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GEOLOGICAL FACTORS THAT INFLUENCE THE EVALUATION AND EXPLOITATION OF CANADIAN COPPER-ZINC MASSIVE SULPHIDE-, AND JAPANESE POLYMETALLIC (KUROKO) DEPOSITS

D. M. VENTER

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ABSTRACT

Volcanogenic massive sulphide deposits are important sources of base metals throughout the world. The Canadian Cu-Zn-(Au, Ag) deposits of Archaean age occur in greenstone terrains within the Canadian Shield. These deposits are closely associated with volcanic vents developed along zones of rifting within mobile belts. The vents are manifested by coarse felsic pyroclastics and/or rhyolitic domes. The Japanese Pb-Zn-Cu-Ba(Ag) deposits, generally known as Kuroko deposits, are of Miocene age, and although also associated with volcanic vents, are developed above zones of subduction.

Mineralization in volcanogenic deposits is a result of submarine exhalation of metalliferous hydrothermal solutions derived from fractionation of predominantly calc-alkaline magmas. The deposits are characterized by certain geological features that result from the interaction of specific physical and chemical conditions during deposition. Primary features include massive and stringer sulphide bodies, alteration zones, mineralogical and metal zoning, and certain depositional textures and structures. These features are commonly modified by subsequent metamorphism and deformation which impart secondary ore textures and affect metal distribution and shape. The disparity in age between Canadian and Japanese deposits allows the entire spectrum of geological features to be studied; from the completely unaltered to the high deformed and recrystallized.

The characteristic geological features are the prime factors which control the metal distribution and concentration, and the size and shape of the deposits, thereby influencing the viability of the respective ore bodies. A knowledge of these factors and the physico-chemical parameters which control them are thus fundamental in the "understanding" of these deposits. They ultimately control the geological interpretations and predictions made during ore body delineation, ore reserve estimation, mining and ore beneficiation.

CONTENTS

INTRODUCTION

Volcanogenic (or volcanic-exhalative) massive sulphide deposits constitute an economically important and distinct class of base metal deposit. The general characteristics and genesis of these deposits have in recent years been reviewed by Anderson (1969), Hutchinson (1973), Solomon (1976), and Large (1977). This class of deposit includes, among others, the Miocene Kuroko deposits of Japan, massive copper-zinc-pyrite deposits in the Archaean Shield of Canada, Paleozoic massive pyritic deposits in Scandinavia and Iberia, and the ophiolite associated deposits of Cyprus and Turkey. Only the Canadian and Japanese deposits will be discussed here. They have most morphological and genetic features in common, and their differences arise not from genetic factors as such, but from the evolution of the earth's crust from Archaean to Miocene times. Canadian Archaean and Japanese Kuroko deposits are well documented (Sangster, 1972; Lambert, 1973; Ishihara, 1974; Lambert and Sato, 1974; Sato, 1976; and Sangster and Scott, 1976), and they display all the features common to volcanogenic deposits, as well as some features peculiar to their class. These deposits are thus ideally suited to be used as a model.

The purpose of this dissertation, which is largely based on existing literature, is to provide some guidelines for the evaluation and exploitation of volcanogenic massive sulphide deposits, particularly those deposits closely associated with volcanic vents. The geological factors which control or influence the size, shape, metal concentration, metal distribution, mineability and/or extractability of the deposits are discussed in detail. The influence of these factors on practical aspects of the mining industry - drilling and bulk sampling, ore reserve estimation, mine development and mining, and ore beneficiation - are considered and the problems encountered are discussed.

It is hoped that this study will contribute to the understanding of these deposits by stressing the importance of a sound geological basis in their evaluation and exploitation.

ARCHAEAN COPPER-ZINC AND KUROKO DEPOSITS - A CONCEPTUAL MODEL

Introduction

Archaean copper-zinc and Miocene polymetallic (Kuroko) deposits are related to subaqueous central vent-type, explosive calc alkaline volcanic activity. They occur directly above, or adjacent to the source vent where they have been precipitated from metalliferous hydrothermal solutions debouching onto the sea floor. The deposits are regarded as paramagmatic since the hydrothermal fluids which formed them ultimately derived their contained metals from differentiating magma bodies at depth. The differences between the two groups of deposit are regarded to be the natural consequence of the evolution of the earth's crust and the changes in tectonic style through time (Hutchinson, 1973, 1976a,b, 1977).

The disparity in age between the two groups of deposit allows the effect of a range of modifying factors, such as pre-consolidation deformation and redistribution of ore, through to high grade metamorphism and intense structural deformation, to be studied and applied to practical aspects of the mining industry.

Geographical distribution

Archaean copper-zinc and Kuroko deposits, respectively have their greatest known concentrations in the Canadian Shield and in the "Green Tuff Belt" of Japan. Kuroko-type deposits also occur in the Philippines (Bryner, 1969 and Gervasio, 1973), and in Fiji (Colley and Rice, 1975). Very few Archaean copper-zinc deposits are known in other Precambrian Shield areas. The Outokumpu deposit in the Baltic Shield, Finland, is a possible example (Jacobsen, 1975). Other possibilities are the Copper Hills and Mons Cupri deposits in the Pilbara block, Australia (Jacobsen, 1975), and the Khetri and Singhbum copper belts in India which are known to be of Archaean age (Jacobsen, 1975). In Southern Africa, Archaean volcanogenic deposits are known only from the Murchison Range greenstone belt. Here several subeconomic zinc-copper lenses occur along the so-called "Copper-zinc Line", which mark the southern contact of a quartz porphyry assemblage (Viljoen et al, 1978).

Figure 1 shows the distribution of Kuroko mines and Miocene igneous rocks in the Japanese Islands. The deposits are restricted to the so-called "Green Tuff Belt" and are clustered within several ore districts. From the northeast, these are: Eastern Hokkaido, Western Hokkaido, Hokuroko, Wagaomono, Aizo, and Sanin (Figure 1).

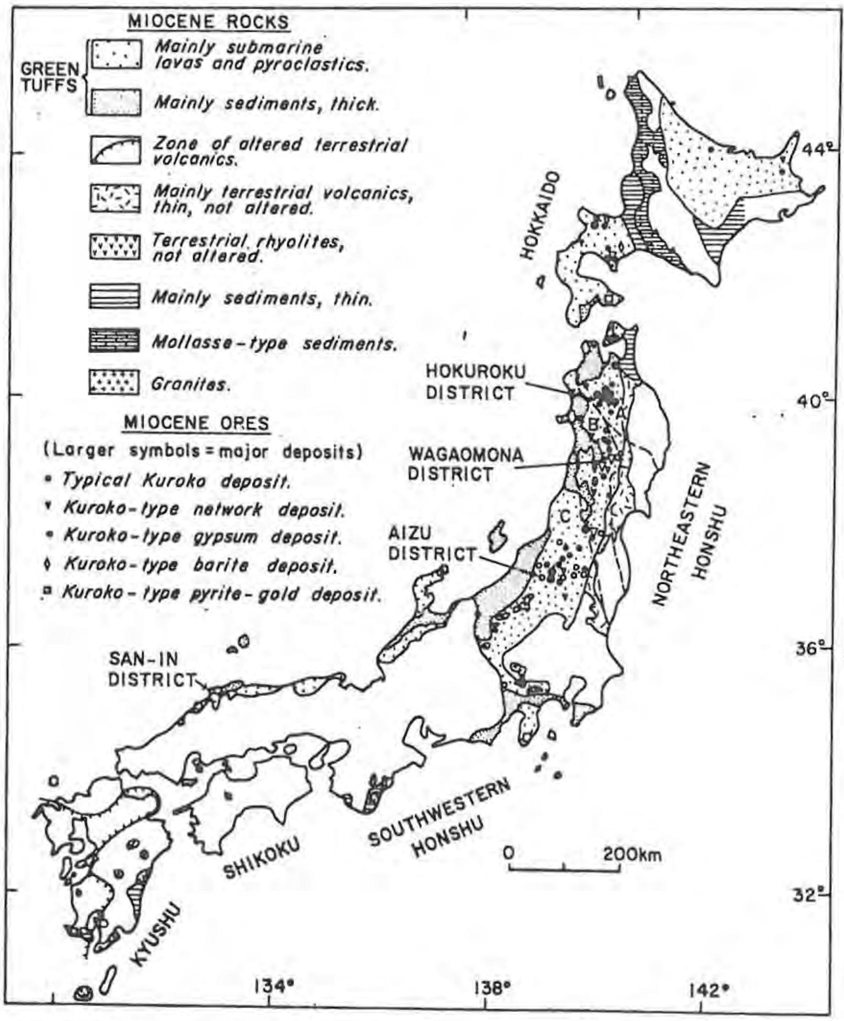

FIG. 1. Distribution of Miocene rocks, typical Kuroko deposits and Kuroko-type deposits in Japan, after Sato (1974). Dashed lines separate major basement provinces (simplified after Isomi, 1968). A = Northern Kitakami province, B = Abukuma province.

From Lambert and Sato (1974)

The Hokuroko District is by far the most important ore field, which includes numerous productive mines such as Kosaka, Hanoaka, Shakanai, Ainai, Furutobe and Hanawa. Most of these mines contain ore bodies of what Sato terms "typical Kuroko ore" and some will be used in subsequent sections to illustrate salient features of these deposits.

In 1972, Kuroko deposits supplied approximately 45% of Japan's domestic production of copper, 26% of its zinc, 33% of its lead, 31% of its silver, and 20% of its gold. Total reserves amounted to approximately 50 million tons of ore containing roughly 2% copper (Lambert and Sato, 1974).

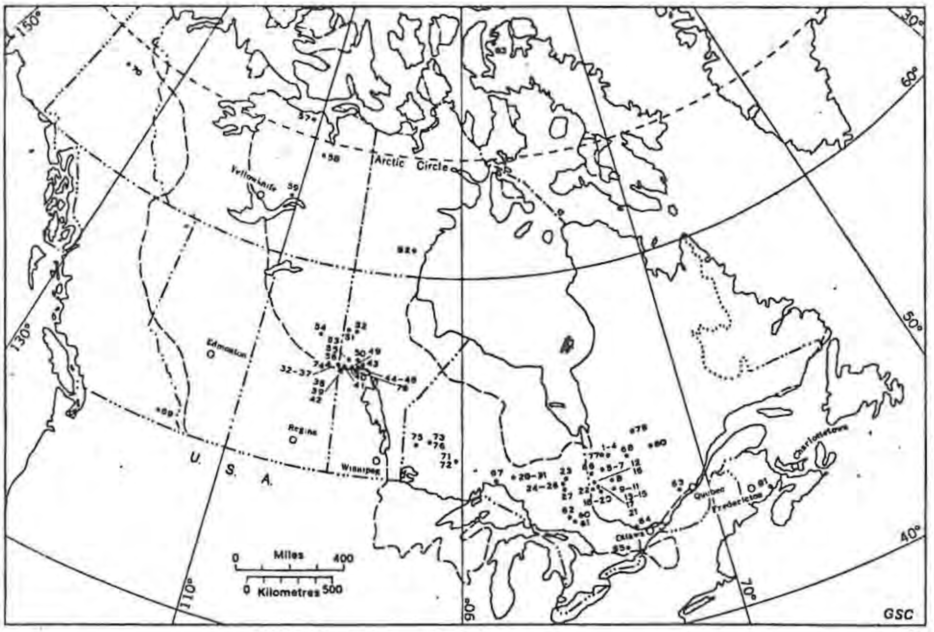

Fig. 2 Location of some Canadian Precambrian massive sulfide deposits. *1* = Mattagami Lake; *2* = New Hosco; *3* = Radiore; *4* = Orchan; *5* = Joutel; *6* = Mines de Poirier; *7* = Northern Exploration; *8* = Barraute; *9* = Manitou–Barvue; *10* = Louvem; *11* = East Sullivan; *12* = Vauze, Magusi River and Iso Copperfields; *13* = West MacDonald; *14* = Waite; *15* = Amulet; *16* = Norbec (Lake Dufault); *17* = Millenbach; *18* = Quemont; *19* = Horne; *20* = Delbridge; *21* = Mobrun; *22* = Aldermac; *23* = Texasgulf (Kidd Creek); *24* = Jameland; *25* = Kam–Kotia; *26* = Canadian Jamieson; *27* = Genex; *28* = Geco; *29* = Willecho; *30* = Willroy; *31* = Nama Creek; *32* = Flexar; *33* = Coronation; *34* = Flin Flon; *35* = Schist Lake; *36* = Mandy; *37* = Birch Lake; *38* = White Lake; *39* = Cuprus; *40* = North Star; *41* = Don Juan; *42* = Centennial; *43* Osborne Lake; *44* = Stall Lake; *45* = Rod; *46* = Anderson Lake; *47* = Ghost Lake; *48* = Chisel Lake; *49* = Dickstone; *50* = Wim; *51* = Fox Lake; *52* Ruttan Lake; *53* = Sherridon; *54* = Brabant; *55* = Bob Lake; *56* = Jungle; *57* = High Lake; *58* = Hackett River; *59* = Big Indian Mountain; *60* = Errington; *61* = Vermillion; *62* = Geneva Lake; *63* = Tetrault; *64* = New Calumet; *65* = Syngenore; *66* = Normetal; *67* = Zenmac; *68* = Coniagas; *69* = Sullivan; *70* = Hart River; *71* = Mattabi; *72* = Sturgeon Lake; *73* = South Bay (Uchi Lake); *74* = Western Nuclear; *75* = Trout Bay (Red Lake); *76* = Copper–Man; *77* = Grasset Lake; *78* = Frotet Lake; *79* = Reed Lake; *80* = Patino; *81* = Teahan and Lumsden; *82* = Spi Lake; *83* = Strathcona Sound.

From Sangster and Scott (1976)

The distribution of Canadian massive sulphide deposits is indicated in

Figure 2. Of the 86 known deposits, all but four of them occur in the Precambrian Shield and all but ten of them occur in the Superior and adjacent Churchill structural provinces (Sangster and Scott, 1976). The deposits are restricted to greenstone belts surrounded by basement and intrusive gneisses and granites. Some of the greenstone belts suffered subsequent high grade polyphase metamorphism and are difficult to recognise as such. Within the greenstone belts most of the deposits occur in clusters within roughly circular or oval areas usually 15 to 30 km in diameter. These areas are characterised by an abundance of felsic volcanic rocks and most probably represent original felsic volcanic centres.

Of the total Canadian metal production in 1971, 80% of the zinc, 39% of the copper, 62% of the silver, and significant amounts of gold came from Archaean copper-zinc deposits (Sangster and Scott, 1976).

Important copper-zinc massive sulphide districts in Canada are the Abitibi greenstone belt, Quebec and Ontario, the Flin Flon-Snow Lake area, Manitoba, the Mattaganic Lake area, Quebec, and the Manitouwadge district, Ontario.

Tectonic setting

The evolution of the earth's crust from the Archaean to the present time has been dominated by distinct stable cratonic blocks separated by tectonically active mobile or orogenic zones. The nature of the tectonics, however, appears to have evolved through time, and the presently active plate tectonic systems, with distinct spreading and subducting zones (Figure 3) cannot be extended back into the Precambrium (Watson, 1973; Hutchinson, 1976a, 1977; and Engel, 1974). Archaean and Proterozoic times were dominated by vertical tectonics along large mantle-tapping transcurrent and normal faults. During the late Proterozoic incipient spreading and continental separation could have been a precursor to the presently active plate movements.

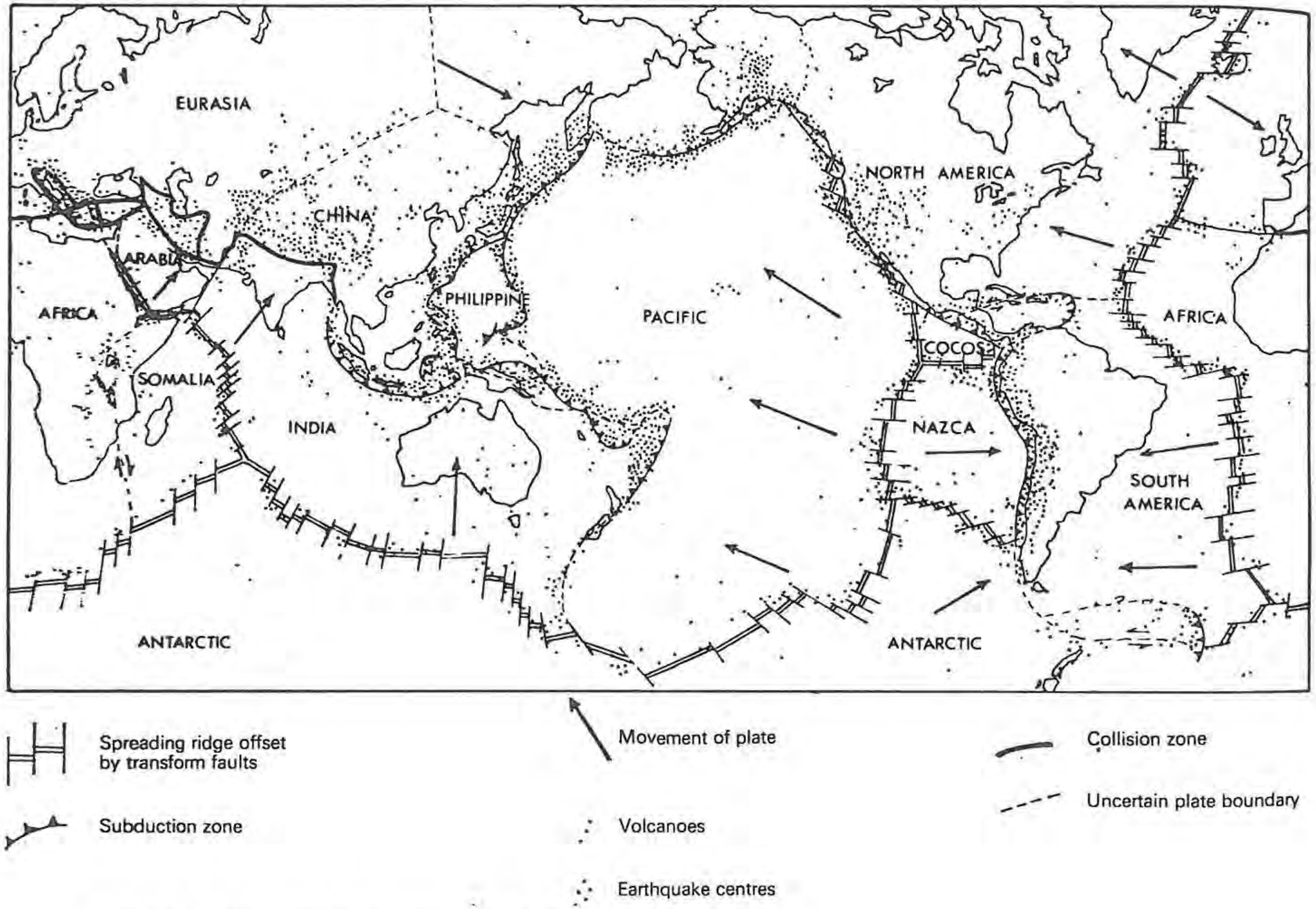

FIGURE 3 Plate boundaries and active zones of the Earth's crust, Institute of Geological Sciences, 1972, HMSO, London.

From Mitchell and Garson (1976)

The genesis of Archaean copper-zinc deposits is closely related to the tectonic conditions prevalent at that time. Hutchinson (1973) suggested that these deposits were formed under relatively thin primitive crustal conditions. Fundamental sutures triggered and localized magmatic activity in the underlying thick, poorly differentiated upper mantle that may have been of intermediate "average composition" (Baragar and Goodwin, 1969, quoted in Hutchinson, 1973). Magmas originating in this mantle during prolonged periods of volcanism, underwent complete differentiation. This resulted in the formation of the characteristic archaean volcanic successions, with a mafic platform of widely distributed tholeiitic basaltic flows, followed by more felsic, calcalkaline, domal volcanic activity in the late differentiation stages (Goodwin 1965, 1968).

The tectonic setting of the Canadian copper-zinc deposits are well illustrated by Goodwin and Ridler (1970) in their study of the Abitibi greenstone belt in the Superior structural province (Figure 4). They identified eleven semi-independent volcanic-sedimentary associations which they termed "Volcanic complexes" (Figure 5). All these have elliptical outlines whose east-west elongations are considered by Goodwin and Ridler (1970) to be the result of tectonic deformation. The complexes are distributed along the northern and southern margins of the orogen and are conspicuously absent from the central axis. They consist of up to 50% felsic volcanics (mainly dacite and some rhyolite), which constitute highly anomalous concentrations above an estimated 5.5-10% of the total volume of volcanic rocks in the Abitibi belt (Goodwin and Ridler, 1970). Most of the complexes constitute important mineral districts with ore deposits clustered around domal centres of felsic volcanism.

The Abitibi Belt was deformed during the Kenoran orogeny (2560 m.y.B.P.)* about predominantly east-west, doubly-plunging, isoclinal fold axes resulting in an estimated 50% or more shortening in the north-south direction (Goodwin and Ridler, 1970) and in pervasive greenschist facies metamorphism (Goodwin, 1972).

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* m.y.B.P. = million years before present.

