nickeline grain boundary (cross polars). Note lamellae visible in nickeline. Sample tot-5b, field of view ~1mm.
- Plate 6.4d** BSE image of all three As bearing phases (cobaltite, nickeline and maucherite). Note cobaltite grain being replaced by nickeline. Sample tot-5b.

Figure 6.2. Relative abundance of Fe-Co-Ni in sulfarsenide grains from the Totten Mine

Figure 6.3. Mineral chemistry of sulfarseindes A) Fe-Co-Ni ternary plot (At. %) displays solid solution between metals B) Binary plot of As vs S (At%) displays negative correlation

Figure 6.4. Metals vs As/S in sulfarsenides. Ni, Fe, Co all have no correlation with the As:S ratio

Figure 6.5. Fe-Ni-Co Ratios in sulfarsenides A) strong negative trend between Ni and Co B), C) weak negative and positive trends respectively

Figure 6.6. Nickeline analyses display a negative correlation between Ni and As

Chapter 7: Precious Metal Minerals, Oxides and Tellurides

7.1 Introduction

The precious metal minerals (PMM) include platinum group minerals (PGM) along with gold and silver bearing minerals. The PGM observed in this study from most abundant to least abundant are: michenerite (PdBiTe), unnamed (Pd-Sb-Te-Bi-Ni) mineral, sperrylite (PtAs_2), and froodite (PdBi_2). Hessite (Ag_2Te), altaite (PbTe) and argentian gold ($\text{Au}_x\text{Ag}_{100-x}$) are also found within the Totten ore. Magnetite (FeO_2) is the most abundant oxide, with minor ilmenite and tsumoite (BiTe) is the bismuth telluride present.

Previous work which examined the PMM within deposits of the SIC include (Hawley, 1962; Hawley and Stanton, 1967; Keays and Crocket, 1970; Cabri and Laflame, 1974; Cabri and Laflamme, 1976; Hoffman et al., 1979; Naldrett, 1984; Li and Naldrett, 1993; Farrow and Watkinson, 1997). This work, combined with other studies, has produced different interpretations on the origin and emplacement of these PMM such as strictly magmatic fractionation (Naldrett et al, 1994), separation of a hydrothermal fluid from a Cu rich fractionate (Li and Naldrett, 1993), post crystallization remobilization and enrichment from hydrothermal fluids (Farrow and Watkinson, 1997; Molnar et al., 2001).

7.2 Textures

The PMM documented in the Totten ore are found in two textural types: discrete grains, and as inclusions within sulfarsenide and within silicates.

7.2.1 Discrete Grains

PMM are most commonly found as discrete grains within sulfide (Plate 7.1a), as discrete grains located at the contact between sulfide and silicate grains (Plate 7.1b), or as discrete grains located at the contact of arsenide and sulfarsenide grains. All PMM can occur as discrete grains, of which the unnamed PGM, argentian gold, and froodite are only found as discrete grains. Argentian gold, hessite and michenerite occur at the contact of silicate grains that are hosted in sulfide. These silicates include amphibole chlorite and epidote.

7.2.2 Inclusions

Sperrylite, tsumoite and michenerite occur as inclusions within other minerals. Sperrylite forms inclusions within the center of discrete grains of cobaltite/gersdorffite. The sperrylite often forms euhedral crystals (Plate 7.1c) but sub-anhedral crystals were observed. Tsumoite occurs as inclusions within silicates (amphibole, chlorite), within cobaltite-gersdorffite and one grain was found as an inclusion within argentian gold. Michenerite occurs as inclusions within quartz and amphibole (Plate 7.1d). The michenerite grains are small ($<10\mu\text{m}$) anhedral grains. These inclusions are found alongside inclusions of chalcopyrite and tsumoite with other small bismuth telluride grains.

7.2.3 Zonation

Two michenerite grains appeared zoned using backscattered electron images. However, due to their small size there was no quantitative difference detected. The michenerite zones are concentric with slight undulating contacts (Plate 7.2a).

7.2.4 Replacement Textures

Magnetite was observed in several textures overgrowing inclusions of amphibolite that were in chalcopyrite. These inclusions are composed primarily of amphibole, along with biotite and chlorite (Plate 7.2c,d). These replacement textures were only observed in chalcopyrite rich sulfides.

7.3 Mineralogy

7.3.1 Michenerite

Michenerite is anhedral, often in close proximity or attached to tsumoite (BiTe). Michenerite is most abundant in the chalcopyrite veins, and is often attached to hydrous silicates such as amphibole, chlorite, epidote as well as quartz and altaite. It is also found in nickeline as elongate grains within small veinlets (Plate 7.3a).

7.3.2 Unnamed (Pd,Sb,Te,Bi,Ni) PGM

The unnamed PGM was only observed within the nickeline veins. It has a creamy pink colour relative to the other PGM. It forms anhedral elongate grains. The majority of the grains are located at sulfarsenide-nickeline contacts or at nickeline grain boundaries (Plate 7.3b). All but one of the unnamed PGM grains is found as a discrete

grain. One grain was found attached to galena (Plate 7.3c,d). None of the grains were attached to any silicates.

7.3.3 Sperrylite

Sperrylite occurs as euhedral to subhedral grains within or attached to cobaltite/gersdorffite grains. The sperrylite grains are most often located in the center of cobaltite/gersdorffite grains or attached to sulfarsenides. As with other PMM the most common occurrence of sperrylite is within chalcopyrite veins.

7.3.4 Froodite

Only one grain of froodite was located in this study. It was found at the edge of a pyrrhotite+pentlandite+chalcopyrite vein. The froodite grain is anhedral, and located within an amphibole.

7.3.5 Argentian Gold

Argentian gold occurs in two different textures within the Totten ore. It is observed in chalcopyrite veinlets and within nickeline veins. The argentian gold found in quartz bearing chalcopyrite veins also has abundant sphalerite, altaite and hessite. The argentian gold forms anhedral grains in small veinlets that splay off the main chalcopyrite vein. These veinlets terminate in epidote, amphibole, and calcite. Altaite chalcopyrite, epidote and amphibole surround the grains. In one sample Au precipitated around a Bi telluride.

