ORE PETROLOGY AND APPLIED MINERALOGY OF THE TROUT LAKE MASSIVE SULFIDE DEPOSIT, FLIN FLON, MANITOBA.

by

RAYMOND E. HEALY

A thesis
presented to the University of Manitoba
in fulfillment of the
thesis requirement for the degree of
MASTER OF SCIENCE
in
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To family and friends.

ABSTRACT

The ore mineralogy of the Trout Lake massive sulfide deposit, Flin Flon, Manitoba has been investigated. Nine ore types are defined, of which seven form a differentiation series from the Zn-rich hangingwall ores to the Cu-rich footwall ores. The remaining two ore types are of tectonic origin. Two groups of elements: (1) the Zn-Group (Zn, Cd, Sb, Pb, Ag, Hg, In, Sn and As), and (2) the Cu-Group (Cu, Se, Te, Co and Fe) form the principal geochemical associations of the ores.

Twenty six ore minerals including sulfides, oxides, sulfosalts, sulfantimonides, alloys, intermetallic compounds, tellurides and selenides have been identified. The principal Zn- and Cu-minerals are sphalerite and chalcopyrite, respectively. Twelve Ag-bearing minerals were identified or inferred, of which sulfosalts and tellurides account for <24% of the Ag, Au-Ag-Hg alloy for <19% of the Ag, and galena for 3% of the Ag in the ore. Chalcopyrite, pyrite and sphalerite are inferred to contain 45, 11 and 55ppm Ag, respectively, corresponding to 23, 14 and 19% of the Ag in the ore. The average composition of Au-Ag-Hg alloy (in wt%) is 49.2% Ag, 38.7% Au, 11.0% Hg and 0.70% Fe. 'Invisible' Au in pyrite (0.72ppm Au) and arsenopyrite (30.2ppm Au) account for 6 and 1%, respectively of the Au in the ore; 93% occurs as Au-Ag-Hg alloy.

From image analysis determined grain size data, minimum grinds for liberating sphalerite, chalcopyrite, pyrite, galena and freibergite are calculated as +208um, -175um, -95um, -48um and -60um, respectively. Similarly, the optimum grinds for liberating the above minerals are -52um, -52um, -26um, -9um and -5um, respectively. Predicted minimum liberations are 73% for sphalerite, and 69% for chalcopyrite.

Two textural types of Au-Ag-Hg alloy are recognized: (1) inclusions, grain coatings on, interstitial-fillings and fracture-fillings in, pyrite; and (2) large (<5mm) anastomosing masses. The losses of Au to the tailings are due largely to extremely fine-grained Type 1 Au-Ag-Hg alloy entrapped in pyrite (64%), and Au in solid solution in pyrite and arsenopyrite (36%). The principal Ag losses to the tailings are largely due to Ag in solid solution in pyrite, and poor recovery of pyrargyrite. The environmentally hazardous elements As and Hg are largely rejected to the tailings, and backfilled underground.

Chalcopyrite Stringer and Disseminated Pyrite + Chalcopyrite ore types represent tectonically flattened feeder pipe mineralization. Vein Quartz + Chalcopyrite ore type is evidence of limited sulfide mobilization during metamorphism. Diablastic texture, characterized by myrmekitic intergrowths of chalcopyrite, sphalerite and pyrrhotite was produced by a quartz-diorite intrusion of the large Lens 2 of north zone. This texture is not amenable to grinding, and may yield middling particles of chalcopyrite and sphalerite, which will be recovered in the Cu-concentrate.

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SYMBOLS AND ABBREVIATIONS

Acan	acanthite	Gal	galena
Asp	arsenopyrite	Gud	gudmundite
Boul	boulangerite	Hess	hessite
Bour	bournonite	Mag	magnetite
Cl	clausthalite	Ma	marcasite
Cst	cassiterite	Nau	naumannite
Cos	costibite	Pil	pilsenite
Cp	chalcopyrite	Po	pyrrhotite
Cub	cubanite	Py	pyrite
Dys	dyscrasite	Pyr	pyrargyrite
El	Au-Ag-Hg alloy	Ru	rucklidgeite
Fr	freibergite	Sp	sphalerite
Frs	freieslebenite	Vol	volynskite