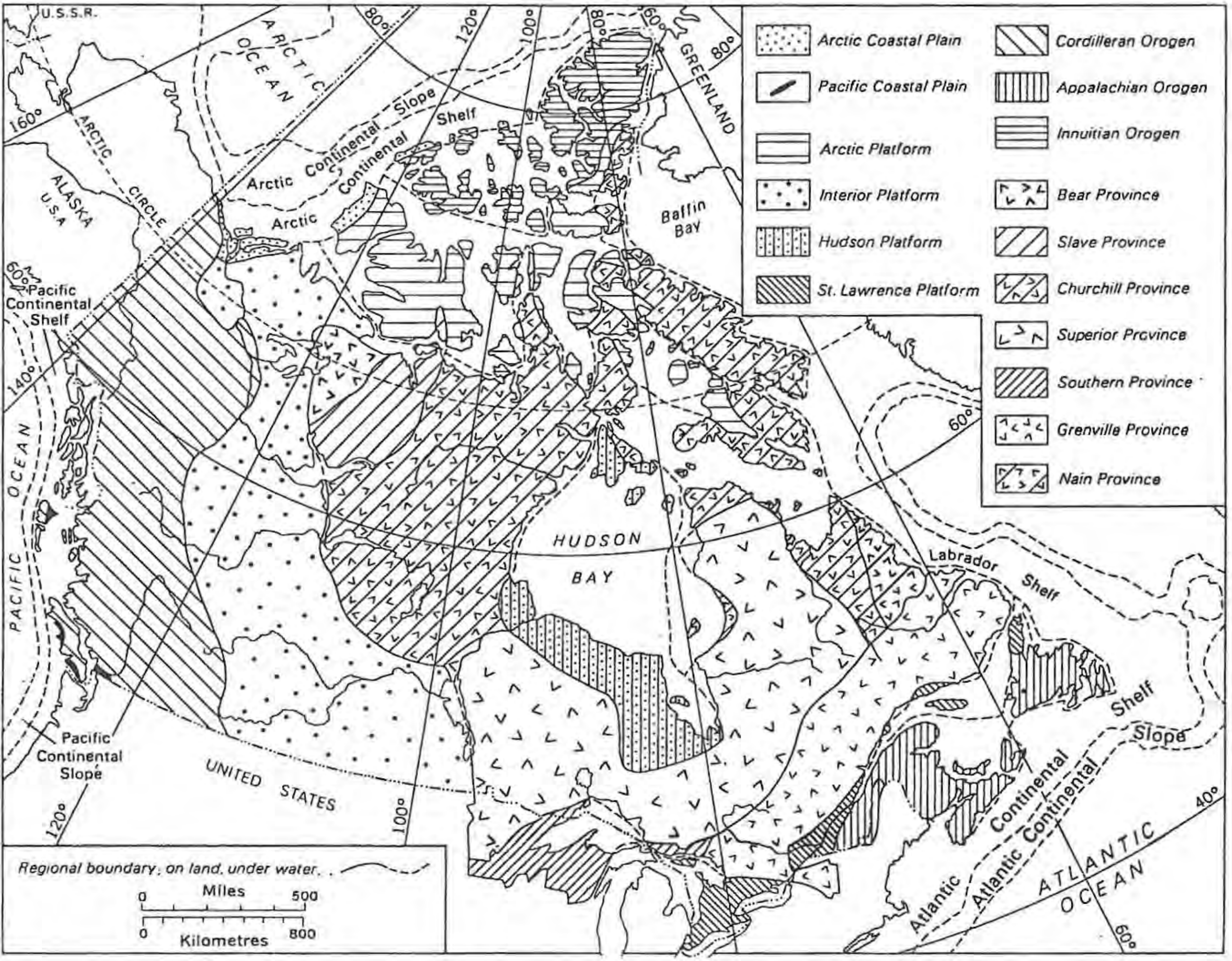


Figure 4: Principal geological elements of Canada: from Douglas, 1970

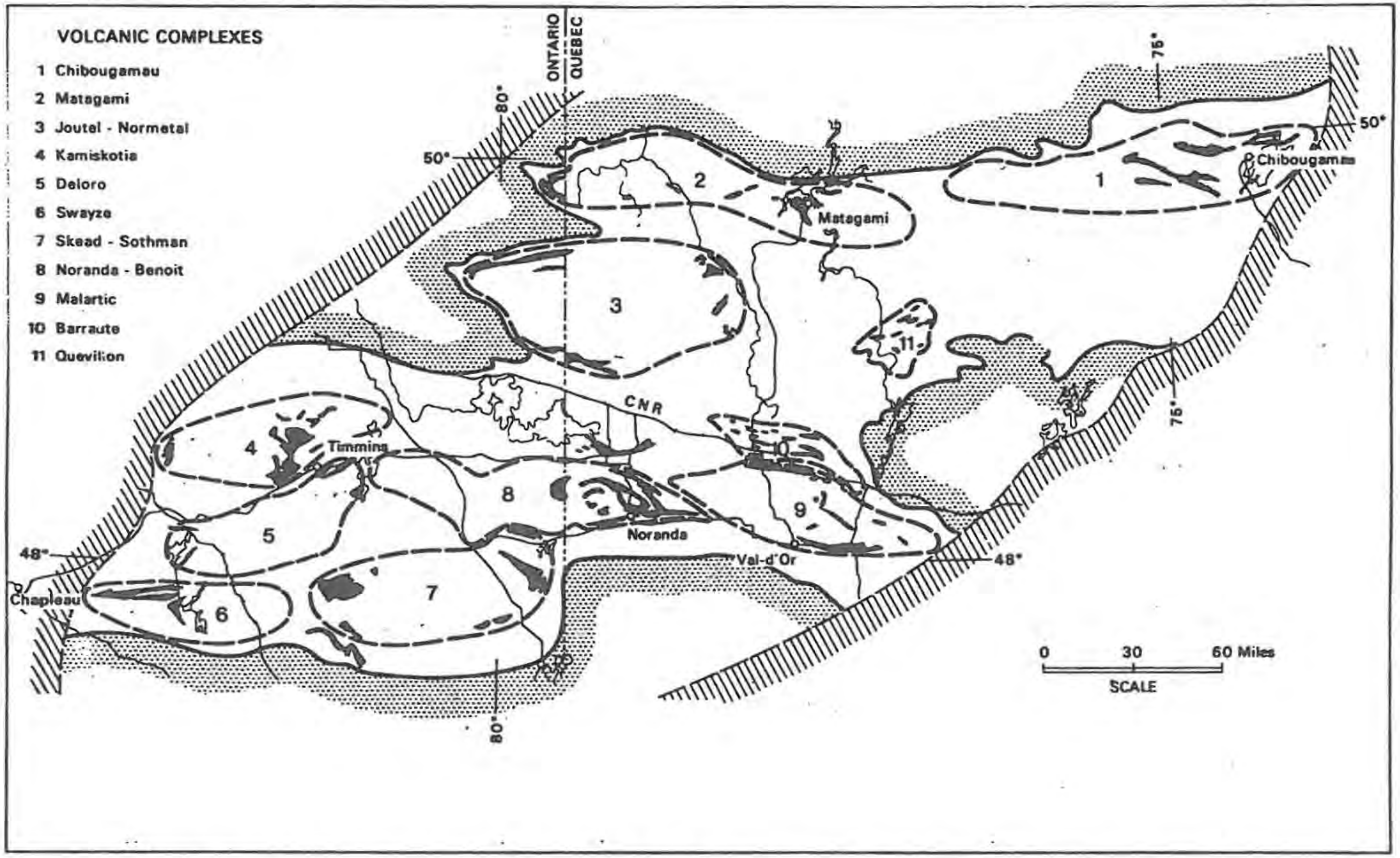


Fig. 5 Distribution of volcanic complexes in the Abitibi orogen. Felsic volcanic rocks are shown by vertically ruled pattern. Approximate outlines of the volcanic complexes including cogenetic intrusions and sediments are shown by heavy dashed lines. (From Goodwin and Ridler, 1970; courtesy of Geol. Surv. Can.)

From Goodwin and Ridler (1970)

Goodwin and Ridler (1970) interpreted the Abitibi Belt as an intercratonic orogen "sandwiched" between two sialic forelands. They interpreted the volcanic centres as "paired island arcs" and postulated a spreading centre along the central axial zone. This application of the plate tectonics model to the Archaean is considered to be incorrect (see also Sillitoe, 1973). Keeping within the framework of Archaean tectonics as stated above, the Abitibi Belt is thought to be bounded by major transcurrent faults along which the volcanic centres developed. Subsidence of the central block formed a graben-like depression in which sedimentary rocks representing erosional products of both volcanic and early sialic crystalline basement rocks were deposited. Coarse, unsorted conglomerates developed along the bounding faults while turbidites and shales filled the central part of the basin (Goodwin, 1972).

Miocene polymetallic (Kuroko) deposits developed in island arc settings at destructive plate margins (Figure 3). Here the oceanic lithosphere bends downwards in a subduction zone and descends along the seismic Benioff zone inclined beneath a curved belt of active volcanoes forming a magmatic arc. Some island arcs developed within the oceans and are underlain by oceanic crust, for example the Melanesian arcs. Others apparently formed initially on continental margins, and following rifting, migrated away from the continent with development of a marginal basin (Karig, 1971). These arcs, for example the Japanese arcs, can include fragments of old crust torn off from the continent (Mitchell and Garson, 1976).

The Kuroko deposits of Japan occur in a narrow zone about 50 km wide and essentially parallel to the east Japan arc system. A less important Kuroko zone is associated with the west Japan arc system. Present Benioff zones are situated approximately 150 km below the Kuroko zones (Figure 6).

Sato (1976) suggested that a change of movement of the Pacific plate at 20 to 25 m.y.B.P., from essentially parallel to north-eastern Japan to perpendicular (transform movement to subduction), triggered the generation, along the newly formed Benioff zone, of a large amount of basic to intermediate magma. This magma subsequently rose through the upper mantle and underwent differentiation when it stopped below the sialic crust. The presence of the magma caused a high heat flow zone (Hasebe, et al., 1970) and a negative isostatic anomaly (Sato, 1976) below the "Green tuff" region (Figure 7). Isostatic readjustment resulted in block faulting. These faults and the steep geothermal gradient caused by the high heat flow enabled ore fluids to reach the sea floor at high temperatures. Ore deposition was preceded by extrusion of felsic magma. This late differentiate formed the white rhyolite domes and associated pyroclastics which characterises the host rocks of Kuroko deposits.

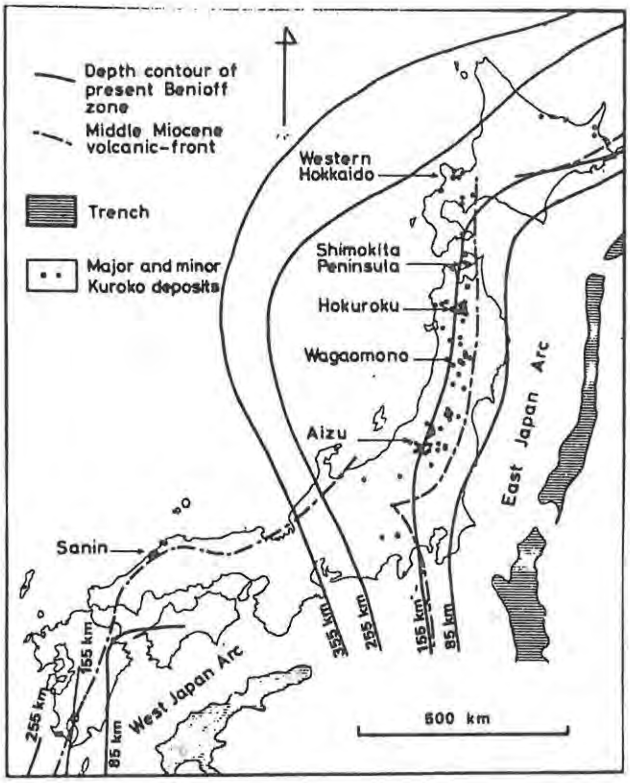


Figure 6: The distribution of the Kuroko deposits of Japan in relation to a linear Miocene volcanic front which developed above the Benioff zone.
From Sato, 1976.

Similarities in the tectonic settings of Archaean and Miocene volcanogenic massive sulphide deposits - i.e., the presence of relative thin crust, magmatic differentiation along the calc-alkaline trend, block faulting providing access to differentiated magma and ore-bearing fluids, marine setting and consequently submarine exhalation of ore fluids - resulted not surprisingly in two groups of deposits which albeit a great disparity in age, have many morphologic and genetic features in common.

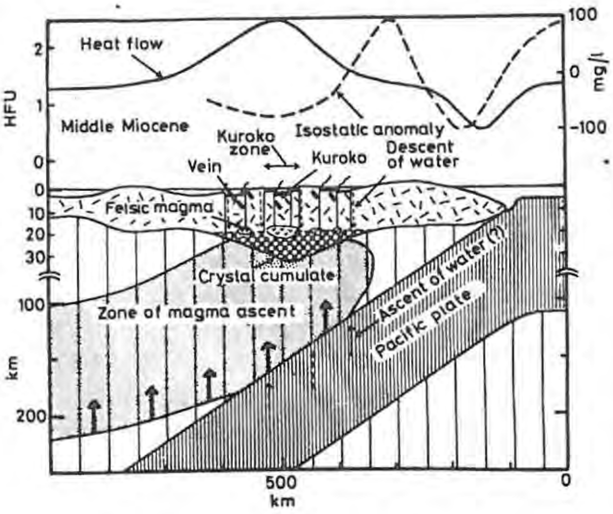
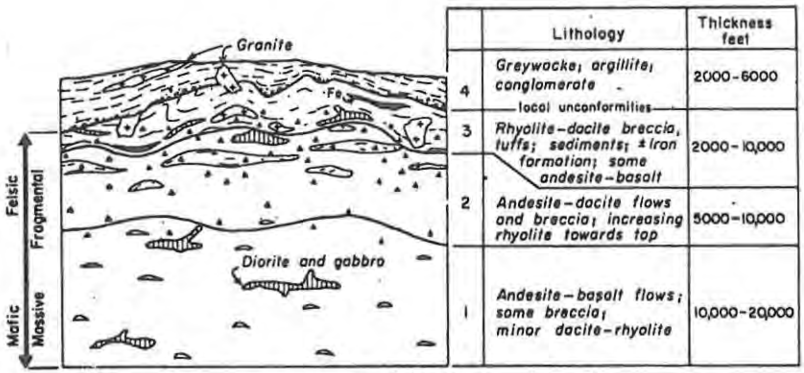


Figure 7: Speculative east-west cross-section of northeast Japan showing its tectonic setting in the middle Miocene. The heat-flow pattern is after Hasebe et al., (1970) and the isostatic anomaly is hypothetical.
From Sato, 1976.

Geological environment

Sangster (1972) summarized the geological environment of Canadian massive sulphide deposits. They typically occur within a volcanic complex several thousand metres thick comprising three main lithologies (Goodwin, 1968) (Figure 8). The lowermost portion of the complex is a series of pillowed, vesiculated basaltic flows. This is followed upward by flows, flow breccias, and tuffs of mainly andesitic composition. The uppermost portion of the complex contains abundant, and is possibly predominantly composed of, volcanics of dacitic to rhyolitic composition. These may either be massive, textureless flows and/or abundant pyroclastics of various size ranges. The felsic phase normally marks the end of a single cycle, after which another cycle may begin, starting again with the extrusion of basalts. These cyclic volcanic events are typical of resurgent caldera complexes which represent the later part of a larger cycle involving the initial formation of a graben and related mafic volcanism (Hodgson and Lydon, 1977). Volcanism may also cease after a felsic phase in which case the complex becomes mantled in a thick sequence of graywackes derived partly or entirely from the volcanics themselves. In a few cases the waning phases of volcanism was contemporaneous with sedimentation so that a complete and almost imperceptive gradation exists between pyroclastics, through reworked pyroclastics, into graywackes.



	Lithology	Thickness feet
4	Greywacke; argillite; conglomerate local unconformities	2000-6000
3	Rhyolite-dacite breccia, tuffs; sediments; ± iron formation; some andesite-basalt	2000-10,000
2	Andesite-dacite flows and breccia; increasing rhyolite towards top	5000-10,000
1	Andesite-basalt flows; some breccia; minor dacite-rhyolite	10,000-20,000

Fig. 8 Diagrammatic section of an Archean volcanic pile illustrating typical mafic to felsic succession with overlying sediments. The principal volcanic trends are from lower predominantly mafic lava flows to upper predominantly felsic fragmental rocks, the latter including both pyroclastics and flow breccias. Basalts predominate in the lower parts, andesites in middle parts and dacite plus rhyolite in upper parts. Compositional trends are transitional and local reversals are present. (From Goodwin, 1965; courtesy of *Econ. Geol.*)

From Sangster and Scott, 1976.

Volcanic complexes are commonly intruded by rocks of diverse composition. These may range from ultramafics, through gabbro, diorite, granodiorite, to granite, but acidic intrusions are usually more abundant. Felsic intrusive rocks are commonly found as large stocks at or near the centre of the volcanic pile. As such, they may represent part of the magma chamber from which the volcanism originated, that later moved upwards to intrude its own daughter products.

Host rocks in the immediate vicinity of ore deposits, most commonly are the felsic, usually clastic, phases of volcanism. Agglomerates, lapilli tuffs and rarely, massive dacitic to rhyodacitic flows constitute the ore-bearing horizon in many massive sulphide deposits. The immediate host rock of the sulphides is usually a chert or cherty tuff. The close spatial relationship between acid agglomerates (or coarse pyroclastics) and massive sulphide ores at so many known deposits in the Canadian Shield, was emphasized by Sangster (1972) who remarked that, whenever he stood on the outcrop containing the largest fragments of acid pyroclastics in any given mining camp, he could invariably hear the mine mill nearby. This very characteristic lithology, locally termed "mill-rock" after this association, is the product of explosive volcanism and can be pre- to post-ore. It commonly contains fragments of massive sulphides, or may have been the site of stringer ore deposition.

In addition to "mill-rock", quartz porphyry domes (rhyolitic to rhyodacitic domes) are commonly closely associated with massive sulphide deposits. These porphyry domes show both intrusive and extrusive characteristics and constitute in many cases the final phase in a specific volcanic cycle. As such, they commonly constitute the immediate footwall of the massive sulphide deposits.

Compositionally, the volcanic host rocks appear to have been derived by differentiation of a tholeiitic-type parent magma. They chemically resemble the standard tholeiitic and calc-alkaline rocks of the basalt-andesite-rhyolite association of the Phanerozoic island arc environment (Wilson et al., 1965; Goodwin, 1968; Baragar and Goodwin, 1969; Fox, 1979).

Canadian massive sulphide deposits and their host rocks underwent orogenesis during the Kenoran orogeny (2560 m.y.B.P.) in the Superior and Slave structural provinces and suffered an additional event during the Hudsonian orogeny (1850 m.y.B.P.) in the Churchill province (Figure 4) (Price and Douglas, 1972). This accounts for the universal metamorphosed nature of these deposits. Metamorphic grade varies between Greenschist and upper Amphibolite and tends to increase in a westerly direction where lower crustal levels are exposed in the western Superior and Churchill provinces (Price and Douglas, 1972).

The geological setting of the Japanese Kuroko deposits has been described by Lambert (1973), Sato (1974, 1976) and Lambert and Sato (1974). The ore bodies are hosted by the so-called "Green Tuff" sequences in which Miocene submarine volcanics are the main constituent. "Green Tuff" rocks are distributed on the Japan Sea side of the Japanese islands from Hokkaido to Kyushu. This area is known as the Green Tuff Region (Figure 1). Following a long period of denudation during the Mesozoic and Paleozoic, subsidence during early Miocene times was initiated by horst-and-graben tectonics (see previous section). Subsidence was followed by submarine volcanism dominated by andesites in the early stages and dacite and rhyolite in the later stages. Kuroko mineralization was associated with the waning stages of volcanism. A second cycle of volcanism was accompanied by compressional stress (Fujii, 1974), and uplift of the Green Tuff region. As a result most of the volcanism was subaerial. The position of the volcanic front during the Miocene is indicated in Figure 6.

The stratigraphic positions of Kuroko deposits in the various mineralized districts are indicated in Figure 9. The time-bound character of the deposits and their close association with felsic volcanic rocks are well illustrated. The deposits are typically situated on the flanks of brecciated white rhyolite lava domes, but in places are hosted by rhyolitic tuff breccia. Horikoshi (1969) interpreted the mineralization as being related to the eruption of the white rhyolite, and concluded that the ore fluids were exhaled during the waning stages of the explosive rhyolite volcanism. He recognized several lava domes in the Kosaka mining area, four of which are associated with economic ore bodies.

After the mineralizing event, intermittent mainly intermediate to felsic volcanism followed. These rocks normally form the hanging-wall of ore bodies, but some deposits are overlain by basaltic pillow lavas. Argillaceous sediments - siltstones, mudstones, and argillaceous sandstones - are interbedded with all these upper volcanic sequences.

Rocks of the Green Tuff region were subjected to regional zeolite facies metamorphism during the Pliocene Green Tuff "orogeny" (Utada, 1965, 1971; Ijiima and Utada, 1971; quoted in Lambert and Sato, 1974). Four zones of metamorphic alteration can generally be recognized with increasing depth; partly altered, clinoptile-mordenite, analcime-heulandite, and laumontite-albite. Since all these zones are recognised in rocks that have never been buried to depths of more than 1 km, very high geothermal gradients, probably >70°C/km, are indicated.

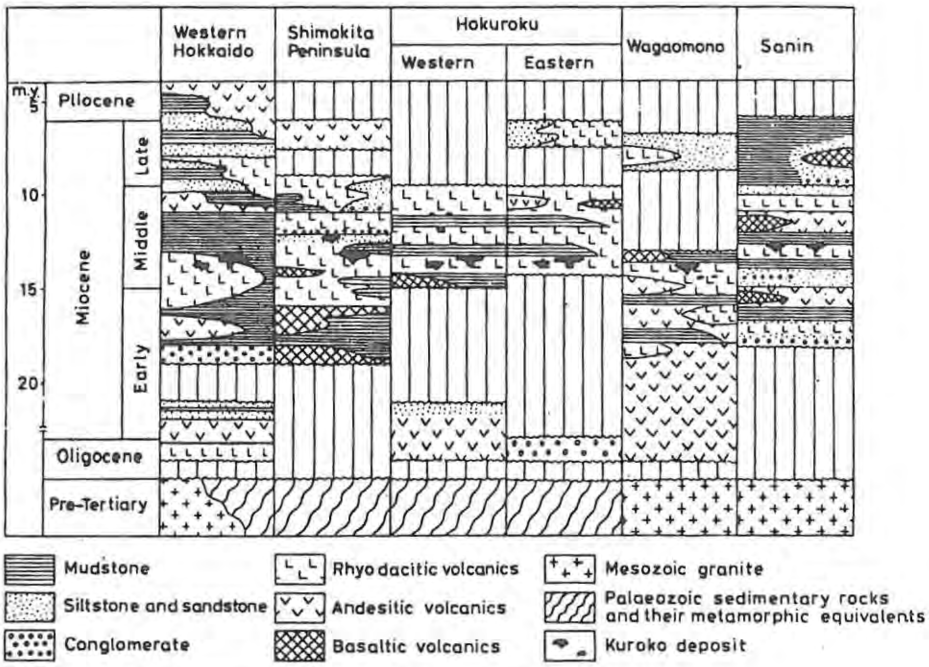


Fig. 9 Stratigraphic positions of Kuroko deposits

From Sato, 1976.

Ore body morphology

Individual Kuroko deposits commonly consist of two or more closely spaced unit ore bodies, the sizes of which are variable. Each mine consists of a number of closely clustered ore deposits. Table 1 lists the dimensions and grades of the ore deposits in the Hokuroku district, and the production rates and total reserves based on 1973 figures.

TABLE 1. Details of Kuroko Deposits in the Hokuroku District. Abbreviations: nd = not determined, — = low, but not analyzed. Updated from Takeuchi (1970).

Name of mine	Name of ore deposit	Year of discovery	Size of ore deposit (meters)	Grade of crude ore (%)				Production in 1972 (per month)	Size of mine[5]
				Cu	Pb	Zn	S		
Kosaka[1]	Motoyama	1861	300 × 700 × 50	2.2	0.8	4.5	23.7	Crude ore = 45,000 tons Acid leached Cu = 70 tons	25 million tons
	Uchinotai-Nishi	1959	400 × 350 × 20	2.8	1.1	4.0	19.8		
	Uchinotai-Higashi	1960	300 × 400 × 16	2.0	1.5	4.4	15.6		
	Uwamuki No. 1	1962	150 × 100 × 7	0.6	4.2	11.5	4.7		
	Uwamuki No. 2	1965	200 × 150 × 40	0.8	1.8	7.8	8.8		
	Uwamuki No. 4	1966	350 × 100 × 17	0.8	2.8	8.3	6.3		
Hanaoka[1]	Tsutsumizawa	1885	350 × 120 × 120	1.2	0.7	1.9	nd	Cu ore = 25,000 tons Pyritic ore = 10,000 tons	35 million tons
	Doyashiki	1916	600 × 350 × 20	2.5	0.5	1.8	nd		
	Kamiyama	1919	260 × 60 × 40	1.5	0.7	4.1	nd		
	Ochiaizawa	1942	150 × 100 × 30	2.4	1.5	5.9	nd		
	Matsumine	1963	800 × 800 × 30	3.2	0.8	2.5	23.9	Crude ore = 50,000 tons	
Fukazawa[1]	Kanayamazawa	1969	210 × 90 × 8	1.6	6.8	19.0	nd	Crude ore = 10,000 tons	8 million tons
	Manzaku	1969	190 × 190 × 13	1.0	1.5	10.1	nd		
	Tsunokakezawa	1970	480 × 400 × 24	1.1	3.2	15.9	nd		
Shakanai[2]	Shakanai No. 1	1962	300 × 150 × 12	2.3	3.2	14.6	14.0	Crude ore = 35,000 tons	10 million tons
	Shakanai No. 3	1963	400 × 120 × 6	1.1	6.2	10.0	12.0		
	Shakanai No. 4	1963	400 × 300 × 40	1.7	0.7	2.9	22.0		
	Shakanai No. 5	1964	350 × 70 × 13	1.9	1.0	3.4	17.0		
	Shakanai No. 7	1965	350 × 250 × 15	1.3	0.9	3.2	26.0		
	Shakanai No. 8	1965	430 × 170 × 40	0.7	0.2	1.0	33.0		
	Shakanai No. 11	1967	400 × 110 × 10	1.9	3.4	11.8	18.0		
Hanawa[2]	Motoyama	>1960	120 × 100 × 150	0.6	—	0.3	24.0	Crude ore = 11,000 tons	2 million tons[6]
	Sandaira	1951	180 × 70 × 190	0.4	—	0.3	23.0		
	Ajiro	1957	130 × 40 × 100	0.8	—	2.5	15.0		
	Akedoshi	1962	650 × 150 × 8	1.5	3.5	10.0	12.0		
	Osaki	1965	70 × 30 × 45	2.0	0.5	3.0	23.0		
Furutobe[3]	Yunosawa	1959	250 × 100 × 15	1.9	0.9	4.3	20.0	Crude ore = 15,000 tons	7 million tons
	Daikokuzawa-Higashi	1959	100 × 80 × 20	2.8	1.4	6.2	28.0		
	Daikakuzawa-Nishi	1960	250 × 70 × 60	1.1	0.1	1.0	17.6		
	Magariyazawa	1962	200 × 150 × 10	1.9	0.3	2.1	20.8		
	Higashimatazawa	1968	150 × 150 × 10	2.3	1.0	2.9	23.0		
Matsuki[3]	Takadate	1963	540 × 120 × 10	3.0	1.0	2.0	23.0	Crude ore = 10,000 tons	10 million tons
	Matsuki	1964	400 × 100 × 10						
Ainai[4]	Yunosawa	1942	150 × 200 × 50	0.7	—	—	25.0	Crude ore = 9,000 tons	10 million tons
	Suehiro	1955	40 × 50 × 30	4.7	1.7	8.3	20.0		
	Daikoku	1956	80 × 180 × 50	2.2	1.3	5.1	18.5		
	Benten	1957	60 × 200 × 20	1.9	1.2	3.1	18.0		
	Yokodawara	1960	150 × 80 × 20	2.0	0.7	2.9	21.0		
	Hagoromo	1967	80 × 150 × 10	1.9	3.5	10.3	23.0		

[1] Dowa Mining Co.
[2] Nippon Mining Co.
[3] Mitsubishi Metal Mining Co.
[4] Nitto Metal Mining Co.
[5] Estimate of total crude ore mined plus reserves (from Watanabe, 1973).
[6] Excluding low-grade ores.

From Lambert and Sato, 1974.