The other texture where the argentian gold is observed is within nickeline veins. It occurs as anhedral grains with pitted surfaces. Within this texture the argentian gold has an average composition of $\text{Au}_{56}\text{Ag}_{44}$.

7.3.6 Hessite

Hessite occurs in all types of sulfide textures; however, it is most abundant in chalcopyrite veins where it is adjacent to bismuth tellurides.

7.3.7 Tsumoite

Tsumoite grains are found in a variety of textures and mineral associations. The majority of tsumoites form anhedral discrete grains or grains attached to oxide/silicates hosted in sulfide, however they can also occur entirely within silicates. They are a bright white in reflected light and have a smooth surface. Tsumoite was observed in all sulfide textural types, with an increase in abundance in chalcopyrite veins, and within Ni rich massive sulfide.

7.3.8 Altaite

Altaite forms anhedral grains which are a bright white in reflected light. Altaite is commonly found attached to hessite, michenerite and tsumoite. In one thin section it occurred as small inclusions in quartz and amphibole within chalcopyrite rich sulfide.

7.3.9 Magnetite

Magnetite is located in all the sulfide textures and within the silicate QD and IQD. In reflected light it has a light grey colour. It forms anhedral grains, often associated with hydrous silicates within sulfides. As previously mentioned, magnetite often is found attached or adjacent to PMM, PGM, tsumoite and altaite.

Less common is euhedral magnetite which was only observed overgrowing amphibolite inclusions in chalcopyrite rich sulfide. These magnetite grains are small (<1mm) in comparison to the anhedral grains.

7.3.10 Ilmenite

Ilmenite is a minor constituent of the IQD mineralogy. It is found in the silicate matrix of the IQD, approaching the ore body. No ilmenite was observed within the sulfides.

7.4 Mineral Chemistry

All quantitative analyses were obtained using the Camebax electron microprobe. See appendix 1 for methods and overlap considerations, data on cd in back pocket.

7.4.1 Michenerite

All michenerite grains contained detectable quantities of Sb. The Sb content varies from 1.6-6.1 (atomic %). The michenerite analyzed from the arsenide bearing veins contains more Pd, and Sb, with less Bi than the grains analyzed from other textures (Fig.7.1a, b, fig. 7.2a).

7.4.2 Unnamed

The unnamed PGM grains have variable Pd, Sb, Te, Bi, and Ni contents. The Pd contents range from 43.1- 48.3 (atomic %), Sb contents range from 24.6- 36.9 (atomic %), Te contents range from 3.8-11.8 (atomic %), Bi contents range from 3.2-8.1 (atomic %) and the Ni contents range from 2.6-9.8 (atomic %). An unnamed PGM from Sudbury has been documented by (Cabri, 1973; Cabri, 1974) which has the formula $\text{Pd}(\text{Te}, \text{Sb}, \text{Bi})$. The analyses are in close agreement with this unnamed mineral with the addition of Ni, and As for one analysis. The average composition is $(\text{Pd}_{0.47} \text{Ni}_{0.06})(\text{Te}_{0.07} \text{Sb}_{0.34} \text{Bi}_{0.06})$, and the one As bearing analysis has a composition of $(\text{Pd}_{0.43} \text{Ni}_{0.10})(\text{Te}_{0.12} \text{Sb}_{0.25} \text{Bi}_{0.07} \text{As}_{0.03})$. The resulting mineral formula would be $(\text{Pd}, \text{Ni})_{53}(\text{Sb}, \text{Te}, \text{Bi}, \text{As})_{47}$ assuming the Ni would occur in the Pd site as it does with sudburyite (Cabri, 1974). This mineral is most similar to UN1974-14 ($\text{Pd}_{0.268} \text{Te}_{0.58} \text{Bi}_{1.0} \text{Sb}_{0.065}$) and to UN1976-5 [$\text{Pd}_{1.0}(\text{Bi}_{0.53} \text{Te}_{0.42} \text{Sb}_{0.09})$] (Cabri, 1981).

There is a good correlation between Sb and Bi (fig 7.2b) along which the michenerite analyses also plot. Visible on the ternary plot (Fig. 7.2a) is the variable composition of the unnamed mineral and the apparent substitution $\text{Sb} \rightarrow \frac{1}{2}\text{Bi} + \frac{1}{2}\text{Te}$ through to the michenerite compositions. When projected onto the Pd-Bi-Te ternary plot this same trend from the unnamed mineral through to the michenerite analyses holds true $\text{Pd} \rightarrow \frac{1}{2}\text{Bi} + \frac{1}{2}\text{Te}$ (Fig. 7.1a). See appendix 4 for quantitative analyses.

7.4.3 Sperrylite

The sperrylite grains plot very close to the stoichiometric formula PtAs_2 (Fig. 7.1b). The sperrylite analyses from the Cu-Ni vein has a slightly elevated Pt content

than the analyses from the arsenide bearing veins. The average composition is $\text{Pt}_{0.29}\text{Sb}_{0.01}\text{As}_{0.58}$. The analyses from the arsenide bearing veins have elevated Ni-Co-As-S which is interpreted as interference with the host Ni-Co-As-S mineralogy.

7.4.4 Froodite

Only one froodite grain was located in this study. It has the composition $\text{Pd}_{0.28}\text{Fe}_{0.05}\text{Te}_{0.01}\text{Bi}_{0.66}$. It does not plot along the same (substitution) line as the michenerite-unnamed mineral (fig 7.1a, fig. 7.2a).

