

APPLIED MINERALOGY IN THE MINING INDUSTRY

William Petruk
Ottawa, Ontario, Canada



2000

ELSEVIER

Amsterdam - Lausanne - New York - Oxford - Shannon - Singapore - Tokyo

TABLE OF CONTENTS

PREFACE	v
ACKNOWLEDGEMENTS	viii
CREDITS	ix
TABLE OF CONTENTS	x

CHAPTER 1

GENERAL PRINCIPLES OF APPLIED MINERALOGY

1.1. INTRODUCTION	1
1.2. APPLIED MINERALOGY INVESTIGATIONS	2
1.2.1. Identifying minerals and determining mineral compositions	3
1.2.1.1. Base metal ores	3
(1) Main minerals of economic value and gangue	4
(2) Silver minerals	4
(3) Sphalerite	4
(4) Gold	4
(5) Tin and indium minerals	5
(6) Secondary copper minerals	5
(7) Anglesite (PbSO_4)	5
(8) Deleterious elements	5
1.2.1.2. Minerals in greisen-type tin-tungsten deposits	6
1.2.1.3. Minerals in porphyry-copper ores	7
1.2.1.4. Minerals in iron ores	7
1.2.2. Quantities of minerals	8
1.2.3. Size distribution	9
1.2.3.1. Predicting grind	9
1.2.3.2. Ground or powdered materials	11
1.2.4. Mineral liberations	12
1.2.4.1. Stereological corrections	16
1.2.4.2. Measurements of mineral liberations in sieved fractions and unsieved samples	20
1.2.4.3. Discussion	22
1.2.5. Textures	23
1.2.6. Mineral associations	24
1.2.6.1. Binary mineral technique	24
1.2.6.2. Dominant mineral technique	24
1.2.6.3. Average composition of average particle	24
1.2.6.4. Proportion of mineral in contact with other minerals	25
1.2.7. Surface coatings on particles	25
1.2.8. Search for rare minerals	25

CHAPTER 2

INSTRUMENTS FOR PERFORMING APPLIED MINERALOGY STUDIES

2.1. INTRODUCTION	27
2.2. OPTICAL MICROSCOPES	28
2.3. X-RAY DIFFRACTOMETER	29
2.4. SCANNING ELECTRON MICROSCOPE (SEM) WITH ENERGY DISPERSIVE X-RAY ANALYSER (EDS)	31
2.4.1. Low-vacuum SEM	34
2.5. ELECTRON MICROPROBE (MP)	34
2.6. PROTON INDUCED X-RAY EMISSION (PIXE)	36
2.7. SECONDARY ION MASS SPECTROMETER (SIMS) AND (ToF-SIMS)	37
2.8. LASER IONIZATION MASS SPECTROMETER (LIMS) AND ToF-LIMS	38
2.9. CATHODOLUMINESCENCE (CL)	39
2.10. INFRARED SPECTROSCOPY	43
2.11. IMAGE ANALYSIS SYSTEM	43
2.11.1. Optical microscope	44
2.11.2. Scanning electron microscope (SEM) or microprobe (MP)	45
2.11.2.1. Discrimination by grey levels (grey level images)	45
2.11.2.2. Discrimination by mineral compositions (several minerals with same grey levels)	46
2.11.3. QEM-SEM	47
2.11.4. Enhancement	47
2.11.5. Preparing binary images of minerals for measurement	47
2.11.6. Mineral quantities	48
2.11.7. Size distributions of minerals	48
2.11.8. Grain shapes and grain boundary irregularities	49
2.11.9. Liberations of minerals	49
2.11.10. Mineral associations	49
2.11.11. Applications of image analysis to on-line control	49