A common form of the unit ore bodies are shown in Figure 10. Zoned massive stratiform ore grades down into less economically important stockwork ore. The massive ore is typically oval-shaped in plan and lensoid in cross-section. The stockwork ore (siliceous or keiko ore) consists of disseminated and network mineralization. It is distributed in an irregular funnel-shaped body in silicified felsic lavas (white rhyolite) and pyroclastics. Siliceous chimneys (feeder zones) protrude upwards into the massive ore in some deposits. Thin beds or small lenses of ferruginous (hematitic) chert are commonly present above the stratiform ore body. These are either directly overlying or are situated within the hanging wall tuffs. Lenticular or irregular masses of gypsum and/or anhydrite (sekkoko ore) are present in most cases and occur on the footwall side of stratiform ore bodies. Massive barite beds occur in the upper part and above the massive stratiform ore.

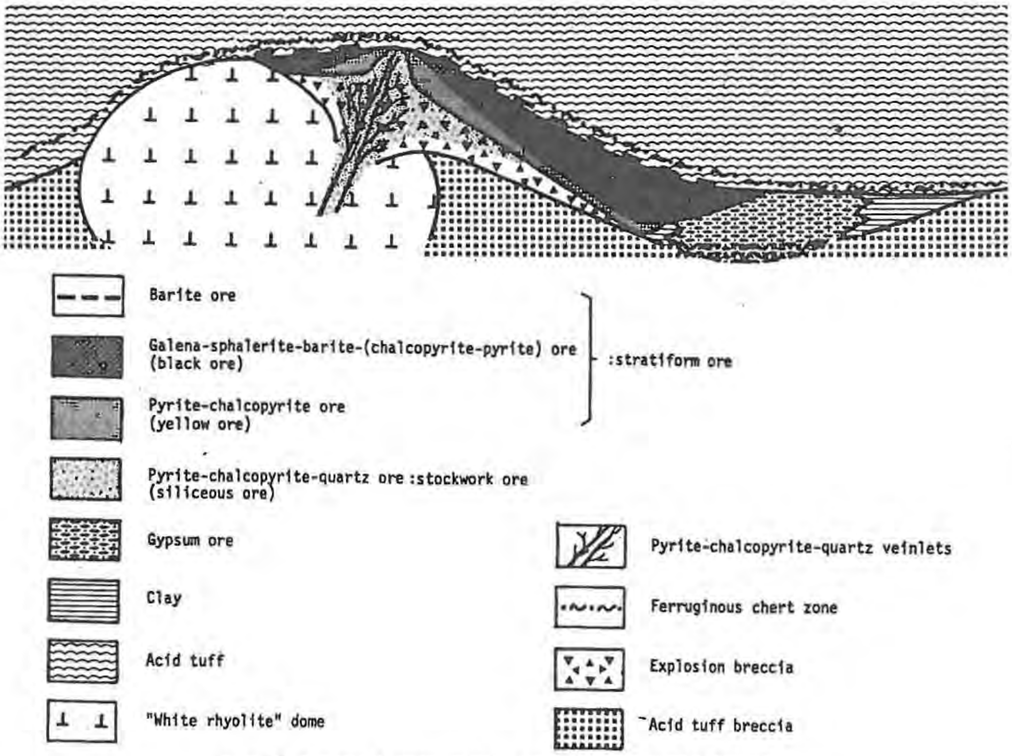


Fig. 10 Schematic cross section of a typical Kuroko deposit.

From Sato, 1974.

The boundaries between stratiform ore and hangingwall rocks (tuff, mudstone, lava) are usually sharp. Laterally, the stratiform ore lenses cut out abruptly in most cases, but in some deposits there are small separate lenses of ore in the marginal zones. A number of deposits are also characterized by breccia ore bodies which are displaced from the main stockwork and stratiform bodies. These are thought to have formed by submarine sliding and mudflows triggered by volcanic explosions (Lee et al., 1974).

The unit ore bodies are characterized by a distinct vertical zoning of their constituent ore minerals, resulting in a vertical layering of distinct ore types. The typical variation of mineral assemblages, in ascending order, is: pyrite - chalcopyrite - quartz (keiko or siliceous ore) in the stockwork zone, pyrite - chalcopyrite (oko or yellow ore) in the lower part of the stratiform body, and sphalerite - galena - tetrahedrite - tennantite - barite in the upper part of the stratiform body. Gold and silver are concentrated in the black ore zone.

Ore textures and structures show considerable variation through the unit ore bodies. In the stockwork siliceous ore, pyrite frequently occurs as euhedral crystals (> 1 mm), but when associated with crypto-crystalline quartz it is finely crystalline or colloform. Chalcopyrite typically occurs interstitial to the pyrite grains. In the yellow ore zone, pyrite and chalcopyrite are considerably finer-grained than in the siliceous ore, except for some coarsely crystalline veins which probably represent "feeders" along which hydrothermal mineralizing fluids passed (Lambert and Sato, 1974). The textures are normally massive, but loosely compacted powdery ore, or breccia ore fragments may be present. In the kuroko zone, the minerals are usually very fine-grained (< 300 µ) and the texture massive or banded. Colloform textures are common in some deposits, especially in pyrite and sphalerite within the uppermost parts of the zone. These include framboidal, pellet, concentrically zoned, and "shrinkage" textures. Some black ores contain chalcopyrite-rich layers and lenses which are parallel to the stratification of the enclosing tuffs and sediments, and in a very few cases the black ore zone may pass upwards into interlaminated mudstone and ore.

Hydrothermal activity resulted in marked alteration of the felsic footwall rocks. The alteration is zoned, with a central quartz-sericite-Mg chlorite core below the massive ore surrounded by mixed sericite-montmorillonite, and marginal montmorillonite-quartz. Alteration may extend up to 20 metres above the ore body and up to 200 metres laterally away from it.

The Archaean Copper-zinc deposits of Canada have analogous features to the Kuroko deposits although these are generally masked by post-ore metamorphism and deformation (Sangster, 1972, Sangster and Scott, 1976). The deposits comprise two main ore types - massive and stringer ore - distinguished largely by the relative proportions of sulphide and silicate minerals. More than 50% of the known deposits in Canada have both massive and stringer ore zones. The majority of the remaining deposits contain massive ore only. Most deposits consist of several distinct massive ore lenses and associated stringer ore zones clustered together. The sizes of ore deposits vary considerably, from a few hundred thousand tons in single massive ore bodies like Amulet C, Amulet F, and Rod No.2, to very large multiple ore bodies like Kidd Creek (>100 million tons). (Table 2).

The ideal form of Archaean copper-zinc ore bodies is displayed by cross-sections of the undeformed Norbec and East Waite deposits, Noranda area (Figures 11 and 12). A massive ore lense occurs at the contact of rhyolitic or rhyodacitic porphyry with overlying andesite. This lense is conformable with its enclosing rocks and commonly grades laterally into ferruginous cherty tuff, which may also overlie the massive ore. This cherty tuff is thus the actual host rock of the massive sulphides. The massive ore is underlain by a discordant cylindrical alteration "pipe" within which are disseminations and veins of sulphides (stringer ore). The stringer ore may, or may not be of economic grade.

The term "massive ore" normally applies to ore consisting of at least 50% sulphides by volume. The iron sulphides, particularly pyrite and pyrrhotite, characteristically comprise at least half the total sulphide content. Sphalerite, chalcopyrite and minor galena constitute most of the remaining sulphides.

The shape of massive ore bodies are usually lensoid in cross-section and circular, or oval to slightly elongated in plan. The two longest dimensions of the bodies and the layering within the mass are, in relatively undeformed ores, parallel to bedding planes or flow contacts in the host rocks. Hangingwall contacts of massive ore bodies are sharp, while footwall contacts are more diffuse and commonly gradational into stringer ore.

TABLE 2

Base- and precious metal content of selected Precambrian massive Cu–Zn–Pb sulfide deposits (partly after Hutchinson, 1973)

Name, district	%Pb	%Zn	%Cu	oz./ton Ag	oz./ton Au	Remarks, reference
Horne mine; Noranda, Que. (Can.)	n.s.	n.s	2.19	n.s	0.152	52.6 million tons production to 1966 (Spence, 1967)
Quemont; Noranda, Que. (Can.)	n.s	1.86	1.27	0.523	0.129	13.5 m.t. production to 1966 (Spence, 1967)
Lake Dufault Norbec; Noranda, Que. (Can.)	n.s.	7.2	4.0	2.2	0.03	initial ore reserve estimate 2.3 m.t. (Purdie, 1967, p. 53)
	n.s.	6.88	5.05	1.81	0.032	1.08 m.t. production to 1966 (Spence, 1967)
Waite; Noranda, Que. (Can.)	n.s.	4.47	7.11	0.70	0.03	total production 1.1 m.t. (Price and Bancroft, 1948, p.748)
Amulet Lower A; Noranda, Que. (Can.)	n.s.	5.69	5.13	1.41	0.041	Millhead ore assays, 2.1 m.t. (Suffel, 1948, p.757)
Amulet C; Noranda, Que. (Can.)	n.s.	14.30	2.62	4.19	0.020	Millhead ore assays, 240,000 t. (Suffel, 1948, p.757)
Amulet F; Noranda, Que.	n.s.	10.88	4.28	1.48	0.017	Millhead ore assays, 150,000 t. (Suffel, 1948, p.757)
Vauze; mine, Noranda, Que. (Can.)	n.s.	0.94	2.90	0.69	0.019	0.39 m.t. production to 1965 (Spence, 1967)
West MacDonald; Noranda, Que. (Can.)	n.s.	2.91	0.012	0.0051	0.0019	1.03 m.t. estimated production 1955–59 (Spence, 1967)
Magusi River deposit; Noranda, Que. (Can.)	n.s.	4.18	1.32	0.92	0.024	3.6 m.t. reserves 1973 (Jones, 1973)
Mattagami Lake; Matagami, Que. (Can.)	n.s.	10.4	0.69	1.13	0.014	18.7 m.t. ore reserves 1966 (Can. Mines Handbook 1967–68 p.213)
Manitou Barvue; Val d'Or, Que. (Can.)	0.38	4.74	0.03	2.57	0.034	production from 6.1 m.t. zinc–lead ore (Ramsay and Swail, 1967, p.19)
	n.s.	n.s.	0.9	0.068	0.012	production from 3.1 m.t. copper ore (Ramsay and Swail, 1967, p.19)
Mattabi; Sturgeon Lake, Ont. (Can)	0.84	7.6	0.91	3.13	0.007	12.9 m.t. ore reserves, 1973; recoverable lead (Franklin et al., 1973)
Flin Flon; Flin Flon, Man. (Can.)	n.s.	4.24	2.99	1.25	0.089	26 m.t. ore reserves, 1964 (Geol. Staff, Hudson Bay Mining and Smelting and Stockwell, 1948, p.295)
	n.s.	4.4	2.2	n.s	n.s	59 m.t. production to 1970 (Coats et al., 1972)
Cuprus mine; Flin Flon, Man. (Can.)	n.s.	6.4	3.75	0.84	0.038	avg. grade 510,000 t. ore mined (Geol. Staff, Hudson Bay Mining and Smelting, 1957, p.253)
Stall Lake mine; Snow Lake, Man. (Can.)	n.s.	0.5	5.2	0.31	0.044	2.1 m.t. reserves, 1968 (Coats et al., 1970, p.971)
Rod Deposit, No. 2; Snow Lake, Man. (Can.)	n.s.	2.88	7.10	0.47	0.05	0.3 m.t. reserves, 1968 (Coats et al., 1970, p.971)
Chisel Lake mine; Snow Lake, Man. (Can.)	0.7	12.00	0.39	1.23	0.049	3.2 m.t. reserves, 1968 (Coats et al., 1970, p.971)
Ghost Lake mine; Snow Lake, Man. Can.)	0.7	11.6	1.42	1.14	0.013	0.26 m.t. reserves, 1968 (Coats et al., 1970, p.971)
Osborne Lake mine; Snow Lake, Man. (Can.)	n.s.	1.4	4.17	n.s.	n.s.	2.7 m.t. reserves, 1968 (Coats et al., 1970, p.971)
Fox Mine; Lynn Lake, Man. (Can.)	n.s.	2.70	1.84	n.s.	n.s.	13.1 m.t. reserves, 1970; (Coats et al., 1972)
Kidd Creek; Timmins, Ont. (Can.)	0.40	9.75	1.52	4.30	n.s.	25 m.t. production to December 1973; significant Sn and Cd recovered; 95 m.t. reserves remaining above 2800' level with higher Cu and lower Zn grade; massive ore extends below 4000' level (Matulich et al., 1974)

n.s. = not stated;

From Sangster and Scott, 1976.

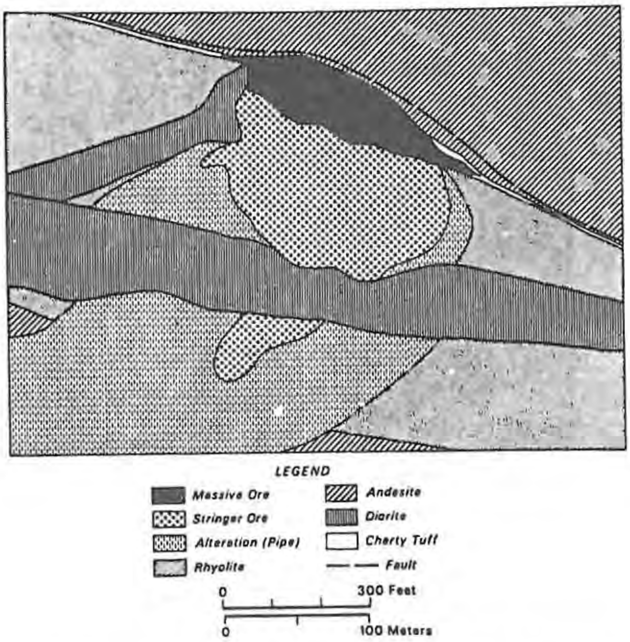


Fig. 11 Generalized east–west section, Norbec deposit, Noranda area. Stratigraphy is right-side-up as shown. (After Purdie, 1967; courtesy of Can. Inst. Min. Metall.)

From Sangster and Scott, 1976.

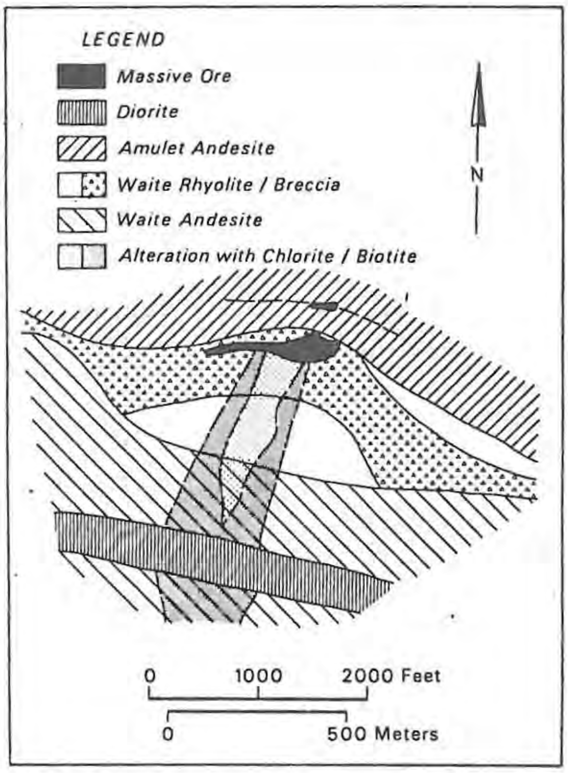


Fig. 12 Schematic east–west section of the East Waite deposit, Noranda area, showing the association of the sulfide body to a rhyolite dome and breccia. (After Spence and De Rosen-Spence, 1975; courtesy of *Econ. Geol.*)

From Sangster and Scott, 1976.

The total sulphide content of stringer ore is considerably less, and much more variable than massive ore. It seldom exceeds 25%. Pyrrhotite, chalcopyrite and pyrite are the major sulphide minerals in the stringer ore. The sulphides occur as anastomosing veinlets, veins, and irregular replacement masses. These extend downward, cross-cutting the stratigraphy, for a few inches, several metres, or hundreds of metres. The shape of the stringer zone is generally cilindrical or funnel-shaped in undeformed ores. The upward dilation of the stringer zone ends at the massive ore and only rarely does it extend beyond it, either laterally or vertically. A few ore bodies are known where two or more massive sulphide lenses are "stacked" one on top of the other with stringer ore intervening. Examples of "stacked" deposits are the Amulet "A" Mine (Dresser and Denis, 1949) and the Millenbach deposit, (Simmonds, 1973).

Ore bodies are characteristically zoned. The zoning is expressed in four ways: morphology, mineralogy, texture, and composition.

Morphological zoning is manifested by the co-existence of massive and stringer ore. Where both are present, the stringer ore occurs on the stratigraphic footwall of the massive ore body (Figures 11 and 12). Mineralogical zoning is in part a function of morphological zoning. In an ideal deposit sphalerite would be much more abundant in the massive ore than in the stringer ore. Galena, where it occurs, is only found in the massive ore and the pyrite/pyrrhotite ratio is commonly much higher in the massive than in the stringer ore. Galena and sphalerite also tends to increase towards the top of the massive ore and chalcopyrite tends to increase towards the base where it grades into chalcopyrite stringer ore. Textural zoning is concomitant with mineralogical zonation in that more chalcopyrite-rich portions seldom show banding. Compositional zoning parallels the distribution of the three major sulphides - sphalerite, chalcopyrite, galena - but has the advantage of being more quantitative and can be detected on routine assay plans. The usual pattern is of an abundance of zinc, (± lead) in the upper part of the massive ore body, with copper increasing towards the footwall. In many ore bodies, however, the zoning is caused by a downward decrease of zinc rather than an increase in copper, so that the very rich "copper keels" of some deposits are the exception rather than the rule (Sangster, 1972; Sangster and Scott, 1976). Economically extractable quantities of gold and silver are usually concentrated in the copper-rich part of the ore bodies. These occur as exolutions or in solid solution with chalcopyrite. High silver values may accompany rare concentrations of galena in the upper parts of massive sulphide lenses.

The wall-rock alteration associated with massive sulphide deposits is easily recognized and commonly occur as a well-defined zone (pipe-or funnel-shaped) on the footwall side of the massive ore (e.g. Dugas, 1966; Gilmour, 1965; Franklin et al., 1975; and Riverin and Hodgson, 1980). Development of chlorite is the main mineralogical expression of footwall alteration. Chlorite is followed, in decreasing order of importance, by sericite, quartz, and graphite. Chloritization and sericitization, the two most common types of alteration, result in a desilication of the host rocks, particularly where they are developed in rhyolitic rocks. The most obvious chemical changes in the alteration pipe are a relative increase of Fe, Mg and S and a decrease of Si, K, Ca, and Na (Franklin et al., 1975; Riverin and Hodgson, 1980).

Metamorphism and associated deformation have profound effects on the shape and attitude of massive sulphide ore bodies. One of the most common results is the development of rod-like or blade-like ore bodies alligned parallel to lineations; fold axes, mineral streaking or elongation, etc. Rod-shaped ore bodies develop in areas of medium to high metamorphic grade which show a penetrative lineation. In rocks of lower metamorphic grade, where deformation is expressed mainly by shearing and folding, without a well-developed lineation, the deposits tend to be flattened parallel to the schistosity. Ore bodies deformed predominantly by shearing commonly have been sliced into several en-echelon lenses separated by narrow zones of highly schistose and altered wall-rock. Due to the relative competency of the pyritic massive sulphides, boudinage is commonly observed in most deformed deposits. The extreme ductility contrast between competent massive sulphides, and schistose, altered wall-rocks in areas of very high metamorphic grade results in ore bodies which have been so distorted that their form is best described as amoeba-like.

Genesis - the volcanic-exhalative theory

Traditional genetic models for stratiform massive sulphide deposits supported an epigenetic or hydrothermal replacement mechanism. These models, based mainly on Lindgren's textbook, "Mineral Deposits" which was first published in 1913, were strictly adhered to in Northern America, and elsewhere, for several decades.

In 1958, Oftedahl popularized the concept of syngenetic sedimentary-exhalative deposition earlier expressed by European workers such as Schneiderhöhn (1944), and Ramdohr (1953). The ideas expressed by Oftedahl were followed up by Stanton (1960), Gilmour (1965), Goodwin (1965), and by Roscoe (1965) who applied the theory to various deposits in the Canadian Shield and elsewhere in North America.

In Japan, the genetic connotation of the close association of Kuroko deposits and Miocene felsic volcanic rocks was recognised much earlier than anywhere else in the world (Hirabayashi, 1908, and Kinoshita, 1931, quoted in Tatsumi and Watanabe, 1971). This is probably because deposits are virtually undeformed, and primary textures and structures have thus not been obscured by recrystallization and deformation.

In general terms, the volcanic-exhalative theory advocates that massive sulphide ores in predominantly volcanic environments are an integral part of, and coeval with, the volcanic complex in which the deposits occur. The exhalative concept further propounds that the massive sulphides are precipitated on the sea floor from hydrothermal fluids originating within the crust and rising along fractures or other zones of weakness. The main difference between exhalative and replacement theories is thus the timing of the mineralization event. Metal-sulphide precipitation (in both theories) was probably controlled by temperature and pressure gradients, dilution of ore fluids, changes in pH and/or Eh etc.

Hutchinson (1977) equated the mineralizing systems with present day convection systems (Figure 13(a) and (b)). He postulated that deposition took place on the sea floor where brines rose through venting channels.

Initial deposition was epigenetic and probably occurred due to mixing of deep circulated reduced brine with shallow circulated relatively oxidized brine in the upper parts of the venting channels themselves. This formed the zones of stringer ore and disseminated mineralization within the alteration zone. Subsequent deposition was apparently by chemical precipitation of the metals, perhaps as gel-like precipitates on the sea floor around and near the vent to form the massive sulphide body. Phreatic and volcanic explosions created the breccia ore which is commonly associated with massive sulphides, and late, less active hydrothermal exhalation created the iron-rich cherty and/or carbonate-rich chemical sediment. Hutchinson further supports leaching of country rocks by the circulating seawater and connate water as a source for the metals and reduction of sulphate from seawater as the major source for the sulphur.

Hodgson and Lydon (1977) refined Hutchinson's model and pointed out the essential features of such a system. These are an aquifer zone, a cap rock (either a self-seal cap or natural cap rock), recharge and discharge channels, and a heat source. The heat source may be volcanic, but is not necessarily so. This model is thus unable to explain the strong lithostratigraphic control of the deposits. Hodgson and Lydon also favoured the leaching of country rocks as the source of the metals, but failed to explain the absence of depletion haloes around deposits of this type.

Henley and Thornley (1979) reviewed data on sub-sea floor geothermal systems, depositional processes, and source of metal. They envisaged the initiation of a geothermal cell by volcanic activity. Differentiation in the magma chamber gives rise to late-stage magmatic fluids enriched in the ore metals. These fluids are sucked up in a bouyant plume by the geothermal cell and exhaled at the sea floor through conduits generated by hydrothermal fracturing (Figure 14). Self-sealing and subsequent phreatic explosions give rise to stringer ore, footwall breccias and brecciated ore.

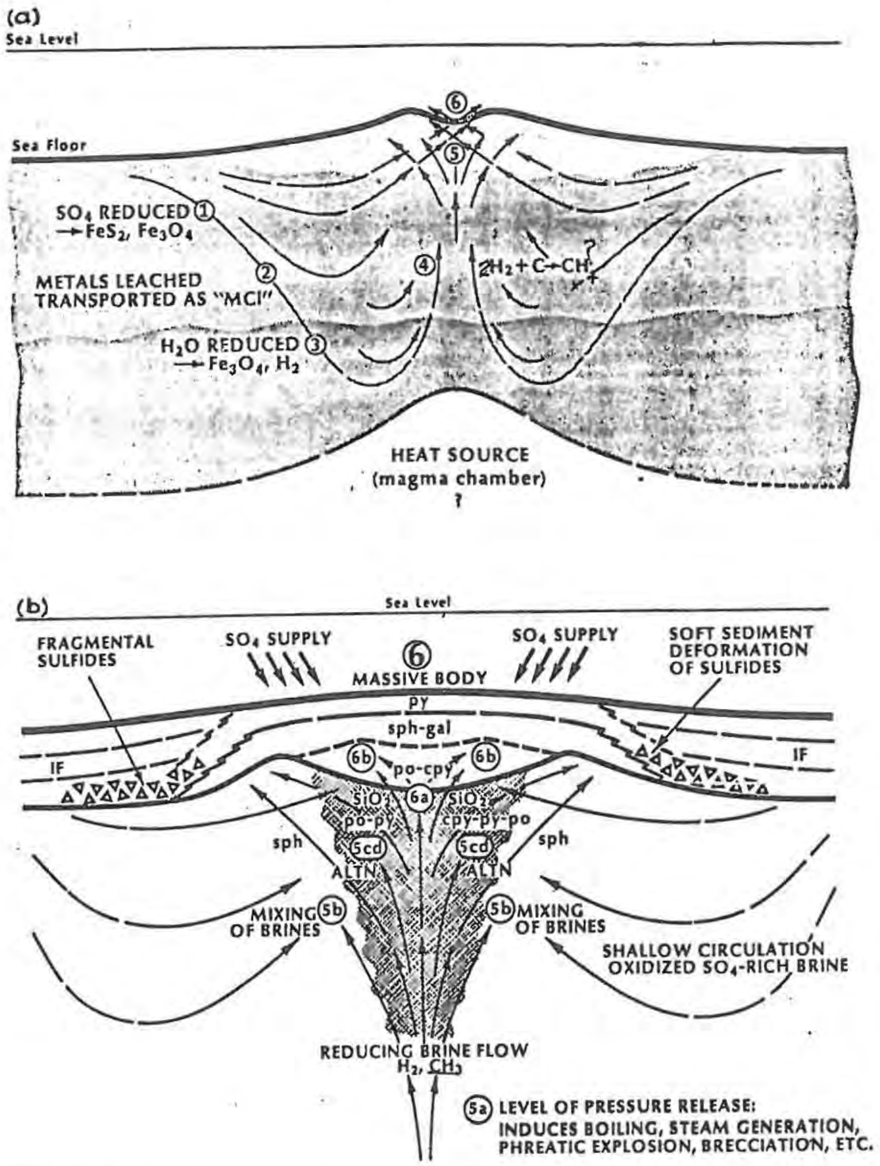


Figure 13: (a) Convective circulation of saline connate and/or marine waters, and (b) precipitation of metals at or just below the sea floor. 1 to 6 indicate the sequence of events.
From Hutchinson, 1977.