7.4.5 Argentian Gold

The argentian gold found within the chalcopyrite veinlets has an average composition of $\text{Au}_{66}\text{Ag}_{34}$, and the average composition of argentian gold from the arsenide bearing veins is $\text{Au}_{51}\text{Ag}_{41}\text{Ni}_6$. The 6% Ni count could be attributed to the NiAs in which it was analyzed, if so the readjusted composition would be $\text{Au}_{56}\text{Ag}_{44}$. Either interpretation demonstrates quite a marked difference in the argentian gold mineral chemistry (Fig.7.3a,b).

7.4.6 Tsumoite

Analyses of the bismuth tellurides display non-stoichiometric mineral compositions. Figure 7.4 demonstrates that tsumoite (BiTe) is the best fit for the data. The average composition of the tsumoites is $\text{Bi}_{0.47}\text{Te}_{0.47}$ with minor background interference from Zn, Cu and Fe.

- Plate 7.1** BSE images and photomicrographs of PMM textures
- Plate 7.1a** Photomicrograph of a discrete grain of michenerite hosted in Ni-rich massive sulfide. Sample tot-79, field of view ~1.5mm.
- Plate 7.1b** BSE image of a hessite and altaite attached to an amphibole hosted in chalcopyrite. Sample tot-73b.
- Plate 7.1c** Photomicrograph of a sperrylite inclusion within a cobaltite grain, all hosted in chalcopyrite. Sample tot-83, field of view ~0.5mm
- Plate 7.1d** BSE image of michenerite and tsumoite inclusions in quartz all hosted in amphibole. Sample tot-46.

- Plate 7.2** BSE images and photomicrographs of PGM and oxide textures
- Plate 7.2a** BSE image of a zoned michenerite grain attached to altaite. Sample tot-45.
- Plate 7.2b** Photomicrograph of magnetite replacing silicates of an amphibolite inclusion, within a chalcopyrite vein. Sample tot-84b, field of view ~2mm, reflected light.
- Plate 7.2c** Photomicrograph of magnetite replacing the silicate assemblage of an amphibolite inclusion, within a chalcopyrite vein. Sample tot-84b, field of view ~2mm PPL.

Plate 7.3 BSE images of PGM Mineralogy

Plate 7.3a BSE image of michenerite forming a late stage veinlet within nickeline. Sample tot-151.

Plate 7.3b BSE image of the unnamed Pd-Sb-Bi-Te-Ni PGM forming an elongate grain at the interface between gersdorffite and nickeline. Sample tot-5b.

Plate 7.3c BSE image of the unnamed Pd-Sb-Bi-Te-Ni PGM attached to galena within a nickeline bearing vein. Sample tot-5b.

Plate 7.3d BSE image of sperrylite, attached to gersdorffite, and hosted in chalcopyrite. Sample tot-73b.

Figure 7.1. A) PGM plotted on Pd-Bi-Te ternary diagram (atomic %)
 B) Sperrylite plotted on Pt vs As binary (atomic %)

Figure 7.2. A) Projection of PGM onto Bi-Sb-Te ternary diagram (at%)
 B) PGM projected onto Bi-Sb binary diagram (at %)

Figure 7.4. Bismuth telluride analyses with ideal tsumoite and pilsenite compositions overlain.

Chapter 8: Discussion

8.1 Field Relations

Emplacement of the Worthington Offset

Geological mapping of field relations lead to following interpretations. There were two separate pulses of quartz diorite and not two separate magmas that intruded at the same time (magma mixing). The geochemical similarity between the QD and IQD (Lightfoot et al., 1997b) suggests a mutual parental magma and not two magmas of separate origin. The first intrusion had no sulfide and carried very few inclusions. The second phase of quartz diorite intruded the first phase and contained abundant inclusions and droplets of magmatic sulfide. The relative timing of these two events is in agreement with the work of Lightfoot et al. (1997b) but not with Grant and Bite (1984). The presence of QD inclusions (and possibly IQD inclusions) and the IQD having a finer grain size at the contact of the QD suggest that the IQD intruded into a consolidated or semi-consolidated QD. This implies a time difference between the two pulses and therefore implies that the sulfide bearing quartz diorite was not emplaced instantaneously, as stated by Wood and Spray (1998) for the Hess Offset.

The increase in size of inclusions toward the center of the IQD may be explained by a velocity differential (Cochrane, 1984); the intruding quartz diorite would have decreased velocity near the contacts with the country rocks caused by cooling and friction. This would have resulted in the highest velocity within the center of the Offset, allowing larger inclusions to be preferentially rotated and transported (Bhattacharji, 1967). The discontinuous nature of the large gabbro clusters reflects areas that had a

lower transport velocity resulting in the accumulation of heavier material (Cochrane, 1984). Changes in the width of the IQD would be one factor that would affect the velocity of the intruding magma.

There is no explanation why the gabbro inclusions are so large while the amphibolite and sedimentary inclusions are small. The gabbro/sedimentary rock contact at the 260 zone did not display any brecciation or fracturing of the gabbro. The sedimentary rock are variably brecciated at the QD contacts. The brecciated sedimentary rock forms blocks that range in size from mm to m scale with the most common clast size 5-10 cm. Differences in mechanical behavior, due to differences in mineralogy and bedding between the sedimentary and the gabbroic rocks, may result in the formation of several small inclusions while the gabbro, with very few fractures, would produce fewer but larger inclusions. In addition to the differences in mechanical behavior is the compositional similarity of the gabbro to the quartz diorite resulting in minimal assimilation into the magma versus the silica rich sedimentary inclusions (Bite, 1984; Lightfoot et al, 1997a) resulting in a reduction in inclusion size. The combination of these two factors would favour the formation of larger gabbro inclusions relative to sedimentary inclusions.

The largest gabbro inclusions occur just 10m SW of the contact of the Nipissing Gabbro and the sedimentary rocks. The amphibole from gabbro and from the gabbro inclusions show increased Mg-Si with decreased Na-K-Al relative to the other analyses. These cummingtonites have a similar composition to rare amphibole from INMS. The latter are interpreted as amphibole xenocrysts from gabbro. Chlorite (ripidolite) analyses clearly distinguish gabbro and gabbro inclusions from the other units. The compositional

similarity of the mineral chemistry between gabbroic country rocks and the gabbro inclusions, along with textural similarity, and geochemistry (Lightfoot et al, 1997b) suggest that the inclusions are of local derivation from the gabbroic host rock.