CHAPTER 3

MINERALOGICAL CHARACTERISTICS AND PROCESSING OF MASSIVE SULFIDE
BASE METAL ORES FROM THE BATHURST-NEWCASTLE MINING AREA

3.1. INTRODUCTION	51
3.2. GENERAL CHARACTERISTICS OF BATHURST-NEWCASTLE BASE METAL DEPOSITS	51
3.2.1. Mineralogical characteristics	52
3.2.1.1. Pyrite	52
3.2.1.2. Sphalerite	52
3.2.1.3. Galena	53
3.2.1.4. Chalcopyrite	54
3.2.1.5. Silver	55

3.2.1.6. Gold	56
3.2.1.7. Trace minerals	57
3.3. APPLIED MINERALOGY STUDIES OF BRUNSWICK No. 12 AND BRUNSWICK No. 6 ORES	57
3.3.1. Size distributions and mineral liberations	58
3.3.2. Texture Analysis	63
3.4. APPLIED MINERALOGY STUDIES OF PRODUCTS FROM THE Cu-Pb ROUGHER CIRCUIT IN BMS CONCENTRATOR	64
3.4.1. Sphalerite	65
3.4.2. Pyrite	66
3.4.3. Galena	66
3.5. SUMMARY	70

CHAPTER 4

VOLCANOGENIC BASE METAL DEPOSITS IN THE FLIN FLON-SNOW LAKE AREAS, MANITOBA, CANADA

4.1. INTRODUCTION	73
4.2. CHARACTERISTICS OF TROUT LAKE AND CALLINAN ORES	73
4.2.1. Trout Lake ores	77
4.2.1.1. Massive sphalerite (MS) ore type	77
4.2.1.2. Banded pyrite + sphalerite (BP+S) ore type	77
4.2.1.3. Massive pyrite (MP) ore type	77
4.2.1.4. Mixed/banded chalcopyrite + sphalerite (M/BC+S) ore type	78
4.2.1.5. Sheared chalcopyrite + sphalerite (SC+S) ore type	79
4.2.1.6. Massive chalcopyrite + pyrrhotite (MC+P) ore type	79
4.2.1.7. Vein quartz and chalcopyrite (VQ+C) ore type	81
4.2.1.8. Chalcopyrite stringer (CS) ore type	81
4.2.1.9. Disseminated pyrite and chalcopyrite (DP+C) ore type	81
4.2.2. Callinan ore types	82
4.2.2.1. Pyrite ore type	82
4.2.2.2. Sheared pyrite ore	82
4.2.2.3. Pyrrhotite ore type	83
4.2.2.4. Sheared pyrrhotite ore type	83
4.3. MINERALS IN TROUT LAKE AND CALLINAN ORES	85
4.3.1. Pyrite (FeS_2)	85
4.3.2. Pyrrhotite ($\text{Fe}_{(1-x)}\text{S}$)	85
4.3.3. Chalcopyrite (CuFeS_2)	87
4.3.4. Sphalerite (ZnS)	88
4.3.5. Galena (PbS)	88
4.3.6. Au-Ag-Hg alloy	88
4.3.7. Other Minerals	89
4.4. MINERAL PROCESSING	90
4.4.1. Cu concentrate	91
4.4.1.1. Chalcopyrite	91

4.4.1.2. Sphalerite	95
4.4.1.3. Pyrite	95
4.4.1.4. Gold	95
4.4.1.5. Silver	96
4.4.1.6. Galena	97
4.4.1.7. Tellurium	97
4.4.1.8. Selenium and antimony	97
4.4.2. Zn concentrate	98
4.4.2.1. Sphalerite	98
4.5. SUMMARY AND CONCLUSIONS	99

CHAPTER 5

RELATIONSHIPS BETWEEN MINERAL CHARACTERISTICS AND FLOTABILITY

5.1. INTRODUCTION	103
5.2. FLOTABILITY OF CHALCOPYRITE-BEARING PARTICLES	103
5.2.1. Chalcopyrite in a base metal ore	103
5.2.1.1. Conclusions	104
5.2.2. Test tube flotation test	104
5.2.2.1. Conclusions	105
5.2.3. Characteristics of chalcopyrite in cleaner flotation tails of a commercial concentrator	105
5.3. NICKEL IN SERPENTINIZED ORE	107
5.3.1. Conclusions	109

