extent veined material, which have unique mineralogical and major-element compositions, have distinct trace-element compositions. The poor correlations for some trace-elements found in veins as unique precious metal minerals, are attributed to the dilution effect of the non-veined specimens in the specimen data set.

In the FANA data (Table 4), Pt correlates weakly with the Os-Ir-Ru-Rh group and Sb, and moderately with Te. Pd exhibits weak negative correlations with the Os-Ir-Ru-Rh group. Pd correlates moderately with Sb and As. Cu correlates strongly with Ag, weakly with Au, and weakly but negatively with the Os-Ir-Ru-Rh group and Pt. Au correlates moderately with Bi. Ag correlates weakly with Sb.

FAAAS data correlations (Table 5a) imply that sulfides enriched in Cu are also weakly to moderately enriched in Pd, Pt, and Co. However, this contradicts the FANA correlations for Pt, and mineralogical observations. The weak correlation of Co and Pt with Ni is not observed in Ni-rich veins; the Co may be related to Co held in pentlandite solid solution (Appendix C-2) and the Pt is thought to be related to the presence of sperrylite in pentlandite-rich sulfide blebs.

The correlation matrices from individual sulfide textural types (Tables 5b to 5f inclusive) show the effect of increasing metamorphic mobilization upon the major elements. The lack of correlation exhibited by Pt and Pd in the disseminated sulfides (Table 5b) is compatible with the

National Library
of Canada

Bibliothèque nationale
du Canada

Canadian Theses Service

Service des thèses canadiennes

Ottawa, Canada
K1A 0N4

NOTICE

The quality of this microform is heavily dependent upon the quality of the original thesis submitted for microfilming. Every effort has been made to ensure the highest quality of reproduction possible.

If pages are missing, contact the university which granted the degree.

Some pages may have indistinct print especially if the original pages were typed with a poor typewriter ribbon or if the university sent us an inferior photocopy.

Previously copyrighted materials (journal articles, published tests, etc.) are not filmed.

Reproduction in full or in part of this microform is governed by the Canadian Copyright Act, R.S.C. 1970, c. C-30.

AVIS

La qualité de cette microforme dépend grandement de la qualité de la thèse soumise au microfilmage. Nous avons tout fait pour assurer une qualité supérieure de reproduction.

S'il manque des pages, veuillez communiquer avec l'université qui a conféré le grade.

La qualité d'impression de certaines pages peut laisser à désirer, surtout si les pages originales ont été dactylographiées à l'aide d'un ruban usé ou si l'université nous a fait parvenir une photocopie de qualité inférieure.

Les documents qui font déjà l'objet d'un droit d'auteur (articles de revue, tests publiés, etc.) ne sont pas microfilmés.

La reproduction, même partielle, de cette microforme est soumise à la Loi canadienne sur le droit d'auteur, S.R.C. 1970, c. C-30.

THE DISTRIBUTION OF PLATINUM-GROUP ELEMENTS AND PLATINUM-
GROUP MINERALS FROM THE DONALDSON WEST AND SURFACE DEPOSITS,
CAPE SMITH BELT, QUEBEC; THE ROLES OF THERMAL AND DYNAMIC
METAMORPHISM.

BY

HENRY C. H. DILLON-LEITCH, M.Sc.

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

Department of Geology
Carleton University
Ottawa, Ontario
June, 20, 1988

Permission has been granted to the National Library of Canada to microfilm this thesis and to lend or sell copies of the film.

The author (copyright owner) has reserved other publication rights, and neither the thesis nor extensive extracts from it may be printed or otherwise reproduced without his/her written permission.

L'autorisation a été accordée à la Bibliothèque nationale du Canada de microfilmer cette thèse et de prêter ou de vendre des exemplaires du film.

L'auteur (titulaire du droit d'auteur) se réserve les autres droits de publication; ni la thèse ni de longs extraits de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation écrite.

ISBN 0-315-46229-9

Carleton University
Ottawa, Canada K1S 5B6

This thesis contains coloured
photographs which may
not film well. The
hardcopy of the thesis is
available upon request
from Carleton University Library.

The undersigned hereby recommend to the Faculty of Graduate Studies and Research acceptance of this thesis, submitted by Henry C. H. Dillon-Leitch, M.Sc., in partial fulfilment of the degree of Doctor of Philosophy of Science.

.....
Chairman, Department of Geology

.....
External Examiner

.....
Thesis Supervisor

Carleton University
Ottawa, Ontario
September, 14 .. 1988.

Abstract

The primary magmatic sulfide and platinum-group element (PGE) distribution in the Aphebian Donaldson West and Surface deposits was extensively modified during regional upper greenschist facies metamorphism. The sulfides exhibit an upward succession of textures from massive (greater than 90% sulfide) through net-textured (15 to 90% sulfide) to disseminated (less than 15% sulfide) and are concentrated above footwall depressions in the symmetrically zoned ultramafic sills. The sills grade inward from hornblende pyroxenite through olivine pyroxenite to peridotite.

Mobilization of elements in the net-textured sulfides during thermal metamorphism caused partial to almost complete pseudomorphic replacement of serpentinized cumulus olivine grains (reverse net-texture) and generation of sulfide blebs after pyroxene oikocrysts in disseminated and net-textured sulfides. The intensity of development of these textures increases toward the contact with massive sulfide reflecting greater fluid circulation and the primary concentration of pyroxene, respectively, within the lower part of the sills. Extensive oxidation in the reverse net-textured zone resulted in magnetite partially replacing pyrrhotite and the generation of a more S-rich fluid which developed pyrite elsewhere.

The reverse net-textured zone, which is developed only at Donaldson West, resulted in a large zone moderately depleted in sulfides, Ni, and the Os-Ir-Ru-Rh group, and moderately enriched in Pd compared to the net-textured zone.

Laminated, massive sulfides are strongly depleted in Cu, Au, Pt, and Pd. During dynamic metamorphism competency contrasts, generated primarily at contacts of units with different sulfide textures, permitted formation of sulfide-carbonate veins or a sulfide breccia rich in platinum-group minerals (PGM) and precious metal (PM) minerals. Veins are primarily chalcopyrite-rich but may be pentlandite-rich, and contain Co-rich pyrite and Co-As minerals. The veins and the sulfide breccia are enriched in Pd, Sb, Te, Bi, Co, and As, and strongly depleted in the Os-Ir-Ru-Rh group characteristic of PGE fractionation during hydrothermal transport. Ni, Cu, and S variations between the two deposits can be explained by element redistribution during thermal and dynamic metamorphic events; magmatic variations are not required.

The largest Pt- and Pd-bearing PGM are located in rocks affected by dynamic events. $Pd_3Sb_2Te_2$, electrum, and hessite are restricted to dynamically mobilized sulfides. Borovskite and merenskyite are more common in rocks with a hydrothermal overprint. PGM grains within and at sulfide grain margins, interpreted to have exsolved from enclosing high temperature sulfides, occur in rocks affected by thermal and dynamic events; however, they are most abundant in the massive sulfides with little evidence of hydrothermal activity. PGM at

sulfide/silicate grain boundaries are interpreted to have exsolved in the presence of a fluid whereas rare free grains precipitated directly from a fluid; these textures are most abundant in dynamically metamorphosed rocks.

Melonite from veins is richer in Pd than grains from massive sulfides and borovskite grains show Pd enrichment with increasing dynamic overprint. Variably altered nickeline grains, restricted to the sulfide breccia zone, exhibit a close association with Pd-rich PGM and Co-As minerals, further supporting PGE assay data which suggests that a fractionated fluid was generated and active during dynamic metamorphism. Elements mobilized during dynamic metamorphic events were fractionated during hydrothermal transport and the resultant sulfides, localized at sites of contrasting competency, exhibit PGM and PM mineral diversity, size, and composition which reflects the unique composition of the fluid.

TABLE OF CONTENTS

Abstract	i
Table of contents	iii
List of figures	v
List of tables	vii
List of appendices	viii

Chapter 1

Purpose, Presentation, and Method of Study	1
Introduction	2
Purpose	6
Presentation	7
Method of study	8

Chapter 2

Distribution of Platinum-Group Elements in the Donaldson West Deposit, Cape Smith Belt, Quebec	10
Abstract	11
Introduction	12
General Geology	14
Petrology of the Donaldson West Sill	15
Primary textures of the sulfides	17
Metamorphic textures of the sulfides	17
Opaque Minerals	21
Platinum-Group Minerals and Platinum-Group Element-, Au-, and Ag-Bearing Minerals	26
Major Element and Platinum-Group Element Distribution	29
Element correlations	31
Analyses recalculated to 100 percent sulfides	34
Discussion	45
Mobilization of Fe-Ni-Cu sulfide	45
Platinum-group element mobilization	46
Conclusions	49

Chapter 3

Platinum-Group Element and Platinum-Group Mineral Distribution in the Donaldson Surface Deposit, Cape Smith Belt, Quebec: the Roles of Thermal and Dynamic Metamorphism	51
Abstract	52
Introduction	53
General Geology	56
Geology of the Donaldson Surface deposit	57
Petrology of the Donaldson Surface Deposit	58
Primary textures of the silicate minerals	62
Primary textures of the opaque minerals	65
Metamorphic textures of the silicate minerals	69
Metamorphic textures of the country rocks	72
Geothermometry	73

Chapter 3 cont.

Metamorphic textures of the opaque minerals	75
Opaque Minerals	82
Sulfide minerals	84
Oxide minerals	89
Sulfarsenide minerals	89
Arsenide minerals	94
Platinum-Group Minerals and Platinum-Group Element- and Ag-Bearing Minerals	98
Major Element and Platinum-Group Element Distribution	102
Element correlations	105
Analyses recalculated to 100 percent sulfides	107
Discussion	116
Mobilization of Fe-Ni-Cu sulfide	116
Platinum-group element mobilization	118
Conclusions	123

Chapter 4

Platinum-Group Minerals, Associated Platinum-Group Element-Bearing Minerals, and Precious Metal Minerals in the Donaldson West Deposit, Cape Smith Belt, Québec Distribution, Mineralogy, and Chemistry	124
Abstract	125
Introduction	126
Geologic setting	128
Sample preparation and study method	129
Analytical techniques	131
Platinum-Group Mineral Distribution, Mineralogy and Chemistry	131
Sperrylite - $PtAs_2$	132
Sudburyite - $PdSb$	135
Testibiopalladite - $PdSbTe$	136
Unknown - $Pd_3Sb_2Te_2$	142
Merenskyite - $PdTe_2$	142
Associated Precious Metal Minerals	145
Electrum - $AuAg$	145
Hessite - Ag_2Te	145
Melonite - $NiTe_2$	146
Ullmannite - $NiSbS$	147
Ionic Substitution in PGM, PGE-Bearing, and Precious Metal Minerals	148
Discussion	151
Distribution of PGM, associated PGE-bearing, and PM minerals	151
Textural characteristics	154
Chemical composition	159
Conclusions	160

Chapter 5

The Relationship Between Metamorphism and the Distribution, Mineralogy, and Chemistry of Platinum-Group Minerals, Associated Platinum-Group Element-Bearing Minerals, and Precious Metal Minerals in the Donaldson Surface Deposit, Cape Smith Belt, Quebec	163
Abstract	164
Introduction	165
Geologic setting	167
Sample preparation and study method	169
Analytical techniques	169
Platinum-Group Mineral Distribution, Mineralogy and Chemistry	170
Sperrylite - $PtAs_2$	170
Sudburyite - $PdSb$	175
Testibiopalladite - $PdSbTe$	178
Borovskite - Pd_3SbTe_4	182
Unknown - $Pd_3Sb_2Te_2$	185
Merenskyite - $PdTe_2$	186
Precious Metal Minerals	187
Hessite - Ag_2Te	187
Melonite - $NiTe_2$	188
Discussion	189
Distribution of PGM, associated PGE-bearing, and PM minerals	189
Textural characteristics	192
Chemical composition	199
Conclusions	200

Chapter 6

Summary, Discussion, and Conclusions	203
Summary and Discussion	204
Primary structure, texture, and mineralogy	204
Metamorphism and deformation	207
Sulfide mobilization	210
PGE mobilization	219
PGM distribution, mineralogy, and chemistry ...	222
Reinterpretation of chondrite normalized profiles in the literature	224
Conclusions	227
Acknowledgments	230
References	231
Appendices	240

LIST OF FIGURES

Chapter 1

1.1 General geology of the Cape Smith foldbelt and the location of the major Ni-Cu-Fe sulfide deposits	3
--	---

Chapter 2

2.1	General geology of the Cape Smith foldbelt and the location of the major Ni-Cu-Fe sulfide deposits	13
2.2	Geology of the Donaldson Mine area	16
2.3	Development of reverse net-texture by variable sulfide replacement	19
2.4	Ni/Fe in pentlandite and Ni in pyrrhotite vs depth	22
2.5	Compositional variation of major sulfide minerals	24
2.6	Location and abundance of PGM and associated minerals	28
2.7	Plots of Cu, Ni, Pt, and Pd assays vs. depth	38
2.8	Plot of Po/Pn vs. depth	41
2.9	Pd/Pt vs. S/Ni	42
2.10	Chondrite normalized PGE in 100% sulfide data	44

Chapter 3

3.1	General geology of the Cape Smith foldbelt and the location of the major Ni-Cu-Fe sulfide deposits	54
3.2	Geology of the Donaldson Mine area	55
3.3	Cross-section C-D through the Donaldson Surface deposit ..	59
3.4	Stratigraphic column with primary mineralogy, rock type, and sulfide textures	61
3.5	Poikilitic pyroxene and enclosed olivine grains	66
3.6	Prismatic and poikilitic hornblende phenocrysts	66
3.7	Interstitial sulfide texture	68
3.8	Pseudomorphic and non-pseudomorphic serpentine textures ..	71
3.9	Mineral zoning in footwall stringers and fabric relationships in adjacent metasedimentary rocks	74
3.10	Sulfide core to olivine pseudomorph	77
3.11	Sulfide blob textures	78
3.12	Textures in the sulfide breccia	80
3.13	Footwall stringer	81
3.14	Fabric orientations in sulfide vein	83
3.15	Ni/Fe in pentlandite and Ni in pyrrhotite vs depth	85
3.16	Pyrite textures	88
3.17	Ni vs. Co in pyrite	90
3.18	Compositional variation of major sulfide minerals	91
3.19	Cobaltite textures and mineral associations	93
3.20	Compositional variation of sulfarsenides	95
3.21	Alteration of nickeline and PGM location	96
3.22	Plots of Cu, Ni, Pt, and Pd assays vs. depth	109
3.23	Plot of Po/Pn vs. depth	112
3.24	Pd/Pt vs. S/Ni	113
3.25	Chondrite normalized PGE data	115

Chapter 4

4.1	General geology of the Cape Smith foldbelt and the location of the major Ni-Cu-Fe sulfide deposits	127
4.2	Location of sperrylite grains and textural relationships ..	134
4.3	Sudburyite grain at pyrrhotite/pentlandite contact	137
4.4	Compositional variation of sudburyite grains	138
4.5	Testibiopalladite intergrowths with PGM and PM grains	140

Chapter 4 cont.

4.6	Compositional variation of testibiopalladite and $\text{Pd}_3\text{Sb}_2\text{Te}_2$ within the PdTe_2 - PdSb_2 - PdBi_2 ternary	141
4.7	$\text{Pd}/\text{Pd}+\text{Ni}$ vs. $\text{Te}/\text{Te}+\text{Sb}+\text{Bi}$ for testibiopalladite, $\text{Pd}_3\text{Sb}_2\text{Te}_2$, merenskyite, and melonite	143
4.8	Grains of the unnamed mineral ($\text{Pd}_3\text{Sb}_2\text{Te}_2$)	144

Chapter 5

5.1	General geology of the Cape Smith foldbelt and the location of the major Ni-Cu-Fe sulfide deposits	166
5.2	Sperrylite grain habits and textural relationships	172
5.3	Sudburyite intergrowths and textural relationships	176
5.4	Compositional variation of sudburyite	179
5.5	Testibiopalladite intergrowths and textural relations	181
5.6	Compositional variation of testibiopalladite and $\text{Pd}_3\text{Sb}_2\text{Te}_2$ within the PdTe_2 - PdSb_2 - PdBi_2 ternary	183
5.7	$\text{Pd}/\text{Pd}+\text{Ni}$ vs. $\text{Te}/\text{Te}+\text{Sb}+\text{Bi}$	184

Chapter 6

6.1	Generalized metamorphic evolution of the Donaldson deposits	205
6.2	Generation of structures at competency contrasts	213
6.3	Chondrite normalized profiles of sulfides from the Levack West and Little Stobie mines, Sudbury	225

LIST OF TABLES

Chapter 2

2.1	Textural distribution and grain location of PGM and associated minerals	27
2.2	Fire assay neutron activation data	30
2.3	Fire assay atomic absorption spectrometry data	32
2.4	Correlation matrix for fire assay neutron activation data	33
2.5	Correlation matrix for fire assay atomic absorption spectrophotometry data	33
2.6	Po, Pn, and Po/Pn data from 100 % sulfides	40

Chapter 3

3.1	Grain type, size, habit, and location of primary minerals	63
3.2	Textures, abundance, and stratigraphic location of selected minerals	64
3.3	PGM and associated mineral textural distribution and grain location	99
3.4	Textural, abundance, and stratigraphic location data of selected minerals	100
3.5	Fire assay neutron activation data	103
3.6	Fire assay atomic absorption spectrophotometry data	104
3.7	Correlation matrix for fire assay neutron activation data	106

Chapter 3 cont.

3.8	Correlation matrix for fire assay atomic absorption spectrophotometry data	106
3.9	Po, Pn, and Po/Pn data from 100 % sulfides	111

Chapter 4

4.1	Textural, abundance, and stratigraphic location data	133
4.2	Physical parameters of PGE, PM, and selected base metals ..	149

Chapter 5

5.1	Textural, abundance, and stratigraphic location data	171
-----	--	-----

Chapter 6

6.1	Average Ni, Cu, Pt, Pd, Ni/Ni+Cu, and Pd/Pd+Pt values in 100 % sulfides for the Donaldson West and Surface deposits with respect sulfide to textural type	215
-----	---	-----

LIST OF APPENDICES

A.	Standards and X-ray lines used for quantitative analyses ..	240
B.	Lower limits of detection	248
C-1	Pyrrhotite from core hole 160-224	249
C-2	Pentlandite from core hole 160-224	252
C-3	Pyrite from core hole 160-224	255
C-4	Cobaltite from core hole 160-224	258
D-1	Pyrrhotite from core hole 160-225	259
D-2	Pentlandite from core hole 160-225	262
D-3	Chalcopyrite from core hole 160-225	265
D-4	Pyrite from core hole 160-225	267
D-5	Cobaltite from core hole 160-225	269
D-6	Nickeline from core hole 160-225	271
E-1	Sperrylite mineral data core hole 160-224	272
E-2	Sudburyite mineral data core hole 160-224	273
E-3	Testibiopalladite mineral data core hole 160-224	274
E-4	$Pd_3Sb_2Te_2$ mineral data core hole 160-224	275
E-5	Merenskyite mineral data core hole 160-224	275
E-6	Electrum mineral data core hole 160-224	276
E-7	Hessite mineral data core hole 160-224	276
E-8	Malonite mineral data core hole 160-224	277
E-9	Ullmannite mineral data core hole 160-224	278
F-1	Sperrylite analyses core hole 160-224	279
F-2	Sudburyite analyses core hole 160-224	280
F-3	Testibiopalladite analyses core hole 160-224	281

LIST OF APPENDICES cont.

F-4	Pd ₃ Sb ₂ Te ₂ analyses core hole 160-224	282
F-5	Merenskyite analyses core hole 160-224	283
F-6	Electrum analyses core hole 160-224	284
F-7	Hessite analyses core hole 160-224	285
F-8	Melonite analyses core hole 160-224	286
F-9	Ullmannite analyses core hole 160-224	288
G-1	Sperrylite mineral data core hole 160-225	289
G-2	Sudburyite mineral data core hole 160-225	290
G-3	Testibiopalladite mineral data core hole 160-225	292
G-4	Borovskite mineral data core hole 160-225	293
G-5	Pd ₃ Sb ₂ Te ₂ mineral data core hole 160-225	294
G-6	Merenskyite mineral data core hole 160-225	295
G-7	Hessite mineral data core hole 160-225	296
G-8	Melonite mineral data core hole 160-225	296
H-1	Sperrylite analyses core hole 160-225	297
H-2	Sudburyite analyses core hole 160-225	298
H-3	Testibiopalladite analyses core hole 160-225	300
H-4	Borovskite analyses core hole 160-225	301
H-5	Pd ₃ Sb ₂ Te ₂ analyses core hole 160-225	304
H-6	Merenskyite analyses core hole 160-225	306
H-7	Hessite analyses core hole 160-225	307
H-8	Melonite analyses core hole 160-225	308
I	Calcite-dolomite geothermometer data core hole 160-224	310
J	Donaldson West deposit geology and discussion of sulfide ratios and textural data	313
J-1	Ni, Cu, Cu/Cu+Ni, and sulfide textural data from the Donaldson West deposit	320
J-2	Cross-section 590405E	339
J-3	Cross-section 590366E	340
J-4	Cross-section 590427E	341
K	Donaldson Surface deposit geology and discussion of sulfide ratios and textural data	342
K-1	Ni, Cu, Cu/Cu+Ni, and sulfide textural data from the Donaldson Surface deposit	348
K-2	Cross-section 590418E	352
K-3	Cross-section 590391E	353
K-4	Cross-section 590449E	354
K-5	Cross-section compilation from the Donaldson Surface deposit	355
L	Experimental FeAsS-NiAsS-CoAsS ternary with compositions of cobaltite and gersdorffite from the Donaldson West and Surface deposits	356

CHAPTER 1

Purpose, Presentation, and Method of Study

Introduction

The Donaldson deposit, composed of three separate Ni-Cu zones (the Donaldson West, East, and Surface deposits), is located in the east central part of the Cape-Smith foldbelt of northern Quebec (Ungava) at approximately $61^{\circ} 40'$ north latitude and $73^{\circ} 17'$ west longitude (Figure 1). Initial exploration in the Cape Smith foldbelt began in the mid 1930's but significant discoveries of Fe-Ni-Cu sulfide deposits in ultramafic intrusions took place in the late 1950's and early 1960's. Extensive subsurface exploration in the 1960's and 1970's, primarily by Falconbridge Ltd., revealed a number of deposits of which the Donaldson deposit is the most extensively drilled and developed.

Early analyses of Fe-Ni-Cu sulfides from the Donaldson deposit (Naldrett and Cabri, 1976; Naldrett and Duke, 1980) revealed platinum-group element concentrations that suggested discrete platinum-group minerals could be present for study.

Many "classic" papers on PGE-bearing Fe-Ni-Cu deposits restricted their arguments on PGE distribution to purely magmatic means, ignoring or downplaying the role of secondary or nonmagmatic processes (Naldrett and Cabri, 1976; Naldrett, 1981; Keays and Campbell, 1981; Campbell and Barnes, 1984). Corresponding investigations of PGM distribution in Fe-Ni-Cu deposits by in situ studies of polished thin sections have not been attempted in the rocks of the

Fig. 1.1 General geology of the Cape Smith foldbelt (Hynes and Francis 1982a) showing the Donaldson (1); Katiniq (2); 2-3 (3); and Cross Lake (4) Fe-Ni-Cu sulfide deposits.

Cape Smith belt.

High concentrations of PGE in sulfide-rich rocks have been attributed to unreasonably high partition coefficients (Rajamani and Naldrett, 1978; Fleet, 1979; Naldrett, 1979; Campbell and Naldrett, 1979; Naldrett et al., 1982). Apparent partition coefficients from the Kambalda area Fe-Ni-Cu deposits are lower than experimental values suggesting that other hypotheses should be considered to model PGE concentrations there (Cowden and Woolrich, 1987).

Inherent to any magmatic argument was the suggestion that the apparent lack of deformation fabrics, veins (manifestation of hydrothermal activity), or a low level of regional metamorphism implied that PGE had not moved about and any observed PGE variation was due to magmatic processes. Some studies suggested that if the primary sulfide/silicate textures did not appear to have been disturbed, little redistribution of major elements had occurred, and by association conferred the same assumption on the PGE (Naldrett et al., 1979). It was also suggested that the inexplicably high PGE values frequently found in disseminated sulfides, possibly an effect of nonmagmatic mobilization, could be minimized by sampling the massive sulfides (Naldrett et al., 1979).

One example of such a hypothesis of strict magmatic control on metal zoning within one orebody are the studies of the Levack West deposit; zoning has been related to diffusion in magma along the thermal gradient (Hoffman et al.,

1979) and to "in situ" fractional crystallization of high temperature monosulfide solutions (Chyi and Crocket, 1976; Naldrett, 1981; Naldrett et al., 1982). Watkinson (pers. comm., 1988) has noted that the extremities of the Levack West deposit contain bornite as well as chalcopyrite and contains abundant native silver, and high PGE contents. Quartz, in chalcopyrite-rich parts of this deposit, contains polyphase fluid inclusions with isometric, presumably halite crystals, gas, and liquid; suggestive of a saline fluid (Watkinson and Jonasson, 1988; unpublished data).

Deposits with very low or high PGE concentrations such as the Pipe and Katiniq orebodies respectively were attributed to the "R factor" or silicate magma/sulfide magma ratio (Naldrett et al., 1979; Campbell and Naldrett, 1979; Duke and Naldrett, 1980; Barnes et al., 1982). It was suggested that if the concentrations of Ni, Cu, and PGE in the sulfide are known and the concentrations in the original silicate liquid are known or can be derived from the literature and using poorly constrained partition coefficients it is possible to calculate the value of R needed to explain the concentrations. Where the calculated R value is much larger than the ratio of silicate magma to sulfide liquid then a continuous magma flow model is required, such as at the Katiniq deposit (Barnes et al., 1982). However, Keays et al. (1981) suggested that f_{O_2} and/or f_{S_2} variations during olivine crystallization may have controlled Pd and Ir variation which the R factor alone could not explain.

Purpose

There are currently many new hypotheses on the mechanisms of distribution of PGE and PGM in Fe-Ni-Cu sulfide deposits, for example, involving the role of fluids, hydrothermal mobilization, metamorphic mobilization, foot-wall contamination (the 4th International Platinum Symposium, University of Toronto, 1985; Hulbert et al., 1988), and the timing of sulfur saturation (Barnes and Naldrett, 1987). The new hypotheses and the lack of unanimity among "magmatists" indicates that perhaps it is necessary to reconsider their models and to re-examine in detail the inter-relationship between PGE and PGM distribution.

The major purpose of this thesis is to examine the hypothesis of PGE mobilization in a detailed examination of PGE and PGM distribution, in two Fe-Ni-Cu sulfide deposits, from the perspective of detailed textural and mineralogical considerations, with the premise that the PGE-PGM distribution was originally magmatic but that redistribution may have occurred during regional metamorphism and deformation.

The "classic" massive, net-textured, and disseminated sulfide types (Usselman et al., 1979) were observed in the field. Massive sulfides were defined as greater than 90 % sulfides, net-textured as sulfide accumulations ranging between 15 and 90 % sulfide surrounding olivine phenocrysts, and disseminated sulfides, composed of less than 15 % sul-

fides, occurring as discrete sulfide grains interstitial to olivine grains or as small, discontinuous patches of net-textured sulfide. Some specimens showed evidence of reverse net-texture (Philpotts, 1961). Sulfide-rich specimens with sulfide compositional banding, sharp boundaries, carbonate- and/or serpentine-rich cores or margins were interpreted, as sulfide veins. They were specifically sampled to investigate the hypothesis that they may represent the mobilization of elements during the late geological history of the deposit and were not primary textural units.

Presentation

The data and their interpretation are presented as four papers in publication format, appendices containing background information on the Donaldson deposits, and a summary chapter which includes a discussion of all aspects of the study and the conclusions. The papers are entitled:

- 1) Distribution of Platinum-Group Elements in the Donaldson West Deposit, Cape Smith Belt, Quebec.
- 2) Platinum-Group Element Distribution in the Donaldson Surface Deposit, Cape Smith Belt, Quebec: the Roles of Thermal and Dynamic Metamorphism.
- 3) Platinum-Group Minerals, Associated Platinum-Group Element-Bearing Minerals, and Precious Metal Minerals in the Donaldson West Deposit, Cape Smith Belt, Quebec: Distribution, Mineralogy, and Chemistry.
- 4) The Relationship Between Metamorphism and the Distribution, Mineralogy, and Chemistry of Platinum-Group Minerals, Associated Platinum-Group Element-Bearing Minerals, and Precious Metal Minerals in the Donaldson Surface Deposit, Cape Smith Belt, Quebec.

At the time of defence of this thesis paper 1 has been published (Dillon-Leitch et al., 1986). The other papers are being prepared for submission.

Method of study

Two field seasons mapping parts of a 60 km long concession held by New Quebec Raglan Mines Ltd., over ultramafic rocks which contain the majority of the known Fe-Ni-Cu deposits of the Cape Smith belt, and the logging of drill core from the Donaldson deposits form the background for the study.

Two core holes, 160-224 and 160-225, were sampled in detail (at one metre intervals) over the length of the sulfide-rich mineralization. From these samples polished thin sections were made. Selected samples were analysed by fire assay neutron activation. New Quebec Raglan Mines Ltd., through Falconbridge Ltd., made available X-ray fluorescence and fire assay atomic absorption spectrophotometry data for these core holes at one to two metre intervals. Some samples from 160-224 were concentrated by heavy mineral liquid separation; magnetic and nonmagnetic fractions were collected, made into monolayer polished sections, and examined by electron microprobe.

Polished thin sections, at approximately one metre to three metre intervals in both core holes, were examined by reflected and transmitted light microscope for petrological

study and to locate PGM and PGE-bearing minerals for electron microprobe examination.

The interpretation of structural features relies totally on drill core as the Donaldson Mine area lacks outcrop. The small diameter of the drill core makes the extension of structural interpretations, based on observations from hand specimens and thin sections, tenuous.

CHAPTER 2

Distribution of Platinum-Group Elements in the Donaldson
West Deposit, Cape Smith Belt, Quebec.

Abstract

Upper greenschist-facies metamorphism of the Aphebian Donaldson West ultramafic sill extensively modified the distribution of primary magmatic sulfides and platinum-group elements (PGE). Mobilization of elements in net-textured sulfides during thermal metamorphism caused partial to almost complete pseudomorphic replacement of serpentinized cumulus olivine grains (reverse net-texture) and generation of sulfide blebs after pyroxene oikocrysts in disseminated and net-textured sulfides. Sulfide-carbonate veins, rich in chalcopyrite and platinum-group minerals (PGM), developed during dynamic metamorphism primarily at contacts of units with differing sulfide textures where there were competency contrasts. Temperature estimates from sulfide-carbonate veins range from 511°C to 549°C.

The abundance of platinum-group minerals varies directly with the sulfide content in disseminated and net-textured sulfides, but it is anomalously low in the reverse net-textured and massive sulfides. Within the net-textured sulfides the greatest abundance, diversity, and size of platinum-group element-, Au-, and Ag-bearing grains is found in veins as inclusions in sulfides, along sulfide grain boundaries, or at sulfide-silicate grain contacts. In these veins, pyrite, Pd-, Sb-, and Te-rich platinum-group minerals are accompanied by hessite, electrum, Co-rich pyrite, As-enriched pentlandite, and Co-As minerals. Rare platinum-group minerals occurring in silicates are confined to sheared and carbonatized rocks which are often associated with sulfide veins.

In comparison with the net-textured sulfide zone, the large zone of reverse net-textured sulfides is moderately depleted in sulfides and Ni, and moderately enriched in Pd; the massive sulfides are strongly depleted in Cu, Au, Pt, and Pd and moderately depleted in Ni. Pd is enriched and Pt is depleted in the veins relative to surrounding sulfides. Ni-rich veins are rare. Cu-rich veins are enriched in Pd, Sb, Te, As, Co, Ag, and Au, a feature which is interpreted to result from their strong partitioning into hydrothermal fluids.

Thermally metamorphosed disseminated and weakly altered net-textured sulfides exhibit chondrite normalized profiles typical of Proterozoic komatiites. Profiles of dynamically metamorphosed sulfides show PGE fractionation characteristic of hydrothermal transport. The reverse net-textured sulfides have chondrite normalized profiles intermediate to the two end members and suggest that a low degree of PGE fractionation may occur with thermal metamorphic events.

Introduction

The Donaldson West deposit, one of three separate Ni-Cu zones comprising the Donaldson deposit, is located in deformed and metamorphosed ultramafic rocks of the eastern part of the Aphebian Cape Smith foldbelt (Fig. 1). Previous studies of sulfide deposits within the foldbelt have described base metal concentrations in ultramafic rocks of lower metamorphic grade, in less deformed terranes (Wilson et al. 1969; Miller, 1977; Barnes, 1979; Barnes et al. 1982; and Albino, 1984).

In these and many other studies of Fe-Ni-Cu-PGE deposits, magmatic phenomena have been considered sufficient to explain metal distribution in the sulfide ores. However, the fractionation of Ir and Pd during hydrothermal mobilization of PGE, was noted by Keays et al. (1981) and Leshar and Keays (1984). Stress-induced hydrothermal mobilization of PGE has been suggested to explain the Cu- and PGE-rich composition of some "magmatic" Cu-Ni deposits such as those in the Kanichee layered complex (James and Hawke, 1984), the Thierry Mine (Patterson and Watkinson, 1984), and the Kambalda area (Keays and Davidson, 1976; Keays et al. 1981; and Cowden et al. 1986).

This paper describes not only the distribution of PGE, Cu and Ni, but most importantly the PGM, and associated Au, Ag, Te, Sb, Bi, Co, and As minerals from the Donaldson West deposit (drill core 160-224). A model is presented to

Fig. 2.1 General geology of the Cape Smith foldbelt (Hynes and Francis 1982a) showing the Donaldson (1); Katiniq (2); 2-3 (3); and Cross Lake (4) Fe-Ni-Cu sulfide deposits.

explain Cu- and Ni-rich veins in the sulfide zones, their high Pd/Pt, the large size of PGM, and the concentration of Pd, Sb, Te, Ag, Au, Co, and As in the veins and their relationship to deformation and metamorphism.

General Geology

The Cape Smith foldbelt (Fig. 1) is composed of the Povungnituk and Chukotat Groups. The Povungnituk Group consists of a lower unit of continental sediments, together with intrusive and extrusive tholeiitic basalts, and an upper turbidite unit. The overlying Chukotat Group is composed of intrusive and extrusive rocks of komatiitic to tholeiitic basalt and minor sediments (Hynes and Francis, 1982a). Fe-Ni-Cu-(PGE) sulfide deposits are located in sub-volcanic sills (Donaldson, Katiniq, 2-3, and Cross Lake deposits), or in intrusive/extrusive rocks at the Boundary complex (Albino, 1984), just above or at the Povungnituk/Chukotat contact.

The Cape Smith foldbelt has undergone three phases of regional deformation and metamorphism (Hynes and Francis, 1982b). In metasedimentary rocks in the Donaldson Mine area D_1 deformation resulted in a steeply north-dipping, strong EW-trending S_1 schistosity and upper greenschist metamorphic conditions. D_2 occurred in lower greenschist facies conditions and resulted in steeply north-dipping reverse faults, and a weak subvertical, EW-trending, S_2 foliation. D_3 con-

sisted of a weak EW compression generating subvertical NS faults and sporadic S_3 fracture cleavage during retrograde conditions (Albino, 1984). In drill core it is rarely possible to distinguish between S_1 and S_2 and the fabric is therefore referred to as S_1 - S_2 .

Petrology of the Donaldson West Sill

The ultramafic sill containing the Donaldson West deposit (Fig. 2) grades upward from pyroxenite through olivine pyroxenite into peridotite with minor dunite. Pyroxenite, which usually forms the thin basal unit of the sill in sulfide-poor areas, does not occur in this core hole. Cumulus olivine grains are completely pseudomorphed by antigorite and magnetite. Pyroxenes are pseudomorphically replaced by either serpentine or an assemblage of serpentine-actinolite-chlorite-calcite. Pyroxene oikocrysts in olivine-pyroxenite and peridotite are inferred from textures of enclosed olivine and ferrochromite grains. These entrained olivines are smaller than their interstitial counterparts and the ferrochromite grains are smaller and more numerous within the oikocrysts compared to those outside.

The Fe-Ni-Cu sulfides are concentrated in depressions at the footwall contact. The primary sulfide content decreases upward from massive (greater than 90 %), through reverse net-textured and net-textured (15-90 %), to dissemi-

Fig. 2.2 Geology of the Donaldson Mine area showing the Donaldson West (1); Donaldson East (2); and Donaldson Surface (3) deposits.

nated (less than 15%) sulfides. The contacts between textural types are sharp and marked by sulfide veins and minor concentrations of ferrochromite (less than 10 %). Similar ferrochromite concentrations have been reported by Groves et al. (1977) and Cowden et al. (1986) in Australian deposits of this general type.

Primary textures of the sulfides

The stratigraphic succession of massive, net-textured, and disseminated sulfides is interpreted to result from magmatic segregation (Usselman et al., 1979). Disseminated sulfides occur as sparse anhedral to lobate blebs (less than 1.0 mm across) interstitial to olivine. Net-textured sulfides comprise the bulk of the sulfides, forming a semicontinuous to continuous network around olivine grains in olivine-pyroxenite through peridotite to dunite. Massive sulfides occur at the base of the sulfide-rich section and may be a primary feature.

Metamorphic textures of the sulfides

Sulfide textures interpreted to be metamorphically generated are: reverse net-texture (Philpotts, 1961), foliated massive sulfides, large blebs, and veins. Reverse-net textures occur between the net-textured and massive sulfide zones, where Fe-Ni-Cu sulfides have variably replaced pseu-

domorphs of olivine. Net-textured sulfides exhibit a continuous range of modification from weakly mobilized (net-textured to reverse net-textured, Fig. 3a), where minor sulfide replacement of olivine pseudomorphs occurs, to strongly mobilized (reverse net-texture, Fig. 3b), where sulfides almost completely replace olivine pseudomorphically. The progressive development of reverse net-texture occurs with increasing pyroxene oikocryst content. The division between net-textured to reverse net-texture (10-30% of the olivine is variably replaced pseudomorphically) and reverse net-texture (greater than 30 % of the olivine is variably replaced pseudomorphically) is arbitrary. A weak S_1 - S_2 schistosity overprints the reverse net-textured rocks indicating sulfide mobilization before or during D_1 - D_2 .

Massive sulfides contain rolled and oriented silicates, sulfide segregations (chalcopyrite- or pentlandite-rich layers), and oriented pyrrhotite grains (S_1 - S_2 fabric). Sparse, irregular sulfide blebs (2 mm to 15 mm across), found in disseminated and net-textured sulfides, may be surrounded by calcite/dolomite reaction fronts and are occasionally linked by very thin calcite veinlets. From the abundance of enclosed ferrochromite grains these blebs are interpreted to represent sulfide-infilled pyroxene oikocrysts.

Mobilized sulfides occur in the footwall rocks as rare stringers and within the disseminated and net-textured sulfides as veins. The stringers contain quartz, albite,

Fig. 2.3 The development of reverse net-textured sulfides from net-textured sulfides showing the variable replacement of cumulus olivine pseudomorphs. A. Intermediate net-textured to reverse net-textured (248.7m). B. Reverse net-textured (269.8m).

carbonate, chalcopyrite, minor pyrrhotite, and rare pentlandite, but no spinel. They crosscut bedding at high angles, have annealed textures, and exhibit discontinuous selvages of chlorite and tremolite. The stringers cut the S_1 - S_2 fabric and may have been emplaced during D_3 .

Veins (1mm-1m thick) within the sill consist of variable proportions of pyrrhotite, pentlandite, and chalcopyrite, and may be zoned with serpentine or chalcopyrite-rich margins and sulfide-carbonate cores. They are prevalent at the contacts of rocks with differing textures (Fig. 6) where competency contrasts existed. Other vein locations, within net- to reverse-net textured sulfides (Fig. 6) where the veins parallel a strong foliation (S_1 - S_2), may reflect the heterogeneous nature of the deformation. A crenulation cleavage (S_2) is present in some veinlets, indicating that they formed before or during the D_1 event. Thin, barren, en-echelon calcite veinlets which crosscut the S_1 - S_2 cleavage are common and were probably emplaced during D_3 .

Dolomite is commonly associated with serpentine-sulfide veinlets in the dunitic rocks, as disseminated euhedral and anhedral grains, or irregular patches of talc-carbonate alteration in peridotite. Discontinuous ferroan calcite or ferroan dolomite patches occur in the sulfide-cored serpentine veinlets. Cm-wide margins of talc-carbonate alteration and reverse net-textured sulfides envelop calcite-rich veins in peridotites containing disseminated sulfides. Dolomite

occurs in the veinlets and in the cores of olivine pseudomorphs in adjacent rocks. Calcite-dolomite geothermometer estimates from chalcopyrite-rich veined samples 160-224-205.3m and -239.5m give temperatures of $549 \pm 8^\circ\text{C}$ and $511 \pm 8^\circ\text{C}$ to $514 \pm 8^\circ\text{C}$ respectively (Appendix I).

Sulfide textural data for part of the Donaldson West deposit (Appendix J) suggest that core hole 160-224, located in the deepest part of the footwall depression where the thickest and best developed sulfide concentration occurs, is representative of high sulfide or "ore grade" material only.

Opaque Minerals

The opaque minerals in the Donaldson West deposit consist of monoclinic (rarely hexagonal) pyrrhotite, pentlandite, chalcopyrite, minor pyrite, sphalerite, chromite, magnetite, ilmenite, titanomagnetite, traces of sulfarsenides and sulfantimonides, and rare PGM, PGE-bearing, and Au- and Ag-bearing minerals.

Pyrrhotites have low Ni, Co, and As contents (Appendix C-1). Pentlandite from vein-free samples has low Co and As concentrations whereas vein pentlandite is As-enriched (Appendix C-2). The Ni/Fe (atomic) of pentlandite and atomic % Ni of pyrrhotite show a strong increase in the reverse net-textured zone compared to other less altered zones (Fig. 4).

Pyrite normally replaces pyrrhotite and to a lesser

Fig. 2.4 Plot of Ni/Fe (atomic) in pentlandite and Ni (atomic) in pyrrhotite against depth and sulfide textural type in core hole 160-224. Note general enrichment trend occurring with increasing textural modification from net-textured to reverse net-textured.

degree pentlandite. It occurs as rare, very small grains in pyrrhotite and locally, in cm-wide zones with chalcopyrite and calcite after pyrrhotite-pentlandite, associated with shears and veins. Pyrite may have Co-rich rims and occasionally Ni-rich cores, similar to those reported by Secombe et al. (1981) for secondary pyrite at Kamalda (Appendix C-3). Chalcopyrite, the only Cu-bearing mineral, occurs abundantly in deformed rocks and Ni-poor veins.

The common assemblage of monoclinic pyrrhotite and pentlandite (from electron microprobe analyses) yields phase relations (Fig. 5) which are compatible with the interpreted upper greenschist facies temperatures (400-550 °C) attained during the regional metamorphism of the Donaldson Mine area (cf. Figures 2b and 2c of Harris and Nickel, 1972). The tie lines between pentlandite and pyrite are consistent with the inferred low temperature nature of the pyritic material, possibly below 300 °C as suggested for pyrite-rich assemblages at the Marbridge deposits (Gratier and Naldrett, 1971).

Cobaltite and arsenopyrite are minor phases associated with pyrite-rich sulfides in veins and in massive sulfides. Cobaltite in massive sulfide occurs as small exsolved grains along sulfide grain contacts, and in veins as rare, large euhedra associated with carbonates, silicates, PGM, and Au- and Ag-bearing phases closely associated with abundant pyrite (Appendix C-4). The composition of cobaltite grains from a vein sample (224-239.5 m) gives temperatures

of formation between 500 and 550 °c (Appendix L).

Rare arsenopyrite, observed only in massive sulfides and in a vein immediately above massive sulfides (Fig. 6), occurs as small grains along sulfide grain contacts.

Sparse, euhedral to anhedral magnetite occurs in the foliated massive sulfides. Tabular ilmenite or titanomagnetite grains in the disseminated, net-textured, and reverse net-textured sulfides are often oriented parallel to the foliation. Chains of irregular to skeletal ferrochromite are concentrated at textural contacts; they also occur throughout the sulfide zone as rare small subhedra interstitial to olivine pseudomorphs and within pyroxene oikocrysts.

Platinum-Group Minerals, PGE-, Au- and Ag-Bearing Minerals

PGM, PGE-bearing sulfides, Au- and Ag-bearing grains, and sulfarsenides were identified microscopically and by energy dispersive electron microprobe analysis. Larger grains were analysed quantitatively by wavelength dispersive electron microprobe techniques. Heavy mineral separates of the -60/+150 mesh fraction were examined in polished section.

PGM (Table 1 and Figure 6) are predominantly sudburyite (PdSb), testibiopalladite (PdSbTe), and sperrylite (PtAs_2). Merenskyite (PdTe_2) and an unknown ($\text{Pd}_3\text{Sb}_2\text{Te}_2$) mineral also occur rarely. Bi is a minor constituent of the Pd-rich minerals. Other minerals containing Pd are melonite (NiTe_2) and ullmannite (NiSbS). Up to 12.5 weight percent Pd substitution for Ni occurs in melonite, with the highest Pd content in vein melonite. The only identified Pt-rich phase is sperrylite (PtAs_2). Trace amounts of Pt were detected in testibiopalladite, melonite, merenskyite, ullmannite, and electrum. Hesseite (Ag_2Te) is associated with sudburyite and/or testibiopalladite and may contain Pd in solid solution or in very fine-grained PGM inclusions. Sperrylite contains traces of Rh and Ru. Au was encountered only as electrum. Ag was found in hesseite and electrum and as traces in sudburyite.

PGM, PGE-bearing, and Au and Ag-bearing phases are concentrated in the sulfide-rich, dynamically and hydrother-

Table 2.1. Platinum-group minerals, platinum-group element-bearing, Au-, and Ag-bearing, and associated mineral distribution in drill core hole 160-224, Donaldson West deposit.

Mineralogy	Ideal composition	Grain size (µm)	Textural distribution							Grain location			
			Diss	Net	Net to Rev	Rev	Msy	Vein	Sulf bleb	In Sulf	Sulf/ Sulf	Sulf/ Sil	In Sil
Sperrylite	PtAs ₂	1-150		x	x	x	A	x	x	x	A	A	
Sudburyite	PdSb	3-60	x	x	x			A		x	A	x	x
Testibiopalladite	PdSbTe	2-250	x	x	x	x		A		x	A	x	x
Merenskyite	PdTe ₂	2-50						x		x	x	x	
Unknown	Pd ₃ Sb ₂ Te ₂	10-60						x		x	x		
Melinite	NiTe ₂	2-50					A	A		A	x	x	
Hessite	Ag ₂ Te	2-60						x			x	x	
Electrum	Au, Ag	10-50						x			x		
Ullmannite	NiSbS	10-50	x					x		x	x	A	
Cobaltite	CoAsS	1-250		x			x	A		x	A	x	
Arsenopyrite	FeAsS	1-15					x	x		x	x		
Pyrite	FeS ₂	10-45	x	x	x	x	A	A		x	x	A	x

Abbreviations: Diss=disseminated, Net=net-textured, Net to Rev=net-textured to reverse-net textured, Rev=reverse net-texture, Msy=massive sulfide, Sulf bleb=sulfide blebs, Sulf=sulfide, Sil=silicate, x=present, A=abundant, as=massive texture. Note: the abundance of sulfides and sulfarsenides are an order of magnitude greater than precious element minerals.

Fig. 2.6 Location and relative abundance of PGM and associated minerals from Donaldson West (160-224). Small dots=present, large dots=common. X=trace for pyrite only, dashed lines=locations of veins; Spr=sperrylite, Sud=sudburyite, Tes=testibiopalladite, Unk=unknown ($\text{Pd}_3\text{Sb}_2\text{Te}_2$), Mer=merenskyite, Mel=melonite, Ele=electrum, Hes=hessite, Cpb=cobaltite, Pyr=pyrite, Asp=arsenopyrite, diss=disseminated, net=net-textured, n to rn=net-textured to reverse net-texture, rev=reverse net-texture, msv=massive sulfide.

mally mobilized parts of the deposit (Fig. 6 and Table 1), where the following features are significant: 1) the abundance, size, and diversity of PGM are greatest in the veins; 2) while PGM are dominantly included in sulfides regardless of the degree of deformation, they also occur as rare, free PGM in silicates (in strongly deformed rocks), and rarely at sulfide/silicate and sulfide/carbonate grain contacts (veins); 3) Au- and Ag-bearing phases have only been observed in veins; 4) the cobaltite content correlates positively with pyrite abundance; 5) pyrite is most abundant in veins and sheared parts of the deposit; 6) Pd-bearing PGM are more common than Pt-bearing PGM, consistent with the relative abundances of Pd and Pt; 7) Bi-rich minerals are absent, reflecting the low abundance of this element; and 8) melonite is an important host for Pd in the massive sulfides.

Major-Element and Platinum-Group-Element Distribution

The investigation of thermal- and dynamic-metamorphic PGE redistribution in the 160-224 drill core is based on 12 fire assay neutron activation (FANA) analyses and 49 fire assay atomic absorption spectrophotometry (FAAAS) analyses. The FANA analyses (Table 2) were performed on small (500 gm) sulfide samples, mainly from veins, by Neutron Activation Services Ltd., Hamilton and Bondar Clegg and Co. Ltd. Ottawa, following the method of Hoffman et al. (1978). Ni and

Table 2.2. Chemical compositions of specimens from Donaldson West core hole 160-224 grab samples. Fire assay neutron activation data. Data in parentheses recalculated to 100 % sulfides.

Depth Ore		Ni	Cu	Co	S	Pt	Pd	Au	Os	Ir	Ru	Rh	Se	As	Ag	Sb	Bi	Te
(m)	text		(wt %)					(ppb)							(ppm)			
198.2	1	1.88	0.39	0.05	2.96	860	1900	17	55	45	260	130	8	4	2.5	9.5	0.5	0.4
		(22.2)	(4.6)	(0.5)	(35.0)	(10156)	(22437)	(200)	(649)	(531)	(3070)	(1535)	(94)	(47)	(30)	(112)	(5.9)	(1.0)
224.0	1	0.56	0.19	0.02	1.67	210	360	97	17	15	76	33	10	2	0.8	2.5	3.0	0.2
		(12.4)	(4.2)	(0.4)	(36.9)	(4635)	(7947)	(2141)	(375)	(331)	(1677)	(728)	(220)	(44)	(17)	(55)	(88)	(4.4)
239.5	6	10.60	8.52	0.06	34.9	1700	17000	1900	<	1	10	6	76	10	76.0	22.0	<	1.0
		(11.1)	(8.9)	(0.1)	(36.5)	(1775)	(17756)	(1984)	<	(1)	(10)	(6)	(79)	(10)	(78)	(23)	<	(1.0)
244.5	2	4.72	1.08	0.06	9.38	1500	4000	32	53	42	220	170	29	24	4.0	4.2	0.4	0.6
		(18.0)	(4.1)	(0.2)	(35.8)	(5726)	(15271)	(122)	(202)	(160)	(840)	(649)	(111)	(92)	(15)	(16)	(1.5)	(2.3)
248.7	2	3.88	0.57	0.04	8.99	2030	1300	35	80	27	860	130	24	17	2.1	2.6	3.0	3.0
		(15.8)	(2.3)	(0.2)	(35.5)	(8240)	(5276)	(142)	(324)	(109)	(3490)	(527)	(97)	(68)	(8)	(11)	(12)	(12)
253.3	6	21.1	0.54	0.22	29.9	1200	25000	510	12	7	35	71	80	98	1.5	20.0	1.5	0.6
		(24.7)	(0.6)	(0.3)	(35.0)	(1406)	(29294)	(597)	(14)	(8)	(41)	(83)	(94)	(115)	(2)	(23)	(1.8)	(0.8)
257.6	3	3.84	0.77	0.06	8.75	630	3600	71	35	29	140	11	23	13	4.0	5.4	1.1	0.4
		(15.9)	(3.2)	(0.2)	(36.3)	(2615)	(14947)	(294)	(145)	(120)	(581)	(456)	(95)	(53)	(17)	(22)	(4.6)	(1.9)
258.5	6	8.92	8.07	0.09	23.6	290	4900	190	3	4	15	19	37	22	18.0	3.9	0.1	0.4
		(13.4)	(12.2)	(0.1)	(35.6)	(436)	(7381)	(286)	(4)	(6)	(23)	(29)	(56)	(33)	(27)	(6)	(0.2)	(0.6)
264.9	4	2.00	0.86	0.03	6.49	2200	3900	275	31	21	101	67	11	8	3.3	7.0	1.0	3.5
		(12.2)	(5.3)	(0.2)	(36.7)	(12455)	(22079)	(1556)	(175)	(118)	(571)	(379)	(62)	(45)	(18)	(40)	(5.7)	(20)
269.8	4	3.76	0.66	0.05	10.9	1630	2900	70	20	14	130	17	36	9	2.7	4.9	1.0	2.5
		(12.8)	(2.3)	(0.2)	(37.0)	(5541)	(9858)	(237)	(67)	(47)	(441)	(57)	(122)	(30)	(9.2)	(17)	(3.4)	(8.5)
273.5	7	11.0	0.05	0.11	40.6	2500	1200	18	380	305	1850	810	78	13	0.5	0.8	2.3	0.6
		(11.0)	(0.1)	(0.1)	(40.6)	(2500)	(1200)	(18)	(380)	(305)	(1850)	(810)	(78)	(13)	(0.5)	(1)	(2.3)	(0.6)
274.0	7	9.08	1.56	0.08	42.1	2000	350	32	300	230	1300	660	83	18	3.5	2.2	2.2	0.7
		(9.1)	(1.6)	(0.1)	(42.1)	(2000)	(350)	(32)	(300)	(230)	(1300)	(660)	(83)	(18)	(4)	(2)	(2.2)	(0.7)

Texture code: 1=disseminated; 2=net-textured; 3=net-textured to reverse net-textured; 4=reverse net-textured; 6=vein; 7=massive sulfide; <=below detection limit. Detection limits: Os=3.0 ppb, Se=5ppm, Ag=2ppm, Bi=0.1 ppm.

2

Cu values greater than 4000 ppm were determined by X-ray fluorescence spectrometry (XRF) with a routine precision of ± 5 %. Ni and Cu values less than 4000 ppm, Co, Ag, Bi, and Te were determined by atomic emission-direct current plasma spectroscopy with a routine precision of ± 10 %. S was determined by XRF with a routine precision of ± 5 %, and the precious metals and Se by neutron activation (NA) analysis with a routine precision of ± 10 %.

The 49 FAAAS analyses (Table 3) were performed commercially for Falconbridge Ltd., Toronto. Ni, Cu, and Co were determined by atomic absorption spectrophotometry with a routine precision of ± 10 -15 % and S was determined gravimetrically with a precision of ± 5 %. Pt and Pd were determined by FAAAS with an estimated precision of ± 400 ppb for Pt and ± 200 ppb for Pd and a detection limit of 800 ppb for both Pt and Pd. The data in Table 3 represent split core samples ranging from 0.6 to 2.7 m in length, averaging 1.0 m in length. The samples termed "veined" (Table 3) refer to sample sections which contain sulfide veins less than 0.2 m in thickness. One sample in Table 3 (253.9 m) is from a 1.0 m thick sulfide vein.

Element correlations

Correlation matrices for mixed data sets are presented in Tables 4 and 5a; they give limited support to the petrographic observations that the veins and to a lesser

Table 2.3. Chemical composition of specimens from Donaldson West core hole 160-224.

Depth range (m)	Ore text	wt %				ppb			
		Ni	Cu	Co	S	Pt		Pd	
211.9-213.9	1	1.03 (20.1)	0.21 (4.1)	0.02 (0.4)	1.82 (35.4)	1600 (31149)		1200 (23362)	
213.9-215.9	1	0.82 (18.7)	0.16 (3.6)	0.03 (0.5)	1.57 (35.8)	1600 (36438)		1200 (27328)	
215.9-217.9	1	1.11 (17.3)	0.21 (3.3)	0.03 (0.4)	2.31 (36.1)	2400 (37464)		1200 (18732)	
217.9-219.9	1	0.93 (16.3)	0.20 (3.5)	0.02 (0.3)	2.07 (36.2)	1600 (28001)		1200 (21001)	
219.9-221.9	1	1.01 (15.8)	0.18 (2.8)	0.02 (0.4)	2.32 (36.4)	800 (12552)		800 (12552)	
221.9-223.9	1	0.73 (15.7)	0.14 (3.0)	0.02 (0.4)	1.69 (36.4)	1600 (34460)		nd	nd
223.9-225.9	1	1.02 (19.0)	0.18 (3.4)	0.02 (0.4)	1.92 (35.7)	1600 (29781)		2000 (37226)	
225.9-227.9	1	0.57 (17.8)	0.11 (3.4)	0.02 (0.5)	1.15 (35.9)	1600 (50010)		800 (25005)	
227.9-229.7	1	0.55 (15.7)	0.24 (6.8)	0.02 (0.4)	1.26 (35.9)	1600 (45557)		1200 (34168)	
229.7-232.4	1	0.75 (16.2)	0.18 (3.9)	0.02 (0.5)	1.67 (36.2)	2400 (51990)		1600 (34660)	
232.4-233.0	1	0.24 (13.1)	0.04 (2.2)	0.01 (0.6)	0.68 (37.0)	1600 (87097)		nd	nd
233.0-235.0	1	0.98 (16.5)	0.18 (3.0)	0.02 (0.3)	2.16 (36.3)	1600 (26859)		1200 (20144)	
235.0-237.0	1	0.79 (16.1)	0.18 (3.7)	0.02 (0.4)	1.78 (36.2)	1600 (32575)		1200 (24431)	
237.0-239.3	2	2.28 (15.1)	0.84 (5.6)	0.05 (0.3)	5.47 (36.2)	800 (5289)		1600 (10578)	
239.3-240.4	5	5.25 (15.9)	1.61 (4.9)	0.06 (0.2)	11.9 (36.1)	2400 (7280)		2400 (7280)	
240.4-241.4	2	4.17 (16.3)	0.99 (3.9)	0.06 (0.2)	9.24 (36.2)	1600 (6262)		6400 (25049)	
241.4-242.4	2	4.17 (15.2)	1.20 (4.4)	0.06 (0.2)	9.95 (36.3)	3200 (11675)		3200 (11675)	
242.4-243.4	2	4.70 (16.4)	0.71 (2.5)	0.06 (0.2)	10.4 (36.3)	2400 (8386)		2800 (9784)	
243.4-244.4	2	4.82 (16.4)	0.75 (2.5)	0.06 (0.2)	10.7 (36.3)	3200 (10868)		4400 (14944)	
244.4-245.4	2	5.33 (16.3)	1.21 (3.7)	0.07 (0.3)	11.8 (36.2)	2800 (8586)		5000 (15332)	
245.4-246.4	2	5.38 (17.0)	1.18 (3.7)	0.06 (0.2)	11.4 (36.1)	4800 (15181)		3200 (10120)	
246.4-247.4	3	5.58 (16.7)	0.82 (2.5)	0.06 (0.2)	12.1 (36.3)	4800 (14394)		6800 (20392)	
247.4-248.4	5	3.94 (12.2)	2.53 (7.9)	0.06 (0.2)	11.7 (36.4)	2400 (7461)		4400 (13679)	
248.4-249.4	2	4.87 (17.3)	1.14 (4.1)	0.06 (0.2)	10.1 (35.9)	3200 (11389)		4000 (14237)	
249.4-250.4	2	4.20 (15.1)	1.13 (4.4)	0.05 (0.2)	10.1 (36.4)	2000 (7200)		2400 (8641)	
250.4-251.4	3	6.14 (18.3)	0.74 (2.2)	0.08 (0.2)	12.1 (36.0)	4000 (11910)		2400 (7146)	
251.4-252.4	5	5.85 (16.4)	1.98 (5.6)	0.07 (0.2)	12.8 (35.9)	3200 (8978)		3800 (10661)	
252.4-253.4	2	4.97 (16.8)	0.95 (3.2)	0.06 (0.2)	10.7 (36.2)	3200 (10816)		1600 (5408)	
253.4-254.4	6	8.71 (17.7)	1.81 (3.7)	0.10 (0.2)	17.7 (35.9)	3200 (6497)		20000 (40606)	
254.4-255.4	2	4.49 (15.7)	1.46 (5.7)	0.06 (0.2)	10.3 (36.1)	3200 (11216)		3200 (11216)	
255.4-256.4	3	3.02 (16.7)	0.45 (2.5)	0.05 (0.2)	6.58 (36.3)	2400 (13239)		3200 (17652)	
256.4-257.4	3	3.32 (15.2)	0.58 (2.7)	0.05 (0.2)	7.98 (36.5)	1600 (7327)		3400 (15571)	
257.4-258.4	3	5.55 (18.3)	0.64 (2.1)	0.08 (0.3)	10.9 (36.0)	2400 (7933)		2400 (7933)	
258.4-259.4	5	2.28 (9.4)	3.05 (12.5)	0.04 (0.1)	8.84 (36.3)	2400 (9847)		3200 (13129)	
259.4-260.4	5	3.84 (13.5)	2.00 (7.0)	0.05 (0.2)	10.3 (36.3)	1600 (5631)		2400 (8447)	
260.4-261.4	3	3.20 (15.6)	0.74 (3.6)	0.05 (0.3)	7.45 (36.3)	2400 (11705)		4400 (21460)	
261.4-262.4	3	2.73 (15.1)	0.83 (4.6)	0.04 (0.2)	6.58 (36.3)	3200 (17655)		5200 (28690)	
262.4-263.4	4	3.03 (15.2)	1.08 (5.4)	0.04 (0.2)	7.21 (36.2)	1600 (8024)		4400 (22068)	
263.4-264.4	4	2.23 (9.8)	1.00 (4.4)	0.04 (0.2)	8.48 (37.3)	1600 (7041)		2800 (12322)	
264.4-265.4	4	2.97 (14.4)	1.25 (6.1)	0.04 (0.2)	7.46 (36.2)	2400 (11651)		4000 (19419)	
265.4-266.4	4	2.64 (14.4)	0.65 (3.6)	0.04 (0.3)	6.68 (36.6)	1600 (8757)		4000 (21893)	
266.4-267.4	4	3.19 (12.3)	1.66 (6.4)	0.05 (0.2)	9.47 (36.6)	1600 (6177)		3200 (12355)	
267.4-268.4	4	3.66 (13.2)	0.88 (3.2)	0.06 (0.2)	10.2 (36.8)	1600 (5779)		3600 (13004)	
268.4-269.4	4	3.68 (13.8)	0.72 (2.7)	0.06 (0.2)	9.79 (36.8)	2400 (9020)		3600 (13531)	
269.4-270.4	4	3.13 (13.5)	0.70 (3.0)	0.06 (0.2)	8.55 (36.8)	2400 (10335)		4800 (20671)	
270.4-271.4	4	3.53 (11.2)	0.90 (2.8)	0.06 (0.1)	11.8 (37.3)	4000 (12638)		5200 (16430)	
271.4-272.4	5	4.38 (9.9)	2.81 (6.3)	0.08 (0.2)	16.4 (37.0)	3200 (7225)		5200 (11741)	
272.4-273.4	5	4.73 (11.4)	1.50 (3.6)	0.09 (0.2)	15.4 (37.1)	3200 (7714)		3600 (8679)	
273.4-274.2	7	12.6 (13.9)	0.77 (0.8)	0.16 (0.2)	33.6 (37.0)	3200 (3528)		1600 (1764)	

X-ray fluorescence and fire assay atomic absorption spectrometry (FAAAS) data. Data in parentheses recalculated to 100% sulfides. Texture code: 1=disseminated; 2=net-textured; 3=net-textured to reverse net-textured; 4=reverse net-textured; 5=veined; 6=vein; 7=massive sulfide; nd=not detected. Ni, Cu, Co, S by X-ray fluorescence; precious metals by FAAAS detection limits for Pt and Pd=800 ppb.