Accounting for the presence of biotite in the inclusions and not within the samples studied from the country rock has two explanations. First, the Nipissing gabbro is widespread and has variable compositions (Card and Pattison, 1973). Blondé (1996) reported variable amounts of biotite from the Nipissing diabase (3-30%), and in gabbro metamorphosed to the amphibolite grade "little to no" biotite present. The inclusions could have been derived from a biotite bearing phase of the Nipissing gabbro. However the biotite does not exhibit equilibrium textures with the other silicates as described for biotite bearing phases by Blondé (1996). The second explanation is that the inclusions within the IQD experienced mild potassic alteration, producing the biotite. This is in agreement with other observations (see 8.2) suggesting the presence of fluid affecting the silicate mineralogy. This interpretation is supported by the textural observations that the biotite is overgrowing amphibole, and is not in equilibrium with the other minerals.

Because of their proximity to the Nipissing Gabbro, geochemical data of these inclusions (Lightfoot et al., 1997), and mineral chemistry of the amphibole and chlorite (this study) it is assumed that these inclusions are Nipissing gabbro and were transported from this contact. This implies that a component of the emplacement vector for QD was away from the SIC contact and/or vertically upward considering that the units dip to the south.

The two pulses of quartz diorite so different in sulfide and inclusion abundance has not been explained. Previous ideas on inclusion source and emplacement of the

Offsets include those of Grant and Bite (1984) who suggested that the intruding magma "picked up" inclusions and sulfide from depth. Late stage tectonic readjustment by the crystallizing main mass and gravitational collapse resulting in sulfide and inclusion rich mafic liquid to be "squeezed" out along the base of the complex and into fractures of the footwall was proposed by Lightfoot (1997) modeled after the work of Irvine (1975). Both of these hypotheses are in agreement with the field observations, except there still is no explanation of why there would be two pulses and why one pulse could be so barren of sulfides and inclusions relative to the other.

Figure 8.1 shows the metal abundances in both the QD and IQD. This whole rock data was collected and processed by Lightfoot et al (1997). The average whole rock composition was used from multiple samples of the QD and IQD of the Worthington Offset in the Totten area. Clearly the IQD is enriched in Co, Cu, Ni, Au, Pd, and Pt. This enrichment is associated with presence and abundance of sulfides found in the IQD, where the metals preferentially partition into the sulfide liquid (Rajamani and Naldrett, 1978; Li et al, 1992; Fleet et al, 1993). This data illustrates that the same quantity of metals is not tied up in silicates within the barren QD as would be expected if the barren QD never attained sulfide saturation.

The simplest explanation for the second phase of the QD having abundant sulfide and abundant inclusions is that the sulfide and inclusions had settled out of the magma chamber, due to gravity, when the first pulse of magma intruded into the offset, and that the second pulse was composed of the inclusion and sulfide rich residual magma from depth. This second pulse of magma may have intruded into the offset environment due to tectonic readjustment and/or a gravitational collapse of the crystallizing main mass as

suggested by (Golightly, 1994; Lightfoot, 1997), forcing the residual sulfide and inclusion rich magma into the offset, and brecciating a semi-consolidated QD.

In the Totten area there is a clear relationship between the occurrence of large gabbro inclusions and concentration of sulfides. Geologists from Inco Technical Services Ltd. (personal communication, 2000) have suggested that these inclusions partially “dammed” the flowage of magma causing an accumulation of sulfide liquid. The surface mapping (Map, Fig 3.3, 3.4) shows that the sulfides and old workings of sulfide ore occur on the lee side of included blocks down the direction of flow, in agreement with the hypothesis of Inco Technical Services Ltd. Therefore, it is suggested that sulfide liquid droplets were deposited due to a decrease in velocity that was caused by the choking effect on the transport of large inclusions (Fig.8.2). They accumulated to form massive, semi-massive, and inclusion rich massive sulfides.

8.2 Secondary Sulfides

Primary sulfides were accumulated mechanically; however, the abundant PMM and chalcopyrite in veins that have hydrous silicates and quartz within and mantling them suggest that they were concentrated and redeposited by hydrothermal fluid. As previously demonstrated for other Sudbury deposits (Farrow, 1992, 1994; Watkinson, 1994, 1999; Farrow and Watkinson, 1992; Farrow et al., 1994; Ames et al., 1998; Molnar et al., 1997, 1999, 2001) there is evidence for late stage remobilization and enrichment of some of the sulfides in the Worthington Offset. The textures of chalcopyrite veins and veinlets suggest that some of the magmatic sulfides were remobilized. The cross cutting relationships of these veins demonstrate that this event occurred after the crystallization

of the magmatic sulfides. The chalcopyrite blebs accompanied by hydrous silicates suggest that some of the magmatic Fe-Ni-Cu sulfide has been replaced by Cu rich sulfide (Watkinson and Melling, 1992; Watkinson, 1999).

The cross cutting relationships of these veins demonstrate that this event occurred after the crystallization of the magmatic sulfides. While both types of chalcopyrite veins contain PGM and hessite, one vein type contains significant amounts of pyrrhotite and pentlandite, and the other contains sphalerite, galena, altaite and argentian gold. The compositional and mineralogical variation in these veins suggests an evolution in fluid composition. This could be due to changes in temperature, salinity, wall rock composition, oxygen fugacity, all of which affect the solubilities of Cu, Ni, PMM and other species (Gammons and Bloom, 1993).