Gan	gangue	um	micrometer
Qtz	quartz	mm	millimeter
Carb	carbonate	cm	centimeter
Bt	biotite	m	meter
Chl	chlorite	ppm	parts per million
PGE	Platinum group element	wt%	weight %
PGM	Platinum group mineral	at%	atomic %
Iss	Intermediate solid solution	vol%	volume %

EMPA	Electron microprobe analysis	Eo	Excitation voltage
IA	Image analysis	Sc	Sample current
EDS	Energy dispersive system	nA	Nanoamperes
EDA	Energy dispersive analysis	kV	Kilovolts
WDS	Wavelength dispersive system	eV	Electron volts
WDA	Wavelength dispersive analysis	ROI	Region of interest
BSE	Backscattered electron	StD	Standard deviation
SEM	Scanning electron microscopy	Z	Average atomic number
SIMS	Secondary ion mass spectrometry		
UoM	University of Manitoba		
MicroPIXE	Micro proton induced X-ray excitation		

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Chapter I

INTRODUCTION

Volcanogenic massive sulfide deposits constitute one of the principal sources of the metals Cu, Zn, Pb, Ag, Au and Cd. In addition, the elements Co, Ni, As, Se, Sn, In, Sb, Te, Hg and Bi may be present in significant concentrations, such that they are economically recoverable as by-products, or strongly influence the processing of the ores from a mineral beneficiation, metallurgical or environmental standpoint (Chen & Petruk 1980, Petruk 1985). Typically Fe is the most abundant metal in these deposits and principally occurs in pyrite or pyrrhotite, both of which constitute economically unrecoverable forms of that metal. These polymetallic ores are commonly fine-grained, texturally complex and are often referred to as complex sulfide ores (Petruk 1985).

The initial step in the processing of complex sulfide ores involves mineral beneficiation, whereby the ores undergo grinding to liberate the valuable mineral(s), and concentrating these minerals into mineral-specific products termed concentrates. Ideally, such a concentrate consists of a specific mineral or minerals, with the minimum of dilution or contamination from other minerals present in the ore. This can only be achieved if the mineral(s) of interest occur as free grains or in composite particles with minimal amounts of other minerals (Petruk 1984). It therefore becomes critical during processing that the mineral(s) of interest occur predominantly as free grains and that these grains are preferentially concentrated in a given product. Thus, the ability of even the most efficient processing plant to produce high grade concentrates with simultaneously high metal recovery hinges on the degree of liberation of the mineral(s) of interest.

Optimum plant efficiency can only be achieved by maximizing the recovery of free grains (Petruk 1984). However, analytical chemistry, the conventional method of evaluating metallurgical products from ore processing plants, fails to address the mineralogical nature of the material, and its control on the chemistry of the products. Critical information pertaining to mineral composition, mode of occurrence, particle size and degree of liberation of the mineral(s) of interest remains neglected or undetermined (Ahlrichs 1984). Because mineral processing operates by exploiting the physico-chemical characteristics of the ore minerals, and not that of their contained metals, 'Applied' or 'Process' Mineralogy is gaining recognition as an integral component in the overall process of extracting metals from ore. In the present highly competitive world market, and with the need to work progressively lower grade and mineralogically complex deposits, with the additional need to select processes that are sensitive to the environment, the procurement of mineralogical control on process selection, design, monitoring, evaluation and optimization is essential to economic viability and sustainable development.

Process mineralogy utilizes advanced analytical techniques such as electron microprobe analysis (EMPA), image analysis (IA) and secondary ion mass spectrometric (SIMS) analysis in order to understand, evaluate, optimize and diversify industrial processes. Two of the more important types of process mineralogical studies are: (1) assess ore and predict it's behaviour during processing; and (2) examine it's behaviour in existing plants, and hence evaluate process performance.

The objective of 'ore assessment' is to determine the mineralogical characteristics of the ore that affect the behaviour of the valuable minerals, and hence metals, during beneficiation. Thus, mineral and metal behaviour during beneficiation can be predicted, the potential viability of a deposit can be assessed, and applicable processes and optimum circuit configuration can be selected. Some of the key factors considered include: (1) grinding charactersitics; (2) ore mineral identification, chemistry and quantities; (3) grain size and degree of intergrowth of the ore minerals; (4) host mineralogy of the precious metals or PGE's, and their amenability to recovery; (5) occurrence of minerals that are likely to interfere with the process; and (6) heterogeneity of the ore, and problems likely to be encountered when processing specific ore types, lenses or veins. These data are also critical to understanding laboratory bench tests that preceed process selection and design and plant production or modification.