Table 2.4. Correlation matrix for fire assay neutron activation data from Donaldson West core hole 160-224. N=12; at 0.95 confidence level values above 0.58 are significant.

	Ni	Cu	S	Co	Pt	Pd	Ir	Os	Ru	Rh	Au	Se	As	Ag	Sb	Bi	Te
Ni	1.00																
Cu	-.18	1.00															
S	-.69	-.42	1.00														
Co	.59	-.07	-.50	1.00													
Pt	.16	-.11	-.24	.46	1.00												
Pd	.72	.09	-.72	.40	.28	1.00											
Ir	.11	-.29	.20	.69	.40	-.13	1.00										
Os	.12	-.35	.20	.64	.50	-.19	.96	1.00									
Ru	.13	-.36	.12	.47	.50	-.30	.70	.87	1.00								
Rh	.22	-.31	.13	.67	.46	-.07	.97	.97	.78	1.00							
Au	-.25	.36	-.21	.12	.10	.29	-.10	-.18	-.27	-.23	1.00						
Se	.00	-.23	-.07	.51	.04	-.13	.33	.28	.21	.21	.41	1.00					
As	.78	-.26	-.57	.31	.24	.61	-.18	-.12	-.02	-.04	-.10	.08	1.00				
Ag	.02	.85	-.55	.34	.20	.30	.10	.02	-.08	.09	.40	-.06	-.22	1.00			
Sb	.46	.09	-.46	.91	.57	.51	.68	.61	.39	.65	.26	.29	.11	.54	1.00		
Bi	-.15	-.04	-.03	.48	.08	-.18	.36	.31	.24	.21	.58	.90	-.01	.06	.31	1.00	
Te	-.11	-.05	-.15	.06	.84	.16	-.06	.08	.22	-.02	.24	-.04	.19	.03	.16	.07	1.00

Table 2.5a. Correlation matrix for fire-assay atomic absorption spectrophotometry data from Donaldson West core hole 160-224. N=49; at 0.95 confidence level values above 0.29 are significant.

	Ni	Cu	Co	S	Pt	Pd
Ni	1.00					
Cu	.45	1.00				
Co	.96	.47	1.00			
S	.95	.55	.97	1.00		
Pt	.62	.33	.56	.57	1.00	
Pd	.49	.42	.45	.43	.38	1.00

Table 2.5b. Correlation matrix for fire-assay atomic absorption spectrophotometry data of disseminated sulfides from Donaldson West core hole 160-224. N=13; at 0.95 confidence level values above 0.55 are significant.

	Ni	Cu	Co	S	Pt	Pd
Ni	1.00					
Cu	.68	1.00				
Co	.85	.52	1.00			
S	.94	.65	.80	1.00		
Pt	.03	.13	.10	-.02	1.00	
Pd	.41	.45	.30	.28	.40	1.00

Table 2.5c. Correlation matrix for fire-assay atomic absorption spectrophotometry data of net-textured sulfides from Donaldson West core hole 160-224. N=11; at 0.95 confidence level values above 0.60 are significant.

	Ni	Cu	Co	S	Pt	Pd
Ni	1.00					
Cu	.25	1.00				
Co	.84	.42	1.00			
S	.97	.32	.83	1.00		
Pt	.79	.39	.62	.76	1.00	
Pd	.34	.11	.44	.32	.03	1.00

Table 2.5d. Correlation matrix for fire-assay atomic absorption spectrophotometry data of net-textured to reverse net-textured sulfides from Donaldson West core hole 160-224. N=7; at 0.95 confidence level values above 0.75 are significant.

	Ni	Cu	Co	S	Pt	Pd
Ni	1.00					
Cu	.28	1.00				
Co	.89	.02	1.00			
S	.98	.36	.82	1.00		
Pt	.60	.67	.20	.65	1.00	
Pd	-.15	.60	-.52	-.01	.54	1.00

Table 2.5e. Correlation matrix for fire-assay atomic absorption spectrophotometry data of reverse net-textured sulfides from Donaldson West core hole 160-224. N=9; at 0.95 confidence level values above 0.67 are significant.

	Ni	Cu	Co	S	Pt	Pd
Ni	1.00					
Cu	-.08	1.00				
Co	.88	-.36	1.00			
S	.68	.01	.70	1.00		
Pt	.43	-.20	.60	.62	1.00	
Pd	.36	-.36	.56	.17	.70	1.00

Table 2.5f. Correlation matrix for fire-assay atomic absorption spectrophotometry data of vein and veined sulfides from Donaldson West core hole 160-224. N=8; at 0.95 confidence level values above 0.70 are significant.

	Ni	Cu	Co	S	Pt	Pd
Ni	1.00					
Cu	-.59	1.00				
Co	.80	-.44	1.00			
S	.74	-.36	.97	1.00		
Pt	.53	.13	.79	.78	1.00	
Pd	.82	-.17	.70	.67	.43	1.00

extent veined material, which have unique mineralogical and major-element compositions, have distinct trace-element compositions. The poor correlations for some trace-elements found in veins as unique precious metal minerals, are attributed to the dilution effect of the non-veined specimens in the specimen data set.

In the FANA data (Table 4), Pt correlates weakly with the Os-Ir-Ru-Rh group and Sb, and moderately with Te. Pd exhibits weak negative correlations with the Os-Ir-Ru-Rh group. Pd correlates moderately with Sb and As. Cu correlates strongly with Ag, weakly with Au, and weakly but negatively with the Os-Ir-Ru-Rh group and Pt. Au correlates moderately with Bi. Ag correlates weakly with Sb.

FAAAS data correlations (Table 5a) imply that sulfides enriched in Cu are also weakly to moderately enriched in Pd, Pt, and Co. However, this contradicts the FANA correlations for Pt, and mineralogical observations. The weak correlation of Co and Pt with Ni is not observed in Ni-rich veins; the Co may be related to Co held in pentlandite solid solution (Appendix C-2) and the Pt is thought to be related to the presence of sperrylite in pentlandite-rich sulfide blebs.

The correlation matrices from individual sulfide textural types (Tables 5b to 5f inclusive) show the effect of increasing metamorphic mobilization upon the major elements. The lack of correlation exhibited by Pt and Pd in the disseminated sulfides (Table 5b) is compatible with the

proposed analytical uncertainty for these weakly altered rocks. Net-textured sulfides show strong correlations between Ni, Co, S, and Pt (Table 5c) compatible with the low degree of metamorphic mobilization there. With increasing sulfide mobilization these correlations decrease and correlations with Pt are not significant (see Tables 5d and 5e). Correlations from the vein and veined data set (Table 5f) show the expected negative correlations between Cu and Ni, Co, and S. The positive correlation between Pd and Ni in the vein and veined sulfide group is suggested to reflect the inclusion of non-veined material in the sample intervals.

Analyses recalculated to 100 % sulfides

Recalculation of the metal concentration in 100 % sulfides, based on the assumption that the trace elements were precipitated as magmatic sulfides, permit the different textural types with widely varying sulfide contents to be compared. The FANA and FAAAS data were recalculated to 100 % sulfides assuming that the original sulfide assemblage was of monoclinic pyrrhotite, pentlandite (36 wt % Ni), and stoichiometric chalcopyrite (cf. Naldrett, 1981).

The Ni and Cu contents of eight specimens containing veins (Table 3) imply that a continuous range of vein compositions occurs from Ni-rich to Cu-rich. Excluding the Ni-rich and Cu-poor vein (253.4-254.4a), five of the seven

veined specimens are Ni-depleted and Cu-rich compared with the adjacent rocks, one veined specimen (251.4-252.4m) has average Ni and high Cu, and one (239.3-240.4m) has average Ni and Cu. This apparent mid range of sympathetic Ni and Cu values may be a sampling problem as suggested by a grab sample (FANA) from 239.5m (Table 2) which shows that this vein is in fact Cu-rich and Ni-poor compared to adjacent sulfides. These observations indicate that two vein types occur; 1) Cu-rich and Ni-poor, and 2) Ni-rich and very Cu-poor. Petrographic examination of sulfide veinlets certainly does not suggest a continuum of vein types with the above types as end members.

High Pt and Pd concentrations in the disseminated sulfides decrease abruptly at the contact between the net-textured and disseminated sulfides (Fig. 7). This may be related in part to the analytical uncertainty of the PGE analyses and low sulfide content of these rocks. Alternatively the high Pt and Pd values could represent either inhomogeneity of the primary magma or metamorphic alteration.

Whole rock analyses of disseminated sulfides (Tables 2 and 3) plot close to the monosulfide solid solution field (at 600 °C); suggesting minimal gain or loss of S during serpentinization and metamorphism, within the precision of the analyses (cf. Barnes and Naldrett, 1987). Examination of FANA analyses of disseminated material (198.2m and 224.2m, Table 2) give recalculated values for Pt and Pd of about 10 and 20 ppm respectively, similar to the average values for

Fig. 2.7 Plots of Cu, Ni, Pt, and Pd (recalculated to 100 % sulfides) vs. depth and textural type. The locations of the veins are shown as dashed lines. Abbreviations given in Figure 2.6.

the net-textured sulfides (see Fig. 7).

The zone of reverse net-textured sulfides (Fig. 6) is moderately depleted in Ni and moderately enriched in Pd compared to the overlying sulfide zones. Massive sulfides are significantly depleted in Cu, Pt, Pd, and to a lesser extent Ni, compared to the overlying zones.

Analyses of veins and veined material do not show small scale (1 to 3 m) symmetrical depletion or enrichment of Ni or Cu (see Fig. 7); this suggests that the vein elements were not locally derived but may have been derived from a large rock volume.

The recalculated S content of the Cu-rich veined material (Table 3) is similar to that of the surrounding rocks except for two specimens at the upper contact with massive sulfides (271.4-273.4m). The high S/Ni of the other Cu-rich veined material may therefore be attributed to the low Ni content of the veins. The high S/Ni of the reverse net-textured sulfides may have resulted from a combination of minor sulfidation and the significant depletion of Ni (Fig. 7).

Po/Pn, calculated from 100 % sulfide data (Table 6), show a steady increase with depth in the reverse net-textured zone reflecting the decrease in Ni. High ratios may occur where chalcopyrite-rich veins or veined sulfides have been identified and elsewhere (Fig. 8).

A plot of metal ratios (Fig. 9) shows that the data from major sulfide textural types may be grouped into three

Table 2.6. Calculated pyrrhotite, pentlandite, and Po/Pn from 100 % sulfides, Donaldson West core hole 160-224.

Depth (m)	Ore texture	Pyrrhotite (% Po)	Pentlandite (% Pn)	Po/Pn
211.9-213.9	1	1.61	2.93	0.55
213.9-215.9	1	1.59	2.35	0.68
215.9-217.9	1	2.66	3.16	0.84
217.9-219.9	1	2.50	2.64	0.95
219.9-221.9	1	2.99	2.87	1.04
221.9-223.9	1	2.16	2.09	1.03
223.9-225.9	1	1.97	2.89	0.68
225.9-227.9	1	1.26	1.63	0.77
227.9-229.7	1	1.26	1.57	0.80
229.7-232.4	1	1.96	2.14	0.92
232.4-233.0	1	1.03	0.70	1.47
233.0-235.0	1	2.66	2.79	0.95
235.0-237.0	1	2.14	2.26	0.95
237.0-239.3	2	6.26	6.46	0.97
239.3-240.4	5	13.6	14.7	0.92
240.4-241.4	2	11.0	11.7	0.94
241.4-242.4	2	12.2	11.8	1.04
242.4-243.4	2	13.4	13.2	1.01
243.4-244.4	2	13.8	13.6	1.01
244.4-245.4	2	14.1	15.0	0.94
245.4-246.4	2	13.1	15.1	0.87
246.4-247.4	5	15.3	15.7	0.98
247.4-248.4	5	13.8	11.1	1.24
248.4-249.4	2	11.1	13.7	0.81
249.4-250.4	2	12.7	11.8	1.08
250.4-251.4	5	14.2	17.3	0.82
251.4-252.4	5	13.5	16.4	0.82
252.4-253.4	2	12.9	14.0	0.92
253.4-254.4	6	19.6	24.5	0.80
254.4-255.4	2	11.7	12.7	0.92
255.4-256.4	3	8.33	8.52	0.98
256.4-257.4	3	10.8	9.37	1.15
257.4-258.4	3	12.8	15.6	0.82
258.4-259.4	5	9.13	6.45	1.42
259.4-260.4	5	11.8	10.8	1.09
260.4-261.4	3	9.36	9.03	1.04
261.4-262.4	3	8.05	7.70	1.04
262.4-263.4	4	8.30	8.54	0.97
263.4-264.4	4	13.6	6.29	2.16
264.4-265.4	4	8.64	8.37	1.03
265.4-266.4	4	8.96	7.46	1.20
266.4-267.4	4	12.1	9.00	1.35
267.4-268.4	4	14.8	10.3	1.44
268.4-269.4	4	14.2	10.4	1.36
269.4-270.4	4	12.4	8.86	1.40
270.4-271.4	4	19.1	9.98	1.91
271.4-272.4	5	23.8	12.4	1.92
272.4-273.4	5	23.8	13.4	1.78
273.4-274.2	7	53.1	35.4	1.50

Texture code: 1=disseminated; 2=net-textured; 3=net-textured to reverse net-textured; 5=veined; 6=vein; 7=massive sulfide.

160-224

Fig. 2.8 Plot of Po/Pn against depth and sulfide textural type. Concentration of pyrrhotite and pentlandite calculated from 100 % sulfide recalculations (Table 6). Note ratio increase in the reverse net-textured zone compared to less modified zones. Stars show location of veins and veined sulfides.

Fig. 2.9 Pd/Pt vs. S/Ni for various strata and textural types. Open symbols=fire assay neutron activation data and closed symbols=fire assay atomic absorption data where: dots=disseminated; stars=net-textured; stars in squares=net-textured to reverse net-textured; diamonds=reverse net-textured; circled triangles=veined (fire assay atomic absorption spectrophotometry only); triangle=vein; and square=massive sulfides.

fields. The disseminated, net-textured, and the net-textured to reverse net-textured sulfides of field A represent the least deformed group of rocks. The order of magnitude range of the Pd/Pt, but only minor S/Ni variation, may reflect a primary magmatic distribution or analytical uncertainty. Field B includes data from reverse net-textured and veined sulfides with high S/Ni. Analyses of massive sulfide (see Tables 2 and 3) also indicate high S/Ni and very low Pd/Pt. Data from Cu- and Ni-rich veins (Tables 2 and 3) plot in field C with high Pd/Pt.

Chondrite-normalized PGE distributions in 100 % sulfides from disseminated, net-textured, and net-textured to reverse net-textured sulfides (Fig. 10) display patterns characteristic of ores from Proterozoic komatiitic magmas (Naldrett, 1981). In contrast, the massive sulfides have much lower contents of Pd and Au, whereas the veins have very low Os-Ir-Ru-Rh contents with associated high Pd and Au concentrations. One specimen of reverse net-texture (analysis 10, Fig. 10), from the most altered part, displays a profile which is intermediate to the least altered and the vein sulfides.

Fig. 2.10 C1 chondrite-normalized PGE data (recalculated to 100% sulfides). Numbers refer to analyses in Table 2.2 where; 1=198.2m, 2=224.0m, 3=239.5m, 4=244.5m, 5=248.7m, 6=253.3m, 7=257.6m, 8=258.5m, 9=264.9m, 10=269.8m, 11=273.5m, and 12=274.0m. Textural symbols as Figure 2.9. Shaded zone refers to the komatiite field of Naldrett (1981). C1 chondrite values after Naldrett et al. (1982).

Discussion

Mobilization of Fe-Ni-Cu sulfide

Examination of drill core 160-224 through the Donaldson West deposit suggests that the primary distribution of sulfides (and PGE) within the deposit has been extensively modified during the prevalent thermal metamorphic regime (D₁-D₂) and localized dynamic metamorphism. The mobilization of sulfides in the disseminated, net-textured, and net-textured to reverse net-textured zones during thermal metamorphism is interpreted to have been dominantly on a cm-scale. The development of the reverse net-texture is believed to reflect the variable transformation of former net-textured sulfides. It is suggested that the depletion of sulfides in this zone may have occurred at the same time as the cumulus olivine grains or their metamorphic-equivalent assemblages were being pseudomorphically replaced by sulfides.

Groves et al. (1974) reported spherical sulfide blebs of the same size and location as olivine pseudomorphs. There However, talc-carbonate alteration postdated the sulfide. Keple and Nickel (1974) reported primary sulfide blebs at Kambalda. The sulfide blebs at Donaldson West are interpreted to be secondary, variably pseudomorphically replaced pyroxene oikocrysts.

The location of chalcopyrite-rich veins, mostly at the

contacts between sulfide textural types, may have been controlled by competency contrasts during deformation. Other Cu-rich and Ni-rich veins within the net-textured sulfides are apparently concordant with the regional S_1 - S_2 schistosity. There is no evidence for local depletions (1 to 3 m-scale) of either Cu or Ni from the adjacent rocks, implying that most vein sulfides were derived from a large volume of rock and transported over distances of perhaps tens of metres. Similarly, the significant depletion of Ni and sulfides in the reverse net-textured sulfide zone suggests their mobilization over a distance of 10 m during thermal metamorphism.

Keays et al. (1981) suggested that the movement of S from matrix sulfides (disseminated and net-textured) to the massive layer at Lunnon Shoot could account for the higher Ni content of the sulfides in the matrix layer and the presence of secondary pyrite in the massive layer. At Donaldson West there is no significant increase in S in the reverse net-textured sulfides compared to its average concentration in the more disseminated sulfides. This implies that Ni was selectively removed from the reverse net-textured sulfides. Ni-rich veins are rare at Donaldson West, but it is possible that areas of Ni enrichment occur outside of the studied core.

Platinum-group element mobilization

The high concentrations of Pd and Pt in the disseminated sulfides may represent fractionation during metamorphism. Cowden and Woolrich (1986) have suggested that fO_2 variations during emplacement of the Kambalda Fe-Ni-Cu sulfides could cause primary variations in base metal and (by extrapolation) precious metal concentrations. However, evidence of primary variable fO_2 concentrations in the sulfide-silicate magma manifested by the presence or absence of magnetite has not been identified at Donaldson West. Metamorphic enrichment of Ni, Cu, Pt, and Pd at Lunnon shoot (Kambalda) was suggested by Ross and Keays (1979) for the disseminated zone where selective element depletion exists in deformed net-textured and massive sulfides.

The high Pd and low Pt concentrations in the reverse net-textured sulfides suggest that Pt was fractionated from Pd and lost, or that Pd was introduced. Pt is low in both the Cu- and Ni-rich veins at Donaldson West in contrast to the high Pt content in Cu-rich stringers at the Levack West deposit, Sudbury (Naldrett et al. 1982).

A potential source of Pd in the reverse net-textured zone could have been the underlying Pd-depleted massive sulfides. Similar strong Cu, Au and Pd depletion of massive sulfides has been reported at Kambalda (Ross and Keays, 1979; Keays et al. 1981; Cowden et al. 1986). The source of Pd and other trace elements found in the veins may have been a large volume of sulfide-bearing rocks as there does not appear to be local mobilization into the veins.

Chondrite normalized PGE data indicate that Pt and Pd in the veins were fractionated from the Os-Ir-Ru-Rh group, as is characteristic of hydrothermal mobilization of PGE at Kambalda (Lesher and Keays, 1984). The intermediate chondrite normalized profile of a specimen from the reverse net-textured zone suggests a low degree of PGE fractionation occurred during thermal metamorphism.

It is proposed that the deformation of the massive sulfides was accompanied by loss of Cu, Pd, Pt, and Au, and to a lesser extent Ni. While some Pd from the massive sulfides may have migrated into the reverse net-textured zone and some Cu may have been mobilized into footwall stringers, both could have been dissolved in hydrothermal fluids and precipitated in veins throughout the Donaldson West deposit. The addition of sulfur to the massive sulfides from footwall contamination would effectively "dilute" all elements, however, the Os-Ir-Ru-Rh group do not show lower values on the chondrite normalized plot, suggesting that selective migration of elements has occurred.

The moderately negative correlation Pd exhibits with the Os-Ir-Ru-Rh group and to a lesser extent Pt, and the strong correlation of Pt and the Os-Ir-Ru-Rh group suggests that the latter elements behaved similarly during metamorphic events and is compatible with the petrographic evidence that, of these elements, Pd was preferentially mobilized at Donaldson West.

The distribution and form of PGM, PGE- and Au- and Ag-

bearing phases, and Co and As minerals in the Donaldson West deposit are generally compatible with their exsolution from enclosing high-temperature sulfides and growth in or along sulfide grain margins in both thermally and dynamically metamorphosed rocks. However, in dynamically metamorphosed rocks they are also found as free grains or at sulfide/silicate grain boundaries, possibly indicating precipitation directly from hydrothermal fluids.

The stress-induced dissolution of sulfides could have released elements that were transported hydrothermally and deposited in fractures. The Pd-bearing PGM and PGE-, Au- and Ag-bearing minerals located in the veins are more abundant, consist of a more diverse assemblage, and are generally coarser-grained than similar minerals in surrounding sulfides, suggestive that they exsolved in the presence of a fluid phase.

Conclusions

During thermal metamorphism of disseminated and net-textured rocks at the Donaldson West deposit the following textures were developed: 1) sulfide/silicate intergrowths in disseminated sulfides, 2) transitions from net-textured to reverse net-textured sulfides, and 3) large (cm-scale) sulfide blebs in disseminated and net-textured sulfides. Thermal metamorphism did not greatly affect the distribution of Pt and Pd, but the reverse net-textured sulfides

were depleted in Ni and enriched in Pd. Deformation of massive sulfides resulted in mobilization of Cu, Au, Pd, Pt, and minor Ni. Hydrothermal transport of PGE, Au, Ag, Sb, Te, Co, and As during upper greenschist facies metamorphism resulted in their precipitation in sulfide veins in the non-massive sulfides.

CHAPTER 3

Platinum-Group Element and Platinum-Group Mineral
Distribution in the Donaldson Surface Deposit, Cape Smith
Belt, Quebec: the Roles of Thermal and Dynamic Metamorphism.

Abstract

The distribution of primary magmatic sulfides and platinum-group elements (PGE) in the symmetrically zoned, ultramafic Donaldson Surface sill was extensively modified during regional upper greenschist facies metamorphism. Mobilization of elements in net-textured sulfides during thermal metamorphism caused partial pseudomorphic replacement of serpentinized cumulus olivine grains (net-texture to reverse net-texture) and generation of sulfide blebs in net-textured sulfides. Sulfide-carbonate veins, rich in chalcopyrite and platinum-group minerals (PGM), developed during dynamic metamorphism primarily at contacts of units with differing sulfide textures where there were competency contrasts. A sulfide breccia, rich in sulfarsenides and PGM, developed by similar means at the footwall contact. Chalcopyrite-rich PGM-poor footwall stringers, along and at high angles to bedding, may have developed under similar conditions.

Pt and Pd concentrations in net-textured and massive sulfides were not significantly affected during thermal metamorphism. Cu, Pt, and Pd concentrations in sulfide-poor, interstitial textured rocks were enriched by diffusion from the massive sulfides. Chondrite normalized profiles of assays from the massive sulfides suggest a significant hydrothermal contribution. Dynamically mobilized sulfides show profiles characteristic of PGE fractionation during hydrothermal transport. The Cu-rich veins and the sulfide breccia zone are enriched in Pd, Sb, Te, As, and Co, a feature which is interpreted to result from their strong partitioning into hydrothermal fluids. The greatest abundance, diversity, and size of PGM, precious metal, and telluride grains are found in veins and the sulfide breccia, rocks interpreted to have been generated during dynamic metamorphic events.

Introduction

The Donaldson Surface deposit, one of three separate Ni-Cu zones comprising the Donaldson deposit, is located in deformed and metamorphosed ultramafic rocks of the eastern part of the Aphebian Cape Smith foldbelt (Fig. 1). The Donaldson Surface deposit, situated about 500 m south of the surface projection of the Donaldson West deposit, occurs as a small exposure of Fe-Ni-Cu sulfides along the footwall contact of a shallowly north dipping ultramafic intrusion (Fig. 2). Previous studies of sulfide deposits within the foldbelt have described base metal concentrations in ultramafic rocks of lower metamorphic grade, in less deformed terranes (Wilson et al., 1969; Miller, 1977; Barnes, 1979; Barnes et al., 1982; Albino, 1984). In these and many other studies of Fe-Ni-Cu and platinum-group element (PGE) deposits, magmatic phenomena have been considered sufficient to explain metal distribution in the sulfide ores. However, the fractionation of Ir and Pd during hydrothermal mobilization of PGE was noted by Keays et al. (1981) and Lesher and Keays (1984). Strong fractionation of the Os-Ir-Ru-Rh group from the Pt-Pd-Au group was noted in hydrothermally mobilized veins (Dillon-Leitch et al., 1986). Stress-induced hydrothermal mobilization of PGE has been suggested to explain the Cu- and PGE-rich composition of some "magmatic" Cu-Ni deposits such as those in the Kanichee layered complex (James and Hawke, 1984), the Thierry mine

Fig. 3.1 General geology of the Cape Smith foldbelt (Hynes and Francis 1982a) showing the Donaldson (1); Katiniq (2); 2-3 (3); and Cross Lake (4) Fe-Ni-Cu sulfide deposits.

Fig. 3.2. Surface projections of the Donaldson Surface (3), Donaldson West (1), and Donaldson East (2) deposits. Line C-D refers to Figure 3.3. Geology by Falconbridge Ltd. staff.

(Patterson and Watkinson, 1984), the Kambalda area (Keays and Davidson, 1976; Keays et al., 1981; Cowden et al., 1986), and the Donaldson West deposit (Dillon-Leitch et al., 1986). This paper describes not only the distribution of PGE, Cu, and Ni, but more importantly, the petrology of PGM and associated Au-, Ag-, Te-, Sb-, Bi-, Co-, and As-bearing minerals from the Donaldson Surface deposit (core 160-225). A model is presented to explain Cu- and Ni-rich veins in the sulfide zones and the PGM-rich sulfide breccia at the base of the sulfide zone, their high Pd/Pt ratio, the large size of platinum-group minerals, and the concentrations of Pd, Sb, Te, Bi, Ag, Co, and As in the veins and sulfide breccia and their relationship to deformation and metamorphism.

General Geology

The Cape Smith foldbelt in the vicinity of the Donaldson mine is composed of the Chukotat and Povungnituk Groups. The Povungnituk Group is subdivided into two units; a lower Lamarche Subgroup and an upper Beuparlant Subgroup (Picard, 1986). The Beuparlant Subgroup is predominantly composed of intrusive and extrusive tholeiitic basalt with minor turbidites. The overlying Chukotat Group is composed of komatiitic to tholeiitic basalt and minor sedimentary rocks (Hynes and Francis, 1982a; Francis et al., 1983). Within the Cape Smith foldbelt three types of Fe-Ni-Cu-PGE sulfide deposits occur; symmetrically zoned ultramafic

sills, zoned ultramafic feeder dykes, and layered ultramafic sills (Lamothe et al., 1987). The Donaldson, Katiniq, 2-3, and Cross Lake deposits belong to the symmetrically zoned, subvolcanic sill grouping. The Boundary complex (Albino, 1984) is an intrusive-extrusive example of the same type. All of these symmetrically zoned ultramafic sill-hosted sulfide deposits occur at or just above the Povungnituk-Chukotat contact.

The Cape Smith foldbelt has undergone three phases of regional deformation and metamorphism (Hynes and Francis, 1982b). In the Donaldson mine area D_1 deformation resulted in a steeply north dipping, strong east-west trending S_1 schistosity and upper greenschist metamorphic conditions. D_2 occurred in lower greenschist facies conditions and resulted in steeply north dipping reverse faults, and a weak subvertical, east-west trending, S_2 foliation. D_3 consisted of a weak east-west compression generating subvertical, north-south faults and sporadic S_3 fracture cleavage during retrograde conditions (Albino, 1984). In drill core it is rarely possible to distinguish S_1 and S_2 and the fabric is therefore referred to as S_1 - S_2 .

Geology of the Donaldson Surface Deposit

At the base of this ultramafic sill, about 300 m SW of the surface exposure of the Donaldson Surface deposit, columnar joints, if perpendicular to the contact, indicate

a dip of 45 to 50 degrees north for the southern part of the sill. Surface exposure of mineralization is approximately 100 m by 60 m. It is not clear if the ultramafic sill containing the Donaldson Surface deposit represents more than one separate sill or is part of a single body hosting all three deposits (Donaldson Surface, West, and East) that has been dismembered during regional deformation and faulting (Fig. 2), however, an initial examination of precious and semi-precious elements and metal ratios suggest that rocks of the Donaldson Surface deposit are not part of the same intrusion.

In cross-section the Donaldson Surface deposit has a concave-up form with the deepest part only 30 m below the surface (Fig. 3). Combined surficial exposure and diamond drill core data indicate that the deposit has a saucer-like form in three dimensions, consistent with the hypothesis that magmatic sulfides collected in a footwall depression. Core hole 160-225, located in the centre of the Donaldson Surface deposit and which transects the thickest concentration of sulfides, is representative of sulfide-rich "ore-grade" material only (Appendix K). Erosion has removed the upper part of the mineralized zone. The sill, intruded before metamorphism, developed a one to ten metre hornfels aureole in the underlying sedimentary rocks.

Petrology of the Donaldson Surface Deposit

Fig. 3.3. Cross-section C-D, looking west, through the Donaldson Surface deposit. Core hole 160-225 is 12 m west of section.

Core hole 160-225, through the Donaldson Surface deposit, was examined at approximately one metre intervals from 6.7 m to 32.6 m below the surface. The ultramafic rocks hosting the Donaldson Surface deposit grade upward from hornblende-rich pyroxenite (Fig. 4), with less than 10% cumulus olivine, through olivine pyroxenite (10 to 40% cumulus olivine) into peridotite (40 to 90% cumulus olivine). Dunite (greater than 90% cumulus olivine) is not present in this core hole. The silicate nomenclature is that of Streckeisen (1976).

Antigorite and magnetite occur as pseudomorphs of cumulus olivine grains. Pyroxene grains are pseudomorphically replaced by either serpentine or an assemblage of serpentine-actinolite-chlorite-calcite. Pyroxene oikocrysts in olivine pyroxenite, and peridotite enclose olivine and chromite grains.

The Fe-Ni-Cu sulfides are concentrated in an apparent footwall depression. The primary sulfide concentration decreases upward from massive (greater than 90%), through a marginal zone with 15% sulfides interstitial to intercumulus pyroxene or hornblende, into net-textured to reverse net-textured and net-textured (15 to 90%) sulfides. No disseminated sulfides (less than 15 % sulfides) are present.

Overlying the massive sulfides is an amphibole-pyroxenite, interpreted as a chilled margin. This may reflect thrusting between the two sulfide types but no evidence of shearing was observed at the contact. A more

Fig. 3.4. Primary silicate concentrations, rock types, sulfide textures, and location of contact chromite concentrations for core hole 160-225, Donaldson Surface deposit. Solid shading=olivine, blank=pyroxene, and diagonal lines=hornblende. PERD=peridotite, OLPX=olivine pyroxenite, HBPX=hornblende pyroxenite, SULF=massive sulfide, SEDM=sedimentary rocks. Net=net-textured, NRN=net-textured to reverse net-textured, INT=interstitial sulfide, MSX=massive sulfide, BXA=sulfide breccia, and STR=stringer. Stars= chromite concentrations.

likely explanation could be that the initial magma was sulfide enriched and the massive sulfides that segregated from it gathered in a depression where they solidified rapidly on contact with footwall sediments; the succeeding komatiitic magma, with a solidus temperature above 1200 °C (Usselman et al., 1979), had a lower sulfide content and chilled against the solidified massive sulfide, which has a solidus below 1100 °C (Naldrett, 1969).

The contacts between textural types are sharp and may be marked by thin sulfide veins or concentrations of chromite. Similar concentrations of chromite have been reported by Groves et al., (1977) in Australian deposits of this general type and in the Donaldson West deposit (Dillon-Leitch et al., 1986).

Primary textures of the silicate minerals

Where feasible the original igneous mineralogy will be used in description of the sill lithologies, although alteration and metamorphism have affected most minerals.

Cumulus olivines vary from subhedral to euhedral, equant to tabular grains and average about 0.8 mm long (Table 1). Mechanically rounded olivine grains are rare and no apparent primary preferred orientation has been observed such as that noted at the Katiniq deposit (Barnes, 1979; Barnes et al., 1982).

Pyroxenes in the olivine pyroxenite and peridotite

Table 3.1. Grain size, habit, and location of primary minerals from drill hole core 160-225, Donaldson Surface deposit.

	Grain Type	Size Range (mm)	Avg. Size (mm)	Habit	Host Lithology
Olivine	phenocryst	0.10-4.5	0.4-1.5	subhedral to euhedral, equant to tabular	ol-pyroxenite to peridotite
	entrained	0.05-0.50	0.25	subhedral, subequant	pyroxenite to ol-pyroxenite
Pyroxene	phenocryst	0.50-5.0	3.0	tabular, subhedral to euhedral	hbl-pyroxenite to ol-pyroxenite
	oikocryst	2.0-20.0	10.0	irregular to subhedral, (round to squarish)	ol-pyroxenite to peridotite
Hornblende	phenocryst	0.05-6.0	1.5	subhedral to euhedral, subequant to tabular	hbl-pyroxenite to ol-pyroxenite
	matrix	0.05-1.5	0.30	subhedral to euhedral, equant to skeletal	all lithologies
Chromite	entrained	0.02-0.50	0.20	skeletal to euhedral, tabular to equant	ol-pyroxenite to peridotite
	contact	0.05-3.5	0.30	subhedral to euhedral, skeletal grains and chains, equant	at inferred contact (layering), i.e., hbl-pyroxenite/ol- pyroxenite and ol- pyroxenite/peridotite

Table 3.2. Textures, abundance, and stratigraphic location of selected minerals in core hole 160-225, Donaldson Surface deposit.

Depth (m)	Lith	Sulf Text	Pyx Pyx Ok	Sulf Blob			Cnt II/		Trace					Minerals					
				Nbl	Cr	+Cr	Cr	Mt	VI	Cc	Tc	Py	Ch	Ger	Asp	Nic	Sl	En	Mol
7.2	PERD	NET	In			X		X	tr	tr		A	tr		?				
8.2	PERD	NET				X		X		tr		A	tr		tr				
9.2	PERD	NET	In			X		X		X		X	X						
10.2	PERD	NET	In			X		X				X	X						
11.2	PERD	NET				X		X	tr			A	X						
12.2	OLPX	NET	X		tr			X	tr	X	tr	tr	X						
13.2	PERD	NRM	X		tr		X	X		tr	tr	tr	tr						
14.2	PERD	NRM	X				X	X	tr				tr				tr		
15.2	OLPX	NET	X			X		X				tr	tr						
16.2	OLPX	NET	X			tr		X				tr	tr					tr	
17.2	OLPX	NRM	?			X	X	X				tr	tr		tr			tr	
18.2	VEIN	VEN						X	tr			tr	X						
19.2	OLPX	NRM	X	tr	tr			tr	tr										
20.2	OLPX	NRM	X	X	X			X									X		
21.2	NBPX	INT	X	X	X	X		X									X		
22.2	NBPX	INT	X		X			X											
22.4	VEIN	VEN						tr	tr			tr	X						tr
23.2	NBPX	INT	X		X	X		X	A			tr	tr				tr		
25.8	NBSX	MSX						?	tr				X						
27.0	NBSX	MSX						?	tr			tr	A				tr		
28.0	BISX	BIA										A	X	A		A	tr		
28.6	BISX	BIA										A	X	A	?	A			
32.5	SEDM	STR										tr					X	tr	

Abbreviations: Lith=lithology; Sulf Text=sulfide texture; Pyx=pyroxene lath; Pyx Ok=pyroxene oikocryst; Nbl=hornblende lath; Sulf Blob=sulfide blob; Sulf Blob no Cr= sulfide blob with no chromite inclusions; Sulf Blob + Cr=sulfide blob with chromite inclusions; Cnt Cr=chromite at textural contact; PERD=peridotite; OLPX=olivine pyroxenite; NBPX=hornblende pyroxenite; VEIN=vein; NBSX=massive sulfide; BISX=sulfide breccia; SEDM=sedimentary rocks; In=inferred; NET=net-textured; NRM=not to reverse net-textured; INT=pyroxene interstitial sulfide; MSX=massive sulfide; BIA=bracciated sulfide; VEN=vein; Il/Mt=ilmenite and/or magnetite; VI=violarite; Cc=calcite; Tc=talc; Py=pyrite; Ch=chalcite; Ger=gerardite; Asp=arsenopyrite; Nic=niceline; Sl=sphalerite; En=galena; Mol=molybdenite. Symbols: tr=trace; X=common; A=abundant; ?=possible occurrence.

zones (see Fig. 4 and Table 2) are large, up to 20 mm across, irregular to subhedral oikocrysts with squarish outlines (Table 1), and poikilitically enclose variable concentrations of chromite and olivine (Fig. 5a); the enclosed olivine grains (Fig. 5b) are commonly smaller, (averaging 0.25 mm across), than those outside the oikocryst which average 0.65 mm across (Table 1).

Between 19.0m and 24.0m the concentration of pyroxene decreases and the primary hornblende content increases proportionately with depth whereas the olivine content remains very low (Fig. 4). This zone is interpreted, from the abundance of pyroxene and hornblende phenocrysts, to be a marginal unit. Within the margin (hornblende pyroxenite) and the lowermost olivine pyroxenite zone, pyroxene and hornblende grains occur as large, randomly oriented, poikilitic prisms, up to 2.0 mm by 6.0 mm, enclosing cumulus olivine (Table 1). The prisms often appear to have irregular or skeletal forms (Figures 6a and 6b).

Primary textures of the opaque minerals

Primary sulfide textures grade upward from massive through interstitial to net-textured (Fig. 4). Disseminated sulfides are absent. Contacts between textural types are sharp. Massive sulfides have metamorphic textures and a possible primary origin is inferred from their stratigraphic position below the net-textured sulfides fol-

Fig. 3.5a. Poikilitic pyroxene phenocrysts, from the pyroxene-rich marginal zone, with prismatic outlines, now altered to an assemblage of tremolite/actinolite. Partly polarized transmitted light, 225-2.4 μ . Bar=0.78mm.

Fig. 3.5b. Pyroxene oikocryst, light coloured area with squarish outline, from peridotitic zone. Enclosed olivines are generally smaller than those outside. Euhedral opaques within the oikocryst are chromite grains. Plane transmitted light, 225-14.2 μ . Bar=0.42 μ .

Fig. 3.6a. Prismatic and irregular hornblende phenocrysts (hbl) from the pyroxenitic marginal zone. Polarized light, 225-21.2 μ . Bar=0.43mm.

Fig. 3.6b. Large skeletal hornblende grain (hbl) enclosing euhedral olivine grains (ol). Irregular white grains are tremolitized pyroxene (pyx). From the marginal zone, 225-22.2 μ . Polarized, light. Bar=0.43 mm.

lowing the relationship suggested by Usselman et al. (1979) (Fig. 4).

The interstitial sulfide texture occurs in the hornblende- and pyroxene-rich marginal rocks between the massive and net-textured sulfides (Fig. 4). There, discontinuous patches of net-textured sulfides are found between large pyroxene and/or hornblende grains. These sulfide-bearing patches are generally discontinuous but in some cases form a weak "net-like" texture about the phenocrysts (Fig. 7).

The abundance of sulfides in this marginal zone is estimated to be about 10 to 15 percent. Whereas the interstitial sulfide texture is interpreted as primary, the zone also contains sulfide blebs and chalcopyrite-rich patches indicative of extensive sulfide mobilization.

Net-textured sulfides, containing between 15 and 90 percent sulfide as a semicontinuous to continuous matrix to cumulus olivine grains, occur from 6.7 m to 21.5 m in peridotite and olivine pyroxenite (Fig. 4).

✓ Chromite grains, in net-textured sulfides, occur interstitial to cumulus olivine and as abundant inclusions in pyroxene oikocrysts or in sulfide blebs. Concentrations of interstitial chromite, as euhedra and skeletal grains and chains, occur at various levels throughout the mineralized zone (Table 1). These concentrations (up to 10 %) occur at or close to changes in sulfide textural types and inferred silicate lithologies (Fig. 4) and therefore are interpreted

Fig. 3.7. Sulfides (black), interstitial to pyroxene grains (pyx), outline phenocrysts. Where sulfide concentration is higher a crude net-texture forms about sparse cumulus olivine grains (ol). Transmitted light, 225-22.2m. Bar=0.78mm.

to be primary.

Chromite grains within the pyroxene oikocrysts, from peridotite and hornblende-free olivine pyroxenite, may be smaller (averaging 0.20 mm across) and more commonly skeletal compared to those outside the oikocrysts, which in these rocks are generally equant euhedra averaging 0.30 mm across (Table 2).

Metamorphic textures of the silicate minerals

Whereas most primary silicate minerals are completely altered, grain outlines and diagnostic secondary assemblages can indicate the original mineralogy (Table 1). Cumulus olivine grains are completely, pseudomorphically replaced by serpentine whereas pyroxene grains are pseudomorphically replaced by amphibole and/or serpentine. Where pyroxene was not an abundant primary mineral, serpentine may replace pyroxene. Only primary hornblende is not completely altered.

The common metamorphic assemblages for greenschist facies metamorphism of olivine-rich ultramafic rocks at low X_{CO_2} is as follows;

olivine ----> serpentine (antigorite or lizardite) +
carbonate (magnesite)

orthopyroxene ----> serpentine + talc

clinopyroxene ----> amphibole (hornblende and/or
tremolite) + carbonate (dolomite or calcite)

after Winkler (1974), Trommsdorff and Evans (1977), Coats

and Buchan (1979), and Park (1983).

Generally metamorphic equilibration has not occurred on a scale greater than a millimetre scale, i.e., the diameter of individual minerals, based on the irregular development of alteration minerals other than serpentine. However, equilibration in talc-carbonate altered rocks, where the alteration occurs over two metres, is on a larger scale.

The serpentinization of cumulus olivine is generally, but not strictly, a pseudomorphic replacement and the serpentine (antigorite) forms coarse radial and interlocking (mesh) textures (Figures 8a and 8b). Fine-grained magnetite may partly outline the pseudomorph margins and mobilized sulfides may fill fractures or former mesh lines in the olivine grains. In many cases, however, coarse antigorite laths overgrow the finer-grained serpentine partially destroying the outlines of cumulus olivine grains.

Pyroxene-laths from the hornblende pyroxenite margin and pyroxene oikocrysts from the olivine pyroxenite zone are completely replaced pseudomorphically by a variable assemblage consisting of actinolite-tremolite with minor serpentine, chlorite, talc, and calcite. Hornblende however, is variably replaced by actinolite which is in turn replaced by tremolite and minor chlorite (Fig. 8c).

Pyroxene interstitial to olivine pseudomorphs in peridotite is completely altered to an assemblage richer in serpentine and containing minor tremolite-actinolite compared to that in the olivine-poor marginal rocks. The ser-

Fig. 3.8a. Coarse-grained, radial serpentine pseudomorphically replacing cumulate olivine in net-textured sulfides (black). Note the later, random lath-like serpentine grains which crosscut sulfides and radial serpentine. Transmitted plane light, 225-10.2m. Bar=0.42mm.

Fig. 3.8b. Predominantly coarse-grained, interlocking serpentine (antigorite) after radial serpentine. Partly polarized, transmitted light, 225-7.2m. Bar=0.78mm.

Fig. 3.8c. Hornblende phenocryst (hbl) retrogressed to actinolite (act) and tremolite (trm). Thin, tabular sulfide growths (arrows) occur along fractures or mesh lines in olivines. As 6b but plane transmitted light, 225-22.2m. Bar=0.43mm.

Fig. 3.8d. Fine-grained, interlocking serpentine (A and B) pseudomorphically replacing pyroxene oikocrysts. Note coarse-grained serpentine, which replaces cumulate olivine, and is overgrown by larger, randomly oriented serpentine laths. Transmitted, partly polarized light, 225-13.2m. Bar=0.21mm.

pyroxene replacing pyroxene there has a fine-grained interlocking texture (Fig. 8d) whereas serpentine in nearby olivines is radial or has coarser-grained, interlocking textures. This textural difference is useful in inferring original concentrations of interstitial pyroxene in most olivine-rich rocks. In some cases though serpentinization, or more likely metamorphic re-equilibration, was strong enough to obliterate this textural contrast.

Dolomite, a minor mineral in this core hole (Table 2), ranges from trace to abundant concentrations in peridotitic rocks over the interval 7.2 m to 13.2 m. These rocks contained between 20 and 50 percent (inferred) clinopyroxene. Disseminated dolomite may occur in and around inferred pyroxene oikocrysts in the net-textured sulfide zone (Table 2), as sparse, disseminated patches between 0.05 mm and 2.0 mm across.

Talc is rare and occurs with dolomite in the weakly altered net-textured and net to reverse net-textured sulfide zone (12.2 m and 13.2 m, Table 2). Carbonate + serpentine veinlets, which are not common, may transect mobilized sulfides and may lie within earlier sulfide veinlets indicating that a number of fracture generations are present.

Metamorphic textures in country rocks

Within the immediately underlying sedimentary rocks rare biotite grains overgrow bedding and a quartz-feldspar-

sericite-chlorite assemblage. Faint outlines of what are interpreted to have been hornfels porphyroblasts (Fig. 9a) occur in this zone similar to those reported by Albino (1984). Whether these were cordierite or andalusite is not clear. The sulfide stringers developed in these rocks commonly have margins of quartz and blue birefringent chlorite. Some stringers also contain quartz grains in their core with chlorite margins (Fig. 9b). A discontinuous selvage of amphibole, in the form of fine acicular laths and clots of actinolite, may envelop the sulfide stringers (Fig. 9c). Small amphibole clots and randomly oriented grains persist for up to two cm away from the stringers.

In pelitic rocks with sulfide stringers which underlie the ultramafic sill a weak, open crenulation (S_2) of bedding (S_0) and S_1 is observed, with an axial planar cleavage defined by elongate grains of sericite-chlorite (Fig. 9c). Sparse biotite porphyroblasts overgrow S_1 indicating an upper greenschist facies peak of metamorphism during D_1 or before D_2 . Metamorphic conditions during D_2 were of mid greenschist facies.

Geothermometry

The silicate assemblages in the net-textured rocks; antigorite, antigorite + tremolite, or antigorite + talc + dolomite/calcite, suggest low X_{CoO} , less than 0.05, and tem-

Fig. 3.9a. Retrograded contact metamorphic porphyroblasts (arrows), associated with the intrusion of the ultramafic sill, overgrow bedding but through which S_1 - S_2 passes. Sulfide stringer (black) has a chloritic margin and crosscuts all fabrics. Transmitted light, 225-32.6m. Bar=0.78mm.

Fig. 3.9b. Sulfide stringer (black) with chlorite (chl) -quartz (qtz) -amphibole (amp) margins and a quartz core. Partly polarized transmitted light, 225-32.6m. Bar=0.78mm.

Fig. 3.9c. S_2 crenulates S_1 fabric which is oblique to bedding (S_0). Sulfide stringer (black) crosscuts all fabrics. Note amphibole clots (amp) and chlorite patches (chl) along stringer margin. Transmitted light, 225-32.6m. Bar= 0.42 mm.

peratures of less than 495 °C (Fig. 7, Trommsdorff and Evans, 1977). The maximum temperature for antigorite (under low X_{Co2}) is approximately 517 °C (ibid). The assemblage of antigorite + calcite or dolomite + tremolite in some sulfide veins suggests that they formed at similar temperatures. Application of calcite-dolomite geothermometry from sulfide-carbonate vein samples was unsuccessful as dolomite was not observed to coexist with calcite. Fluid inclusions were not identified in quartz or carbonate from these veins.

Metamorphic textures of the opaque minerals

Sulfide textures interpreted to be metamorphically generated are: net-texture to reverse net-texture (Dillon-Leitch et al., 1986), foliated massive sulfides, brecciated massive sulfides, large blebs, and veins.

Reverse net-texture is arbitrarily defined as olivine grains which are more than 30 percent replaced by sulfides whereas less than 30 percent sulfide replacement is denoted as net to reverse net-texture (Dillon-Leitch et al., 1986). The increased development of net-textured to reverse net-textured sulfides occurs with increasing inferred pyroxene content (see Fig. 4 and Table 2). However, sulfide-replaced olivine grains also occur in peridotitic rocks (Table 2) in close proximity to small serpentine-carbonate veinlets. The sulfide replacement of individual olivine grains is variable and generally is not complete. The dis-

tribution of infilled olivine grains is patchy on the thin-section scale. Specimens with less than ten percent reverse net-texture are referred to as primary net-textured sulfide. Reverse net-texture, as defined above, is not observed in this core hole. A weak S_1 - S_2 schistosity may overprint the net to reverse net-textured rocks (17.2 m) indicating sulfide mobilization before or during D_1 - D_2 .

Sulfide cores of olivine pseudomorphs are most common where the pseudomorphs consist of radial serpentine (Fig. 10). It is at the focus of these radii that sulfide replacement appears to have begun. Most sections containing numerous sulfide-cored, former olivine, grains do not exhibit any evidence of talc-carbonate or carbonate alteration.

Concentrations of chromite, especially irregular and skeletal grains, in many sulfide blebs (Fig. 11a) in peridotite and olivine pyroxenite suggest that these sulfide blebs represent pseudomorphically replaced former pyroxene oikocrysts. This replacement texture is inferred to have developed during the peak of sulfide mobilization, after serpentinization. The abundance of sulfide blebs has been used to infer the original pyroxene oikocryst content in rocks that have undergone a high degree of sulfide mobilization. Carbonate aureoles associated with the sulfide blebs are rare.

Not all sulfide blebs enclose chromite grains. Some sulfide blebs in the interstitial sulfide marginal zone

Fig. 3.10. Sulfide core at the centre of radial serpentine (antigorite) which has pseudomorphically replaced a cumulus olivine grain. Partly polarized, transmitted light, 225-17.2 μ . Bar=0.10mm.

Fig. 3.11a. Concentration of chromite grains in sulfide bleb interpreted to be a sulfide-replaced pyroxene oikocryst. Note light coloured ferrochromite rims to chromite grains. Irregular lines of sulfide in partially replaced olivine pseudomorphs are inferred former serpentine mesh lines. Reflected light, 225-10.2m. Bar=0.43mm.

Fig. 3.11b. Sulfide bleb (black), from the interstitial sulfide textured marginal zone, surrounded by fine-grained (acicular) amphibole. Polarized transmitted light, 225-21.2m. Bar=0.78mm.

are very chalcopyrite-rich and may be surrounded by a selvage of fine- to coarse-grained actinolite (Fig. 11b). This is in contrast to most blebs (including chromite-bearing blebs) which are pyrrhotite- and/or pentlandite-rich and contain negligible chalcopyrite.

Massive sulfides contain rolled silicate patches, sulfide segregations (chalcopyrite- and pentlandite-rich layers), oriented pyrrhotite grains, and rarely oriented silicates (S_1 - S_2 fabric). A 1.5 m wide zone of sulfide/silicate breccia underlies the massive sulfides (Fig. 4). This zone consists of angular silicate fragments (serpentine/biotite/chlorite) in a sulfide matrix (Figures 12a and 12b). The sulfide content of the breccia decreases with depth and there is a sharp contact with the footwall. Commonly the silicate fragments are oriented parallel to the foliation defined by sulfide segregations. In places the serpentine fragments have cataclastic textures or grain-size reduction, with strained and rotated grains.

Mobilized sulfides occur in the footwall rocks as stringers and within net-textured and net to reverse net-textured sulfides as veins. Immediately underlying the sulfide breccia zone is a two to three metre wide zone of sulfide stringers which were emplaced along and at a high angle to bedding (Figures 4 and 13). Patchy concentrations of quartz, chlorite, carbonate, and amphibole may occur along the stringer selvages. Some stringers have quartz cores. The stringers are chalcopyrite-rich, contain minor pyrrhotite,

Fig. 3.12a. Sulfide breccia with pyrite replacing pyrrhotite/pentlandite about silicate fragments as light coloured rims to silicates (arrows). Note quartz blebs (qtz) in sulfide/silicate matrix. Plane light, 225-28.0m. True size.

Fig. 3.12b. Sulfide breccia with angular fragments of serpentine and pelitic sediment (black). Large quartz and serpentine inclusion shows internal banding parallel to sulfide and silicate fragment banding (white line). Plane light, 225-28.6m. True size.

2

MICRO

Fig. 3.13. Chalcopyrite-rich stringer, in footwall turbidites, emplaced along and at a high angle to bedding. Note continuation of stringer, to lower left, where bleaching occurs about a sulfide-poor, quartz- and amphibole-rich extension. Plane light, 225-32.55a. True size.

pentlandite, and pyrite with rare traces of sphalerite and galena, but no spinel, and are often zoned with chalcopyrite margins and chalcopyrite-pyrrhotite-pentlandite cores. The stringers cut the S_1 fabric and what is interpreted to be the S_2 crenulation fabric suggesting that they are post D_2 , possibly D_3 features.

Veins (1mm-60cm thick) within the sill consist of variable proportions of pyrrhotite, pentlandite, and chalcopyrite and may be zoned with chalcopyrite-rich margins and serpentine-carbonate cores. Within the small thickness of the Donaldson Surface deposit large veins occur at the contacts of rocks with differing textures (Table 2) where competency contrasts existed. A crenulation cleavage (S_2) is present in one vein (18.5m) indicating that it formed before or during the D_1 event (Fig. 14). Other vein locations, within net-textured and net to reverse net-textured sulfides, where the veins parallel a strong foliation (S_1 - S_2), are rare and may reflect the heterogeneous nature of the deformation. Discontinuous, en echelon carbonate-serpentine veinlets which crosscut the S_1 - S_2 fabric are rare and were probably emplaced during D_3 .

Ilmenite and magnetite form secondary tabular to lath-like grains commonly crosscutting coarse radial serpentine and rarely paralleling the local S_1 - S_2 fabric, indicating a metamorphic origin.

Opaque Minerals

Fig. 3.14. S_2 crenulation of a strong S_1 cleavage/mineral fabric in a pentlandite-rich sulfide vein. Chalcopyrite (yellow) and pentlandite (white) and some silicate laths are oriented parallel to S_1 . Reflected light, 225-18.2m. Bar=0.42mm.

Opaque minerals in the Donaldson Surface deposit consist of monoclinic and hexagonal pyrrhotite, pentlandite, minor chalcopyrite, pyrite, and oxides (chromite, ferrochromite, ilmenite, and magnetite), and rare traces of sulfarsenides, (cobaltite, gersdorffite, and arsenopyrite), nickeline, sphalerite, galena, molybdenite, and platinum-group minerals, platinum-group element-bearing, and Ag-bearing minerals.

Sulfide minerals

Monoclinic and rarely hexagonal pyrrhotite are the most common opaque minerals in core hole 160-225. The structural composition is based on the atomic proportion of S (Misra and Fleet, 1973) as determined by quantitative electron microprobe analyses (Appendix D-1). Exsolution "flames" of pentlandite are not common, especially in massive and vein sulfides where equilibration of sulfide assemblages is inferred to be the most complete.

Pyrrhotites contain low Ni, Co, Cu, and As concentrations (Appendix D-1). The highest Co concentrations occur in massive sulfides, sulfide breccias, and footwall stringers. Pyrrhotites from sulfide veins contain low Co concentrations (see Appendix D-1). The atomic % Ni in pyrrhotite appears to be uniform in nickel-rich sulfides (Fig. 15). Pyrrhotite from chalcopyrite-rich veined material may be enriched in Ni. Pyrrhotite from the chalcopyrite-rich footwall stringers

160-225

Fig. 3.15. Plot of Ni/Fe (atomic) in pentlandite and Ni (atomic) in pyrrhotite against depth and sulfide textural type in core hole 160-225.

exhibit low Ni contents compared to more sulfide rich zones (Fig. 15).

Pentlandite commonly forms subequant, subhedral grains. Large lensoid patches of subhedral equant grains with well annealed textures occur in veins and massive sulfides parallel to shears or the S_1 - S_2 fabric. The highest Co values in pentlandite are found in deformed massive sulfides, chalcopyrite-rich veined, and net to reverse net-textured specimens (Appendix D-2). Pentlandite in the Co-rich sulfide breccia zone is Co-poor. Pentlandite grains coexisting with pyrite are low in Co (Appendix D-2). Ramsden (1975) suggested that Co favors pyrite over coexisting pentlandite during crystallization or recrystallization. As concentrations are low and variable. Cu is rarely detected. Pd, Pt, Sb, were sought with extended counting times but not detected (Appendix D-2). The Ni/Fe (atomic) of pentlandite is greatest in net-textured and net-textured to reverse net-textured sulfides and decreases in the basal sulfide breccia and Ni-rich sulfide vein (Fig. 15). Rh is generally at or below the lower limit of detection (0.15 wt%, see Appendix B).

Chalcopyrite, the only Cu-bearing sulfide, is a minor sulfide, commonly occurring in veins and deformed rocks. It may occur as small blebs within pentlandite and pyrrhotite. Isolated anhedral and lath-like grains interstitial to serpentine blades are common within olivine and pyroxene pseudomorphs. Sulfide stringers are very chalcopyrite-rich.

Veins may be chalcopyrite-rich or -poor. Co concentrations are low and As is erratic (Appendix D-3). Pd is at or below detection limits. Ag, Sb, and Te were sought but not detected.

Sphalerite, a rare sulfide, is closely associated with chalcopyrite as inclusions or in close proximity to chalcopyrite concentrations. Rare galena may be associated with footwall stringers or net-textured and net to reverse net-textured sulfides (Table 2). Molybdenite, even more rare than galena, is found in close proximity to platinum-group minerals in a sulfide vein (Table 2).

Pyrite ranges from absent to very abundant (Table 2) with its greatest concentration in the sulfide breccia zone where it constitutes up to 70 percent of the sulfides locally. There it has replaced both pyrrhotite and to a lesser degree pentlandite (Fig. 16a). Within the net-textured sulfides pyrite is present in minor amounts (Table 2) as small amoeboid to subhedral grains replacing pyrrhotite and rarely pentlandite and forming rare vermiciform intergrowths with chalcopyrite (Fig. 16b). In the net-texture to reverse net-textured, pyroxene-interstitial, massive sulfides, and stringer- and vein-sulfides, pyrite is present in trace amount as small grains in pyrrhotite (see Table 2). Magnetite is not present with the pyrite indicating that pyrite was developed by sulfidation and not oxidation (Secombe et al. 1981). Quantitative analyses (Appendix D-4) indicate that the cores of pyrite grains are

Fig. 3.16a. Massive and coalescing pyrite grains (white) replacing the pyrrhotite-pentlandite matrix (light grey) in the sulfide breccia zone. Black areas are pits and dark grey grains are serpentine. Reflected light, 225-28.6m. Bar=0.42mm.

Fig. 3.16b. Vermicular intergrowth of pyrite (white) and chalcopyrite (yellow). Note that some pyrite is replacing pentlandite (cream) along grain boundaries and most pyrite has formed in pyrrhotite (light grey). Black areas are pits and dark grey laths are serpentine. Reflected light, 225-11.2m. Bar=0.10mm.

commonly Ni-rich and rims are Co-rich similar to those reported by Seccombe et al. (1981) for secondary pyrite at Kambalda. Pyrite from the footwall stringer is Ni-rich and Co-poor whereas pyrite from the sulfide breccia zone is Ni-poor and exhibits variable Co concentrations (Fig. 17).