Spatial Relationships with Fe-Cl Hydrous Silicates, Sulfides and PMM

The formation of hydrothermal systems after emplacement of the SIC has been well documented (Farrow and Watkinson, 1997, 1999; Molnar et al, 1997, 1999, 2001; Watkinson, 1999). The resulting changes in mineral chemistry have been documented as well with respect to the proximity to footwall hosted deposits; Watkinson (1994) documented Cl-Mn-Fe rich hydrous minerals attached to PGM; Farrow and Watkinson (1997, 1999) focused on the marked increase in Cl content of hydrous silicates associated with PMM; McCormick and MacDonald (1999) and McCormick et al (1999) documented changes in the Cl/F ratios in amphibole from the Fraser Mine in relation to the proximity with sulfide. The silicates formed from convecting cells would logically produce Fe rich minerals, whereby the Fe that was removed from the abundant Fe rich

magmatic sulfide, precipitated Fe rich hydrous minerals elsewhere. Marshall et al. (1999) documented Fe-Ni sulfides that were replaced by quartz. Presumably the Fe and Ni dissolved by fluid would precipitate elsewhere.

The major silicates analyzed (amphibole, biotite, chlorite) and the minor silicates analyzed (epidote) all produce the same Fe:Mg changes relative to the distance from a known orebody. An increase in the Fe content (coupled with a decrease in the Mg content) with increasing proximity to the ore holds true for all silicates analyzed. This local change in mineral chemistry is interpreted as an alteration, and not a metamorphic effect. Simply the scale at which these changes take place (10-100m) casts doubt on regional metamorphism being the cause. Interestingly, several studies of hydrous silicate mineral chemistry as a function of distance from metamorphosed orebodies have been completed (Marshall and Spry, 2000 and references therein), which have documented detailed changes in the chemical composition of several hydrous silicates and certain oxides in relation to the proximity of an orebody. These results reveal a marked increase in the Mg vs Fe content of hydrous silicates including amphibole, biotite, and chlorite. This is the opposite of what has been observed at the Totten ore body. Admittedly, the metamorphosed orebodies studied are hosted in sedimentary rocks and the interpretations attribute the presence of graphite in the sedimentary rocks to buffer the sulphidation of the sulfides and the resulting formation of Fe-rich silicates. Nonetheless, an "open system" approach is taken to these studies and having the Totten orebody surrounded by sedimentary rocks would likely allow for the physio-chemical conditions to be met for sulphidation and oxidation to take place.

Figure 8.3 compares the mineral chemistry of biotite in relation to previous analyses from other Ni-Cu-PGE deposits including Sudbury (Farrow and Watkinson, 1999). No biotite was located within the Cu-rich veins, but biotite within Ni rich massive sulfide from Totten plots in regions interpreted to have compositions related to post crystallization processes. This increase in Cl content of hydrous silicates with proximity to the orebody is described in chapter 4.4. Farrow and Watkinson (1999) suggested the variation in Cl content of biotite could be related to the amount of Ni within its structure after work by (Volfinger et al., 1985). Not all biotite was analyzed for Ni, but those from Ni-rich massive sulfide show quite a variation in Cl content and they contain up to 0.22 wt% NiO. This implies there was Ni present in the Cl bearing fluid.

The distribution of the PGM and their mineral association is consistent with precipitation from hydrothermal solutions. In particular having PMM attached or within amphibole, epidote and chlorite suggests a Cl and hydrous environment during formation. Tsumoite and magnetite were also formed in this environment. Cl rich mineralogy associated with PGM reflects Cl complexing with PGE during transport via hydrothermal fluid (Farrow et al, 1994; Watkinson, 1994; Farrow and Watkinson, 1997, 1999) based on experimental studies by (Wood, 1987; Mountain and Wood, 1988; Wood et al, 1989; Gammons et al, 1992; Gammon and Bloom, 1993). In general the positive correlation of Fe with Cl accommodation indicates that the Cl is structurally controlled by the amount of Fe incorporated into the mineral (biotite and amphibole), and therefore Cl is present in excess in the fluid phase (Volfinger, 1985; Zhu and Sverjensky, 1992), however no quantitative interpretation on the concentration of Cl can be made.

Apatite grains were analyzed from the QD and from the IQD. The similarity in the major and minor element composition (in particular Cl and F) suggests similar "volatile" concentrations during crystallization. However Warner et al. (1998) documented apatite from the SW of the SIC that they interpreted as being recrystallized due to metamorphism, and that low Cl values can be attributed to metamorphic fluid interaction with the apatite whereby Cl would exchange for F. Boudreau and McCallum (1990) documented this process at low temperatures. While the recrystallization of the apatite "masks" the original volatile differences between the QD and IQD it has several implications, including a Cl source for the fluid, and that metamorphic conditions may have been prevalent after the emplacement of the Worthington Offset and coeval with alteration.

The spatial association of Fe-Cl-rich hydrous silicates with Cu-Ni-PGM rich sulfides combined with an increase in gabbro inclusions with sulfide content establishes a good criterion for areas that warrant further exploration. In particular surface mapping could easily delineate gabbro inclusion clusters, while analyses of mineral chemistry would depict Fe-Cl enrichment trends toward Cu-Ni-PGM rich sulfide.

Metamorphism

The metamorphic history has been well studied and disputed in this region of the Southern Province (Card, 1964; Rousell, 1975; Fleet et al, 1987; Easton, 1996; Riller and Schwerdtner, 1997; Magyarosi, 1998; Riller et al, 1999). In summary, the peak of Penokean metamorphism produced a lower amphibolite facies/ upper greenschist facies in the Totten area. It is the timing of the peak metamorphic conditions that is in dispute,

in particular if the peak of metamorphism occurred before or after the Sudbury event. Having metamorphic conditions coeval with alteration processes makes any distinction problematic. The changes in mineralogy and mineral chemistry are viewed as an alteration (presence of fluid, open system) under metamorphic conditions (Warner et al., 1998).