Late stage fluids during the waning phases of the geothermal cell cause the deposition of siliceous ironstones capping the deposit. When magmatism ceases, the plume collapses, but geothermal activity may continue for several thousand years. Mineralogical and isotopic features derived from the magmatic source would be progressively obliterated by dissolution and mineral-fluid reactions.

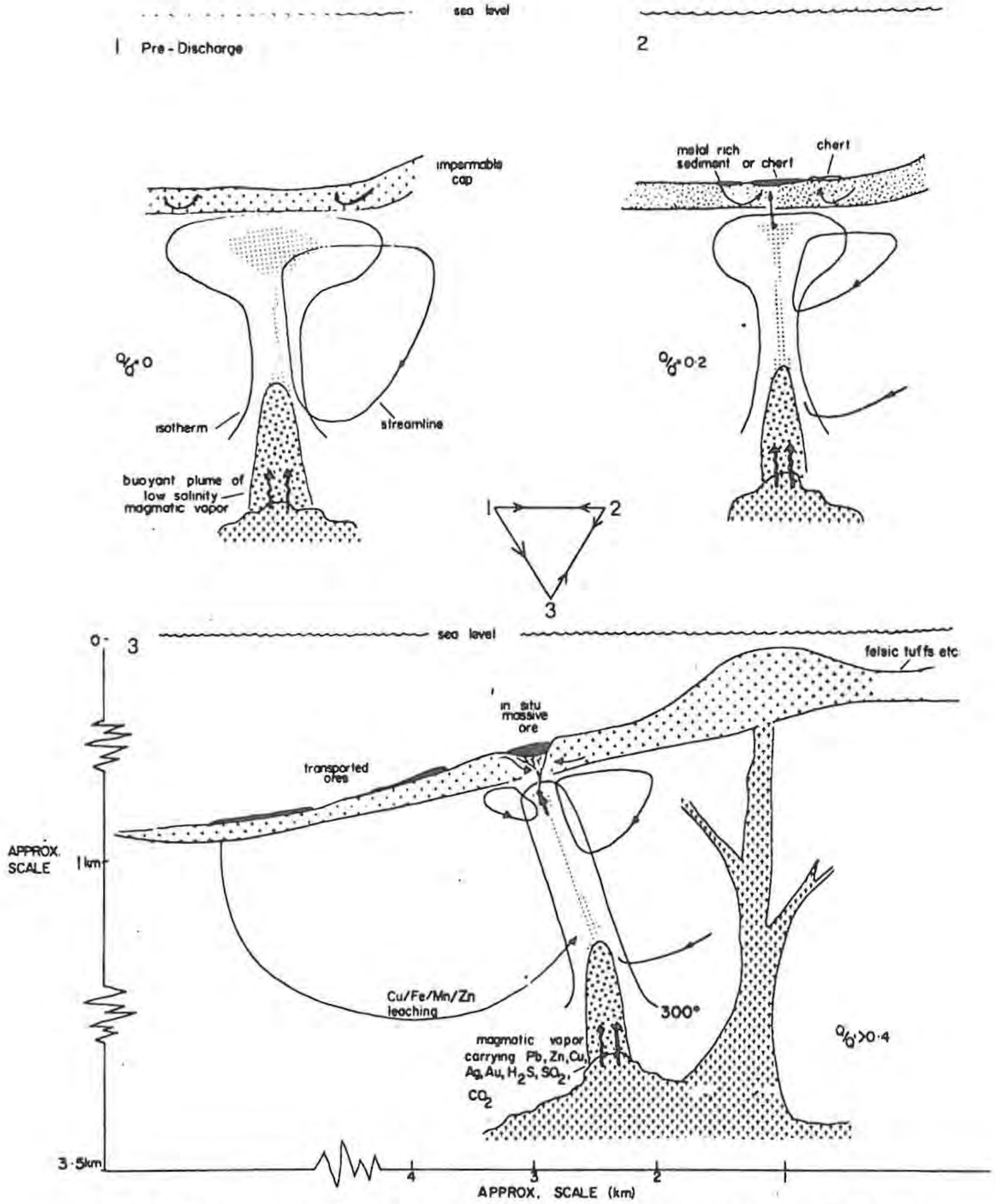


FIG. 14 Influence of discharge on temperature-streamline distribution of convective flow and dispersion plumes generated by interaction of sub-sea-floor, sea-water-fed convective system and metalliferous magmatic vapor evolved from felsic pluton in or below the convective system. Q' = power input, Q = power output.

1. No discharge. Surface phenomena due to parasitic systems.
2. Steady state low-power discharge. Deposition of metal-rich sediments, massive ores, or cherts in relatively reducing basinal environments.
3. General schema of Kuroko-type massive sulfide formation. Off-axis relatively high-power discharge, probably initiated by earthquake and hydrothermal explosion.

Rapid discharge from dispersion plumes generates stockwork and in situ massive ore. Discharge subsequently decays, due to self-sealing, to state 2 then to state 1 or renewal of high-power discharge may occur. Mass flow of transported ores may be initiated and supplied by initial violent activity near the discharge point. Streamlines and isotherms after Elder (1965).

From Henley and Thornley, 1979.

In spite of a vast amount of empirical data, models are perforce the result of conceptual thinking, and not of studies of mechanisms operative deep within the crust. Genetic models are thus at best guesswork and not provable hypotheses.

GEOLOGICAL FACTORS THAT INFLUENCE ORE BODY MORPHOLOGY, METAL CONTENT AND METAL DISTRIBUTION

PRIMARY FACTORS

Primary factors are those inherent in the genesis of ore bodies. They are thus interrelated and control the original wall-rock association, size, shape, metal content, and metal distribution of the deposits. Primary factors include structural and lithologic control, mode and rate of precipitation of ore minerals, ore body zoning, wall-rock alteration, and soft-sediment deformation. Although not one of these factors can be seen in isolation, they are treated separately to make discussion easier.

Lithostratigraphic and structural control

The association of massive sulphide deposits with the end products of differentiated calc-alkaline magmatism is well established in Canada and Japan (Wilson et al., 1965; Horikoshi, 1969). Progressive differentiation of the subvolcanic complex allows the build-up of incompatible elements until an aqueous phase can separate (Burnham, 1979). The aqueous phase interacts with geothermal waters and is exhaled as an aqueous brine onto the sea floor. This is generally in association with, or closely follows the most felsic and final extrusive phase of a particular volcanic cycle (Figure 15).

Late stage rhyolitic or rhyodacitic lavas are very viscous and typically form domical masses. Phreatic explosions as a result of the hydrous nature of the lava provide conduits for the subsequent hydrothermal activity. Concentration of the metals contained within the hydrothermal fluid can only occur when there is a significant break in volcanic activity. This is then followed by the initiation of the next volcanic cycle with the eruption of basaltic or andesitic lavas which then form the hangingwall of the ore deposits. Should volcanism cease entirely, then deposits are eventually covered by volcaniclastic and other sediments.

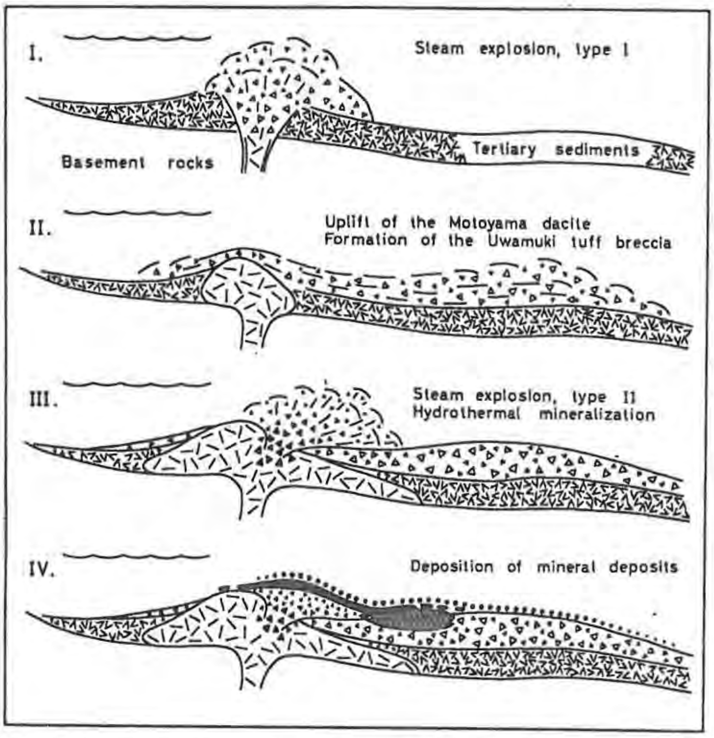


Fig. 15 Schematic figures showing the history of development of the Kosaka Volcano in a single eruptive cycle

From Horikoshi, 1969.

Smith and Bailley (1969), and later Ohmoto (1978) and Harley (1979) equated the formation of domical felsic volcanic complexes with the development of resurgent calderas. A large number of faults and fractures that can act as conduits both for lavas and hydrothermal fluids form as a result of the combined effects of updoming due to the upward and outward directed force of a vertically elongate rising magma body (Koide and Bhattacharji, 1975), the separation and rise of an immiscible hydrothermal fluid within the rising magma column (Burnham, 1967, 1979), and brittle failure along radial and concentric normal faults of the domed and extended roof rocks. The sequence of events in the formation of a caldera complex is schematically represented in Figure 16.

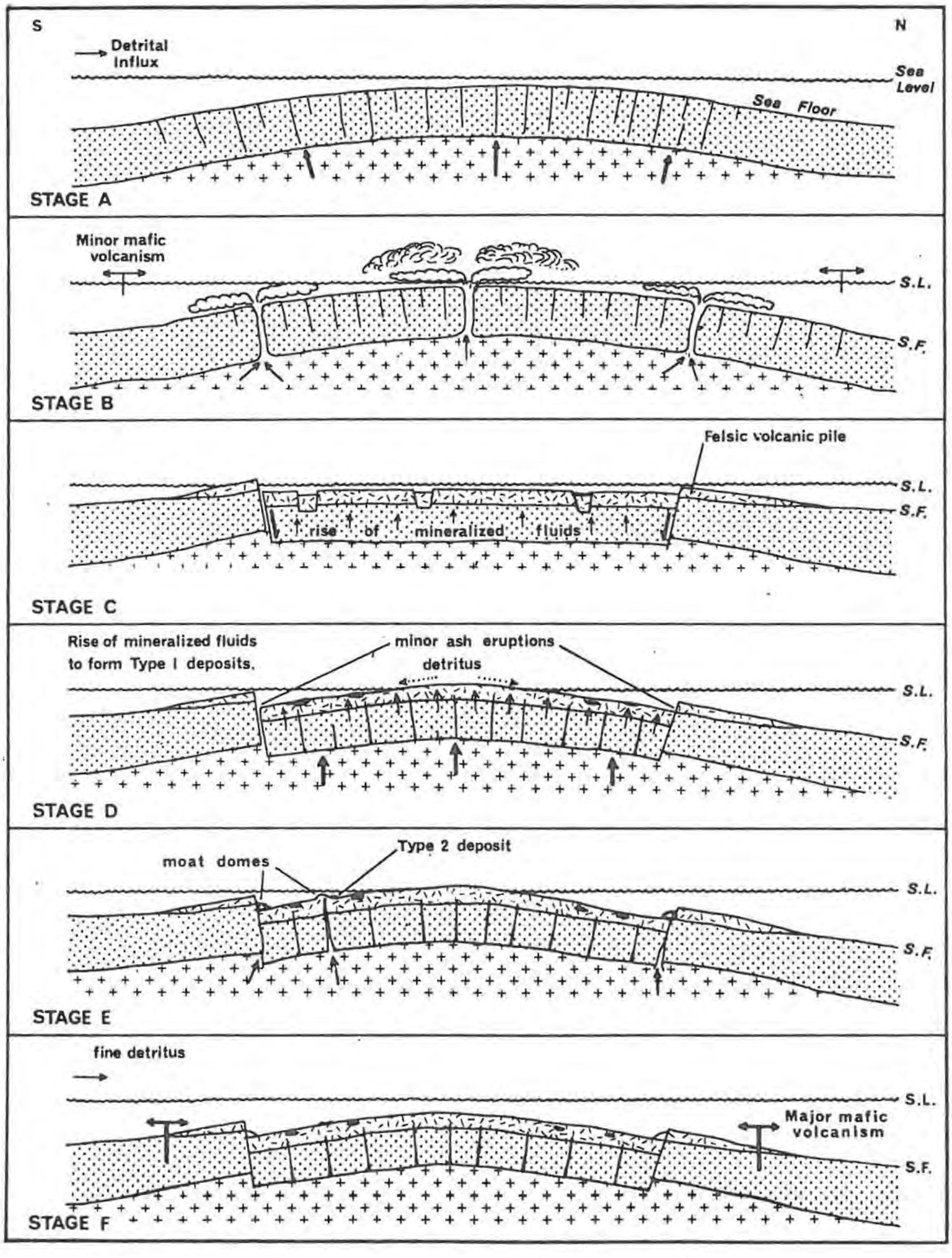


Figure 16: A caldera hypothesis for the development of a mineralized felsic volcanic complex. Stage A: magma insurgence; Stage B: caldera-forming eruptions; Stage C: caldera subsidence and minor mineralization; Stage D: resurgent doming and major mineralisation; Stage E: post-resurgence volcanism and minor mineralization; Stage F: final stage or start of next cycle of mafic volcanism.
From Harley, 1979.

Updoming and resulting ring fractures are followed by major extrusion of felsic lavas. This depletes the top of the magma chamber and results in caldera collapse. Resurgent doming causes extension of the roof and enhances the permeability of the fracture system, providing the most favourable conditions for the formation of a hydrothermal system. During this stage the felsic magma contributing the heat source and key fluid constituents to the system also make their closest approach to the lithosphere surface (i.e. at the time of maximum thermal gradient). It is thus not surprising that the precipitates from surface discharge of such hydrothermal systems will be associated in both time and space with the late viscous extrusions from the magma chamber.

In a recent study by Frith and Roscoe (1980), massive sulphide deposits of the Hacket River Belt, Slave Province, Canada, are related to hydrothermal activity on the fractured floor of a flooded caldera basin. So-called "chaotic zones" of disoriented blocks of mafic and felsic volcanics are associated with synvolcanic faults and are thought to have formed during multiple caldera collapses.

The control of regionally developed fault directions on the localization and spacing of ore bodies was demonstrated by Kutina (1972) for deposits in the Noranda area. These are probably reactivated faults along old crustal sutures. Fujii (1974) related major north-south and northwest-southeast trending faults in northern Honshu to the tectonic development of the Green Tuff region in that area. These major deepseated faults localized the development of calderas, and thus of felsic complexes and massive sulphide deposits.

Nature of the ore fluid and precipitation of the ore minerals

Hydrothermal solutions responsible for the formation of massive sulphide deposits are thought to be at least partly derived from magmatic fluids (Henley and Thornley, 1979). Fractional crystallization of anhydrous minerals in a rising magma will increase the water content of the magma until it is saturated, when an aqueous phase will separate. In case of anhydrous magmas this will only occur after 75% to 85% crystallization

(Burnham, 1979). A decrease in the pressure of an incipiently saturated magma, for example by volcanic eruption, will also allow an aqueous phase to separate. According to Burnhan (1979) chlorite will strongly partition into this aqueous phase because it does not form stable complexes with either Si or Al and thus is not soluble in an alumina-silica melt. Minerals that can contain OH, F, and Cl are found to preferentially incorporate F in crystal lattices. The partition coefficient $D^{A/B}_{M}$ for chlorine is large so that an aqueous phase separating from a melt initially containing 0,1% Clwill contain 4,6 wt % Cl at 0,6 Kb or 7,5 wt % Cl at 2,1 Kb (Burnham, 1979). The high ionisation constants of the alkali and hydrogen chlorides enable chlorine to enhance the solvent properties of the aqueous phase. NaCl, KCl, HCl, $CaCl_2$, $FeCl_2$, and $FeCl_3$ are stable complexes in aqueous solutions at magmatic temperatures.

The results of fluid inclusion studies and the compositions of modern hydrothermal solutions in active geothermal systems indicate that chloride complexes are probably the most important agents in the transport of base metals. Chloride complexes are capable of transporting base metals in both sulphur deficient and sulphur-rich fluids with neutral to acid pH values at most temperatures (Large, 1977). At high temperatures (>270°C), and mildly acid pH, H_2S is the dominant sulphur species, while at low temperatures, and acid to alkaline pH, $SO_4^{=}$, KSO_4^-, or HSO_4^- predominates. The stability and hence increased solubility of base metal chloride complexes increase with a decrease in pH and ΣS, and an increase of temperature and NaCl content of the solution. Crerar and Barnes (1976) demonstrated the solubility of the assemblage chalcopyrite + pyrite + bornite in a hydrothermal NaCl and NaHS - H_2S solution. The effect of changes in temperature, pH and Eh on this assemblage is well illustrated by Figure 17. It is clear from the figure that a drop in temperature has the most drastic effect on the stability of both Fe and Cu, e.g. at 350°C 1000 ppm Cu can be held in solution at a pH of 3,5, while at 250°C only 10 ppm remains in solution at the same pH. The main effect of the temperature decrease, in this case, is a decrease of oxygen fugacity (fO_2), and thus a change from the oxidized to the reduced state.

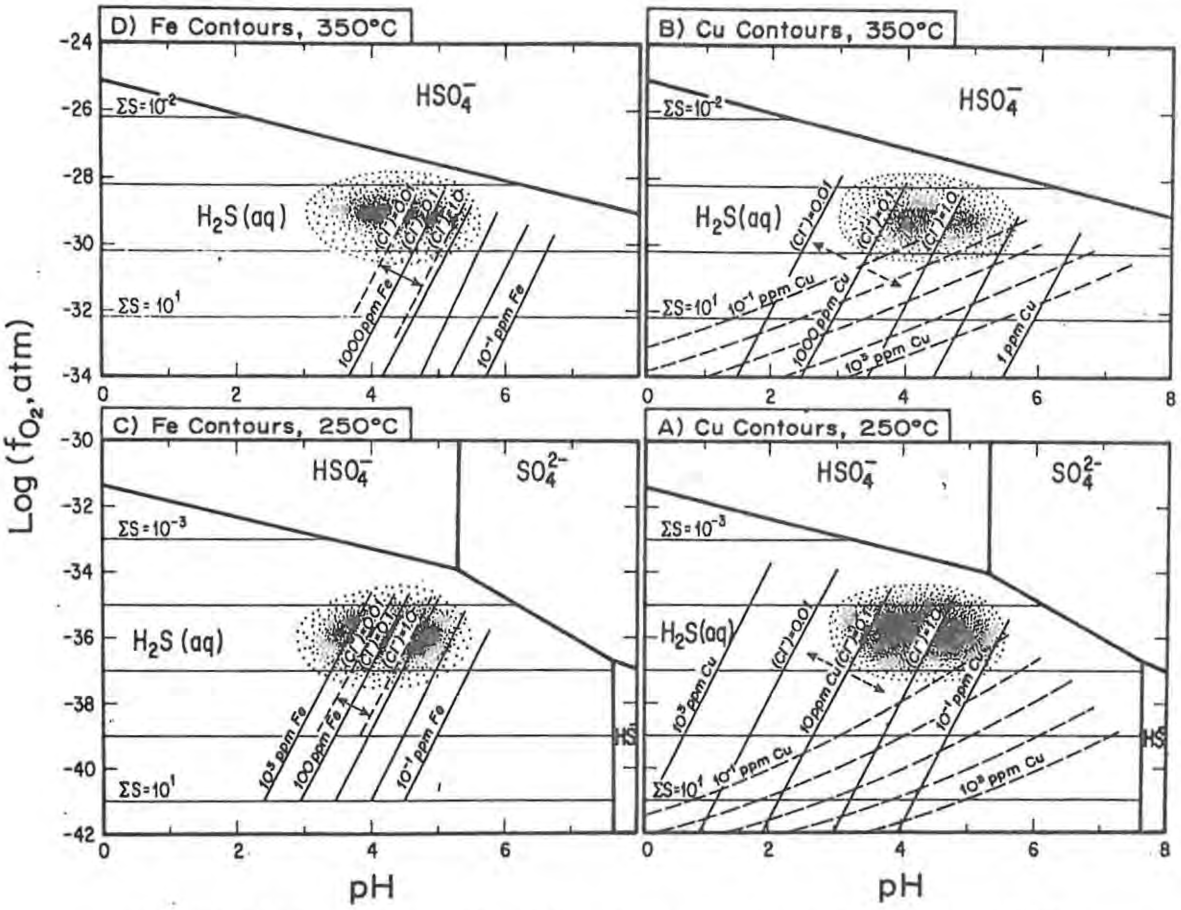


FIG. 17 Solubility of the assemblage chalcopyrite + pyrite + bornite in hydrothermal NaCl and NaHS-H_2S solutions. ΣS is contoured for stable coexistence of chalcopyrite + pyrite + bornite. Stippled area is "average" ore fluid within the sericite stability field. Cl^- activity = 0.1. Ranges of concentrations along contours are shown for a_{Cl^-} between 10^{-2} and 1.0. (A) and (B). Solid contours show the concentration of the CuCl complex at 250°C and 350°C respectively. Dashed contours represent the concentration of $[Cu(HS)_2^- + Cu(HS)_2(H_2S)^-]$. (C) and (D). Contours represent the concentration of $(Fe^{2+} + FeCl^+)$ at 250°C and 350°C, respectively.

From Crerar and Barnes, 1976.

The most important cause for a major drop in temperature is the mixing of a hot, rising solution with a near surface mass of cold water. This happens when a hydrothermal solution is debouched onto the sea floor or when it mixes with relatively cold circulating geothermal waters.

Changes in the pH also greatly affects the capacity of the solution. These are brought about by solution mixing or by subsurface boiling caused by pressure release at constant temperature. Boiling causes a release of volatile constituents from the solution, thereby leaving the residue more alkaline and less capable of metal transport. The effect of pH is nearly as drastic as that of temperature. It can be seen from Figure 17 that an increase of one pH unit will cause 99% of the contained Cu or Fe to precipitate.

Pb and Zn behave very much like Cu and precipitate in the presence of reduced sulphur when temperature decreases or pH increases. A change in fO_2 has negligible effect.

Fluid inclusion studies of Kuroko deposits (Lu, 1969; Enjoji, 1972; Mukaiyama et al., 1974; Tokunuga and Honma, 1974; quoted in Urabe and Sato, 1978) indicate that the filling temperatures were in the range from 150°C to 300°C, and equivalent NaCl salinities were in the range from 2.1 to 8.4 wt % NaCl. If the temperatures and salinities established from fluid inclusions in the siliceous ore zones are accepted as being representative of active mineralizing solutions, it can be assumed that the ascending ore solutions had temperatures around 250°C to 300°C and salinities higher than normal sea water. The yellow, black, and barite ore, and the ferruginous chert were deposited from more dilute solutions with salinities similar to normal sea water and at much lower temperatures. At these temperatures and salinities these brine solutions would be bouyant - ± 25% lighter than sea water - when they emerge on the sea floor.