Pentlandite, pyrrhotite, and pyrite analyses indicate phase relations (Fig. 18) which are consistent with upper greenschist facies conditions attained during D₁-D₂ where silicate assemblages suggest temperatures of less than 320 °C. Tie lines between coexisting pentlandite and pyrite are compatible with the lower temperature (non magmatic) origin of the pyrite.

Oxide minerals

Tabular ilmenite and magnetite grains in net-textured, net to reverse net-textured, and interstitial sulfides often parallel the foliation. Magnetite has not been observed in foliated massive and brecciated sulfides. Chromite occurs as sparse small subhedra interstitial to olivine and pyroxene pseudomorphs and within pyroxene oikocrysts. Skeletal chains are concentrated at some textural contacts.

Sulfarsenide minerals

Cobaltite is the most widespread sulfarsenide followed by arsenopyrite and gersdorffite (Table 2). The volume of

Fig. 3.17. Plot of Ni versus Co in pyrite from core hole 160-225. Triangles=footwall stringer (32.6m), solid dots=sulfide breccia (28.6m), solid squares=rims-sulfide breccia (28.0m), and open circles=cores-sulfide breccia (28.0m).

Fig. 3.18. Pyrrhotite (po), pentlandite (pn), and pyrite (py) compositions plotted as weight percent. Area enclosed by dashed line refers to whole rock analyses (Tables 5 and 6). Boundary of monosulfide solid solution (mss) field at 600 °C after Naldrett et al. (1967). Open triangles are chalcopyrite-rich footwall stringers. Solid symbols: stars=net-textured; star in square=net-textured to reverse net-textured; diamond=reverse net-textured; triangle=vein(ed); and square=massive sulfide.

gersdorffite, however, in the brecciated sulfide zone (1.5 m wide) is probably similar to that of cobaltite throughout the examined core hole (26 m).

Cobaltite grains range from anhedral to euhedral and vary from subequant to tabular shapes (Fig. 19a). Single grains range in length from 2 μm to 100 μm with most between 10 μm and 25 μm . Cobaltite grains occur within pyrrhotite, pentlandite, and rarely in chalcopyrite grains. Most commonly cobaltite is found at sulfide/sulfide or sulfide/silicate grain boundaries. In rare instances very small grains of cobaltite are closely associated with small PGM (Figures 19b and 19c). Cobaltite in the sulfide breccia zone occurs as free grains and as mantles about sulfides that are not closely related to nickeline alteration.

Gersdorffite occurs as large multiple grains and thin elongate, subhedral chains only in the sulfide breccia zone where it may be closely associated with the breakdown of nickeline or as rims on sulfide patches and free grains in silicates (Fig. 19b).

Arsenopyrite occurs as subhedral, tabular to rarely equant grains, (5 to 20 μm long) most commonly in the sulfide breccia zone and rarely elsewhere (Table 2). The small grains preclude quantitative analysis, and the difficulty distinguishing between sub 10 μm cobaltite and arsenopyrite by qualitative analysis is considerable as Ni and Fe fluorescence from host pentlandite can result in misidentification. Consequently the abundance and stratigraphic

Fig. 3.19a. Euhedral and subhedral cobaltite grains (cob) at pyrrhotite grain boundaries. Note the development of violarite in pentlandite (pn) "flames" situated along pyrrhotite grain margins (arrows). Partly polarized reflected light, 225-28.0m. Bar=26 μ m.

Fig. 3.19b. Subhedral to anhedral grains and chains of gersdorffite-cobaltite (white) mantling pyrrhotite grains, growing into serpentine, and as free grains (arrows). Reflected light, 225-28.0m. Bar=0.42mm.

Fig. 3.19c. Subhedral, subequant cobaltite grain at pyrrhotite grain boundaries with an anhedral PGM (Pd-, Sb-, and Te-bearing). Partly polarized reflected light, 225-28.0m. Bar=26 μ m.

Fig. 3.19d. Euhedral cobaltite grain in chalcopyrite with an attached PGM (Pd-, Sb-, and Te-bearing). Reflected light, 225-28.0m. Bar=10 μ m.

distribution of arsenopyrite could be greater than indicated in Table 2.

The proportion of Co, Fe, and Ni in cobaltite is variable, with grains from massive and net-textured sulfides showing considerable variation (Appendix D-5; Fig. 20). Gersdorffite grains may have Ni-rich cores and Co-rich rims. The cobaltite grains occurring in the sulfide breccia zone have Fe concentrations comparable to the gersdorffite grains (Fig. 20). Sb concentration in these cobaltites is significantly lower than concentrations in gersdorffite, which is close to Sb concentrations in parent nickeline. Pd where sought is below the detection limit (Appendix B).

Compositions of cobaltite (Appendix D-5) from massive and net-textured sulfides suggest formation temperatures of about 600 °C (Appendix L). Cobaltite-gersdorffite grains from the sulfide breccia zone suggest formation temperatures between 420 and 480 °C. However, one analysis from this zone gives a temperature of about 550 °C possibly reflecting a range of retrograde conditions during brecciation.

Arsenide minerals

Nickeline has only been observed in the sulfide breccia zone (Table 2) where it occurs as large round to ovoid grains ranging from 30 μm to 800 μm in length (Figures 21a and 21b). These grains are found in both pentlandite- and

Fig. 3.20. Compositional variation of sulfarsenides from the Donaldson Surface deposit. Stars=net-texture, open squares=massive sulfide (25.8m), solid squares=massive sulfide (27.0m), open circles=sulfide breccia (28.0m), and solid circles=sulfide breccia (28.6m).

Fig. 3.21a. Large, round nickeline grain (orange) at pyrrhotite grain boundaries. Note grey (gersdorffite) alteration rim which completely surrounds the nickeline and includes anhedral grains of sudburyite (yellow). Reflected light, 225-28.0m. Bar=0.10mm.

Fig. 3.21b. Round to irregular nickeline grains (orange), at pyrrhotite grain boundaries, surrounded by a thin rim of gersdorffite (grey). Note large anhedral inclusions of sudburyite (yellow) within the gersdorffite alteration. Reflected light, 225-28.0m. Bar=0.10mm.

Fig. 3.21c. Completely altered nickeline grain pseudomorphically replaced by gersdorffite (bright grey) and chalcopryite (yellow). Note inclusions of PGM (arrows). Reflected light, 225-28.0m, Bar=0.10mm.

Fig. 3.21d. Nickeline (orange) altering to Co-rich gersdorffite (bright grey, smooth rim and inclusions) and an Ni-rich, Sb-bearing gersdorffite (dull grey, pitted). Arrows indicate minute PGM inclusions (mostly sudburyite). Reflected light, 225-28.0m. Bar=0.10mm.

pyrrhotite-rich patches at grain margins. The nickeline grains are interpreted, on the basis of habit, to be a primary phase that exsolved from high temperature sulfides rich in As. The source of the As may have been from footwall contamination. The interpretation that the breccia zone was originally part of the massive sulfide zone and the restriction of nickeline to the breccia is compatible with a contact phenomena.

All nickeline grains have been variably altered, from incipient (Figures 21a and 21b) with marginal rims to complete (Fig. 21c). Intermediate stages of alteration, between 10 and 60 percent replacement, are predominant (Fig. 21d). Nickeline compositions are homogeneous with traces of Pd, Pt, and Sb (Appendix D-6). Nickeline alters to at least two phases in some cases (Fig. 21d). Qualitative and quantitative electron microprobe analyses indicate that the bright rims are Co-rich, Sb-poor gersdorffite whereas the dull grey cores appear to be a Ni-rich, Sb-bearing gersdorffite. It is notable that most of the Pd-bearing PGM in this zone were found within or in contact with altered nickeline grains (see Figures 21a, 21b, 21c, and 21d).

It is proposed that nickeline altered to gersdorffite during deformation and sulfidation of the major sulfides which released Fe, Co, and S as follows:

Continued alteration of the gersdorffite depleted it in Ni and Sb developing Co-rich rims. The cobaltite grains mantling sulfides or as free grains suggest continued Ni and Sb depletion and Fe enrichment.

Platinum-Group Minerals and Platinum-Group Element-, and Ag-Bearing Minerals

Platinum-group minerals, platinum-group element-bearing minerals, Ag-bearing grains, and sulfarsenides were identified microscopically (between two and six polished thin sections from each interval; see Table 2 for the location of thin sections), followed by qualitative energy dispersive (EDS) electron microprobe analysis, and for grains larger than 20 μm across, quantitative wavelength dispersive (WDS) electron microprobe analysis.

Platinum-group minerals (Table 3) are predominantly sudburyite (PdSb), testibiopalladite (PdSbTe), borovskite (Pd_3SbTe_4), an unknown mineral ($\text{Pd}_3\text{Sb}_2\text{Te}_2$), merenskyite (PdTe_2), and sperrylite (PtAs_2). Michenerite (PdBiTe) and kotulskite (PdTe) may occur rarely. Melonite (NiTe_2), another Pd-bearing mineral, occurs rarely. Up to 15 wt percent Pd substitution for Ni occurs in melonite, with the highest Pd content in vein melonite. Bi is major component in testibiopalladite, borovskite, and melonite. The only identified Pt-rich phase, sperrylite (PtAs_2), has a wide distribution (Table 4). Trace amounts of Pt were identified

Table 3.3. PGM, PGE-, and Ag-bearing and associated mineral distribution in core hole 160-225, Donaldson Surface deposit.

Mineralogy	Ideal Composition	Grain Size (µm)	Textural distribution							Grain location			
			Net to		Sulf					In		In	
			Net	Rev	Int	Msv	Bxa	Vein	Str	Sulf/ Sulf	Sulf/ Sulf	Sil	Sil
Sperrylite	PtAs ₂	1-250	X	X		C		X		X	X	C	X
Sudburyite	PdSb	3-90				X	C	C		C			
Testibiopalladite	PdSbTe	2-250	X			X	C	C		C	X	X	X
Borovskite	Pd ₃ SbTe ₄	10-80				C		X		C		X	
Unknown	Pd ₃ Sb ₂ Te ₂	10-60					C	C		C		X	
Michenerite	PdBiTe	2-15				?						X	
Kotulskite	PdTe	2-20				?						X	
Merenskyite	PdTe ₂	3-25	X			X		?			X	X	
Melinite	NiTe ₂	10-50	X			X		X		X	X		
Hessite	Ag ₂ Te	2-40				X				X		X	
Nickeline	NiAs	30-800					C			X		X	
Cobaltite	CoAsS	1-100	X	C	X	C	X	C		C	C	C	X
Gersdorffite	NiAsS	1-250					C						C
Arsenopyrite	FeAsS	1-35	X	X			X			X	X	X	
Pyrite	FeS ₂	5-as	X			X	C	X	X	C			

Abbreviations: Net=net-textured, Net to Rev=net to reverse net-textured, Int=interstitial sulfide, Msv=massive sulfide, Sulf Bxa=sulfide breccia, Str=footwall stringer, Sulf=sulfide, Sil=silicate, x=present, C=common, ?=possible occurrence, as=massive texture.

Table 3.4. Textural, abundance, and stratigraphic location data of selected minerals in core hole 160-225, Donaldson Surface deposit.

Depth (m)	NA	Sulf Text	Trace										Minerals						
			Py	Ch	Ger	Asp	Nic	Sl	Gn	Mol	Spr	Sud	Tes	Bor	Unk	Mer	Nch	Hes	Mel
7.2	X	NET	A	X		?													
8.2		NET	A	X		A					X					X			
9.2		NET	X	X															
10.2		NET	X	X							X								
11.2		NET	A	X							X		X			X			X
12.2	X	NET	tr	X															
13.2		NRN	tr	X															
14.2		NRN		X				X			X								
15.2		NET	tr	X							X								
16.2	X	NET	tr	X					X		X								
17.2		NRN	tr	X		X			X		X								
18.2		VEN	tr	A							X	A	A		A				
19.2		NRN																	
20.2		NRN						X											
21.2		INT						X											
22.2		INT																	
22.4	X	VEN	tr	X						X		?	X		A	X			X
23.2		INT	tr	tr				tr											
25.8	X	MSI		X							A	X		X	X	A	A		X
27.0	X	MSI	tr	A				tr			X	X	X	A	X	X	X	X	
28.0		BIA	A	X	A	X	A	tr				A	X		X				
28.6	X	BIA	A	X	A		A					A			X				
32.5	X	STR	X					X	X										

Symbols: NA=neutron activation analysis; Sulf Text=sulfide texture; NET=net-textured; NRN=net to reverse net-textured; INT=pyroxene interstitial sulfide; MSI=massive sulfide; BIA=brecciated sulfide; VEN=vein; Py=pyrite; Ch=cobaltite; Ger=gersdorffite; Asp=arsenopyrite; Nic=nickeline; Sl=sphalerite; Gn=galenite; Mol=molybdenite; Spr=sperrylite; Sud=sudburyite; Tes=testibiopalladite; Bor=borovskite; Unk=unknown (Pd-Sb-Te); Mer=mercurite; Nch=nickanite; Hes=hesite; Mel=melonite; tr=trace; X=common; A=abundant; ?=possible occurrence. Note: abundance of pyrite and nickeline is an order of magnitude greater than trace and precious metal minerals.

in sudburyite, testibiopalladite, borovskite, merenskyite and melonite. Hesseite (AgTe_2) has only been observed in deformed massive sulfides (Table 3) where it is closely associated with borovskite and testibiopalladite. Sperrylite contains traces of Ir, Rh, Sb, and S. Au was not encountered. Ag was found in sudburyite, testibiopalladite, borovskite, and the unknown at or slightly above detection limits.

Platinum-group minerals, platinum-group bearing, and Ag-bearing phases are concentrated in the sulfide-rich, mechanically and hydrothermally mobilized parts of the deposit (veins and sulfide breccia; see Tables 3 and 4), where the following features are significant: (1) the abundance, size, and diversity of platinum-group minerals are greatest in veins and highly deformed rocks; (2) although platinum-group minerals are dominantly within sulfides regardless of the degree of deformation, they also occur as rare free minerals in silicates and abundantly at sulfide/silicate contacts in veins and strongly tectonized rocks; (3) Ag-bearing minerals have only been observed in deformed massive sulfide; (4) the cobaltite content correlates positively with pyrite abundance; (5) pyrite is most abundant in tectonized parts of the deposit and minor in veins; (6) Pd-bearing platinum-group minerals are more abundant than Pt-bearing ones, consistent with the relative abundances of Pd and Pt; (7) Bi dominant minerals are absent reflecting the low abundance of this element; (8) melonite,

due to its low abundance, is not an important Pd host in any sulfide texture; (9) the highly tectonized sulfide breccia zone exhibits similar characteristics of platinum-group mineral concentration compared to veins.

Major Element and Platinum-Group Element Distribution

The investigation of thermal and dynamic metamorphic redistribution of platinum-group elements in drill core 160-225 is based on eight fire assay neutron activation analyses and 23 fire assay atomic absorption spectrophotometry analyses. The former (Table 5) were performed on small (300 g) sulfide samples, from all sulfide types, by Bondar-Clegg and Company Ltd., Ottawa, Canada, following the nickel sulfide collection method of Hoffman et al. (1978). Ni and Cu values greater than 4,000 ppm were determined by X-ray fluorescence spectrometry (XRF) with a routine precision of ± 5 percent. Ni and Cu values less than 4,000 ppm, Co, Ag, Bi, and Te were determined by emission-direct current plasma spectroscopy with a routine precision of ± 10 percent. S was determined gravimetrically with a routine precision of ± 5 percent, and the precious metals, As, and Se, by neutron activation analysis with a routine precision of ± 10 percent.

The 23 fire assay atomic absorption analyses (Table 6) were performed commercially for Falconbridge Ltd., Toronto. Ni, Cu, and Co were determined by atomic absorption spectrophotometry with a routine precision of ± 10 to 15 per

Table 3.5. Chemical Compositions of Specimens from Donaldson Surface Core Hole 160-225 Grab Samples.

Depth (m)	Ore text	Ni	Cu	Co	S (wt %)	Pt	Pd	Au	Os (ppb)	Ir	Ru	Rh	Se	As	Ag (ppm)	Sb	Bi	Te
7.2	2	3.96 (12.0)	0.96 (2.9)	0.06 (.18)	12.2 (37.1)	1410 (4288)	1770 (5381)	53 (161)	60 (182)	17 (51)	600 (1824)	75 (228)	20 (60)	11 (33)	3.3 (10)	8.9 (27)	1.0 (3.0)	1.5 (4.6)
12.2	2	2.20 (8.8)	0.43 (1.7)	0.05 (.21)	9.41 (37.9)	640 (2375)	450 (1811)	53 (213)	129 (619)	89 (358)	590 (2374)	200 (804)	15 (60)	15 (60)	1.5 (6.0)	2.3 (9.0)	< (<)	.4 (1.6)
16.2	3	3.96 (10.6)	0.43 (1.2)	0.07 (.19)	14.1 (37.6)	860 (2295)	1150 (3069)	36 (96)	135 (360)	140 (373)	600 (1601)	200 (533)	33 (88)	11 (29)	1.7 (4.5)	2.3 (6.1)	3.0 (8.0)	.5 (1.3)
22.4	6	10.4 (11.7)	3.68 (4.1)	0.23 (.26)	33.0 (37.0)	155 (174)	3251 (3641)	100 (112)	MA (<)	< (<)	MA (<)	MA (<)	50 (56)	43 (48)	7.5 (8.4)	1.9 (2.1)	1.0 (1.1)	1.0 (1.1)
25.8	7	8.16 (10.2)	7.52 (9.4)	0.15 (.18)	29.2 (36.5)	4600 (5756)	4500 (5631)	160 (200)	48 (60)	37 (46)	171 (213)	165 (206)	59 (73)	44 (55)	14.2 (18)	2.7 (3.4)	< (<)	3.0 (3.8)
27.0	7	8.00 (8.2)	0.60 (.6)	0.12 (.12)	37.0 (38.2)	5100 (5257)	11600 (11958)	28 (28)	94 (96)	59 (60)	250 (257)	184 (189)	88 (90)	37 (38)	5.1 (5.2)	7.6 (7.8)	6.0 (6.2)	4.0 (4.1)
28.6	9	5.28 (7.7)	0.74 (1.1)	0.16 (.23)	26.2 (38.2)	395 (575)	16500 (24045)	280 (408)	24 (34)	< (<)	170 (247)	22 (32)	45 (65)	1960 (2856)	2.4 (3.5)	28.4 (41)	2.0 (2.9)	2.0 (2.9)
32.6	10	0.32 (1.8)	3.36 (19.3)	0.01 (.07)	6.39 (36.7)	310 (1782)	640 (3679)	82 (471)	40 (229)	3 (17)	340 (1954)	26 (149)	< (<)	66 (379)	26.8 (154)	1.5 (8.6)	1.0 (4.7)	.8 (4.6)

Fire-assay neutron activation data. Data in parentheses recalculated to 100 % sulfides. Texture code: 2=net-textured; 3=net-textured to reverse net-textured; 6=vein; 7=massive sulfide; 9=sulfide breccia; 10=stringer. MA=not analysed. <=below detection limit. Detection limits: Ir=0.5 ppb, Bi=1.0 ppm, and Se=10 ppm.

Table 3.6. Chemical composition of specimens from Donaldson Surface core hole 160-225.

Depth range (m)	Ore text	Ni	Cu (wt %)	Co	S	Pt (ppb)	Pd
6.70-7.70	2	3.86 (12.7)	1.09 (3.6)	0.07 (0.23)	11.2 (36.8)	1600 (5263)	2800 (9211)
7.70-8.70	2	3.65 (12.7)	1.09 (3.8)	0.07 (0.24)	10.6 (36.8)	800 (2778)	2800 (9726)
8.70-9.70	2	4.26 (12.6)	1.09 (3.2)	0.08 (0.24)	12.5 (36.9)	1600 (4725)	3600 (10632)
9.70-10.70	2	4.36 (12.5)	0.90 (2.6)	0.07 (0.20)	12.9 (37.0)	800 (2296)	1600 (4592)
10.70-11.70	2	3.55 (10.7)	1.03 (3.1)	0.06 (0.18)	12.3 (37.3)	1600 (4849)	2000 (6062)
11.70-12.70	2	3.60 (11.0)	0.67 (2.1)	0.07 (0.21)	12.2 (37.4)	1600 (4901)	2000 (6127)
12.70-13.70	3	3.73 (10.5)	0.72 (2.0)	0.08 (0.22)	13.4 (37.5)	1600 (4476)	1600 (4476)
13.70-14.70	3	3.92 (10.8)	0.85 (2.3)	0.09 (0.25)	13.6 (37.4)	1600 (4397)	2800 (7696)
14.70-15.70	2	3.73 (10.9)	0.75 (2.2)	0.09 (0.26)	12.8 (37.4)	800 (2335)	1600 (4671)
15.70-16.70	2	4.23 (10.8)	0.77 (2.0)	0.10 (0.26)	14.7 (37.4)	1600 (4074)	2000 (5092)
16.70-17.77	3	4.32 (10.6)	1.12 (2.7)	0.09 (0.22)	15.3 (37.4)	1600 (3908)	1600 (3908)
17.77-18.35	6	10.3 (10.6)	0.13 (0.1)	0.19 (0.20)	36.8 (37.7)	800 (802)	1600 (1604)
18.35-19.35	3	4.29 (11.4)	0.95 (2.5)	0.07 (0.19)	14.0 (37.2)	2400 (6384)	5200 (13833)
19.35-20.82	3	2.67 (10.1)	0.70 (2.7)	0.05 (0.19)	9.86 (37.5)	800 (3039)	1600 (6079)
20.82-21.82	10	1.49 (9.2)	0.79 (4.9)	0.03 (0.19)	6.02 (37.3)	2400 (14879)	2000 (12399)
21.82-22.82	5	0.77 (7.4)	0.66 (6.4)	0.02 (0.19)	3.88 (37.5)	1600 (15445)	2400 (23168)
22.82-24.15	10	1.45 (11.6)	0.75 (6.0)	0.02 (0.16)	4.60 (36.7)	1600 (12774)	2400 (19162)
24.15-25.15	7	7.70 (10.5)	1.25 (1.7)	0.12 (0.16)	27.4 (37.5)	1600 (2191)	2400 (3286)
25.15-26.15	7	8.98 (9.9)	2.12 (2.3)	0.16 (0.18)	34.0 (37.6)	5600 (6185)	8800 (9719)
26.15-27.15	7	10.40 (11.6)	0.93 (1.0)	0.19 (0.21)	33.6 (37.4)	6400 (7126)	13200 (14699)
27.15-28.60	8	6.45 (9.7)	1.85 (2.7)	0.14 (0.20)	25.7 (37.4)	1600 (2336)	40400 (59002)
28.60-30.60	9	2.13 (14.8)	0.84 (5.8)	0.04 (0.28)	5.20 (36.1)	1600 (11115)	6000 (41682)
30.60-32.60	9	0.18 (3.2)	0.88 (16.1)	0.01 (0.18)	2.02 (36.9)	< <	< <

X-ray and fire-assay atomic absorption spectrophotometry data. Data in parentheses recalculated to 100% sulfides. Textural code: 2=net-textured; 3=net to reverse net-textured; 5=veined; 6=vein; 7=massive sulfide; 8=sulfide breccia; 9=stringer; and 10=interstitial sulfide; <=below detection limit. Detection limits for Pt and Pd=800 ppb.

cent and S was determined gravimetrically with a precision of ± 5 percent. Pt and Pd were determined by fire assay atomic absorption spectrophotometry with an estimated precision of ± 400 ppb for Pt and ± 200 ppb for Pd and a detection limit of 800 ppb for both Pt and Pd. The data in Table 6 represent split core samples ranging from 0.6 to 2.0 m in length, averaging 1.0 m in length. The sample termed "veined" (Table 6) refers to a sample where the vein is less than 0.2 m in thickness. One sample (18.6 m) is from a 0.6 m thick sulfide vein (see Tables 5 and 6).

Element correlations

Correlation matrices are presented in Tables 7 and 8a; they show that the vein, sulfide breccia, and to a lesser extent veined material, which have unique mineralogical and major element compositions, have only marginally distinct trace element compositions. The low correlations for some trace elements found in veins as unique precious metal minerals are attributed to the dilution effect of the non-veined specimens in the specimen data set.

In the fire assay neutron activation data, Pt correlates strongly with Te, weakly with Rh, and shows no consistent sense of correlation with the Os-Ir-Ru group. Pd correlates strongly with As and Sb and weakly with Au and Te. Pd exhibits a weak negative correlation with the Os-Ir-Ru-Rh group. Cu correlates moderately with Ag and weakly nega-

Table 3.7. Correlation matrix for fire-assay neutron activation data from Donaldson Surface core hole (160-225). N=8; at 0.95 confidence level values above 0.71 are significant.

	Ni	Cu	S	Co	Pt	Pd	Ir	Os	Ru	Rh	Au	Se	As	Ag	Sb	Bi	Te
Ni	1.00																
Cu	.30	1.00															
S	.94	.19	1.00														
Co	.86	.23	.87	1.00													
Pt	.85	.44	.81	.53	1.00												
Pd	.57	-.16	.76	.80	.26	1.00											
Ir	.02	-.31	-.09	-.13	.02	-.37	1.00										
Os	-.10	-.46	-.19	-.30	.60	-.43	.94	1.00									
Ru	-.55	-.52	-.72	-.69	-.48	-.72	.56	.68	1.00								
Rh	.36	-.04	.22	.08	.46	-.28	.85	.84	.31	1.00							
Au	.22	.28	.30	.65	-.14	.65	-.56	-.71	-.67	-.56	1.00						
Se	.94	.10	.98	.79	.85	.66	.09	.01	-.57	.39	.11	1.00					
As	.11	-.19	.27	.56	-.32	.79	-.44	-.53	-.49	-.57	.88	.12	1.00				
Ag	-.30	.64	-.22	-.35	.03	-.28	-.48	-.50	-.37	-.42	.03	-.30	-.23	1.00			
Sb	.23	-.30	.37	.60	-.20	.85	-.48	-.53	-.44	-.56	.78	.23	.95	-.37	1.00		
Bi	.42	-.46	.58	.25	.42	.50	.24	.24	-.18	.22	-.27	.67	.03	-.26	.16	1.00	
Te	.88	.30	.93	.70	.89	.64	-.29	-.32	-.72	-.10	.17	.90	.09	.00	.23	.53	1.00

Table 3.8a. Correlation matrix for fire-assay atomic absorption spectrophotometry data for all sulfide textural types from Donaldson Surface core hole 160-225. N=22; at 0.95 confidence level values above 0.42 are significant.

	Ni	Cu	Co	S	Pt	Pd
Ni	1.00					
Cu	.28	1.00				
Co	.98	.28	1.00			
S	.99	.32	.98	1.00		
Pt	.57	.44	.56	.54	1.00	
Pd	.36	.59	.40	.45	.28	1.00

Table 3.8b. Correlation matrix for fire-assay atomic absorption spectrophotometry data for net-textured and net to reverse net-textured sulfides from Donaldson Surface core hole 160-225. N=22; at 0.95 confidence level values above 0.55 are significant.

	Ni	Cu	Co	S	Pt	Pd
Ni	1.00					
Cu	.43	1.00				
Co	.62	-.11	1.00			
S	.75	.03	.82	1.00		
Pt	.44	.18	.19	.54	1.00	
Pd	.35	.39	-.15	.06	.63	1.00

tively with the Os-Ir-Ru-Rh group. Of the Os-Ir-Ru-Rh group the element Ru exhibits a less negative correlation with Cu, weak positive correlations with Ni and Co, and correlates weakly with Pt, compared to the rest of the group.

Fire assay atomic absorption spectrophotometry data correlations for all sulfide textural types (Table 8a) show Cu to exhibit a weak correlation with Pd. Ni correlates strongly with S and Co and weakly with Pt. The least altered textural types, net-textured and net to reverse net-textured sulfides (Table 8b), indicate moderate correlations for Ni, Co, and S. Cu and Pd do not correlate with the major elements; suggestive of mobilization.

Analyses recalculated to 100 percent sulfides

Recalculation of the metal concentration in 100 percent sulfides, based on the assumption that the trace elements were precipitated as magmatic sulfides, enables the different sulfide textural types with widely varying sulfide contents to be compared. The fire assay neutron activation and atomic absorption spectrophotometry data were recalculated to 100 percent sulfides, assuming that the original sulfide assemblage was of monoclinic pyrrhotite, pentlandite (36 wt % Ni), and stoichiometric chalcopyrite (cf. Naldrett, 1981).

The Ni and Cu contents of the vein and veined specimens (Table 6) indicate that two types of veins occur:

Cu rich and Ni poor, and Ni rich and very Cu poor. There are not enough data to suggest that a continuum of vein types exists with the above types as end members.

Whereas the net-textured and net-textured to reverse net-textured sulfides have similar Cu, Ni, Pt, and Pd values, the latter exhibits lower concentrations of Ni. The zone of interstitial sulfides (marginal zone) is enriched in Cu, Pt, and Pd compared to surrounding sulfides (Fig. 22). Massive sulfides are somewhat depleted in Cu compared to the net-textured zone. Pt and Pd are lower in the upper part of the massive sulfide zone and higher in the lower part (Fig. 22) compared to the net-textured and net-textured to reverse net-textured sulfide zones.

The sulfide breccia zone is slightly Ni and Pt depleted whereas Pd is greatly enriched compared to the overlying sulfide zones (Fig. 22). The stringer zone shows strong enrichment of Cu, Ni, Pt, and Pd close to the overlying sulfides (Fig. 22), whereas specimens located two to four metres from the tectonized massive sulfides do not contain detectable amounts of Pt or Pd (Table 6) indicating the limited extent of mobilization into stringers.

The Ni-rich, Cu-poor vein (18.2 m, Fig. 22) is depleted in Pt and Pd. The veined interval (21.8-22.8 m) is Cu-rich, Ni-poor, Pt and Pd enriched (Fig. 22). There is no small-scale enrichment or depletion about the vein or veined material; this suggests that the vein elements were not lo-

Fig. 3.22. Plots of Cu, Ni, Pt, and Pd (recalculated to 100 % sulfides) vs. depth and textural type. The locations of the veins are shown as stars. Abbreviations: NET=net-textured, NRN=net-textured to reverse net-textured, VND=veined, INT=interstitial texture, MSV=massive sulfide, BXA=sulfide breccia, STR=stringer.

cally derived but may have been derived from a larger rock volume.

The Po/Pn , calculated from 100% sulfide data (Table 9), shows a relatively uniform value close to 2.0 for most sulfide types (Fig. 23). Mobilized sulfides, veins and veined material, show a variable increase above this value.

The recalculated S contents of vein and veined material (Tables 5 and 6) are similar to that of the surrounding rocks. The high S/Ni of the Cu-rich veined material (22.4 m) is attributed to the low pentlandite content of the vein. Most specimens from this core hole have S/Ni greater than 2.5 (Fig. 24), a value interpreted to be indicative of sulfide mobilization for veined and reverse net-textured material from the Donaldson West deposit (Dillon-Leitch et al., 1986). The high S/Ni of weakly mobilized sulfides at Donaldson Surface suggests that these sulfides may have resulted from a combination of minor sulfidation and minor depletion of Ni (Fig. 22). However, the textural types of the sulfides do not indicate extensive mobilization, suggesting that primary processes may partially control the higher S/Ni values.

A plot of metal ratios (Fig. 24) shows that the data from major sulfide textural types may be grouped into three fields. The specimens of field A represent the least deformed group of rocks in core hole 160-225. These sulfides exhibit a narrow range of Pd/Pt with a large range of S/Ni, perhaps indicative of a weakly modified primary mag.

Table 3.9. Calculated pyrrhotite, pentlandite, and Po/Pn from 100 % sulfides, Donaldson Surface core hole 160-225.

Depth (m)	Ore texture	Pyrrhotite (% Po)	Pentlandite (% Pn)	Po/Pn
6.70-7.70	2	16.3	10.9	1.50
7.70-8.70	2	15.3	10.3	1.48
8.70-9.70	2	18.7	12.0	1.55
9.70-10.70	2	19.9	12.3	1.62
10.70-11.70	2	20.0	10.3	1.99
11.70-12.70	2	20.5	10.2	2.01
12.70-13.70	3	23.0	10.6	2.18
13.70-14.70	3	22.8	11.1	2.04
14.70-15.70	2	21.5	10.6	2.03
15.70-16.70	2	25.0	12.0	2.08
16.70-17.77	3	25.5	12.2	2.08
17.77-18.35	6	68.0	29.1	2.33
18.35-19.35	3	22.7	12.1	1.88
19.35-20.82	3	16.7	7.56	2.21
20.82-21.82	10	9.63	4.22	2.28
21.82-22.82	5	6.26	2.19	2.86
22.82-24.15	10	6.26	4.09	1.53
24.15-25.15	7	47.7	21.7	2.20
25.15-26.15	7	59.0	25.4	2.32
26.15-27.15	7	57.7	29.4	1.96
27.15-28.60	8	44.2	18.9	2.34
28.60-30.60	9	5.94	6.03	0.99
30.60-32.60	9	2.41	0.52	4.63

Texture code: 1=disseminated; 2=net-textured; 3=net-textured to reverse net-textured; 5=veined; 6=vein; 7=massive sulfide; 8=sulfide breccia; 9=footwall stringer; 10=interstitial sulfide.

Fig. 2.23. Plot of Po/Pn calculated from 100% sulfide recalculation against depth and sulfide textural type. Note increased values from mobilized sulfides.

Fig. 3.24. Pd/Pt versus S/Ni for various strata and textural types. Open symbols=fire assay neutron activation data and closed symbols=fire assay atomic absorption data where: stars=net-textured, star in square=net-textured to reverse net-textured, upright triangle=vein, circled upright triangle=veined, cross=interstitial textured, square=massive sulfide, half circle=sulfide breccia, circled inverted triangle=stringer. See text for a description of fields.

matic distribution. Group B, with high S/Ni and restricted Pd/Pt, includes data from veined, stringer, and deformed massive sulfides. Data from the sulfide breccia and veined material plot in field C with high Pd/Pt and variable S/Ni.

Chondrite-normalized platinum-group element distributions in 100 percent sulfides from net-textured and net-textured to reverse net-textured sulfides (Fig. 25) display patterns characteristic of ores from Proterozoic komatiitic magmas (Naldrett, 1981). In contrast, the massive sulfides have lower contents of Os, Ir, Ru, and to a lesser extent Rh accompanied by high Pt and Pd. The sulfide breccia has very low Os-Ir-Ru-Rh contents with associated high Pd concentrations. The stringer has erratic Os and Ru values, but the low Ir and Rh values suggest similarity to the sulfide breccia pattern. The veined specimen has characteristic high Pd, low Pt, and very low Ir (below detection levels). The remaining platinum-group elements in the veined specimen could not be analysed due to matrix difficulties (R. Callow, pers. comm., 1986).

Fig. 3.25. C1 chondrite-normalized PGE data (recalculated to 100% sulfides). Numbers refer to analyses in Table 5. Textural symbols as Figure 24. Shaded zone refers to the komatiite field of Naldrett (1981). C1 chondrite values after Naldrett et al. (1982).

Discussion

Mobilization of Fe-Ni-Cu sulfide

The distribution of sulfide textures in drill core 160-225 through the Donaldson Surface deposit indicates that most of the primary mineralized section is represented, with possibly only the disseminated sulfide zone missing due to erosion. Examination of sulfide textures suggests that the primary distribution of sulfides and platinum-group elements within the deposit has been extensively modified during the prevalent thermal regime (D_1 - D_2) and localized dynamic metamorphism. The development of reverse net-texture is believed to represent the variable transformation of former net-textured sulfides where sulfides replaced cumulus olivine grains or their metamorphic-equivalent assemblages. Mobilization in the net-textured, net-textured to reverse net-textured, and interstitial sulfide zones during thermal metamorphism is interpreted to have been dominantly on a centimetre scale.

Groves, et al. (1974) reported spherical sulfide blebs at the Black Swan deposit of the same size and location as olivine pseudomorphs; there, however, talc-carbonate alteration post dated the sulfide crystallization. The location of these sulfide blebs in olivine pseudomorphs would be somewhat analogous to the reverse net-texture (Dillon-Leitch et al., 1986).

The sulfide blebs at the Donaldson Surface deposit containing chromite grains are interpreted to represent secondary, variably, pseudomorphically replaced pyroxene oikocrysts. Other sulfide blebs in the marginal zone which are lacking in chromite, rich in chalcopyrite, and mantled by fine epidote, are also interpreted to be secondary; however, their genesis is not clear as they do not appear to be a phenocryst-replacement feature.

The Ni-rich vein, interpreted as a D₁ feature, and the Cu-rich vein, which is apparently concordant with the regional S₁-S₂ schistosity, are located close to but not at the contacts between sulfide textural types in this core hole, reflecting the heterogeneity of deformation. Occurrences at such contacts in the Donaldson West deposit were attributed to concentration of deformation where competency contrasts existed. The lack of evidence for depletion of either Cu or Ni, one to three metres from the adjacent rocks, implies that the vein sulfides may have been derived from a large volume of rock and perhaps transported over distances of tens of metres.

The movement of S from matrix sulfides (disseminated and net-textured) to massive sulfides has been suggested by Keays et al. (1981) at Lunnun shoot to account for the higher Ni content of the matrix sulfides and the presence of secondary pyrite in the massive sulfide layer. The abundant secondary pyrite in the sulfide breccia zone at the base of the massive sulfides may support this hypothesis; however,

secondary pyrite is found throughout the examined core-hole and is common in the net-textured sulfides about thin veins suggesting that the mobilization of S was not unidirectional but rather controlled by competency variations and fractures.

At the Donaldson Surface deposit there is no significant variation in S and all whole rock analyses, from nonveined specimens, plot within the boundary of the monosulfide solid solution field at 600 °C. There is a slight decrease in Ni content in all sulfide types below the net-textured zone, with the exception of the stringer zone in the footwall. This implies that, for this core hole, Ni was not selectively removed from any textural type as noted at Donaldson West (Dillon-Leitch et al., 1986). Cu is enriched in the interstitial and stringer zones and depleted in the massive sulfides. It is possible that Cu was mobilized from the massive sulfides and transported hydrothermally to these surrounding zones.

Platinum-group element mobilization

The Ni-rich vein exhibits low Pt and Pd contents which is contrary to petrological observations. It may be that the platinum-group minerals in this vein are restricted to the vein core and the platinum-group element concentrations are diluted by the surrounding sulfides.

Chondrite-normalized platinum-group element data indi-

cate that Pt and Pd in the sulfide breccia, and to a lesser extent in the stringer, were fractionated from the Os-Ir-Ru-Rh group, as is characteristic of hydrothermal mobilization of platinum-group elements at Kamalda (Leshar and Keays, 1984) and Donaldson West (Dillon-Leitch et al., 1986). Whereas data for the Cu-rich veined specimen is limited, the trend of Pd enrichment and Pt and Ir depletion is similar to that of Cu-rich veins at Donaldson West (Dillon-Leitch et al., 1986).

The generally Pt-poor nature of sulfides interpreted to have been affected by hydrothermal solutions during dynamic metamorphism, contrasts with observations in similar, but talc-carbonate altered, rocks where Pt, Pd, and Au are considered to have been mobilized together (Cowden et al., 1986). Barnes et al, (1985) suggested that solutions generated during talc-carbonate alteration may be an important factor in mobilizing Au and Pt together. The lack of evidence for widespread talc-carbonate alteration at Donaldson Surface may be responsible for the low degree of Pt mobilization in the sulfide veins.

The high Pt and Pd concentrations (recalculated to 100 % sulfides) in the interstitial textured sulfides, together with their Cu enrichment, compared to surrounding sulfides, suggest that some of these elements were introduced. A potential source of Pd and Pt in this zone could have been the immediately underlying massive sulfides. Although much of the massive sulfide zone is not appreciably depleted in

these elements, the low sulfide concentrations in the interstitial zone suggest that very small additions of these elements could develop the apparent enrichment.

It is suggested that the sulfide breccia zone, which exhibits a chondrite normalized platinum-group element profile similar to veins, was developed where competency contrast was high (the massive sulfide/footwall contact), and that the distribution of platinum-group minerals there is controlled in part by the breakdown and replacement of primary nickeline blebs. This implies that, in some cases, the deposition of hydrothermally transported platinum-group elements may be controlled by the availability of chemically compatible elements. In this case it is proposed that Sb and, to a lesser extent, Te were released from solid solution in the nickeline during replacement and combined with hydrothermally mobilized Pd to form Pd-rich phases.

The extensive development of sulfarsenide minerals (gersdorffite, cobaltite, and minor arsenopyrite) and sulfides (pyrite), in the sulfide breccia zone, indicates that S, Fe, Ni, Co, and As were mobile in these rocks. It is proposed that the breakdown of nickeline, which released Ni, As, and Sb and trace elements, and the alteration of pentlandite and pyrrhotite, which could release Ni, Co, Fe, and S, generated sufficient quantities of these elements to account for the abundance of secondary minerals.

Pt and Pd in the Cu-rich footwall stringers, interpreted as late hydrothermal features, may have been derived

from immediately overlying tectonized massive sulfides or may have been transported over considerable distances. The apparent absence of platinum-group minerals in the stringers may be related to their heterogeneous distribution and small grain size, or may suggest that the elements are in solid solution. The limited microprobe data are not supportive of this, however.

The moderately negative correlation of Pd with the Os-Ir-Ru-Rh group, the weak correlation with Pt, and the lack of correlation between Pt and the Os-Ir-Ru group suggests that the latter elements behaved similarly during metamorphic events. This is compatible with the petrographic evidence that, of these elements, Pd was preferentially mobilized at the Donaldson Surface deposit. The weak correlation of Pt and Rh is in contrast to observations at Donaldson West but is compatible with the suggestion that the platinum-group elements and gold can be subdivided into an "Ir group" composed of Os, Ir, and Ru, and a "Pd group" consisting of Rh, Pt, Pd, and Au and the observation of chondrite normalized profiles from different rock types (Barnes et al., 1985).

The mobilization of Pt is variable. Under conditions interpreted to be hydrothermal Pt is fractionated from Pd which is enriched in these rocks. Enriched Pt concentrations in the interstitial textured marginal zone are not attributed to hydrothermal transport during deformation on the basis of the lack of veins. It is suggested that Pt mobi-

lization there may represent local, diffusion away from the massive sulfide zone, in response to mechanical deformation.

The high Pt and Pd concentrations in the massive sulfides may in part reflect original concentrations, which were subsequently enriched during dynamic metamorphism based on the interpretation of the chondrite normalized profile.

The distribution and habit of platinum-group minerals, PGE- and Ag-bearing phases, and Co and As minerals in the Donaldson Surface deposit are generally compatible with their exsolution from enclosing high-temperature sulfides and growth in or along sulfide grain margins in both thermally and dynamically metamorphosed rocks. However, in the latter they are also found as rare free grains in silicates, or more commonly, at sulfide/silicate grain boundaries, possibly indicating precipitation directly from hydrothermal fluids. Similar textural associations of platinum-group minerals are reported in deposits where PGM precipitation is interpreted to be of hydrothermal origin; i.e., Rathbun Lake, (Rowell and Edgar, 1986), the Rambler Mine, (McCallum et al., 1976), and the Coldwell Complex (Dahl et al., 1987a and 1987b).

It is proposed that the deformation of the mineralized section of the Donaldson Surface deposit was accompanied by the stress-induced dissolution of sulfides which released elements that were transported hydrothermally and deposited in fractures and/or at chemically attractive sites. The Pd-

bearing platinum-group minerals located in the veins and tectonized massive sulfides (sulfide breccia zone) are more abundant, consist of a more diverse assemblage, are generally coarser grained, and occur more commonly at silicate/sulfide grain boundaries than similar minerals in surrounding sulfides; these suggest that they exsolved in the presence of a fluid phase.

Conclusions

The following textures were developed during thermal metamorphism of net-textured rocks at the Donaldson Surface deposit: (1) transitions from net-textured to net-textured to reverse net-textured sulfides and (2) replacement of pyroxene oikocrysts to form centimetre-scale chromite/sulfide blebs. Thermal metamorphism did not greatly affect the distribution of Pt and Pd. Deformation of massive sulfides resulted in the mobilization of Cu and minor Pt, Pd, and Ni into the interstitial sulfide and sulfide breccia zones. Hydrothermal transport of platinum-group elements, Ag, Sb, Bi, Te, Co, and As during upper greenschist facies metamorphism resulted in their precipitation in sulfide veins in the nonmassive sulfides, in breccias at the base of the massive sulfides, and later, possibly under lower greenschist facies metamorphism, in footwall stringers.

CHAPTER 4

**Platinum-Group Minerals, Associated Platinum-Group Element-
Bearing Minerals, and Precious Metal Minerals from the
Donaldson West deposit, Cape Smith belt, Quebec:
Distribution, Mineralogy, and Chemistry.**

Abstract

The distribution of platinum-group minerals (PGM), precious metal (PM) minerals, and platinum-group element (PGE) bearing minerals in core hole 160-224, Donaldson West deposit, confirm PGE distribution data which suggest that sulfides affected by a dynamic metamorphic event have unique elemental and mineral characteristics. Sperrylite, the only Pt-bearing mineral, is commonly observed in thermally metamorphosed rocks and is very rare in rocks which have been dynamically metamorphosed. Pd-bearing minerals are sudburyite, testibiopalladite, $\text{Pd}_3\text{Sb}_2\text{Te}_2$ (an unnamed mineral), merenskyite, the telluride melonite, and the sulfantimonide ullmannite. Widespread sudburyite and testibiopalladite are observed in veins and all thermally metamorphosed sulfides except massive sulfides. $\text{Pd}_3\text{Sb}_2\text{Te}_2$, merenskyite, and PM minerals electrum and hessite are restricted to veins. Melonite only occurs in the massive sulfides and veins.

The largest Pd-bearing PGM are located in rocks affected by dynamic events. Rare, elongate chains of sperrylite subhedra, intergrown with chalcopyrite and serpentine, appear to have precipitated in the presence of a fluid phase in both thermally and dynamically metamorphosed rocks.

PGM and melonite, from thermally and dynamically metamorphosed rocks occur in sulfides or at sulfide grain boundaries and are interpreted to have exsolved from enclosing high temperature sulfides. Grains located at sulfide/silicate contacts or in silicates are interpreted to have precipitated directly from a fluid. Hessite, intergrown with sudburyite, testibiopalladite, and cobaltite in a vein, gives a maximum formation temperature of 460 °C, consistent with proposed upper greenschist facies metamorphic conditions. Vein melonite is richer in Pd than grains from the massive sulfides.

The assemblage and composition of PGM, PM minerals, and tellurides from veins are compatible with PGE assay data and indicate that the fluids active during upper greenschist facies dynamic events at the Donaldson West deposit were fractionated (Pt-poor) and rich in Pd, Sb, Bi, Te, Au, Ag, Co, and As.

Introduction

The Donaldson West deposit, part of three separate Fe-Ni-Cu zones comprising the Donaldson deposit, is located in regionally metamorphosed (upper greenschist facies) ultramafic rocks of the eastern part of the Aphebian Cape Smith foldbelt (Fig. 1). Platinum-group element distribution in sulfide deposit have only been described for the Katiniq (Barnes, 1979; Barnes et al., 1982) and Donaldson West deposits (Dillon-Leitch et al., 1986). The identification of platinum-group minerals (PGM) and platinum-group element (PGE) bearing minerals from the Donaldson West deposit and their distribution have been described briefly (Dillon-Leitch et al., 1986). Descriptions of PGM in the Cape Smith belt are sparse; Barnes (1979) noted sperrylite at Katiniq and Daxl (1986) reported sperrylite, sudburyite, and an unnamed Pd-Sb-Ag-Te mineral in the Bravo intrusion. Platinum-group minerals from "magmatic" Fe-Cu-Ni deposits, which have been metamorphosed and deformed, such as the Shebandowan Mine (Morton, 1982), the Thierry mine (Patterson and Watkinson, 1984), the Kambalda area (Hudson and Donaldson, 1984; Leshar and Keays, 1984; Cowden et al., 1986; Hudson, 1986), and the Donaldson West deposit (Dillon-Leitch et al., 1986) are noted to be predominantly Pd species and to contain variable concentrations of Sb, Bi, Te, and As. The association of Fe-Ni-Cu sulfides with 1) PGM and PGE-bearing minerals containing Sb, Bi, and Te, 2) sulfarsenides, and

Fig. 4.1 General geology of the Cape Smith foldbelt (Hynes and Francis 1982a) showing the Donaldson (1); Katinig (2); 2-3 (3); and Cross Lake (4) Fe-Ni-Cu sulfide deposits.

3) tellurides, is an indication that the deposit is not just a magmatic sulfide concentration since these elements and minerals are commonly associated with lower temperature, hydrothermal mobilization (Leshner and Keays, 1984; Dillon-Leitch et al., 1986). This paper describes the mineralogy, mode of occurrence, and geochemistry of the PGM, PGE-bearing phases, and associated precious metal phases in the Donaldson West deposit and relates this to the distribution of PGE assays. Dillon-Leitch et al. (1986) proposed that deformation, localized at lithologic contacts where competency contrasts were inferred, resulted in mobilization and hydrothermal transportation of Pd, (Pt), Au, Ag, Sb, Bi, Te, Co, and As during upper greenschist facies metamorphism, extensively modifying the primary sulfide mineralogy and PGE distribution.

Geologic setting

The Fe-Ni-Cu-PGE sulfide concentration at the Donaldson West deposit occurs in a topographic low near the base of what is interpreted to be a symmetrically zoned, mafic to ultramafic sill. The stratigraphic succession of massive, net-textured, and disseminated sulfides is interpreted to result from magmatic segregation (Usselman et al., 1979); however, the sulfide textures, and base metal and platinum-group element distribution have been extensively modified during regional upper greenschist facies metamorphism and

multiphase deformation (Dillon-Leitch et al., 1986).

Metamorphic modification of the Donaldson West deposit has been subdivided into two distinct generations: 1) thermal metamorphism, after serpentinization, where the net-textured sulfides were progressively altered to the "net-texture to reverse net-texture" and the "reverse net-texture" (Dillon-Leitch et al., 1986) during partial sulfide replacement of olivine pseudomorphs, and 2) dynamic metamorphism, during which veins, parallel to the local S_1 - S_2 fabric, were developed mainly at contacts of differing textural types and chalcopyrite-rich stringers were generated in the footwall metasedimentary rocks along and at high angles to bedding.

It has been suggested that the major and platinum-group elements were only weakly mobilized during thermal metamorphism (and serpentinization) with the exception of minor migration of Pd into the reverse net-texture sulfide zone, possibly from the underlying massive sulfides (Dillon-Leitch et al., 1986). During dynamic mobilization, PGE fractionated resulting in the generation of Pd-rich, Pt-poor sulfides as veins and to a lesser extent the footwall stringers. The veins are commonly chalcopyrite-rich but may also be pentlandite-rich (Dillon-Leitch et al., 1986).

Sample preparation and study method

Polished sections and polished thin sections of

selected samples collected at one metre to five metre intervals were made from 10 cm long, halved NQ core and are representative of all rock/sulfide types encountered. In most cases two thin sections and one to two polished sections per sample were examined. Stratigraphic coverage per sample ranges from one to five metres in disseminated sulfides and between one and three metres in all other sulfide types.

In order to examine larger volumes of the samples and to find large grains for quantitative electron microprobe analyses heavy mineral liquid separation techniques were employed for selected intervals. Samples (about 200 g) were crushed to -60 mesh and sieved into -60 +150 (420 to 170 μ m) and -150 +325 (170 to 70 μ m) mesh fractions. The smaller size fraction was not used as the settling rates of minerals in methylene iodide were too slow. One to three sinks were recovered, separated into magnetic and non magnetic populations, and made into polished sections (see Cabri and Laflamme, 1981a for details of the techniques involved).

Sections were examined by reflected light microscopy using a mechanical stage to ensure that all sulfides were examined systematically. A magnification of 160 times was used, enabling highly reflectant grains as small as one micron across to be detected. Minerals with anomalous reflectance or birefringence were circled using a diamond stylus. The selected grains were analyzed qualitatively by energy dispersive (EDS) techniques on the electron microprobe, and if PGE or precious metal spectra were iden-

tified and the grain was larger than 10 to 20 μm in the smallest dimension, it was quantitatively analysed by electron microprobe. Some grains smaller than 10 μm in width or those with complex intergrowths were photographed using secondary and backscattered electron images on a scanning electron microscope (SEM) which had qualitative chemical analytical capabilities.

Analytical techniques

A Cambridge Mark V electron microprobe analyzer, with a beam width of approximately 1 μm , was operated at 15 to 25 kV with a specimen current of about 0.05 microampere to determine mineral compositions. Counting times between 20 and 60 seconds were used for major and minor elements. Counting times up to 100 seconds were used for trace elements. The X-ray lines and the standards used for each mineral are listed in Appendix A.

The microprobe data were corrected using the EMPADR VII computer program of Rucklidge and Gasparri (1969) modified by Watkinson, Mainwaring, and Yzerdraat in 1972 and updated by Jones and Marshall in 1984. The lower limits of detection (LLD) for major and trace element microprobe analyses are tabulated in Appendix B.

Platinum-Group Mineral Distribution, Mineralogy, and Chemistry

Sperrylite - PtAs₂

The data on distribution of platinum-group minerals (Table 1) shows that sperrylite, the only Pt-bearing PGM, is widespread in core hole 160-224. Sperrylite grains (Appendix E-1) range from very small euhedra (3 to 10 μ m across), through tabular-, subequant- and irregular-subhedra (1 to 25 μ m across), to long, thin chains of subhedra (40 to 150 μ m long; Figures 2a and 2b). Intergrowths with PGM have not been observed and intergrowths with cobaltite are rare (Fig. 2c). The occurrences of a very small sperrylite grain within a large subhedral cobaltite grain and the location of small cobaltite grains about a large, irregular sperrylite subhedra suggests that a close relationship between the two phases may exist. The location, habit, size, and other comments on sperrylite or its relationship to other phases are tabulated in Appendix E-1.

Sperrylite grains from massive sulfides occur in sulfide grains (pyrrhotite) or at sulfide/sulfide grain boundaries. Grains from net-textured and modified net-textured sulfides commonly occur at sulfide/serpentine grain margins. Chains of subhedra, occurring in net-textured, net-textured to reverse net-textured, and veined sulfides, are aligned along sulfide/sulfide or sulfide/serpentine grain boundaries and may contain inclusions of chalcopyrite. Sperrylite from the pentlandite-rich vein (253.5m) occurs as euhedra in pyrrhotite whereas the grain from a chalcopyrite-rich vein

Table 4/1. Textural, abundance, and stratigraphic location data of selected minerals in core hole 160-224, Donaldson West deposit.

Depth (m)	NA	Lith	Sulf Text	Sulf Bleb	Trace					Minerals						
					Py	Cob	Asp	Uil	Spr	Sud	Tes	Unk	Mer	Ele	Hes	Mel
198.2	X	PERD	DIS		X					X	?					
205.3		"	DIS		X			X		X						
209.4		"	DIS		X											
212.0		"	DIS							X						
216.2		"	DIS													
224.0	X	"	DIS		X											
239.5	X		VEN		A	X	X			A	A			X	X	X
242.0		PERD	NET													
243.2		"	NET	X	A											
244.2		"	NET		X	X			X							
244.5	X	"	NET	A	tr	X			X							
246.8		"	VND		tr				X	X	X			X		
248.7	X	"	NET						X							
251.2		"	NRN	X		X			X		X					
253.5	X		VEN		X	A			X	X	X	X		X		
254.5			VND		X	X				X	X					
257.6	X	PERD	VND		X					X		X				
258.5	X		VEN		X					X	X		X		X	X
260.6		PERD	NRN		tr					X						
262.7		OLPX	RN								X					
263.3		"	RN	X					X							
264.9	X	"	RN		X											
269.8	X	"	RN		A											
271.2		"	VND		A						A		?			
273.5	X		MSX		tr				X							A
274.0	X		MSX		X		tr		A							A

Abbreviations: NA=neutron activation analysis; Lith=lithology; Sulf Text=sulfide texture; Sulf Bleb=sulfide bleb; PERD=peridotite; OLPX=olivine pyroxenite; DIS=disseminated sulfides; MET=net-textured; NRN=net to reverse net-textured; RN=reverse net-textured; MSI=massive sulfide; VEN=vein; VND=veined; Py=pyrite; Cob=cobaltite; Asp=arsenopyrite; Ull=ullmannite; Spr=sperryllite; Sud=sudburyite; Tes=testibiopalladite; Unk=unknown ($Pd_{2}Sb_{2}Te_{2}$); Mer=merenskyite; Ele=electrum; Hes=hessite; Mel=melonite. Note: abundance of pyrite is one to two orders of magnitude greater than trace and precious metal minerals. Symbols: tr=trace; X=common; A=abundant; ?=possible occurrence.

Fig. 4.2a. Amoeboid sperrylite (s) chain overgrowing pyrrhotite (po) and serpentine matrix (black laths). Note chalcopyrite (c) inclusions and ragged margins with serpentine. Vein sulfides. 160-224-246.8m, reflected light. Bar=40 μ m.

Fig. 4.2b. Chainlike sperrylite (s) grain located at the boundary of pyrrhotite (po) and pentlandite (pn) and sulfide/serpentine grains. Note free grains of sperrylite at upper left corner. Net-textured sulfides. 160-224-248.7m, reflected light. Bar=50 μ m.

Fig. 4.2c. Subhedral sperrylite grain (s) with small attached cobaltite (c) anhedral (arrows) in pyrrhotite (po) host at grain margin. Net-textured sulfides 160-224-244.2m, secondary electrons (SEM).

(251.2m) is an irregular subhedra located at sulfide/serpentine grain boundaries.

Microprobe analyses (Appendix F-1) show sperrylites to contain trace amounts of Sb and Rh. Low totals are attributed to the small grain size of the tabular and chain-like grains. The stoichiometry is close to ideal, however, with traces of Rh substituting for Pt and Sb for As.

Sudburyite - PdSb

Sudburyite, perhaps the most widespread Pd-bearing PGM in core hole 160-224 (Table 1), occurs in disseminated, net-textured, net-textured to reverse net-textured, and vein sulfides. The size, habit, grain location with respect to host minerals, and comments on associated phases are presented in Appendix E-2. In general, sudburyite grains range from 3 to 65 μm long. Their habits range from tabular- and subequant-anhedra to a variety of subhedral forms. Idiomorphic and anhedral habits are rare.

Grains occur at sulfide grain boundaries and rarely in sulfides. Grains situated at sulfide/serpentine grain boundaries occur in disseminated, net-textured, and modified net-textured sulfides. Free grains of sudburyite are rare.

Intergrowths with PGM and/or PM occur in all sulfide types where sudburyite has been observed but they are most common in vein sulfides. Intergrowths occur with tennantite $\pm$ hessite, or $\text{Pd}_3\text{Sb}_2\text{Te}_2$ (Appendix E-2). Of

C

the two vein types, pentlandite- and chalcopyrite-rich, only the latter type contain examples of PGM intergrowths. Rare intergrowths of testibiopalladite, hessite, and cobaltite occur in a Cu-rich vein (239.5m). Sudburyite grains in the pentlandite-rich vein (253.5m) are not intergrown with PGM or PM and only occur at sulfide grain margins (Fig. 3). Veins contain the greatest abundance of sudburyite and the largest grains.

Microprobe analyses (Appendix F-2) indicate compositions close to stoichiometric PdSb. Te, Bi, Ag, As, and Ni are present in trace to minor amounts. Pd concentration from vein sudburyite is greater than those from net-textured sulfides (Fig. 4).

A narrow range of Te and Bi substitution for Sb occurs in grains from this core hole in contrast to the very wide range of Te and Bi substitution for Sb, with up to 15 wt % Te and 5.3 wt % Bi, reported for Kambalda sudburyite from similar sulfide types (Hudson and Donaldson, 1984). Ni substitution for Pd is generally small but the larger amount indicated by analysis 5 (1.87 wt %) is in accord with concentrations from Sudbury (Cabri and Laflamme, 1981b) where up to 10.3 wt % Ni may occur.

Testibiopalladite - PdSbTe

The distribution of testibiopalladite, almost as great as that of sudburyite in core hole 160-224, occurs in all

Fig. 4.3. Anhedral sudburyite grain at pentlandite (pn)/pyrrhotite (po) grain margin. Black areas are pits in surface. Pentlandite-rich vein. 160-224-253.5m, reflected light. Bar=80 μ m.

Fig. 4.4. Compositional variation of sudburyite grains from the Donaldson West deposit. Inverted solid triangles=pentlandite-rich vein (253.5m), circled solid upright triangles=veined material.

sulfide types except massive sulfide (Table 1). However, occurrences in the disseminated sulfides are rare. Grain habits range from equant, tabular, and irregular anhedral and subhedral to rare euhedral. The grains are dominantly tabular and range from $2 \times 6 \mu\text{m}$ to $100 \times 200 \mu\text{m}$ (Appendix E-3). The greatest observed abundance and largest grains are from vein or veined samples. However, some vein samples contain sparse, small grains.

Testibiopalladite grains from net-textured and vein sulfides commonly occur in sulfide grains where chalcopyrite and pentlandite are the most common hosts. Many grains occur at sulfide grain margins in contact with serpentine. Free grains are rare. Intergrowths may occur with sudburyite (see Fig. 5a) or sudburyite and hessite (Fig. 5b) or sudburyite, hessite and cobaltite (Fig. 5c, Appendix E-3).

Quantitative analyses (Appendix F-3), indicate testibiopalladite from core-hole 160-224 to contain variable traces of Pt, Ni, Ag, Fe and S. The stoichiometry indicates minor Ni, Pt, Ag and Fe substitution for Pd. The large trace concentrations of Fe in analyses 2 and 7 are not matched with proportional amounts of S suggesting that host fluorescence is not the whole source of Fe. Bi substitutes for Sb on a moderate scale.