8.3 Deformation

A deformational event occurred after the consolidation of both quartz diorites and the sulfide within them. Both silicate matrix, inclusions and sulfide blebs are deformed. The zones of intense shearing occur in large gabbro clusters within the IQD. These areas were locally deformed because i) there is an abundance of sulfide (Barnes and Hill, 2000) and ii) there is an increase in platy minerals at the alteration selvage of the inclusions. Both of these factors would reduce the competency of the IQD allowing ductile deformation to take place. The presence of deformed chalcopyrite rich blebs and foliated chalcopyrite within veins, suggests that the deformation occurred after the remobilization of the Cu-rich sulfides.

This deformational event (post 1850Ma) could relate to four tectonic events that have been documented in the Sudbury area. 1) Penokean Orogeny 1900-1700Ma (Bennett et al., 1991) and related South Range Shear Zone (Shanks and Schwerdtner, 1990) 2) Doming and rifting 1838-1700Ma (Rousell et al., 1997) 3) a contractional orogeny 1450 Ma (Fueten and Redmond, 1997) 4) Grenville Orogeny 1000Ma (Rousell et al., 1997). The NE-SW strike of the shear zones mapped in the field area is compatible with the orientation of the closure during the Penokean Orogeny (Rousell et al., 1997).

Foliated Silicates

The foliated amphibole and biotite have a composition comparable with those from Ni rich massive sulfides. Because the Ni-rich massive sulfide is layered (pyrrhotite, chalcopyrite bands), the pentlandite megacrysts display a varied Fe-Ni-Co-S content, and because the silicate mineral chemistry is most similar to other deformed areas of the IQD, it is interpreted that the deformational event is associated with the Ni enrichment. The large pentlandite eyes could form from a) mechanical accumulation of smaller pentlandite megacrysts during deformation b) during metamorphism of the sulfides or, c) from fluids associated with the shear zones.

The accumulation of preexisting megacrysts during deformation likely occurred, but would not account for an increase in the Ni /pyrrhotite ratio. Metamorphism of sulfides can increase the grain size of pentlandite and Ni content of the sulfides (Barnes and Hill, 2000). However, the silicate mineral chemistry, and lack of abundant magnetite are not compatible with a metamorphosed orebody. The presence of biotite along pentlandite megacryst grain boundaries suggests that it is in equilibrium and co-precipitated with the sulfide in the presence of fluid during the formation of the large pentlandite grains. Shear zones and foliation may act as conduits for fluid (Marshall et al., 2000; Cartwright and Oliver, 2000). Fluid interaction with the Ni-Cu-Fe sulfide produced an enrichment in Ni by the addition of Ni, or by the removal of Fe. The presence of fluid associated with the generation of sulfide at Totten has been documented by Marshall et al. (1999). Pentlandite is observed in Cu rich veins, and fluid containing

Ni (among other elements) has been documented as the source for Cu-Ni-PGE enrichment in Sudbury (Farrow and Watkinson, 1997).

8.4 Sulfarsenides and Arsenides

Undoubtedly, assimilation of country rock resulted in the addition of As into the sulfide melt (Farrow and Watkinson, 1999) and the large influence the inclusions have on the melt composition (Lightfoot et al., 1997) could add As to the melt. However, the presence of relatively abundant cobaltite/gersdorffite, nickeline $\pm$ maucherite found in veins cross cutting both QD silicate matrix and sulfides suggests that sulfarsenides and arsenides were largely formed by late stage fluid interaction with the magmatic sulfides, QD silicate matrix, and the surrounding country rock. Discrete grains of cobaltite/gersdorffite hosted within Fe-rich massive sulfide could have crystallized from a sulfide liquid; however, evidence of fluid interaction with the Fe-Ni-rich sulfide does not discount the discrete grains being precipitated from an As bearing fluid.

Comparison of the Fe-Ni-Co content of the sulfarsenides with experimental data from Klemm (1965) gives temperatures of formation between 400-600°C, with the majority of the grains at ~500°C. Interestingly, the crystallization trend for the magmatic sulfarsenides is the reverse of that for hydrothermal origin (Barkov, 1999), and indicates there could be a solid solution between NiAsS and $\text{Co}_{0.667}\text{Fe}_{0.333}\text{AsS}$. This trend also implies an ordered distribution of Co and Fe within the crystal structure (Beziat, 1996).

The zoned grains are interpreted to reflect changing fluid conditions (Ohnenstetter et al., 1991; Stewart, 1999; Carter, 2000) resulting in the precipitation of a Co/Fe core and evolving toward an increase in Ni content. The sperrylite in the center and attached

to sulfarsenides appears to have acted as nucleation sites for the sulfarsenides (Stewart, 1999; Carter, 2000). The presence of the dianion $(As_2)^{4-}$ in the early fluid, pairing with Pt^{4+} and forming $PtAs_2$ could explain the formation of sperrylite as an early phase. Gervilla et al. (1996) noted that PGE prefer arsenide melts over sulfide melts. A progressive change in fluid composition carrying $(As_2)^{4-}$, $(AsS)^{3-}$, $(S_2)^{2-}$ and corresponding metals (Co^{3+} , Co^{2+} , Ni^{3+}) (Wood and Strens, 1979) to balance the charge (Barkov, 1999) explains the zoning. The negative correlation between As and S, and Ni with Co reflects the mutual substitution for each other (Barkov, 1999). Unlike the grains of magmatic origin, the lack of correlation of As/S with the metals suggests that charge balance between Me^{x+} and $(As_{2-x}S_x)^{x-}$ is not be the controlling factor of sulfarsenide composition during precipitation.

The nickeline bearing veins cross cutting chalcopyrite veins proves that they are younger than the chalcopyrite veins. Figure 8.4 displays the spherical nickeline blebs + pyrrhotite cross cutting the foliated chalcopyrite rich sulfide indicating that nickeline formed after the deformational event. This is further supported by the chlorite fans overgrowing foliated biotite at the selvage (Fig. 8.5) of a nickeline bearing vein which has propagated along sheared IQD. The chlorite fan represents precipitation in a static (post deformational) environment.