The focussed discharge of hydrothermal fluids through a conduit will result in the generation, and maintenance of an axisymetric plume. A wedge-shaped line plume would be generated by exhalation from a fissure (Turner and Gustafson, 1978; Solomon and Walshe, 1979). The plumes originating at a point source widen rapidly during their upward acceleration due to entrainment of sea water (Figure 18). The brine plume would rise several hundred metres into the ocean, depending on the density gradient. Should it achieve neutral buoyancy, the plume would spread out laterally. If it retains its positive buoyancy, the plume would eventually dissipate as the entrainment of the sea water increased upwards. Subsurface mixing of the hydrothermal brine with seawater, quenching and precipitation at the vent, and entrainment of some of the metal components lead to the typical zonal pattern of the massive sulphide deposits, which will be discussed in the next section.

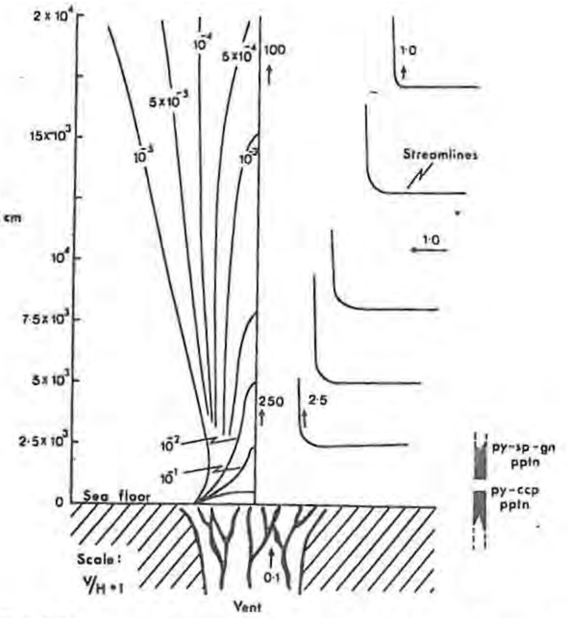


FIG. 18 A speculative reconstruction of stream lines and velocity (to the right) and relative buoyancy values (to the left) in a maintained axisymmetric plume derived from a finite but not continuous source, using a 25 percent density contrast, sea water of constant density, and a mass rate of 10^6g sec^{-1}. Velocities in cm sec^{-1}.

From Solomon and Walshe, 1979.

Discharge and metal sulphide deposition from active hydrothermal vents have been observed and photographed on the East Pacific Rise (Cyamex Scientific Team, 1979; Ballard and Grassle, 1979). Ballard and Grassle (1979, p.702) give the following vivid description of an active hydrothermal vent: "Like a factory at full throttle, a submarine chimney ... belches hot mineral-laden water that rises through cold seawater pressing down at nearly two tons per square inch. As the solution mixes with the near freezing water, it precipitates yellow, ochre and reddish brown deposits of iron, copper, and zinc sulphides." The columnar edifices which are built up around the emanating plume consist of an intricate network of thin channels and tubes of silica and/or sulphides. Mounds of sulphide encrustations - chalcopyrite, pyrite, sphalerite - form around the vents. In a number of Kuroko deposits similar edifices remained the feeder zone during massive sulphide precipitation (Urabe and Sato, 1978). This is illustrated by the well-developed siliceous "chimneys" in the Uchinotai-nishi deposit (Figure 19), which accumulated as drusy siliceous sinter deposits and remained a point source throughout massive sulphide deposition. Spence (1975) in his description of the Vauze massive sulphide deposit, Noranda, concluded that the massive ore was hard and brittle at an early stage. Since the sulphide mound remained intact on a slope of some 30° it must have been deposited in this hard form. He attributed its formation to the growth of an encrustation, or sinter, of sulphides on the slopes of a rhyolite dome from metal-rich solutions emanating from a submarine hot spring.

In contrast to precipitation around a siliceous "chimney", deposition of sulphide over a negative feeder zone, which probably had very low permeability to start with, would choke the orifice and deflect the rising fluid to the margins of the sulphide deposit. Because of lack of supply in the centre, the plume collapses inward and appears to be derived from the centre of an anulus or ring source. This allows the brine plume to maintain a constant relationship with the growing massive sulphide mound. A similar effect may be obtained from the interference of two adjacent plumes, so that a single mineral deposit may be deposited from two feeder pipes (Figure 20).

It might be expected that line sources would be important in massive sulphide genesis because faults are likely to be important channelways of high permeability. Faults are obviously important on the regional scale, controlling the location of deposits, but seem to be unimportant on deposit scale (Solomon and Walshe, 1979). It is likely that, as in the case of most felsic volcanic eruptions (Macdonald, 1972), precipitation of silicates and ore minerals in the feeder tend to focus the discharge into a few pipe-like zones which occur at intervals along the fault. Nevertheless, observations on relatively unmetamorphosed deposits in the Noranda area indicate that the original shape of some deposits was oval to slightly elongate in plan (Sangster, 1972), which indicate that linear sources could have been important in the Archaean.

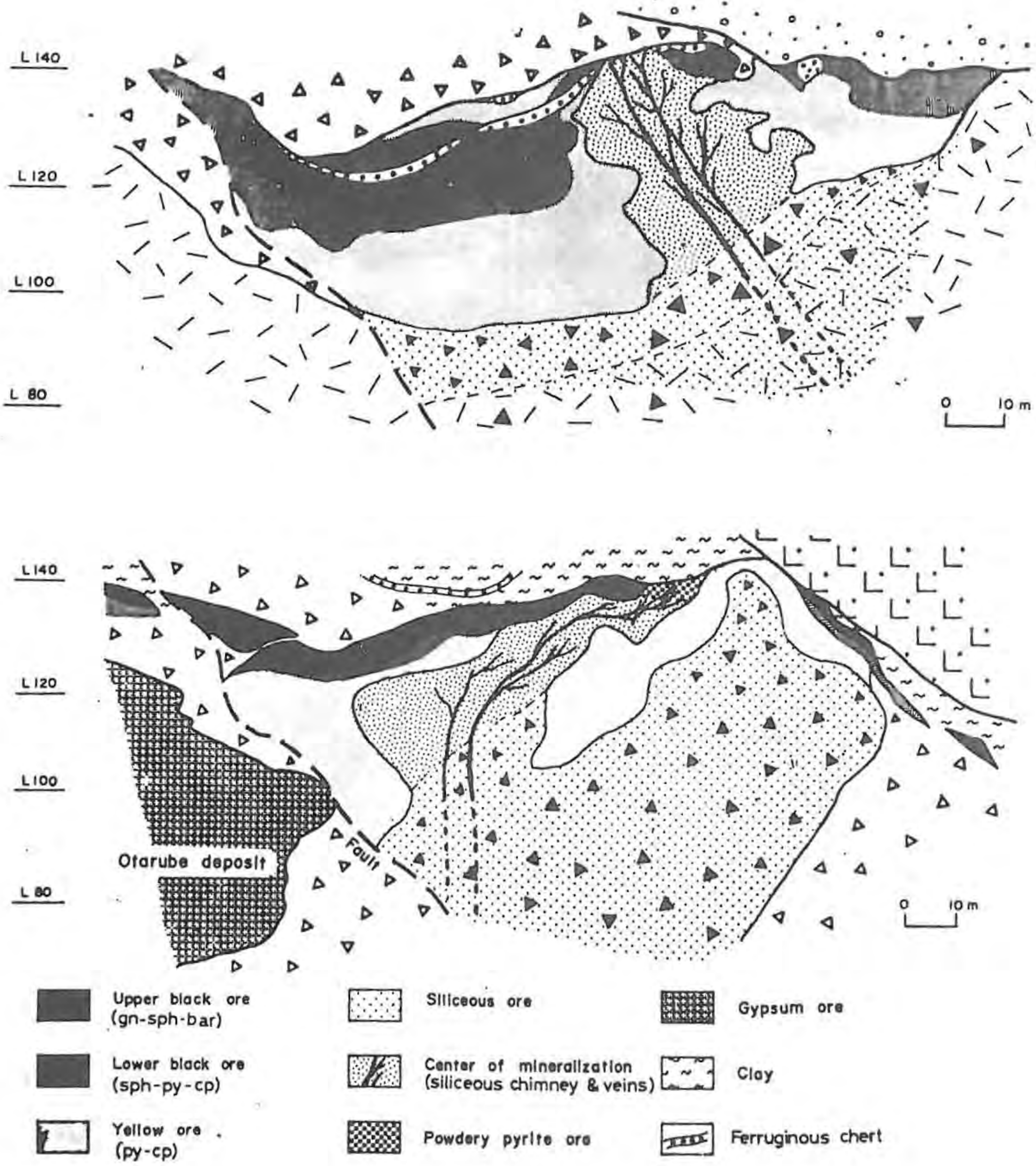


Figure 19: Detailed sections through the Uchinotai-nishi deposit Kosaka Mine. The relationship of siliceous chimneys with massive lower chalcopyrite-pyrite and upper galena-sphalerite-pyrite ore is well illustrated.
From Urabe and Sato, 1978.

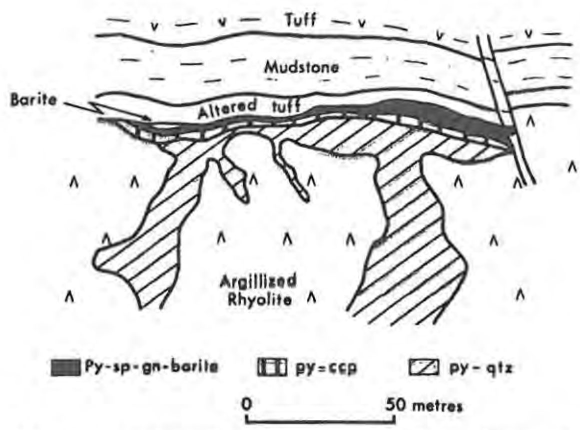


FIG. 20 A north-south cross section of the Upper Motoyama orebody (Yokota mine), after Hirabayashi (1974, Fig. 3). A postore sandstone dike has been excluded. Note the dual pipe system. The extent of hydrothermal alteration outside the pipes is not known.

From Solomon and Walshe, 1979.

The strength and duration of the hydrothermal discharge is the most obvious factor determining the ultimate size of a massive sulphide deposit. This can be directly correlated with the strength and duration of the preceding volcanic activity, and thus with the size of the volcanic system, as a result of the bigger heat source and larger quantities of magmatic metal-bearing fluids involved. It seems likely that one can expect both larger and a higher frequency of deposits in association with big volcanic complexes. For instance, the Noranda area with 50,000 ft. of volcanics has 1 deposit per square mile. This contrasts with the Sturgeon Lake area with its 25,000 ft. of volcanics and 1 deposit per 125 square miles (Boldy, 1977; Franklin et al., 1975; Spence and De Rosen-Spence, 1975).

Ore body zonation

Morphological, mineral, and metal zoning in massive sulphide deposits are interrelated and are functions of the chemical and physical conditions at the time of deposition. Ore body zonation in fairly typical Archaean and Kuroko deposits is illustrated in Figures 21 and 22.

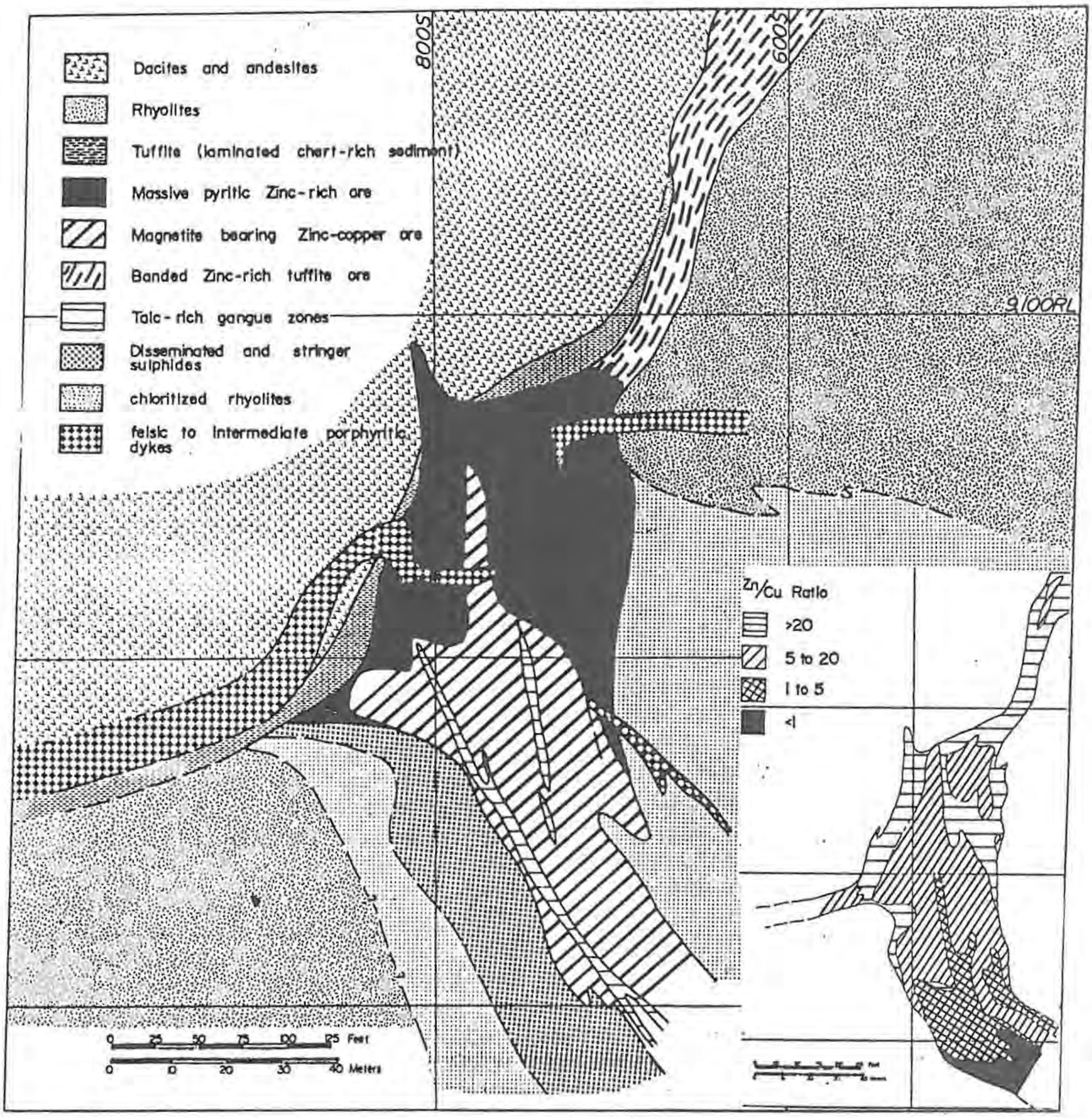


Figure 21: Geological section through the Orchan No.3 deposit showing typical zonation in an Archaean Cu-Zn ore body. Inset depicts Zn/Cu ratios. From Large, 1977.

The earliest stages of hydrothermal activity probably involve temperatures of between 300°C and 350°C in the subsurface zone (Solomon and Walshe, 1979). Some or most of the gypsum (presumably derived from anhydrite) beneath Kuroko deposits may have formed at this time. As the initial wave of hot hydrothermal solution displaces sea water in the secondary circulation zone, heating of this sea water would cause precipitation of a substantial part of its sulphate content both on and below the sea floor. A more important heating event may however have occurred during intrusion of the rhyolite domes and sulphate may have been precipitated then (Kajiiwara, 1971).

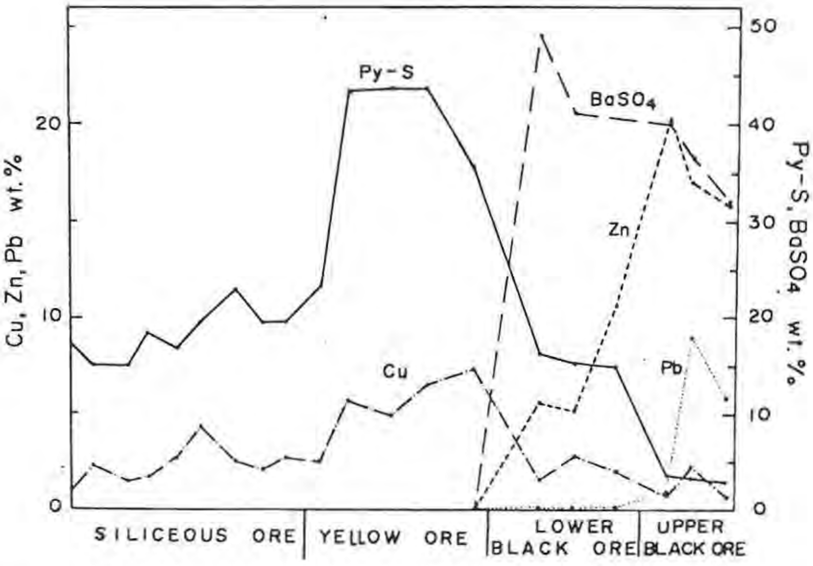


Figure 22: Mineralogical and metal zoning in the Uchinotai-nishi deposit illustrated by the change in ore assays along an adit through the deposit (See also Figure 19).
From Urabe and Sato, 1978.

Mixing of the hydrothermal solutions with sea water in the subsurface secondary circulation zone changes the physico-chemical conditions, resulting in a lowering of the temperature and an increase in the oxygen fugacity. This leads to precipitation of copper and iron sulphides and/or iron oxides within the feeder pipe, thereby creating stringer and disseminated ore zones.

At the vents discharging into the sea, cooling on the margins of the plume would result in immediate precipitation of chalcopyrite and pyrite from the saturated solution. Cooling of the solution in Figure 23 from 300° to 250°C along the path indicated would result in precipitation of some 90% of the copper in solution at the starting point. This quenching and rapid precipitation probably explains the typical massive form and gel-like textures and structures of the pyrite-chalcopyrite ores (Hutchinson, 1965; Kinkel, 1966; Watanabe, 1974; Sangster and Scott, 1976). Provided the solutions can rise through or around the gel, a mound will rapidly grow over the vent. Collapse of the mound due to gravitational instability or occasional steam explosions will result in the brecciated ore commonly observed in the lower portions of massive sulphide deposits. The other more stable metal-chloride complexes would remain in solution within the discharging plume and would only precipitate after further cooling to saturation levels. The delay between the saturation and precipitation of chalcopyrite, and that of sphalerite and galena is probably sufficient to entrain a major proportion of the sphalerite and galena particles in the rising plume. These particles are very small - the maximum grain size of Kuroko ore is <300µ (Shimazaki, 1974) - and may be carried up to considerable heights. This separation of the copper phases from the lead and zinc phases is likely to be inefficient. Irregular flow along the edges of the plume would result in considerable spillage of zinc and lead particles. This would account for the sphalerite-galena rims around pyrite-chalcopyrite lenses in some Kuroko and Archaean deposits (Matsuki Mine, Kuroda, 1978; Millenbach deposit, Simmons, 1974). In addition, some of the larger particles may settle back onto the mound and thus account for the substantial amounts of zinc and/or lead in the copper ores (and vice versa) in many Kuroko and Archaean deposits. Sphalerite and galena carried up in the central part of the plume will remain suspended until the buoyancy is lowered by a reduction of the flow rate or changes in density. Overloading of the plume may cause the fluid to become dense enough to collapse back onto the mound and would result in repetitively zoned copper-and lead-zinc-rich layers. Slow cooling of the system without a significant change in the flow rate would thus produce an overall metal zoning pattern (Figure 24).

As the discharge temperature falls below 250°C chalcopyrite would only precipitate below the rock-sea interface and the solution would become saturated with respect to sphalerite and/or galena at the discharge point (Solomon and Walshe, 1979). It is likely that a banded sphalerite (and/or galena) -rich mound would begin to grow over the chalcopyrite-pyrite-rich mound. Further sphalerite and/or galena would be added by collapse of the plume.

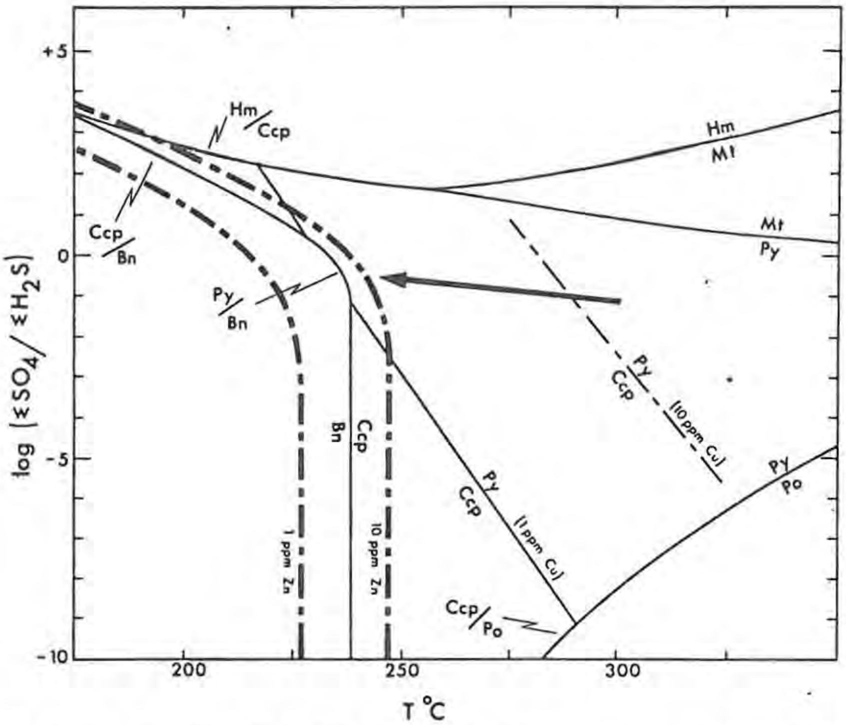


FIG. 23 Diagram of $\Sigma SO_4/\Sigma H_2S$ v T°C for the Cu-Fe-S-O system, assuming $m_{Cl^-} = 0.6$, $m_{Na^+} = 0.5$, $m_{K^+} = 0.04$, $\Sigma S = 10^{-2} m$, $\Sigma Cu = 1$ ppm, pH = 0.5 units acid, and I = 0.6. The py-ccp boundary for $\Sigma Cu = 10$ ppm is shown as a dashed line. A possible evolutionary path for the cooling Cyprus solution is indicated by the thick line. Solubility curves for zinc-chloride (approximately equal to Pb) are also shown. Data from Helgeson (1969), Hattori (1975), Crerar and Barnes (1976), and method of construction from Ripley and Ohmoto (1977), and Walshe (1977).

From Solomon and Walshe, 1979.

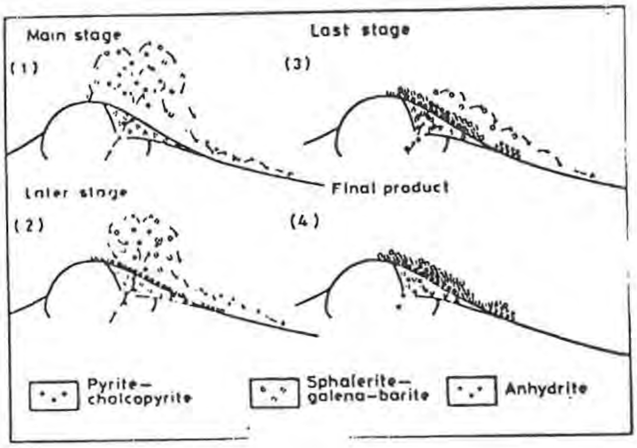


Figure 24: Schematic representation of three successive stages in the formation of Kuroko deposits due to the decrease of the temperature of the hydrothermal fluid. Consequent changes in the minerals being precipitated result in an overall mineral-zoning pattern. From Sato, 1976.

Ocean currents flowing at velocities greater than the entrainment velocities in the plume may sweep the particle laden plume away from the system. In such cases the sudden collapse of the source could leave a mound composed largely of pyrite-chalcopyrite, the zinc (± lead) being essentially lost from the system. This mechanism is a possible explanation for those Canadian Archaean deposits that have virtually no zinc associated. These deposits and the ones with very high copper to zinc ratios may thus have lost most of their zinc into the ocean, which explains the fact that these deposits are on average smaller than the ones with low copper to zinc ratio. Sangster (1977) plotted ore tonnage of 83 Archaean deposits against Zn/Zn+Cu ratios (Figure 25). He found that when points are divided into two groups - those above and those below a Zn/Zn+Cu ratio of 0,5 - an uneven distribution of metal ratios becomes evident, i.e. more than 70% of the deposits contain more zinc than copper. The average size of the copper-rich deposits was found to be 4,7 million tons, compared with 6,2 million tons for the zinc rich deposits.