Grains from veined samples are richer in Te than those from the modified net-textured sulfides (Field A, Fig. 6). Testibiopalladite grains show limited substitution of Pd for

Fig. 4.5a. Intergrowth of testibiopalladite (t) and sudburyite (s) in pyrrhotite (po), chalcopyrite (cp), and serpentine (dark lathlike groundmass). Note free grain of sudburyite. Veined material. 160-224-254.5m, reflected light. Bar=25 μ m.

Fig. 4.5b. Complex intergrowth of testibiopalladite (t), sudburyite (s), and hessite (h) in chalcopyrite (cp). Chalcopyrite-rich vein. 160-224-258.5m, reflected light. Bar=30 μ m.

Fig. 4.5c. Intergrowth of testibiopalladite (t), sudburyite (s), hessite (h), and cobaltite (cob) at the margin between pyrrhotite (po), pentlandite (pn), and serpentine-carbonate mass (black area) below cobaltite. Other black areas are surface pits. Note pyrite (py) in close association to the PGM-PM intergrowth. From a chalcopyrite- and pyrite-rich vein. 160-224-239.5m, reflected light. Bar=100 μ m.

Fig. 4.6. Compositional variation of minerals within part of the PdTe₂-PdSb₂-PdBi₂ ternary for phases from the Donaldson West deposit. Field A-testibiopalladite and field B-projection of the unnamed mineral (Pd₃Sb₂Te₂). Solid diamond=reverse net-texture, circled solid, upright triangles=veined material, large circled triangles=veined sample analyses by (Lafamme, 1985).

Ni (Field A, Fig. 7).

Unknown - $\text{Pd}_3\text{Sb}_2\text{Te}_2$

The unnamed PGM phase ($\text{Pd}_3\text{Sb}_2\text{Te}_2$) has been quantitatively identified in two sections, a chalcopyrite-rich vein and a microveined, net-textured to reverse net-textured sample (Table 1; Appendix E-4). The grains are dominantly tabular subhedra. Two grains are within pyrrhotite. The others occur at sulfide/serpentine (Fig. 8a), sulfide/serpentine/PGM, or sulfide/PM grain boundaries (Appendix E-4). One grain is intergrown with electrum in a pyrite/chalcopyrite vein and one is intergrown with a two small grains of sudburyite (Fig. 8b). $\text{Pd}_3\text{Sb}_2\text{Te}_2$ grains are a bright white colour in air compared to pentlandite and pyrrhotite. The reflectance is less than sudburyite and greater than testibiopalladite. Bireflectance is low and anisotrophism is high, from white to dark grey.

Quantitative analyses of $\text{Pd}_3\text{Sb}_2\text{Te}_2$ (Appendix F-4) exhibit a range in Bi content from below detection to 0.78 weight percent and rare traces of Pt and As. A Ni-analog of the unknown has been identified (analyses 5 and 7; Appendix F-4; and Laflamme, 1985). Bi substitution for Sb is minimal (Field B, Fig. 6). Extensive substitution of Ni for Pd occurs (Field B, Fig. 7) in the nickel analog (Laflamme, 1985).

Merenskyite - PdTe_2

Fig. 4.7. $Pd/Pd+Ni$ versus $Te/Te+Sb+Bi$ for some Pd-bearing phases from the Donaldson West deposit. Field A= testibiopalladite, B=unnamed mineral ($Pd_3Sb_2Te_2$), C=merenskyite, D=melonite from massive sulfides, and E= melonite from vein or veined material. Solid squares= massive sulfides, solid upright triangles=veins, circled, solid upright triangles=veined material, large circled triangles=analyses by Laflamme (1985).

Fig. 4.8a. Unnamed mineral $(\text{Ni}, \text{Pd})_3\text{Sb}_2\text{Te}_2$ (white) at boundary between pyrrhotite (po), pentlandite (pn), and serpentine (black laths). The grains appear to be oriented parallel to the po/pn contact. Veined sulfide. 160-224-257.6m, secondary electrons (SEM).

Fig. 4.8b. Unnamed mineral $(\text{Pd}, \text{Ni})_3\text{Sb}_2\text{Te}_2$ (white) at pyrrhotite (po) and serpentine grain (black laths) margin. Intergrown with sudburyite (sud). Veined sulfides. 160-224-157.6m, secondary electrons (SEM).

The identification of merenskyite is tenuous, as quantitative analysis of the small grains resulted in low totals. The crystal habit, grain size, and location of tentatively identified grains are tabulated in Appendix E-5. Merenskyite would appear to occur in vein or veined sulfides (Table 1; Appendix F-5).

The one quantitative analysis (258.5m, vein; Appendix F-5) has a high Pd/Pd+Ni (Field C, Fig. 7).

Associated Precious Metal Minerals

Electrum - AuAg

Electrum occurs in chalcopyrite- and pentlandite-rich veins, 239.5m and 253.5m respectively, and a highly foliated, net-textured to reverse net-textured sulfide (246.8m). All electrum grains are in sulfide veins (Table 1). Pyrite, sulfarsenides, and PGM are usually closely associated. The grains are generally subtabular anhedral. They are located at sulfide grain margins and are rarely intergrown with PGM (Fig. 9; Appendix E-6).

Electrum ranges from $Au_{88.4}Ag_{11.6}$ to $Au_{88.4}Ag_{11.6}$. Consistent traces of Pt, Sb, and Te occur whereas Ru, Os, and Ir are erratic traces (Appendix F-6).

Hessite - Ag₂Te

Hessite, a rare mineral in core hole 160-224, has only been observed in chalcopryrite-rich veins at 239.5m and 258.5m (Table 1; Appendix E-7). All grains occur as sub-tabular subhedra and are intergrown with PGM. The grains are located at sulfide/PGM (Fig. 5b) or sulfide/sulfarsenide/PGM (Fig. 5c) grain boundaries.

The stoichiometry is close to ideal (Appendix F-7); however, the erratic totals are attributed to the high kilovoltage employed (25 kV). Very low, variable traces (less than 0.25 wt %) of Sb and Cu occur. These grains range between 62.3 and 64.3 atomic % Ag; hessites with these compositions have a maximum temperature of formation of $460 \pm 5^\circ\text{C}$ and a minimum of about 120°C (Stumpfl and Rucklidge, 1968) based on experimental data.

Melonite - NiTe_2

Melonite has been identified in specimens from chalcopryrite-rich veins (239.5m and 258.5m) and massive sulfides at 273.5m and 274.0m (Table 1; Appendix E-8). Grains from the veins are dominantly tabular subhedra whereas grains from the massive sulfides range from equant euhedra and anhedral to tabular subhedra.

Grains, regardless of textural type, are located in sulfides, predominantly pyrrhotite (Appendix E-8). Grains at sulfide/sulfide or sulfide/serpentine grain contacts are minor and not restricted to either textural type. Euhedral

forms occur only in the massive sulfides. No intergrowths with PGM or PM have been observed.

Quantitatively analysed melonites contain between 1.41 and 12.5 wt % Pd (Appendix F-8). Melonite contains variable, low traces of Pt. Grains from the massive sulfides (Field D, Fig. 7) exhibit a wide variation of Te-Sb-Bi substitution over a narrow Pd/Pd+Ni. Grains from the veins (Field E, Fig. 7) exhibit a small range of Pd substitution for Ni within a narrow Te/Te+Sb+Bi. These grains appear to have similar Te/Te+Sb+Bi as the merenskyite grain (Field C, Fig. 7). The extensive substitution of Pd for Ni is well documented; complete solid solution between merenskyite and melonite is reported (Garuti and Rinaldi, 1986; Hudson, 1986).

Ullmannite - NiSbS

Ullmannite has only been observed in one sample from the disseminated sulfide zone at 205.3m (Table 1). The grains occur in a sulfide-carbonate veined specimen as tabular and irregular anhedral or subhedral (Appendix E-9). Grains are located in sulfides, or at sulfide/serpentine grain boundaries.

Stoichiometry is close to ideal (Appendix F-9). Consistent traces of Pt, Pd, Cu, As, Fe, and Co occur. Although Bayliss (1977) suggested that trace amounts of As could substitute for Sb and/or S. It is apparent that a number of

element substitutions are possible for Ni, including platinum-group elements (Appendix F-9).

Ionic Substitution in PGM, PGE-Bearing, and PM Minerals

The substitution of PGE in PGM, precious metal minerals, sulfides, and tellurides is well known; however the extent, the relationship to temperature, and the influence of fluids during metamorphism are poorly understood. Skinner et al. (1976), Distler (1980), and Makovicky et al. (1985) note limited solid solution of Pd and Pt in pyrrhotite and pentlandite at magmatic temperatures (1000 °C) which decreases rapidly at subsolidus temperatures to close to or below microprobe detection limits at 400 °C (Makovicky et al., 1985).

PGE ions, of +2 charge, have ionic size and charge characteristics (Table 2) that should allow them to substitute freely with base metals (Barnes et al., 1985). It is not clear, however, if PGE ions are actually in this state in PGM, PGE-bearing, and PM minerals. Microprobe data in this study suggest that substitution of Pd for Ni occurs in many minerals and may be quite extensive, as in melonite. Ag substitution for Au occurs over a wide range in electrum (Kingston and El Dosuky, 1982; and Hudson and Donaldson, 1984); compatible with their ionic radii. The substitution of Sb, Te, and Bi for one another in sudburyite and melonite, and Bi for Sb in testibiopalladite and the unknown

Table 4.2. Charge and size parameters of Platinum-Group, Precious Metal, and Selected Base Metal Elements.

Element	Z	Charge	Size ¹ (Å)	OFBE ²
Fe	26	+2 +3 +4	0.78 0.645 0.585	
Co	27	+2 +3 +4	0.745 0.61 0.53	
Ni	28	+2 +3 +4	0.69 0.56 0.48	
Cu	29	+2 +3	0.65 0.54	
As	33		0.58	
Ru	44	+2 +3 +4	0.74 0.68 0.62	12/5 10/5 8/5
Rh	45	+2 +3 +4	0.72 0.66 0.60	9/5 12/5 10/5
Pd	46	+2 +3 +4	0.86 0.76 0.615	6/5 9/5 12/5
Ag	47		1.28	
Sb	51		0.76	
Te	52		0.66	
Os	76	+2 +4	0.74 0.63	12/5 8/5
Ir	77	+2 +3	0.74 0.68	9/5 12/5
Pt	78	+2 +4	0.80 0.625	6/5 12/5
Au	79	+1	1.37	
Bi	83		1.03	

OFBE = octahedral field stabilization energy
¹ - Shannon (1976); ² - Barnes et al. (1985).

are indicated by microprobe analyses, however, the charge states are likely to vary suggesting metallic rather than ionic bonding.

The Os-Ir-Ru-Rh group substitution for Pt in sperylite, albeit at low levels, reflects the compatible size and charge parameters of these elements and is consistent with their correlation as a group during metamorphic processes. However, the general lack of Pt substitution, in Pd-bearing PGM, tellurides, and sulfantimonides, may not depend upon physical parameters but rather the availability of Pt which is proposed to have been low due to fractionation during hydrothermal transport at the Donaldson West deposit.

Discussion

Distribution of PGM, associated PGE-bearing, and PM minerals

The distribution of PGM, PGE-bearing, and PM minerals at the Donaldson West deposit is interpreted to be closely related to the metamorphic events. Thermally metamorphosed rocks lacking evidence of a dynamic event consist of disseminated, net-textured, net-textured to reverse net-textured, reverse net-textured, and massive sulfides and contain most of the Pt-bearing PGM and few of the Pd-bearing PGM or PM minerals. Dynamically overprinted metamorphosed rocks, veins and veined sulfides, which consist of pentlandite- and chalcopyrite-rich veins, contain most of the Pd-bearing PGM and Pd-rich melonite grains, all Au- and Ag-bearing PM minerals, and rarely contain Pt-bearing PGM.

The massive sulfides, which exhibit metamorphic fabrics but do not show any chemical influence of dynamic metamorphism overprinting thermal metamorphism, as indicated by chondrite normalized profiles (Dillon-Leitch et al., 1986) contain numerous grains of Pt-bearing PGM (sperrylite) and an abundant Pd-bearing PGE phase (melonite) which has low concentrations of Pd. The abundance of sperrylite is compatible with the moderate Pt concentration. It is suggested that massive sulfides developed melonite rather than sudburyite or other Pd-rich minerals in response to the low Pd concentrations in these rocks.

Both pentlandite- and chalcopyrite-rich veins contain abundant Pd-Sb-Bi-Te bearing phases whereas Pt-bearing phases are either absent or very rare; this suggests that the vein composition is not an important factor in controlling PGM mineralogy but rather that the hydrothermal transport fractionated PGE.

The regular occurrence of sperrylite in thermally metamorphosed sulfides is interpreted to be compatible with the moderate concentration of Pt in these rocks. The rare occurrence of sperrylite in dynamically mobilized sulfides (veins) is interpreted to reflect the low capacity of the hydrothermal fluids, generated during dynamic metamorphism of the Donaldson West deposit, to transport Pt to the same degree as Pd. This is in contrast to chalcopyrite-rich veins from the Kambalda deposits which commonly contain sperrylite (Hudson, 1986). The metamorphic mineral assemblage for ultramafic rocks of the Kambalda area is serpentine-talc-carbonate-chlorite (Hudson and Donaldson, 1984; Cowden et al., 1986); it is suggested that the fluids active during dynamic metamorphism there were richer in CO₂. Barnes et al. (1985) have suggested that Pt and Au are more readily mobilized than Pd during talc-carbonate alteration.

The abundance of sperrylite in the massive sulfides is interpreted to reflect the original moderate concentration of Pt there as chondrite normalized profiles or textural data do not suggest a hydrothermal contribution.

The greatest abundance and largest sudburyite grains

occur in dynamically mobilized sulfides (veins and veined sulfides), supporting the hypothesis that PGE (Pd) mobilization was greatest during dynamic metamorphism. The paucity of sudburyite in the massive sulfides may reflect an original low Pd concentration, or, more likely, the depletion (by stress induced diffusion) of Pd, during thermal metamorphism, to the overlying reverse net-textured sulfides (Dillon-Leitch et al., 1986).

Testibiopalladite grains, rare in thermally metamorphosed sulfides, are the most common in dynamically metamorphosed sulfides, where the largest grains occur, supportive of the hypothesis that the grain size and abundance of PGM are directly related to hydrothermal transport (Dillon-Leitch et al., 1986). The unnamed mineral ($\text{Pd}_3\text{Sb}_2\text{Te}_2$) and merenskyite, observed in only dynamically metamorphosed sulfides, suggests that the abundance of these minerals is controlled by dynamic metamorphism and accompanying hydrothermal transport of Pd-rich fluids.

The confinement of electrum and hessite to veins or veined sulfides is compatible with the interpretation that these phases were generated from hydrothermal solutions precipitated in dilational structures.

Melonite occurs in thermally metamorphosed sulfides (massive sulfides) and in dynamically metamorphosed sulfides (veins); however, the amount in the massive sulfides is twice as great suggesting that this phase is an important host for Pd in the massive sulfides.

Ullmannite has only been observed in thermally metamorphosed disseminated sulfides; however, the sample is foliated and carbonate-veined suggesting that dynamic metamorphism was the important catalyst for the generation of this rare, Pd-bearing mineral.

Textural characteristics

Sperrylite grains from the thermally metamorphosed massive sulfides have a small grain size and are located in sulfide grains (most commonly pyrrhotite) or at sulfide grain boundaries suggesting that these grains exsolved from the enclosing high temperature sulfides. Grains from net-textured and reverse net-textured sulfides are commonly located at sulfide/serpentine grain boundaries suggestive of precipitation in the presence of a fluid phase. Some of the grains in thermally metamorphosed rocks appear to overgrow randomly oriented serpentine laths, which are interpreted to have been generated before or during recrystallization accompanying the peak of thermal metamorphism (D₁; Dillon-Leitch et al., 1986) suggesting a mid to late D₁ origin for these sperrylite grains. Alternatively it is possible that the apparent overgrowth of sperrylite on serpentine may be attributed to the higher energy of crystallization of sperrylite and the serpentine is coeval or later.

The occurrence of Pt-PGM interpreted to have precipitated in the presence of a fluid phase and/or to have

exsolved from enclosing high temperature sulfides during thermal metamorphism, may suggest that Pt was mobile during these conditions but apparently³ underwent only local redistribution. It is possible that fluids generated during serpentinization or the early stages of thermal metamorphism were Cl-rich but microprobe analyses do not support Cl-enriched silicate phases. The low Cl content of greenschist facies silicate assemblages at Donaldson West is, however, compatible with the suggestion of Boudreau et al. (1986) that fluids generated during greenschist facies metamorphism are depleted in Cl. It is proposed that the serpentinization of olivine, which may concentrate Cl at the olivine/serpentine reaction front (Rucklidge and Patterson, 1977), may have mobilized some Pt, from discrete PGM or as solid solution in high temperature sulfides, and precipitated it locally when the Cl concentration of the fluid decreased during metamorphic dilution or a drop in temperature.

Barnes et al. (1985) noted that chondrite normalized profiles of talc-carbonate altered komatiitic rocks are depleted in Au and Pt and suggested that these elements should be mobile during talc-carbonate alteration where oxidizing conditions are believed to occur after reducing conditions of serpentinization (Eckstrand, 1975). Although talc-carbonate alteration in the Donaldson West deposit is minor, it appears to have been restricted to cm-wide zones about sulfide-carbonate veins or inferred, sulfide replaced

pyroxene oikocrysts (Dillon-Leitch et al., 1986). It is in these rocks that sperrylite occurs, where the grains are interpreted to have precipitated in the presence of a fluid phase during thermal metamorphism.

Studies from the Bushveld Complex suggest that C-O-H-S fluids may have been important in the concentration of PGE (Ballhaus and Stumpfl, 1985a) where fluid inclusion studies suggest CO₂ and CH₄ filled inclusions (Ballhaus and Stumpfl, 1985b). Albino (1984) noted that the meta-argillites which underlie the Boundary Complex are highly carbonaceous. The increase in the regional metamorphic grade toward the Donaldson Mine area has destroyed graphite in the metasedimentary rocks underlying the Donaldson West deposit. However, early metamorphic fluids in the Donaldson Mine area could have been reducing, facilitating the redistribution of PGE during thermal metamorphism.

Rare sperrylite grains from dynamically metamorphosed rocks (veined sulfides) may occur in sulfide grains suggestive of exsolution from the enclosing sulfides, or at sulfide/serpentine grain margins suggestive of precipitation in the presence of a fluid.

The rare chainlike sperrylites, from veined sulfides and one net-textured sample, are aligned along sulfide grain boundaries, may overgrow serpentine grains, and may contain chalcopyrite inclusions. Whereas this suggests that the chainlike texture is not restricted to grains generated by dynamic metamorphism and suggests that in some cases the

grains may have exsolved in the presence of a fluid phase, it is compatible with the interpreted secondary nature of the grains.

Sperrylite grains coexisting with cobaltite in net-textured sulfides suggest that in both cases sperrylite acted as a nucleus for cobaltite growth. A similar relationship between sperrylite or irarsite (IrAsS) and cobaltite has been noted from Sudbury ores (Cabri, 1981).

Grains of sudburyite and the unknown ($\text{Pd}_3\text{Sb}_2\text{Te}_2$) in dynamically and thermally metamorphosed sulfides have grain boundary characteristics which suggest formation by exsolution from enclosing sulfides or exsolution in the presence of a fluid phase may occur in rocks affected by either metamorphic events. Free grains, interpreted to have precipitated directly from a fluid phase, are rare.

Complex intergrowths involving sudburyite occur in both thermally and dynamically metamorphosed sulfides; however, intergrowths are more common in dynamically mobilized sulfides supportive of the hypothesis that the hydrothermal solutions associated with dynamic metamorphism were rich in Pd, Sb, Bi, and Te.

Testibiopalladite grains from thermally metamorphosed sulfides occur at sulfide/serpentine grain boundaries suggestive of precipitation in the presence of a fluid phase or an unrecognized dynamic component. Grains from dynamically mobilized sulfides occurring in sulfides or at sulfide grain margins suggest exsolution from the enclosing sul-

fides, whereas those at sulfide/serpentine grain margins suggest the presence of a fluid phase. Rare free grains are interpreted to have precipitated directly from a fluid phase.

Testibiopalladite intergrowths, single or multiple, occurring with sudburyite, hessite, and cobaltite, more common in dynamically metamorphosed sulfides, are interpreted to support the hypothesis that the fluids generated and active during dynamic metamorphism were of a unique composition. Intergrowth of $\text{Pd}_3\text{Sb}_2\text{Te}_2$ with sudburyite or electrum, are interpreted to reflect the elevated PGE and precious metal trace concentrations in the sulfide veins.

Some merenskyite grains from dynamically metamorphosed sulfides are interpreted to have exsolved from enclosing chalcopyrite and to reflect the mobilized nature of the sulfides. The occurrence of electrum and hessite in only dynamically metamorphosed sulfides reflects the elevated PM concentration in the hydrothermal fluid.

The composition of the hessite grains intergrown with sudburyite, testibiopalladite, cobaltite, and serpentine give a temperature range of formation between $460 \pm 5^\circ\text{C}$ and about 120°C . The upper range is compatible with upper greenschist facies conditions interpreted to have prevailed during D_1 .

Melonite grains, from the thermally metamorphosed massive sulfides, occurring predominantly in sulfides or at sulfide boundaries suggest exsolution from enclosing high

temperature sulfides, compatible with no hydrothermal overprint. Ullmannite grains are located in sulfides and at sulfide/serpentine grain boundaries suggestive of exsolution from enclosing sulfides or precipitation in the presence of a fluid phase. The latter is compatible with the microveined nature of the sample.

It is suggested that grain boundary textures are not specific to either metamorphic event. This is interpreted to reflect the important role of fluids in the formation of PGM during thermal metamorphism at greenschist facies temperatures. Alternatively, it is possible that microveining and fabric development during deformation are responsible for local fluid movement and reflect a continuum of hydrothermal transport along structures attributed to dynamic metamorphism.

Chemical composition

Melonites from the chalcopyrite-rich vein and veined sulfides are richer in Pd than melonites from the massive sulfides compatible with their proposed generation in dynamically mobilized sulfides developed during hydrothermal transport of solutions enriched in Pd. The Pd-poor melonites from the massive sulfides at the Donaldson West deposit exhibit minor substitution of Pd for Ni and extensive substitution of Sb and Bi for Te; this may suggest that the low Pd concentration there was homogeneously distributed, pos-

sibly in solid solution in the host pyrrhotite, but that the Te, Sb, and Bi concentrations were not. Sudburyite grains from the Ni-rich vein appear to be somewhat richer in Pd compared to those from the chalcopyrite veined sulfides.

Conclusions

The distribution, abundance, and diversity of Pd-Sb-Bi-Te bearing phases in the Donaldson West deposit is closely related to the mobilization of PGE and associated elements during dynamic metamorphism when veins were developed mainly at textural contacts. Minerals composed of these elements are rare in the thermally metamorphosed sulfides. The paucity of these phases there is not simply a function of the lower sulfide or PGE concentrations, as small Pt-bearing grains are commonly identified in the thermally metamorphosed sulfides even though Pt and Pd have similar trace concentrations there. The distribution of Pt-bearing phases appears to be related to original concentrations whereas the grain location may reflect early thermal metamorphic mobilization in the presence of chlorine-bearing solutions generated during serpentinization. It is more likely that Pt was mobilized during limited talc-carbonate alteration about veins. The lack of evidence for Cl⁻ enrichment about sperylite grains interpreted to have formed in the presence of a fluid phase suggests that other ligands should be considered.

Textural characteristics, such as grain boundary relationships and coexistence of PGM, PGE-bearing, and PM minerals, while not unique to thermally or dynamically mobilized sulfides, in general support the hypothesis that the distribution of these phases is largely controlled by dynamic metamorphism. Grain size appears to be positively related to dynamic metamorphism. Grain habit for sperrylite, in the form of chains, generally appears to reflect dynamic mobilization.

The trend of Pd enrichment in melonite is directly related to dynamic metamorphism and the accompanying generation of Pd-rich fluids during hydrothermal transport.

CHAPTER 5

The Relationship Between Metamorphism and the Distribution,
Mineralogy, and Chemistry of Platinum-Group Minerals,
Associated Platinum-Group Element-Bearing Minerals, and
Precious Metal Minerals from the Donaldson Surface deposit,
Cape Smith Belt, Quebec.

Abstract

The distribution of platinum-group minerals (PGM) and precious metal (PM) minerals in core hole 160-225, Donaldson Surface deposit, support platinum-group element (PGE) assay data which suggest that thermal metamorphic events did not significantly alter PGE concentrations; however, sulfide veins, developed during dynamic metamorphic events, have distinctive elemental and mineral characteristics.

Sperrylite, the only Pt-bearing PGM, is widespread in rocks affected by thermal metamorphism but is rare in veins. The distribution and abundance of Pd-bearing minerals, sudburyite, testibiopalladite, borovskite, $\text{Pd}_3\text{Sb}_2\text{Te}_2$ (an unnamed mineral), merenskyite, mitchenerite, and the tellurides hessite and melonite, correlate strongly with rocks which have been dynamically metamorphosed; these rocks include veins, sulfide breccia, and to a lesser extent the massive sulfides. Sudburyite, borovskite, $\text{Pd}_3\text{Sb}_2\text{Te}_2$, and hessite are restricted to rocks influenced by dynamic events.

The largest Pd-bearing PGM grains occur in dynamically metamorphosed rocks. Long chains of sperrylite grains occur in the massive sulfides, where, intergrown with chalcopyrite and epidote and occurring rarely as free grains, they are interpreted to have precipitated in the presence of a fluid phase. Pd-PGM grains may be exsolved from enclosing high temperature sulfides. However, in rocks affected by dynamic events they are also found at sulfide/silicate grain margins or as rare free grains, and may have precipitated directly from a fluid phase. Sperrylite grains in rocks affected by thermal metamorphism are commonly located at sulfide/silicate grain margins and their characteristics do not support more than local redistribution.

Nickeline grains, restricted to the sulfide breccia zone, are variably altered to a gersdorffite-cobaltite-PGM assemblage. The close association of Pd-PGM to the altered nickeline grains suggests that the alteration was accomplished by fluids generated during dynamic metamorphism; the total lack of Pt-PGM in this zone confirms PGE assay data indicating the fractionated nature of the hydrothermal fluids.

The composition of hessite grains, intergrown with borovskite and testibiopalladite in dynamically overprinted massive sulfides, indicates a maximum temperature of formation of 460 °C, compatible with estimates derived from silicate assemblages developed during upper greenschist facies metamorphism. The orientation of exsolution lamellae and the long axes of some Pd-PGM parallel to vein margins suggest a D₁ origin for the veins.

Vein melonite is richer in Pd compared to grains from massive sulfides. Borovskite grains show Pd-enrichment with increasing dynamic overprint. The distribution, assemblage, and composition of PGM and PM minerals from dynamically metamorphosed rocks are consistent with PGE data and the hypothesis that hydrothermal transport fractionated fluids active during dynamic events.

Introduction

The Donaldson Surface deposit, part of three separate Fe-Ni-Cu zones comprising the Donaldson deposit, is located in regionally metamorphosed (upper greenschist facies) ultramafic rocks of the eastern part of the Aphebian Cape Smith foldbelt (Fig. 1). Previous studies of sulfide deposits within the foldbelt have described the base metal concentrations in ultramafic rocks (Wilson et al., 1969; Miller, 1977; Barnes, 1979; Albino, 1984). Platinum-group element distribution in sulfide deposits have only been described at Katiniq (Barnes, 1979; Barnes et al., 1982) and at Donaldson West (Dillon-Leitch et al., 1986).

The qualitative identification of platinum-group minerals (PGM) and platinum-group element (PGE) bearing minerals from the Donaldson West deposit and their distribution have been described briefly (Dillon-Leitch et al., 1986). Barnes (1979) noted sperrylite at Katiniq and Daxl (1986) reported sperrylite, sudburyite, and an unnamed Pd-Sb-Ag-Te mineral in the Bravo intrusion.

Platinum-group minerals from "magmatic" Fe-Cu-Ni deposits, which have been metamorphosed and deformed, such as the Shebandowan Mine (Morton, 1982), the Thierry mine (Patterson and Watkinson, 1984), and the Kambalda area (Hudson and Donaldson, 1984; Lesher and Keays, 1984; Cowden et al., 1986; Hudson, 1986) are noted to be predominantly Pd species and to contain variable concentrations of Sb, Bi,

Fig. 5.1 General geology of the Cape Smith foldbelt (Hynes and Francis 1982a) showing the Donaldson (1); Katinik (2); 2-3 (3); and Cross Lake (4) Fe-Ni-Cu sulfide deposits.

Te, and As. The association of Fe-Ni-Cu sulfides with: 1) PGM and PGE-bearing minerals containing Sb, Bi, and Te; 2) sulfarsenides, and 3) tellurides, is an indication that the sulfide concentration is not just magmatic since these elements and minerals are commonly associated with lower temperature, hydrothermal mobilization (Leshar and Keays, 1984; Dillon-Leitch et al., 1986).

This paper describes the mineralogy, mode of occurrence, and geochemistry of the PGM, PGE-bearing phases, and associated precious metal phases in the Donaldson Surface deposit and relates this to the distribution of PGE assays (Chapter 3). It was proposed there that deformation, localized at lithological contacts where competency contrasts were inferred, resulted in mobilization and hydrothermal transportation of Pd, (Pt), Au, Ag, Sb, Bi, Te, Co, and As during upper greenschist facies metamorphism, extensively modifying the primary sulfide mineralogy and PGE distribution.

Geologic Setting

The Fe-Ni-Cu-PGE sulfide concentration at the Donaldson Surface deposit occurs in a topographic low near the base of what is interpreted to be a symmetrically zoned (Picard, 1986), mafic to ultramafic sill. The stratigraphic succession of massive, interstitial, and net-textured sulfides is interpreted to result from magmatic segregation (Usselman et

al., 1979); however, the sulfide textures, and base metal and platinum-group element distribution have been extensively modified during regional upper greenschist facies metamorphism and multiphase deformation.

Metamorphic modification of the Donaldson Surface deposit has been subdivided into two distinct generations: 1) thermal metamorphism, after serpentinization, where the net-textured sulfides were altered to the "net-texture to reverse net-texture" (Dillon-Leitch et al., 1986) during partial sulfide replacement of olivine pseudomorphs, and 2) dynamic metamorphism, during which veins, parallel to the local S_1 - S_2 fabric, were developed mainly at contacts of differing textural types. Elsewhere, sulfide breccias formed at the massive sulfide/footwall contact (a zone of high competency contrast), and chalcopyrite-rich stringers were generated in the footwall metasedimentary rocks along and at high angles to bedding.

It has been suggested that the major and platinum-group elements were only weakly mobilized during thermal metamorphism (and serpentinization) with the exception of minor migration of Cu, Pt, and Pd into the interstitial sulfide zone, possibly from the immediately underlying massive sulfides.

During dynamic mobilization, PGE fractionated resulting in the generation of Pd-rich, Pt-poor sulfides as veins, sulfide breccia, and, to a lesser extent, the stringer zone. The massive sulfides have chondrite normalized profiles sug-

gestive of a moderate degree of hydrothermal fractionation of PGE and are moderately enriched in Pt and Pd.

Sample preparation and study method

Polished thin sections of each sample, taken at one metre to two metre intervals were made from 10 cm long, halved NQ core and are representative of all rock/sulfide types encountered. In most cases two to four thin sections per sample were examined.

Polished thin sections were examined by reflected light microscopy using a mechanical stage to ensure that all sulfides were examined systematically. A magnification of 160 times was used, enabling highly reflectant grains as small as one micron across to be detected. Minerals with anomalous reflectance or birefringence were circled using a diamond stylus. The selected grains were analyzed qualitatively by EDS on the electron microprobe, and if PGE or precious metal spectra were identified and the grain was larger than 10 to 20 μm in the smallest dimension, it was quantitatively analysed by electron microprobe. Some grains smaller than 10 μm in width or those with complex intergrowths were photographed using secondary and backscattered electron images on a scanning electron microscope (SEM) which had qualitative chemical analytical capabilities.

Analytical Techniques

A Cambridge Mark V electron microprobe analyzer, with a beam width of approximately 1 μm , was operated at 15 to 25 kV with a specimen current of about 0.05 microampere to determine mineral compositions. Counting times between 20 and 60 seconds were used for major and minor elements. Counting times up to 100 seconds were used for trace elements. The X-ray lines and the standards used for each mineral are listed in Appendix A.

The microprobe data were corrected using the EMPADR VII computer program of Rucklidge and Gasparri (1969) modified by Watkinson, Mainwaring, and Yzerdraat in 1972 and updated by Jones and Marshall in 1984. The lower limits of detection (LLD) for major and trace element microprobe analyses are tabulated in Appendix B.

Platinum-Group Mineral Distribution, Mineralogy, and Chemistry

Sperrylite - PtAs_2

The data on distribution of platinum-group minerals (Table 1) shows that sperrylite, the only Pt-bearing PGM, is the most widespread in core hole 160-225. Sperrylite grains range from very small euhedra (2 to 5 μm across), through rare irregular subhedra (5 to 50 μm across, Fig. 2a), and more common tabular subhedra (5 to 55 μm long, Fig. 2b) to very long, thin chains of subhedra (Figures 2c and

Table 5.1. Textural, abundance, and stratigraphic location data of platinum-group and precious metal minerals in core hole 160-225, Donaldson Surface deposit.

Depth (m)	Sulf Text	Spr	Sud	Tes	Bor	Unk	Mer	Mch	Hes	Mel
7.2	NET									
8.2	NET	X					X			
9.2	NET									
10.2	NET	X								
11.2	NET	X		X			X			X
12.2	NET									
13.2	NRN									
14.2	NRN	X								
15.2	NET	X								
16.2	NET	X								
17.2	NRN	X								
18.2	VEN	X	A	A		A				
19.2	NRN									
20.2	NRN									
21.2	INT									
22.2	INT									
22.4	VEN		?	X	?	A	X			X
23.2	INT									
25.8	MSX	A	X		X	?	A	?		X
27.0	MSX	X	X	X	A	?	X	?	X	
28.0	BXA		A	A		A				
28.6	BXA		A			A				
32.5	STR									

Symbols: Sulf Text=sulfide texture; NET=net-textured; NRN=net-textured to reverse net-textured; INT=interstitial sulfide; MSX=massive sulfide; BXA=brecciated sulfide; VEN=vein; STR=footwall stringer; Spr=sperrylite; Sud=sudburyite; Tes=testibiopalladite; Bor=borovskite; Unk=unknown ($\text{Pd}_3\text{Sb}_2\text{Te}_2$); Mer=merenskyite; Mch=michenerite; Hes=hessite; Mel=melonite; tr=trace; X=common; A=abundant; ?=possible occurrence.

Fig. 5.2a. Irregular sperrylite (s) in pyrrhotite (po), pentlandite (pn), and serpentine (dark laths) matrix. Reflected light, 160-225-11.2m, net-textured. Bar=26 μ m.

Fig. 5.2b. Subequant sperrylite (s) grain in chalcopyrite (cp) and serpentine matrix (dark grey fibrous mass). Sperrylite may be pseudomorphically replacing chalcopyrite at arrows. Reflected light, 160-225-17.2m, net-textured to reverse net-textured. Bar=26 μ m.

Fig. 5.2c. Sperrylite chain (s) parallels pentlandite (pn), pyrrhotite (po), and chalcopyrite (cp) grain margins and extends into epidote grains (ep). Note free grains (arrows). Reflected light, 160-225-27.0m, massive sulfide. Bar=26 μ m.

Fig. 5.2d. Sperrylite chain (s) adjacent to chalcopyrite (cp), pyrrhotite (po), and serpentine (black masses). Note how sperrylite mantles curved serpentine lath and the close association of unidentified Pd-Sb-Bi-Te bearing PGM (arrows). Reflected light, 160-225-25.8m, massive sulfide. Bar=53 μ m.

Fig. 5.2e. Skeletal sperrylite grain (s) in chalcopyrite (cp) and epidote (ep). Reflected light, 160-225-25.8m, massive sulfide. Bar=26 μ m.

Fig. 5.2f. Intergrowth of sperrylite (s) and merenskyite (m) in chalcopyrite (cp) and serpentine (dark laths). Note anhedral habit of the merenskyite and location in serpentine. Reflected light, 160-225-8.2m, net-textured. Bar=26 μ m.

3

Micro-D

2d) which range between 30 and 300 μm long (Appendix G-1). Intergrowths with other PGM are rare (Figures 2d and 2e). The location, size, crystal habit, host mineralogy, and other comments on its relationship to silicate or PGM phases are tabulated in Appendix G-1. Sperrylite grains, regardless of sulfide type, are commonly found at sulfide/silicate grain contacts and rarely at sulfide/sulfide grain boundaries.

Chains, tabular, and equant grains generally exhibit one or more well developed crystal face, whereas rare irregular grains may have round or jagged forms. Rare skeletal grains are probably former chains which have grown together (Fig. 2f). Whereas no true inclusions were noted in this core hole, a sperrylite chain, with a skeletal appearance (Appendix G-1), partially encloses chalcopyrite and an unidentified Pd mineral.

Sperrylite may be associated with any of the major sulfides and aligned along pyrrhotite, pentlandite, or chalcopyrite grain boundaries; however, silicate grains commonly form part of the grain margin. Many sperrylites appear to overgrow serpentine laths (Figures 2a and 2b) and to replace host sulfides (Fig. 2c).

Pd-Sb-Te-bearing PGM are commonly closely associated with the sperrylite chains and some skeletal grains from the massive sulfides, but rarely coexist with subhedra found in other sulfide types. A grain in net-textured sulfides at B.2m (Fig. 2e), is intergrown with merenskyite, where the

latter has a vermiform habit and appears to be located within serpentine, suggesting a secondary genesis.

Sperrylite, present in a pentlandite-rich and chalcopyrite-poor vein (18.2m; Appendix G-1), has not been observed in the chalcopyrite-rich vein (22.4m), the sulfide breccia zone, or the chalcopyrite-rich stringer (32.6m). However, the massive sulfide specimens at 25.8m and 27.0m (Table 1; Appendix G-1), which exhibit metamorphic-deformational features such as sulfide compositional banding and oriented silicates, contain chainlike and skeletal sperrylite associated with chalcopyrite- and amphibole-rich zones (Figures 2c and 2d). There some sperrylite grains, forming chains, which appear to penetrate the epidote euhedra to the point of becoming free grains. In one case a sperrylite chain is observed to form a rim about a folded serpentine lath (Fig. 2d). Elsewhere the chains may be closely associated with Pd-Sb-Te-bearing PGM which also penetrate epidote and serpentine grains.

Microprobe analyses (Appendix H-1) show sperrylites to contain trace amounts (less than 1.00 wt %) of Sb, Ir, and Rh with erratic traces of Pd and Ru. Low totals are attributed to the small grain size of the tabular and chainlike grains. The stoichiometry is good, however, with traces of Sb and S substituting for As. The presence of S may reflect fluorescence from the host sulfides although Cabri (1981) reported trace amounts of S in sperrylite.

Sudburyite - PdSb

Occurrences of sudburyite, perhaps the most volumetrically abundant Pd-bearing PGM in core hole 160-225 (Table 1), are restricted to the lower part of the core hole where it is associated with sulfide veins, deformed massive sulfides, and the sulfide breccia zone.

The size, habit, grain location with respect to host mineral(s), and comments on associated phases are presented in Appendix G-2. In general, sudburyite grains range from submicroscopic to 190 μm long. The habits range from tabular anhedral through equant subhedral to tabular subhedral. Equant or triangular forms are rare whereas irregular anhedral are common.

Most sudburyite occurrences are from the sulfide breccia zone (27.8m to 30.0m) where they are closely associated with altered nickeline. There, the sudburyite is predominantly enclosed in cobaltite-gersdorffite or a Sb-bearing cobaltite-gersdorffite/pyrrhotite assemblage. Only rarely does sudburyite contact nickeline; a very thin margin of cobaltite-gersdorffite separates the two phases.

The common host minerals are pyrrhotite, chalcopyrite, pentlandite, and cobaltite/gersdorffite. Rare grains are found in nickeline. Intergrowths with testibiopalladite (Fig. 3a) or the unknown $(\text{Pd}_3\text{Sb}_2\text{Te}_2)$ are common in the sulfide breccia. Intergrowths with sperrylite (PtAs_2) , or borovskite $(\text{Pd}_3\text{SbTe}_4)$, or $\text{Pd}_3\text{Sb}_2\text{Te}_2$ occur in massive sul-

Fig. 5.3a. Intergrowth of sudburyite (sud), testibiopalladite (tes), and gersdorffite (ger) close to and within the outline of altered nickeline (nic) in pentlandite (pn)/pyrrhotite (po) host. Note numerous small anhedral sudburyite grains in the gersdorffite alteration embayment. Reflected light, 160-225-28.0m, sulfide breccia. Bar=26 μ m.

Fig. 5.3b. Intergrowth of sudburyite (cream) and $\text{Pd}_3\text{Sb}_2\text{Te}_2$ (light grey) at pyrrhotite (po) grain boundaries from pentlandite-rich vein. Note lamellae of $\text{Pd}_3\text{Sb}_2\text{Te}_2$ in sudburyite. Reflected light, 160-225-18.2m, pentlandite-rich vein. Bar=53 μ m.

Fig. 5.3c. Intergrowth of sudburyite (cream) and $\text{Pd}_3\text{Sb}_2\text{Te}_2$ in pentlandite (pn). Note the orientation of the grain and lamellae of $\text{Pd}_3\text{Sb}_2\text{Te}_2$ in sudburyite which are interpreted to parallel the S_1 fabric. Reflected light, 160-225-18.2m, pentlandite-rich vein. Bar=53 μ m.

Fig. 5.3d. Large irregular sudburyite grain (cream) bounded by pyrrhotite (po), pentlandite (pn), and serpentine (black). Grey areas are remnant carbon coating. Note inclusions of fine serpentine laths similar to those in the groundmass and the small pentlandite inclusions (arrows). Reflected light, 160-225-18.2m, pentlandite-rich vein. Bar=53 μ m.

fides (see Appendix G-2). Veins, Ni-rich and Cu-rich types, contain many examples of intergrowths with $\text{Pd}_3\text{Sb}_2\text{Te}_2$. Rare intergrowths of three PGM phases occur with testibiopalladite and the unknown and with borovskite and the unknown (see Appendix G-2).

Sudburyite is abundant within the pentlandite-rich vein (18.2m), less common in the massive sulfides (25.8m and 27.0m), and rare in the chalcopyrite-rich vein (22.4m, see Table 1). Sudburyite from the pentlandite-rich vein occurs as large tabular grains (40 to 190 μm long) commonly containing intergrown lamellae of $\text{Pd}_3\text{Sb}_2\text{Te}_2$ (Figures 3b and 3c). These lamellae appear to be oriented parallel to serpentine laths in the sulfide host which parallel the vein margins and are crenulated by a later fabric (S_2) suggesting that the intergrowths developed during D_1 or before D_2 .

One very large sudburyite grain from this Ni-rich vein is not intergrown with PGM but rather contains fine, randomly oriented silicate laths similar to those in the host pyrrhotite which it appears to have overgrown (Fig. 3d). It also contains very fine grained inclusions of pentlandite and is bounded on one long margin by serpentine; suggestive of a secondary origin.

Sudburyite grains in the sulfide breccia zone are very abundant and may be located within the mass of altered nickeline. They may extend into adjacent sulfides (pyrrhotite, pentlandite, or chalcopyrite), or they may be solely within the adjacent sulfides up to 5.0 mm distant.

These grains are characteristically tabular to irregular anhedral or subhedral (Appendix G-2), range from abundant, disseminated minute anhedral (submicron to 10 μm across) to large tabular anhedral up to 40 μm long (Fig. 3a). Inter-growths with testibiopalladite or $\text{Pd}_3\text{Sb}_2\text{Te}_2$ occur commonly.

Microprobe analyses (Appendix H-2) indicate compositions close to ideal (PdSb). Te, Bi, and Ni are present in trace to minor amounts. Arsenic concentrations in grains from the sulfide breccia are at or below detection limits suggesting that the Ni concentrations there are in solid solution rather than indicating fluorescence from the host. Pt, As, and Ag appear as variable, trace concentrations in grains from most sulfide types, but Pt and As are below the limits of detection in grains from the sulfide breccia. Traces of As are present in grains from the Ni-rich vein. Bi appears to be consistently lower in grains from the sulfide breccia compared to grains from other sulfide types. Grains from the Ni-rich vein are richer in Te compared to those from the sulfide breccia. A narrow range of Te substitution for Sb occurs in grains from this core hole (Fig. 4). However, a very wide degree of Te and Bi substitution for Sb, with up to 15 wt % Te and 5.3 wt % Bi, is reported for Kambalda sudburyites from similar sulfide types (Hudson and Donaldson, 1984).

Testibiopalladite - PdSbTe

Fig. 5.4. Compositional variation of sudburyite grains from the Donaldson Surface deposit. Solid circles are grains from the sulfide breccia zone, inverted triangles are grains from the pentlandite-rich vein (18.2a).

Testibiopalladite is found in the lower part of the core hole 160-225 (Table 1). Grain habits range from tabular anhedral through irregular, and tabular, to rare equant euhedra. The grains vary from $5 \times 6 \mu\text{m}$ to $35 \times 80 \mu\text{m}$ and are dominantly tabular (Appendix G-3). Rarely is testibiopalladite found within pyrrhotite. Most are found at sulfide/sulfide, sulfide/silicate or sulfide/PGM grain boundaries. Intergrowths may occur with sudburyite (see Fig. 3a) or borovskite and hessite (Fig. 5a) or sudburyite and the unknown (Fig. 6; Appendix G-3).

Testibiopalladite occurs at the foliated, chalcopyrite-rich margin of a pentlandite-rich sulfide vein (18.2m), where tabular grains are oriented parallel to the sulfide-silicate elongation direction (S_1 fabric; Fig. 5b). Similarly a large testibiopalladite/borovskite/hessite intergrowth, located along a chalcopyrite/serpentine grain boundary, occurs in a chalcopyrite-rich vein (22.4m) at the most chalcopyrite-rich part.

Quantitative analyses (Appendix H-3), indicate testibiopalladite from core-hole 160-225 to contain variable traces of Ag, Ni, Pt, and As. The stoichiometry indicates minor Ni substitution for Pd, with amounts greater than 0.2 wt % Ni possibly attributed to fluorescence from the Ni-rich hosts (nickeline and cobaltite-gersdorffite). Bi and As substitute for Sb on a limited scale. As is very low in specimens from the nickeline-rich sulfide breccia zone and considerably higher in analyses from assemblages poor in

Fig. 5.5a. Complex intergrowth of testibio-palladite (t), borovskite (b), and hessite (h) at chalcopyrite (cp), pentlandite (pn), pyrrhotite (po), and serpentine (dark grey) grain margins. Arrows indicate small borovskite grains. Light grey patches in serpentine are remnant carbon coating. Reflected light, 160-225-27.0m, massive sulfide. Bar=26 μ m.

Fig. 5.5b. Testibiopalladite grains (white) in pyrrhotite (po) and at chalcopyrite (cp), pyrrhotite (po), and serpentine (black laths) grain boundaries. The grains parallel the interpreted S_1 fabric direction defined by serpentine laths and the long axis of pyrrhotite grains. Reflected light, 160-225-18.2m, pentlandite-rich vein. Bar=53 μ m.

Fig. 5.5c. Complex intergrowth of testibio-palladite (t), the unnamed mineral $Pd_3Sb_2Te_2$ (u), and sudburyite (s) at a fractured pyrrhotite (po)/serpentine (dark grey) grain boundary in close association with a large molybdenite (mol) lath. Flame-like pentlandite (pn) is altered to violarite (viol). Reflected light, 160-225-22.4m, chalcopyrite-rich vein. Bar=53 μ m.

As. It appears that grains from the Cu-rich vein (22.4m) are richer in Sb than those from the massive sulfides, sulfide breccia, or the Ni-rich vein (18.2m) which exhibit moderate Bi substitution for Sb (Field A, Fig. 7). Testibiopalladite grains show limited substitution of Pd for Ni (Field A, Fig. 8).

Borovskite - Pd_3SbTe_4

Borovskite has only been quantitatively characterized in deformed massive sulfides, at 25.8m and 27.0m (Table 1). Grains range from 8 μm to 35 μm wide by 12 μm to 70 μm long (Appendix G-4). Crystal habit varies from tabular-subhedra and anhedral to irregular anhedral. Grains occur at sulfide/sulfide, sulfide/PGM, and sulfide/silicate boundaries. Borovskite may be intergrown with testibiopalladite and hessite (Fig. 5a). Interpreted intergrowths with testibiopalladite or hessite or Pd-Sb-Te-bearing PGM appear to be continued in other grains, based on reflectance, but several large grains have been observed at pyrrhotite/pyrrhotite grain boundaries without intergrown PGM.

Borovskite (Appendix H-4) contains variable traces of Pt and erratic traces of As, Ag, Co, and Pb. Bi shows limited substitution for Te. This is in contrast to analyses from the type locality where Bi substitutes for Sb (Cabri, 1981). It would appear that the grains from the lower part

Fig. 5.6. Compositional variation of minerals within part of the PdTe_2 - PdSb_2 - PdBi_2 ternary for phases from the Donaldson Surface deposit. Field A-testibiopalladite, field B-borovskite, and field C-projection of the unnamed mineral ($\text{Pd}_3\text{Sb}_2\text{Te}_2$) onto the ternary. Closed circles=sulfide breccia, closed squares=massive sulfides (27.0m), open squares=massive sulfides (25.8m), solid triangles=chalcopyrite-rich vein (22.4m), and inverted solid triangles=pentlandite-rich vein (18.2m).

Fig. 5.7. Pd/Pd+Ni versus Te/Te+Sb+Bi for some Pd-bearing phases from the Donaldson Surface deposit. Field A-testibiopalladite, field B-borovskite, field C-unnamed mineral (Pd₃Sb₂Te₂), field D-merenskyite, field E-melonite, and field F-possible melonite. Symbols as in Fig. 5.6.

of the massive sulfide zone, 27.0m, are lower in Bi compared to those from 25.8m (Field B, Fig. 7). Ni substitutes extensively for Pd (Field B, Fig. 8); to the point that a Ni analog occurs (see analyses 6 to 10; Appendix H-4), where Ni is greater than or equal to Pd. Hak et al. (1985) note borovskite from the Wellgreen deposit to have significant Ni concentrations.

Unknown - $\text{Pd}_3\text{Sb}_2\text{Te}_2$

The unnamed PGM phase ($\text{Pd}_3\text{Sb}_2\text{Te}_2$) is common in the two vein specimens (18.2m and 22.4m) and in the sulfide breccia zone (28.0m and 28.6m). Other occurrences are in massive sulfides at 25.8m and 27.0m (Table 1). Grains are commonly tabular and less commonly irregular with anhedral, subhedral, and euhedral habits. Round, anhedral occur rarely. Grains of the unknown are rarely noted within sulfide grains (chalcopyrite or pyrrhotite) and most commonly are aligned along sulfide/sulfide, sulfide/silicate, or sulfide/PGM grain boundaries (Appendix G-5). Sudburyite is commonly intergrown with $\text{Pd}_3\text{Sb}_2\text{Te}_2$ in the Ni-rich vein (see Figures 3b and 3c) and less commonly in the sulfide breccia. Other intergrown PGM are testibiopalladite, borovskite, and unidentified PGM (Appendix G-5). In one example the unknown is intergrown with testibiopalladite and sudburyite in a foliated zone with molybdenite lath in close proximity (Fig. 5c).

In air $\text{Pd}_3\text{Sb}_2\text{Te}_2$ is a light grey colour with a rose tint compared to sudburyite but brighter than testibiopalladite which is distinctly more grey. Anisotrophism is strong.

Quantitative analyses of $\text{Pd}_3\text{Sb}_2\text{Te}_2$ (Appendix H-5) exhibit a range in Bi content from 0.10 to 2.67 weight percent and variable traces of Pt, As, and Ag. The As content, which ranges from below detection to 0.68 weight percent, may be related to the presence of cobaltite in analyses 12 to 14 only (Appendix H-5). The Ni-analog of the unknown, reported for a specimen from core hole 160-224 (Laflamme, 1985), was not noted in this core hole, however, limited substitution of Ni for Pd occurs (Field C, Fig. 8). Grains from the sulfide breccia zone are richer in Ni than those from the sulfide veins. Bi substitution for Sb is minimal (Field C, Fig. 7).

An attempt to determine the bulk composition of the sudburyite- $\text{Pd}_3\text{Sb}_2\text{Te}_2$ intergrowths, based on area (Figures 3b and 3c), indicates compositions of;

$(\text{Pd}_{41.4}\text{Ni}_{8.7})_{47.1}$ $(\text{Sb}_{41.4}\text{Bi}_{0.3})_{41.7}$ $\text{Te}_{11.2}$ and
 $(\text{Pd}_{38.4}\text{Ni}_{7.7})_{44.1}$ $(\text{Sb}_{38.4}\text{Bi}_{0.7})_{37.3}$ $\text{Te}_{14.4}$ respectively. No known experimental or natural phase approximates these compositions.

Merenskyite - PdTe_2

The identification of merenskyite is tenuous, as most

identifications are qualitative, because the grains are generally too small for good quantitative analysis. The crystal habit, grain size, and location of tentatively identified grains are noted in Appendix G-6. Merenskyite would appear to occur in a range of sulfide types (Table 1) but is most common in the massive sulfides.

The one quantitative analysis (27.0m; massive sulfide; Appendix H-6) has high Pd/Pd+Ni (Field D, Fig. 8). This grain coexists with borovskite and hessite (Appendix G-6). Intergrowths may occur with melonite in massive sulfides (25.8m and 27.0m). Some grains are closely associated with sperrylite, sudburyite, and possibly michenerite.

Precious Metal Minerals

Hessite - Ag_2Te

Hessite, a rare mineral in core hole 160-225 (Table 1), has only been observed in one sample interval (27.0m, deformed massive sulfides) as intergrowths with borovskite and testibiopalladite (see Fig. 5a) or intergrown with merenskyite and an unidentified PGM (Appendix G-7).

Grains of hessite are irregular to tabular subhedra and anhedral (Appendix G-7). The stoichiometry is close to ideal (Appendix H-7). Very low, variable traces (less than 0.25 wt %) of Sb, Ni, As, and Bi occur. Pd, Pt, and Pb are at or below detection limits. These grains range between 64.33 and

65.66 atomic % Ag; hessites with these compositions have a maximum temperature of formation of $460 \pm 5^\circ\text{C}$ (Stumpfl and Rucklidge, 1968).

Melonite - NiTe_2

Melonite has been identified in specimens from 11.2, 22.4, and 25.8m from net-textured, sulfide vein, and deformed massive sulfides respectively (Table 1). Crystal habit varies from tabular through irregular to equant subhedra. Grains are located at sulfide/sulfide, sulfide/PGM, or sulfide/silicate grain boundaries. Qualitatively identified intergrowths with merenskyite and possibly michenerite may occur (Appendix G-B).

Quantitatively analysed melonites contain between 10.6 and 15.2 wt % Pd (Appendix H-B). Melonite analyses 1 to 5 contain consistent traces of Sb, Pt, and As (Field E, Fig. 7). Analysis 6, based on stoichiometry, appears to be a melonite but may well be a complex grain as it does not contain similar Sb, Bi, Pt, or As concentrations (Appendix H-B). Based on the $\text{Te}/(\text{Te}+\text{Sb}+\text{Bi})$ (Field F, Fig. 7) this grain appears to have an affinity to the merenskyite grain (Field D, Fig. 7).

Discussion

Distribution of PGM, PGE-bearing, and PM minerals

The distribution of PGM, PGE-bearing, and PM minerals at the Donaldson Surface deposit is interpreted to be closely related to the metamorphic events. Thermally metamorphosed rocks without evidence of a dynamic event include net-textured, net-textured to reverse net-textured, and interstitial sulfides and contain most Pt-bearing grains and few Pd-bearing grains. Dynamically overprinted metamorphosed rocks, which include pentlandite- and chalcopyrite-rich veins, sulfide breccia, and footwall stringers, contain predominantly Pd-bearing phases. The massive sulfides are interpreted to be of a hybrid nature; they have textures indicative of thermal metamorphism overprinted by a significant dynamic metamorphic event and contain both Pt- and Pd-bearing phases.

PGM, PGE-bearing, and PM minerals have not been observed in the interstitial sulfide zone or the footwall stringers. Within the interstitial sulfides this may be attributed to low sulfide concentrations (less than 15 %) and heterogeneous grain distribution. The lack of observed PGM in the stringers, which can not be readily explained by solid solution of Pd in host sulfides as shown by microprobe analyses, may be attributed to the low PGE concentrations there or alternatively, heterogeneous grain distribution.

Both pentlandite- and chalcopyrite-rich veins contain abundant Pd-Sb-Bi-Te bearing phases whereas Pt-bearing phases are either absent or very rare; this suggests that the vein composition is not an important factor controlling PGM mineralogy but rather that PGE were fractionated during hydrothermal transport.

The sulfide breccia contains only Pd-Sb-Bi-Te bearing PGM, and many grains are closely associated with altered nickeline blebs and may represent the local mobilization of elements held in solid solution in nickeline. However, the PGM mineralogy is compatible with the high concentration of Pd, the chondrite normalized profile, and the cataclastic textures of the host sulfides which are interpreted to result from the hydrothermal transport of fractionated solutions mobilized during dynamic metamorphism.

The presence of both Pd- and Pt-bearing minerals in the massive sulfides is compatible with concentrations of these elements there; however, textural and mineralogical data, and chondrite normalized profiles suggest a significant hydrothermal contribution to these sulfides.

Sperrylite occurs regularly in thermally metamorphosed sulfides and rarely in dynamically mobilized sulfides (veins). This is interpreted to reflect the inability of the hydrothermal fluids, generated during dynamic metamorphism of the Donaldson Surface deposit, to transport Pt to the same degree as Pd. Alternatively Pt may have been in a stable state, as sperrylite, whereas Pd may have been in

solid solution in pentlandite and pyrrhotite or in soluble minerals such as nickeline (Watkinson, pers. comm., 1987). Makovicky et al. (1985) noted that pyrrhotite at 500 °C can contain up to 0.5 wt % Pd and less than microprobe detection limits of Pt (0.03 wt %).

The absence of sperrylite in the sulfide breccia zone confirms geochemical data which indicate a very low Pt concentration. Whereas the abundance of sperrylite in the deformed massive sulfides may, in part, reflect the original concentration of Pt there, the large grain size supports geochemical data that suggest a moderate degree of PGE fractionation and hydrothermal transport.

The greatest abundance and largest sudburyite grains occur in dynamically mobilized sulfides (veins and sulfide breccia), supporting the hypothesis that PGE mobilization was greatest during dynamic metamorphism. The abundance of sudburyite in the massive sulfides may reflect an originally high Pd concentration, the influence of Pd-rich hydrothermal solutions, generated and active during deformation, or a combination of the two.

Testibiopalladite grains, rare in thermally metamorphosed sulfides, are the most common in dynamically metamorphosed sulfides, where the largest grains occur, further supporting the hypothesis that PGM grain size and abundance is directly related to dynamic metamorphism. The unnamed mineral ($\text{Pd}_3\text{Sb}_2\text{Te}_2$), observed in both thermally and dynamically metamorphosed sulfides, also has its greatest abundance

and largest grain size in dynamically mobilized sulfides.

Merenskyite grains occur in thermally and dynamically metamorphosed sulfides, although the greatest abundance is in the massive sulfides which are interpreted to have been considerably affected by hydrothermal processes. The confinement of borovskite and hessite to the massive sulfides is compatible with the interpretation that these sulfides have interacted significantly with a hydrothermal fluid; occurrences of hessite from the Donaldson West deposit are restricted to dynamically mobilized sulfides (Dillon-Leitch et al., 1986).

The lack of observed Au-bearing minerals in dynamically metamorphosed sulfides at Donaldson Surface contrasts with observations at Donaldson West in similar rocks (Dillon-Leitch et al., 1986) and may be attributed to the lower concentrations of Au or heterogeneous grain distribution.

Textural characteristics

Sperrylite grains from thermally and dynamically metamorphosed sulfides are almost exclusively bounded by serpentine grains, suggestive of precipitation in the presence of a fluid phase. They also appear to overgrow randomly oriented serpentine laths which are interpreted to have been generated before or recrystallized during the peak of thermal metamorphism (D_1 ; Dillon-Leitch et al., 1986) suggesting a mid to late D_1 origin. This suggests that Pt

was mobilized and precipitated from a fluid phase during thermal metamorphism but apparently underwent only local redistribution.

It is possible that fluids generated during serpentinization or the early stages of thermal metamorphism were Cl-rich, even though there is no current evidence for Cl-enriched silicate phases. Boudreau et al. (1986) suggested that fluids in completely altered dunites are depleted in Cl as the infiltrating fluid redissolves Cl after serpentinization is completed. It is proposed that the serpentinization of olivine, which may concentrate Cl at the olivine/serpentine reaction front (Rucklidge and Patterson, 1977) may have mobilized some Pt, from discrete PGM or as solid solution in high temperature sulfides, and precipitated it locally when the Cl concentration of the fluid decreased during metamorphic dilution or a drop in temperature.