CHAPTER 6

APPLIED MINERALOGY RELATED TO GOLD

6.1. INTRODUCTION	111
6.2. MINERALOGY	111
6.3. TEXTURES AND MICROSTRUCTURES	113
6.3.1. Gold in fractures and microfractures in rocks, and in veinlets and microveinlets in minerals	113
6.3.2. Gold in interstitial spaces between mineral grains and at borders of mineral grains	115
6.3.3. Encapsulated gold in a host mineral	115
6.3.4. Submicroscopic gold associated with framboidal pyrite	115
6.3.5. Submicroscopic gold associated with very fine-grained clay minerals	118
6.3.6. Gold in oxidized zones	118
6.4. TYPES OF GOLD DEPOSITS	118
6.4.1. Gold in shear zones	119
6.4.2. Gold in Carlin-type deposits	119
6.4.3. Gold in volcanogenic massive sulfide base metal deposits	120
6.4.4. Gold associated with porphyry copper deposits	121
6.4.5. Gold in conglomerate (Witwatersrand-type) deposits	121

6.4.6. 'invisible' gold	121
6.5. CHARACTERIZING GOLD ORE WITH RESPECT TO PROCESSING	122
6.5.1. Selecting samples and fractions for analysis	122
6.5.2. Assaying the sample and fractions	123
6.5.3. Identifying the minerals	123
6.5.4. Determining mineral contents	123
6.5.5. Proportion of exposed and encapsulated gold in each sieved fraction	124
6.5.6. Amount of cyanidable gold	124
6.5.7. Diagnostic leaching	125
6.5.8. 'Invisible' gold (microbeam analysis and staining)	125
6.5.9. Calculating mineral balance for gold among different minerals	126
6.6. PROCESSING GOLD ORES	126
6.6.1. Leaching (Cyanidation)	126
6.6.2. Refractory gold ores	127
6.6.2.1. Roasting	127
6.6.2.2. Pressure leaching	128
6.6.2.3. Bioleaching	128
6.6.3. Flotation	128
6.6.4. Gravitational techniques	129
6.6.5. Heap Leaching	129
6.6.5.1. Vein type deposits	130
6.6.5.2. Carlin-type deposits	130
6.6.5.3. Volcanogenic massive sulfide base metal deposits	131
6.6.5.4. Porphyry copper deposits	131
6.6.5.5. Bioleaching	131
6.7. SELECTED EXAMPLES OF CHARACTERIZING GOLD TAILINGS	132
6.7.1. Gold in tailings from David Bell circuit, Teck-Corona, Hemlo, Ontario	132
6.7.2. Gold tailings, Nor Acme Mine, Snow Lake, Manitoba	132

CHAPTER 7

APPLIED MINERALOGY: PORPHYRY COPPER DEPOSITS

7.1. INTRODUCTION	135
7.2. CHARACTERISTICS OF PORPHYRY COPPER DEPOSITS	135
7.2.1. Primary ore minerals	136
7.2.1.1. Vein density	136
7.2.1.2. Silicification	136
7.2.2. Alteration	137
7.2.2.1. Potassic alteration	138
7.2.2.2. Phyllic alteration	138
7.2.2.3. Argillic alteration	139
7.2.2.4. Propylitic alteration	139
7.2.2.5. Distribution of other minerals	139
7.2.2.6. Hypogene and alteration non-metallic minerals	140
7.2.3. Maturity	140

7.2.4. Role of sulfur	141
7.2.5. Depth of porphyry copper system	141
7.2.6. Supergene mineralization	142
7.2.6.1. Mineralogy of cap	142
7.2.6.2. Mineralogy of blanket zone	143
7.3. APPLIED MINERALOGY RELATED TO MINERAL PROCESSING	144
7.3.1. Mineralogical characterization of intensely oxidized ores	144
7.3.2. Mineralogical characterization of partly oxidized ores	144
7.3.3. Mineralogical characterization of primary ores	145
7.4. IDENTIFYING MINERALS	146