The objective of 'process evaluation' is to examine the behaviour of minerals through circuits, by material balance modelling any specific category of mineral or particle (e.g., free grains of sphalerite) through the circuit under simulated steady-state conditions. Thus, circuit performance can be quantitatively modelled and the distribution process parameters or variables (e.g., chemical assays, mineral abundances, grain sizes and liberations) can be assessed. Problem areas in circuit performance can thus be identified, and remedial actions can be proposed such as: (1) pre-concentration; (2) adjust grinding conditions; (3) selection of regrind; (4) optimum reagent conditions; and (5) others. Such studies may be undertaken for circuit optimization, periodic monitoring or trouble shooting on a 'one of a kind' basis. Importantly, process optimization not only aims at improving metal recoveries, but also in reducing process costs and environmentally hazardous emissions.

A research project entitled "The mineralogical characteristics that affect metal recoveries from the Cu, Zn, Pb and Ag ores from Manitoba" was established under the auspices of 1984 CANADA-MANITOBA MINERAL DEVELOPMENT AGREEMENT. The objective of the project was to establish whether the volcanogenic massive sulfide deposits of Manitoba contain unique mineralogical characteristics, and to determine whether these characteristics can be utilized to modify metallurgical practises, so that recovery could be optimized. The first deposit selected for study was the Trout Lake mine. Trout Lake was selected because: (1) it is the richest deposit in the Flin Flon - Snow Lake mining camp; (2) the Cu-concentrate commonly assays 5 wt% Zn, corresponding to losses of 15% Zn; (3) approximately 30% of the Au and of the Ag are lost to the tailings; and (4) the ore is processed in a separate, dedicated concentrator circuit, permitting direct translation of mineralogical data from the ore to the plant environment. The Trout Lake deposit consists of complex sulfide ores that contain economically recoverable quantities of the metals Cu, Zn, Au, Ag, Pb and Cd.

The study was divided into two parts: Part 1, to define the mineralogical characteristics that could have a bearing on mining and mineral processing (Healy & Petruk 1988), and Part 2, a mineralogical study of the behaviour of the minerals in the concentrator (Healy & Petruk 1989). Part 1 involved collecting a representative suite of samples from the deposit, fitting them into a classification based largely on that developed by the mine geologist, and characterizing the ore from each classification. The ore characterization involved identifying the minerals, determining mineral quantities, determining the average chemical composition, defining the host mineral(s) for each element of interest, determining the size distribution of the minerals in the unbroken ore, and noting mineral textures that might have a bearing on mineral beneficiation. Importantly, although this study defines mineralogical characteristics that affect processing, many of these same characteristics also provide fundamental information on ore genesis. This thesis is a synthesis of several reports and papers that were done under Part 1 of the study (Healy & Petruk 1988, 1990a, 1990b, In Prep.), and additionally incorporates some of the findings of Part 2 where these superscede those of Part 1.

Chapter II

DISCOVERY, DEVELOPMENT AND PRODUCTION

The Trout Lake deposit is located 5km northeast of Flin Flon (Fig. 1). The deposit was discovered by Granges Exploration in the winter of 1976 during a diamond drilling follow-up program to airborne and ground geophysical surveys (Muzylowski 1979). The mine is a joint venture of Hudson Bay Mining & Smelting Co. Ltd. (HBM&S), Granges Exploration, Manitoba Mineral Resources and Outokumpu Oy. The mine was brought into production by HBM&S (operator) in 1982 at a cost of $30.3 million (Duval 1985). As of the 1st of January 1986 six lenses had been proven and developed, the grades and tonnages of which are given in Table 1

Because the mine underlies Trout (Embury) Lake it is accessed by a decline, and uses largely trackless vehicles. These include 40 ton Toro ore trucks, which haul the ore to the primary crusher just below the surface. From here the minus 6 inch ore is conveyed to two 300 ton ore bins in the load-out building on surface, from where trucks haul it to Flin Flon. Further proven and probable ore has been delineated at depth necessitating a $20 million shaft development to the 560 m level, with hoisting of ore to start in 1991. The operation presently produces approximately 3,400 ton per day, and employs a mechanized 'Cut and Fill' mining method. Mining costs are approximately $19 per ton, and average productivity is 4.2 tons per manhour, making Trout Lake one of the lowest-cost, and the most productive underground base metal mines in the world (Yungwirth 1988). Based on the average metal content per ton, and average market price received in 1988 (Inspiration Resources 1989), it is apparent that the 'simplified market value' of \$152 greatly exceeds the combined mining (approximately \$19) and processing (approximately \$10) costs per ton, making Trout Lake one of HBM&S' most lucrative operations.