PGE may also be transported in reduced solutions as suggested by the occurrences of $\text{CH}_4 + \text{N}_2 \pm \text{CO}_2$ fluid inclusions from the Bushveld Complex (Johan and Watkinson, 1987). Methane could suggest an originally cyanide- or thiocyanide-bearing fluid (Watkinson, pers. comm., 1987); such fluids should be capable of transporting precious metals (Ballhaus and Stumpfl, 1985b). Single phase nitrogen-methane fluid inclusions are also present in the Coldwell Complex (Marathon PGE prospect) (Watkinson, pers. comm., 1987).

The formation of chainlike sperrylite, found in

chalcopyrite- and epidote-rich massive sulfides, and as rare free grains in epidote, suggests that dynamic metamorphism played an important role in their generation and location there and that the free grains may have precipitated directly from a fluid phase; possibly a metamorphic fluid.

Sperrylite grains coexisting with Pd-Sb-Bi-Te bearing PGM in the massive sulfides suggest, in some cases, that PGM were precipitated over a period of time at the same site; Pt-phases are interpreted to have formed first as they are mantled by the Pd-phases.

Sudburyite grains in dynamically mobilized sulfides are rarely observed within sulfide grains suggesting that their exsolution from enclosing sulfides was not of major importance there. Some sudburyite grains from the hydrothermally mobilized veins are bounded by or include serpentine, suggestive of growth in the presence of a metamorphic fluid. One grain is closely associated with a large molybdenite sheet. Molybdenite, a rare mineral in ultramafic rocks, has been noted with PGE-bearing tellurides in pipelike bodies from the Ivrea-Verbano Basin complex, Italy, where some grains are in contact with hydrous silicates and molybdenite; these are interpreted to have developed during deuteric alteration and dynamic metamorphism (Garuti and Rinaldi, 1986).

Sudburyite grains from the sulfide breccia zone may be subdivided into two types: 1) those in contact or close association with the cobaltite/gersdorffite alteration product

of altered nickeline blebs, and less commonly, 2) grains at major sulfide grain contacts. It is possible that the grains associated with the alteration of nickeline reflect the very local mobilization and deposition of trace concentrations of Pd, Sb, and Te held in solid solution in the nickeline. However, the very low concentrations of Pd and Te measured in nickeline do not support this. Similarly volume considerations do not support local mobilization of PGE; many of the partly altered nickeline blebs are associated with areas of PGM much larger than the altered area.

A rough visual estimate of altered nickeline grains suggests that perhaps less than half of the nickeline is unaltered and that the ratio of cobaltite to gersdorffite alteration product is 1:4 by area (=volume). This suggests that a volume estimate of the process can be made.

It is clear that large amounts of S and Co are added during the alteration process, as is Fe (not shown in cobaltite and gersdorffite formulae). The volume of Sb in the alteration product plus PGM is greater than can be supplied by nickeline; however the factor involved is not clear. The volume of Pd is much greater than could be derived from simply alteration of nickeline.

The common intimate association of sudburyite, in particular, with the altered nickeline grains suggests that

these latter grains were chemically attractive sites for the precipitation of Pd-bearing PGM from hydrothermally transported concentrations. The other sudburyite grains in the sulfide breccia zone may represent exsolution from the surrounding high temperature sulfides and reflect thermal metamorphism prior to brecciation, as do grains in massive sulfides.

Complex intergrowths involving sudburyite occur in all sulfide types but are most abundant in the veins and sulfide breccia, supportive of the hypothesis that the hydrothermal solutions associated with dynamic metamorphism were rich in Pd, Sb, Bi, and Te.

Testibiopalladite grains from the sulfide breccia are included in or at sulfide grains, boundaries and may reflect exsolution from enclosing high temperature sulfides prior to deformation. Grains associated with sudburyite, gersdorffite, and serpentine suggest exsolution in the presence of a fluid phase during nickeline alteration. Gersdorffite-cobaltite grains in this zone mantle sulfides or occur as free grains and are interpreted to have precipitated directly from a fluid phase. Intergrowths with sudburyite and/or the unknown ($\text{Pd}_3\text{Sb}_2\text{Te}_2$) occur in the chalcopyrite-rich vein and the sulfide breccia. Testibiopalladite grains in the pentlandite-rich vein are not observed to form intergrowths and appear to be oriented parallel to the local S_1 fabric, indicating a D_1 origin in the vein. In the massive sulfides testibiopalladite may be intergrown with

borovskite and hessite suggesting a lower temperature genesis than the enclosing sulfides.

Borovskite occurs as tabular grains at sulfide and sulfide/serpentine/PGM/PM grain boundaries and as such is not interpreted to have exsolved from enclosing high temperature sulfides. Intergrowths with hessite, testibiopalladite, and unidentified Pd-bearing PGM and possibly merenskyite are bounded by serpentine. Grains intergrown with hessite suggest a maximum temperature of formation of 460 ± 5 °C (Stumpfl and Rucklidge, 1968). This temperature is at the lower end of stability of monosulfide solid solution in the Cu-Ni-Fe-S system (Craig and Kullerud, 1969) and is compatible with temperatures developed during upper greenschist facies metamorphism, i.e., less than 550 °C.

Most grains of the unnamed mineral ($\text{Pd}_3\text{Sb}_2\text{Te}_2$) are located at sulfide grain boundaries and rarely as inclusions in sulfide grains or in contact with serpentine. Intergrowths with sudburyite are common whereas intergrowths with testibiopalladite or unidentified Pd-bearing PGM are rare. However, lamellae of the unknown in sudburyite, from complex grains in the pentlandite-rich vein, are oriented parallel to the S_1 fabric and a D_1 origin of the intergrowth is implied.

Merenskyite grains from thermally and dynamically metamorphosed sulfides, are rarely included within sulfides but more commonly located at sulfide grain boundaries, suggestive of exsolution from the enclosing high temperature

sulfides. Grains from massive sulfides are common and may be bounded by serpentine and sulfides and intergrown with sperrylite. Intergrowths of merenskyite with PGM and PGE-bearing phases, which occur in all rock types and include sudburyite, sperrylite, melonite, and possibly michenerite, are the most abundant in the massive sulfides where they commonly occur with silicates and are interpreted to reflect the significant hydrothermal contribution to the zone.

Hessite occurs as small grains intergrown with borovskite and testibiopalladite or merenskyite and an unidentified Pd-bearing PGM only in the massive sulfides; a zone interpreted to reflect hydrothermal mobilization. The composition of the the grains intergrown with borovskite and testibiopalladite give a temperature range of formation between 460 ± 5 °C and about 120 °C (Stumpfl and Rucklidge, 1968).

Melonite grains, from net-textured and chalcopyrite-rich vein sulfides, occur at sulfide boundaries suggestive of exsolution from enclosing high temperature sulfides. Grains from the massive sulfides occur at sulfide/serpentine, or sulfide/PGM grain boundaries, compatible with exsolution in the presence of a fluid phase.

It is apparent that PGM, PGE-bearing, or PM minerals located in sulfide grains or at sulfide grain boundaries occur in thermally and dynamically metamorphosed sulfides, and in both cases these phases may well have exsolved from enclosing sulfides. Similarly, grains bounded by serpentine,

interpreted to reflect exsolution in the presence of a fluid phase, are not specific to either type of metamorphic event.

Chemical composition

It is proposed that the composition of certain Pd-bearing phases may reflect their mode of generation. Melonite from the chalcopyrite-rich vein is richer in Pd than melonites from the massive sulfides, compatible with their exclusive generation from dynamically mobilized sulfides developed from hydrothermally transported solutions enriched in Pd. Melonites from the massive sulfides at the Donaldson Surface deposit, which are richer in Pd compared to melonites from massive sulfides from the Donaldson West deposit, are attributed to the moderate hydrothermal contribution of the former sulfides.

Borovskite from the lower part of the massive sulfides (27.0m) is richer in Pd than grains from 25.8m. This is interpreted to reflect the progressive influence of hydrothermal mobilization toward the footwall contact as shown by the increase in deformation seen in the sulfide breccia zone.

There are no trace element concentration differences between sudburyite grains from the Ni-rich vein and the brecciated sulfide zone; this is compatible with a common genesis, i.e., precipitation from hydrothermal solutions; the alternative, low temperature re-equilibration, is not likely to be effective in this instance.

$\text{Pd}_3\text{Sb}_2\text{Te}_2$ grains from the sulfide breccia zone are Ni-enriched compared to grains from sulfide veins; this may reflect the high concentration of Ni released during the breakdown of nickeline in these rocks.

Conclusions

The distribution, abundance, and diversity of Pd-Sb-Bi-Te bearing phases in the Donaldson Surface deposit are closely related to the mobilization of PGE and associated elements during dynamic metamorphism when veins and the sulfide breccia were developed. Minerals composed of these elements are rare in the thermally metamorphosed sulfides, i.e., net-textured and net-textured to reverse net-textured sulfides. The paucity of these phases there is not simply a function of the lower sulfide or PGE concentrations, as small Pt-bearing grains are commonly identified in the thermally metamorphosed sulfides even though Pt and Pd have similar trace concentrations there. The distribution of Pt-bearing phases is interpreted to be related to the original concentrations as thermal metamorphic events resulted in only local mobilization.

The hydrothermal transport of PGE, mobilized during dynamic metamorphic events, generated fractionated PGE patterns resulting in the rare occurrence of Pt-bearing minerals in the dynamically metamorphosed sulfides.

Textural characteristics, such as grain boundary

relationships and coexistence of PGM, PGE-bearing, and PM minerals, whereas not unique to thermally or dynamically mobilized sulfides, in general support the hypothesis that the distribution of these phases is largely controlled by dynamic metamorphism. Grain size appears to be positively related to dynamic metamorphism as does the chainlike grain habit for sperrylite.

Estimates of PGM, trace, and major element volumes about altered nickeline grains strongly suggests the addition of these elements during alteration rather than strictly local mobilization from enclosing minerals.

Melonite and borovskite show a trend of Pd enrichment associated with the degree of dynamic metamorphism. The composition of hessite indicates that it and intergrown minerals formed at a temperature between 460 °C and about 120 °C.

CHAPTER 6

Summary, Discussion, and Conclusions

Summary and Discussion

Primary structure, texture, and mineralogy

The Donaldson West and Donaldson Surface Fe-Ni-Cu-PGE deposits have many features in common. The deposits occur in E-W trending, symmetrically zoned, mafic to ultramafic intrusions (sills) which are situated along the Povungnituk Group/Chukotat Group boundary and dip moderately toward the north. The sills grade inward from thin pyroxenite or olivine pyroxenite margins to peridotite cores (Fig. 1a). Pyroxene oikocryst concentration increases gradually toward the footwall contact. Pyroxene, in peridotite and olivine pyroxenite, occurs as large oikocrysts containing olivine grains which are commonly smaller than those in the matrix. A similar observation at Katiniq was attributed to the armouring of the olivine and chromite by augite, preventing further adcumulus growth, or alternatively, a peritectic relationship between the two phases (Barnes et al., 1982). Pyroxene laths are prismatic or skeletal in the discontinuous margin suggestive of rapid cooling. Abundant hornblende prisms in the lower part of this zone are interpreted to result from the increased f_{H_2O} along the contact with pelitic sedimentary rocks. Both pyroxene and hornblende in this zone contain enclosed olivine. Miller (1977) noted poikilitic hornblende, in a hornblende-rich pyroxenite along the upper and lower contacts at the 2-3 deposit and inter-

Fig. 6.1 Interpretation of geological events.

Fig. 6.1a. Intrusion of olivine and pyroxene phyric, sulfide droplet bearing melt, developing pyroxenite and olivine pyroxenite marginal phases and peridotite to dunite cores. Immiscible sulfides settle as droplets gravitationally into footwall embayments (D_{0-1}). Enlargement shows upward succession of massive, net-textured, and disseminated sulfides. Principal opaques are pyrrhotite (hexagonal and monoclinic), pentlandite, chalcopryite, chromite, and magnetite. Massive sulfides may have had an equigranular texture with pentlandite exsolution as flames along pyrrhotite margins. Chalcopryite occurred as discrete grains. Pt may have occurred as high temperature alloys, possibly sperrylite, and as dilute solid solutions in pentlandite and pyrrhotite. Pd may have formed sulfides, possibly sudburyite, and solid solutions in melonite, pentlandite, and pyrrhotite.

Fig. 6.1b. Serpentinization (D_{0-2}) of olivine and pyroxene developed antigorite + magnesite $\pm$ brucite + magnetite. Very minor sulfide mobilization in sulfide-rich parts of the mineralized succession. Possibly minor local sulfide mobilization in the disseminated sulfides.

Fig. 6.1c. D_1 deformation with upper greenschist facies metamorphic conditions. Development of sulfide mobilization textures under oxidizing condition during early prograde metamorphism. S_1 fabric overprints the reverse net-textured sulfides. Massive sulfides develop sulfide laminations with pentlandite- and chalcopryite-rich patches parallel to local contacts. Generation of sulfide veins and breccias with unique PGM and trace element concentrations at textural and lithological contacts. D_2 deformation, at lower greenschist facies metamorphic conditions, develops a weak crenulation fabric; degree of sulfide mobilization is minor. After these two dynamic events Pt is concentrated in sperrylite and occurs as traces in PGM and PM minerals. Pd is concentrated in PGM and PM minerals; may occur as dilute solid solutions in pentlandite and nickeline.

Fig. 6.1c. Weak D_3 deformation develops subvertical fractures and veins in the footwall metasedimentary rocks under retrograde conditions.

Fig. 6.1a D_{0A} Intrusion

Fig. 6.1b D_{0B} Serpentinization

Fig. 6.1c D₁ Deformation

Fig. 6.1d D₃ Deformation

Opakes	PGE - PGM
po (m>h) +	Pt - spr
pn + cp + mt	- tr in PGM and PM
+ crm + ilm	- PGM and PM
	Pd - ss in pn

Sulfide	Textures
	diss
	net
	net to rev
	rev
	massive (lineated)

puted this mineral to be a primary magmatic phase.

The sulfide concentration decreases from the footwall contact upward and appears to be concentrated in depressions along this contact. The generalized stratigraphic succession of massive overlain by net-textured and disseminated sulfides (Fig. 1a) is interpreted to be original magmatic; sulfide magma settled by gravity and competed for space with precipitating Fe-Mg silicates. Concentrations of chromite at the contacts between sulfide and/or rock types are primary features. However, whether the concentrations represent new magma batches, convective overturn, or contamination is not clear.

The sulfide concentrations examined in detail in core holes 160-224 and -225 are shown to be representative of thick, sulfide-rich central parts of the footwall trough (Appendices J and K). Distal parts of the trough, where sulfide concentrations are thinner, do not exhibit the complete sulfide textural succession.

The primary assemblage, formed from monosulfide solid solution by exsolution, is interpreted to be pyrrhotite (hexagonal and monoclinic) + pentlandite + chalcopyrite; there is no indication of primary pyrite. Average grade (raw data) per metre for net-textured and massive sulfides from core hole 160-224 (Donaldson West deposit) is 4.3 wt % Ni and 1.2 wt % Cu. Core hole 160-225 (Donaldson Surface deposit) contains 4.3 wt % Ni and 0.98 wt % Cu.

Metamorphism and deformation

The interpretation of structural features relies totally on drill core as the Donaldson Mine area lacks outcrop. The small diameter of the drill core makes the extension of structural interpretations, based on observations from hand specimens and thin sections, tenuous.

The sills were likely serpentinized before and during prograde metamorphism (D_{ss} ; Fig. 1b). The serpentinization of cumulus olivine and most intercumulus pyroxene is pseudomorphic as grain boundaries were generally not destroyed and are outlined by fine-grained iron oxides. It is considered probable that olivine initially altered to an assemblage of lizardite and magnesite or brucite during early M_1 prograde conditions and that the magnesite and brucite were preferentially replaced by sulfides during late M_1 metamorphism during which antigorite replaced lizardite.

The prograde assemblages of antigorite + calcite + tremolite, antigorite + calcite, antigorite + tremolite, and the absence of metamorphic olivine suggest maximum formation temperatures of about 495 °C at 2 Kb (Trommsdorff and Evans, 1977) during D_1 in the presence of a metamorphic fluid composed of H_2O and little CO_2 . The maximum temperature for these assemblages would be at least 20 °C higher for pressures of 4.0 Kb, proposed for the Donaldson Mine area. This is comparable with maximum P and T estimates for metamorphism of the Boundary area, located about 3 km west of the

Donaldson deposits, which ranged between 425-500 °C and 2.5 to 4.0 Kb (Albino, 1984). The low abundance of tremolite suggests a low X_{Coz} , less than 5 %, and likely less than 1 %.

Three phases of metamorphism and deformation are recognized in metasedimentary rocks of the upper part of the Povungnituk Group (Beauparlant Subgroup; Picard, 1986) which immediately underlie the sills. These are: D_1) which produced an E-W trending, steeply north dipping S_1 cleavage, during upper greenschist metamorphic conditions, D_2) which occurred during lower greenschist facies conditions, producing steeply north dipping, E-W trending, reverse faults and a weak subvertical, E-W trending S_2 foliation; and D_3) which generated subvertical N-S faults and a sporadic S_3 fracture cleavage during retrograde conditions. Within the sills fabrics are weakly developed and only rarely is it possible to distinguish between S_1 and S_2 ; single fabrics are referred to as S_1 - S_2 . The limited second and third dimensions of the NQ drill core (5 cm) make the distinction between cleavage fabric and shear fabrics tenuous.

Veins of sulfide-serpentine-(calcite and/or dolomite) were generated during D_1 , and probably D_2 , and are interpreted to parallel local fabrics. Minor talc, tremolite, and dolomite may occur as weakly developed cm-scale patches about some serpentine-carbonate-sulfide veins. These veins do not show a consistent sense of sulfide or silicate zoning or any inward growth textures, features associated with open

space filling. Some sulfide-rich veins have crenulated, serpentine-rich margins, suggesting a D_1 origin. Some sulfide veins, containing assemblages of antigorite + calcite + dolomite $\pm$ tremolite, suggest maximum formation temperatures of 475 to 490 °C at 2 Kb (Trommsdorff and Evans, 1977) and give calcite-dolomite geothermometer temperatures of 515 to 549 °C. These temperatures are compatible with temperatures proposed for the formation of metamorphic olivine at 4 Kb. Jenkins (1981) suggests an upper limit for the stability of antigorite of 550°C, in a CO_2 free system at 4 Kb (assemblage of antigorite + chlorite + amphibole).

Cobaltite compositions, from a sulfide-carbonate-PGM vein, give temperatures of formation of 525 to 550°C (Appendix L). The same sample gave calcite-dolomite geothermometer temperatures of 515 to 549°C (Appendix J).

It is clear that these veins contain assemblages which were not in equilibrium with the wallrocks. This is interpreted to suggest that the veins were generated during deformation which sporadically released pore fluid and that the veins do not represent long lived, large circulation systems. The lack of mineral zoning combined with the anastomosing nature of serpentine + carbonate mineral concentrations (from vein margins to cores) suggests reopening of a short lived fracture system, consistent with the low levels of wallrock alteration.

Abundant barren, en-echelon serpentine-carbonate veins were developed during D_2 ; some exhibit colloform-like tex

tures. Sulfide-rich, quartz-carbonate-chlorite-tremolite veins (stringers), exhibiting compositional zoning frequently associated with hydrothermal veins, occur along and at high angles to bedding in the footwall metasediments, cut S_1 , and appear to crosscut S_2 , suggesting a D_3 generation.

Sulfide mobilization

Sulfide mobilization textures have been assigned to both thermal and dynamic metamorphic events; the development of sulfide mobilization is illustrated in Figure 1. Thermal metamorphism of net-textured sulfides mobilized sulfides during D_1 prograde conditions, where the sulfides are interpreted to have variably replaced olivine pseudomorphs which are proposed to have been replaced earlier by an assemblage of lizardite + magnesite and/or brucite (D_{-1}). The replacement textures culminated in the reverse net-texture, with greater than 30 percent of the cumulus olivine being crudely pseudomorphically replaced by sulfides. The overprint of the reverse net-texture by a strong cleavage (S_1) limits most sulfide mobilization to before and during D_1 . The extent of sulfide mobilization during D_2 is not possible to assess as the S_2 cleavage is only sporadically developed in the mineralized rocks.

Pseudomorphic sulfide replacement of pyroxene oikocrysts during thermal metamorphic events is characterized by sulfide blebs containing abundant enclosed

chromite grains. The small grain size of the enclosed chromite grains, compared to those outside, is attributed to their armouring from accumulative growth by the nucleation of pyroxene early in the crystallization history. The abundance of sulfide replacement blebs increases toward the footwall contact and reflects the original increased concentration of pyroxene.

Mobilization of disseminated sulfides, during thermal metamorphism is interpreted to be minor. Thin cm-scale zones of pseudomorphic replacement of olivine by sulfides accompanied by minor talc-carbonate alteration occur about serpentine-sulfide-carbonate veinlets suggesting that the degree of sulfide mobilization is related directly to increased movement of fluids in and around veins.

Dynamic metamorphic mobilization in the massive sulfides developed laminations, rich in pentlandite or chalcopyrite, and elongate pyrrhotite grains parallel to the interpreted S_1 - S_2 fabric and to the contacts. It is not considered likely that this texture is related to monosulfide solid solution (Mss) unmixing (Groves and Hudson, 1981); Cowden and Archibald (1987) noted that even where subjected to prograde amphibolite facies metamorphism, reversion of a sulfide assemblage to Mss did not destroy pentlandite and pyrite layering in the Kambalda area Fe-Ni-Cu deposits.

Sulfide veins, occurring at the contacts between major sulfide textural types are interpreted to have developed because of competency contrasts during dynamic metamorphic

events. Veins occurring elsewhere in the mineralized succession are attributed to the heterogeneity of deformation.

Competency contrasts may develop between rock types of differing rheologies, and sulfide movement from areas of high strain to areas of low strain may occur (Vokes, 1971). Contrasting competency between pyrite or pentlandite and chalcopyrite may result in diffusion of chalcopyrite into pressure shadows or fractures in the former minerals. On a deposit scale Patterson and Watkinson (1984) have suggested that the copper-rich mylonite ores of the Thierry mine developed at the contact between mafic metagabbroic and metavolcanic rocks.

Sulfide veins, breccias, and mylonites occur at sites of contrasting competency where porosity is increased during dilation or shearing. It is suggested that interstitial metamorphic fluid moved into these open spaces during dynamic events localizing elements concentrated in the fluid. In some cases, where the units are less than five metres wide, a simple brittle response to a ductile shear strain, could cause dilation (Fig. 2a). However, an orientation parallel to the contacts and a sheetlike form, as envisaged to occur in the Donaldson deposits, is not likely to develop. It is possible that the apparent location of veins at and parallel to the contacts is fortuitous; the limited view afforded by the drill core precludes other interpretations.

Differential movement, ductile shearing, confined along

Fig. 6.2a. Brittle fracture in a thin unit of different competency during ductile shear.

Fig. 6.2b. Ductile shear at the contact of units of different sulfide texture with the development of high angle extension fractures and parallel principal shear fractures.

Fig. 6.2c. Continued ductile shear with rotation of extension fractures closer to the plane of shear.

the contact between units of contrasting competency during regional compression is envisaged to develop the veins observed at textural contacts. Initially extension fractures, at high angles to the shear boundary, and principal shear fractures, parallel to the shear boundary (Roberts, 1987), may form; but continued shearing would rotate the high angle fractures into the plane of the shear (Fig. 2b) resulting in veins parallel to the contact. A sulfide breccia which may occur at the massive sulfide/footwall contact, a zone of high competency contrast, suggests that deformation may also be gradational; a transition from brittle to ductile.

Examination of sulfide textural data from drill core holes adjacent to those reported in this study indicates that veins or veined sulfides can not be easily extrapolated from hole to hole, distances on the order of 30 to 50 metres, suggesting the limited lateral development of these structures. However, this may be a reflection of the width of the sample interval, i.e. dilution of vein material and the reliance upon geological data collected by other workers (identification of veins).

The mobilization of Ni, Cu, Fe, and S during thermal metamorphism was considerable and varied directly with the degree of pseudomorphic replacement. Disseminated sulfides at Donaldson West have Ni, Cu, and S values (recalculated to 100 % sulfides) similar to those in the underlying net-textured zone (Table 1). Compared to the net-textured zone, which textural observations suggest to be the least affected

Table 6.1. Average Ni, Cu, S, Pt, Pd, Ni/Ni+Cu, and Pd/Pd+Pt values in 100 % sulfides from the Donaldson West deposit (core hole 160-224) and the Donaldson Surface deposit (core hole 160-225).

Donaldson West deposit								Donaldson Surface deposit						
Text type	Ni	Cu	S	Pt	Pd	Cu/ Cu+Ni	Pt/ Pt+Pd	Ni	Cu	S	Pt	Pd	Cu/ Cu+Ni	Pt/ Pt+Pd
	wt %			ppm				wt %			ppm			
Diss	16.0	3.6	36.1	34.7	25.3	0.184	0.578							
Net	16.2	3.8	36.2	10.2	12.6	0.182	0.447	11.5	2.7	37.2	4.0	6.8	0.187	0.370
NRN	16.2	3.1	36.3	11.6	18.3	0.161	0.388	10.7	2.6	37.4	4.4	7.9	0.198	0.358
Rev	13.1	4.2	36.7	8.8	16.8	0.233	0.344							
Int								10.4	5.4	37.0	13.8	15.8	0.349	0.466
Mss	13.9	0.8	37.0	3.5	1.8	0.058	0.660	10.7	1.7	37.5	5.2	9.2	0.140	0.363
Bssx								9.7	2.7	37.4	2.3	59.0	0.203	0.038

Abbreviations: Text type=textural type; Diss=disseminated; Net=net-textured; NRN=net-textured to reverse net-textured; Rev=reverse net-textured; Int=interstitial; Mss=massive sulfides; Bssx=brecciated sulfides.

of the sulfide types, the average Ni and S concentrations (Table 1) in the weakly altered net-textured to reverse net-textured zone are unchanged, whereas Cu is 18 % less; the reverse net-textured zone is significantly depleted in Ni (24 %) and slightly enriched in Cu (10 %) and S is unchanged. Massive sulfides are moderately depleted in Ni (16 %), strongly depleted in Cu (80 %), and weakly enriched in S (2 %).

At the Donaldson Surface deposit the weak alteration of net-textured sulfides resulted in a 7 % depletion of Ni and no change in Cu and S (Table 1). There the concentration of pyrite (without accompanying magnetite) in veins and in close association to veins, in the least altered rocks also suggests a role of S-rich fluids and accompanying oxidation elsewhere in the deposit. Magnetite and/or ilmenite concentration is greater in the weakly altered net-textured to reverse net-textured sulfide zone, suggesting that this zone was developed under oxidizing conditions.

The Cu-enriched, weakly Ni depleted (10 % in 100 % sulfides), and constant S interstitial zone may reflect the addition of Cu by stress-induced diffusion from nearby massive sulfides during deformation. The concentration of fine prismatic amphibole about chalcopyrite-rich blebs in this zone suggests, however, that the sulfides were mobilized in a fluid phase during metamorphism and growth of amphibole.

The significant increase in pyrite concentration in the massive sulfide and sulfide breccia zone toward the footwall

contact, suggests increasing fluid circulation with increasing concentration of shearing at the contact. The lack of a pyrite-rich upper margin to the massive sulfides may be attributed to the heterogeneity of deformation or that the overlying interstitial textured zone did not permit fluid circulation.

It is suggested that Ni, Cu, Fe, and S redistribution during thermal metamorphism in the reverse net-textured sulfide, where abundant magnetite may occur, was accomplished by the partial oxidation of pyrrhotite to form magnetite and more S-rich fluids. This fluid in turn formed pyrite by sulfidation elsewhere in the mineralized succession as exemplified by the massive sulfide zones. This is similar to the model proposed for the generation of secondary magnetite and pyrite at Kambalda by Cowden and Woolrich (1986). There, metamorphic magnetite is confined to matrix (net-textured) sulfides whereas pyrite occurs as bands at the upper and, to a lesser extent, the lower contact of the massive sulfides, and in brittle fractures throughout the mineralized succession.

In the Donaldson deposits it is suggested that the movement of fluid, generated during metamorphism, was controlled by greater permeability at contacts between sulfide textural types; this is compatible with the enhanced shearing and/or brecciation there.

Ni mobilization in net-textured rocks appears to be closely related to the degree of oxidation. Cu does not fol-

low Ni, possibly because Cu is more readily mobilized. It is proposed that the Ni, Cu, and S variations within each of the two deposits can be explained by element redistribution during thermal and dynamic metamorphic events; magmatic variations are not required.

The Ni tenors of the least altered net-textured sulfides from the Donaldson West and Donaldson Surface deposits are quite different, 16.2 versus 12.0 wt % respectively in 100 % sulfides. This may suggest that the two Donaldson deposits represent sulfide accumulations from separate silicate/sulfide melts. Cowden and Woolrich (1986) noted that there may be large variations in Ni tenors between orebodies in the Kambalda area and have attributed this to fluctuations in f_{O_2} during magma emplacement; there, low f_{O_2} is proposed to polymerize the silicate melt, decreasing the number of octahedral sites Ni^{2+} can occupy, enhancing Ni partition into the sulfide liquid.

Alternative magmatic models that could be invoked to account for the Ni variation between deposits include variable R factor (Leshner et al., 1984), changes in f_{O_2} (Cowden and Woolrich, 1986), and variable partition coefficients (Campbell and Barnes, 1984).

However, whereas the low level of alteration in the Donaldson Surface deposit makes it difficult to envisage that it originally had the same Ni concentration as comparable rocks of the Donaldson West deposit, closer inspection of data suggest postmagmatic processes can account for the

differences. For example, the Donaldson West samples, which lie close to the experimentally determined 600 °C mss boundary (Fig. 2.4), lie mostly outside the 500 °C mss boundary, the proposed maximum metamorphic temperature. Barnes et al. (1987) have suggested that if S does not correlate with the base metals and PGE then S has been lost during postmagmatic events. In the fire assay atomic absorption data (Table 2.5) S correlates strongly with Ni and Co and to a lesser extent with Cu, Pt, and Pd. However, the more precise fire assay neutron activation data (Table 2.4) suggests no correlation with S. Should S have been lost, the process of recalculation to 100 % sulfides would make the recalculated sulfides anomalously enriched in Ni (and PGE). Correlation data for both assay methods from the Donaldson Surface deposit (Tables 3.7 and 3.8), indicate strong correlations between S and Ni, and Co, and to a lesser extent Cu, Pt, and Pd, suggestive that the Ni values for this hole are reasonable. The sampling of single core holes through a deposit may not be representative or statistically valid and hence the interpretation of the data on an inter "deposit" scale may not be meaningful.

PGE mobilization

Mobilization of Pt and Pd during thermal metamorphism was minor; the greatest redistribution occurred during the formation of the reverse net-textured sulfides. Then, Pd,

concentrations increased compared to those in overlying net-textured sulfides, and the underlying, strongly Pd-depleted, massive sulfides are the preferred source. The chondrite normalized profile of some reverse net-textured rocks suggests weak fractionation of PGE; this is compatible with the proposed oxidation of this zone by circulating metamorphic fluids. Pt may be strongly depleted in the massive sulfide zone at Donaldson West, but no Pt-enriched zones are recognized in the sampled drill hole. Pt may have been dispersed or accumulated away from the sampled hole.

The apparent high Pt and Pd concentrations in the disseminated sulfides are not attributed to metamorphic redistribution but rather to the analytical uncertainty in atomic absorption spectrophotometry analyses. For example; two more precise neutron activation analyses of disseminated material have average Pt and Pd values in 100 % sulfides of 7.3 and 15 ppm respectively, which are closely comparable to the average Pt and Pd concentrations in the underlying, least altered, net-textured zone (10.2 and 12.6 ppm respectively).

At the Donaldson Surface deposit, Pt and Pd concentrations were enriched in the interstitial zone, relative to the net-textured zone, by redistribution during thermal metamorphism. It is suggested that the low sulfide and PGE concentrations of this zone reflect analytical uncertainty or alternatively that the minor addition of PGE during metamorphism or loss of S is greatly magnified by the recal-

culation process to 100 % sulfides.

During dynamic metamorphism, sulfide veins were generated as open space fillings parallel to local fabric directions, in some cases parallel to S_1 . Chondrite normalized profiles of vein samples show low Os-Ir-Ru-Rh and Pt values and enriched Pd values relative to the least altered disseminated and net-textured sulfides. Au may be weakly enriched in the veins. This pattern is also found in the sulfide breccia zone and suggests a similar generation. Footwall stringers do not show the same pattern; this may be due to their origin as late metamorphic features (D_3) with different fluid compositions or related to the dilution from non-stringer sulfides in the specimen. The latter is considered more likely and further sampling is required to characterize the stringers.

Massive sulfides from the Donaldson Surface deposit exhibit a chondrite normalized profile with Os-Ir-Ru-Rh values intermediate to those of the hydrothermally mobilized sulfide breccia zone and the net-textured sulfides. This feature, combined with the enriched Pt and Pd values, suggests the effect of a moderate hydrothermal overprint. Massive sulfides at Donaldson West exhibit chondrite normalized profiles similar to those of the least altered, net-textured sulfides, with the exception of low Pd and Au values; this is interpreted to reflect the effect of stress-induced diffusion during deformation as the Os-Ir-Rh group, commonly fractionated during hydrothermal mobilization, are not af-

fected.

The steep chondrite normalized pattern associated with dynamically mobilized sulfides is attributed to the fractionation of PGE and Au during hydrothermal transport. The hydrothermal fluids were enriched in Pd and Au; Pt is generally depleted. The apparent inability of the fluids, associated with dynamic metamorphism, to transport Pt is compatible with the petrographic data on PGM.

PGM distribution, mineralogy, and chemistry

The distribution of PGM in both deposits is shown to be greatly influenced by dynamic metamorphic events. Pd-bearing PGM occur in most rock types, but the greatest concentration, diversity, and largest grain size are found in rocks interpreted to have been affected by dynamic metamorphic events. Sperrylite, the Pt-bearing mineral, is widespread in thermally metamorphosed rocks and rare in rocks affected by dynamic metamorphism. The largest sperrylite grains are, however, dominantly located in rocks with a dynamic overprint.

PGM located in sulfide grains or at sulfide grain boundaries are interpreted to have exsolved from the enclosing high temperature sulfide precursors in both thermally and dynamically metamorphosed rocks. PGM occurring at sulfide/silicate grain contacts are interpreted to have exsolved in the presence of a fluid phase whereas free grains

represent direct precipitation from a fluid. Pd-bearing PGM from dynamically affected rocks commonly exhibit the latter two grain contact characteristics. Sperrylite, from both metamorphic types, is commonly aligned along sulfide/silicate contacts, suggestive of exsolution in the presence of a fluid phase; however, the source of Pt is proposed to be local as there is no evidence of veining.

Whereas the low concentration of Pt in veins suggests that the composition of the fluids active during dynamic events was not suitable for the mobilization of Pt, it is apparent that Pt was slightly mobile early in the metamorphic history of the rocks, perhaps during serpentinization.

The composition of melonite shows enriched Pd concentrations in rocks affected by dynamic metamorphism. The extensive substitution of Ni and Pd in borovskite can be related to the degree of dynamic metamorphism as this mineral is only found in rocks with an overprint of dynamic events; the Ni-rich grains occur in the least dynamically affected rocks.

Other PGM show little variation of Pd concentration with metamorphism. In these deposits the restriction of certain minerals such as hessite, borovskite, electrum, gersdorffite, and Co-rich pyrite to veins or rocks affected by dynamic events suggests that the fluids generated and active during dynamic metamorphism were rich in Pd, Au, Ag, Te, Sb, Co, and As.

Reinterpretation of chondrite normalized profiles in the literature

Barnes et al. (1985) presented chondrite normalized (CN) profiles for sulfide-bearing komatiitic rocks (their Fig. 1g - profiles A and D), basaltic komatiites of the Cape Smith belt (their Fig. 1g - profile I), and continental tholeiites (their Fig. 1h - profiles C, D, and F). These profiles compare with Fig. 3 of Naldrett et al. (1979) which indicate that komatiitic rocks have relatively flat CN trends, and tholeiitic rocks from Sudbury deposits have steeper (positive) trends. Basaltic komatiites from Ungava have profiles intermediate to the above; this is interpreted to reflect the degree of partial melting involved (Barnes et al., 1985).

The CN profile for sulfide stringer material from the Levack West deposit (Hoffman et al. 1979, Fig. 2; Naldrett et al. 1982, Fig. 3B) exhibits Os-Ir-Ru depletion and Pt-Pd-Au enrichment compared to massive and disseminated sulfides from the granite breccia zone, and Pd/Ir of about 19800. Footwall stringers from the Little Stobie #1 deposit (Hoffman et al., 1979; Fig. 6) exhibit a steeply positive CN profile with a Pd/Ir of about 310 (Fig. 6.3); this suggests a profile intermediate to the stringers from Levack West and massive sulfides from the Little Stobie #1 main orebody. Hoffman et al., (1979) interpreted the Cu-rich stringers at Levack West to reflect diffusion of Cu, ~~Co~~, Pd, and Au in

Fig. 6.3. Chondrite normalized 100 % sulfide data from the Levack West and Little Stobie mine of Hoffman et al. (1979) showing the steep profiles of Cu-rich stringer material.

response to a thermal gradient. Naldrett et al., (1982) suggested that although massive diffusion of iron sulfide down a thermal gradient could result in PGE fractionation, the textures of the ores do not support this. Alternatively they proposed fractional crystallization of the sulfide magma to explain the large scale metal zoning, and that the veins represent residual liquid that was filter-pressed into foot-wall fractures.

This study of the Donaldson deposits provides strong support for the fractionation of Os-Ir-Ru-Rh group from the Pt-Pd-Au group during hydrothermal transport as proposed by Lesher and Keays (1984). The resultant CN profiles exhibit a steeply positive trend from Os to Pd-Au. Pd/Ir values greater than about 200 from sulfide-rich basaltic komatiites of the Cape Smith belt are considered to represent non magmatic PGE fractionation.

On this basis it is possible to reinterpret the CN profiles of some Cu-rich stringer material from some Sudbury deposits as having been fractionated during hydrothermal mobilization. The abundance of fluid inclusions in quartz from some Cu-rich vein material, bornite and native silver in the chalcopyrite from Levack West (McCreedy Mine) and the occurrence of hydrous silicate minerals about the veins suggests the presence of a fluid during redistribution (D. H. Watkinson, pers. comm., 1986). Other steep CN profiles from layered intrusions such as those from the J-M Reef, Stillwater Complex, the Crystal Lake gabbroic intrusion

(Great Lakes Nickel prospect), and the Coldwell Complex (Fleck Resources Marathon prospect) may be similarly reinterpreted only if petrographic data on hydrous phases and fluid inclusions and the abundance of chromite are considered. The absence of chromite in these rocks may deplete the rocks in Os-Ir-Ru-Rh and affect the CN profile.

Conclusions

Maximum metamorphic conditions attained in the Donaldson deposits were of upper greenschist facies; maximum temperatures from stable mineral assemblages of the host rocks were less than the forsterite-in reaction (about 525 °C at 4 Kb for X_{Co2} less than 0.1), whereas vein and mineral compositions suggest maximum formation temperatures of 480 to 549 °C.

The following textures developed during thermal metamorphism of the Donaldson West and Surface deposits in disseminated and net-textured sulfides: 1) intergrowths of sulfides and silicates in the disseminated sulfides, 2) the variable transition from net-texture to reverse net-texture which increases toward the footwall, and 3) centimetre scale sulfide blebs after pyroxene oikocrysts in net-textured and disseminated sulfides. The development of reverse net-texture reflects extensive oxidation in a zone of high metamorphic fluid circulation.

Ni and Cu were variably mobilized during thermal

metamorphic events. The depletion of Ni varies directly with development of the reverse net-texture. Pd is moderately enriched in these rocks and the Os-Ir-Rh concentrations are intermediate to values from dynamically affected sulfides; this is compatible with minor PGE fractionation accompanying widespread oxidation (fluid circulation) during thermal metamorphism. The distribution of Pt was not greatly affected by thermal metamorphism.

Metamorphic redistribution can explain variation within a single core hole and, possibly, distinctions in the Ni contents of the two deposits. Thus, the two deposits may be dismembered parts of the same intrusion.

The distribution, mineralogy, grain size, and grain location data support the distribution and correlation data from PGE analyses. The minerals in rocks affected by dynamic metamorphism reflect the fractionation arising from hydrothermal redistribution. The large grain size and the location of minerals in these rocks along silicate grain margins or as free grains further supports the importance of a fluid phase and in some cases indicates precipitation directly from the fluid. The diversity of PGM and in some cases the unique mineral chemistry or the PGM restriction to dynamically affected rocks is directly related to the fluid composition.

Hydrothermal fractionation and transport, of elements mobilized during upper greenschist facies dynamic events, generated sulfides rich in Pd-PGM, Au, Ag, Co, and As

minerals at sites of contrasting competency.

Acknowledgments

I wish to thank Dr. Watkinson for his advice, encouragement, and financial support (NSERC grant A7874 and GR-5 grants from Carleton University) during the course of research and writing. The author wishes to acknowledge Colin Coats and Falconbridge Ltd., Toronto, for their financial support, release of information, and permission to publish the research. The introduction to the electron microprobe and the diligence with data manipulation by Peter Jones is much appreciated.

I thank Z. Johan (CNRS-BRGM, France) for access to his laboratory, P. Mainwaring (CANMET) for access to his laboratory and for providing polished sections of heavy mineral liquid separates, and I. Jonasson (GSC) for some polished sections. R. Conlon (Carleton) performed X-ray diffraction work. P. Jones (Carleton) and G. Laflamme (CANMET) provided some microprobe analyses.

This study would not have been possible without the tireless support and persistent encouragement of my wife Jane.

References

- Albino, G. V., 1984, Petrology, geochemistry and mineralization of the Boundary ultramafic complex, Quebec, Canada: Unpub. M.Sc. thesis, Colorado State Univ.
- Ballhaus, C. B. and Stumpfl, E. F., 1985a, Graphite, Platinum, and the C-O-H-S system: Abstr. Fourth Int. Platinum Symposium, Can., Mineral., 23, p. 293-294.
- Ballhaus, C. B. and Stumpfl, E. F., 1985b, Fluid inclusions in Merensky and Bastard Reefs, western Bushveld Complex: Abstr. Fourth Int. Platinum Symposium, Toronto, Can., Mineral., 23, p. 294.
- Barnes, S.-J., Naldrett, A. J., and Gorton, M. P., 1985, The origin of the fractionation of platinum-group elements in terrestrial magmas: Chemical Geology, 53, p. 303-323.
- Barnes, S.-J. and Naldrett, A. J., 1987, Fractionation of the platinum-group elements and gold in some komatiites of the Abitibi greenstone belt, northern Ontario: Econ. Geol., 82, p. 165-183.
- Barnes, S. J., 1979, Petrology and geochemistry of the Katiniq nickel deposit and related rocks, Ungava, northern Quebec: Unpub. M.Sc. thesis, Univ. Toronto.
- Barnes, S. J., Coats, C. J. A., and Naldrett, A. J., 1982, Petrogenesis of a Proterozoic nickel sulfide-komatiite association: the Katiniq sill, Ungava, Quebec: Econ. Geol., 77, p. 413-429.
- Bayliss, P., 1977, Crystal structure refinements of ullmannite: Am. Mineral., 62, p. 369-373.
- Boudreau, A. E., Mathez, E. A., and McCallum, I. S., 1986, Halogen geochemistry of the Stillwater and Bushveld Complexes: evidence for transport of the platinum-group elements by Cl-rich fluids: J. Petrology, 27, p. 967-986.
- Cabri, L. J., 1981, The Platinum-Group Minerals: in L. J. Cabri, ed., Platinum-Group Elements: Mineralogy, Geology, Recovery. Ch. 7: The platinum-group minerals. Can. Inst. Min. Met., Special Vol. 23, Montreal, p. 83-150.
- Cabri, L. J. and Laflamme, J. H. G., 1981a, in L. J. Cabri, ed., Platinum-Group Elements: Mineralogy, Geology, Recovery. Ch. 5: Sample preparation techniques for PGE-bearing materials. Can. Inst. Min. Met., Special Vol. 23, Montreal, p. 65-70.

- Cabri, L. J. and Laflamme, J. H. G., 1981b, in L. J. Cabri, ed., *Platinum-Group Elements: Mineralogy, Geology, Recovery*. Ch. 8: Analyses of minerals containing platinum-group elements. Can. Inst. Min. Met., Special Vol. 23, Montreal, p. 151-174.
- Campbell, I. H. and Naldrett, A. J., 1979, The influence of silicate:sulfide ratios on the geochemistry of magmatic sulfides: *Econ. Geol.*, 74, p. 1503-1506.
- Campbell, I. H. and Barnes, S. J., 1984, A model for the geochemistry of the platinum group elements in magmatic sulfide deposits: *Can. Mineral.*, 22, p. 151-160.
- Chyi, L. L. and Crocket, J. H., 1976, Partition of platinum, palladium, iridium, and gold among coexisting minerals from the deep ore zone Strathcona Mine, Sudbury, Ontario: *Econ. Geol.*, 71, p. 1196-1205.
- Coats, C. J. A., and Buchan, R., 1979, Petrology of serpentinized metamorphic olivine, Bird River Sill, Manitoba: *Can. Mineral.*, 17, p. 847-855.
- Cowden, A., Donaldson, M. J., Naldrett, A. J., and Campbell, I. H., 1986, Platinum group elements and gold in the komatiite-hosted Fe-Ni-Cu sulfide deposits at Kambalda, Western Australia: *Econ. Geol.*, 81, p. 1226-1235.
- Gowden, A., and Woolrich, P., 1986, Geochemistry of the Kambalda iron-nickel sulfides: implications for sulfide-silicate partitioning models: *Can. Mineral.*, 25, p. 21-36.
- Craig, J. R. and Kullerud, G., 1969, Phase relations in the Cu-Fe-Ni-S system and their application to magmatic ore deposits: *Econ. Geol. Mon.* 4, p. 344-358.
- Dahl, R., Watkinson, D. H., and McGoran, J. W., 1987a, Two Duck Lake Intrusion, Coldwell Alkaline Complex, Ontario: I. Geology and Structure: *Inst. Lake Superior Geology (Abst.)*
- Dahl, R., Watkinson, D. H., and McGoran, J. W., 1987a, Two Duck Lake Intrusion, Coldwell Alkaline Complex, Ontario: II. Petrology and base metal/PGE geochemistry: *Inst. Lake Superior Geology (Abst.)*
- Daxl, H., 1986, The chlorite-hosted PGM of the Bravo Sill, Ungava Trough, New Quebec: unpub. B.Sc. thesis, Concordia Univ., Montreal.
- Dillon-Leitch, A. C. H., Watkinson, D. H., and Coats, C. J. A., 1986, Distribution of platinum-group elements in the Donaldson West deposit, Cape Smith belt, Quebec: *Econ. Geol.*, 81, p. 1147-1158.

- Distler, V. V., 1980, Solid solutions of platinoids in sulfides, p. 191-200 in Sidorenko, A. V., Sobolev, V. S., Rundquist, D. V., Nekrasov, I. YA., Shadlun, T. N., Genkin, A. D., Mosgova, N. N., and Bortnikov, N. S., editors, Sulfosalts, Platinum Minerals, and Ore Microscopy, Proceedings of the IMA Conference, Novosibirsk 1978, Acad. Nauk. SSSR, Moscow.
- Eckstrand, O. R., 1975, The Dumont serpentinites: a model for control of nickeliferous opaque mineral assemblages by alteration reactions in ultramafic rocks: *Econ. Geol.*, 70, p. 183-201.
- Ewert, W. D., 1977, Metamorphism of siliceous/carbonate rocks in the Grenville Province of southeastern Ontario: unpub. Ph.D. thesis, Carleton University, Ottawa.
- Fleet, M. E., 1979, Partitioning of Fe, Co, Ni, and Cu between sulfide liquid and basaltic melts and the composition of Ni-Cu sulfide deposits - a discussion: *Econ. Geol.*, 74, p. 1517-1519.
- Francis, D. M., Ludden, J., Hynes, A. J., 1983, Magma evolution in a Proterozoic rifted environment: *J. Petrol.*, 24, p. 556-582.
- Garuti, G. and Rinaldi, R., 1986, Mineralogy of melonite-group and other tellurides from the Ivrea-Verbano basic Complex, Western Italian Alps: *Econ. Geol.*, 81, p. 1213-1217.
- Graterol, M. and Naldrett, A. J., 1971, Mineralogy of the Marbridge No. 3 and No. 4 nickel-iron sulfide deposits: *Econ. Geol.*, 66, p. 886-900.
- Groves, D. I., Hudson, D. R., and Hack, T. B. C., 1974, Modification of iron-nickel sulfides during serpentinization and talc-carbonate alteration at Black Swan, Western Australia: *Econ. Geol.*, 69, p. 1263-1281.
- Groves, D. I., Barrett, F. M., Binns, R. A., and McQueen, K. G., 1977, Spinel phases associated with metamorphosed volcanic-type iron-nickel sulfide ores from Western Australia: *Econ. Geol.*, 72, p. 1224-1244.
- Hak, J., Watkinson, D. H., and Jonasson, I. R., 1985, New microprobe data on platinum-group minerals and their relationships to metamorphism and deformation of host Ni-Cu sulfide deposits: *Abstr. Fourth Int. Platinum Symposium, Toronto, Can., Mineral.*, 23, p. 304-305.
- Harris, D. C. and Nickel, E. H., 1972, Pentlandite compositions and associations in some mineral deposits: *Can. Mineral.*, 11, p. 861-878.

- Hoffman, E. L., Naldrett, A. J., van Loon, J. C., Hancock, R. G. V., and Mason, A., 1978, The determination of all platinum group elements and gold in rocks and ore by neutron activation analysis after preconcentration by nickel sulfide fire-assay technique on large samples: *Anal. Chimie. Acta.*, 102, p. 157-166.
- Hoffman, E. L., Naldrett, A. J., Alcock, R. A., and Hancock, R. G. V., 1979, The noble-metal content of the Levack West and Little Stobie mines, Ontario: *Can. Mineral.*, 17, p. 437-451.
- Hudson, D. R., 1986, Platinum-group minerals from the Kambalda nickel deposits, Western Australia: *Econ. Geol.*, 81, p. 1218-1225.
- Hudson, D. R. and Donaldson, M. J., 1984, Mineralogy of platinum-group elements in the Kambalda nickel deposits, Western Australia, in Buchanan, D. L. and Jones, M. J., eds., *Sulphide deposits in mafic and ultramafic rocks*: London Inst. Mining Metallurgy, p. 55-61.
- Hulbert, L. J., Duke, J. M., Eckstrand, O. R., Lydon, J. W., Scoates, R. F. J., Cabri, L. J., and Irvine, T. N., 1988, Geological environments of the platinum group elements: *Geol. Surv. Can.*, Open File 1440, 148 p.
- Hynes, A. and Francis, D., 1982a, Komatiite basalts of the Cape Smith foldbelt, New Quebec, Canada: in Arndt, N. T. and Nesbit, E. G., eds., *Komatiites*, Allen and Unwin, London, p. 159-170.
- Hynes, A. and Francis, D., 1982b, A transect of the early Proterozoic Cape Smith Foldbelt, New Quebec: *Tectonophysics*, 88, p. 23-59.
- James, R. S. and Hawke, D., 1984, Geology and petrogenesis of the Kanichee layered complex, Ontario: *Can. Mineral.*, 22, p. 93-109.
- Jenkins, D. M., 1981, Experimental phase relations of hydrous peridotites modelled in the system $H_2O - CaO - MgO - Al_2O_3 - SiO_2$: *Contrib. Mineral. Petrol.*, 77, p. 166-176.
- Jenkins, R. and DeVries, J. L., 1970, *Worked examples in X-ray analysis*: Springer-Verlag, New York, 198 p.
- Keays, R. R., and Davidsohn, R. M., 1976, Palladium, iridium, and gold in the ores and host rocks of nickel sulfide deposits in Western Australia: *Econ. Geol.*, 71, p. 1214-1228.

- Keays, R. R. and Campbell, I. H., 1981, Precious metals in the Jamberlana Intrusion, Western Australia. Implications for genesis of platiniferous ores in layered intrusions: *Econ. Geol.*, 76, p. 1118-1141.
- Keays, R. R., Ross, J. R., and Woolrich, P., 1981, Precious metals in volcanic peridotite-associated nickel sulfide deposits in Western Australia. II: Distribution within the ores and host rocks at Kambalda: *Econ. Geol.*, 76, p. 1645-1674.
- Keele, R. A. and Nickel, E. H., 1974, The geology of a primary millerite-bearing sulfide assemblage and supergene alteration at the Otter Shoot, Kambalda, Western Australia: *Econ. Geol.*, 69, p. 1102-1117.
- Kingston, G. A. and El-Dosuky, B. T., 1982, A contribution on the platinum-group mineralogy of the Merensky Reef at the Rustenburg Mine: *Econ. Geol.*, 77, p. 1367-1384.
- Klemm, D. D., 1965, Synthesen und analysen in den dreiecksdiagrammen $\text{FeAsS} - \text{CoAsS} - \text{NiAsS}$ und $\text{FeS}_2 - \text{CoS}_2 - \text{NiS}_2$: *Neues. Jahrb. Mineral. Abh.*, 103, p. 205-255.
- Laflamme, J. H. G., Electron microprobe analyses of unnamed Pd-Ni-Sb-Te minerals from Cape Smith, Quebec: Unpubl. CANMET report, M-3492, 3p.
- Lamothe, D., Giovenazzo, D., and Picard, C., 1987, Platinum group element occurrences in the Ungava Trough, New Quebec: Document de promotion n° 15, Gouvernement du Quebec, Ministère de l'Énergie et des Ressources, 14 p.
- Leshar, C. M. and Keays, R. R., 1984, Metamorphically and hydrothermally mobilized Fe-Ni-Cu sulphides at Kambalda, Western Australia: in Buchanan, D. L. and Jones, M. J., eds., *Sulphide Deposits in Mafic and Ultramafic Rocks*. Institution of Mining and Metallurgy, London, p. 62-69.
- McCallum, M. E., Loucks, R. R., Carlson, R. R., Cooley, E. F., and Doerge, T. A., 1976, Platinum metals associated with hydrothermal copper ores of the New Rambler mine, Medicine Bow Mountains, Wyoming: *Econ. Geol.*, 71, p. 1429-1450.
- Makovicky, E., Makovicky, M., and Rose-Hansen, J., 1985, Experimental studies on the solubility and distribution of platinum-group elements in base-metal sulfides in platinum-group-mineral deposits: *Abstr. Fourth Int. Platinum Symposium, Toronto, Can.*, *Mineral.*, 23, p. 307.
- Miller, A. R., 1977, Petrology and geochemistry of the 2-3 ultramafic sill and related rocks, Cape Smith-Wakeham Bay foldbelt, Quebec: Unpub. Ph.D. thesis, Univ. Western Ontario.

- Misra, K. C. and Fleet, M. E., 1973, The chemical compositions of synthetic and natural pentlandite assemblages: *Econ. Geol.*, 68, p. 518-539.
- Morton, P., 1982, Archean volcanic stratigraphy, and petrology and chemistry of mafic and ultramafic rocks, chromite, and the Shebandowan Ni-Cu mine, Shebandowan, northwestern Ontario: unpub. Ph.D. thesis, Carleton Univ.
- Naldrett, A. J., 1979, Partitioning of Fe, Co, Ni, and Cu between sulfide liquid and basaltic melts and the composition of Ni-Cu sulfide deposits - a reply and further discussion: *Econ. Geol.*, 74, p. 1520-1528.
- Naldrett, A. J., 1981, Nickel sulfide deposits: classification, composition, and genesis: *Econ. Geol.*, 75th Anniv. Vol., p. 628-685.
- Naldrett, A. J. and Cabri, L. J., 1976, Ultramafic and related mafic rocks: their classification and genesis with special reference to the concentrations of nickel sulfides and platinum-group elements: *Econ. Geol.*, 71, p. 1131-1158.
- Naldrett, A. J. and Duke, J. M., 1980, Platinum metals in magmatic sulfide ores: *Science*, 208, p. 1417-1424.
- Naldrett, A. J., Craig, J. R., and Kullerud, G., 1967, The central portion of the Fe-Ni-S system and its bearing on pentlandite exsolution in iron-nickel ores: *Econ. Geol.*, 62, p. 826-847.
- Naldrett, A. J., Hoffman, E. L., Green, A. H., Chen-Lin Chou, and Naldrett, S. R., 1979, The composition of Ni-sulfide ores, with particular reference to their content of PGE and Au: *Can. Mineral.*, 17, p. 403-415.
- Naldrett, A. J., Innes, D. G., Sowa, J., and Gorton, M. P., 1982, Compositional variations within and between five Sudbury ore deposits: *Econ. Geol.*, 77, p. 1519-1534.
- Park, A. R., 1983, Sequential development of metamorphic fabric and structural elements in polyphase deformed serpentinites in the Svecokarelidides of eastern Finland: *Trans. R. Soc. Edinburgh Earth Sci.*, 74, p. 33-60.
- Patterson, G. C. and Watkinson, D. H., 1984, Metamorphism and supergene alteration of Cu-Ni sulfides, Thierry Mine, northwestern Ontario: *Can. Mineral.*, 22, p. 13-21.
- Philpotts, A. R., 1961, Textures of the Ungava nickel ores: *Can. Mineral.*, 6, p. 680-688.

- Picard, C., 1986, Lithogeochemie de la partie centrale de la Fosse de l'Ungava: Ministère de l'Energie et des Ressources du Québec, DV 86-16, p. 57-72.
- Rajamani, V. and Naldrett, A. J., 1978, Partitioning of Fe, Co, Ni, and Cu between sulfide liquid and basaltic melts and the composition of Ni-Cu sulfide deposits: Econ. Geol., 73, p. 82-93.
- Ramsden, A. R., 1975, Compositions of coexisting pyrrhotites, pentlandites and pyrites at Spargoville, Western Australia: Can. Mineral., 11, p. 861-878.
- Roberts, R. G., 1987, Ore deposit models #11. Archean lode gold deposits: Geoscience Can., 14, p. 37-52.
- Ross, J. R. and Keays, R. R., 1979, Precious metals in volcanic-type nickel sulfide deposits in Western Australia. I: Relationship with the composition of the ores and their host rocks: Can. Mineral., 17, p. 417-435.
- Rowell, W. F. and Edgar, A. D., 1986, Platinum-group element mineralization in a hydrothermal Cu-Ni sulfide occurrence, Rathbun Lake, northeastern Ontario: Econ. Geol., 81, p. 1272-1277.
- Rucklidge, J. C. and Gasparini, E. L., 1969, Electron microprobe analytical data reduction (EMPADR VII), Dept. of Geol. Univ. Toronto.
- Rucklidge, J. C. and Patterson, G. C., 1977, The role of chlorine in serpentinization: Contrib. Mineral. Petrol., 65, p. 39-44.
- St-Onge, M. R., Lucas, S. B., Scott, D. J., and Begin, N. J., 1986, Eastern Cape Smith Belt: an early Proterozoic thrust-fold belt and basal shear zone exposed in oblique section, Wakeham Bay and Cratère du Nouveau Québec map areas, northern Québec: in Current Research, Part A, Geol. Surv. Can., Paper 86-1A, p. 1-14.
- Seccombe, P. K., Groves, D. I., Marston, R. J., and Barrett, F. M., 1981, Sulfide paragenesis and sulfur mobility in Fe-Ni-Cu sulfide ores at Lunnon and Juan shoots, Kambalda: textural and sulfur isotopic evidence: Econ. Geol., 76, p. 1675-1685.
- Shannon, R. D., 1976, Revised effective ionic radii and systematic studies of interatomic distances in halides and chalcogenides: Acta Crystallogr., 32, p. 751-767.
- Sheppard, S. F. and Schwarz, H. P., 1970, Fractionation of carbon and oxygen isotopes and magnesium between coexisting metamorphic calcite and dolomite: Contrib. Min. Pet., 26, p. 161-198.

- Skinner, B. J., Luce, F. D., Dill, J. A., Ellis, P. E., Hagan, H. A., Lewis, D. M., Odell, D. A., Sverjensky, D. A., and Williams, N., 1976, Phase relationships in ternary portions of the system Pt-Pd-Fe-As-S: *Econ. Geol.*, 71, p. 1469-1475.
- Streckeisen, A., 1976, To each plutonic rock its proper name: *Earth Sci. Rev.*, 12, p. 1-33.
- Stumpfl, E. F. and Rucklidge, J., 1968, New data on natural phases in the system Ag-Te: *Am. Mineral.*, 53, p. 1513-1522.
- Taylor, F. C., Gordon, T.M., and Henderson, J. B., 1974, Operation Nuvilik, New Quebec and Northwest Territories: *Geol. Surv. Can., Report of Activities*, paper 74-1, p. 1480-1502.
- Taylor, F. C., 1982, Reconnaissance Geology of a part of the Canadian Shield, northern Quebec and Northwest Territories: *Geol. Surv. Can., Memoir* 399, 32p.
- Trommsdorff, V. and Evans, B.W., 1977, Antigorite-opphicarbonates: phase relations in a part of the system $\text{CaO-MgO-SiO}_2\text{-H}_2\text{O-CO}_2$: *Contrib. Mineral. Pet.*, 60, p. 39-56.
- Usselman, T. M., Hodge, D. S., Naldrett, A. J., and Campbell, I. H., 1979, Physical constraints on the characteristics of nickel-sulfide ore in ultramafic lavas: *Can. Mineral.*, 17, p. 361-372.
- Vokes, F. M., 1971, Some aspects of the regional metamorphic mobilization of preexisting sulfide deposits: *Mineral. Deposita.*, 6, p. 122-129.
- Wilson, D. H. B., Kilburn, L. C., Graham, A. R., and Ramdal, K., 1969, Geochemistry of some Canadian nickeliferous ultrabasic intrusions: *Econ. Geol. Mon.* 4., p. 294-309.
- Winkler, H. G. F., 1974, Petrogenesis of the Metamorphic Rocks, 3rd ed., Springer-Verlag, New York, 334 p.