The replacement of cobaltite/gersdorffite by nickeline in the presence of maucherite is in agreement with experimental data (Yund, 1962) which does not document gersdorffite-nickeline-maucherite in equilibrium at any temperature investigated. The replacement texture of the discrete grains also implies that gersdorffite precipitated before the formation of the arsenides. However the rim textured gersdorffite

appears to have formed after the nickeline. The late stage gersdorffite rim may reflect a reaction between the nickeline and pyrrhotite.

The presence of an unnamed PGM at the contact of the nickeline with the gersdorffite rims suggests that the change in fluid conditions resulting in the precipitation of gersdorffite over nickeline resulted in the precipitation of Pd and Sb as well. Speculation on the causes of Pd precipitation include changes in fS_2 , resulting in the formation of sulfarsenides (vs arsenides), and having S come out of the fluid. This would be compatible with the transport of Pd as a sulfide complex (Gammons and Bloom, 1993), triggering Pd precipitation. The comparison of chlorite between Cu-PGE-rich veins and nickeline bearing veins displays somewhat elevated Cl concentrations in the chalcopyrite dominated assemblage, indicative of Pd being transported as a chloride complex within the chalcopyrite rich veins vs Cl poor environment and transport as a sulfide complex within the arsenide bearing veins. This unnamed Pd-Sb-Te-Bi-Ni mineral has compositions that plot along a trend toward the ideal michenerite composition, perhaps indicative of a solid solution. Another clear difference in mineral chemistry between the Cu-PGE rich veins and the arsenide rich veins is the composition of the argentian gold. This difference in composition of this alloy reflects different conditions upon precipitation (White et al., 1957).

The pyrrhotite polymorphs hosting the blebby nickeline within foliated chalcopyrite (Fig.8.5) show no sign of deformation and the pyrrhotite is interpreted to have precipitated contemporaneously with the nickeline. The blebby textured nickeline appears to have formed due to immiscibility with the pyrrhotite. Immiscibility between nickeline and sulfides has been reported by (Gervilla et al, 1996) by moderate

temperature (~600°C) magmatic processes. Chen et al. (1993) documented similar immiscibility textures at the Thompson Mine, Manitoba, and interpreted the process as low temperature (250-300°C) alteration. Clearly the nickeline veins from the Totten ore are not orthomagmatic and represent late stage alteration after primary Ni-Cu-PGE enrichment and after a deformational event.

8.5 Alteration Conditions

"Intermediate temperature" (200-850°C) alteration assemblages of quartz, epidote, amphibole, chlorite, sericite, titanite and biotite described by Farrow and Watkinson (1999) are similar to silicates associated with the Cu-PGE-rich chalcopyrite veins found in the Totten ore. Marshall et al. (1999) documented multiple hydrothermal events (5) in the SIC including the Totten property. Molnar et al. (2001) documented multiple hydrothermal events in the North Range of the SIC in three main stages, of which fluid inclusion studies constrained the Cu-PGE enrichment hydrothermal activity to 400-480°C. The textures, mineralogy, composition (Cu-PGE-Au-Ag-Bi-Te-As) and the temperature from the cobaltite/gersdorffite mineral chemistry suggests that the first hydrothermal event described by Farrow and Watkinson (1999) is also responsible for the Cu-rich veins at the Totten property.

The nickeline Pd-Sb-rich veins formed well after the formation (and deformation) of the first hydrothermal event. Of the 5+ documented stages of hydrothermal activity (Molnar et al., 1997; Marshall et al., 1999) in the south range, carbonic fluids are associated with metamorphism and deformation (Molnar et al., 1997). The observed similarity in mineral chemistry among deformed fabrics (including Ni enriched sulfide)

could be related to this event. Supporting this is the observation that these "late stage fluids" are not ubiquitous and likely only permeated along certain structures (Molnar et al., 1997). This local concentration of late stage fluids would account for the presence of nickeline veins along sheared IQD, and explain why they have not been observed throughout the orebody. The measured decrease in salinity of these late stage fluids (29-41 and 26-31 wt % NaCl equivalent) relative to the first hydrothermal event, and lack of Cl-rich alteration associated with these late stage fluids (Molnar et al., 1997) is consistent with the arsenide bearing vein mineralogy and mineral chemistry and no PGM associated with Cl-rich hydrous minerals.

8.6 Relative Timing of Events

This study, combined with previous work cited lead to the following interpretation on the petrogenesis of the Totten orebody (Fig. 8.6):

Order of Events

Sudbury event/brecciation

QD emplaced, begins to crystallize and differentiate

IQD emplaced with immiscible sulfide liquid+inclusions

Flow causing mechanical accumulation of sulfide droplets

First hydrothermal event; Cu-Ni-PGE-Au-Ag-Co-Bi-Te-Pb enrichment

Deformational event

Second hydrothermal event; Ni-Co-As-Pd-Sb-Au-Ag

Brittle deformation (faulting)

Emplacement of quartz and olivine diabase dikes

Figure 8.1. Comparison metal abundances from whole rock data, QD vs IQD (after Lightfoot, 1997a).

Figure 8.2. Schematic of IQD velocity profile during intrusion. A) Decrease in velocity due to friction with country rock and temperature decrease B) Highest velocity in centre of dike (carrying largest inclusions) C) Local velocity decreases due to choking effect of large inclusions resulting in mechanical accumulation of sulfide

Figure 8.3. $Cl/(Cl+F)$ vs X_{Mg} of biotite (after Farrow and Watkinson, 1999), Copper Cliff South (CCS). Data from this study in colour.

Figure 8.4. a) foliated chalcopyrite cross-cut by pyrrhotite+nickeline blebs
b) chlorite overgrowing foliated biotite at selvage of nickeline vein

Figure 8.5. Comparison of Totten sulfarsenides with magmatic Mount General'skaya data (Barkov, 1999). Phase diagram after Klemm (1965). Overlain is the crystallization trend for Mount General'skaya, data and the Totten data.