CHAPTER 8

MINERALOGICAL CHARACTERISTICS AND PROCESSING OF IRON ORES

8.1. INTRODUCTION	149
8.2. IRON ORES IN THE LABRADOR TROUGH	149
8.2.1. Characteristics of the ores	149
8.2.1.1. Ores of the Iron Ore Company of Canada (IOC), Labrador City, Newfoundland	150
8.2.1.2. Ores in the Wabush deposits	150
8.2.1.3. Ores in the Mount Wright deposits	150
8.2.2. Mineralogy	150
8.2.2.1. Hematite (Fe_2O_3)	151
8.2.2.2. Magnetite (Fe_3O_4)	151
8.2.2.3. Martite	151
8.2.2.4. Goethite ($\text{FeO}(\text{OH})$)	151
8.2.2.5. Limonite	153
8.2.2.6. Mn Minerals	154
8.2.2.6.1. Pyrolusite (MnO_2)	154
8.2.2.6.2. Psilomelane (Mn oxide with 40 to 50 wt % Mn)	154
8.2.2.6.3. Wad (Mn oxide with 18 to 22 wt % Mn)	154
8.2.2.6.4. Ankerite and Siderite	154
8.2.3. Mining	155
8.2.4. Mineral Processing	155
8.2.4.1. A case history: determining mineral characteristics that affect mineral processing of IOC ores	155
8.2.4.1.1. Mineral characteristics of ore and concentrator products	156
8.2.4.1.2. Pilot plant tests and mineralogical characteristics of products	160
8.2.4.1.3. Modifications to IOC plant	165
8.2.4.2. Mineralogical characteristics of ore from the Wabush Deposits	166
8.2.4.3. Mineralogical Characteristics of ore from the Mount Wright deposits and evaluation of QCM concentrator	172
8.3. OOLITIC IRON ORE IN THE PEACE RIVER DEPOSIT	176
8.3.1. Mineralogical characteristics of the Peace River iron deposits	176
8.3.2. Laboratory mineral processing tests	179

8.4. SUMMARY	180
8.4.1. Carol Lake ores	180
8.4.2. Wabush ore	181
8.4.3. Mount Wright ores	182
8.4.4. Minette-type Peace River ironstone	182

CHAPTER 9

APPLIED MINERALOGY INVESTIGATIONS OF INDUSTRIAL MINERALS

9.1. INTRODUCTION	185
9.2. GRAPHITE	186
9.2.1. A case history of characterizing a graphite ore	186
9.2.2. Method of Analysis	187
9.2.3. Results	187
9.2.4. Interpretation of Results	189
9.2.5. Recommendations	190
9.2.6. Beneficiation improvement	190
9.3. TALC	190
9.3.1. Applied Mineralogy in exploration	190
9.3.2. Applied Mineralogy related to mineral processing	191
9.3.3. Applied mineralogy in quality control of cosmetic products	192
9.4. WOLLASTONITE	192
9.4.1. A case history of characterizing a wollastonite ore	193
9.5. GARNET	194
9.5.1. Mineralogical study of a garnet deposit	195
9.6. QUARTZ	195
9.6.1. Mineralogical study of quartz	196
9.6.2. Characterizing quartz with respect to manufacturing silicon and ferrosilicon ...	197
9.7. METHOD OF CHARACTERIZING AIRBORNE DUSTS	198

CHAPTER 10

APPLIED MINERALOGY TO TAILINGS AND WASTE ROCK PILES - SULFIDE OXIDATION REACTIONS AND REMEDIATION OF ACIDIC WATER DRAINAGE