Appendix A. Electron Microprobe Standards and X-Ray Lines.

SPERRYLITE - PtAs₂ accelerating voltage = 20kv

ELEMENT	X-RAY LINE	STANDARD	COMPOSITION WT %
Pt	PtMa	PtAs ₂	Pt(56.56); As(43.44)
	"	PtPdS	Pt(68.10); Pd(15.92); S(15.98)
As	AsKa	PtAs ₂	Pt(56.56); As(43.44)
	"	CoAs ₂	Co(28.22); As(71.77)
Rh	RhLa	Pure Rh	
Ir	IrLa	Pure Ir	
Ru	RuLa	Pure Ru	
Os	OsLa	Pure Os	
Pd	PdLa	PdSb	Pd(46.63); Sb(53.37)
	"	PtPdS	Pt(68.10); Pd(15.92); S(15.98)
Sb	SbLa	PdSb	Pd(46.63); Sb(53.37)
	"	Pt ₃ Sb ₂	Pt(70.63); Sb(29.37)
S	SKa	PtPdS	Pt(68.10); Pd(15.92); S(15.98)

SUDBURYITE - PdSb accelerating voltage = 20 to 25 kv

ELEMENT	X-RAY LINE	STANDARD	COMPOSITION WT %
Pd	PdLa	PdTe	Pd(44.34); Te(55.66)
	"	PdSb	Pd(46.63); Sb(53.37)
Te	TeLa	PdTe	Pd(44.34); Te(55.66)
Sb	SbLa	PdSb	Pd(46.63); Sb(53.37)
Ni	NiKa	(Pd,Ni)Te ₂	Pd(27.84); Ni(1.71); Te(70.45)
	"	(Ni,Pt)Te ₂	Ni(19.45); Pt(0.11); Te(80.44)
Pt	PtLa	Pt ₃ Sb ₂	Pt(70.63); Sb(29.37)
Ag	AgLb	AgSb	Ag(89.99); Sb(10.01)
Pb	PbLa	PbTe	Pb(61.88); Te(38.12)
As	AsKa	Pd ₃ Sb ₂ As ₂	Pd(74.84); Sb(15.58); As(9.58)
Bi	BiLa	PdBi	Pd(33.74); Bi(66.26)

TESTIBIOPALLADITE - PdSbTe

accelerating voltage = 25kv

ELEMENT	X-RAY LINE	STANDARD	COMPOSITION WT %
Pd	PdLa	PdTe	Pd(44.34); Te(55.66)
	"	PdSb	Pd(46.63); Sb(53.37)
Te	TeLa	PdTe	Pd(44.34); Te(55.66)
Ag	AgLb	AgSb	Ag(89.99); Sb(10.01)
Sb	SbLa	PdSb	Pd(46.63); Sb(53.37)
Ni	NiKa	(Pd,Ni)Te _{1.9}	Pd(27.84); Ni(1.71); Te(70.45)
	"	(Ni,Pt)Te ₂	Ni(19.45); Pt(0.11); Te(80.44)
Bi	BiLa	PdBi	Pd(33.74); Bi(66.26)
Pt	PtLa	Pt ₃ Sb ₂	Pd(70.63); Sb(29.37)
Pb	PbLa	PbTe	Pb(61.88); Te(38.12)
Fe	FeKa	Cu _{1.2} FeSb ₄ S _{1.3}	Cu(42.14); Fe(3.87); Sb(29.36); S(25.13)
Cu	CuKa	(Pd,Cu) _{1.5} Sb ₂	Pd(67.10); Cu(1.25); Sb(31.65)
As	AsKa	Pd _{1.1} Sb ₂ As ₂	Pd(74.84); Sb(15.58); As(9.58)

BOROVSKITE - Pd₃SbTe₄

accelerating voltage = 20 to 25kv

ELEMENT	X-RAY LINE	STANDARD	COMPOSITION WT %
Pd	PdLa	PdSb	Pd(46.63); Sb(53.37)
Sb	SbLa	PdSb	Pd(46.63); Sb(53.37)
Bi	BiLa	PdBi	Pd(33.74); Bi(66.26)
Te	TeLa	PdTe	Pd(44.34); Te(55.66)
Ni	NiKa	(Ni,Pt)Te ₂	Ni(19.45); Pt(0.11); Te(80.44)
Pt	PtLa	Pt ₃ Sb ₂	Pt(70.63); Sb(29.37)
	"	PtPdS	Pt(68.10); Pd(15.92); S(15.98)
As	AsKa	Pd _{1.1} Sb ₂ As ₂	Pd(74.84); Sb(15.58); As(9.58)
Ag	AgLb	AgSb	Ag(89.99); Sb(10.01)
Pb	PbLa	PbTe	Pb(61.88); Te(38.12)

Appendix A cont.

UNKNOWN - Pd₂Sb₂Te₂ accelerating voltage 20 - 25kv

ELEMENT	X-RAY LINE	STANDARD	COMPOSITION WT %
Pd	PdLa	PdTe	Pd(44.34); Te(55.66)
	"	PdSb	Pd(46.63); Sb(53.37)
Te	TeLa	Pure Te	
	"	(Pd,Ni)Te _{1.9}	Pd(27.84); Ni(1.71); Te(70.45)
Ag	AgLb	AgSb	Ag(89.99); Sb(10.01)
Sb	PdLa	PdSb	Pd(46.63); Sb(53.37)
Pt	PtLa	Pt ₂ Sb ₂	Pt(70.63); Sb(29.37)
	"	PtPdS	Pt(68.10); Pd(15.92); S(15.98)
Ni	NiKa	Pure Ni	
	"	(Ni,Pt)Te ₂	Ni(19.45); Pt(0.11); Te(80.44)
Bi	BiLa	PdBi	Pd(33.74); Bi(66.26)
As	AsKa	Pd ₁₁ Sb ₂ As ₂	Pd(74.84); Sb(15.58); As(9.58)

MERENSKYITE - PdTe₂ accelerating voltage = 25kv

ELEMENT	X-RAY LINE	STANDARD	COMPOSITION WT %
Pd	PdLa	PdSb	Pd(46.63); Sb(53.37)
Sb	SbLa	PdSb	Pd(46.63); Sb(53.37)
Te	TeLa	PdTe	Pd(44.34); Te(55.66)
Ni	NiKa	(Ni,Pt)Te ₂	Ni(19.45); Pt(0.11); Te(80.44)
Pt	PtLa	PtPdS	Pt(68.10); Pd(15.92); S(15.98)
As	AsKa	Pd ₁₁ Sb ₂ As ₂	Pd(74.84); Sb(15.58); As(9.58)
Bi	BiLa	PdBi	Pd(33.74); Bi(66.26)

Appendix A cont.

HESSITE - Ag₂Te accelerating voltage = 20 to 25kv

ELEMENT	X-RAY LINE	STANDARD	COMPOSITION WT %
Ag	AgLa	AgSb	Ag(89.99); Sb(10.01)
Te	TeLa	PdTe	Pd(44.34); Te(55.66)
Pd	PdLa	PdSb	Pd(46.63); Sb(53.37)
Sb	SbLa	PdSb	Pd(46.63); Sb(53.37)
Au	AuLa	AuCu	Au(81.236); Cu(18.764)
Cu	CuKa	AuCu	Au(81.236); Cu(18.764)
Pb	PbLa	PbTe	Pb(61.88); Te(38.12)
Ni	NiKa	(Ni,Pt)Te ₂	Ni(19.45); Pt(0.11); Te(80.44)
As	AsKa	Pd ₁ Sb ₂ As ₂	Pd(74.84); Sb(15.58); As(9.58)
Bi	BiLa	PdBi	Pd(33.74); Bi(66.26)

ELECTRUM - AuAg accelerating voltage = 20kv

ELEMENT	X-RAY LINE	STANDARD	COMPOSITION WT %
Ag	AgLa	AuM44	Ag(14.70); Au(85.30)
Au	AuLa	AuM44	Ag(14.70); Au(85.30)
Pd	PdLa	PdTe	Pd(44.34); Te(55.66)
Te	TeLa	PdTe	Pd(44.34); Te(55.66)
Ru	RuLa	Pure Ru	
Sb	SbLa	Pt ₃ Sb ₂	Pt(70.67); Sb(29.37)
Os	OsLa	Pure Os	
Pt	PtLa	Pt ₃ Sb ₂	Pt(70.67); Sb(29.37)
Ir	IrLa	Pure Ir	
Rh	RhLa	Pure Rh	

Appendix A cont.

MELONITE - NiTe_2 accelerating voltage = 25kv

ELEMENT	X-RAY LINE	STANDARD	COMPOSITION WT %
Pd	PdLa	PdTe	Pd(44.34); Te(55.66)
	"	PdSb	Pd(46.63); Sb(53.37)
Te	TeLa	Pure Te	
	"	(Pd,Ni)Te _{1.9}	Pd(27.84); Ni(1.71); Te(70.45)
Ag	AgLb	AgSb	Ag(89.99); Sb(10.01)
Sb	PdLa	PdSb	Pd(46.63); Sb(53.37)
Pt	PtLa	Pt ₃ Sb ₂	Pt(70.63); Sb(29.37)
	"	PtPdS	Pt(68.10); Pd(15.92); S(15.98)
Ni	NiKa	Pure Ni	
	"	(Ni,Pt)Te ₂	Ni(19.45); Pt(0.11); Te(80.44)
Bi	BiLa	PdBi	Pd(33.74); Bi(66.26)
Pb	PbLa	PbTe	Pb(61.88); Te(38.12)
As	AsKa	Pd ₁₁ Sb ₂ As ₂	Pd(74.84); Sb(15.58); As(9.58)

ULLMANNITE - NiSbS accelerating voltage = 25kv

ELEMENT	X-RAY LINE	STANDARD	COMPOSITION WT %
Pd	PdLa	PdBi	Pd(33.74); Bi(66.26)
Bi	BiLa	PdBi	Pd(33.74); Bi(66.26)
Ag	AgLa	AgSb	Ag(89.99); Sb(10.01)
Fe	FeKa	$\text{Cu}_{12}\text{FeSb}_4\text{S}_{13}$	Cu(42.14); Fe(3.37); Sb(29.36); S(25.13)
Ni	NiKa	NiSb	Ni(32.53); Sb(67.47)
Sb	SbLa	NiSb	Ni(32.53); Sb(67.47)
Pt	PtLa	PtTe ₂	Pt(43.32); Te(56.68)
Te	TeLa	PtTe ₂	Pt(43.32); Te(56.68)
S	Ska	$\text{Cu}_{12}\text{FeSb}_4\text{S}_{13}$	Cu(42.14); Fe(3.37); Sb(29.36); S(25.13)
Cu	CuKa	CuFeS_2	Cu(34.62); Fe(30.43); S(34.94)
As	AsKa	CoAs_2	Co(28.22); As(71.77)
Co	CoKa	CoAs_2	Co(28.22); As(71.77)

Appendix A cont.

NICKELINE - NiAs accelerating voltage = 15kv.

ELEMENT	X-RAY LINE	STANDARD	COMPOSITION WT %
As	AsKa	CoAs ₂	Co(28.22); As(71.77)
Co	CoLa	CoAs ₂	Co(28.22); As(71.77)
Ni	NiKa	NiS	Ni(64.67); S(35.33)
Fe	FeKa	FeS ₂	Fe(46.55); S(53.45)
Pd	PdLa	PdTe	Pd(44.34); Te(55.66)
Sb	SbLa	Cu _{1.2} Sb ₄ S _{1.3}	Cu(45.76); Sb(29.23); S(25.02)
Pt	PtLa	PtTe ₂	Pt(43.32); Te(56.68)
Te	TeLa	PtTe ₂	Pt(43.32); Te(56.68)

COBALTITE - (Co,>Ni,Fe)AsS and GERSDORFFITE - (Ni,>Co,Fe)AsS accelerating voltage = 20 to 25kv

ELEMENT	X-RAY LINE	STANDARD	COMPOSITION WT %
Co	CoKa	CoAs ₂	Co(28.22); As(71.77)
As	AsKa	CoAs ₂	Co(28.22); As(71.77)
Fe	FeKa	FeS ₂	Fe(46.55); S(53.45)
	"	(Fe,Ni,Co) ₃ S ₈	Fe(31.02); Ni(29.95); Co(1.95); S(37.10)
S	SKa	FeS ₂	Fe(46.55); S(53.45)
Sb	SbLa	NiSb	Ni(32.53); Sb(67.47)
	"	PdSb	Pd(46.63); Sb(53.37)
Ni	NiKa	NiSb	Ni(32.53); Sb(67.47)
	"	(Fe,Ni,Co) ₃ S ₈	Fe(31.02); Ni(29.95); Co(1.95); S(37.10)
Ag	AgLa	Cu ₂ Fe ₂ Ag ₂ Sb ₄ S _{1.3}	Cu(24.93); Fe(6.26); Ag(18.14); Sb(27.30); S(23.37)
Pt	PtLa	Pt ₃ Sb ₂	Pt(70.63); Sb(29.37)
	"	Pt _{1.0} Fe _{0.00} Cu _{0.10}	Pt(77.36); Fe(18.61); Cu(4.03)
Pd	PdLa	PdTe _{1.0}	Pd(30.50); Te(69.50)
	"	PdSb	Pd(46.63); Sb(53.37)
Te	TeLa	PdTe _{1.0}	Pd(30.50); Te(69.50)
Bi	BiLa	PdBi	Pd(33.74); Bi(66.26)

Appendix A cont.

PYRRHOTITE - $(\text{Fe,Ni})_7\text{S}_8$ accelerating voltage = 20kv

ELEMENT	X-RAY LINE	STANDARD	COMPOSITION WT %
S	SKa	$(\text{Fe,Ni,Cu,Co})_7\text{S}_8$	Fe(57.47); Ni(1.35); Cu(1.38); Co(1.35); S(38.45)
Fe	FeKa	$(\text{Fe,Ni,Cu,Co})_7\text{S}_8$	Fe(57.47); Ni(1.35); Cu(1.38); Co(1.35); S(38.45)
Ni	NiKa	$(\text{Fe,Ni,Cu,Co})_7\text{S}_8$	Fe(57.47); Ni(1.35); Cu(1.38); Co(1.35); S(38.45)
Pd	PdLa	PtPdS	Pt(68.10); Pd(15.92); S(15.98)
Pt	PtLa	PtPdS	Pt(68.10); Pd(15.92); S(15.98)
Rh	RhLa	Pure Rh	
As	AsKa	$\text{Pd}_{11}\text{Sb}_2\text{As}_2$	Pd(74.84); Sb(15.58); As(9.58)
Cu	CuKa	$(\text{Fe,Ni,Cu,Co})_7\text{S}_8$	Fe(57.47); Ni(1.35); Cu(1.38); Co(1.35); S(38.45)

PENTLANDITE - $(\text{Fe,Ni})_9\text{S}_8$ accelerating voltage = 20kv

ELEMENT	X-RAY LINE	STANDARD	COMPOSITION WT %
S	SKa	$(\text{Fe,Ni,Co})_9\text{S}_8$	Fe(31.02); Ni(29.95); Co(1.95); S(37.10)
Fe	FeKa	$(\text{Fe,Ni,Co})_9\text{S}_8$	Fe(31.02); Ni(29.95); Co(1.95); S(37.10)
Ni	NiKa	$(\text{Fe,Ni,Co})_9\text{S}_8$	Fe(31.02); Ni(29.95); Co(1.95); S(37.10)
Co	CoKa	$(\text{Fe,Ni,Cu,Co})_9\text{S}_8$	Fe(57.47); Ni(1.35); Cu(1.38); Co(1.35); S(38.45)
	"	CoAs_2	Co(28.22); As(71.77)
As	AsKa	CoAs_2	Co(28.22); As(71.77)
	"	$\text{Cu}_{12}\text{Sb}_4\text{S}_{13}$	Cu(45.76); Sb(29.23); S(25.02)
Pd	PdLa	PdSb	Pd(46.63); Sb(53.37)
Sb	SbLa	PdSb	Pd(46.63); Sb(53.37)
Rh	RhLa	Pure Rh	
Pt	PtLa	PtPdS	Pt(68.10); Pd(15.92); S(15.98)
Cu	CuKa	$(\text{Fe,Ni,Cu,Co})_9\text{S}_8$	Fe(57.47); Ni(1.35); Cu(1.38); Co(1.35); S(38.45)

CHALCOPYRITE - CuFeS_2 accelerating voltage = 20kv

ELEMENT	X-RAY LINE	STANDARD	COMPOSITION WT %
S	SKa	(Fe, Ni, Co) $\cdot$ S $_8$	* Fe(31.02); Ni(29.95); Co(1.95); S(37.10)
	"	CuFeS $_2$	Cu(34.62); Fe(30.63); S(34.94)
Fe	FeKa	CuFeS $_2$	Cu(34.62); Fe(30.63); S(34.94)
	"	(Fe, Ni, Co) $\cdot$ S $_8$	Fe(31.02); Ni(29.95); Co(1.95); S(37.10)
Cu	CuKa	CuFeS $_2$	Cu(34.62); Fe(30.63); S(34.94)
Ni	NiKa	(Fe, Ni, Co) $\cdot$ S $_8$	Fe(31.02); Ni(29.95); Co(1.95); S(37.10)
Co	CoKa	CoAs $_2$	Co(28.22); As(71.77)
As	AsKa	CoAs $_2$	Co(28.22); As(71.77)
Ag	AgLb	AgSb	Ag(89.99); Sb(10.01)
Pd	PdLa	PdSb	Pd(46.63); Sb(53.37)
Sb	SbLa	PdSb	Pd(46.63); Sb(53.37)
Te	TeLa	PdTe $_{1.7}$	Pd(30.50); Te(69.50)

PYRITE - FeS_2 accelerating voltage = 20kv

ELEMENT	X-RAY LINE	STANDARD	COMPOSITION WT %
Fe	FeKa	FeS $_2$	Fe(46.55); S(53.45)
S	SKa	FeS $_2$	Fe(46.55); S(53.45)
Ni	NiKa	(Fe, Ni, Cu, Co) $\cdot$ S $_8$	Fe(57.47); Ni(1.35); Cu(1.38); Co(1.35); S(38.45)
Co	CoKa	(Fe, Ni, Cu, Co) $\cdot$ S $_8$	Fe(57.47); Ni(1.35); Cu(1.38); Co(1.35); S(38.45)
Cu	CuKa	(Fe, Ni, Cu, Co) $\cdot$ S $_8$	Fe(57.47); Ni(1.35); Cu(1.38); Co(1.35); S(38.45)
As	AsKa	CoAs $_2$	Co(28.22); As(71.77)
Pd	PdLa	PtPdS	Pt(68.10); Pt(15.92); S(15.98)
Pt	PtLa	PtPdS	Pt(68.10); Pt(15.92); S(15.98)
Rh	RhLa	Pure Rh	

Appendix B.³ Lower limits of detection (LLD) for major, trace, and platinum-group elements by electron microprobe.

Element	Routine analysis (T=20 to 40 sec) wt %	Trace analysis (T=80 to 200 sec) wt %
Pd	.09	.05
Pt	.13	.09
Ru	.13	.07
Rh	.16	.08
Ir	.16	.08
Os	.16	.08
Sb	.06	.04
Te	.06	.05
Bi	.22	.15
Ag	.15	.13
Au	.20	.10
Pb	.21	.15
S	.03	.03
Ni	.03	.03
Fe	.03	.03
Cu	.04	.03
Co	.04	.03
As	.13	.04

$$LLD = \frac{2\sqrt{2}}{\frac{R_p - R_b}{X}} \times \sqrt{\frac{R_b}{T}}$$

Where:

X=concentration in standard

T=counting time x 2

R_p=counts at peak in counts per second

R_b=counts at background in counts per second

Source - Jenkins and DeVries (1970).

Appendix C-1. Electron Microprobe Analyses of Pyrrhotite - M_7S_8
from core hole 160-224, Donaldson West deposit.

Smpl #	1	2	3	4	5	6	7
Fe	59.9*	59.8	60.1	60.7	60.6	60.5	60.6
Ni	0.31	0.30	0.31	0.17	0.22	0.22	0.25
Co	ND	ND	ND	0.11	0.12	0.09	0.09
Cu	NA	NA	NA	NA	NA	NA	NA
As	ND	ND	ND	ND	ND	ND	ND
S	38.6	38.9	38.7	38.1	39.2	38.9	39.7
Total	98.81	99.00	99.11	99.08	100.1	99.71	100.6
	$M_{7.18}S_8$	$M_{7.07}S_8$	$M_{7.18}S_8$	$M_{7.34}S_8$	$M_{7.18}S_8$	$M_{7.18}S_8$	$M_{7.08}S_8$

Smpl #	8	9	10	11	12	13	14
Fe	60.6	60.9	60.6	59.6	59.8	60.9	59.6
Ni	0.48	0.19	0.19	0.38	0.38	0.51	0.83
Co	0.11	0.11	0.09	ND	ND	0.04	0.11
Cu	NA	NA	NA	NA	NA	NA	NA
As	0.05	ND	ND	ND	ND	ND	ND
S	39.9	39.2	39.1	38.9	38.9	38.9	40.0
Total	101.1	100.4	99.98	98.88	99.08	100.4	100.5
	$M_{7.02}S_8$	$M_{7.18}S_8$	$M_{7.18}S_8$	$M_{7.07}S_8$	$M_{7.07}S_8$	$M_{7.28}S_8$	$M_{6.78}S_8$

Appendix C-1 cont.

Smp1 #	15	16	17	18	19	20	21
Fe	59.4	58.8	59.2	59.5	59.4	60.1	60.2
Ni	0.67	0.96	0.70	1.42	1.32	0.29	0.58
Co	0.10	0.09	0.08	0.04	0.04	0.09	0.10
Cu	NA	NA	NA	NA	NA	NA	NA
As	ND	ND	ND	0.09	0.08	0.07	ND
S	40.0	39.1	39.8	38.3	38.8	40.0	39.2
Total	100.2	98.95	99.78	99.35	99.64	100.6	100.1

M_{6.71S} M_{7.02S} M_{6.72S} M_{7.32S} M_{7.17S} M_{6.70S} M_{7.12S}

Smp1 #	22	23	24	25	26	27	28
Fe	60.7	60.5	60.2	60.1	60.7	60.5	60.6
Ni	0.46	0.46	0.42	0.51	0.45	0.51	0.48
Co	0.12	0.08	0.13	0.13	0.14	0.11	0.14
Cu	NA	NA	NA	NA	NA	NA	NA
As	ND	ND	0.06	ND	ND	ND	ND
S	39.2	39.4	39.4	39.5	38.9	39.0	39.0
Total	100.5	100.5	100.2	100.2	100.2	100.1	100.2

M_{7.16S} M_{7.07S} M_{7.00S} M_{7.04S} M_{7.22S} M_{7.17S} M_{7.17S}

Smpl #	29	30	31	32	33	34
Fe	60.1	60.4	60.0	59.9	59.7	60.0
Ni	0.26	0.25	0.33	0.39	0.4	0.38
Co	0.13	0.10	0.13	0.12	0.12	0.12
Cu	NA	NA	0.04	ND	0.04	ND
As	ND	ND	ND	ND	ND	ND
S	39.6	39.7	38.8	39.1	39.2	38.7
Total	100.1	100.4	99.30	99.51	99.47	99.20

M_{7.01S} M_{7.02S} M_{7.13S} M_{7.04S} M_{7.04S} M_{7.13S}

Abbreviations: NA=not analysed; ND=not detected; pn=pentlandite; cp=chalcopyrite; py=pyrite; cob=cobaltite; serp=serpentine; crm=chromite. Analyses 1-3 at 239.5m (vein), 4-6 at 248.7m (net-textured), 7-10 at 251.2m (net-textured to reverse net-textured), 11-12 at 254.5m (vein), 13 at 263.2m (reverse net-textured), 14-17 at 269.8m (reverse net-textured), 18-19 at 271.2m (veined), 20-23 at 273.5m (massive sulfide), 24-30 at 274.0m (massive sulfide), 31 (n=2) at 244.3m (net-textured), and 32-34 (n=2 each) at 205.3m (disseminated). See Appendix B for lower limits of detection.

Assemblages in contact;

1 - cp	
2 - py	20 - 25 pn
3 - 12 pn	26 - cp
13 - serp/crm	27 - pn
14 - 17 pn	28 - 30 pn/cp
18 - serp	31 - pn
19 - pn/py/serp	32 - 34 pn/py

Appendix C-2. Electron microprobe analyses of Pentlandite - Ni_3S_2 from core hole 160-224, Donaldson West deposit.

Smpl #	1	2	3	4	5	6	7
Ni	35.7	35.8	35.9	35.8	35.9	36.4	35.9
Fe	31.2	30.9	30.8	30.8	30.4	30.6	30.2
Co	0.12	0.13	0.15	0.14	0.49	0.55	0.55
As	0.18	0.28	0.19	0.18	0.08	0.07	0.12
S	33.1	33.2	33.2	33.1	32.4	32.6	31.6
Total	100.3	100.3	100.2	100.0	99.27	100.2	98.37

$\text{Ni}_{7.07}\text{S}_{10}$ $\text{Ni}_{7.04}\text{S}_{10}$ $\text{Ni}_{7.02}\text{S}_{10}$ $\text{Ni}_{7.02}\text{S}_{10}$ $\text{Ni}_{7.24}\text{S}_{10}$ $\text{Ni}_{7.26}\text{S}_{10}$ $\text{Ni}_{7.43}\text{S}_{10}$

Smpl #	8	9	10	11	12	13	14
Ni	36.4	36.1	35.6	36.2	36.7	36.1	35.9
Fe	30.6	30.2	30.1	30.4	30.0	30.3	30.0
Co	0.54	0.65	0.64	0.64	0.55	0.50	0.58
As	ND	0.10	0.09	ND	0.08	ND	0.19
S	32.8	33.3	32.8	33.2	31.8	32.8	33.0
Total	100.3	100.3	99.17	100.5	99.11	99.75	99.70

$\text{Ni}_{7.20}\text{S}_{10}$ $\text{Ni}_{7.46}\text{S}_{10}$ $\text{Ni}_{7.06}\text{S}_{10}$ $\text{Ni}_{7.06}\text{S}_{10}$ $\text{Ni}_{7.47}\text{S}_{10}$ $\text{Ni}_{7.07}\text{S}_{10}$ $\text{Ni}_{7.02}\text{S}_{10}$

Appendix C-2 cont.

Smpl #	15	16	17	18	19	20	21
Ni	35.9	36.0	36.8	37.3	36.7	36.9	36.7
Fe	30.2	30.0	29.2	28.8	28.8	28.6	28.9
Co	0.70	0.72	0.56	0.64	0.64	0.59	0.58
As	0.25	0.29	0.10	ND	0.05	0.10	0.06
S	33.3	33.1	33.7	33.0	32.9	33.3	32.8
Total	100.2	100.1	100.3	99.79	99.13	99.57	99.06

M_{0.75S} M_{0.02S} M_{0.01S} M_{0.02S} M_{0.75S} M_{0.02S} M_{0.02S}

Smpl #	22	23	24	25	26	27	28
Ni	38.0	37.4	37.6	35.3	35.2	29.6	35.4
Fe	28.9	28.3	28.7	31.0	31.2	35.6	31.0
Co	0.61	0.62	0.70	0.53	0.53	0.34	0.53
As	0.09	0.18	0.15	0.07	0.07	0.12	0.06
S	32.9	32.6	33.0	33.1	33.4	34.6	33.3
Total	100.4	99.09	100.2	100.0	100.4	100.3	100.2

M_{0.17S} M_{0.09S} M_{0.04S} M_{0.02S} M_{0.75S} M_{0.03S} M_{0.02S}

Appendix C-2 cont.

Smpl #	29	30	31	32	33
Ni	35.2	35.2	35.3	35.2	35.2
Fe	31.1	31.3	31.3	30.9	31.1
Co	0.52	0.48	0.47	0.45	0.50
As	0.11	0.07	0.06	ND	0.04
S	33.2	33.0	32.7	32.9	33.0
Total	100.1	100.2	99.83	99.45	99.94

$M_{7.02S}$ $M_{7.07S}$ $M_{7.17S}$ $M_{7.06S}$ $M_{7.06S}$

Abbreviations: NA=not analysed; ND=not detected; po=pyrrhotite; cp=chalcopyrite; py=pyrite; cob=cobaltite; serp=serpentine. Analyses 1-4 at 239.5m (vein), 5-8 at 248.7m (net-textured), 9-13 at 251.2m (veined), 14-16 at 254.5m (net-textured), 17 at 263.2m (reverse net-textured), 18-21 at 269.8m (reverse net-textured), 22-24 at 271.2m (veined), 25-29 at 273.5m (massive sulfide), and 30-33 at 274.0m (massive sulfide). Analysis 27 from pentlandite exsolution flame. Pd, Pt, Sb, and Te sought for in analyses 5-13 with counting times of 100 seconds. See Appendix B for lower limits of detection.

Assemblages in contact;

1 - po/cp	26 - po/cp
2 - po/py	27 - po
3 - 18 po	28 - 30 po/cp
19 - po/py/serp	31 - po
20 - 25 po	32 - 33 po/py

Appendix C-3. Electron microprobe analyses of Pyrite - FeS_2
from core hole 160-224, Donaldson West deposit.

Smpl #	1	2	3	4	5	6	7
Fe	43.7	44.8	44.5	44.3	44.3	45.7	45.1
As	0.17	0.22	0.12	0.17	0.17	0.12	0.08
Co	2.66	0.16	2.06	1.68	1.48	0.18	0.23
Ni	0.09	0.18	0.06	0.06	0.06	0.46	0.23
Cu	0.09	0.07	0.07	0.08	0.07	0.09	0.04
S	52.1	52.3	52.5	51.2	52.3	52.3	51.8
Total	98.81	97.73	99.31	97.49	98.38	98.85	97.48

Atomic proportions based on three atoms

Fe	.95	.98	.97	.98	.97	1.00	1.00
Co	.05	---	.04	.04	.03	---	.01
Ni	---	---	---	---	---	.01	.01
Sum	1.00	.98	1.01	1.02	1.00	1.01	1.02
S	1.98	2.00	1.99	1.98	2.00	1.99	1.99

Appendix C-3 cont.

Smpl #	8	9	10	11	12	13	14
						rim	core
Fe	45.6	46.4	45.2	45.3	46.1	46.1	45.7
As	0.12	0.14	0.10	0.07	0.04	ND	ND
Co	0.13	0.16	0.80	0.61	0.11	ND	0.34
Ni	0.27	0.21	0.10	0.05	0.33	0.42	0.32
Cu	0.13	0.09	0.06	0.06	0.05	NA	NA
S	51.8	52.2	52.7	50.9	52.8	54.0	53.6
Total	98.05	99.20	98.96	96.99	99.43	100.5	99.96

Atomic proportions based on three atoms

Fe	1.01	1.01	.98	1.00	1.00	.98	.98
Co	---	---	.02	.01	---	---	.01
Ni	.01	---	---	---	.01	.01	.01
Sum	1.01	1.01	1.00	1.00	1.01	.99	1.00
S	1.98	1.98	2.00	1.97	1.99	2.00	2.00

Appendix C-3 cont.

Smpl #	15	16	17	18	19	20	21
	core	rim	rim	core	rim	core	
Fe	46.0	46.3	46.7	45.8	45.9	45.8	45.0
As	ND	ND	ND	ND	ND	ND	ND
Co	0.21	0.13	ND	ND	0.43	0.68	0.04
Ni	0.09	0.09	0.41	0.11	0.38	ND	2.78
S	53.9	54.2	54.2	54.2	54.3	54.1	53.4
Total	100.2	100.7	101.3	100.1	101.0	100.6	101.2

Atomic proportions based on three atoms

Fe	.98	.98	1.00	.98	1.00	1.00	1.02
Co	---	---	.01	---	.01	---	---
Ni	---	---	.01	---	.01	---	.06
Sum	.98	.98	1.02	.98	1.02	1.00	1.08
S	2.01	2.01	2.00	2.02	2.00	2.01	1.98

Abbreviations: NA=not analysed; ND=not detected; po=pyrrhotite; pn=pentlandite; cp=chalcopyrite; serp=serpentine. Analyses 1-5 at 205.3m (disseminated, veined), 6-20 at 239.5m (vein), and 21 at 271.2m (veined). See Appendix B for lower limits of detection.

Assemblages in contact;

1 - 3 po/pn	10 - 11 cp
4 - po/serp	12 - po
5 - 9 po/pn	13 - 21 po/pn

Appendix C-4. Electron microprobe analyses of Cobaltite - CoAsS
from core hole 160-224, Donaldson West deposit.

Smpl #	1	2	3
Co	16.3	17.3	16.8
Ni	14.8	13.7	13.0
Fe	4.44	4.57	4.41
Sb	0.06	ND	ND
As	44.7	44.5	44.6
S	18.8	18.9	18.8
Total	99.10	99.05	97.66

Atomic proportions based on three atoms

Co	.46	.49	.49
Ni	.42	.39	.38
Fe	.13	.14	.14
SUM	1.01	1.02	1.01
As	1.00	.99	1.01
S	.98	.98	1.00

Abbreviations: NA=not analysed; ND=not detected; po=pyrrhotite; pn=pentlandite; py=pyrite; serp=serpentine; sud=sudburyite; tes=testibiopalladite; hes=hessite. All analyses from 239.5m (vein). Pd, Pt, Te, and Ag sought for. See Appendix B for lower limits of detection.

Assemblages in contact;
1 -3 po/pn/py/serp/sud/tes/hes

Appendix D-1. Electron microprobe analyses of Pyrrhotite - M_7S_8 from core hole 160-225, Donaldson Surface deposit.

Smpl #	1	2	3	4	5	6	7
S	41.3	39.0	39.0	39.0	39.4	38.3	39.2
Fe	57.7	60.3	60.2	60.0	59.9	59.3	59.3
Ni	.39	.44	.44	.33	.36	.89	.82
Co	.04	.09	.08	.09	.08	.08	.10
Cu	ND	ND	ND	ND	ND	ND	ND
As	ND	ND	.12	ND	ND	ND	ND
Total	99.45	99.83	99.84	99.42	99.74	98.57	99.42

$M_{6.44}S_8$ $M_{7.17}S_8$ $M_{7.17}S_8$ $M_{7.10}S_8$ $M_{7.03}S_8$ $M_{7.21}S_8$ $M_{7.08}S_8$

Smpl #	8	9	10	11	12	13	14
S	39.0	39.0	40.2	39.9	39.6	39.6	39.8
Fe	59.3	59.0	58.0	60.4	60.5	60.0	60.3
Ni	.85	.80	.56	.37	.30	.33	.42
Co	.09	.08	.05	.19	.17	.19	.16
Cu	ND	ND	.12	.05	.06	.05	.05
As	ND	ND	ND	NA	NA	NA	NA
Total	99.24	98.88	99.00	100.9	100.6	100.2	100.7

$M_{7.07}S_8$ $M_{7.04}S_8$ $M_{6.71}S_8$ $M_{7.01}S_8$ $M_{7.04}S_8$ $M_{7.01}S_8$ $M_{7.01}S_8$

Appendix D-1. cont.

Smp1 #	15	16	17	18	19	20	21
S	39.1	39.4	39.6	39.7	39.7	40.0	39.9
Fe	61.5	60.5	60.0	60.4	60.3	60.2	60.0
Ni	.47	.33	.29	.13	.43	.36	.39
Co	.15	.16	.15	.14	.14	.13	.12
Cu	.04	ND	ND	NA	NA	NA	NA
As	ND	ND	ND	ND	ND	ND	ND
Total	101.3	100.4	100.0	100.4	100.6	100.7	100.4

M_{7.30S} M_{7.12S} M_{7.01S} M_{7.02S} M_{7.04S} M_{6.75S} M_{6.76S}

Smp1 #	22	23	24	25
S	39.8	39.8	39.7	39.8
Fe	60.0	60.0	59.8	59.5
Ni	.42	.45	.53	.44
Co	.10	.09	.12	.10
Cu	NA	NA	NA	NA
As	ND	ND	ND	ND
Total	101.3	100.4	100.0	99.84

M_{6.75S} M_{6.77S} M_{6.78S} M_{6.79S}

Appendix D-1 cont.

Abbreviations: NA=not analysed; ND=not detected; pn=pentlandite; cp=chalcopyrite; py=pyrite; cob=cobaltite; ger=gersdorffite; nic=nickeline; viol=violarite. Analyses 1 at 15.2m (net-textured); 2-5 at 18.2m (vein); 6-9 at 22.4m (vein); 10 at 25.8m (massive sulfide); 11-15 at 28.0m (sulfide breccia); 16-17 at 28.6m (sulfide breccia); 18-21 at 32.6m (stringer); and 22-25 at 27.0m (massive sulfide). All analyses of separate grains (n=1). See Appendix B for lower limits of detection.

Assemblages in contact;

- 1 - pn
- 2 - 5 pn/cp
- 6 - 9 pn
- 10 - pn/cp
- 11 - 17 pn/py/ger/nic
- 18 - 21 py/cp
- 22 - 25 pn/cp/viol

Appendix D-2. Electron microprobe analyses of Pentlandite - M_2S_2
from core hole 160-225, Donaldson Surface deposit.

Smpl #	1	2	3	4	5	6	7
S	33.4	33.3	33.3	33.8	33.8	34.7	33.6
Fe	28.0	28.0	28.6	28.3	28.5	29.4	30.0
Ni	37.2	36.8	37.2	37.0	37.0	34.0	35.9
Co	.86	.82	.89	.77	.83	.65	.49
Cu	NA	NA	NA	NA	NA	ND	.07
As	ND	ND	ND	ND	ND	ND	ND
Pd	NA	NA	NA	NA	NA	NA	ND
Sb	NA	NA	NA	NA	NA	NA	ND
Rh	NA	NA	NA	NA	NA	NA	ND
Pt	NA	NA	NA	NA	NA	NA	ND
Total	99.46	98.92	99.92	99.87	100.1	98.76	100.0

$M_{0.84}S_2$ $M_{0.81}S_2$ $M_{0.78}S_2$ $M_{0.75}S_2$ $M_{0.77}S_2$ $M_{0.77}S_2$ $M_{0.77}S_2$ $M_{0.84}S_2$

Smpl #	8	9	10	11	12	13	14
S	34.0	34.0	33.1	33.3	35.8	33.2	33.5
Fe	30.2	30.4	28.7	28.2	28.4	28.1	30.1
Ni	35.9	35.4	36.1	35.1	36.4	36.0	35.9
Co	.51	.48	.79	.76	.76	.70	.14
Cu	.07	ND	.05	.06	.05	.05	ND
As	.05	.14	.09	.13	ND	.15	NA
Pd	ND	ND	NA	NA	NA	NA	NA
Sb	ND	ND	NA	NA	NA	NA	NA
Rh	ND	ND	NA	NA	NA	NA	NA
Pt	ND	ND	NA	NA	NA	NA	NA
Total	100.7	100.4	98.83	97.55	101.3	98.20	99.64

$M_{0.74}S_2$ $M_{0.73}S_2$ $M_{0.67}S_2$ $M_{0.61}S_2$ $M_{0.17}S_2$ $M_{0.75}S_2$ $M_{0.82}S_2$

Appendix D-2 cont.

Smpl #	15	16	17	18	19	20	21
S	33.4	33.4	33.1	33.0	33.5	33.0	33.3
Fe	30.1	30.1	31.2	30.6	30.8	30.9	30.6
Ni	36.3	36.3	36.1	35.4	35.4	35.3	35.6
Co	.17	.14	.13	.07	.07	.08	.07
Cu	ND	ND	ND	NA	NA	NA	NA
As	NA	NA	NA	ND	ND	.16	.13
Pd	NA	NA	NA	ND	ND	ND	ND
Sb	NA	NA	NA	ND	ND	ND	ND
Rh	NA	NA	NA	ND	ND	ND	ND
Pt	NA	NA	NA	ND	ND	ND	ND
Total	99.97	99.95	100.5	99.07	99.82	99.44	99.70

M_{0.11S} M_{0.11S} M_{0.07S} M_{0.14S} M_{0.07S} M_{0.08S} M_{0.07S}

Smpl #	22	23	24	25	26	27	28
S	33.3	32.9	33.2	33.3	33.0	32.8	33.0
Fe	30.8	30.7	30.7	30.5	30.7	29.6	29.7
Ni	35.6	35.4	35.8	35.7	35.6	36.4	36.4
Co	.05	.07	.13	.13	.13	.81	.81
Cu	NA	NA	ND	ND	ND	NA	NA
As	ND	ND	NA	NA	NA	ND	ND
Pd	ND	ND	NA	NA	NA	ND	ND
Sb	ND	ND	NA	NA	NA	ND	ND
Rh	ND	ND	NA	NA	NA	ND	.20
Pt	ND	ND	NA	NA	NA	ND	ND
Total	99.75	99.11	99.83	99.63	99.43	99.67	100.1

M_{0.11S} M_{0.07S} M_{0.13S} M_{0.13S} M_{0.13S} M_{0.81S} M_{0.81S}

Appendix D-2 cont.

Sapl #	29	30	31	32	33	34
B	33.2	33.4	33.2	33.5	33.2	33.0
Fe	29.6	29.4	29.0	29.3	29.4	29.4
Ni	36.0	36.0	36.3	36.3	36.3	36.3
Co	.83	.83	.78	.77	.72	.76
Cu	NA	NA	NA	NA	NA	NA
As	ND	ND	.06	ND	ND	ND
Pd	ND	ND	ND	ND	ND	ND
Sb	ND	ND	ND	ND	ND	ND
Rh	ND	ND	ND	ND	ND	ND
Pt	ND	ND	ND	ND	ND	ND
Total	99.63	99.67	99.40	99.97	99.65	99.48

Mo₁₋₂S₂ Mo₁₋₃S₂ Mo₁₋₄S₂ Mo₁₋₅S₂ Mo₁₋₆S₂ Mo₁₋₇S₂

Abbreviations: NA=not analysed; ND=not detected; po=pyrrhotite; cp=chalcopyrite; py=pyrite; viol=violarite; cob=cobaltite; ger=gersdorffite; and nic=nickeline. Analyses 1-5 at 13.2m (net to reverse net-texture); 6-9 at 18.2m (vein); 10-13 at 22.4m (vein), 14-23 at 28.0m (sulfide breccia), 24-26 at 28.6m (sulfide breccia), 27-34 at 25.8m (massive sulfide). All analyses of separate grains (n=1). See Appendix B for lower limits of detection.

Assemblages in contact;

1 - 2 (sulfide bleb) po	20 - po/py/ger/nic
3 - (sulfide bleb) po	21 - po/py/ger/nic/cp
4 - 5 (net-texture) po	22 - " "
6 - 9 po/cp	23 - " "
10 - 13 po/cp	24 - po/py/ger
14 - po/py	25 - "
15 - "	26 - "
16 - py/ger	27 - 28 po/py/cp
17 - po/py/ger/nic	29 - 30 po/cp
18 - 19 po/py	31 - 32 "
	33 - 34 po

Appendix D-3. Electron microprobe analyses of Chalcopyrite - CuFeS_2
from core hole 160-225, Donaldson Surface deposit.

Smpl #	1	2	3	4	5	6	7
Cu	34.6	34.4	34.4	34.3	34.4	34.4	34.5
Fe	30.6	30.1	30.3	30.4	30.4	30.4	30.5
Co	.06	.05	.07	.06	.07	.07	.06
As	ND	ND	.11	ND	ND	ND	.13
Pd	.06	ND	ND	ND	ND	ND	ND
S	34.2	34.7	34.3	35.0	34.9	34.7	34.9
Total	99.52	99.25	99.18	99.76	99.71	99.77	100.0

Atomic proportions based on four atoms

Cu	1.00	1.00	1.00	.99	1.00	.99	1.00
Fe	1.01	1.00	1.00	1.00	1.00	1.01	1.00
S	1.97	2.00	1.98	2.00	2.00	1.99	1.99

4 of /de 4

MicroD

Appendix D-3 cont.

Smpl #	8	9	10	11	12
Cu	34.2	33.9	34.3	34.2	33.4
Fe	30.5	30.1	30.6	30.5	30.0
Co	.07	.06	.08	.06	ND
As	ND	ND	.22	ND	ND
Pd	ND	ND	ND	ND	ND
S	34.8	35.0	34.6	34.8	36.1
Total	99.57	99.06	99.58	99.56	99.50

Atomic proportions based on four atoms

Cu	.99	.98	.99	.99	.96
Fe	1.00	.99	1.01	1.00	.98
S	2.00	2.02	1.99	2.00	2.06

Abbreviations: NA=not analysed; ND=not detected; po=pyrrhotite; cp=chalcopyrite; py=pyrite; serp=serpentine; cob=cobaltite; and nic=nickeline. Analyses 1-7 at 32.6m (stringer), 8-11 at 27.0m (massive sulfide), and 12 at 25.8m (massive sulfide). N=1 for all analyses. Ag, Te, and Sb sought for but not detected. See Appendix B for lower limits of detection.

Assemblages in contact;

1 - cp	7 - po/pn
2 - po/pn/py	8 - po
3 - serp	9 - po
4 - cp	10 - po/pn
5 - serp	11 - serp
6 - po/pn	12 - po/pn

Appendix D-4. Electron microprobe analyses of Pyrite - FeS_2
from core hole 160-225, Donaldson Surface deposit.

Smpl #	sulfide breccia					sulfide breccia		
	core	rim	rim	core	rim			
	1	2	3	4	5	6	7	8
S	53.1	53.1	53.7	53.6	52.8	53.0	53.2	53.4
Fe	45.5	45.8	45.8	45.6	46.7	46.0	46.2	46.2
Ni	.34	.06	ND	.40	.13	.15	ND	.07
Co	.46	.65	.60	.64	.73	.24	.39	.26
Cu	.06	.13	.05	.03	ND	.03	.04	ND
As	NA	NA	NA	NA	NA	NA	NA	NA
Total	99.46	99.74	100.2	100.3	100.4	99.42	99.83	99.94

Atomic proportions based on three atoms

Fe	.99	.99	.99	.99	1.02	.99	.99	.99
Ni	---	---	---	.01	---	---	---	---
Sum	.99	.99	.99	1.00	1.02	.99	.99	.99
S	2.01	1.98	2.01	2.01	1.98	1.98	1.98	2.01

Appendix D-4 cont.

Smpl #	footwall			stringer		
	9	10	11	12	13	14
S	52.7	52.4	52.6	53.0	52.4	52.2
Fe	46.3	46.5	46.6	46.4	46.3	46.4
Ni	.72	.44	.45	.62	.44	.72
Co	.07	.07	.09	.09	.09	.10
Cu	NA	NA	NA	NA	NA	NA
As	ND	ND	ND	ND	ND	ND
Total	99.79	99.41	99.74	100.1	99.23	99.42

Atomic proportions based on three atoms

Fe	1.00	1.01	1.01	1.00	1.01	1.01
Ni	.02	.01	.01	.01	.01	.01
Sum	1.02	1.02	1.02	1.01	1.02	1.02
S	1.98	1.98	1.98	1.99	1.98	1.98

Abbreviations: NA=not analysed; ND=not detected; po=pyrrhotite; pn=pentlandite; cp=chalcopyrite; cob=cobaltite; and nic=nickeline. Analyses 1-5 at 28.0m (sulfide breccia); 6-8 at 28.6m (sulfide breccia); and 9-14 at 32.6m (stringer). NA for all analyses. See Appendix B for lower limits of detection.

Assemblages in contact:

1 - po/pn/cp	5 - po/pn	9 - po/pn
2 - " "	6 - " "	10 - po/pn
3 - po/pn	7 - " "	11 - 12 po/pn/cp
4 - " "	8 - " "	13 - 14 " "

Appendix D-5. Electron microprobe analyses of Cobaltite - CoAsS
and Gersdorffite - NiAsS from core hole 160-225,
Donaldson Surface deposit.

Sapl #	cobaltite							ger	cobaltite	
	1	2	3	4	5	6	7	8	9	10
Co	19.4	20.0	17.0	16.4	18.8	15.9	15.2	9.28	18.0	17.6
Fe	5.62	5.15	6.95	10.4	6.95	8.39	7.75	3.04	4.17	3.94
Ni	9.64	9.84	11.6	10.4	10.2	11.8	12.4	22.8	12.8	13.5
Pd	NA	NA	NA	NA	NA	NA	NA	ND	ND	ND
Sb	NA	NA	NA	NA	NA	NA	NA	.65	ND	.16
As	43.0	43.8	44.0	40.4	42.3	43.2	44.1	44.8	44.5	44.6
S	19.5	19.4	20.3	19.7	19.6	22.0	19.0	19.4	19.5	19.5
Total	97.16	98.19	99.85	97.30	97.85	101.3	98.45	99.97	99.02	99.33

Atomic proportions based on three atoms

Co	.56	.57	.47	.46	.53	.43	.43	.26	.51	.50
Fe	.17	.15	.20	.31	.21	.24	.23	.09	.12	.12
Ni	.27	.28	.32	.30	.29	.32	.35	.64	.36	.38
Sum	1.00	1.00	0.99	1.07	1.03	.99	1.01	.99	.99	1.00
As	.97	.98	0.96	.90	.95	.92	.99	.99	.99	.99
Sb	---	---	---	---	---	---	---	.01	---	---
Sum	.97	.98	0.96	.90	.95	.92	.99	1.00	.99	.99
S	1.03	1.01	1.04	1.03	1.02	1.09	.99	1.00	1.01	1.01

Appendix D-5 cont.

gersdorffite

Sapl #	11	12	13	14	15	16	17	18	19
Co	10.6	10.7	10.7	11.7	9.88	11.6	10.7	9.97	8.40
Fe	3.04	3.44	3.35	4.87	3.11	4.45	4.00	3.62	4.37
Ni	21.3	20.4	20.4	19.1	22.8	19.8	21.0	22.1	24.2
Pd	ND	ND	ND	ND	ND	ND	ND	ND	ND
Sb	ND	.38	.55	.61	.48	.19	.20	.28	.62
As	44.2	44.0	43.9	46.0	45.7	44.5	43.9	44.6	40.9
S	19.6	19.5	19.6	19.5	19.2	19.3	19.5	19.5	21.0
Total	98.74	98.42	98.60	101.8	101.2	99.85	99.30	100.0	99.49

Atomic proportions based on three atoms

Co	.30	.31	.30	.32	.28	.32	.30	.28	.23
Fe	.09	.10	.10	.14	.09	.13	.12	.11	.13
Ni	.60	.58	.58	.53	.64	.45	.59	.62	.67
Sum	.99	.99	.98	.99	1.01	1.01	1.01	1.01	1.03
As	.98	.98	.98	1.00	1.00	.98	.97	.98	.89
Sb	---	---	.01	.01	---	---	---	---	.01
Sum	.98	.98	.99	1.02	1.00	.98	.97	.98	.90
S	1.02	1.02	1.02	.99	.98	1.01	1.01	1.00	1.07

Abbreviations: NA=not analysed; ND=not detected; po=pyrrhotite; py=pyrite; pn=pentlandite; cp=chalcopyrite; viol=violarite; nic=nickeline. Analyses 1-2 at 9.2m (net-textured), n=1 and 2; 3, 4, and 5 at 25.8m (massive sulfide), n=2, 1, and 1; 6-7 at 27.0m (massive sulfide), n=1 and 2; 8, 9, 10, 11, 12, and 13 at 28.0m (sulfide breccia), n=1 for all; and analyses 14-19 at 28.6m (sulfide breccia), n=1 each. Analyses 14 and 15 rim and core of same grain, and 18 and 19 rim and core analyses of one grain. See Appendix B for lower limits of detection.

Assemblages in contact with analysed grains:

1 - po/pn	5 - po	9 - po/cp	13 - po
2 - pn	6 - po	10 - py/po	14 - 19 po/py/pn/yiol
3 - pn/po/cp	7 - po	11 - po/pn/nic	
4 - po/cp	8 - po/cp	12 - po	

Appendix D-6. Electron microprobe analyses of Nickeline - NiAs from core hole 160-225, Donaldson Surface deposit.

Sep#	0	1	2	3	4	5	6	7	8	9	10
As		54.2	54.2	54.5	54.6	54.2	54.6	54.7	54.9	54.8	55.0
Ni		43.4	43.3	43.5	43.6	43.8	43.8	43.9	44.0	44.2	44.0
Fe		.08	.10	.18	.06	.05	.03	.05	.06	.11	.05
Co		.11	.11	.07	.16	.15	.13	.08	.07	.05	.09
Pd		ND	ND	ND	.05	ND	.06	ND	ND	ND	.06
Te		ND	ND	ND	ND	ND	ND	ND	.06	.05	ND
Sb		.53	.46	.42	.59	.47	.50	.55	.41	.50	.50
Total		98.37	98.22	98.73	99.11	98.76	99.16	99.32	99.51	99.70	99.72

Atomic proportions based on two atoms

Ni	1.01	1.00	1.00	1.00	1.02	1.00	1.01	1.01	1.01	1.01
As	.98	.98	.99	.98	.98	.98	.98	.98	.98	.98
Sb	.01	.01	---	.01	.01	.01	.01	---	.01	.01
Sua	.99	.99	.99	.99	.99	.99	.99	.98	.99	.99

Abbreviations: NA=not analysed; ND=not detected; po=pyrrhotite, pn=pentlandite, cp=chalcopyrite, py=pyrite, viol=violarite, cob=cobaltite; ger=gersdorffite; serp=serpentine; PGM=unidentified platinum-group mineral. Analyses 1 to 6 at 28.0m (sulfide breccia) and 7 to 10 at 28.6m (sulfide breccia). N=1 for all analyses. Pt sought but not detected. See Appendix B for lower limits of detection.

Assemblages in contact:

1 - po/pn/ger	7 - po/pn/ger/serp
2 - " "	8 - " "
3 - po/ger/viol/PGM	9 - po/py/pn
4 - " "	10 - " "
5 - po/ger	
6 - " "	

Depth (m)	Sulf Text	Size (microns)	Crystal Habit	Grain Location	Comments
244.2	NET	20	subhedral-irregular	po/cob/serp	intergrown with cob
244.5	NET	8x10 1x1	subhedral-irregular subhedral-equant	po/serp in cob	appears to overgrow serp tiny grain in cob
246.8	VND	4-10x40	subhedral-chain	po/cp/serp	amoeboid chain, overgrows serp cp inclusions
248.7	NET	10-35x150	subhedral-chain	po/pn/cp/serp	irregular chain, follows grain boundaries and does not appear to overgrow serp
251.2	VND	40x60	subhedral-irregular	pn/cp/serp	amoeboid chain, cp inclusion
253.5	VEN	10	euhedral-equant	in po	octahedral form
263.2	RN	6x10 2x5	subhedral-tabular subhedral-irregular	po/serp po/serp	
273.5	MSX	25 5x7 10x15 10	subhedral-subequant euhedral-tabular subhedral-subequant	po/pn po/po "	
274.0	MSX	two-7 12 3x3 5x12 10 20	anhedral-subequant euhedral-equant subhedral-tabular anhedral-subequant anhedral-subequant	in po po/po in po " "	rhombohedral form rounded form

Abbreviations: Sulf Text=sulfide texture; DIS=disseminated; NET=net-textured; NRN=net-textured to reverse net-textured; RN=reverse net-textured; MSX=massive sulfide; VEN=vein; VND=veined; po=pyrrhotite; pn=pentlandite; cp=chalcopyrite, py=pyrite; cob=cobaltite; si=sphalerite; serp=serpentine; PGM=platinum-group mineral; PM=precious metal mineral; sud=sudburyite, tes=testibiopalladite; unk=unknown (Pd₃Sb₂Te₂); aer=aerenskyite; ele=electrum; hes=hessite; mel=melonite.

Depth (m)	Sulf Text	Size (microns)	Crystal Habit	Grain Location	Comments
198.2	DIS	10x11	subhedral-equant	po/serp/P6M	intergrown with tes?
205.3	DIS	25x30	subhedral-subequant	po/pn	
212.0	DIS	3x5	subhedral-subequant	in pn	idiomorphic
239.5	VEN	15x35	subhedral-tabular	P6M/PM	intergrown with tes and hes
	"	two-5x10	"	"	"
	"	15x20	"	po/cob/P6M/PM	intergrown with cob, tes, and hes
	"	20x30	"	"	"
	"	20x40	"	"	"
246.8	VND	6x20	subhedral-tabular	pn/cp/serp	
253.5	VEN	45x60	anhedral-tabular	pn/pn	round form
	"	60x65	anhedral-subequant	po/po	"
	"	2x3	subhedral-subequant	pn/pn	"
	"	5x10	subhedral-tabular	pn/cp	"
254.5	VND	35x60	subhedral-irregular	po/cp/serp/P6M	intergrown with tes
	"	10x15	subhedral-subequant	serp	free grain
	"	7x11	euhedral-angular	"	"
	"	20x30	subhedral-subequant	po/serp/P6M	intergrown with tes
	"	15x25	subhedral-irregular	po/serp	"
257.6	VND	3x12	subhedral-irregular	po/cp	
	"	2x5	subhedral-tabular	po/P6M	intergrown with unk
	"	1x11	"	"	"
258.5	VND	15x60	subhedral-irregular	cp/P6M/PM	intergrown with tes and hes
260.6	NRN	5x10	subhedral-tabular	po/pn/serp	

Abbreviations: Sulf Text=sulfide texture; DIS=disseminated; NET=net-textured; NRN=net-textured to reverse net-textured; RM=reverse net-textured; MSI=massive sulfide; VEN=vein; VND=veined; po=pyrrhotite; pn=pentlandite; cp=chalcopyrite; py=pyrite; sl=sphalerite; cob=cobaltite; serp=serpentine; P6M=platinum-group mineral; PM=precious metal mineral; spr=sperrylite; tes=testibiopalladite; unk=unknown ($\text{Pd}_3\text{Sb}_2\text{Te}_2$); ser=serpentine; ele=electrum; hes=hessite; mel=melonite.

Appendix E-3. Mineral Data Core Hole 160-224 (Donaldson West) Testibiopalladite - PdSbTe

Depth (m)	Sulf Text	Size (microns)	Crystal Habit	Grain Location	Comments
198.2	DIS	2x3	anhedral-equant	po/serp/PGM	intergrown with sud?
239.5	VEN	20x28	subhedral-irregular	in pn	
	"	3x15	subhedral-tabular	in pn	
	"	12x12	anhedral-equant	in pn	round form
	"	2x10	subhedral-tabular	in po	idiomorphic
	"	2x10	"	in cp	"
	"	3x8	"	"	"
	"	two-3x6	"	"	"
	"	4x10	"	"	"
	"	3x15	subhedral-tabular	po/cp	
	"	two-30x100	"	po/cob/PGM/PM	intergrown with cob, sud, and hes
246.8	VND	45x250	anhedral-tabular	in serp	free grain
	"	60x200	"	po/serp	
	"	30x40	subhedral-subequant	"	
251.2	NRN	2x3	subhedral-equant	po/serp	
253.5	VEN	6x10	anhedral-tabular	pn/serp	
	"	4x5	subhedral-tabular	in pn	
	"	2x5	"	pn/cp/cob	idiomorphic
	"	2x6	anhedral-irregular	"	"
254.5	VND	4x7	subhedral-tabular	in pn	
	"	35x60	anhedral-irregular	po/cp/serp/PGM	intergrown with sud
	"	15x25	subhedral-tabular	po/serp	
	"	30x30	"	po/cp/serp	cp inclusion
258.5	VEN	3x25	subhedral-tabular	cp/PGM	intergrown with sud and hes
262.7	RN	20x35	subhedral-tabular	po/pn/serp	
	"	20x25	subhedral-subequant	po/pn/serp	
	"	20x20	"	"	
271.2	VND	50x100	subhedral-tabular		
	"	60x110	subhedral-irregular	cp	
	"	40x80	"	"	
	"	90x90	subhedral-subequant	po	
	"	20	subhedral-irregular	"	
	"	90	"	"	
	"	100x200	subhedral-tabular		
	"	40x50	anhedral-irregular	pn	
	"	100x150	subhedral-irregular	"	

Abbreviations: Sulf Text=sulfide texture; DIS=disseminated; NET=net-textured; NRN=net-textured to reverse net-textured; RN=reverse net-textured; MSI=massive sulfide; VEN=vein; VND=veined; po=pyrrhotite; pn=pentlandite; cp=chalcopyrite, pyrrhotite; sl=sphalerite; cob=cobaltite; serp=serpentine; PGM=platinum-group mineral; PM=precious metal mineral; sud=sudburyite, tes=testibiopalladite; unk=unknown ($Pd_{25}Sb_{27}Te_{22}$); ser=serpentine; ele=electrum; hes=hessite; mel=melonite. Grains at 271.2m from heavy mineral liquid separate.

Appendix E-4.

Mineral Data Core Hole 160-224 (Donaldson West)

Unknown - $\text{Pd}_3\text{Sb}_2\text{Te}_2$

Depth (m)	Sulf Text	Size (microns)	Crystal Habit	Grain Location	Comments
253.5	VEN	5x10 1x3 4x9	subhedral-tabular " "	py/cp/PM in po "	intergrown with ele
257.6	VND	20x25 20x50	subhedral-irregular subhedral-tabular	po/pn/cp/serp po/serp/PSM	cp inclusion intergrown with sud

Appendix E-5.