Figure 8.6. Schematic cross section through orebody. A) Blebby and disseminated sulfide in IQD with small gabbro inclusions. B) Ragged disseminated sulfide often Cu rich, increase in gabbro inclusion size and abundance. C) Massive and inclusion massive sulfide bounded by large gabbro inclusions D) Large gabbro inclusions.

Chapter 9: Conclusions

- 1) The Worthington Offset is composed of two separate pulses; the older barren (of inclusions and sulfide) amphibole-biotite-quartz diorite and the younger inclusion bearing amphibole-biotite-quartz diorite.
- 2) The gabbro inclusions are locally derived from the Nipissing gabbro.
- 3) Fe-Ni-rich sulfide is associated with large Nipissing gabbro inclusions.
- 4) The sulfide is composed of pyrrhotite, pentlandite, and chalcopyrite with minor galena and sphalerite.
- 5) MASU1 texture has the largest proportion of hexagonal pyrrhotite relative to monoclinic pyrrhotite, and MASU2 texture has the smallest proportion of hexagonal pyrrhotite relative to monoclinic pyrrhotite.
- 6) The PGM observed in order of abundance are: michenerite, unnamed PGM, sperrylite and froodite. Other PGM observed in this study include hessite, argentopentlandite, and argentian gold.
- 7) There is an increase in the Fe and Cl content of hydrous silicates with proximity to the orebody.
- 8) The QD, IQD, magmatic sulfide and the remobilized sulfide have been locally deformed.
- 9) Foliated hydrous silicates contemporaneous with deformation and associated with Ni-rich massive sulfide suggest fluid was present during deformation and possibly responsible for Ni enrichment.

- 10) Veins containing abundant nickeline, cobaltite-gersdorffite, and the unnamed PGM precipitated post deformation, and used the local shear zones as conduits.
- 11) Discrete grains of cobaltite-gersdorffite precipitated before nickeline and maucherite, and after as rims between the nickeline and the host sulfide.
- 12) Abundant Pd, Sb, Bi, Te, and minor Au, and Ag are associated with As.

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Appendix 1: Microprobe Analysis and Techniques

Polished thin sections were coated with 250Å of carbon and analyzed on the 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 operated at 20 KV accelerating potential, beam current of 35 nA for sulfides and 15 kV accelerating potential with a 15 nA beam current for silicates. Sulfide and PGM elements and x-ray lines analyzed include S(K α) , As(K α), Fe(K α), Cu(K α), Co(K α), Ni(K α), Pt(M α) , Pd(L α), Ir(L α), Os(M α), Rh(L α), Ru(L α), Sb(L α), Pb(M α), Zn(L α), Bi(L α), Te(L α), Au(L α) and Ag(L α).

Silicate elements and x-ray lines analyzed include Si(K α), Al(K α), Ti(K α), Mg(K α), Mn(K α), K(K α), K(K α), Ca(M α) , Ba(L α), Na(K α).

The major elements were analyzed for 15 seconds count peak and background while the minor elements were analyzed with a 40 second counting time for both peak and background.

Apatite counting times were 30-50 seconds. F was counted for 60 seconds while REE were counted for 50 seconds. Elements and x-ray lines analyzed include P(K α), Si(K α), Na(K α), F(K α), Cl(K α), Sr(L α), Ba(L α), Y(L α), La(L α), Ce(L α), Pr(L β), Nd(L β), and Sm(L β).

A suite of well characterized natural and synthetic minerals and compounds were used as calibration standards. Analyses are accurate to 1-2 % relative for major elements, 3-10 % relative for minor elements (< 1 wt %).

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. Corrections were made to the Pd data due to an overlap with Rh(L β) and an overlap with Ag. As well the Os data was corrected for an overlap with the Cu K β x-ray line.

Raw X-ray data were converted to elemental weight percent using the Cameca PAP matrix correction program. Images were obtained by using backscattered electron imaging.

All analyses were performed by P. C. Jones at Carleton University.

Appendix 2: Chlorite Trace Metal Compositions

Appendix 3: Correlation coefficients among sulfarsenide mineral chemistry data

	Fe	Co	Ni	Fe/Fe+Co+Ni	Co/Fe+Co+Ni	Ni/Fe+Co+Ni	As	S	As/S	As/As+S
Fe	1									
Co	0.078	1								
Ni	-0.365	-0.914	1							
Fe/Fe+Co+Ni	0.986	0.022	-0.353	1						
Co/Fe+Co+Ni	0.099	0.99	-0.943		1					
Ni/Fe+Co+Ni	-0.331	-0.957	0.987			1				
As	-0.04	-0.075	0.025		-0.971	0.057				
S	0.180	-0.244	-0.049		-0.057	0.079	-0.325	1		
As/S	-0.158	0.163	0.055		0.102	-0.037	0.641	-0.933	1	
As/As+S	-0.159	0.165	0.052		0.105	-0.03	0.646	-0.931	0.999	1

Appendix 4: Unnamed PGM Quantitative Analyses

Mineral	SAMPLE	Location	Pd	Ni	total	Sb	Te	Bi	total	As	TOTAL
unnamed	AS88-1	arsenide	0.465	0.063	0.528	0.328	0.068	0.066	0.462	0.008	0.998
unnamed	AS88-9	arsenide	0.483	0.04	0.523	0.369	0.049	0.054	0.472	0.003	0.998
unnamed	AS88-12	arsenide	0.459	0.072	0.531	0.293	0.089	0.081	0.463	0.004	0.998
unnamed	AS88-13	arsenide	0.471	0.056	0.527	0.352	0.066	0.05	0.468	0.004	0.999
unnamed	AS88-14	arsenide	0.431	0.098	0.529	0.246	0.118	0.072	0.436	0.003	0.99
unnamed	AS88-15	arsenide	0.475	0.048	0.523	0.364	0.059	0.041	0.464	0.003	0.99
Average											
Pd	Ni	total	Sb	Te	Bi	total	As	TOTAL			

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