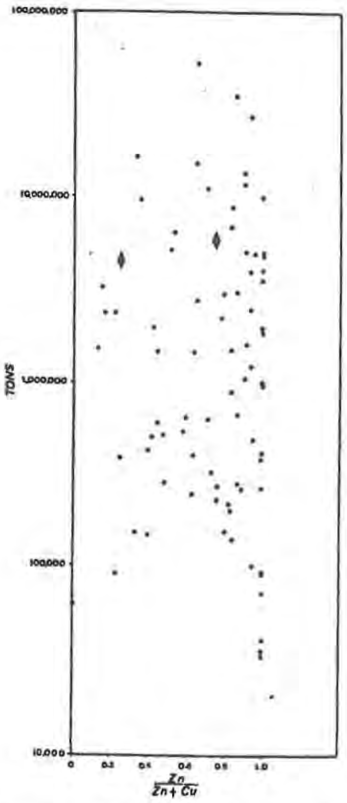


Figure 25; Ore tonnage (short tons) vs Zn/Zn+Cu ratio for Archaean deposits. Diamond on left side of diagram represents average size (4.7 million tons) of deposits with a ratio less than 0.5. Right-hand diamond is average (6.2 million tons) of deposits with ratio greater than 0.5. From Sangster, 1977.

Large (1977) explains the zonation of metal sulphides and Fe-S-O minerals within volcanogenic massive sulphide deposits by considering the progressive changes in solution chemistry as the rising hydrothermal solution mixes with sea water. This mixing leads to decreasing temperatures, increasing pH, and increasing ΣS. Differences in the fO_2 of the depositional environment, and more particularly in the resulting ratio of oxidized sulphur to reduced sulphur ($^{So}/_{Sr}$), explain the differences in zonal patterns between Archaean Cu-Zn, and Miocene Kuroko deposits.

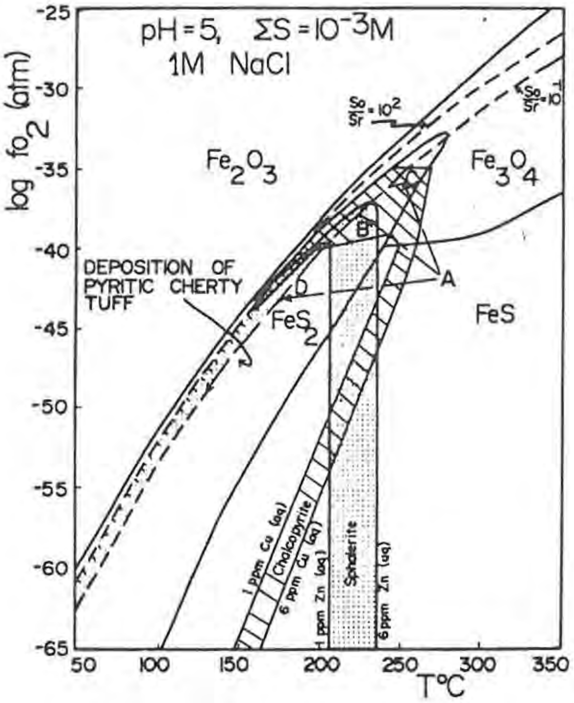


Fig. 2.6 Family of mixing paths AB, AC, AD, in f_{O_2}-T space to represent sequential deposition and zonation of Archean massive sulfides from a 1 M NaCl solution at pH = 5 with $\Sigma S = 10^{-3}$ M. The diagonally shaded area represents chalcopyrite deposition between the 6-ppm and 1-ppm contours of soluble copper. The stippled area represents sphalerite deposition between the 6-ppm and 1-ppm contours of soluble zinc.

From Large, 1977.

During the development of Archaean massive sulphides the atmosphere is considered to have been essentially free of oxygen (Cloud, 1973), and much of the ocean floor was probably somewhat reducing (Borcherd, 1960). The complete lack of sulphate gangue minerals and the association of black shales with the upper lenses of some Archaean deposits (e.g. Kidd Creek;

Walker et al., 1975) lend support to this supposition. It is thus reasonable to assume a very low So/Sr ratio (say So/Sr=0,1; Large, 1977) during the formation of the Archaean deposits. Point B in Figure 26, which lies on the So/Sr=0,1 contour, represents the point at which aqueous sulphur within the hydrothermal solution has completely mixed, and equilibrated, with sea water sulphur during a temperature drop of 50°C (from 275° to 225°C). If the temperature drop during mixing was less, say 25°C, then the fO_2 increase within the rising solution would be greater, as in path AC. If the solution cooled through 100°C during mixing, then the fO_2 increase would be considerably less (path AD). A temperature drop to below 200°C will result in the evolution of a solution along the So/Sr=0,1 contour line (Figure 26) since equilibration of aqueous sulphate and sulphide species does not readily occur at such low temperatures. The temperature drop would result in the saturation of silica and iron within the solution and in the consequent deposition of pyritic cherts. The So/Sr ratio would be too low to allow the precipitation of sulphates (Large, 1977). More important than the actual fO_2 change is the change in the So/Sr ratio, which will always tend towards the value within the ocean.

The temperatures within the hydrothermal pipe or vent will tend to be greatest in the centre, decreasing towards the periphery (Figure 27). Path AC might thus represent a solution passing straight up the centre of the pipe (Figures 26, 27), whereas paths AB and AD will represent solutions which moved toward the edges of the pipe, and possibly into the wall rocks. Path AC will precipitate chalcopyrite with pyrrhotite and/or magnetite but no sphalerite within the pyrite zone, while path AD gives rise to an extensive sphalerite zone with pyrrhotite and pyrite. Although path AB passes through the chalcopyrite zone in the pyrite field, chalcopyrite will not precipitate with pyrite, as the trend is towards increasing copper solubility from the 1 ppm to the 6 ppm Cu contour in this region.

The scarcity of lead in Archaean ores, coupled with the similarity in galena and sphalerite solubilities (Anderson, 1973), indicates that lead was depleted within the ore-forming hydrothermal solutions. The reason for this depletion of lead in the early deposits, in comparison to Proterozoic and later deposits, is not clear, but could be related to the evolution of the upper mantle and lower crust and the build-up of radiogenic lead through time (Sangster, 1972; Hutchinson, 1973). Lambert and Sato (1974), on the other hand, pointed out that the lead in crustal rocks should have been more radiogenic than is generally observed if the majority of this element formed by radio-active decay. A more tenable explanation is probably in the fact that Archaean deposits are generally associated with less differentiated rocks (rhyodacite, dacite, andesite, rhyolite) while Kuroko deposits are hosted by white rhyolite domes, which are products of far greater fractionation. The greater fractionation would allow incompatible lead ions to be concentrated in the late-stage aqueous magmatic fluid, and to be incorporated in the ore-forming hydrothermal solutions.

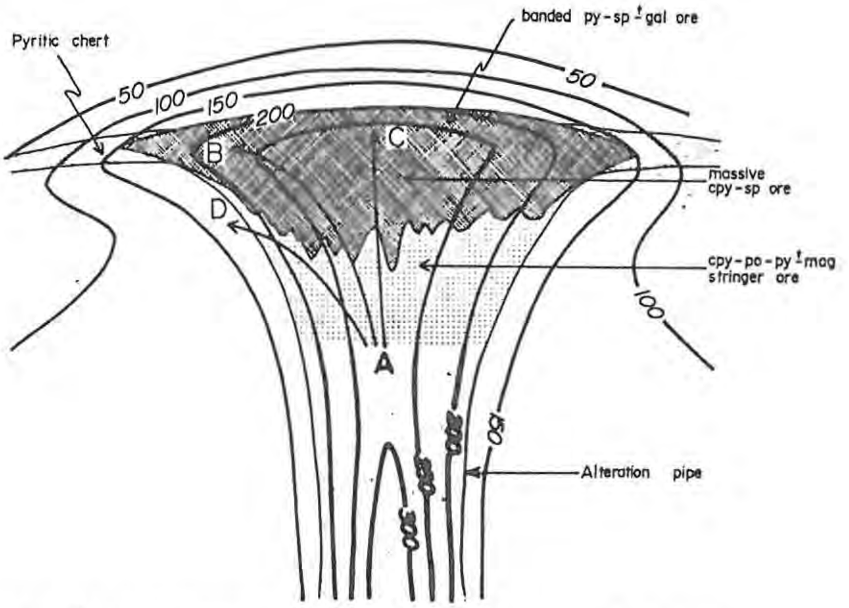


FIG. 27 Idealized temperature regime during the formation of a proximal massive sulfide deposit. Contours in degrees Centigrade.

From Large, 1977.

The similarity in metal zonation between the Kuroko ores and the Archaean ores suggests that the trends in solution chemistry in the two ore-forming environments were probably similar. In mineralogical terms the Kuroko ores are enriched in galena and sulphates (barite and gypsum), but completely lacking in pyrrhotite and magnetite. These factors suggest that the Kuroko ores were formed at a higher fO_2 level, and that the solutions may have contained more total dissolved sulphur (Large, 1977). Figure 28, a temperature - log fO_2 plot, adequately explains zonation patterns in the Kuroko deposits. The trends produce an increase in the So/Sr ratio, although the fO_2 may increase, decrease, or remain constant depending on changes in pH and temperature. The Japanese Miocene ocean was probably similar to the present day ocean, with a very large So/Sr ratio. Continued mixing of the rising hydrothermal solutions would thus have pushed the mixing paths in Figure 26 through the barite stability field and out into the hematite field. This explains the abundance of barite within the upper part of the banded galena-sphalerite ore and also the occurrence of hematitic cherty sediments above the ore.

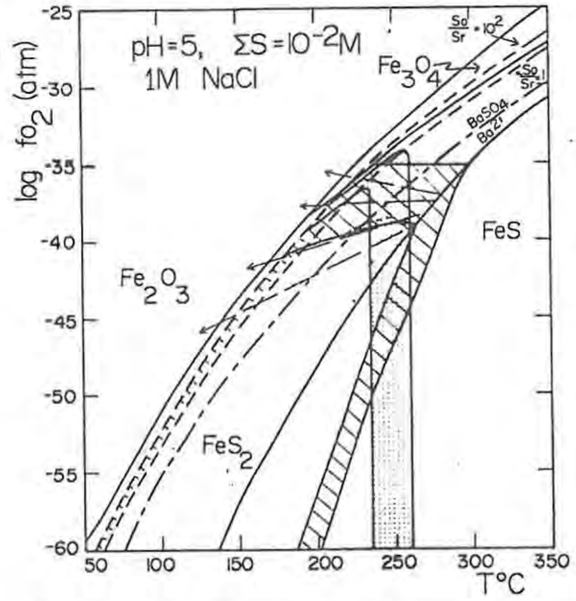


FIG. 28 Family of mixing paths (———) in f_{O_2}-T space to represent deposition and zonation of type 2 (kuroko) ores from a 1 M NaCl solution at pH = 5 and $\Sigma S = 10^{-2}$ M.

From Large, 1977.

The influence of ore body zonation on grade and tonnage relationships within individual ore bodies can readily be imagined. From the foregoing discussions it is clear that volcanic-exhalative ore bodies are geological entities having definite geological boundaries. These boundaries represent the outer limits of the geological processes that produced the ore bodies. Massive sulphide ore bodies thus have sharp "geological cut-offs", and are not merely high points or anomalies in a smoothly fluctuating curve of copper-zinc-lead abundance in rocks. On the stratigraphic footwall-side, however, massive chalcopyrite-rich ore grades into pyrite- or pyrrhotite-chalcopyrite stockwork or stringer ore. The inclusion of a major portion of the stringer ore into the mineable tonnage would increase the tonnage substantially but lower the combined grade. Within individual massive ore lenses the combined metal content remain fairly constant throughout, but Cu values tend to increase towards the footwall at the cost of Zn (±Pb), whereas Zn(±Pb) increases towards the hangingwall at the cost of Cu. In some deposits the actual amount of copper increases towards the footwall and forms high grade zones, the so-called "copper-keels". Since mineable grade also depend on economic considerations such as the price structures and marketability of various mineral commodities, the influence of metal zoning is considerable, and should be studied in detail.

Ore textures and structures

Most of the textures and structures now present in Archaean massive sulphide deposits are the result of post-depositional processes, such as diagenesis and metamorphism. Metamorphic textures are by far the most common and will be dealt with in a later section. Kuroko deposits on the other hand are undeformed and have undergone hardly any metamorphism. Primary depositional ore textures and structures are thus well preserved and are probably analogous to the pre-deformational textures and structures of the Archaean deposits.

Watanabe (1974) described the ore textures and structures of the Daikoku ore deposit, a typical Kuroko deposit in the Ainai Mine near Kosaka in the Hokuroko Mining District (Figure 1). The Daikoku deposit consists of the usual siliceous ore zone in the footwall, followed upwards by yellow and black ore zones. The siliceous ore zone consists of euhedral pyrite, chalcopyrite and quartz in altered acid to intermediate pyroclastic rocks. The ore minerals and quartz gangue commonly fill interstitial cavities in the pyroclastic matrix, but also occurs as fracture fillings and cross-cutting veinlets in breccia fragments. The siliceous ore is generally coarser-grained than the other ore types and euhedral pyrite grains of >5 mm diameter are quite common.

Chalcopyrite and minor sphalerite and galena are much finer-grained than the pyrite and commonly fill fractures in the pyrite or quartz gangue. Colloform-banded pyrite and sphalerite co-exist with pyrite euhedra. The coarser grain size and abundance of euhedral crystals indicate relatively high temperatures and slower rates of crystallization.

The yellow ore zone is characterised by fine-grained euhedral to anhedral pyrite and chalcopyrite. Chalcopyrite grains are usually <50µ in diameter, but some very coarse grains occur with sphalerite in druses. Small amounts of sphalerite, galena, tetrahedrite-tennantite, electrum, barite, sericite and quartz occur interstitially in the fine-grained mosaic of pyrite and quartz grains. The general lack of gangue minerals in the upper part indicates that this portion of the zone probably formed above the rock-seawater interface, while the lower part grades into the underlying siliceous ore. The upper part is characterised by colloform, framboidal, and pelletal textures. These may be indicative of colloidal precipitation or rapid deposition and encrustation of ore minerals. Roeder (1968) considered these textures to represent a high degree of supersaturation of the mineralizing fluids resulting in high rates of nucleation and crystallization. The result is the radiating growth of euhedral crystals from numerous points of nucleation on a substratum. The predominance of colloform textures over others in the upper part of the yellow zone, together with a substantial increase in the barite content, indicate an increase in the oxidation state of the hydrothermal ore fluid, probably due to increased mixing with sea water.

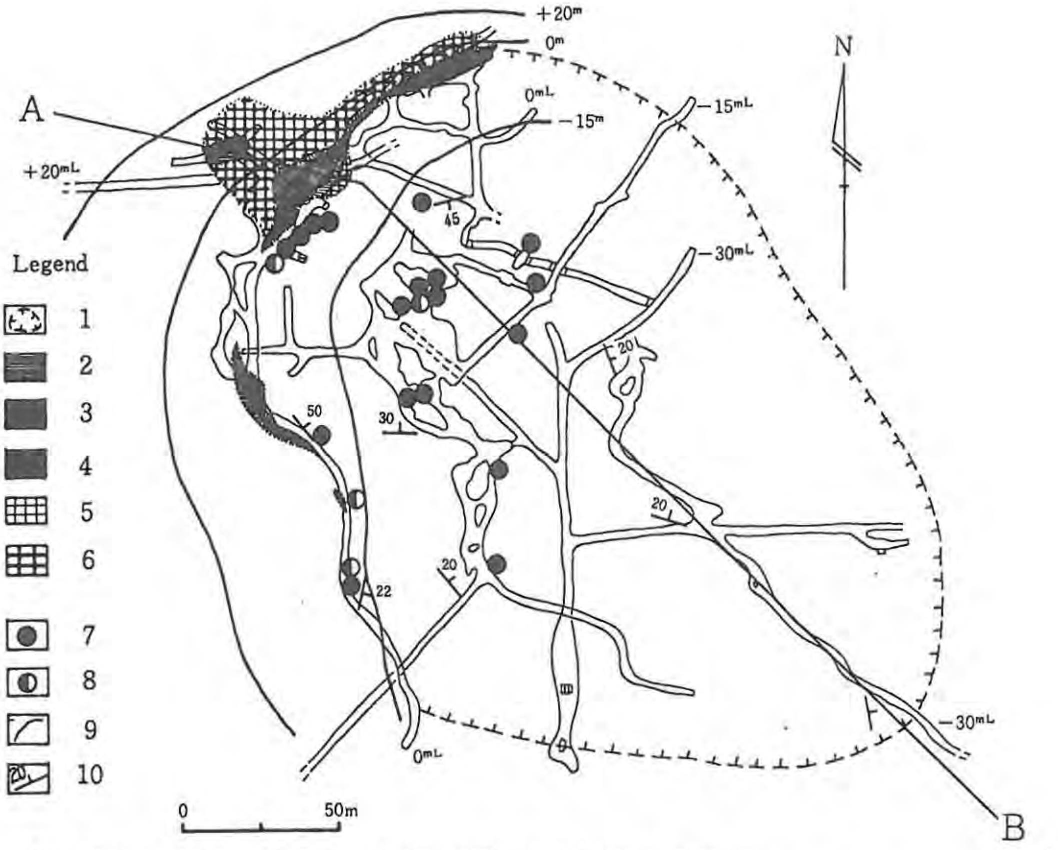
The black ore zone consists of sphalerite, galena, tetrahedrite-tennantite, chalcopyrite, pyrite and barite. Electrum, sericite, and quartz are present as accessory minerals. The black ore forms a conformable lense consisting of a diversity of ore types. These are banded ore, fine-grained irregularly-shaped intergrowths of galena and sphalerite, and coarse-grained ore. The northwestern part of the lense consits of graded and massive portions. Textural and structural relationships are dominated by colloform and compositional layering parallel to the hangingwall contact. Colloform textures are commonly formed by pyrite, sphalerite and chalcopyrite, while the compositional layering is caused by varying amounts of galena, sphalerite, chalcopyrite, and tetrahedrite-tennantite. Dendritical intergrowths of barite with galena and sphalerite, and irregular intergrowths of sphalerite and galena are characteristic of the black ore zone. The average grain-size of the zone is less than 50μ with a large proportion of the ore minerals as very fine intergrowths.

The northwestern part of the black ore zone at the Daikoku deposit shows evidence of soft sediment deformation and sedimentary reworking. Most striking is the presence of graded bedding and fragmental textures. The co-existence of irregular "schlieren" (or streaky-textured) and blocky ore indicates that both consolidated and unconsolidated material occurred at the time of formation. Colloform pyrite, forming continuous bands through the interstices of the ore fragments, may be indicative of the infiltration of the ore breccia by a pyritic gel.

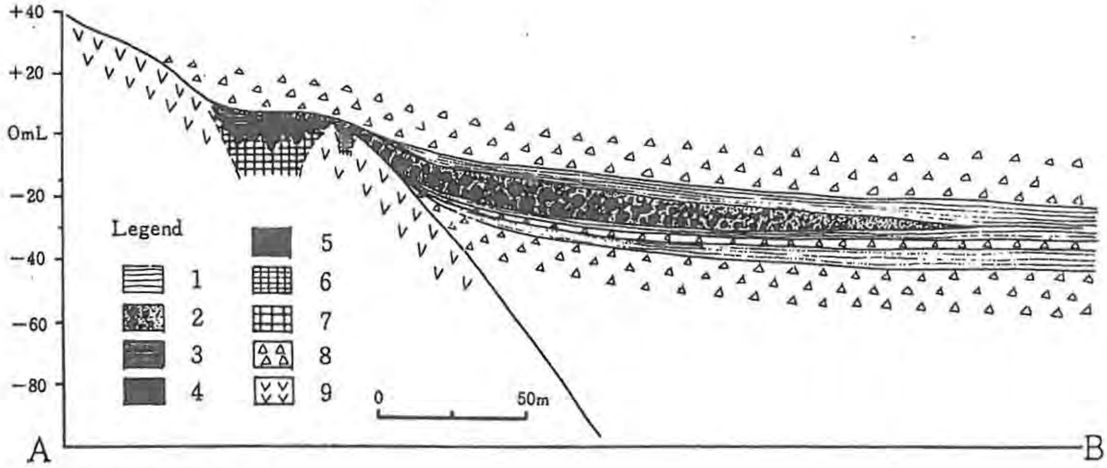
Soft sediment deformation and sedimentary reworking has been recognised in a number of Canadian mines, e.g. Mattagami (Roberts, 1975), Kidd Creek (Walker, et al., 1975), Vauze (Spence, 1975), and Magusi River (Jones, 1973, quoted in Sangster and Scott, 1976). Volcanic and phreatic explosions generate submarine slides and turbidity currents on the flanks of volcanic domes which result in the redistribution of massive sulphide accumulations. These features are however much better preserved in the Kuroko deposits. The Kamikita Mine in the Hokuroko District of Japan is one of the best recorded examples of this phenomenon and will serve to illustrate the effect it has on ore body morphology.

The Kaminosawa No.3 Shitaban-hi ore bodies of the Kamikita Mine (Lee et al., 1974) consist essentially of two parts: a fairly typical Kuroko-type unit ore body in the northwest and a fragmental ore body extending to the southeast (Figure 29).

The bedded fragmental ore body is composed of fragments of ore and wallrocks in a fine-grained clastic to non-clastic matrix. The matrix consists of minute grains of sphalerite, pyrite, galena, chalcopyrite, and tetrahedrite-tennantite. The non-clastic material is characterised by colloform and framboidal textures and rhythmic compositional banding. The clastic part of the matrix consists mainly of fine-grained pyrite clasts (<2mm diameter) with sparse fragments of finely intergrown sphalerite-galena.



A: Map showing various characters of ores in the No. 3 Shitaban-hi orebodies.
1: Bedded fragmental orebody, 2: Bedded compact sphalerite-rich orebody, 3: Bedded compact chalcopyrite-rich orebody, 4: Massive pyrite orebody, 5: Stockwork sphalerite orebody, 6: Stockwork pyrite orebody, 7: Massive sphalerite-rich ore boulder (more than 1 m in diameter), 8: Massive pyrite ore boulder (more than 1 m in diameter), 9: Contours of the older rhyolite dome, 10 Strike and dip.



B: Section along A–B
1: Mudstone, 2: Bedded fragmental orebody, 3: Bedded compact sphalerite-rich orebody, 4: Bedded compact chalcopyrite-rich orebody, 5: Massive pyrite orebody, 6: Stockwork sphalerite orebody, 7: Stockwork pyrite orebody, 8: Rhyolitic tuff breccia, 9: Older rhyolite dome.

Figure 29: Distribution of ore types in the Kaminosawa No.3 Shitaban-hi ore bodies.
From Lee et al., 1974.

Ore fragments range in size from more than 1 metre to 10 cm in diameter, and are roughly graded from coarse-grained in the northwest to fine-grained in the southwest. Sphalerite-rich fragments, displaying the textural relationships normal to black ores, are the most abundant. Chalcopyrite-rich fragments are quite rare. Lithic fragments consist mainly of rhyolitic pyroclastics and lavas. Some of these have been strongly altered prior to the formation of the breccia ore.

As a whole, the ore body is very poorly sorted, but locally such sedimentary structures as grading, lamination, and cross-bedding become prominent. Imbrication, sole marks and load casts are observed in places. There is thus no doubt that the breccia (or fragmental) ore formed through the action of a submarine slide or mudflow triggered by a volcanic, or phreatic explosion. Explosive activity explains the presence of altered footwall rocks in the breccia. Continuing, or renewed hydrothermal activity at the original vent resulted in the formation of a second unit ore body on the site of the original one (Figure 29).

It is obvious that in the case of the Kaminosawa ore bodies, soft sediment deformation and sedimentary redistribution substantially enlarged the mineable tonnage. The incorporation of fragments of the footwall into the ore body would however lower the grade somewhat, but is probably largely compensated for by the influx of non-clastic matrix minerals. A major consequence is the destruction of the ore body zonation, which greatly affects the mineable grade since it causes a primary blending of the ore.

Wall-rock alteration

Chlorite and sericite are commonly the dominant minerals in alteration pipes which underlie massive sulphide deposits in the Superior Province of Canada, while clay minerals predominate in the alteration zones of the Kuroko deposits of Japan.

Gilmour (1965) reported that the alteration pipes at the Old Waite and East Waite mines, Noranda, extend to a depth of more than 3000 feet below the ore bodies, gradually becoming less distinct and then non-existent. At the Vauze Mine, Gilmour (1965) and Spence (1975) observed that the alteration pipe is composed of a central massive chlorite pipe surrounded by an incomplete zone of massive sericite. Riverin and Hodgson (1980) described a similar zonation at the Millenbach deposit and observed a lateral decrease in "alteration grade" outwards from the centre of the pipe (Figure 30).

Wall rock alteration is the result of reactions between a migrating hydrothermal solution and the rocks through which it passes. In the absence of a thermal gradient, mineralogical and chemical zoning can thus be interpreted as the result of chemical evolution of the initial solution as it progressively reacted with the rocks. According to Riverin and Hodgson (1980) it seems unlikely that large thermal gradients (i.e. more than a few degrees per cm) existed in most hydrothermal systems on the scale of alteration selvages bordering individual sulphide veinlets. They suggest that on this scale chlorite zones formed contemporaneously with sericite and encroached on it. However, zonation may also develop as a result of thermal gradients in an alteration system since mineral-fluid equilibria depend on temperature. The zonation which would develop as a result of decreasing temperature would be very similar to that developed as a result of progressive reaction of rocks and fluids. Riverin and Hodgson proposed the following model reactions leading to the development of sericite and chlorite zones at the expense of fresh rock, and of chlorite zones at the expense of sericite.