To simplify accounting with its partners in the Trout Lake Joint Venture, HBM&S process the ore in a separate concentrator circuit in their concentrator-smelter complex in Flin Flon. The ore is crushed to minus 1.75 inch and fed to the rod mill and ball mill in a closed circuit configuration (Wells 1985). The grind is generally set at 60 to 65% minus 325 mesh (43um), and after reagent conditioning is fed to the head of the flotation circuit. HBM&S practise standard flotation, with chalcopyrite recovery in the Cu-circuit, followed by $CuSO_4$ activation and recovery of sphalerite in the Zn-circuit. A secondary ball mill is used to regrind one of several streams so as to increase liberation at those points in the circuit. Both the Cu- and the Zn-concentrates are combined with the corresponding concentrates from the main HBM&S circuit, which presently processes ore from the Callinan mine, and are fed to the Cu-Smelter and Zinc Plant, respectively. The circuit tailings are trucked back to the mine for use as hydraulic backfill. The combined production and ore reserves, and the remaining proven ore reserves as of January 1st 1986 (Ko, 1986) are presented in Table 2. The concentrate and tailings grades and the metal recoveries are presented in Table 3.

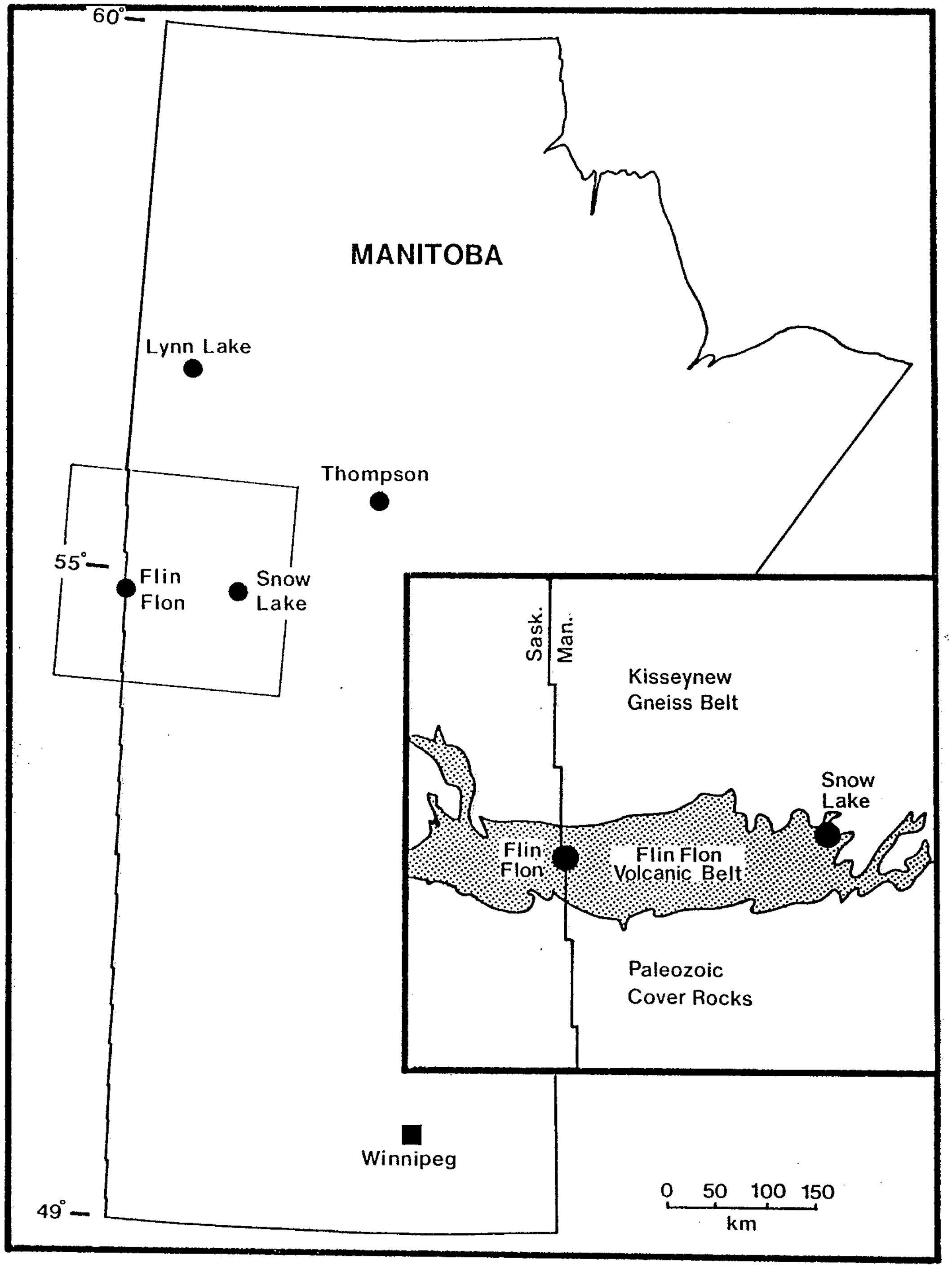

Figure 1: Location Map of the Proterozoic Flin Flon - Snow Lake Greenstone Belt. The insert shows the location of the Flin Flon and Snow Lake mining camps within the east-west trending greenstone belt, which straddles the Manitoba - Saskatchewan border. Redrawn from Ko (1986).