Mineral Data Core Hole 160-224 (Donaldson West)

Merenskyite - PdTe_2

Depth (m)	Sulf Text	Size (microns)	Crystal Habit	Grain Location	Comments
258.5	VEN	2x5 8x20	euhedral-tabular subhedral-irregular	in cp "	low total
271.2	VND	40x50	subhedral-irregular	"	low total

Abbreviations: Sulf Text=sulfide texture; DIS=disseminated; NET=net-textured; WRN=net-textured to reverse net-textured; RN=reverse net-textured; MSI=massive sulfide; VEN=vein; VND=veined; po=pyrrhotite; pn=pentlandite; cp=chalcopyrite, py=pyrite; sl=sphalerite; cob=cobaltite; serp=serpentine; PSM=platinum-group mineral; PM=precious metal mineral; sud=sudburyite, tes=testibiopalladite; unk=unknown ($\text{Pd}_3\text{Sb}_2\text{Te}_2$); mer=merenskyite; hes=hessite; ele=electrum; mel=melonite. Grain at 271.2m from heavy mineral liquid separate.

Appendix E-6.

Mineral Data Core Hole 160-224 (Donaldson West)

Electrum - AgAu

Depth (m)	Sulf Text	Size (microns)	Crystal Habit	Grain Location	Comments
239.5	VEN	16	anhedral-equant	in cp	
	"	15x22	anhedral-irregular	cp/py	
	"	2x3	subhedral-irregular	"	
246.8	VND	two-10x30	anhedral-tabular	pn/pn	
253.5	VEN	20x30	anhedral-irregular	cp/py/PGM	intergrown with unk
	"	25x35	"	cp/py/sl	

Appendix E-7.

Mineral Data Core Hole 160-224 (Donaldson West)

Hessite - Ag₂Te

Depth (m)	Sulf Text	Size (microns)	Crystal Habit	Grain Location	Comments
239.5	VEN	50x60	subhedral-irregular	po/py/cob/PGM/serp	intergrown with tes, sud, cob, serp, and calcite
	"	20x30	"	"	intergrown with tes, sud, cob, serp, and calcite
	"	2x5	subhedral-tabular	pn/PGM	intergrown with sud
258.5	VEN	15x60	subhedral-irregular	cp/PGM	intergrown with tes and sud

Abbreviations: Sulf Text=sulfide texture; DIS=disseminated; NET=net-textured; NRN=net-textured to reverse net-textured; RN=reverse net-textured; MSI=massive sulfide; VEN=vein; VND=veined; po=pyrrhotite; pn=pentlandite; cp=chalcopyrite; py=pyrite; sl=sphalerite; cob=cobaltite; serp=serpentine; PGM=platinum-group mineral; PM=precious metal mineral; sud=sudburyite; tes=testibiopalladite; unk=unknown (Pd₃Sb₂Te₂); ser=serpinskyite; hes=hessite; sel=selonite.

Depth (m)	Sulf Text	Size (microns)	Crystal Habit	Grain Location	Comments
239.5	VEN	15x50	subhedral-tabular	po/po	
	"	4x15	euhedral-tabular	in po	
	"	2x5	anhedral-tabular	in pn	
258.5	VEN	6x12	subhedral-tabular	in po	
	"	11x22	"	"	
	"	10x15	subhedral-irregular	po/cp/serp	
	"	4x20	subhedral-tabular	cp/sl	
	"	8x12	subhedral-irregular	"	
273.5	MSX	5	anhedral-equant	in po	round form
	"	3x5	euhedral-angular	in po	triangular form
	"	10	subhedral-equant	in po	round form
	"	15x30	subhedral-tabular	in po	
	"	10x30	"	po/serp	
	"	9x10	subhedral-subequant	in po	
	"	4x9	subhedral-tabular	po/po	
	"	15	euhedral-equant	po/po	
	"	20x30	anhedral-irregular	po/po	
274.05	MSX	20	anhedral-subequant	in pn	
	"	5x12	subhedral-tabular	po/po	
	"	5	"	po/serp	
	"	three-5x6	anhedral-subequant	in po	
	"	3	anhedral-equant	in po	round form
	"	2x10	subhedral-tabular	in po	
	"	7x	euhedral-equant	in po	hexagonal form
	"	10x30	euhedral-angular	in po	triangular form
	"	5x10	euhedral-tabular	in po	
	"	15	euhedral-equant	po/po/serp	rhombohedral form
	"	5x10	subhedral-tabular	in po	
	"	20x30	subhedral-irregular	in po	
	"	5x16	subhedral-tabular	in po	
	"	10x18	"	in po	

Abbreviations: Sulf Text=sulfide texture; DIS=disseminated; NET=net-textured; NRN=net-textured to reverse net-textured; RN=reverse net-textured; MSX=massive sulfide; VEN=vein; VND=veined; po=pyrrhotite; pn=pentlandite; cp=chalcopyrite, py=pyrite; sl=sphalerite; cob=cobaltite; serp=serpentine; GM=platinum-group mineral; PM=precious metal mineral; sud=sudburyite; tes=testibiopalladite; unk=unknown ($\text{TPd}_3\text{Sb}_2\text{Te}_2$); ser=serrenskyite; hes=hessite; mel=melonite.

Depth (m)	Sulf Text	Size (microns)	Crystal Habit	Grain Location	Comments
205.3	DIS	30x50	anhedral-tabular	po/pn/cp/serp	round form, cp inclusion
	"	25x50	"	pn/serp	round form
	"	20x30	subhedral-tabular	"	
	"	5x15	anhedral-irregular	in pn	
	"	two-3x5	subhedral-irregular	"	

Abbreviations: Sulf Text=sulfide texture; DIS=disseminated; NET=net-textured; NRN=net-textured to reverse net-textured; RN=reverse net-textured; MSX=massive sulfide; VEN=vein; VND=veined; po=pyrrhotite; pn=pentlandite; cp=chalcopyrite; py=pyrite; sl=sphalerite; cob=cobaltite; serp=serpentine; PGM=platinum-group mineral; PM=precious metal mineral; sud=sudburyite; tes=testibiopalladite; unk=unknown ($\text{Pd}_3\text{Sb}_2\text{Te}_2$); ser=serenskyite; hes=hessite; mel=melonite.

Appendix F-1. Electron microprobe analyses of Sperrylite - PtAs₂ from core hole 160-224 - Donaldson West deposit.

Sepi #	1	2	3	4	5	6
Pt	51.5	50.8	53.3	51.8	55.6	56.8
As	39.9	39.8	39.9	39.0	42.7	42.3
Rh	0.30	0.21	0.15	0.14	ND	ND
Sb	0.33	0.23	0.22	0.15	0.29	0.26
Total	92.03	91.04	93.57	91.09	98.67	99.52

Atomic proportions based on three atoms

Pt	.99	.99	1.02	1.01	1.00	1.02
Rh	.01	.01	.01	.01	---	---
Sum	1.00	1.00	1.03	1.02	1.00	1.02
As	1.99	2.00	1.97	1.98	1.99	1.97
Sb	.01	.01	.01	.01	.01	.01
Sum	2.00	2.01	1.98	1.99	2.00	1.98

Abbreviations: NA=not analysed; ND=not detected; po=pyrrhotite; pn=pentlandite; cp=chalcopyrite; py=pyrite; cob=cobaltite; sl=sphalerite; serp=serpentine; PGM=platinum-group mineral; PM=precious metal mineral; sud=sudburyite; tes=testibiopalladite; unk=unknown (Pd₃Sb₂Te₂); aer=aerenskyite; ele=electrum; hes=hessite; mel=melonite. Analyses 1-4 at 248.7m (net-textured) and 5-6 at 251.2m (veined). Pd, Ir, Os, and Ru sought for. See Appendix B for lower limits of detection.

Assemblages in contact:

- 1 - 2 po/cp/serp
- 3 - 4 po/pn/serp
- 5 - 6 pn/cp

Appendix F-2.

Electron microprobe analyses of Sudburyite - PdSb from core hole
160-224 - Donaldson West deposit.

Sapl #	1	2	3	4	5	6
Pd	46.5	46.4	46.6	46.1	41.8	45.8
Ni	0.12	0.15	0.21	0.35	1.87	0.29
Ag	0.18	0.20	0.26	0.22	0.53	0.30
Pb	NA	NA	NA	NA	0.54	ND
Sb	50.5	50.4	49.0	49.7	51.3	53.1
Te	2.01	2.00	3.47	3.29	2.20	2.03
Bi	1.20	1.12	0.89	1.10	1.71	2.31
As	0.10	0.07	ND	0.07	NA	NA
Total	100.6	100.3	100.4	100.8	99.95	103.8

Atomic proportions based on two atoms

Pd	1.00	1.00	1.00	.98	.89	.95
Ni	---	.01	.01	.01	.07	.01
Ag	---	---	.01	---	.01	.01
Pb	---	---	---	---	.01	---
Sum	1.00	1.01	1.02	.99	.98	.97
Sb	.94	.94	.92	.93	.96	.97
Te	.04	.04	.06	.06	.04	.04
Bi	.01	.01	.01	.01	.02	.02
Sum	.99	.99	.99	1.00	1.02	1.03

Abbreviations: NA=not analysed; ND=not detected; po=pyrrhotite; pn=pentlandite; cp=chalcopyrite; py=pyrite; cob=cobaltite; sl=sphalerite; serp=serpentine; PGM=platinum-group mineral; PM=precious metal mineral; sud=sudburyite; tes=testibiopalladite; unk=unknown ($\text{Pd}_2\text{Sb}_2\text{Te}_2$); aer=aerenskyite; ele=electrum; hes=hessite; sel=selenite. Analyses 1-4 at 253.5m (vein) and 5-6 at 254.5m (veined). Pt sought for. See Appendix B for lower limits of detection.

Assemblages in contact:

- 1 - 2 po
- 3 - 4 pn/cp
- 5 - 6 po/serp/tes

Appendix F-3.

Electron microprobe analyses of Testibiopalladite - PdSbTe from core hole 160-224 - Donaldson West deposit.

Sapl #	1	2	3	4	5	6	7	8
Pd	27.4	27.7	26.7	27.3	27.7	26.7	27.9	27.0
Pt	0.52	0.37	0.75	0.72	ND	0.31	0.12	0.21
Ni	0.08	0.32	0.33	0.53	0.53	0.49	0.97	0.45
Ag	0.41	0.16	ND	ND	ND	ND	ND	ND
Pb	ND	ND	1.34	ND	NA	NA	NA	NA
Cu	ND	0.10	NA	0.13	ND	NA	ND	ND
Fe	0.13	1.41	NA	NA	0.16	0.14	0.37	0.04
Sb	24.0	24.1	25.5	26.2	26.7	24.1	27.2	24.6
Bi	13.6	12.3	12.0	9.3	8.6	12.5	8.4	12.3
Te	33.7	34.2	32.6	36.0	36.6	35.7	37.2	35.9
S	0.07	0.15	NA	NA	ND	ND	0.04	ND
Total	99.91	100.8	99.22	100.2	100.3	99.94	102.2	100.5

Atomic proportions based on three atoms

Pd	.97	.94	.95	.94	.94	.94	.94	.94
Pt	.01	.01	.02	.01	---	.01	---	---
Ni	---	.02	.02	.03	.03	.03	.06	.03
Ag	.01	.01	---	---	---	---	---	---
Pb	---	---	.02	---	---	---	---	---
Cu	---	.01	---	.01	---	---	---	---
Fe	.01	.06	---	---	.01	.01	.02	---
Sua	1.00	1.05	1.01	.99	.98	.99	1.02	.97
Sb	.74	.81	.80	.80	.80	.74	.80	.75
Bi	.25	.21	.22	.16	.15	.22	.14	.22
Sua	.99	1.02	1.02	.96	.95	.96	.94	.97
Te	.99	.97	.97	1.03	1.05	1.05	1.04	1.05
S	---	.01	---	---	---	---	---	---
Sua	.99	.98	.97	1.03	1.05	1.05	1.04	1.05

Abbreviations: NA=not analysed; ND=not detected; po=pyrrhotite; pn=pentlandite; cp=chalcopyrite; py=pyrite; cob=cobaltite; sl=sphalerite; serp=serpentine; PGM=platinum-group mineral; PM=precious metal mineral; sud=sudburyite; tes=testibiopalladite; unk=unknown ($\text{Pd}_3\text{Sb}_2\text{Te}_2$); mer=merenskyite; ele=electrum; hes=hessite; mel=melonite. Analysis 1 at 246.8m (veined, n=3), 2 at 262.7m (reverse net-textured), 3 at 254.5m (veined), 4-8 at 271.2m (veined; 4-n=2, 5-n=3, 6-n=3, 7-n=3, 8-n=5). Grains at 271.2m from heavy mineral liquid separates. See Appendix B for lower limits of detection.

Assemblages in contact:

1 - po/serp

2 - po/pn/serp

3 - po/serp/tes

Appendix F-4.

Electron microprobe analyses of Unknown - $\text{Pd}_3\text{Sb}_2\text{Te}_2$ from core hole 160-224 Donaldson West deposit.

Sapl #	1	2	3	4	5	6	7
Pd	28.1	27.9	22.6	23.0	18.6	23.0	20.2
Pt	ND	ND	ND	0.14	ND	ND	ND
Ni	7.2	7.3	10.2	10.1	12.4	10.0	11.9
Sb	30.7	33.4	32.0	31.6	30.8	31.1	31.7
Bi	0.78	0.78	0.65	0.74	0.40	ND	ND
As	0.08	NA	NA	NA	NA	ND	ND
Te	33.4	32.2	35.1	35.4	37.5	34.1	36.1
Total	100.3	101.6	100.6	101.0	99.70	98.2	99.9

Atomic proportion based on seven atoms

Pd	2.04	2.00	1.61	1.63	1.31	1.67	1.42
Pt	---	---	---	.01	---	---	---
Ni	.94	.94	1.31	1.30	1.58	1.31	1.52
Sum	2.98	2.94	2.92	2.94	2.89	2.98	2.94
Sb	4.95	2.09	1.99	1.95	1.90	1.97	1.95
Bi	.03	.03	.02	.03	.01	---	---
As	.01	---	---	---	---	---	---
Sum	1.99	2.12	2.01	1.98	1.91	1.97	1.95
Te	2.02	1.92	2.07	2.07	2.20	2.06	2.12

Abbreviations: NA=not analysed; ND=not detected; po=pyrrhotite; pn=pentlandite; cp=chalcopyrite; py=pyrite; cob=cobaltite; sl=sphalerite; serp=serpentine; PGM=platinum-group mineral; PM=precious metal mineral; sud=sudburyite; tes=testibiopalladite; unk=unknown ($\text{Pd}_3\text{Sb}_2\text{Te}_2$); ser=serrenskyite; ele=electrum; hes=hessite; mel=melonite. All analyses from 257.6m (veined). Analyses 1-2 and 3-5 (Carleton University) from separate grains. Ag sought for. Analyses 6 and 7 by J. H. G. Laflamme (1985) at CANMET. Analysis 6=1-2 and 7=3-5; Pt, Ag, As, and Bi sought for; n=5 for each grain. See Appendix B for lower limits of detection (Carleton University analyses only).

Assemblages in contact:

1 - 2 and 6 po/serp/sud

3 - 5 and 7 po/pn/cp/serp

Appendix F-5. Electron microprobe analyses of Merenskyite - PdTe_2 from
core hole 160-224 - Donaldson Surface deposit.

Sapl #	1

Pd	19.9
Sb	21.4
Te	45.3
Ni	9.74
Pb	0.34
Bi	1.00

Total 97.68

Atomic proportions based on three atoms

Pd	.63
Ni	.59
Sum	1.22

Te	1.19
Sb	.59
Bi	.02

Sum 1.80

Abbreviations: NA=not analysed; ND=not detected; po=pyrrhotite; pn=pentlandite; cp=chalcopyrite; py=pyrite; cob=cobaltite; sl=sphalerite; serp=serpentine; PGM=platinum-group mineral; sud=sudburyite; tes=testibiopalladite; unk=unknown ($\text{Pd}_3\text{Sb}_2\text{Te}_2$); ele=electrum; hes=hessite; mel=melonite. Analysis at 258.5m (vein). Pt and Ag sought for. See Appendix B for lower limits of detection.

Assemblage in contact:

1 - cp/sl

Appendix F-6.

Electron Microprobe Analyses of Electrum - AuAg from
core hole 160-224 Donaldson West deposit.

Sampl #	1	2	3	4	5	6
Au	77.3	74.8	72.5	72.2	72.5	70.6
Ag	21.6	24.9	27.5	27.7	27.5	26.9
Pt	0.55	0.26	0.27	0.29	ND	0.28
Te	0.06	ND	0.10	0.08	0.07	0.12
Sb	0.06	ND	0.06	0.10	0.05	ND
Ru	ND	0.12	ND	0.16	ND	0.09
Os	0.31	ND	ND	ND	0.39	ND
Ir	0.32	ND	ND	ND	ND	ND
Total	100.2	100.0	100.4	100.5	100.5	97.99

Atomic proportion based on one atom

Au	.65	.62	.59	.58	.59	.59
Ag	.33	.38	.41	.41	.41	.41
Sum	.98	1.00	1.00	0.99	1.00	1.00

Abbreviations: NA=not analysed; ND=not detected; po=pyrrhotite; pn=pentlandite; cp=chalcopryite; py=pyrite; cob=cobaltite; sl=sphalerite; serp=serpentine; PGM=platinum-group mineral; PM=precious metal mineral; sud=sudburyite; tes=testibiopalladite; unk=unknown ($\text{Pd}_3\text{Sb}_2\text{Te}_2$); eer=erenskyite; ele=electrum; hes=hessite; sel=selenite. Analyses 1-2 at 239.5m (vein) and 3-6 at 253.5m (vein). Pd and Rh sought for. See Appendix B for lower limits of detection.

Assemblages in contact:

- 1 - cp
- 2 - po/py/cp
- 3 - cp/py/unk
- 4 - " "
- 5 - cp/py/sl
- 6 - " "

Appendix F-7. Electron microprobe analyses of Hessite - Ag_2Te from core hole 160-224 - Donaldson West deposit.

Sapl #	1	2	3

Ag	56.5	59.8	56.5
Te	39.0	42.2	36.9
Sb	0.25	0.23	0.11
Cu	0.10	0.06	ND
Total	95.85	102.3	93.51

Atomic proportions based on three atoms

Ag	1.89	1.87	1.93
Te	1.10	1.12	1.07

Abbreviations: NA=not analysed; ND=not detected; po=pyrrhotite; pn=pentlandite; cp=chalcopyrite; py=pyrite; cob=cobaltite; sl=sphalerite; serp=serpentine; PGM=platinum-group mineral; PM=precious metal mineral; spr=sperrylite; sud=sudburyite; tes=testibiopalladite; unk=unknown ($\text{Pd}_3\text{Sb}_2\text{Te}_2$); mer=merenskyite; ele=electrum; hes=hessite; mel=melonite. All analyses at 239.5m (vein) from a single grain. Pd, Au, and Pb sought for. See Appendix B for lower limits of detection.

Assemblages in contact:

1 - 3 po/cob/serp/tes/sud

Appendix F-8.

Electron microprobe analyses of Melonite - NiTe_2 from core hole
160-224 - Donaldson West deposit.

Sapl #	1	2	3	4	5	6	7	8
Ni	15.3	16.0	16.7	18.1	18.9	20.2	17.2	15.6
Pd	4.26	3.23	2.13	1.41	4.24	4.06	4.04	12.3
Pt	0.12	0.18	0.14	0.11	ND	ND	ND	0.16
Cu	NA	NA	NA	NA	NA	NA	NA	0.05
Te	72.1	72.3	75.3	68.1	59.0	56.0	59.5	48.7
Sb	1.22	1.21	1.19	10.2	16.2	20.7	16.7	23.6
Bi	6.04	6.82	4.83	4.83	4.10	0.79	1.19	1.19
Total	99.04	99.74	100.3	102.8	102.4	101.8	98.63	101.6

Atomic proportions based on three atoms

Ni	.86	.89	.92	.96	.99	1.04	.94	.83
Pd	.13	.10	.07	.04	.12	.11	.12	.36
Sum	.99	.99	.99	1.00	1.11	1.15	1.06	1.19
Te	1.87	1.87	1.91	1.66	1.42	1.32	1.48	1.18
Sb	.03	.03	.03	.26	.41	.51	.44	.60
Bi	.10	.11	.08	.07	.06	.01	.02	.02
Sum	2.00	2.01	2.02	1.99	1.89	1.84	1.94	1.80

Appendix F-8 cont.

Sapl #	9	10	11	12
Ni	15.1	16.4	17.0	20.1
Pd	12.5	10.7	10.8	4.13
Pt	ND	0.12	ND	ND
Cu	0.05	NA	NA	NA
Te	47.7	50.5	49.4	50.3
Sb	23.4	23.6	24.2	23.3
Bi	0.89	0.82	0.94	ND
Total	99.64	102.1	102.3	97.83

Atomic proportions based on three atoms

Ni	.82	.86	.88	1.06
Pd	.37	.31	.31	.12
Sum	1.19	1.17	1.19	1.18
Te	1.18	1.21	1.18	1.22
Sb	.61	.59	.61	.59
Bi	.02	.01	.02	---
Sum	1.81	1.81	1.81	1.81

Abbreviations: NA=not analysed; ND=not detected; po=pyrrhotite; pn=pentlandite; cp=chalcopyrite; py=pyrite; cob=cobaltite; sl=sphalerite; serp=serpentine; PGM=platinum-group mineral; PM=precious metal mineral; sud=sudburyite; tes=testibiopalladite; unk=unknown-(Pd₂Sb₂Te₂); mer=merenskyite; ele=electrum; hes=hessite; mel=melonite. Analyses 1-2 at 273.5m (massive sulfide), 3-4 at 274.0m (massive sulfide), 5-7 at 273.5m (massive sulfide), 8-9 at 271.2m (veined), 10 at 258.5m (vein), and 11-12 at 239.5m (vein). Ag sought for. See Appendix B for lower limits of detection.

Assemblages in contact:

- 1 - 7 po 10 - 12 po
- 8 - 9 magnetic fraction of heavy mineral liquid separation

Appendix F-9.

Electron microprobe analyses of Ullmannite - NiSbS from core hole
160-224 - Donaldson West deposit.

Spl #	1	2	3	4
Ni	27.6	27.1	27.4	27.5
Pd	0.24	0.22	0.18	0.17
Pt	0.20	0.23	ND	0.21
Cu	0.66	0.63	0.61	0.59
Sb	58.8	57.3	55.8	57.1
S	14.2	14.6	14.4	14.6
As	0.09	0.43	0.19	0.44
Co	0.20	0.19	0.17	0.20
Fe	0.19	0.23	0.35	0.26
Total	102.2	101.0	99.10	101.0

Atomic proportions based on three atoms

Ni	1.01	.98	1.00	.99
Pd	.01	---	---	---
Cu	.02	.02	.02	.02
Co	.01	.01	.01	.01
Fe	.01	.01	.01	.01
Sua		1.02	1.04	1.03
Sb	.98	1.00	.98	.99
S	.95	.97	.96	.96
As	---	---	.01	.01
Sua	.95	.97	.97	.97

Abbreviations: NA=not analysed; ND=not detected; po=pyrrhotite; pn=pentlandite; cp=chalcopyrite; py=pyrite; cob=cobaltite; sl=sphalerite; serp=serpentine; PGM=platinum-group mineral; PM=precious metal mineral; sud=sudburyite; tes=testibiopalladite; unk=unknown ($Pd_2Sb_2Te_2$); aer=aerenskyite; ele=electrum; hes=hessite; mel=melonite. All analyses from 205.3m (disseminated sulfide; veined). Ag and Te sought for. See appendix B for lower limits of detection.

Assemblages in contact:

1 - 2 po/pn/cp/serp

3 - 4 pn/serp

Appendix 6-1. Mineral Data Core Hole 160-225 (Donaldson Surface) Sperrylite - $PtAs_2$

Depth (m)	Sulf Text	Size (microns)	Crystal Habit	Grain Location	Comments
8.2	MET	5x10	subhedral-tabular	po/serp	intergrown with aer?
10.2	MET	10x18	subhedral-tabular	cp/serp	overgrows serp
11.2	MET	10-30x55	anhedral-tabular	po/pn/serp	overgrows serp
14.2	NRN	12	subhedral-equant	pn/serp	
15.2	MET	12	subhedral-equant	po/po/serp	overgrows serp
16.2	MET	5x6	subhedral-equant	po/serp	overgrows serp
	"	15x25	subhedral-irregular	"	"
	"	8x10	"	"	"
17.2	NRN	20x35	subhedral-irregular	cp/serp	
18.2	VEN	11x15	subhedral-tabular	po/serp	overgrows serp
	"	2x5 to	anhedral to subhedral	"	"
	"	5x15	-tabular	"	"
25.8	MSI	22x33	subhedral-chain	cp/serp/amph	skeletal chain
	"	20x30	"	cp/amph/PGM	intergrown with Pd-Sb-Bi-Te PGM
	"	two 5x12	subhedral-tabular	cp/sl/amph/PGM	skeletal, intergrown with sl and PGM
	"	10-30x100	subhedral-chain	cp/po/serp/PGM	intergrown with Pd-Sb-Bi-Te PGM
	"	3-15x300	"	cp/po/amph	rare free grains in amph
27.0	MSI	3-20x250	subhedral-chain	po/pn/cp/amph	rare free grains in amph
	"	5-10x100	"	po/po	

Abbreviations: Sulf Text=sulfide texture; MET=met-textured; NRN=net-texture to reverse net-texture; MSI=massive sulfide; BIA=sulfide breccia; VEN=vein; po=pyrrhotite; pn=pentlandite; cp=chalcopyrite; pyp=pyrite; cob=cobaltite; nic=nickeline; sl=sphalerite; serp=serpentine; amph=amphibole; PGM=platinum-group mineral; sud=sudburyite; tes=testibiopalladite; bor=borovskite; unk=unknown ($Pd_3Sb_2Te_2$); aer=aeronskyite; ach=achenite; hes=hessite; sel=selonite.

Depth (m)	Sulf Text	Size (microns)	Crystal Habit	Grain Location	Comments
18.2	VEN	4x8	subhedral-angular	po/po	
	"	30x90	subhedral-tabular	po/pn/serp	heterogeneous Ni, serp inclusions
	"	3x8	subhedral-triangular	in cp	
	"	12x15	subhedral-equant	po/cob	abuts tiny cob grain
	"	20x25	subhedral-irregular	po/po/PGM	abuts unk
	"	50x100	anhedral-tabular	pn/PGM	contains lamellae of unk
	"	30x75	anhedral-tabular	po/po	contains intergrowth of unk
	"	40x190	"	po/cob/pn/cp	intergrown with unk and cob
22.4	VEN	4x7	subhedral-tabular	po/cp	
	"	3x8	subhedral-irregular	po/serp/PGM	intergrown with tes, unk, near aol
25.8	MSI	3x6	anhedral-tabular	cob/po	abuts euhedral cob
	"	2x3	euhedral-angular	cob/cp	abuts euhedral cob
	"	3x4	anhedral-equant	in po	within po grain
	"	3x5	anhedral-tabular	in cp	within cp grain
27.0	MSI	5x10	anhedral-irregular	po/PGM	intergrown with bor and unk
	"	4x9	"	po/po	associated with spr in po
28.05	BXA	40x60	subhedral-irregular	po/pn/PGM	assoc with tes, ger, nic, po, and pn
	"	numerous, 12 to 10x15	anhedral-irregular	ger/po	assoc with nic alteration to ger/po
	"	15x40	anhedral-tabular	in ger	in ger assoc with nic alteration
	"	2x5	anhedral-irregular	in ger	"
	"	10x15	anhedral-tabular	in ger	"
	"	12x18	subhedral-tabular	po/pn/ger	"
	"	two-2x3	anhedral-tabular	in ger	in ger assoc with nic alteration
	"	20x40	"	in ger	"
	"	5x8	subhedral-tabular	po/PGM	intergrown with tes

Appendix 6-2. cont.

Depth (m)	Sulf Text	Size (microns)	Crystal Habit	Grain Location	Comments
28.05	BIA	numerous	anhedral-tabular	in ger	in ger assoc with nic alteration
	"	2x5 to	to irregular	"	"
	"	10x15	"	"	"
	"	"	"	"	"
	"	"	"	"	"
	"	15x37	anhedral-tabular	in ger	"
	"	10x28	"	"	"
	"	45x60	anhedral-irregular	in ger	assoc with ger/unk in altered nic
	"	30x50	"	"	in ger assoc with altered nic
	"	35x50	subhedral-tabular	po/po	"
	"	12x22	anhedral-tabular	"	"
	"	20x25	subhedral-equant	po/P6M	assoc with unk in po
	"	23x50	"	"	"
	"	10x15	subhedral-irregular	cp/P6M/serp	in serp with cp/tes
	"	20x35	anhedral-irregular	in ger	assoc with altered nic
	"	30x50	"	"	"
28.6	BIA	15x30	anhedral-irregular	P6M/py/pn/po/ger	intergrown with tes
	"	15x18	"	"	"
	"	10x22	anhedral-tabular	in ger	assoc with altered nic
	"	11x20	"	cp/ger	"
	"	10x15	anhedral-irregular	in ger	"
	"	15x25	"	"	"
	"	10x35	"	"	"
	"	13x35	subhedral-tabular	ger/py	"
	"	17x70	anhedral-tabular	"	"

Abbreviations: Sulf Text=sulfide texture; NET=net-textured; MRN=net-textured to reverse net-textured; VEN=vein; MSX=massive sulfide; BIA=sulfide breccia; po=pyrrhotite; pn=pentlandite; cp=chalcopyrite; py=pyrite; cob=cobaltite; ger=gersdorffite; nic=nickeline; eol=molybdenite; P6M=platinum-group mineral; serp=serpentine; amph=amphibole; spr=sperryite; tes=testibiopalladite; bor=borovskite; unk=unknown (Pd₂Sb₂Te₂); ser=serenskyite; sch=schrenkerite; eel=aelonite; hes=hessite.

Appendix 6-3. Mineral Data 160 - 225 (Donaldson Surface) Testibiopalladite - PdSbTe

Depth (m)	Sulf Text	Size (microns)	Crystal Habit	Grain Location	Comments
11.2	NET	10x15	subhedral-tabular	po/cp/pn/serp	
18.2	VEN	5x25	anhedral-tabular	po/po	
	"	15x22	subhedral-tabular	cp/cp	
	"	8x12	"	po/po	parallel to S ₁
	"	22x32	"	"	"
	"	12x18	anhedral-tabular	"	"
	"	10-25x45	subhedral-irregular	"	"
	"	10x15	euhedral-equant	po/po/pn	
22.4	VEN	30x45	subhedral-irregular	cp/serp/P6M	intergrown with bright P6M
	"	8x12	"	po/serp/P6M	intergrown with sud, unk, near sol
27.0	MSX	20x25	subhedral-irregular	po/serp/P6M/PM	intergrown with bor and hes
	"	12x20	anhedral-tabular	po/serp	
	"	5x6	subhedral-equant	po/po/pn	
28.05	BIA	20x30	subhedral-irregular	ger/po/pn/P6M	intergrown with sud, ger, and nic
	"	35x80	"	pn/pn	
	"	12x20	anhedral-tabular	in po	
	"	13x30	subhedral-tabular	po/po/P6M	intergrown with sud
	"	15x20	"	in po	
	"	15x20	anhedral-irregular	ger/P6M	intergrowth with sud and ger
	"	5x8	euhedral-equant	cp/serp/P6M	intergrown with sud

Abbreviations: Sulf Text=sulfide texture; NET=net-textured; NRN=net-textured to reverse net-textured; MSX=massive sulfide; BIA=sulfide breccia; VEN=vein; po=pyrrhotite; pn=pentlandite; cp=chalcopyrite; py=pyrite; cob=cobaltite; ger=gersdorffite; nic=nickeline; sol=molybdenite; P6M=platinum-group mineral, PM=precious metal mineral; serp=serpentine; asph=amphibole; spr=spherrillite; sud=sudburyite, bor=borovskite; unk=unknown (PdSb₂Te₂); ach=aichenerite; hes=hessite; mel=melonite.

Appendix 6-4. Mineral Data 160 - 225 (Donaldson Surface) Borovskite - Pb_3SbTe_4 .

Depth (m)	Sulf Text	Size (microns)	Crystal Habit	Grain Location	Comments
25.8	MSX	35x60	subhedral-tabular	po/po	
	"	30x70	"	"	
	"	12x25	"	"	
27.0	MSI	15x40	subhedral-tabular	cp/po/pn/serp/P6M	intergrown with unidentified P6M
	"	10x16	anhedral-tabular	pn/pn/serp	
	"	10x20	subhedral-tabular	po/P6M/PM/serp	intergrown with tes and hes
	"	20x25	anhedral-irregular	"	
	"	35x55	"	"	intergrown with hes and ser

Abbreviations: Sulf Text=sulfide texture; MET=net-textured; MRN=net-textured to reverse net-textured; MSI=massive sulfide; BIA=sulfide breccia; VEN=vein; po=pyrrhotite; pn=pentlandite; cp=chalcopyrite; py=pyrite; cob=cobaltite; nic=nickeline; P6M=platinum-group mineral; PM=precious metal mineral; serp=serpentine; asph=asphibole; spr=sperryite; sud=sudburyite; tes=testibiopalladite; unk=unknown ($Pd_3Sb_2Te_2$); ser=serenskyite; sch=schenebergerite; hes=hessite; mel=melonite.

Appendix 6-5. Mineral Data 160 - 225 (Donaldson Surface) Unknown - $\text{Pd}_3\text{Sb}_2\text{Te}_2$

Depth (m)	Sulf Text	Size (microns)	Crystal Habit	Grain Location	Comments
18.2	VEN	9x14	anhedral-round	pn/pn	
	"	45x65	subhedral-irregular	po/po/P6M	intergrown with sud, lamellae parallel to S,
	"	25x30	anhedral-tabular	po/po	
	"	40x45	subhedral-irregular	"	
	"	30x100	subhedral-tabular	pn/P6M	intergrown with sud, lamellae parallel to S,
	"	15-40x60	subhedral-irregular	po/po/P6M	intergrown with sud and cob
22.4	VEN	7x12	anhedral-tabular	po/po	has a round form
	"	12x19	"	"	"
	"	15x20	subhedral-irregular	po/pn/P6M	intergrown with sud, tes, near eol
	"	2x3	subhedral-tabular	po/serp	
	"	8x13	subhedral-irregular	po/po/	
	"	7x9	anhedral-tabular	po/po/P6M	round, intergrown with unident P6M
25.8	MSI	20x25	subhedral-tabular	cp/serp	
	"	3x12	anhedral-tabular	in cp	
27.0	MSI	25x50	subhedral-tabular	po/po	
28.0	BXA	10x20	subhedral-tabular	po/po/P6M	intergrown with sud
	"	20x50	subhedral-tabular	"	"
28.6	BXA	20x65	anhedral-irregular	po/pn/py/P6M	intergrown with sud
	"	15x55	"	"	"
	"	12-16	subhedral-tabular	in pn	
	"	15x40	"	po/pn/	

Abbreviations: Sulf Text=sulfide texture; NET=net-textured; NRM=net-textured to reverse net-textured; MSI=massive sulfide; BXA=sulfide breccia; VEN=vein; po=pyrrhotite; pn=pentlandite; cp=chalcopyrite; py=pyrite; cob=cobaltite; nic=nickeline; eol=molybdenite; P6M=platinum-group mineral; serp=serpentine; amph=amphibole; spr=sperrylite; sud=sudburyite; tes=testibiopalladite; bor=borovskite; ach=michenerite; hes=hessite; mel=melonite; ser=serrenskyite;

Appendix 6-6. Mineral Data 160 - 225 (Donaldson Surface) Merenskyite - PdTe₂

Depth (m)	Sulf Text	Size (microns)	Crystal Habit	Grain Location	Comments
8.2	NET	2x8	anhedral-irregular	po/PGM/serp	intergrown with spr
	"	10x50	subhedral-tabular	cp/serp	
	"	12x20	anhedral-tabular	"	
11.2	NET	10x12	euhedral-tabular	po/pn	
22.4	VEN	13x15	anhedral-irregular	cp/cob/serp/PGM	assoc with cob and sud
25.8	MSX	6x12	subhedral-tabular	pn/PM	intergrown with mel
	"	1x2	"	po/pb	
	"	12x18	euhedral-tabular	cp/pn	
	"	8x25	anhedral-tabular	cp/PGM/serp	intergrown with ach?
	"	12x25	subhedral-tabular	"	
	"	2x5	euhedral-tabular	in cp	
	"	2x3 to 8x12	anhedral-irregular to subhedral-tabular	cp/PGM/serp	intergrown with spr chain
	"	2x6 to 12x15	subhedral-tabular to subhedral-irregular	cp/po/PGM/serp	intergrown with spr chain
27.0	MSX	10x15	euhedral-rhomb	po/pn	
	"	10x35	subhedral-irregular	po/pn/cp/PM	intergrown with mel

Abbreviations: Sulf Text=sulfide texture; NET=net-textured; MRN=net-textured to reverse net-textured; MSX=massive sulfide; BIA=sulfide breccia; VEN=vein; po=pyrrhotite; pn=pentlandite; cp=chalcopyrite; py=pyrite; cob=cobaltite; nic=nickeline; PGM=platinum-group mineral; PM=precious metal mineral; serp=serpentine; amph=amphibole; spr=sperrylite; sud=sudburyite; tes=testite; pall=palladite; bor=borovskite; unk=unknown (Pd-Sb-Te₂); mer=merenskyite; ach=aichenerite; hes=hessite; mel=melonite.

Appendix 6-7. Mineral Data 160 - 225 (Donaldson Surface) Hessite - Ag₂Te

Depth (m)	Sulf Text	Size (microns)	Crystal Habit	Grain Location	Comments
27.0	MSI	10x12	subhedral-tabular	po/PGM/serp	intergrown with bor and tes
	"	20x35	anhedral-irregular	po/PGM	intergrown with unidentified PGM and aer
	"	5x13	subhedral-tabular	po/serp	

Appendix 6-8. Mineral Data 160 - 225 (Donaldson Surface) Melonite - NiTe₂

Depth (m)	Sulf Text	Size (microns)	Crystal Habit	Grain Location	Comments
11.2	NET	20x30	subhedral-irregular	po/po	low total, could be tes
22.4	VEN	3x6	euhedral-tabular	po/po	
	"	12x15	anhedral-tabular	"	round shape
25.8	MSI	24x47	subhedral-tabular	pn/pn/PGM	intergrown with aer
	"	12x25	subhedral-irregular	cp/PGM/serp	intergrown with ach?
	"	8x25	"	"	"
	"	18x20	subhedral-equant	po/serp	

Abbreviations: Sulf Text=sulfide texture; NET=net-textured; NRN=net-textured to reverse net-textured; MSI=massive sulfide; BIA=sulfide breccia; VEN=vein; po=pyrrhotite; pn=pentlandite; cp=chalcopyrite; py=pyrite; cob=cobaltite; nic=nickeline; PGM=platinum-group mineral; PM=precious metal mineral; serp=serpentine; amph=amphibole; spr=sperrylite; sud=sudburyite; tes=testibiopalladite; bor=borovskite; unk=unknown (Pd₂Sb₂Te₂); aer=aerenskyite; ach=aichenerite; hes=hessite; mel=melonite.

Appendix M-1. Electron microprobe analyses of Sperrylite - PtAs₂ from core hole 160-225 - Donaldson Surface deposit.

Samp #	1	2	3	4	5	6
Pt	55.9	55.5	55.3	50.7	54.9	54.9
As	41.9	41.7	41.8	38.7	41.3	41.5
Ir	.23	.29	.28	.49	.32	ND
Rh	.13	.18	ND	ND	.24	ND
Ru	ND	.14	NA	NA	NA	NA
Pd	ND	ND	ND	ND	.09	ND
Sb	.34	.39	.31	ND	.06	ND
S	.23	.38	NA	NA	NA	NA
Total	98.83	98.44	97.79	89.89	96.01	96.45

Atomic proportions based on three atoms

Pt	1.00	.99	1.00	1.00	1.00	1.01
Rh	---	---	---	---	.01	---
Sum	1.00	.99	1.00	1.00	1.01	1.01
As	1.95	1.94	1.98	1.99	1.97	1.99
Sb	.01	.01	.01	---	---	---
S	.02	.04	---	---	---	---
Sum	1.98	1.99	1.99	1.99	1.97	1.99

Abbreviations: NA=not analysed; ND=not detected. po=pyrrhotite; pn=pentlandite; cp=chalcopyrite; py=pyrite; cob=cobaltite; nic=nickeline; serp=serpentine; amph=amphibole; PGM=platinum-group mineral; sud=sudburyite; unk=unknown (PdSb₂Te₂); tes=testibiopalladite; bor=borovskite; aer=aerenskyite; eich=eichenerite; hes=hessite; mel=melonite. Analyses 1 and 2 at 27.0m (massive sulfide), n=2 each and 3, 4, 5, and 6 at 25.8m (massive sulfide) where n=2, 1, 3, and 2 respectively. See Appendix B for lower limits of detection.

Assemblages in contact:

1 - po/pn/cp/serp	4 - cp/serp/unk/bor
2 - po/sud/unk	5 - cp/po/unk
3 - cp/serp	6 - cp/po

Appendix H-2. Electron microprobe analyses of Sudburyite - PdSb from core hole 160-225 - Donaldson Surface deposit.

Sepi #	1	2	3	4	5	6	7	8
Pd	45.9	46.5	44.0	46.0	46.2	46.9	46.7	47.0
Ag	ND	ND	ND	ND	ND	.17	.18	ND
Ni	.24	.22	.31	.17	.45	.38	.38	.26
Pt	.24	.14	.13	.14	ND	ND	ND	ND
Sb	48.0	48.6	48.2	48.7	48.8	49.3	50.9	52.6
Te	4.33	4.82	4.72	3.77	3.67	3.16	2.60	1.35
As	.11	.23	.19	ND	ND	ND	ND	ND
Bi	1.93	1.57	1.60	1.31	1.27	1.38	.70	.29
Total	100.8	102.0	99.21	100.2	100.4	101.4	101.5	101.7

Atomic proportions based on two atoms

Pd	.99	.98	.96	.99	.99	.99	.99	.99
Ni	.01	.01	.01	---	.02	.01	.01	.01
Sum	1.00	.99	.97	.99	1.01	1.00	1.00	1.00
Sb	.90	.90	.92	.92	.91	.91	.94	.97
Te	.08	.09	.09	.07	.07	.06	.04	.01
Bi	.02	.02	.02	.01	.01	.01	.01	---
Sum	1.00	1.01	1.03	1.00	.99	.98	.99	.98

Appendix H-2 cont.

Sapl #	9	10	11	12	13	14	15
Pd	45.6	46.1	46.0	46.2	46.0	46.2	46.8
Ag	ND	.19	ND	ND	ND	.14	.17
Ni	.86	.22	.33	1.13	.66	.80	.65
Pt	ND	ND	ND	ND	ND	ND	ND
Sb	50.0	49.2	49.5	50.9	50.0	50.2	50.6
Te	2.10	2.40	3.16	1.65	2.52	2.28	2.70
As	ND	ND	ND	ND	.10	ND	ND
Bi	.33	1.98	1.11	.43	.80	.23	.95
Total	99.02	100.0	100.2	100.4	100.0	99.85	102.0

Atomic proportions based on two atoms

Pd	.98	.99	.99	.98	.98	.99	.98
Ni	.03	.01	.01	.04	.03	.03	.02
Sua	1.01	1.00	1.00	1.02	1.01	1.02	1.00
Sb	.94	.93	.93	.94	.93	.94	.93
Te	.04	.04	.06	.03	.04	.04	.05
Bi	---	.02	.01	---	.01	---	.01
Sua	.98	.99	1.00	.97	.98	.98	.99

Abbreviations: NA=not analysed; ND=not detected; po=pyrrhotite; pn=pentlandite; cp=chalcopyrite; py=pyrite; cob=cobaltite; ger=gersdorffite; nic=nickeline; serp=serpentine; aaph=amphibole; PGM=platinum-group mineral; spr=sperrylite; tes=tesitite; unk=unknown ($Pd_{.5}Sb_{.5}Te_{.5}$); bor=borovskite; aer=aerenskyite; ach=aichenerite; hes=hessite; sel=selonite. Analyses 1 to 5 at 18.2m (vein), where n=2, 1, 3, 1, and 1; 6 to 15 at 28.0m (sulfide breccia), where n=1 for 6 to 13, and n=2 and 3 for 14 and 15 respectively. See Appendix B for lower limits of detection.

Assemblages in contact;

1 - po/pn/unk	5 - pn/unk	9 - po/tes	13 - po/ger/nic
2 - po/py/cob/unk	6 - po/pa/ger/nic	10 - po/tes	14 - nic/ger/unk
3 - po/pa/serp	7 - po/pn/ger/nic	11 - serp/tes	15 - nic/ger/unk
4 - po/pa/unk	8 - po/py	12 - po/ger/nic	

Appendix H-3. Electron microprobe analyses of Testibiopalladite - PdSbTe from core hole 160-225 - Donaldson Surface deposit.

Sapl #	1	2	3	4	5	6	7	8
Pd	27.4	27.4	27.8	27.8	28.2	28.3	27.9	27.9
Sb	24.8	24.4	21.9	25.1	25.2	23.6	26.8	26.8
Ag	.20	.41	.24	.14	.22	.15	ND	ND
Te	34.1	34.1	34.1	34.3	34.4	33.6	34.9	34.6
Ni	.16	.12	.15	.62	.97	.74	.17	.20
Pt	.61	.66	.65	ND	.25	.46	.19	.34
As	.52	.66	NA	ND	ND	ND	.73	.64
Bi	13.36	13.31	14.94	11.89	12.05	15.11	10.5	9.10
Pb	NA	NA	.42	NA	NA	NA	NA	NA
Total	101.1	101.0	100.2	99.84	101.3	102.0	101.2	99.78

Atomic proportions based on three atoms

Pd	.96	.96	.99	.97	.97	.98	.96	.97
Ag	---	.02	.01	---	.01	---	---	---
Ni	.01	---	.01	.04	.06	.04	.01	.01
Pt	.01	.01	.01	---	---	.01	---	---
Sum	.98	.99	1.02	1.01	1.04	1.03	.97	.98
Sb	.76	.74	.68	.77	.76	.72	.81	.82
As	.03	.03	---	---	---	---	.04	.03
Pb	---	---	.01	---	---	---	---	---
Bi	.24	.24	.27	.21	.21	.27	.18	.16
Sum	1.03	1.01	.96	.98	.97	.99	1.03	1.01
Te	.99	.99	1.02	1.00	.99	.97	1.00	1.00

Abbreviations: NA=not analysed; ND=not detected; po=pyrrhotite; pn=pentlandite; cp=chalcopyrite; py=pyrite; cob=cobaltite; ger=gersdorffite; nic=nickeline; serp=serpentine; amph=amphibole; PGM=platinum-group mineral; spr=sperrylite; sud=sudburyite; bor=borovskite; unk=unknown ($Pd_3Sb_2Te_2$); mer=merenskyite; ech=richenerite; hes=hessite; mel=melonite. Analyses 1-2 at 18.2m (vein), 3 at 27.0m (massive sulfide), 4-6 at 28.0m (sulfide breccia), and 7-8 at 22.4m (vein). See Appendix B for lower limits of detection.

Assemblages in contact:

1 - po	3 - cp/po/bor	5 - pn	7 - cp/serp/PGM
2 - po	4 - pn	6 - nic/ger/po/sud	8 - " "

Appendix H-4. Electron microprobe analyses of Borovskite - Pd_3SbTe_4 from core hole 160-225 - Donaldson Surface deposit.

Sep. #	1	2	3	4	5	6	7	8
Pd	24.8	24.8	24.4	24.1	24.6	19.0	18.6	17.6
Sb	13.0	12.6	12.8	13.0	12.7	12.7	13.1	13.2
Bi	8.29	8.76	7.59	7.73	8.15	10.1	9.55	8.94
Te	50.3	50.0	50.4	50.6	50.9	50.1	49.9	51.8
Ni	4.73	4.51	4.75	4.87	4.45	9.19	9.48	9.86
Pt	.28	.23	.12	.09	ND	.50	.33	.41
As	ND	ND	ND	ND	ND	.42	.97	.31
Ag	ND	ND	ND	ND	ND	ND	ND	ND
Pb	NA	NA	NA	NA	NA	NA	NA	NA
Co	ND	ND	ND	ND	ND	NA	NA	NA
Total	101.4	100.9	100.0	100.4	100.9	102.0	101.9	102.1

Atomic proportions based on eight atoms

Pd	2.18	2.20	2.17	2.12	2.18	1.61	1.57	1.47
Ni	.75	.72	.76	.78	.71	1.41	1.44	1.50
Pt	.01	.01	---	---	---	.02	.02	.02
Ag	---	---	---	---	---	---	---	---
Sum	2.94	2.93	2.93	2.90	2.89	3.04	3.03	2.99
Sb	1.00	.98	.99	1.00	.98	.94	.96	.97
As	---	---	---	---	---	.05	.11	.04
Sum	1.00	.98	.99	1.00	.98	1.04	1.07	1.01
Te	3.68	3.69	3.73	3.71	3.76	3.54	3.50	3.62
Bi	.37	.40	.34	.36	.37	.44	.41	.38
Sum	4.05	4.09	4.07	4.07	4.13	3.98	3.91	4.00

Appendix H-4 cont.

Sepi #	9	10	11	12	13	14	15	16
Pd	17.6	17.4	29.8	30.4	29.9	30.3	30.4	30.6
Sb	13.2	13.2	13.3	13.2	13.5	13.1	13.4	13.4
Bi	7.77	7.99	5.45	5.00	5.62	5.18	4.73	5.13
Te	52.9	52.4	48.7	49.0	48.3	48.6	48.0	47.9
Mi	9.89	9.96	1.95	1.67	1.71	2.31	2.08	2.44
Pt	.28	.26	.14	.12	.34	ND	ND	.24
As	.21	.38	NA	NA	NA	NA	NA	NA
Ag	NA	NA	ND	ND	ND	ND	.21	.13
Pb	NA	NA	ND	.26	.24	ND	ND	.29
Co	NA	NA	NA	NA	NA	NA	NA	NA
Total	101.8	101.6	99.42	99.72	99.65	99.58	99.05	99.53

Atomic proportions based on eight atoes

8

Pd	1.48	1.45	2.70	2.74	2.70	2.72	2.74	2.70
Mi	1.50	1.51	.30	.27	.28	.38	.34	.40
Pt	.02	.02	---	---	.02	---	---	---
Ag	---	---	---	---	---	---	.02	---
Pb	---	---	---	---	.02	---	---	.02
Sum	3.00	2.98	3.00	3.01	3.02	3.10	3.10	3.12
Sb	.97	.97	1.06	1.04	1.06	1.02	1.06	1.06
As	.02	.05	---	---	---	---	---	---
Sum	.99	1.02	1.06	1.04	1.06	1.02	1.06	1.06
Te	3.69	3.66	3.68	3.69	3.65	3.64	3.62	3.58
Bi	.33	.34	.25	.23	.26	.24	.22	.23
Sum	4.02	4.00	3.93	3.92	3.91	3.88	3.84	3.81

Appendix H-4 cont.

Sapl #	17	18	19
Pd	26.4	26.7	26.4
Sb	13.8	13.4	13.6
Bi	5.43	5.23	5.97
Te	51.7	51.0	51.2
Ni	4.17	3.69	3.97
Pt	ND	.14	.15
As	ND	.19	ND
Ag	ND	.14	ND
Pb	NA	NA	NA
Co	NA	NA	NA
Total	101.6	100.5	101.3

Atomic proportions based on eight atoms

Pd	2.30	2.35	2.31
Ni	.66	.59	.63
Pt	---	---	---
Ag	---	.01	---
Pb	---	---	---
Sua	2.96	2.95	2.94
Sb	1.05	1.03	1.04
As	.01	.02	.01
Sua	1.06	1.05	1.05
Te	3.74	3.75	3.74
Bi	.24	.23	.26
Sua	3.98	3.98	4.00

Abbreviations: NA=not analysed; ND=not detected; po=pyrrhotite; pn=pentlandite; cp=chalcopyrite; py=pyrite; cob=cobaltite; nic=nickeline; serp=serpentine; amph=amphibole; PGM=platinum-group mineral; spr=sperrylite; sud=sudburyite; tes=testibiopalladite; unk=unknown (PdSb₂Te₂); ser=sereniskyite; nch=nichenerite; hes=hessite; mel=melonite. Analyses 1-10 at 25.8e (massive sulfide), where 1-5, 6-7, and 8-10 are from separate grains, 11-19 at 27.0e (massive sulfide), where 11, 12-13, 14-16, and 17-19 are from separate grains. See Appendix B for lower limits of detection.

Assemblages in contact:

1 - 5 po/po	11 - po/cp/pn/serp/PGM	17 - 19 po/hes/tes
6 - 7 po/po	12 - 13 po/tes/hes/serp	
8 - 10 po/po	14 - 16 po/cp	

Appendix H-5. Electron microprobe analyses of Unknown - $\text{Pd}_3\text{Sb}_2\text{Te}_2$ from core hole 160-225 - Donaldson Surface deposit.

Sepl #	1	2	3	4	5	6	7	8
Pd	26.6	27.0	26.4	26.7	27.9	28.0	26.8	26.6
Sb	31.0	30.6	31.4	31.0	29.9	30.4	31.6	30.3
Bi	1.64	1.61	1.44	1.31	1.65	2.17	1.79	1.92
Te	33.5	32.8	33.3	33.2	32.8	33.3	32.8	33.1
Ni	8.19	7.72	8.32	7.86	7.29	7.31	7.68	7.73
Pt	ND	ND	ND	ND	ND	ND	ND	ND
As	.68	.14	.14	ND	ND	ND	ND	.21
Ag	ND	.19	ND	ND	ND	ND	ND	ND
Total	101.6	100.0	101.0	100.0	99.54	101.2	100.8	99.86

Atomic proportions based on seven atoms

Pd	1.90	1.97	1.89	1.94	2.04	2.03	1.94	1.94
Ni	1.06	1.02	1.08	1.04	.97	.96	1.00	1.02
Ag	---	.01	---	---	---	---	---	---
Sum	2.96	3.00	2.97	2.98	3.01	2.99	2.94	2.96
Sb	1.93	1.95	1.97	1.97	1.92	1.92	2.00	1.93
As	.07	.01	.01	---	---	---	---	.02
Bi	.06	.06	.06	.05	.06	.08	.06	.07
Sum	2.06	2.02	2.04	2.02	1.98	2.00	2.06	2.02
Te	1.99	1.99	2.00	2.00	2.00	2.00	1.98	2.00

Appendix H-5 cont.

Sapl #	9	10	11	12	13	14
Pd	26.9	23.0	24.2	24.8	23.9	24.0
Sb	30.6	30.0	32.5	31.2	31.6	31.9
Bi	1.63	2.67	ND	.90	.33	.47
Te	31.6	30.6	32.8	32.8	33.0	32.5
Ni	8.07	9.94	8.84	8.59	9.22	8.91
Pt	ND	ND	ND	ND	ND	ND
As	ND	ND	ND	.12	.30	.08
Ag	ND	ND	ND	ND	ND	ND
Total	98.80	96.21	98.44	98.41	98.35	97.86

Atomic proportions based on seven atoms

Pd	1.97	1.73	1.76	1.81	1.74	1.76
Ni	1.07	1.29	1.17	1.14	1.22	1.18
Su	3.04	3.02	2.93	2.95	2.96	2.94
Sb	1.96	1.97	2.07	2.00	2.00	2.04
As	---	---	---	---	.03	---
Bi	.06	.10	---	.04	.01	.02
Su	2.02	2.07	2.07	2.04	2.04	2.06
Te	1.93	1.92	2.00	2.00	2.00	1.99

Abbreviations: NA=not analysed; ND=not detected; po=pyrrhotite; pn=pentlandite; cp=chalcopryite; py=pyrite; cob=cobaltite; ger=gersdorffite; nic=nickeline; serp=serpentine; aaph=aaphibole; PGM=platinum-group mineral; spr=sperryllite; sud=sudburyite; tes=testibiopalladite; bor=borovskite; unk=unknown ($Pd_3Sb_2Te_2$); ser=serrenskyite; ach=achenerite; hes=hessite; mel=melonite. Analyses 1-8 at 18.2m (vein), where 1, 2, 3, 4, 5-6, and 7-8 are from separate grains, 9-10 (separate grains) at 28.0m (sulfide breccia), and 11-14 at 28.6m (sulfide breccia), where 11-12 and 13-14 are from separate grains. See Appendix B for lower limits of detection.

Assemblages in contact:

1 - po/sud/cob	4 - po	9 - po	13 - 14 po/pn/py/sud
2 - po/sud	5 - 6 pn/sud	10 - po/sud	
3 - po	7 - 8 po/sud	11 - 12 po/pn/py/sud	

Appendix H-6. Electron microprobe analyses of Merenskyite - PdTe₂ from core hole 160-225 - Donaldson Surface deposit.

Sep1 #	1

Pd	27.0
Sb	16.6
Te	43.6
Ni	1.75
Pt	.28
As	.62
Bi	11.2
Total	101.0

Atomic proportions based on three atoms

Pd	.92
Ni	.11
Sua	1.03
Te	1.24
Sb	.50
Bi	.20
As	.03
Sua	1.97

Abbreviations: NA=not analysed; ND=not detected; po=pyrrhotite; pn=pentlandite; cp=chalcopyrite; py=pyrite; cob=cobaltite; nic=nickeline; serp=serpentine; amph=amphibole; PGM=platinum-group mineral; spr=sperrylite; sud=sudburyite; bor=borovskite; unk=unknown (Pd₃Sb₂Te₂); mer=merenskyite; eich=eichenerite; hes=hessite; mel=melonite. Analysis at 27.0m (massive sulfide). Ag sought and not detected. See Appendix B for lower limits of detection.

Assemblages in contact:
1 - po/bor/hes/serp

Appendix H-7. Electron microprobe analyses of Hesseite - Ag_2Te from core hole 160-225 - Donaldson Surface deposit.

Sepi #	1	2	3	4
Ag	61.2	62.0	61.0	59.8
Ni	.05	ND	.06	.15
As	NA	NA	ND	.16
Te	38.3	38.4	38.4	38.4
Sb	.06	.10	ND	ND
Bi	.25	.15	ND	ND
Pb	ND	ND	NA	NA
Total	99.86	100.7	99.46	98.53

Atomic proportions based on three atoms

Ag	1.97	1.97	1.96	1.93
Ni	---	---	---	.01
Sua	1.97	1.97	1.96	1.94
Te	1.03	1.03	1.04	1.05

Abbreviations: NA=not analysed; ND=not detected; po=pyrrhotite; pn=pentlandite; cp=chalco-pyrite; py=pyrite; cob=cobaltite; nic=nickeline; serp=serpentine; asph=amphibole; PGM=platinum-group mineral; spr=sperryllite; sud=sudburyite; tes=testibio-palladite; bor=borovskite; unk=unknown ($\text{Pd}_3\text{Sb}_2\text{Te}_2$); eer=eerenskyite; ach=achenerite; hes=hessite; mel=melonite. All analyses at 27.0 μ (massive sulfide), analyses 1, 2, and 3-4 from separate grains. Pt and Pd sought but not detected. See Appendix B for lower limits of detection.

Assemblages in contact:

- 1 - po/bor/tes
- 2 - po/bor/ear

Appendix H-8. Electron microprobe analyses of Melonite - NiTe_2 from core hole 160-225 - Donaldson Surface deposit.

Sapl #	1	2	3	4	5	6
Pd	13.3	13.2	11.4	11.3	10.6	15.2
Sb	.96	.99	1.04	.84	.84	23.5
Te	67.1	66.9	67.5	67.0	68.5	49.2
Ni	10.4	10.7	10.6	11.0	11.1	12.7
Pt	.52	.39	.67	.45	.76	ND
As	.51	.28	.11	.50	.62	ND
Bi	9.37	9.72	9.62	9.81	9.20	ND
Total	102.2	102.2	100.9	100.9	101.6	100.6

Atomic proportions based on three atoms

Ni	.59	.61	.62	.64	.64	.69
Pd	.42	.42	.37	.36	.34	.46
Pt	.01	---	.01	.01	.01	---
Sua	1.02	1.03	1.00	1.01	.99	1.15
Te	1.77	1.77	1.81	1.79	1.81	1.23
Sb	.03	.03	.03	.02	.02	.62
As	.02	.01	---	.02	.03	---
Bi	.15	.16	.16	.16	.15	---
Sua	1.97	1.97	2.00	1.99	2.01	1.85

Abbreviations: NA=not analysed; ND=not detected; po=pyrrhotite; pn=pentlandite; cp=chalcopyrite; py=pyrite; cob=cobaltite; nic=nickeline; serp=serpentine; aaph=amphibole; PGM=platinum-group mineral; spr=sperrylite; sud=sudburyite; tes=testibiopalladite; bor=borovskite, unk=unknown ($\text{Pd}_3\text{Sb}_2\text{Te}_2$); eer=erenskyite; ach=aichenerite; hes=hessite; mel=melonite. Analyses 1-2 and 3-5 at 25.8e (massive sulfide) on separate grains, and 6 at 22.4e (vein). Ag sought but not detected. See Appendix B for lower limits of detection.

Assemblages in contact:

1 - 2 pn/er

6 - po

3 - 5 po/serp

The MgCO_3 content of calcite coexisting with dolomite is the basis of the calcite-dolomite geothermometer. The pressure effect on the solubility of MgCO_3 in calcite, while often considered negligible, has been calculated for pressures of one and five kbars (Ewert, 1977). Sheppard and Schwarz (1970) estimated that the indicated temperatures will increase by 8°C for one mole percent FeCO_3 . Microprobe analysis does not distinguish between the $++$ and $+++$ charge state for Fe and Mn. If all the Fe and Mn were assumed to be the $++$ state the estimated temperatures below would increase by no more than 4°C .