(i) At constant volume, the sericitization of plagioclase (here andesine) can be described by the reaction:

$$\underset{\text{Andesine}}{2Ca_{0,5}Na_{0,5}Al_{0,5}Si_{2,5}O_8} + 0{,}48Al(OH)_4^- + 1{,}16K^+ + 2{,}32H^+$$

$$= \underset{\text{Sericite}}{1{,}16KAl_3Si_3O_{10}(OH)_2} + \underset{\text{Quartz}}{1{,}52SiO_2} + Na^+ + Ca^{+2} + 0{,}96H_2O$$

(ii) Chloritization of mafic minerals (here diopside) can be accounted for by the constant volume reaction;

$$2Ca(Mg,Fe)Si_2O_6. + 0,58Al(OH)_4^- + 5.68H^+$$
Diopside

$$=0,29(Mg,Fe)_5Al_2Si_3O_{10}(OH)_8 + 3.13SiO_2 + 2Ca^{+2} + 0.55(Fe,Mg)^{+2} + 2.84H_2O$$
Chlorite

(iii) Chloritization of sericite at constant volume is represented by the following reaction:

$$3KAl_3Si_3O_{10}(OH)_2 + 10(Fe,Mg)^{+2} + 32H_2O$$
Sericite

$$=2(Mg,Fe)_5Al_2Si_3O_{10}(OH)_8 + 3Si(OH)_4 + 5Al(OH)_4^- + 3K^+ + 22H^+$$
Chlorite

The reactions as written predict the movement of considerable amounts of Al across alteration zone boundaries. This is contradictory to chemical analyses which show only minor changes in Al content of the rocks during alteration (Riverin and Hodgson, 1980). This discrepancy may to a large extent be due to the fact that the reactions were chosen for convenience of balancing and do not necessarily represent compositions of the real minerals involved.

The reactions leading to the formation of the sericite zone are base-leaching reactions, whereas those involved in the formation of the chlorite zone are base-fixation reactions. An important feature of these reactions is that the products of the base-fixation reaction ($Al(OH)_4^-$,K^+,H^+) are exactly the reagents needed for the base leaching reactions. It is thus possible that, in the absence of a thermal gradient, a single solution could cause both types of reactions by undergoing chemical evolution. For example, an increment of fresh solution fed into a fracture would cause the destruction of some sericite in the inner zone of the alteration selvedge and result in an increment growth of the chlorite zone. The same increment of solution, on reacting on the outer margin of the sericite zone of the alteration selvedge, would expand it outwards by the sericitization of feldspars in the fresh rock. The model thus requires that, at any point in space, rocks must first be subjected to base-leaching reactions before being affected by the base-fixation reactions, a fact which is consistent with field observations (Riverin and Hodgson, 1980).

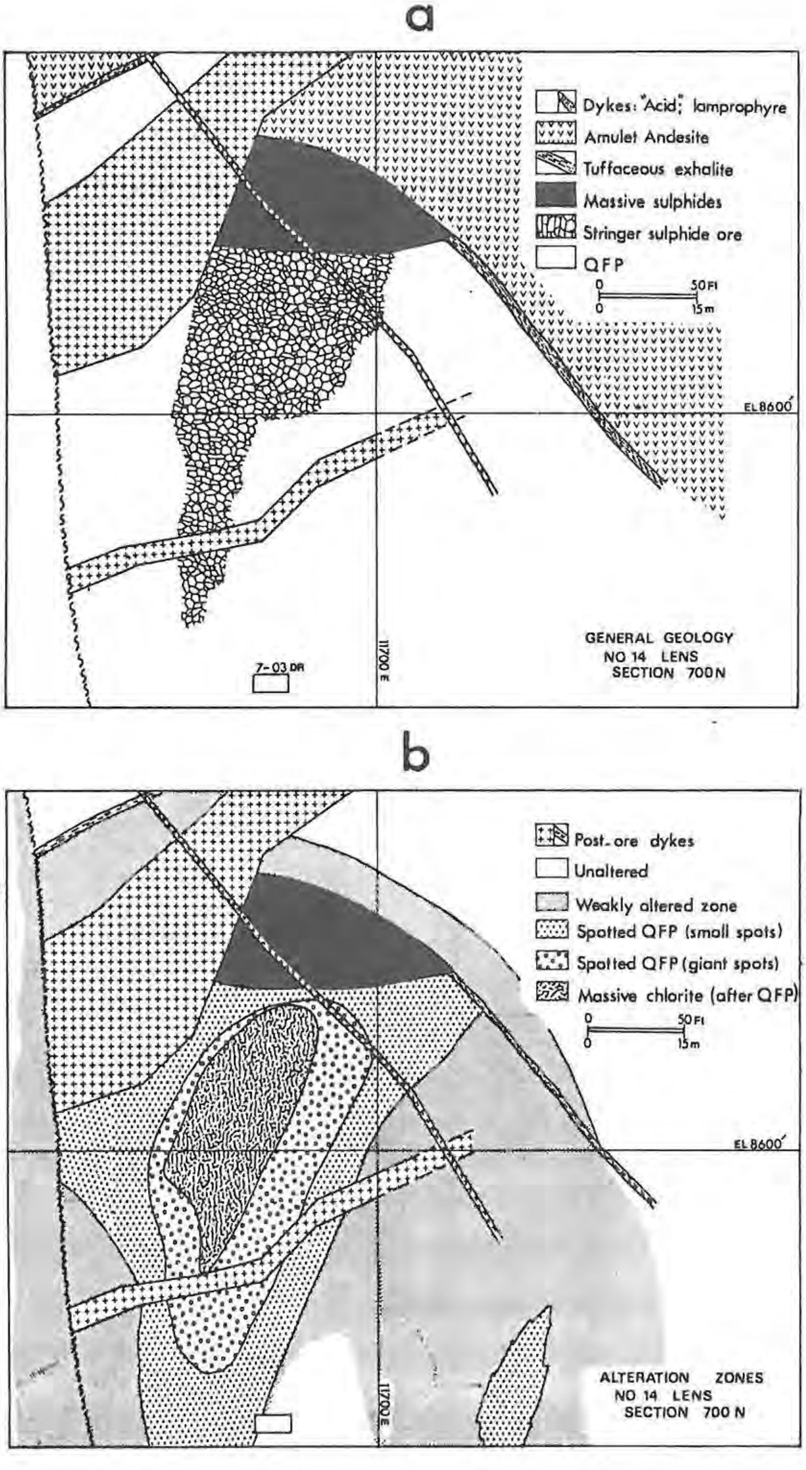


Figure 30: (a) Geological section through the No.14 ore lense, Millenbach deposit. (b) Alteration zones below No.14 ore lense. The section is oblique to the elongation of the alteration pipe and stringer ore zone and shows the concentric nature of the zoning. From Riverin and Hodgson, 1980.

It is probable that considerable thermal gradients existed within alteration pipes below massive sulphide deposits. This was either due to progressive mixing of hydrothermal solutions with sea water in a secondary circulation zone (Large, 1977, Solomon and Walshe, 1979), or because the hydrothermal fluids were boiling (White, 1968, Hodgson and Lydon, 1977). Figure 31 shows the stabilities of some minerals in alteration zones in terms of the ratios of the activities of Mg^{+2} , and K^{+} to that of H^{+} at progressively lower temperatures. The starting temperature of 250°C is that calculated for Kuroko deposits from stable isotope fractionation and fluid inclusion studies (Ohmoto et al., 1970; Kajiwara, 1971; Lambert and Sato, 1974).

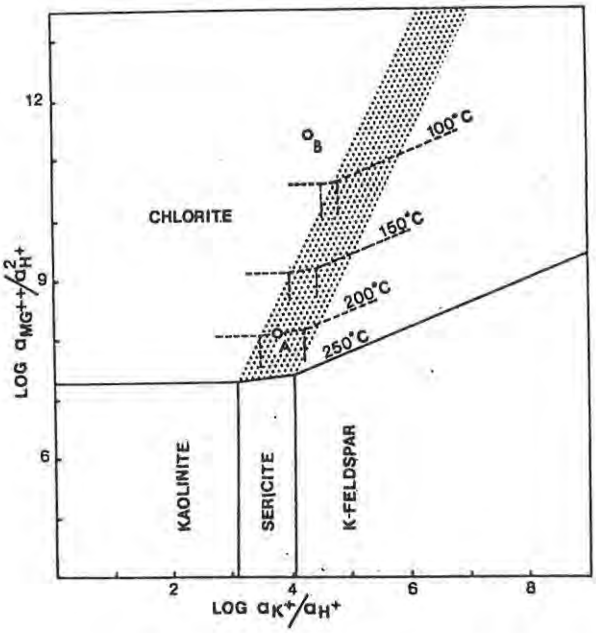


Figure 31: Stability fields of chlorite, sericite, kaolinite, and potassium feldspar. All these phases are in equilibrium with quartz. The shaded area outlines the approximate limits of composition of a solution that will react with sericite to form chlorite at 250 C. A is a possible initial fluid in this field. B is sea water at 250 C. From Riverin and Hodgson, 1980.

A solution starting out with a composition somewhere in the shaded area on Figure 31 will in the isothermal case react with its wall rocks and evolve toward decreasing values of log $a_{Mg^{+2}}/a^2_{H^+}$ and log a_{K^+}/a_{H^+} along a line with a slope equal to 2 (Helgeson, 1969). The first increment of fluid originating in the shaded area (Figure 31) will react with feldspar-bearing, sericite-free rock to form chlorite by losing Mg^{+2} and gaining K^+ and H^+ until it intersects the chlorite-sericite field boundary. It will then move along the boundary, forming mainly sericite but also some chlorite until it comes to the potassium feldspar-sericite-chlorite point (Riverin and Hodgson, 1980). Once the chlorite and sericite-chlorite zones have been established any new increments of fluid will encounter sericite before feldspar and will convert it to chlorite before intersecting the chlorite-sericite field boundary, at which point feldspar will once again be altered to sericite and chlorite. Reaction will proceed until eventually the hydrothermal fluid reaches equilibrium with the assemblage chlorite-feldspar-sericite of the fresh rock.

In the case where fluids are moving down a steep thermal gradient they do not completely equilibrate with the rocks, either because of the high rate of flux of the fluids, or the low rate of fluid-rock reaction. The reaction will start out as in the isothermal case, but once the sericite-chlorite field boundary is intersected, the fluid will move into the sericite field and may even eventually reach the koalin field, since, as shown in Figure 31, the kaolin-sericite field boundary shifts to substantially higher values of a_{K^+}/a_{H^+} as temperature decreases (Riverin and Hodgson, 1980). If at any point the fluid starts reacting with the rocks, the composition of the fluid will eventually reach the chlorite-sericite field boundary and move along this to the point of intersection with the feldspar field, as is illustrated in Figure 32. The figure also shows the resulting mineral zonation in the case where there is a large vertical thermal gradient and no significant change in fluid composition. Figure 33 is a modification of this limiting case in which, away from the central axis of a vertical permeable zone, there is increasing reaction between rock and vertically moving fluid. The resulting zonation pattern is very similar to that of the Main Lens of the Millenbach deposit (Riverin and Hodgson, 1980).

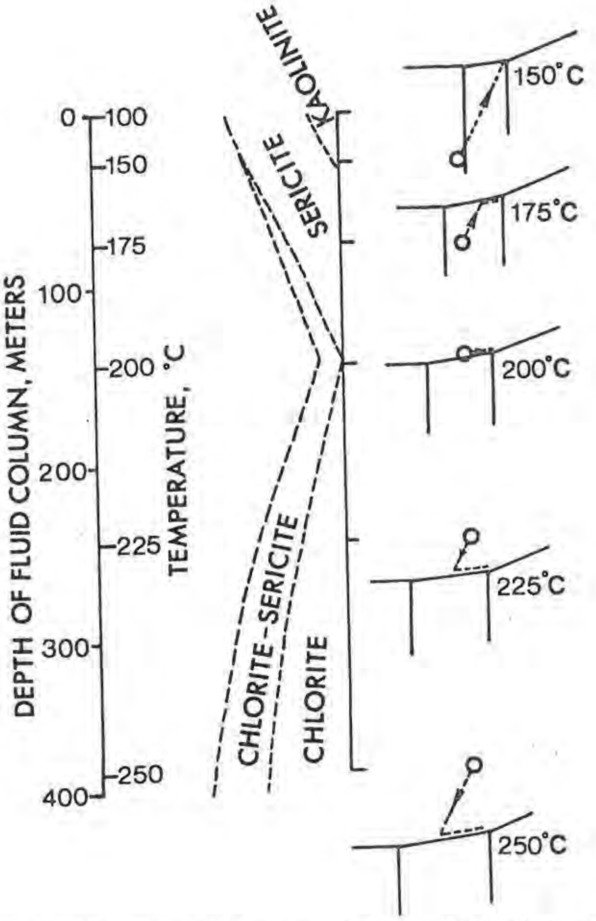


FIG. 32 Alteration produced in the rocks bordering a vertical permeable zone in a system in which the vertical thermal gradient is controlled by the boiling temperature of a hydrostatically pressured column of sea water. The flux of fluids and rate of fluid-rock reaction is such that the composition of fluids in the conduit does not change measurably due to wall-rock reaction. On the other hand, fluids permeating laterally into wall rocks are considered to react isothermally with the rocks, so that the solution moves along the paths shown in the inset diagrams from Figure 16. It is assumed that the widths of the alteration zones formed in the conduit walls is proportional to the length of the reaction path of the evolving solution.

From Riverin and Hodgson, 1980

It should be emphasised that not all the Archaean deposits show this same alteration pattern. For example the alteration zones at Kidd Creek are relatively enriched in silica and carbonate (Walker and Mannard, 1974), while stringer zones at Mattabi are composed chiefly of siderite, sericite and chloritoid (Franklin et al., 1975). The occurrence of siderite at Mattabi is probably related to the relatively high and constant CO_2 content of the host volcanic rocks. Dolomite is the predominating carbonate species in these rocks and was probably replaced by siderite according to the equation:

$$\underset{\text{dolomite}}{CaMg(Co_3)_2} + 2Fe^{+2} = \underset{\text{siderite}}{2FeCo_3} + Ca^{+2} + Mg^{+2}$$

Magnesium and calcium released by this reaction were probably carried to the overlying sea water (Franklin et al., 1975).

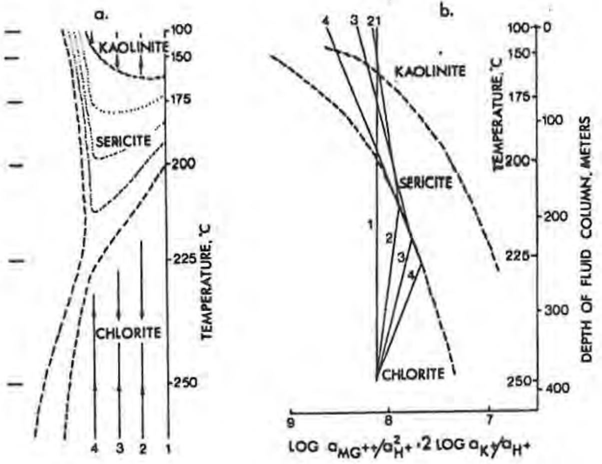


FIG. 33 Idealized possible wall-rock alteration pattern developed in a vertical conduit in which the extent to which the rising fluid is modified by reaction with wall rocks ranges from nil for path 1 in the solution conduit to maximal for path 4 in the solution conduit. Figure 18b shows mineral stability fields, as a function of temperature and fluid composition, for fluid compositions along a line of slope 2 through point A in Figure 16. In the area to the left of path 4 in Figure 18a, alteration is assumed to be developed by fluids migrating laterally out from conduit 4 and reacting isothermally with the rock, as represented in Figure 17. Dotted lines in the sericite field of Figure 18a represent diagramatically the upward decrease in the amount of mineral reactants being converted to sericite in the rock.

From Riverin and Hodgson, 1980.

In contrast to the Archaean deposits, the Japanese Kuroko deposits do not have extensive zones of footwall chloritization, but generally have a silicified stockwork zone with encompassing clay-rich alteration zones containing varying amounts of sericite, chlorite, montmorillonite, kaolinite, and zeolites (Iijima, 1974; Lambert and Sato, 1974). Alteration zones around a Kuroko deposit is schematically represented in Figure 34. Superimposed on these zones is a pervasive regional zeolite facies alteration related to the Late Miocene Green Tuff "orogeny" (Utada, 1971; Lambert and Sato, 1974). Sangster (1972) suggested that fundamental and long term changes in earth chemistry, resulting in the evolution of hydrothermal solutions, may have been responsible for the differences in footwall alteration zones between Archaean and Kuroko deposits. Large (1977), on the other hand, is of the opinion that the observed differences are a function of differences in the evolved sea water chemistry during recycling in a secondary circulation zone.

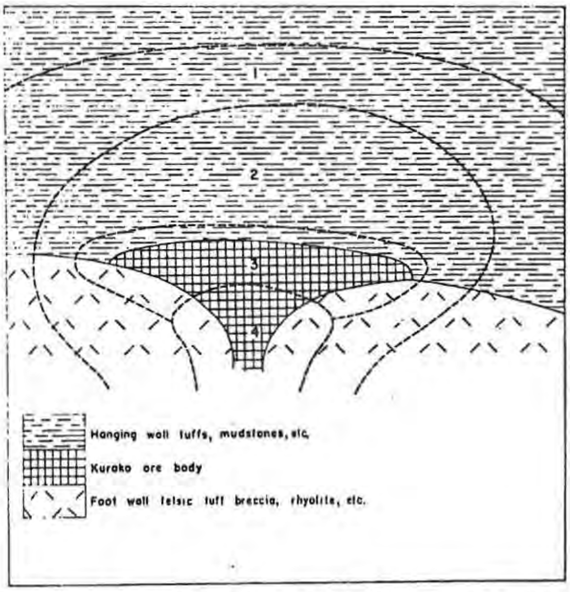


FIG. 34 Schematic section showing clay alteration zones surrounding Kuroko deposits. Based on Iijima (1972, 1974); Shirozu (1974). Zone 1: montmorillonite, zeolites, cristobalite. Zone 2: sericite, interstratified sericite-montmorillonite, Fe/Mg chlorite, (albite, K-feldspar). Zone 3: sericite, interstratified sericite-montmorillonite, Mg chlorite, kaolinite. Zone 4: Quartz, sericite, Mg chlorite.

From Lambert and Sato, 1974.

He postulates that intermediate to basic volcanic piles, like the Archaean greenstone belts, which are dominated by basalt, andesite, and dacite with only relatively minor rhyolites, will probably generate evolved sea water solutions enriched in Mg^{+2}, Fe^{+2}, and Ca^{+2} with lesser K^{+} and Si^{+4}. In contrast, the more differentiated felsic to intermediate volcanic piles of the Kuroko districts, which are dominated by rhyolite, dacite, and andesite will probably generate evolved sea water solutions enriched in K^{+} and Si^{+4} but generally depleted in Mg^{+2}, and Ca^{+2}. Since the earth's crust with its related tectonic processes, and the surface environment of the earth both evolved through time, the answer probably lies in a combination of Sangster's and Large's proposals.

Alteration minerals form a large proportion of the gangue minerals in especially the stringer ore zones of massive sulphide deposits, and as such have an influence on the in situ and mineable grades of deposits. The considerable effect of these mainly platy minerals on mining and ore recovery will be discussed in a later section, as will be the effect on deformation, and as a result, on the shape and size of the ore body.

SECONDARY FACTORS

Secondary factors are those resulting from processes such as metamorphism, deformation and weathering which affect ore deposits at some time after their formation. The common situation of massive sulphide deposits in mobile belts makes their later subjection to metamorphism and deformation of some degree almost inevitable. A massive sulphide deposit, after undergoing even mild metamorphism, is commonly radically different in many ways from what it was before metamorphism. These changes greatly affect the morphology and other features of the ore bodies, which again influence the later evaluation and exploitation. The effect of metamorphism on sulphide assemblages has been reviewed by Stanton (1964, 1972), Kalliokoski (1965), McDonald (1967), Vokes (1969, 1971), Shadlum (1971), and Mookerjee (1976) and the following sections are largely based on these sources.

Contact metamorphism

Contact metamorphism of massive sulphide deposits may take place whenever they are heated by later intrusive bodies. The effects produced will vary according to the amount and duration of the temperature rise, the type of sulphide body, and the effects of any previous thermal event. The effect of high temperature contact metamorphism is usually fairly localized and restricted to the margins of dykes or sills which probably constitute the feeder channels of subsequent volcanic cycles. This then may result in the recrystallization of the existing sulphides, producing either new minerals or a new coarser texture, or both. In cases of extreme temperatures of intrusion partial melting of sulphides may occur.

Mookerjee and Dutta (1970) described small sulphide "veins" projecting into a post-ore olivine diabase dyke from the coarse-grained massive sulphide body at the Geco mine, Manitouwadge, Canada. These veins consist of a very fine-grained vermicular intergrowth of pyrrhotite-chalcopyrite-sphalerite with corroded, angular to subrounded inclusions of diabase. The sulphide veins further display flow banding parallel to their contacts and around inclusions, and the presence of pyrrhotite-quartz reaction rims. In the absence of any textural evidence of plastic deformation, open-space filling, or diffusion, these features were interpreted as being indicative of incipient melting of the sulphides and rheomorphic injection into the already crystalline diabase. Mookerjee and Dutta (1970) suggested that a liquid consisting of iron- ,zinc-, and copper-sulphides was generated at a temperature above the incongruent melting point of pyrite and that monotectic crystallization under invariant conditions produced the fine-grained texture and the observed mineralogy. This is supported by experimental work of Brett and Kullerud (1969) which indicated that the selective melting of sulphide assemblages of specific compositions can take place at temperatures far below the melting points of constituent minerals. In both studies, ternary liquids generated at remarkably low temperatures (716°C for Fe-Pb-S and 508°C for Cu-Pb-S) congealed into a fine-grained myrmekitic intergrowth of appropriate sulphide phases.

Other common contact metamorphic effects are the dissociation of primary pyrite to pyrrhotite and/or magnetite, subsequent growth of secondary pyrite from pyrrhotite and ferromagnesian silicates, development of chalcopyrite-rich zones near the contacts, abundant development of reaction rims between sulphides and sulphides and between sulphides and silicates, and the development of pyrite within diabase dykes at the expense of magnetite and/or ferromagnesian silicates with concomitant release of TiO_2 (Vokes, 1969). The presence of pyrrhotite in the ore seems to be important in creating changes in mineral composition since this mineral breaks down in the presence of O_2, forming porphyroblasts of magnetite, while the released sulphur combines with existing pyrrhotite to form pyrite.

The effect of contact metamorphism is on the whole very localized and does not greatly affect ore body morphology, metal distribution, or metal content.

Regional metamorphism

Metamorphic effects in massive sulphide ores parallel those that can be observed in their enclosing rocks, but is commonly masked by the ability of high temperature sulphide phases to revert to low temperature phases on cooling. This, together with the wide stability range of most sulphides, and the relatively few phases (and components) present in most ores, contribute to ensure that metamorphism of sulphide masses is generally not reflected by their mineral assemblages. Host rocks thus often supply the best, or only, quantitative indicators of strain and of the grade of metamorphism which affected the ore deposits.

Certain mineralogical changes do however occur during the metamorphism of massive sulphide deposits. Most of these changes are brought about by thermal events and most occur in the iron sulphide species. The generation of pyrrhotite from pyrite is the most common change and it is probable that a large proportion of the pyrrhotite in Canadian Archaean deposits formed in this manner. This is especially true for pyrrhotite occurring with sphalerite in the massive part of the deposit, since primary pyrrhotite commonly occur in the stringer zone (Sangster, 1972). Sphalerite is also affected by regional metamorphism. It tends to become increasingly iron-rich (marmatitic) with increasing metamorphic grade.

Evidence of the earlier existence of high temperature mineral phases comprise the so-called "exolution" or "unmixing" textures. Correctly interpreted, textures of this type indicate that a previous mineral phase has, under falling temperature conditions, separated into two phases stable at the lower temperature. Exolution of chalcopyrite in sphalerite is common in most metamorphosed ores, and the degree of exolution was for many years accepted as being indicative of specific minimum metamorphic temperatures (the so-called sphalerite geothermometer), until work by Brett (1964) and Barton and Skinner (1967) threw considerable doubt on the validity of these temperatures. They demonstrated that exolution is not exclusively dependent upon temperature, but is a complex process leading to supersaturation of one phase within another, and is influenced by temperature, pressure, concentration, purity, grain size, and stress distribution within the crystal. The exolution takes place in the solid state by nucleation and growth at imperfections in the crystal structure, e.g. at grain boundaries, dislocations, slip planes and twinning planes. Evolved lamelli thus generally show a high degree of crystallographical control. Once the exolved phase has nucleated, it starts growing, driven by the need to reduce the supersaturation. As it grows, it depletes the surroundings of suitable components, thereby creating a concentration gradient which leads to solid state diffusion and the replenishing of the exolved elements.