TABLE 1

Grades and Tonnages of the Six Proven Ore Lenses

Lense	Tonnage (1000's)	Au Grade (ppm)	%	Ag Grade (ppm)	%	Cu Grade (wt%)	%	Zn Grade (wt%)	%
North Zone									
No. 1 Lens	487	1.303	6.	13.03	6.	2.22	8.	4.0	6.
No. 2 Lens	2213	2.367	48.	17.49	39.	2.69	41.	7.4	47.
South Zone									
No. 1 Lens	1098	1.715	17.	18.87	21.	2.25	17.	4.2	13.
No. 2 Lens	307	1.372	4.	20.24	6.	0.84	2.	6.1	5.
No. 3 Lens	1591	1.303	19.	7.546	12.	2.81	31.	4.2	19.
No. 5 Lens	613	1.029	6.	25.38	16.	0.29	1.	6.0	11.

Notes: 1. '%' denotes percentage of total inventory of that metal (Ko 1986).

2. Precious metal data is given in ppm, and is recalculated from oz/t using a conversion factor of 34.3.

TABLE 2

Trout Lake Production and Reserves as of January 1st 1986

	Tons (million)	Au (ppm)	Ag (ppm)	Cu (%)	Zn (%)
Combined Production and Reserves	6.31	1.715	15.78	2.28	5.6
Proven Reserves	4.63	1.749	16.81	2.32	6.1

Note: Data includes 15% dilution and 92.9% mining recovery (Ko 1986).

TABLE 3

Trout Lake Circuit Balance on February 5th 1986

Product		Assays				
	wt %	Au(ppm)	Ag(ppm)	Cu(%)	Zn(%)	Pb(%)
Head	100.000	2.230	12.35	2.16	2.07	0.038
Cu Conc.	7.064	18.69	84.86	28.00	3.99	0.070
Zn Conc.	4.485	7.580	59.92	1.67	47.29	0.381
Tailings	88.451	0.652	4.150	0.12	0.19	0.018
			Recovery(%)			
Cu Conc.		59.22	48.49	91.74	10.96	13.09
Zn Conc.		15.25	21.74	3.47	82.47	45.59
Tailings		25.54	29.77	4.80	6.57	41.40

Note: Data from Healy & Petruk (1989).