10.1. INTRODUCTION	201
10.2. GENERAL CHARACTERISTICS OF TAILINGS AND WASTE ROCK PILES ..	202
10.3. MINERALOGICAL STUDIES OF TAILINGS AND WASTE ROCK PILES	204
10.3.1. Objective	204
10.3.2. Sampling and method of analysis	204
10.4. MINERALS	206
10.5. REACTIONS IN TAILINGS PILES	206
10.5.1. Oxidation of sulfide minerals	206
10.5.1.1. Pyrite	208
10.5.1.2. Pyrrhotite	209

10.5.2. Dissolution of Carbonate minerals	210
10.5.3. Dissolution of aluminum hydroxides, aluminosilicates and silicates	210
10.5.4. Precipitation of secondary minerals	212
10.5.4.1. Soluble iron sulfates	212
Melanterite ($\text{Fe}^{2+}\text{SO}_4 \cdot 7\text{H}_2\text{O}$)	212
rozenite ($\text{Fe}^{2+}\text{SO}_4 \cdot 4\text{H}_2\text{O}$)	212
siderotil ($\text{Fe}^{2+}\text{SO}_4 \cdot 5\text{H}_2\text{O}$)	212
10.5.4.2. Less soluble sulfate minerals	213
10.5.4.3. Insoluble ferric oxyhydroxides and sulfates	213
Goethite ($\alpha\text{-FeO(OH)}$)	213
Lepidocrocite ($\gamma\text{-FeO(OH)}$)	213
Ferrihydrite ($\text{Fe}_2\text{O}_3 \cdot 9\text{H}_2\text{O}$)	213
Schwertmannite ($\text{Fe}_8\text{O}_8\text{SO}_4(\text{OH})_6$)	213
Jarosite ($\text{KFe}_3(\text{SO}_4)_2(\text{OH})_6$)	213
10.5.5. Precipitation of arsenic-bearing minerals	214
Scorodite ($\text{Fe}^{3+}\text{AsO}_4 \cdot 2\text{H}_2\text{O}$)	214
Mansfieldite ($\text{AlAsO}_4 \cdot 2\text{H}_2\text{O}$),	214
Beudantite ($\text{PbFe}^{3+}_3(\text{AsO}_4)(\text{SO}_4)(\text{OH})_6$)	214
10.5.6. Precipitation of phosphates	214
10.5.7. Predicting secondary minerals	215
10.5.8. Correlating pH, pore water concentrations, rock chemistry and mineralogy in tailings piles	216
10.5.8.1. pH in site O tailings pile	216
10.5.8.2. primary minerals in site O tailings pile	216
10.5.8.3. Pore water chemistry in site O tailings pile	216
10.5.8.4. Secondary minerals in site O tailings pile	218
10.6. REMEDIATION AND PREVENTION OF ACIDIC DRAINAGE FROM MINE WASTES	218
10.6.1. Treatment of acidic water	219
10.6.1.1. On-site treatment facilities	219
10.6.1.2. Continuous flow reactors	219
10.6.1.3. Downstream wetlands	219
10.6.2. Infiltration controls	220
10.6.3. Sulfide oxidation controls (Tailings Management Programs)	220
10.6.3.1. Restricting entrance of oxygen	221
Disposal of tailings into deep lakes	221
A water pond established above tailings behind retention dams	221
A bog on the tailings surface	221
Oxygen-consuming covers	221
Dry covers	222
10.6.3.2. Enhanced sulfate reduction	222
10.6.3.3. Thickened slurry with moisture retaining capabilities	222
10.6.3.4. Precipitates that coat sulfide mineral surfaces	222
10.6.3.5. precipitation of heavy metals in reservoir minerals.	223
10.6.3.6. Bactericidal controls	223
10.6.3.7. Cemented "hardpan" layers	223

10.6.3.8. Separating sulfide minerals from gangue minerals	223
10.7. SUMMARY	223
REFERENCES	227
SUBJECT INDEX	259
MINERAL INDEX	265