For each sample the maximum MgCO_3 content is used to estimate the temperature because retrograde metamorphic processes will reduce the original amount of magnesium (Ewert, 1977). A pressure of 5 kbar was selected for the calculation of calcite-dolomite geothermometer temperatures at the Donaldson Mine as a pressure of 1 kbar is not warranted. Albino (1984) suggested metamorphic pressures of 3.5 kbar for the Boundary ultramafic complex three km to the west of the Donaldson Mine area. St. Onge et al. (1986) have suggested a minimum metamorphic pressure of 5.5 kbar for the eastern extension of the Cape Smith foldbelt in the Wakeham Bay area. A better approximation of the metamorphic pressure in the Donaldson Mine area would be about 4 Kb.

Solving the equation;

$$T=474.96 + 82.24X - 5.11X^2 + 0.17X^3 - 0.0022X^4$$

(eqn. 6, 5kb; Ewert, 1977)

yields temperatures of 511°C and 515°C for Donaldson West deposit vein sample 160-224-239.5m and 549°C for veined sample 160-224-205.3m.

Examination of veined material from core hole 160-225, Donaldson Surface deposit, did not reveal calcite coexisting dolomite and the $MgCO_3$ content of calcite alone will not give valid temperatures.

Calcite, with coexisting dolomite, from sulfide-carbonate-PGM veins in the Donaldson West deposit. Single analyses. Maximum temperatures are underlined.

160-224-239.5

	1		2		3	
	wt %	mol %	wt %	mol %	wt %	mol %
Ca	39.2	1.990	41.3	1.987	40.2	1.987
Fe	0.00	0.000	0.11	0.004	0.00	0.000
Mn	0.08	0.003	0.12	0.004	0.11	0.004
Mg	0.09	0.008	0.07	0.005	0.11	0.009
	-----	-----	-----	-----	-----	-----
	39.4	2.000	41.6	2.000	40.4	2.000
	T=507°C		T=495°C		<u>T=511°C</u>	

	4		5		6	
	wt %	mol %	wt %	mol %	wt %	mol %
Ca	41.3	1.990	40.7	1.992	40.2	1.981
Fe	0.01	0.000	0.03	0.001	0.17	0.006
Mn	0.00	0.000	0.01	0.000	0.11	0.004
Mg	0.12	0.010	0.08	0.007	0.11	0.009
	-----	-----	-----	-----	-----	-----
	41.4	2.000	40.8	2.000	40.6	2.000
	<u>T=515°C</u>		T=503°C		T=511°C	

160-224-205.3m

	1		2		3	
	wt %	mol %	wt %	mol %	wt %	mol %
Ca	39.9	1.976	40.2	1.979	40.4	1.975
Fe	0.03	0.001	0.00	-----	0.01	-----
Mn	0.18	0.006	0.13	0.005	0.16	0.006
Mg	0.20	0.016	0.20	0.016	0.24	0.019
	-----	-----	-----	-----	-----	-----
	40.3	2.000	40.5	2.000	40.8	2.000
	T=537°C		T=537°C		<u>T=549°C</u>	

Introduction

Surface exposure is extremely limited in the Donaldson Mine area. The geology of the area (Fig. J.1) is derived from a compilation of surficial, geophysical, and drill core data interpreted by Falconbridge Ltd. Drill core holes from the Donaldson West deposit were selected to form three north-south cross-sections through the central, sulfide-rich part of the deposit (Figures J.1 and J.2). Sulfide concentration and textural data from these cross-sections are presented in Appendix J-1. The central cross-section (590405E; Appendix J-2) contains core hole 160-224, the metallurgical core hole examined in detail in Chapters 2 and 4. Cross-section 590366E (Appendix J-3) is located approximately 40 m to the west and section 590427E (Appendix J-4) about 20 m to the east (see Fig. J.2 for locations).

The local geology consists of NNW trending ultramafic sills which have intruded at the interface between Povungnituk metasedimentary and tholeiitic metavolcanic rocks and the overlying mafic to ultramafic Chukotat metavolcanic and intrusive suite.

The ultramafic sills are concentrically zoned (Fig. J.3) grading inward from pyroxenite or olivine pyroxenite to peridotite and minor dunite. The Donaldson West sulfide deposit lies in a footwall depression immediately above the

basal contact. The surface projection of "ore-grade" sulfide mineralization is about 300m by 120m (Fig. J.1).

Steeply N dipping, WNW trending faults, subparallel to the stratigraphy, transect the mine area. A series of later, widely spaced NNE trending subvertical faults further complicate the structure (Fig. J.1).

Discussion

Ni, Cu, Cu/Cu+Ni data and sulfide textures are presented for drill core holes comprising these cross-sections. The textural codes, derived from company drill core logs completed by various geologists, were interpreted to conform with the terminology used for the sulfide concentrations outlined in Chapter 2. Previous workers, not as concerned with textural data, did not always record sulfide concentrations or textures such as veining on a scale less than one metre, such that textural comparison, even with core holes immediately adjacent to 160-224, is difficult.

The cross-sections (Appendices J-2, J-3, and J-4) indicate a broad, asymmetric north-dipping trough. The centre of the trough trends approximately 162° and appears to plunge gently to the southeast. The complete upward stratigraphic sulfide succession of massive through net-textured to disseminated sulfides is only present in drill holes intersecting the deepest part of the trough. Concentration of sulfides appear to be asymmetrically distributed in the trough

in a similar fashion to that reported for sulfides in the the Katiniq sill (Barnes et al., 1982). Massive sulfides in sections 590366E and 590405E are very thin and deposited on the southern flank of the trough. The distribution of net-textured sulfides is generally concentrated towards the footwall contact and the thickest concentration occurs above the trough core.

Scattered thicknesses of net-textured sulfide located well above the inferred footwall contact on section 590427E are though to reflect the problem of assigning a sulfide textural code to rocks logged by others. In core holes 160-13 and 160-133 the inferred occurrences of net-textured sulfides are closely associated with veined sulfides and the increased sulfide content may reflect mobilization rather than primary concentrations. Alternatively, it is possible that these sulfide concentrations well above basal accumulations may reflect the influx of later, sulfide-bearing magma which did not settle gravitationally. In the northern part of section 590427E the sulfide concentrations rapidly fluctuate laterally, suggesting tectonic disruption of the mineralization.

Copper-rich stringers are frequently found at the footwall contact. Copper- or nickel-rich veins between 20 cm and one metre wide are rare and do not appear to correlate between drill holes. Nickel-rich veins, -veined material, and massive sulfide sections exhibit distinctive, low Cu/Cu+Ni values. Copper-rich veins, -veined material, and -footwall

stringers exhibit enriched Cu/Cu+Ni values.

Mobilized sulfides, interpreted from increased Cu/Cu+Ni values compared to surrounding sulfides, occur at the contact between sulfide textural types and elsewhere. Sulfide mobilization in large thicknesses of disseminated sulfides is interpreted to reflect the heterogeneity of deformation. Sulfide veins and veined material in the more sulfide-rich net-textured and massive sulfides occur at the contact of textural types and elsewhere. The development of net-textured to reverse net-textured, and reverse net-textured sulfides, difficult to interpret from drill core logs, does not appear to significantly modify the Cu/Cu+Ni.

The re-examination of the drill core is required to clarify textural types as used in this study and to identify veined sulfides before more meaningful conclusions can be made about the metamorphic redistribution of sulfides in this deposit.

Fig. J.1. Geology of the Donaldson Mine area showing the Donaldson West (1); Donaldson East (2); and Donaldson Surface deposits. Geology after Coats, 1981. North-south section lines for the Donaldson West deposit are detailed in Fig. J.2 and Appendices J-1, J-2, J-3, J-4.

Fig. J.2. Location of drill core holes through the Donaldson West deposit.

Fig. J.3. Vertical cross-section through the Donaldson West deposit showing the form of the concentrically zoned ultramafic sill and the location of sulfide concentrations. Geology and sulfide concentrations from Coats (pers. comm., 1983).

Appendix J-1

Donaldson West - Section 590427E

DDH 160-13 (590424E, 6839330N, -90°)

Depth range (m)	Ore texture	Ni	Cu	Cu/Cu+Ni	Comments
145.7-146.0	6	2.32	0.06	0.026	Ni vein
146.0-147.8	1	0.43	0.05	0.104	
147.8-150.6	1	0.49	0.08	0.140	
150.6-151.8	1	0.96	0.19	0.165	
151.8-153.3	1	1.78	0.11	0.058	
153.3-153.9	1	0.65	0.11	0.145	
153.9-154.3	6	2.17	5.12	0.702	Cu vein
154.3-154.6	2	2.82	0.33	0.104	
154.6-156.0	2	7.56	0.81	0.096	
156.0-157.6	2	1.08	0.22	0.169	
157.6-158.3	5	4.37	2.86	0.396	
158.3-159.1	6	2.93	5.29	0.654	Cu vein
159.1-160.3	1	0.79	0.16	0.168	
160.3-164.6	1	0.24	0.03	0.111	
164.6-167.0	1	0.75	0.09	0.107	
167.0-170.0	1	0.63	0.10	0.137	
170.0-173.7	1	0.91	0.10	0.100	
173.7-176.8	1	0.96	0.09	0.086	
176.8-179.8	1	0.69	0.05	0.067	
179.8-182.9	1	0.79	0.05	0.059	
182.9-185.9	1	0.63	0.05	0.074	
185.9-189.3	1	0.61	0.06	0.089	
189.3-193.8	1	0.69	0.05	0.067	
193.8-198.1	1	0.83	0.10	0.108	
198.1-201.1	2	1.02	0.15	0.128	
201.1-201.7	2	2.19	0.25	0.102	
201.7-202.0	6	17.0	0.95	0.053	Ni vein
202.0-203.5	1	0.51	0.08	0.136	
203.5-210.3	1	0.55	0.13	0.191	
210.3-211.8	1	0.77	0.14	0.154	
211.8-214.2	1	0.83	0.19	0.186	
214.2-217.3	1	0.53	0.16	0.232	
217.3-220.4	1	0.45	0.18	0.286	
220.4-223.0	5	0.65	0.56	0.463	
223.0-224.1	2	1.46	0.42	0.223	
224.1-225.2	2	5.16	1.46	0.220	
225.2-226.0	6	2.28	5.53	0.708	Cu vein
226.0-228.3	2	1.14	0.32	0.219	
228.3-232.0	9	0.45	0.14	0.237	stringers
232.0-234.9	9	0.10	0.20	0.667	"
234.9-237.7	9	0.08	0.18	0.690	"
237.7-238.9	9	0.08	1.37	0.945	"

Donaldson West - Section 590427E

DDH 160-13 cont.

Depth range (m)	Ore texture	Ni	Cu	Cu/Cu+Ni	Comments
272.9-274.9	1	0.53	0.23	0.303	
274.9-276.4	1	0.57	0.33	0.367	
276.4-279.2	1	0.73	0.18	0.198	
279.2-279.3	6	3.29	0.38	0.104	Ni vein
279.3-282.8	1	0.61	0.10	0.140	
282.8-285.0	1	0.73	0.09	0.110	
285.0-287.4	1	0.79	0.11	0.122	
287.4-290.8	1	0.65	0.08	0.110	
290.8-290.9	5	1.61	0.36	0.183	brecciated
290.9-292.6	1	0.53	0.08	0.131	
292.6-294.1	1	0.89	0.23	0.205	
294.1-295.6	8	4.51	0.60	0.117	brecciated
295.6-297.2	7	5.45	2.07	0.275	Cp veined
297.2-299.7	7	4.80	0.59	0.109	
299.7-301.0	9	1.65	0.57	0.257	stringers

DDH R-344 (590427E, 6839309N, -70°, S72W)

Depth range (m)	Ore texture	Ni	Cu	Cu/Cu+Ni	Comments
136.9-139.9	1	0.24	0.07	0.226	
139.9-143.0	1	0.21	0.07	0.250	
143.0-146.0	1	0.36	0.06	0.143	
146.0-149.0	1	0.52	0.09	0.148	
149.0-152.1	1	0.20	0.05	0.200	
243.1-244.7	6	5.50	13.9	0.716	Cu vein
244.7-246.2	7	10.8	0.97	0.082	
246.2-247.6	5	13.8	4.20	0.233	Cp veined

Texture code: 1=disseminated; 2=net-textured; 3=net-textured to reverse net-textured; 4=reverse net-textured; 5=veined; 6=vein; 7=massive sulfide; 8=sulfide breccia; 9=footwall stringer; 10=interstitial sulfide; Tr=trace; Ni=nickel; Cu=copper; Cp=chalcopyrite; sulf=sulfide.

Donaldson West - Section 590427E

DDH R-328 (590426E, 6839263N, -80°S)

Depth range (m)	Ore texture	Ni	Cu	Cu/Cu+Ni	Comments
265.2-266.8	1	0.37	0.06	0.140	
266.8-268.3	1	0.45	0.13	0.224	
268.3-271.3	1	0.41	0.09	0.180	
271.3-274.4	1	0.55	0.14	0.203	sulf blebs
274.4-277.4	1	0.47	0.14	0.230	" "
277.4-280.4	1	0.67	0.14	0.173	
280.4-282.5	1	1.08	0.28	0.206	
282.5-284.0	1	0.69	0.18	0.207	

DDH 140-133 (590445E, 6839245N, -90°)

Depth range (m)	Ore texture	Ni	Cu	Cu/Cu+Ni	Comments
128.6-134.7	1	0.25	0.02	0.074	
134.7-140.8	1	0.40	0.06	0.130	
140.8-146.9	1	0.27	0.03	0.100	
146.9-153.0	1	0.39	0.03	0.071	
153.0-159.1	1	0.26	0.01	0.037	
159.1-165.2	1	0.32	0.04	0.111	
165.2-171.3	1	0.32	0.11	0.256	
171.3-171.6	5	0.66	0.42	0.389	Cp veined
171.6-171.8	2	1.34	0.52	0.280	
171.8-172.3	2	5.00	0.84	0.144	
172.3-175.8	2	5.14	0.76	0.129	
175.8-179.8	2	5.08	0.88	0.148	
179.8-180.3	2	2.28	0.34	0.130	
180.3-180.8	2	1.14	0.44	0.278	
180.8-186.9	1	0.29	0.05	0.147	
186.9-191.2	1	0.24	0.03	0.111	
191.2-191.7	2	1.59	0.34	0.176	
191.7-195.4	2	2.94	0.46	0.135	
195.4-196.6	1	0.80	0.16	0.167	
196.6-196.7	6	14.7	0.62	0.040	Ni vein
196.7-197.2	2	1.24	0.16	0.114	
197.2-197.4	6	8.94	0.80	0.082	Ni vein
197.4-201.5	1	0.79	0.12	0.133	
201.5-207.6	1	0.60	0.12	0.167	
207.6-213.7	1	0.67	0.15	0.183	
213.7-216.1	1	0.47	0.10	0.175	
216.1-222.2	1	0.26	0.03	0.103	
222.2-224.8	1	0.19	0.02	0.095	

Donaldson West - Section 590427E

DDH 160-133 cont.

Depth range (m)	Ore texture	Ni	Cu	Cu/Cu+Ni	Comments
224.8-226.7	1	0.57	0.12	0.174	
226.7-227.8	1	0.88	0.16	0.154	
227.8-230.7	1	0.92	0.29	0.240	
230.7-232.8	1	0.81	0.23	0.221	
232.8-233.8	1	0.88	0.28	0.241	
233.8-234.5	1	0.64	0.21	0.247	
234.5-234.9	2	2.89	0.92	0.241	
234.9-236.4	1	0.88	0.30	0.254	
236.4-239.9	1	0.37	0.09	0.196	
239.9-242.3	1	0.41	0.11	0.212	
242.3-246.0	1	0.27	0.04	0.129	
246.0-249.0	1	0.43	0.08	0.157	
249.0-252.0	1	0.36	0.07	0.167	
252.0-255.1	1	0.89	0.07	0.073	
255.1-256.9	1	0.52	0.10	0.161	
256.9-257.5	1	0.56	0.12	0.176	
257.5-258.6	1	0.61	0.16	0.208	
258.6-261.2	1	0.58	0.12	0.171	
261.2-262.7	1	0.70	0.15	0.176	
262.7-264.0	1	0.66	0.16	0.195	
264.0-264.3	1	0.94	0.32	0.254	
264.3-266.9	1	0.45	0.19	0.297	
266.9-268.5	1	0.94	0.24	0.203	
268.5-271.6	1	0.35	0.10	0.222	
271.6-274.6	1	0.33	0.11	0.250	
274.6-277.7	1	0.40	0.14	0.318	
277.7-280.7	1	0.37	0.15	0.288	
280.7-282.5	1	0.39	0.15	0.270	
282.5-284.0	1	0.39	0.09	0.188	
284.0-285.7	1	0.30	0.08	0.210	
285.7-287.1	1	0.46	0.14	0.233	
287.1-288.6	1	0.55	0.36	0.395	veined ?
288.6-289.4	1	0.62	0.16	0.205	
289.4-290.2	1	0.51	0.12	0.190	
290.2-290.9	1	0.61	0.19	0.238	
290.9-291.7	2	1.44	0.32	0.182	
291.7-293.6	2	3.70	0.60	0.140	
293.6-296.6	2	6.24	1.18	0.159	
296.6-298.3	7	13.5	1.12	0.077	
298.3-298.6	9	0.69	3.63	0.840	stringers

Texture code: 1=disseminated; 2=net-textured; 3=net-textured to reverse net-textured; 4=reverse net-textured; 5=veined; 6=vein, 7=massive sulfide; 8=sulfide breccia; 9=footwall stringer; 10=interstitial sulfide; Tr=trace; Ni=nickel; Cu=copper; Cp=chalcopyrite; sulf=sulfide.

Donaldson West - Section 390427E

DDH 160-B (590426E, 6839205N, -90°)

Depth range (m)	Ore texture	Ni	Cu	Cu/Cu+Ni	Comments
171.9-175.0	1	0.49	0.08	0.140	
175.0-176.5	1	0.91	0.10	0.099	
176.5-178.0	1	0.85	0.15	0.150	
178.0-179.5	1	0.87	0.08	0.084	
179.5-181.0	1	0.87	0.13	0.130	
181.0-184.4	1	0.73	0.10	0.120	
184.4-188.1	1	0.67	0.11	0.141	
188.1-191.1	1	0.59	0.04	0.063	
191.1-192.5	1	0.53	0.03	0.053	
192.5-194.0	1	0.57	0.08	0.123	
194.0-195.7	1	0.49	0.06	0.109	
195.7-198.7	1	0.63	0.06	0.087	
198.7-200.2	1	0.53	0.05	0.086	
200.2-207.9	1	0.45	0.04	0.082	
207.9-209.4	1	0.53	0.14	0.209	sulf blebs
209.4-212.4	1	0.69	0.06	0.080	
212.4-215.5	1	0.49	0.04	0.075	
215.5-217.0	1	0.73	0.09	0.110	
217.0-218.5	1	0.65	0.09	0.122	
218.5-221.6	1	0.51	0.07	0.120	
221.6-223.1	1	0.53	0.07	0.117	
223.1-227.7	1	0.55	0.14	0.203	
227.7-232.2	1	0.49	0.08	0.140	
232.2-235.5	1	0.65	0.13	0.167	
235.5-238.4	1	0.47	0.11	0.190	
238.4-240.5	1	0.96	0.13	0.119	
240.5-241.4	1	0.63	0.11	0.149	
241.4-243.8	1	0.49	0.08	0.140	
243.8-246.0	1	0.75	0.11	0.128	
246.0-249.0	1	0.39	0.05	0.114	
249.0-253.6	1	0.35	0.05	0.125	
253.6-256.7	1	0.41	0.06	0.128	
256.7-258.2	1	0.55	0.08	0.128	
258.2-261.3	1	0.41	0.01	0.020	
261.3-264.3	1	0.39	0.09	0.188	sulf blebs
264.3-267.3	1	0.43	0.09	0.173	" "
267.3-268.9	2	1.57	0.37	0.190	" "
268.9-269.4	1	0.73	0.15	0.170	" "
269.4-271.9	2	2.32	0.45	0.162	" "
271.9-274.0	2	1.99	0.43	0.178	" "
274.0-276.4	1	0.47	0.06	0.113	" "
276.4-276.9	2	2.68	1.11	0.293	" "
276.9-278.0	1	0.57	0.09	0.136	" "
278.0-281.0	1	0.59	0.14	0.192	" "
281.0-284.0	1	0.69	0.11	0.138	" "
284.0-288.6	1	0.59	0.09	0.132	" "

Donaldson West - Section 590427E

DDH 160-B cont.

Depth range (m)	Ore texture	Ni	Cu	Cu/Cu+Ni	Comments
288.6-291.0	1	0.49	0.09	0.155	sulf blebs
291.0-293.2	2	2.11	0.29	0.120	" "
293.2-294.7	2	2.66	0.38	0.125	" "
294.7-296.9	2	3.44	0.46	0.118	
296.9-300.4	2	5.53	1.18	0.176	
300.4-301.0	2	3.74	0.51	0.120	

DDH 160-1 (590427E, 6839145N, -90°)

Depth range (m)	Ore texture	Ni	Cu	Cu/Cu+Ni	Comments
102.1-106.7	1	0.28	0.03	0.096	
106.7-111.3	1	0.17	0.04	0.190	
111.3-115.8	1	0.30	0.04	0.118	
115.8-120.1	1	0.52	0.08	0.133	
120.1-125.0	1	0.24	0.04	0.143	
125.0-129.6	1	0.21	0.03	0.125	
129.6-134.1	1	0.28	0.05	0.152	
134.1-138.7	1	0.24	0.03	0.111	sulf blebs
138.7-141.8	1	0.39	0.03	0.071	
141.8-143.3	1	0.15	0.01	0.062	
143.3-144.8	1	0.31	0.03	0.088	sulf blebs
144.8-146.3	1	0.82	0.11	0.118	" "
146.3-148.5	2	1.97	0.36	0.154	
148.5-149.4	2	3.19	0.18	0.053	
149.4-150.8	5	6.54	4.37	0.400	Cp breccia
150.8-152.4	7	6.45	1.49	0.188	
152.4-153.8	7	5.86	0.93	0.137	veined
153.8-154.6	7	11.4	0.63	0.052	brecciated
154.6-156.0	7	5.97	1.81	0.232	
156.0-158.0	7	6.86	1.50	0.179	

Texture code: 1=disseminated; 2=net-textured; 3=net-textured to reverse net-textured; 4=reverse net-textured; 5=veined; 6=vein, 7=massive sulfide; 8=sulfide breccia; 9=footwall stringer; 10=interstitial sulfide; Tr=trace; Ni=nickel; Cu=copper; Cp=chalcopyrite; sulf=sulfide.

Donaldson West - Section 590427E

* DD# 160-205 (590430E, 6839114N, -90°)

Depth range (m)	Ore texture	Ni	Cu	Cu/Cu+Ni	Comments
138.0-140.0	1	0.21	0.03	0.125	
140.0-142.0	1	0.20	0.03	0.130	
142.0-144.0	1	0.26	0.05	0.161	
144.0-146.0	1	0.28	0.06	0.176	
146.0-148.0	1	0.32	0.07	0.179	
148.0-150.0	1	0.28	0.05	0.152	
150.0-152.0	1	0.27	0.04	0.129	
152.0-153.2	1	0.28	0.03	0.097	
153.2-155.2	1	0.31	0.02	0.060	
155.2-157.2	1	0.24	0.01	0.046	
157.2-159.2	1	0.22	0.01	0.043	
159.2-161.2	1	0.25	0.05	0.167	
161.2-163.2	1	0.28	0.05	0.152	
163.2-165.2	1	0.23	0.03	0.115	
165.2-167.2	1	0.18	0.03	0.143	
167.2-168.2	1	0.17	0.01	0.056	
168.2-170.2	1	0.13	0.02	0.133	
187.0-189.0	6	1.58	1.50	0.487	Cp vein
189.0-191.0	1	0.34	0.02	0.056	
191.0-193.0	1	0.41	0.04	0.089	
193.0-195.0	1	0.48	0.07	0.127	
195.0-197.0	1	0.63	0.09	0.125	
197.0-199.0	1	0.36	0.08	0.182	
199.0-201.5	5	0.30	0.13	0.302	veined

Texture code: 1=disseminated; 2=net-textured; 3=net-textured to reverse net-textured; 4=reverse net-textured; 5=veined; 6=vein, 7=massive sulfide; 8=sulfide breccia; 9=footwall stringer; 10=interstitial sulfide; Tr=trace; Ni=nickel; Cu=copper; Cp=chalcopyrite; sulf=sulfide.

Donaldson West - Section 590405E

DDH 160-211 (590397E, 6839145N, -90°)

Depth range (m)	Ore texture	Ni	Cu	Cu/Cu+N _i	Comments ²
89.7-91.7	1	0.24	0.05	0.172	
91.7-93.7	5	5.56	1.05	0.159	Ni veined
93.7-94.3	5	3.69	0.47	0.114	" "
93.4-96.3	1	0.33	0.09	0.214	
96.3-98.3	1	0.28	0.07	0.200	
98.3-100.3	1	0.26	0.05	0.161	
100.3-101.5	1	0.29	0.05	0.147	
101.5-103.5	1	0.47	0.09	0.161	
103.5-105.5	1	0.62	0.13	0.173	
105.5-107.5	1	0.38	0.10	0.208	
107.5-109.5	1	0.31	0.09	0.225	
109.5-111.5	1	0.29	0.07	0.194	
111.5-113.5	1	0.25	0.06	0.194	
113.5-115.5	1	0.39	0.07	0.152	
115.5-117.5	1	0.25	0.04	0.138	
117.5-119.5	1	0.23	0.02	0.080	brecciated
119.5-121.5	1	0.26	0.02	0.071	"
121.5-123.5	1	0.40	0.07	0.149	
123.5-125.5	1	0.54	0.09	0.143	
125.5-127.5	1	0.82	0.21	0.204	
146.0-148.0	1	0.28	0.06	0.176	
148.0-150.0	1	0.37	0.06	0.140	
150.0-152.0	1	0.35	0.05	0.125	
152.0-154.0	1	0.33	0.07	0.175	
154.0-156.0	1	0.51	0.09	0.150	
156.0-157.2	1	0.37	0.08	0.178	
157.2-159.2	1	0.21	0.04	0.160	
159.2-161.2	1	0.43	0.07	0.140	
161.2-163.2	1	0.65	0.14	0.177	
163.2-165.2	1	0.41	0.11	0.212	
165.2-167.2	1	0.54	0.13	0.194	
167.2-169.2	1	0.35	0.07	0.167	
169.2-171.2	1	0.44	0.01	0.022	
171.2-173.2	1	0.45	0.03	0.062	
173.2-175.2	1	0.38	0.16	0.296	
175.2-177.2	1	0.38	0.09	0.243	
177.2-179.2	1	0.53	0.14	0.209	
179.2-181.2	1	0.69	0.18	0.207	
181.2-182.3	1	0.54	0.12	0.182	
192.6-194.6	1	0.64	0.07	0.098	
194.6-196.6	1	0.34	0.07	0.170	
196.6-198.6	1	0.31	0.08	0.205	
198.6-200.6	1	0.37	0.06	0.140	

Donaldson West - Section 590405E

DDH 160-211 cont.

Depth range (m)	Ore texture	Ni	Cu	Cu/Cu+Ni	Comments
200.6-202.6	1	0.28	0.03	0.097	
202.6-205.1	1	0.33	0.05	0.132	
205.1-207.1	5	0.28	0.07	0.200	veined
207.1-508.2	5	0.52	0.35	0.402	"

DDH 160-54 (590397E, 6839173N, -90°)

Depth range (m)	Ore texture	Ni	Cu	Cu/Cu+Ni	Comments
127.7-133.8	1	0.23	0.06	0.207	
133.8-135.2	1	0.31	0.05	0.139	
135.2-135.8	1	1.21	0.24	0.166	veined ?
135.8-141.7	1	0.36	0.07	0.163	
141.7-144.8	1	0.37	0.07	0.159	
144.8-148.4	1	0.33	0.06	0.156	
148.4-153.0	1	0.30	0.05	0.143	
153.0-156.0	1	0.59	0.12	0.169	
156.0-160.3	1	0.28	0.10	0.263	
160.3-164.6	1	0.70	0.18	0.204	
164.6-168.8	1	0.55	0.15	0.214	
168.8-175.0	1	0.87	0.20	0.187	
175.0-181.0	1	0.85	0.28	0.248	
181.0-187.1	1	0.75	0.25	0.250	
187.1-193.2	1	0.56	0.16	0.222	
193.2-199.3	1	0.58	0.15	0.205	
199.3-206.4	1	0.67	0.15	0.183	
206.4-207.9	1	1.24	0.25	0.168	
207.9-211.2	1	0.56	0.13	0.188	
211.2-212.8	1	0.72	0.15	0.172	
212.8-218.2	1	0.41	0.12	0.226	
218.2-222.0	1	0.34	0.12	0.260	
222.0-225.1	5	2.74	0.52	0.307	veined ?
225.1-226.8	1	1.27	0.24	0.156	
226.8-228.3	1	0.36	0.09	0.200	
228.3-231.6	1	0.33	0.09	0.214	
231.6-234.1	1	0.38	0.09	0.191	
234.1-237.1	1	0.57	0.08	0.123	
237.1-239.6	1	0.45	0.11	0.196	
239.6-241.4	1	0.48	0.12	0.200	
241.4-244.5	1	0.36	0.08	0.182	
244.5-250.6	5	0.56	0.24	0.300	veined ?

Donaldson West - Section 590405E

DDH 160-54 cont.

Depth range (m)	Ore texture	Ni	Cu	Cu/Cu+Ni	Comments
250.6-253.0	5	0.47	0.41	0.465	veined ?
253.0-253.6	1	0.01	Tr	-----	fault
253.6-254.6	5	1.00	1.84	0.648	veined
254.6-255.1	6	13.6	1.50	0.099	Ni vein
255.1-255.7	5	0.84	0.37	0.306	veined
255.7-261.8	1	0.06	0.05	0.454	
261.8-262.4	7	9.80	3.15	0.243	
262.4-264.6	9	0.21	0.12	0.363	stringers

Texture code: 1=disseminated; 2=net-textured; 3=net-textured to reverse net-textured; 4=reverse net-textured; 5=veined; 6=vein, 7=massive sulfide; 8=sulfide breccia; 9=footwall stringer; 10=interstitial sulfide; Tr=trace; Ni=nickel; Cu=copper; Cp=chalcopyrite; sulf=sulfide.

DDH 160-224M (590402E, 6839200N, -90°)

Depth range (m)	Ore texture	Ni	Cu	Cu/Cu+Ni	Comments
211.9-213.9	1	1.03	0.21	0.169	
213.9-215.9	1	0.82	0.16	0.163	
215.9-217.9	1	1.11	0.21	0.159	
217.9-219.9	1	0.93	0.20	0.177	
219.9-221.9	1	1.01	0.18	0.151	
221.9-223.9	1	0.73	0.14	0.161	
223.9-225.9	1	1.02	0.18	0.150	
225.9-227.9	1	0.57	0.11	0.162	
227.9-229.7	1	0.55	0.24	0.304	
229.7-232.4	1	0.75	0.18	0.194	
232.4-233.0	1	0.24	0.04	0.143	
233.0-235.0	1	0.98	0.18	0.155	
235.0-237.0	1	0.79	0.18	0.184	
237.0-239.3	2	2.28	0.84	0.269	
239.3-240.4	5	5.25	1.61	0.234	Cp veined
240.4-241.4	2	4.17	0.99	0.192	
241.4-242.4	2	4.17	1.20	0.223	
242.4-243.4	2	4.70	0.71	0.131	
243.4-244.4	2	4.82	0.75	0.134	
244.4-245.4	2	5.33	1.21	0.185	
245.4-246.4	2	5.38	1.18	0.180	
246.4-247.4	3	5.58	0.82	0.128	

Donaldson West - Section 590405E

DDH 160-224M cont.

Depth range (m)	Ore texture	Ni	Cu	Cu/Cu+Ni	Comments
247.4-248.4	5	3.94	2.53	0.391	Cp veined
248.4-249.4	2	4.87	1.14	0.190	
249.4-250.4	2	4.20	1.13	0.212	
250.4-251.4	3	6.14	0.74	0.108	
251.4-252.4	5	5.85	1.98	0.253	Cp veined
252.4-253.4	2	4.97	0.95	0.160	
253.4-254.4	6	8.71	1.81	0.170	Ni vein
254.4-255.4	2	4.49	1.46	0.245	
255.4-256.4	3	3.02	0.45	0.130	
256.4-257.4	3	3.32	0.58	0.149	
257.4-258.4	3	5.55	0.64	0.103	
258.4-259.4	5	2.28	3.05	0.572	Cp veined
259.4-260.4	5	3.84	2.00	0.342	" "
260.4-261.4	3	3.20	0.74	0.188	
261.4-262.4	3	2.73	0.83	0.233	
262.4-263.4	4	3.03	1.08	0.263	
263.4-264.4	4	2.23	1.00	0.309	
264.4-265.4	4	2.97	1.25	0.296	
265.4-266.4	4	2.64	0.65	0.198	
266.4-267.4	4	3.19	1.66	0.342	
267.4-268.4	4	3.66	0.88	0.194	
268.4-269.4	4	3.68	0.72	0.195	
269.4-270.4	4	3.13	0.70	0.183	
270.4-271.4	4	3.53	0.90	0.203	
271.4-272.4	5	4.38	2.81	0.391	Cp veined
272.4-273.4	5	4.73	1.50	0.240	" "
273.4-274.2	7	12.6	0.77	0.058	

Texture code: 1=disseminated; 2=net-textured; 3=net-textured to reverse net-textured; 4=reverse net-textured; 5=veined; 6=vein, 7=massive sulfide; 8=sulfide breccia; 9=footwall stringer; 10=interstitial sulfide; Tr=trace; Ni=nickel; Cu=copper; Cp=chalcopyrite; sulf=sulfide.

Donaldson West - Section 590405E

DDH 160-129 (590405E, 6839228N, -90°)

Depth range (m)	Ore texture	Ni	Cu	Cu/Cu+Ni	Comments
144.5-150.6	1	0.28	0.03	0.097	
150.6-156.7	1	0.27	0.02	0.067	
156.7-162.8	1	0.27	0.03	0.100	
162.8-168.8	1	0.62	0.12	0.162	
168.8-170.6	1	0.54	0.20	0.270	
170.6-173.6	5	6.68	1.86	0.218	veined
173.6-173.7	5	3.89	1.46	0.273	"
173.7-175.6	5	1.41	0.40	0.221	"
175.6-178.6	1	0.90	0.20	0.182	
178.6-181.7	1	0.86	0.20	0.189	
181.7-184.7	1	0.82	0.20	0.196	
184.7-187.4	1	0.61	0.15	0.197	
187.4-193.5	1	0.50	0.08	0.138	
193.5-199.6	1	0.52	0.16	0.235	
199.6-205.7	1	0.67	0.13	0.162	
205.7-208.8	1	0.66	0.12	0.154	
208.8-214.9	1	0.87	0.19	0.179	
214.9-221.0	1	0.92	0.28	0.233	
221.0-227.0	1	0.61	0.19	0.238	
227.0-232.0	1	0.35	0.04	0.102	
232.0-234.7	1	0.55	0.16	0.225	
234.7-235.6	1	0.81	0.36	0.308	veined ?
235.6-237.1	1	1.22	0.24	0.164	
237.1-239.3	1	0.47	0.09	0.161	
239.3-240.8	1	0.29	0.04	0.121	
240.8-242.3	1	0.73	0.18	0.198	
242.3-242.9	1	0.96	0.24	0.200	
242.9-246.2	1	0.87	0.20	0.187	
246.2-248.7	2	4.56	0.84	0.156	
248.7-250.2	2	4.70	1.02	0.178	
250.2-251.8	2	4.23	1.00	0.191	
251.8-252.4	2	5.20	1.28	0.198	
252.4-253.3	2	5.32	1.28	0.194	
253.3-255.0	2	5.78	1.02	0.150	
255.0-255.2	6	15.0	1.50	0.091	Ni vein
255.2-258.2	5	5.03	1.92	0.276	
258.2-261.2	2	5.20	1.08	0.172	
261.2-264.3	5	1.92	1.14	0.372	veined
264.3-267.6	2	5.32	1.12	0.174	
267.6-269.7	2	4.36	0.96	0.180	
269.7-271.0	2	1.18	0.60	0.337	veined ?
271.0-273.4	2	6.08	0.90	0.129	
273.4-276.4	2	3.12	0.60	0.161	

Donaldson West - Section 590405E

DDH 160-129 cont.

Depth range (m)	Ore texture	Ni	Cu	Cu/Cu+Ni	Comments
276.4-279.2	5	3.58	2.00	0.358	veined
279.2-282.4	2	5.12	1.12	0.179	
282.4-283.2	2	3.89	1.00	0.204	
283.2-284.1	7	13.9	2.00	0.126	

Texture code: 1=disseminated; 2=net-textured; 3=net-textured to reverse net-textured; 4=reverse net-textured; 5=veined; 6=vein, 7=massive sulfide; 8=sulfide breccia; 9=footwall stringer; 10=interstitial sulfide; Tr=trace; Ni=nickel; Cu=copper; Cp=chalcopyrite; sulf=sulfide.

Donaldson West - Section 590366E

DDH 160-9 (590365E, 6839270N, -90=)

Depth range (m)	Ore texture	Ni	Cu	Cu/Cu+Ni	Comments
153.3-158.2	1	0.67	0.09	0.118	
158.2-163.1	1	0.51	0.10	0.164	
163.1-166.2	1	0.63	0.09	0.125	
166.2-167.7	1	1.00	0.06	0.056	
167.7-169.2	1	0.87	0.09	0.094	
169.2-170.7	1	0.94	0.05	0.050	
170.7-172.2	1	1.06	0.11	0.094	
172.2-173.8	1	1.00	0.17	0.145	
173.8-178.4	1	1.00	0.14	0.122	
178.4-181.6	1	0.75	0.10	0.118	
181.6-181.8	1	0.87	0.18	0.171	
181.8-182.9	1	0.81	0.06	0.069	
182.9-184.4	1	0.55	0.14	0.202	
184.4-187.6	1	0.69	0.10	0.126	
187.6-189.0	1	1.26	0.13	0.094	
189.0-191.5	1	1.42	0.37	0.206	
191.5-194.2	1	0.96	0.13	0.119	
194.2-200.3	1	0.28	0.01	0.034	
200.3-203.0	1	0.77	0.14	0.154	
203.0-207.0	1	0.81	0.22	0.214	
207.0-210.4	1	0.83	0.13	0.135	
210.4-213.4	1	0.77	0.08	0.094	
213.4-216.5	1	0.51	0.09	0.128	
216.5-218.0	1	0.71	0.17	0.193	
218.0-219.5	1	0.63	0.14	0.182	

Texture code: 1=disseminated; 2=net-textured; 3=net-textured to reverse net-textured; 4=reverse net-textured; 5=veined; 6=vein, 7=massive sulfide; 8=sulfide breccia; 9=footwall stringer; 10=interstitial sulfide; Tr=trace; Ni=nickel; Cu=copper; Cp=chalcopyrite; sulf=sulfide.

DDH R-319 (590366E, 6839250N, -90=)

Depth range (m)	Ore texture	Ni	Cu	Cu/Cu+Ni	Comments
152.7-155.7	1	0.12	0.06	0.333	
155.7-157.2	5	1.52	0.26	0.146	
157.2-158.8	1	1.16	0.14	0.108	
158.8-161.6	1	0.75	0.09	0.107	
161.6-164.6	1	1.01	0.14	0.122	
164.6-167.4	1	1.08	0.18	0.142	
167.4-169.2	1	0.99	0.13	0.116	

Donaldson West - Section 590366E

DDH R-319 cont.

Depth range (m)	Ore texture	Ni	Cu	Cu/Cu+Ni	Comments
169.2-172.2	1	1.06	0.09	0.078	
172.2-173.8	1	0.93	0.23	0.198	
173.8-176.2	1	0.79	0.10	0.112	
176.2-179.2	1	0.83	0.09	0.098	
179.2-182.2	1	0.49	0.12	0.196	
182.2-185.3	1	0.81	0.10	0.110	
185.3-188.4	5	0.89	0.14	0.136	veined
188.4-191.4	1	0.65	0.05	0.071	
191.4-194.4	1	0.61	0.08	0.116	
194.4-197.5	1	0.65	0.07	0.097	
197.5-200.5	1	0.61	0.07	0.103	
200.5-203.6	1	0.63	0.09	0.125	
203.6-206.6	1	0.81	0.13	0.138	
206.6-208.2	1	0.81	0.13	0.138	
208.2-210.3	1	0.71	0.15	0.174	
210.3-212.9	1	0.97	0.16	0.141	
212.9-214.3	5	0.83	0.20	0.194	veined
214.3-217.4	5	0.97	0.20	0.170	"
217.4-220.4	1	0.81	0.13	0.138	
220.4-223.6	1	0.65	0.09	0.121	
223.6-226.6	1	0.81	0.13	0.138	
226.6-229.6	1	0.73	0.09	0.110	
229.6-232.6	1	0.49	0.05	0.092	
232.6-234.1	5	0.36	0.05	0.122	veined
234.1-237.2	1	0.89	0.10	0.101	sulf blebs
237.2-240.2	5	1.71	0.28	0.140	veined
240.2-242.0	1	1.34	0.11	0.077	
242.0-244.6	2	3.17	0.64	0.168	
244.6-247.3	2	2.03	0.47	0.188	
247.3-250.0	5	3.58	0.58	0.139	veined
250.0-251.5	2	4.43	0.49	0.100	sulf blebs
251.5-253.7	5	4.26	1.47	0.256	" "
253.7-256.7	2	4.26	0.86	0.168	" "
256.7-259.8	2	3.38	0.95	0.219	" "
259.8-262.8	2	3.66	0.74	0.168	" "
262.8-265.9	3	2.84	0.39	0.120	" "
265.9-268.9	3	2.52	0.64	0.202	" "
268.9-271.7	4	1.26	0.27	0.176	" "
271.7-273.2	4	1.67	0.45	0.212	
273.2-275.4	4	0.97	0.26	0.211	
275.4-277.3	7	4.46	1.26	0.220	banded
277.3-278.8	5	2.24	1.26	0.360	veined
278.8-280.6	9	0.69	0.27	0.201	stringers

Donaldson West - Section 590366E

DDH 160-2 (590366E, 6839202N, -90°)

Depth range (m)	Ore texture	Ni	Cu	Cu/Cu+Ni	Comments
164.6-166.1	1	0.71	0.08	0.102	
166.1-167.7	1	1.35	0.23	0.146	
167.7-169.2	1	1.15	0.18	0.135	
169.2-170.7	1	0.78	0.10	0.114	
170.7-172.7	1	0.79	0.10	0.112	
172.7-173.8	1	0.69	0.10	0.126	sulf blebs
173.8-175.3	1	0.83	0.11	0.117	
175.3-176.8	1	0.82	0.14	0.146	
176.8-178.4	1	0.83	0.13	0.135	
178.4-179.9	1	0.89	0.09	0.092	
179.9-180.5	1	0.86	0.09	0.095	
180.5-181.4	1	0.91	0.09	0.090	sulf blebs
181.4-184.6	1	0.67	0.08	0.107	" "
184.6-186.3	1	0.72	0.06	0.077	
186.3-187.8	1	0.79	0.23	0.225	
187.8-189.2	1	0.83	0.06	0.067	
189.2-190.5	1	0.75	0.08	0.096	
190.5-192.2	1	0.77	0.09	0.104	
192.2-193.6	1	0.75	0.06	0.074	sulf blebs
193.6-195.1	1	0.81	0.05	0.058	" "
195.1-196.6	1	0.87	0.09	0.094	" "
196.6-198.2	1	0.80	0.09	0.101	" "
198.2-199.7	1	0.70	0.09	0.114	" "
199.7-201.2	1	0.75	0.06	0.074	" "
201.2-202.7	1	1.02	0.11	0.097	" "
202.7-204.2	1	0.99	0.11	0.100	" "
204.2-205.8	1	0.87	0.15	0.147	" "
205.8-207.3	1	0.85	0.09	0.096	" "
207.3-208.8	1	0.93	0.13	0.122	" "
208.8-210.4	1	1.23	0.18	0.128	" "
210.4-211.9	1	1.48	0.24	0.140	
211.9-213.4	1	1.36	0.34	0.200	
213.4-214.9	1	1.86	0.30	0.139	
214.9-216.5	1	1.40	0.34	0.195	
216.5-218.0	2	3.41	0.60	0.150	
218.0-219.5	2	3.41	1.10	0.244	
219.5-221.0	2	4.67	0.77	0.142	
221.0-223.6	2	4.14	1.01	0.196	
223.6-224.0	2	3.15	0.58	0.155	
224.0-225.6	2	2.97	0.45	0.132	
225.6-227.1	2	2.99	0.79	0.209	
227.1-228.6	2	3.74	0.50	0.118	
228.6-230.2	2	3.62	0.69	0.160	
230.2-231.7	2	3.21	1.36	0.298	veined ?

Donaldson West - Section 590366E

DDH 160-2 cont.

Depth range (m)	Ore texture	Ni	Cu	Cu/Cu+Ni	Comments
231.7-233.2	7	13.2	1.06	0.074	
233.2-234.8	7	11.5	2.11	0.155	
234.8-236.3	7	12.0	2.54	0.174	
236.3-237.8	7	13.8	1.36	0.090	
237.8-239.3	7	14.4	2.34	0.140	
239.3-240.8	7	11.7	2.79	0.192	
240.8-242.0	7	13.0	0.70	0.051	
242.0-243.6	7	11.9	0.88	0.069	
243.6-243.9	9	3.25	1.86	0.364	stringers
243.9-245.4	9	0.41	0.96	0.700	"

Texture code: 1=disseminated; 2=net-textured; 3=net-textured to reverse net-textured; 4=reverse net-textured; 5=veined; 6=vein, 7=massive sulfide; 8=sulfide breccia; 9=footwall stringer; 10=interstitial sulfide; Tr=trace; Ni=nickel; Cu=copper; Cp=chalcopyrite; sulf=sulfide.

DDH R-324 (590366E, 6839180N, -80°S)

Depth range (m)	Ore texture	Ni	Cu	Cu/Cu+Ni	Comments
154.5-156.0	1	0.36	0.06	0.143	
156.0-157.5	1	1.14	0.18	0.136	
157.5-159.0	1	0.47	0.05	0.096	
159.0-161.6	1	0.41	0.05	0.109	
161.6-164.6	1	0.43	0.08	0.156	
164.6-167.7	1	0.43	0.13	0.232	
167.7-170.7	1	0.53	0.09	0.145	
170.7-173.8	1	0.57	0.02	0.034	
173.8-176.8	1	0.47	0.04	0.078	
176.8-179.9	1	0.45	0.10	0.182	
179.9-182.9	1	0.41	0.08	0.163	
182.9-186.0	1	0.53	0.06	0.102	
186.0-189.0	1	0.36	0.09	0.200	
189.0-192.0	1	0.53	0.05	0.086	
192.0-195.1	1	0.39	0.04	0.093	
195.1-198.2	1	0.43	0.05	0.104	
198.2-201.2	1	0.45	0.06	0.118	
201.2-204.3	1	0.41	0.05	0.109	
204.3-207.3	1	0.34	0.05	0.128	
207.3-210.4	1	0.45	0.06	0.118	

Donaldson West - Section 590366E

DDH R-324 cont.

Depth range (m)	Ore texture	Ni	Cu	Cu/Cu+Ni	Comments
210.4-213.4	1	0.18	0.04	0.182	
213.4-215.3	1	0.10	Tr	-----	
215.3-217.2	9	0.81	0.45	0.357	stringers

Texture code: 1=disseminated; 2=net-textured; 3=net-textured to reverse net-textured; 4=reverse net-textured; 5=veined; 6=vein, 7=massive sulfide; 8=sulfide breccia; 9=footwall stringer; 10=interstitial sulfide; Tr=trace; Ni=nickel; Cu=copper; Cp=chalcopryite; sulf=sulfide.

DDH 160-220 (590367E, 6839145N, -90°)

Depth range (m)	Ore texture	Ni	Cu	Cu/Cu+Ni	Comments
100.9-102.9	1	0.33	0.05	0.132	
102.9-104.9	1	0.36	0.08	0.182	
104.9-106.9	1	0.38	0.04	0.095	
106.9-108.9	1	0.33	0.07	0.175	
108.9-110.9	1	0.76	0.15	0.164	
110.9-111.9	1	0.31	0.04	0.114	
111.9-113.9	1	0.28	0.07	0.200	
137.9-139.9	1	0.33	0.04	0.108	
139.9-141.9	1	0.27	0.06	0.182	
141.9-143.9	1	0.34	0.06	0.150	
143.9-145.9	1	0.30	0.07	0.189	
145.9-147.9	1	0.33	0.06	0.154	
147.9-149.9	1	0.51	0.09	0.150	
149.9-151.9	1	0.61	0.14	0.187	
151.9-153.9	1	0.39	0.06	0.133	
153.9-155.9	1	0.58	0.14	0.194	
155.9-157.9	1	0.43	0.06	0.122	
157.9-160.0	1	0.30	0.07	0.189	
160.0-162.0	1	0.51	0.13	0.203	
162.0-164.0	1	0.99	0.17	0.146	
164.0-166.0	1	1.41	0.18	0.113	
166.0-168.0	1	0.51	0.12	0.190	
168.0-170.0	1	0.43	0.09	0.173	
170.0-172.0	1	0.40	0.08	0.167	
172.0-174.0	1	0.73	0.18	0.198	
174.0-176.8	1	0.50	0.10	0.167	

Donaldson West - Section 590366E

DDH 160-220 cont.

Depth range (m)	Ore texture	Ni	Cu	Cu/Cu+Ni	Comments
196.9-198.9	1	0.22	Tr	-----	
198.9-200.9	1	0.46	0.08	0.148	
200.9-202.9	1	0.39	0.06	0.133	
202.9-204.9	1	0.36	0.11	0.234	
204.9-206.9	5	0.57	0.12	0.174	veined
206.9-208.9	5	0.55	0.22	0.287	"
208.9-210.9	5	0.35	0.11	0.239	"
210.9-212.9	5	0.26	0.10	0.278	"
212.9-213.9	5	0.27	0.05	0.156	"

Texture code: 1=disseminated; 2=net-textured; 3=net-textured to reverse net-textured; 4=reverse net-textured; 5=veined; 6=vein, 7=massive sulfide; 8=sulfide breccia; 9=footwall stringer; 10=interstitial sulfide; Tr=trace; Ni=nickel; Cu=copper; Cp=chalcopryite; sulf=sulfide.

Donaldson West - Section 590405 E

Cu/Cu-Ni vs Depth

Appendix J-3

Donaldson West - Section 590366 E

Cu/Cu+Ni vs Depth

Appendix J-4

Donaldson West Section -590427E

Cu/Cu+Ni vs Depth

Introduction

Surface exposure of the Donaldson Surface deposit is high, about 60 %, however, extensive fracturing from frost action obscures textural relationships, especially in the sulfide mineralized part. The surface extent of sulfide mineralization is about 60 by 100 m (Fig. K.1). Three north-south cross-sections were selected through the Donaldson Surface deposit (Figures K.1 and K.2). Erosion has removed much of the deposit, however, the ultramafic sill is believed to have been of the concentrically zoned type (Lamothe et al., 1987), grading upward from a thin pyroxenite to olivine pyroxenite margin into a peridotite core (Fig. K.3). While the Donaldson Surface deposit has an elliptical, basinlike form, columnar jointing to the south-west suggests that the basal contact of the host sill dips towards the north at about 45 degrees. The sulfide concentration, which is interpreted to be located in a footwall embayment, does not indicate a northward dip. It is possible that the Donaldson Surface deposit represents a reverse fault block of the footwall contact or alternatively, that there are two sills in the immediate area.

Discussion

Ni, Cu, Cu/Cu+Ni, and sulfide textural data from drill core holes which make up three north-south cross-sections through the Donaldson Surface deposit are presented in Appendix K-1. The central cross-section (590418E, Appendix K-2) contains drill core hole 160-225, the metallurgical core hole examined in detail in Chapters 3 and 5. Cross-sections 590391E (Appendix K-3) and 590449E (Appendix K-4) lie about 30 m west and east respectively of the section containing core hole 160-225 (see Fig. K.2).

A compilation of the three cross-sections (Appendix K-5) shows the Donaldson Surface deposit to be located in a shallow east-west trending trough. The complete stratigraphic succession of massive, net-textured, and disseminated sulfides, from base to top, occurs only in the core of the footwall depression. The thin layer of massive sulfides and most of the net-textured sulfides are located over the deepest part of the trough and have an east-west trending, elliptical plan.

Veins and veined material, as indicated from drill core logs or interpreted from Cu/Cu+Ni data, are not common. Chalcopyrite-rich veined sulfides are more abundant than Ni-rich veined material. Chalcopyrite-rich footwall stringers are rare. Sulfide mobilization, as indicated by sulfide veins or Cu/Cu+Ni values, may occur at the contacts.

However, the requirement to interpret drill core data renders the contact relationship obscure. Hand specimen examination of the sulfide-rich part of the footwall trough is required to substantiate these proposed features in the Donaldson Surface deposit.

Fig. K.1. Surface projections of the Donaldson Surface (3), Donaldson West (1), and Donaldson East (2) deposits. Line C-D refers to Fig. K.3. Geology by Falconbridge Ltd. staff. Note NS cross-sections flanking line C-D, see Fig. K.2 for locations.

Fig. K.2. Location of drill core holes through the Donaldson Surface deposit.

Fig. K.3. Cross-section C-D, looking west, through the Donaldson Surface deposit. Core hole 160-225 is 12 m west of section.

Appendix K - 1

Donaldson Surface - Section 590391E

DDH 160-78 (590395E, 6838652N, -90°)

Depth range (m)	Ore texture	Ni	Cu	Cu/Cu+Ni	Comments
4.6-6.6	5	0.08	0.33	0.805	veined diss
6.6-8.6	5	0.06	0.98	0.942	" "
8.6-10.6	5	0.04	0.95	0.960	" "
10.6-13.1	5	0.05	0.47	0.904	" "

DDH 160-71 (590387E, 6838686N, -90°)

Depth range (m)	Ore texture	Ni	Cu	Cu/Cu+Ni	Comments
4.9-6.9	1	0.53	0.14	0.209	sulfide blebs
6.9-8.9	1	0.69	0.17	0.198	sulfide blebs
8.9-10.9	1	0.77	0.39	0.336	
10.9-12.9	2	0.97	0.46	0.322	
12.9-14.9	2	1.59	0.27	0.145	
14.9-16.9	2	2.32	0.57	0.197	
16.9-18.9	2	2.04	0.31	0.132	
18.9-20.9	2	1.58	0.47	0.229	
20.9-21.3	7	3.54	0.52	0.128	

DDH 160-85 (590388E, 6838716N, -90°)

Depth range (m)	Ore texture	Ni	Cu	Cu/Cu+Ni	Comments
2.4-4.9	1	0.22	0.08	0.267	
4.9-7.0	1	0.33	0.09	0.214	
7.0-10.0	1	0.21	0.06	0.222	
10.0-11.3	1	0.52	0.12	0.188	
11.3-13.3	1	0.47	0.10	0.175	
13.3-16.8	1	0.24	0.08	0.250	
16.8-18.6	1	0.24	0.09	0.272	
18.6-21.0	2	2.86	0.76	0.211	
21.0-24.7	9	0.26	0.26	0.500	stringers

Texture code: 1=disseminated; 2=net-textured; 3=not-textured to reverse net-textured; 4=reverse net-textured; 5=veined; 6=vein, 7=massive sulfide; 8=sulfide breccia; 9=footwall stringer; 10=interstitial sulfide; Tr=trace; Ni=nickel; Cu=copper; Cp=chalcopryite; sulf=sulfide.

Donaldson Surface - Section 590418E

DDH 160-225M (590418E, 6838700N, -90°)

Depth range (m)	Ore texture	Ni	Cu	Cu/Cu+Ni	Comments
6.7-7.7	2	3.86	1.09	0.220	
7.7-8.7	2	3.65	1.09	0.230	
8.7-9.7	2	4.26	1.09	0.204	
9.7-10.7	2	4.36	0.90	0.171	
10.7-11.7	2	3.55	1.03	0.224	
11.7-12.7	2	3.60	0.67	0.157	
12.7-13.7	2	3.73	0.72	0.162	
13.7-14.7	2	3.92	0.85	0.178	
14.7-15.7	2	3.73	0.75	0.167	
15.7-16.7	2	4.23	0.77	0.154	
16.7-17.8	2	4.32	1.12	0.206	
17.8-18.4	6	10.3	0.13	0.012	Ni vein
18.4-19.4	2	4.29	0.95	0.181	
19.4-20.8	3	2.67	0.70	0.208	
20.8-21.8	10	1.49	0.79	0.346	interstitial
21.8-22.8	5	0.77	0.66	0.462	Cp veined
22.8-24.2	10	1.45	0.75	0.340	interstitial
24.2-25.2	7	7.70	1.25	0.140	
25.2-26.2	7	8.98	2.12	0.191	
26.2-27.2	7	10.4	0.93	0.082	
27.2-28.6	8	6.65	1.85	0.218	
38.6-30.6	9	2.13	0.84	0.283	
30.6-32.6	9	0.18	0.88	0.830	

Texture code: 1=disseminated; 2=net-textured; 3=net-textured to reverse net-textured; 4=reverse net-textured; 5=veined; 6=vein, 7=massive sulfide; 8=sulfide breccia; 9=footwall stringer; 10=interstitial sulfide; Tr=trace; Ni=nickel; Cu=copper; Cp=chalcopryite; sulf=sulfide.

Donaldson Surface - Section 590449E

DDH 160-91 (590450E, 6838732N, -90°)

Depth range (m)	Ore texture	Ni	Cu	Cu/Cu+Ni	Comments
2.4-4.7	1	0.46	0.08	0.148	
4.7-8.5	1	0.46	0.10	0.178	
8.5-11.5	1	0.57	0.09	0.136	
11.5-14.6	1	0.35	0.08	0.186	
14.6-17.7	1	0.34	0.08	0.190	
17.7-18.7	1	0.30	0.06	0.167	
18.7-20.3	1	0.31	0.06	0.162	
20.3-23.2	1	0.24	0.03	0.111	
23.2-27.6	1	0.24	0.04	0.142	
27.6-29.3	1	0.28	0.06	0.176	
29.3-30.7	1	0.28	0.06	0.176	

DDH 160-80 (590449E, 6838718N, -90°)

Depth range (m)	Ore texture	Ni	Cu	Cu/Cu+Ni	Comments
2.4-5.4	1	0.64	0.12	0.159	
5.4-8.5	1	0.71	0.15	0.174	
8.5-11.5	1	0.46	0.13	0.220	
11.5-14.6	1	0.53	0.12	0.184	
14.6-18.1	1	0.45	0.10	0.182	
18.1-19.8	1	0.57	0.13	0.186	
19.8-21.0	2	1.97	0.26	0.117	
21.0-22.5	2	2.30	0.38	0.142	
22.5-23.3	2	2.46	0.46	0.158	
23.3-26.2	2	1.50	0.58	0.279	
26.2-26.8	1	0.49	0.14	0.222	
26.8-27.8	1	0.58	0.14	0.226	
27.8-29.6	1	0.24	0.05	0.172	
29.6-33.2	1	0.21	0.04	0.160	

Texture code: 1=disseminated; 2=net-textured; 3=net-textured to reverse net-textured; 4=reverse net-textured; 5=veined; 6=vein, 7=massive sulfide; 8=sulfide breccia; 9=footwall stringer; 10=interstitial sulfide; Tr=trace; Ni=nickel; Cu=copper; Cp=chalcopyrite; sulf=sulfide.

Donaldson Surface - Section 590449E

DDH 160-67 (590446E, 6838688N, -90°)

Depth range (m)	Ore texture	Ni	Cu	Cu/Cu+Ni	Comments
4.5-5.6	2	1.90	0.56	0.228	
5.6-8.5	2	1.11	0.30	0.212	
8.5-11.6	1	0.31	0.14	0.311	
11.6-14.3	1	0.47	0.17	0.265	
14.3-15.0	5	0.28	0.35	0.555	Cp veined
15.0-17.0	5	0.51	0.59	0.536	" "
17.0-17.8	1	0.44	0.12	0.214	
17.8-18.7	1	0.28	0.21	0.428	
18.7-18.9	6	3.92	0.68	0.148	Ni vein
18.9-22.9	1	0.47	0.14	0.229	
22.9-25.9	9	0.11	0.19	0.633	stringers
25.9-28.9	9	0.08	0.07	0.466	stringers

Texture code: 1=disseminated; 2=net-textured; 3=net-textured to reverse net-textured; 4=reverse net-textured; 5=veined; 6=vein, 7=massive sulfide; 8=sulfide breccia; 9=footwall stringer; 10=interstitial sulfide; Tr=trace; Ni=nickel; Cu=copper; Cp=chalcopyrite; sulf=sulfide.

Appendix K-2

Donaldson Surface - Section 509418 E

Cu/Cu+Ni vs Depth

Appendix K-3

Donaldson Surface - Section 590391E

Appendix K-4

Donaldson Surface - Section 590449 E

Cu/Cu+Ni vs Depth

DONALDSON SURFACE

Cu/Cu+Ni and sulfide textural data

Appendix K-5

Key for Appendix K - 5.

footwall contact

massive sulfide/net-textured
sulfide contact

net-textured/disseminated
sulfide contact

Appendix L

Compositions of cobaltite-gersdorffite grains plotted on the experimental FeAsS - CoAsS - NiAsS ternary (Klemm, 1965). Solid triangles=160-224-239.5m (vein), solid dots=160-225 net-textured sulfides, solid squares=160-225 massive sulfides, and empty squares=160-225-32.6m (sulfide breccia).

END

29/06/89

FIN