Chapter III

GEOLOGY

The Trout Lake deposit is hosted in the Amisk Group volcanic strata of the Proterozoic Flin Flon greenstone belt (Fig. 1). The Flin Flon belt is part of the southern Churchill structural province and was deformed and metamorphosed prior to 1,750 Ma during the Hudsonian Orogeny (Syme et al. 1982). The metamorphic grade of the rocks in the Flin Flon area corresponds to greenschist facies and progressively increases northward where the almandine-amphibolite metamorphic grade has been recognized in the Kisseynew gneisses (Syme et al. 1982). Aggarwal & Nesbitt (1987) estimate that temperatures reached between 400 and 450°C in the vicinity of Flin Flon, which includes the Trout Lake locality.

The Flin Flon belt consists of a sequence of volcanic rocks with associated subordinate sediments, an overlying sequence of terrestrial sediments and a diversity of intrusive rocks. The Amisk Group comprises the lower stratigraphic elements of the Flin Flon belt. This group is dominated by subaqueous and subaerial volcanics of tholeitic and calc-alkaline affinity, and are interpreted as having been deposited in an island arc setting (Syme et al. 1982). The volcanics consist of massive to pillowed basalt and andesite flows, overlain by pyroclastic andesite breccias and rhyolitic and dacitic quartz-porphyry (Koo & Mossman 1975). The Amisk Group underwent plutonism, uplift and deformation prior to the deposition of the unconformably overlying fluviatile sedimentary strata of the Missi Group (Syme et al. 1982). The Missi Group constitutes sediments derived from the uplifted and deeply eroded Amisk terrain, including unroofed pre-Missi felsic plutons. Numerous small intrusives are interpreted as being correlative with the Amisk volcanism, whilst the larger intrusive bodies are less clearly syn-volcanic, or are interpreted as being post-volcanic (Price 1977).

The metamorphic peak occurred during the second of three deformational events associated with the Hudsonian Orogeny (Price 1977). The earliest deformation event (D1) resulted in east-trending tightly closed folds with steeply dipping axial surfaces and non-penetrative metamorphism. The second deformation event (D2) resulted in north-trending isoclinal folding about steep to vertical dipping axial surfaces (Price 1977). This folding was associated with penetrative metamorphism (axial foliation) as well as the emplacement of syn-tectonic plutons (Koo 1973). The latest deformation event (D3) resulted in refolding the rocks about the northeast trending Embury Lake antiform and associated shearing and drag-folding along northwesterly trending faults (Price 1977, Koo & Mossman 1975). There is no evidence of post-tectonic magmatism in the Flin Flon area (Price 1977).

The Trout Lake deposit consists of a series of steeply dipping stacked lenses (6 proven) occurring in two (North and South) zones. The zones strike at 140° azimuth and have a relatively constant dip of 60-70° to the northeast. Each lens consists of two principal types of mineralization: massive mineralization occurring in quartz-sericite schists, and disseminated mineralization occurring in chlorite schists, where the hostrock types represent the metamorphosed equivalents of hydrothermally altered quartz-porphyry fragmental pyroclastics. The lenses generally consist of massive sulfides which are commonly separated by zones of disseminated pyrite and chalcopyrite. The massive mineralization is interpreted as exhalative mineralization deposited on the seafloor proximal to a fumarolic vent. The disseminated mineralization, which does not constitute ore, together with chalcopyrite stringer ore (described in Chapter 5) are interpreted as the metamorphosed equivalent of the feeder pipe stockwork mineralization (C. Ko, pers. comm., 1985).

The footwall contact of the stockwork ore is diffuse, whereas the hangingwall contact of the massive ore is sharp. The margins of the lenses commonly display open to tightly closed and isoclinal folding with shearing and dislocations on a mesoscopic scale. The relative distribution of the massive and stockwork mineralization strongly suggests intense shearing of the highly chloritized footwall rocks, the stringer ore and disseminated mineralization (C. Ko, pers. comm., 1985).

The lenses generally exhibit a zonation from a graphitic argillite in the hangingwall, to massive sphalerite, to massive pyrite, to massive chalcopyrite + pyrite + sphalerite + pyrrhotite to footwall semi-massive chalcopyrite stringers and disseminated pyrite and chalcopyrite (Fig. 2). This zonation is locally reversed or disturbed by folding, as well as by emplacement of quartz-diorite intrusions. Generally, increases in the Cu/Cu+Zn ratio correlate with higher Au and lower Ag values. The metal zonation can be generalized as high Ag and Pb values associated with low Cu/Cu+Zn ratios in the hangingwall, and high Au, low Ag values