The fabrics of sulphide ores are often changed drastically during metamorphism. Original depositional textures and structures may be modified or obliterated by recrystallization and/or deformation. Recrystallization (metablastic growth or metablastesis, Vokes (1969)) leads to changes in form and grain-size of mineral grains. Characteristic shapes and intergrowths as a result of recrystallization is a consequence of the ability of various minerals to take on euhedral shapes. The general result is to produce fabrics in which the minerals of high form energy-pyrite, arsenopyrite, magnetite - grow as metacrysts, commonly porphyroblasts, in a surrounding matrix of sulphides of lower form energy, e.g. galena, chalcopyrite, sphalerite, and pyrrhotite, which rarely develop crystal faces. At the same time metamorphism of gangue minerals may contribute to changes in ore fabric, especially through the growth of platy and tabular minerals such as sericite, chlorite, amphiboles, etc., which result in complex sulphide-silicate intergrowths. Stanton (1964) emphasized that these textures are not evidence of a paragenetic sequence, in which late matrix sulphides filled the spaces between early-formed subhedral to euhedral forms. They are expressions of a "crystalloblastic series" where each mineral has exerted its own "force of crystallization" against the surrounding, essentially solid, medium. He proposed a general "silicate-oxide-sulphide crystalloblastic series" to cover the minerals generally involved in massive sulphide ores. The series, based on relative tendencies to idiomorphism and considerations of interfacial free energy, comprises the following minerals (in order of decreasing tendency to idiomorphism): garnet, magnetite-arsenopyrite, pyrite, dolomite, tremolite, muscovite, chlorite, pyrrhotite, sphalerite, chalcopyrite, and galena. Stanton concluded that since the series is controlled by the natural tendency toward the establishment of minimum free energy, it is commonly modified by factors such as variations in free energy with variation in orientation, the average free energy, degree of dissimilarity of bonding and spacing of the structure on either side of the interface, the degree of linkage across the boundary, the effect of impurities, and the effect of non-stoichiometry on interfacial free energies. These factors commonly result in deviations from the norm.

Since pyrite is usually the dominant mineral in most massive sulphide deposits, the forms exhibited by it commonly dominate the ore fabrics. In sulphide ores pyrite only rarely occurs as perfect cubes. They are usually subhedral with "embayments" and/or inclusions of matrix minerals - sphalerite, galena, chalcopyrite, pyrrhotite - and of gangue minerals. The matrix minerals also show mutual intergrowths as a result of metamorphic recrystallization. These are mainly allotriomorphic mosaics where adjacent grains meet in "triple junctions" (Stanton, 1964). Minor phases occur along grain boundaries of major phases as "lozenge"-shapes, convex triangles, polygons, or near circles. The shape of the minor phase is controlled by the free energy ratio between the two phases. Where the minor phase has a relatively high surface free energy (e.g. sphalerite in galena) it tends to form nearly spherical bodies at the triple junctions between grains of the major phase. In the opposite case (e.g. galena in sphalerite) the minor phase occurs as small lenses and cuspate triangles, the disposition of which shows the control by the grain boundaries of the major phase (Figure 35).

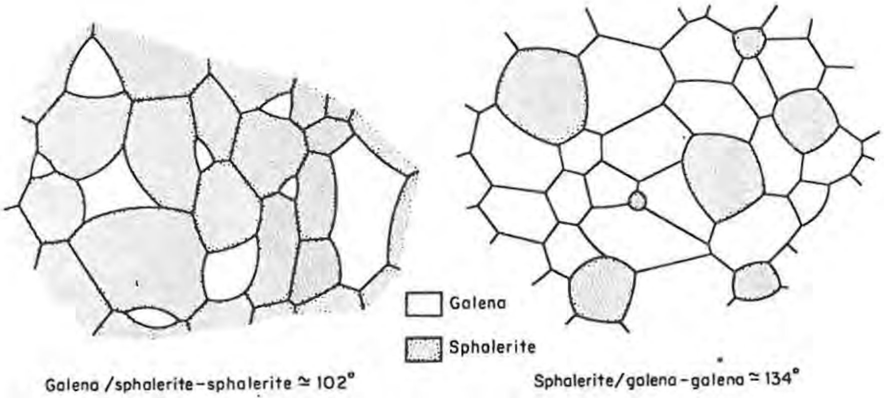


Fig. 35 Schematic diagram of grain shape when galena occurs as a minor phase in sphalcrite and vice versa.

From Stanton, 1972.

In general, progressive regional metamorphism leads to an increase in grain size of sulphide ores. An attempt by Templeman-Kluit (1970) to quantify this relationship was only partly successful. The absence of a precise correlation between sulphide grain and metamorphic grade as determined by index minerals probably indicate that silicate index minerals are not the best way of measuring metamorphism as it affects sulphide grain-sizes. This is probably because variables such as stress, confining pressure, duration of metamorhpism, and the original composition and grain-size of the sulphides, are not all quantifiable, and as a consequence their individual effects on grain-size are hard to assess.

Fabrics due to deformation vary widely depending on the relative plasticity of the ore mass at the time of deformation, probably as a function of temperature (Vokes, 1969). The preservation of strain fabrics and of strain in individual mineral grains is probably dependent upon the relative timing of maximum stress with respect to maximum thermal effects (Sangster, 1972). Sulphides lacking strain texture may indicate that thermal annealing took place after the release of stress. On the other hand, the application of stress without appreciable heat, such as deformation in rocks of low metamorphic grade, or the continuation of stress after the thermal event, leads to formation of cataclastic textures. These include comminution of pyrite and sphalerite, "steely" galena, and "streaky" chalcopyrite (Sangster, 1972). These ores are fine-grained consisting of "ore breccia" fragments infilled by the finer-grained products of attrition of the sulphides or by more ductile minerals such as galena or chalcopyrite.

In areas of higher metamorphic grade deformation is often accompanied by recrystallization. Large elongate pyrite crystals are common in the less massive parts of ore bodies. These are commonly spindle-shaped and lie parallel to the foliation. Chalcopyrite or other ductile sulphides may occur in "pressure shadows" adjacent to these porphyroblasts. Pyrite granules in massive ores may also be deformed to form "gneissic" or other oriented textures. Deformation of the more ductile minerals is less conspicuous. Observable effects are glide and translation twinning, gneissic textures, and curved or otherwise distorted textures in chalcopyrite, galena, sphalerite and pyrrhotite. When deformation has been accompanied by recrystallization, annealed textures result, which if allowed to proceed to completion, will end in textural equilibrium among the sulphide phases. Thermodynamic stability and equilibrium is indicated by specific dihedral angles at triple junctions. In monomineralic aggregates, for example, these angles approach 120° (Figure 36), while for instance at a junction of two sphalerite grains and one galena, the dihedral angle of the galena will be 102° (Stanton, 1964).

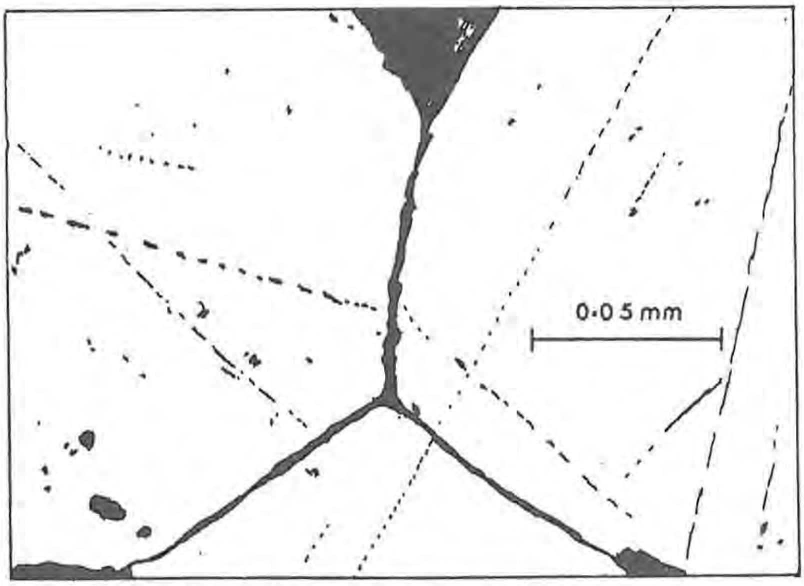


Figure 36: Triple junction between pyrite grains in textural equilibrium. The interfacial angles are approximately 120° :traced from Sangster and Scott (1976), p.194.

With the continuation of stress beyond the stage of plastic deformation and lattice distortion, the newly formed mineral grains may be subjected to a further cataclastic deformation. The harder, more brittle idioblastic minerals such as pyrite, magnetite, arsenopyrite and to a lesser extent pyrrhotite are granulated and brecciated, and sometimes rounded. Matrix minerals still behave plastically and fill in between the fragments. The resulting flow textures may again be destroyed by late annealing. Boudinage and attenuation of interbedded meta-chert and meta-tuff lenses and bands in the ore, with the accompanying flow of ductile sulphides to fill the voids created, results in what Vokes (1969) termed "Durchbewegung" textures. The non-sulphide fragments in such "durchbewegt" masses resemble waterworn rounded pebbles, commonly having a highly polished surface due to a thin film of sulphides.

Mobilization of sulphide minerals, especially of the more ductile species such as galena, chalcopyrite, and pyrrhotite appears to be a common result of high grade metamorphism (Vokes, 1969). Movements of the order of a few millimetres or even centimetres can be ascribed to plastic flow. Some of these have already been described and include such phenomena as the "healing" of cataclastic textures by ductile minerals, the general flow of sulphides in "Durchbewegung" structures, and the movement of chalcopyrite, galena, and pyrrhotite into "pressure shadow tails" of deformed pyrite or silicate grains. The often-cited example of the thickening of sulphides in the crests and troughs of folds may however be the result of an attenuation of the limbs without movement of the sulphides relative to their wall-rocks. Slight enrichment of copper or lead at cost of zinc in fold hinges, on the other hand, reflects on the relatively higher mobility of chalcopyrite and galena compared to sphalerite and must be accepted as evidence that some movement of sulphides took place. These movements, however, result in only slight relative movements of the various ductile sulphides, giving rise to mild differentiation which does not greatly affect the natural ore body zonation. Vokes (1971) in a review on mobilization of sulphides concluded from the available literature and his own observations that metamorphic mobilization occur at the most over distances of several metres. At this scale, mobilization then involves the generation of sulphide melts at temperatures exceeding 500°C, resulting in coarse-grained sulphide pegmatoids. The melts would presumably stay where they had been generated in the absence of tectonically controlled migration.

Sulphide-silicate reactions as a result of regional metamorphism have been described from a few deposits. Howard (1965) (quoted in Mookerjee, 1976) suggested that pale-brown biotite-tremolite schist at the Elizabeth Mine resulted from the sulphurization of dark-brown biotite schists and amphibolites into which they grade away from the ore body. Similar reactions are believed to have resulted in the formation of amesitic chlorite and anthophyllite at the Geco and Willroy mines, Manitouwadge, Ontario (Mookerjee, 1970). At the same deposits reactions between sphalerite and aluminosilicates lead to the formation of synkinamatic gahnite ($Zn\ Al_2O_4$) (Mookerjee and Dutta, 1970).

Metamorphism thus results in the establishment of new relationships between sulphide grains, between sulphide grains and gangue minerals, and in the creation of new ore and gangue minerals. It is obvious that these changes greatly affects the mineability and extractability of the ore, as will be discussed in a later section.

Retrograde metamorphism

Apart from the re-equilibration and recrystallization of sulphides during cooling, retrograde metamorphism affects wall-rock and gangue minerals. High grade metamorphic minerals like cordierite and garnet break down to form micaceous minerals like muscovite, chlorite, and biotite, and chlorite may break down to form talc. The overall effect is thus to lower the competency of the wall-rocks which is detrimental to the mineability of the deposit.

Deformation

Structurally, the host environments of Canadian copper-zinc deposits represent a small portion of much larger regional fold belts. These are commonly characterized by a sequence of multiple deformations, which can be roughly subdivided into three phases within an apparently continuous progression (Hopwood, 1976). The first phase comprises the folding of initially, essentially flat-lying bedding or volcanic layering about variably plunging sub-horizontal axes. This is accompanied by the development of a steep axial planar foliation and a mineral streaking lineation in the plane of the foliation. The second phase consists of sub-horizontal or sub-vertical crenulation folds with crenulation cleavages often at high angle to the foliation developed as a result of the first phase. The third phase represents brittle fracture along kink surfaces and is gradational into the second phase.

Hopwood (1975) concluded from a study of the structural-lithostratigraphic settings of six deposits in the Canadian Shield that these are comprised of elongate, flat lense-shaped bodies, occurring singly or as multiple bodies within a pyritic zone in close proximity to a body of quartz porphyry. In all cases where the relationship between the mineralization and the first generation mineral streaking lineation had been observed, the elongation of the ore bodies was found to be parallel to this lineation. Figure 37, a simplified map of the structural geology in the vicinity of the Rod No.1 and Rod No.2 deposits, Stall Lake Mines, Manitoba (Coats et al., 1970), illustrates this relationship very well. Here the enclosing rocks strike at 045° and dip 58° NW. A well-developed foliation parallel to bedding is defined by compositional layering and alignment of biotite and muscovite flakes. A prominent lineation within the plane of the foliation is defined by orientation of elongated minerals and by the axes of minor folds. The lineation plunges at 37° in the direction 025°. The attitude of both ore lenses closely approximates the mean plunge angle and direction of this lineation (Coats et al., 1970).

Hopwood (1975, 1978) related the formation of elongate ore lenses to the generation of intrafolial folds during the first phase of folding. His model is based on the concept of continuously evolving strain and cleavage development and is illustrated in Figure 38. A condition of the model is that strain does not occur parallel to the B-axis of the bulk regional strain, i.e. $B < \frac{A+C}{2}$ (Figure 38).

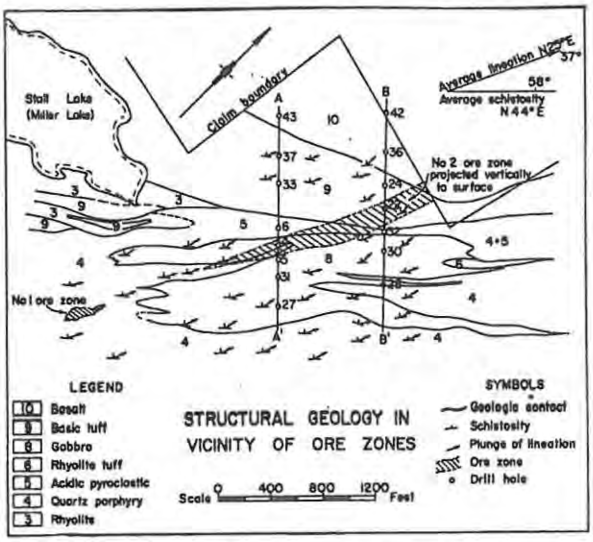


Figure 37: Structural geology in the vicinity of the Rod No.1 and Rod No.2 ore zones, Stall Lake Mines, Manitoba. From Coats et al., 1970.

Initial flexure of the bedding (Figure 38 A,B) is by inhomogeneous strain and tends to form axial culminations and depressions. The size of the folds is controlled by the ductility contrast and the thickness of the stratigraphic units. Continued stress will cause these early folds to become tighter (Figure 38 C). With the continuing rotation of the bedding, strain will increasingly take place on the micro-scale, resulting in homogeneous flattening and the development of a regional schistosity, causing flattening of earlier formed folds, and introducing ellipsoidal shapes in strain markers. The "transposition" of bedding parallel to schistosity probably develops at this stage. In this steep orientation no further rotation can take place. With further stress the transposed layers would tend to flatten and extend in the direction of the fold axis (Block $Q_1Q_2 \rightarrow Q_1'Q_2'$, Figure 38 D), but is prevented from such extension by the strain condition $B < \frac{A+C}{2}$. In other words the confining stress in the direction of the fold axes becomes greater than the applied stress. As a result folds will develop within the transposed bedding-foliation plane (B-C strain plane) with axes parallel to the mineral streaking lineation and to the A-axis of regional strain. The axial planes of these folds are sub-parallel to the regional foliation, and fans slightly about the plunge of the L_2F_2 lineation (Figure 38 E).

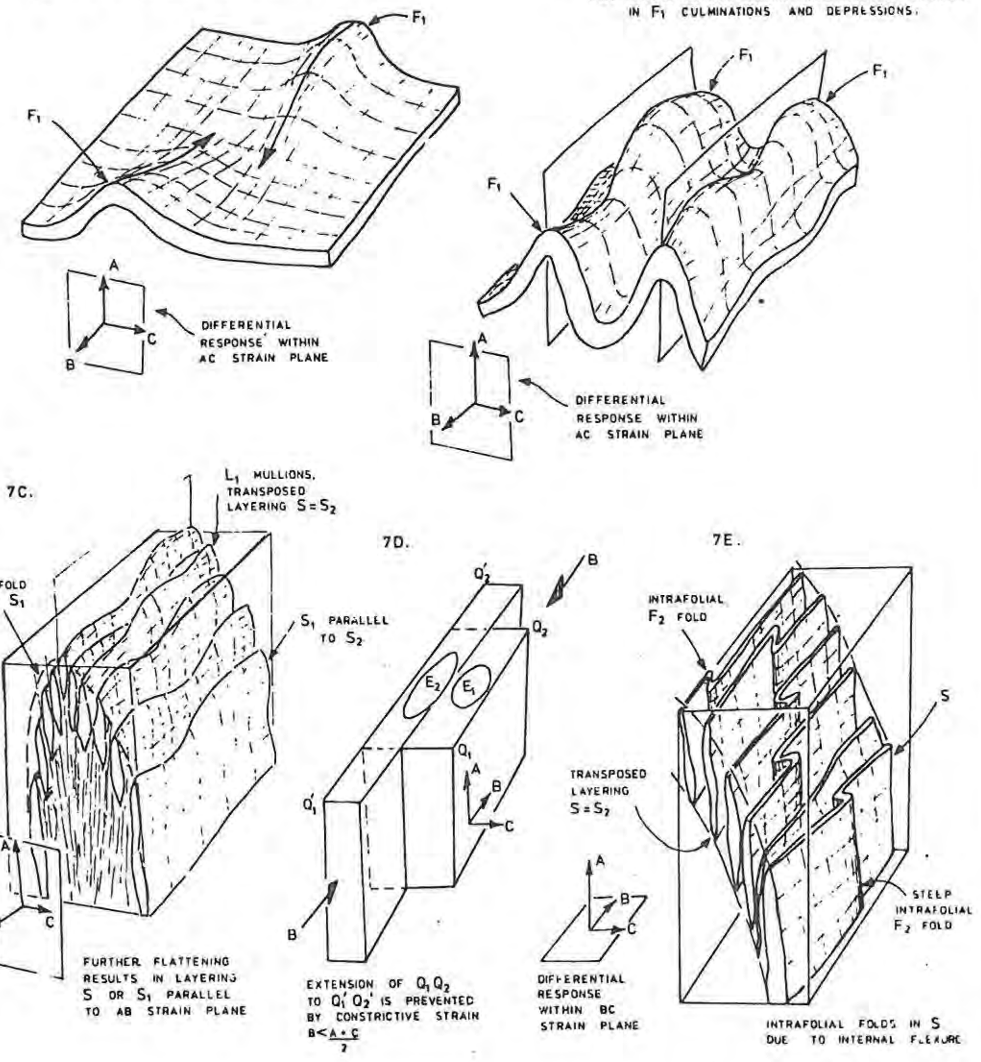


Figure 38: Various block diagrams illustrating the development of intrafolial folds by continuously developing strain. A, B and C are the main axes of strain. E is the strain ellipsoid. S_1 = bedding, S_2 = foliation, S = transposed layering, F_1 = first phase of folding, and F_2 = intrafolial folds. From Hopwood, 1978.

Many massive sulphide ore bodies in the Canadian Shield are observed to be steeply elongate within the regional foliation, and are enclosed by, or associated with, steeply plunging intrafolial folds, formed apparently in bedding or transposed bedding (Hopwood, 1978). Examples are the elongated multiple ore lenses at Kidd Creek (Walker and Mannard, 1974; Walker et al., 1975) Flin Flon (Coats et al., 1972; Koo and Mossman, 1975), amongst others. These massive ore lenses overlie one or more stringer zones, generally contained within chloritic-sericitic alteration zones. These massive ore lenses probably represent separate accumulations of sulphides over source vents, which may have been fed by the same conduit, or by separate conduits. During deformation these ore lenses, and associated altered zones, exist as inhomogeneities within the bedding or volcanic layering, and would localize the formation of intrafolial folds. The massive sulphide-cherty tuff ore package acts competently during folding. It tends to fold upon itself and to elongate in the direction of the A-axis of the bulk regional strain. During any subsequent deformation, the massive ore tends to stay in a coherent mass. The alteration zone and contained stringer sulphides, on the other hand, acts incompetently and tends to flatten by shearing along the schistosity (Figures 39, 40). The control of massive sulphide deformation by intrafolial folds provides an explanation for occurrence of alteration zones on only one side of folded ore bodies (Figures 39, 40). Deformation during Hopwood's Phases 2 and 3 causes superimposed folds which may result in "rolls" down the plunge of the ore body, and late faulting may disrupt and displace parts of it.

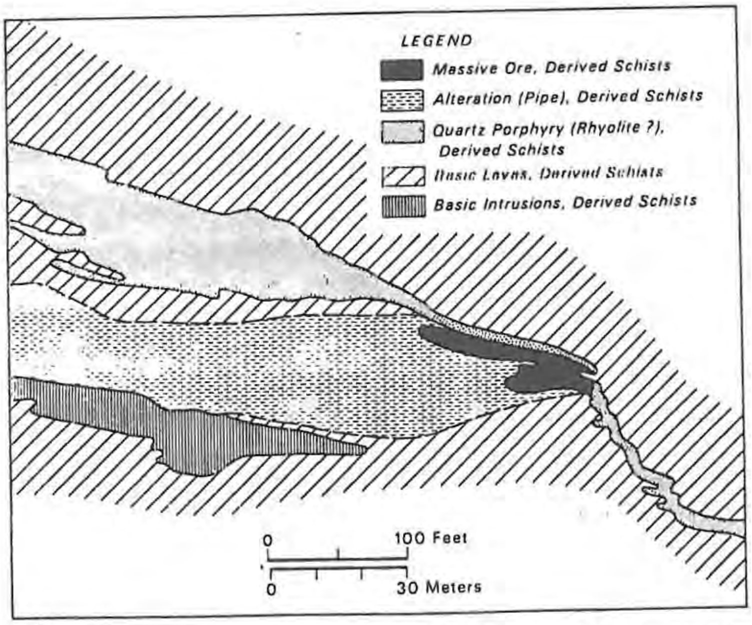


Fig.39 Flin Flon mine, Manitoba. Plan of 3000-ft. level. Stratigraphic top is to the top of the diagram. (After Byers et al., 1965; courtesy of Saskatchewan Dept. of Mineral Resources.)

From Sangster and Scott, 1976.

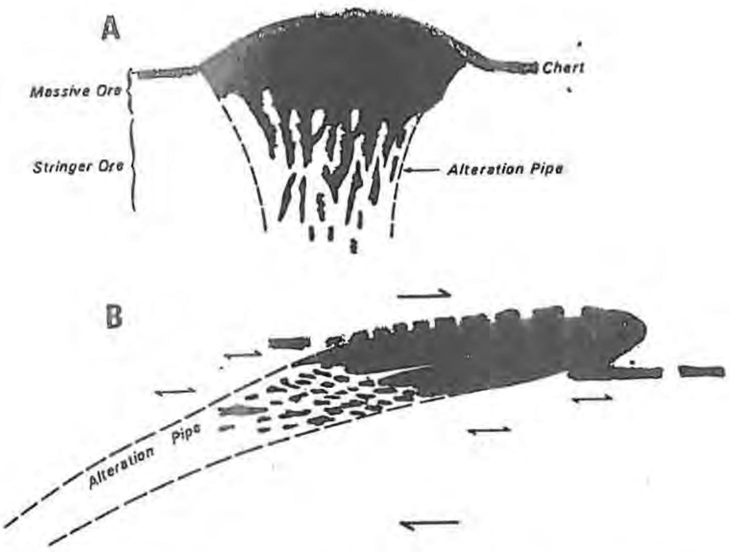


Figure 40: A: Schematic diagram illustrating the main geological features of an undeformed massive sulphide deposit. B: The same deposit after folding and modification by shearing parallel to the regional schistosity. Heavy arrows above and below the ore body indicate the sense of shearing. Compare with Figure 39 of the Flin Flon mine.
Modified from Sangster and Scott, 1976.

Shearing may have an averse effect on small or disseminated ore bodies which lack the coherence of large sulphide masses. These are generally stretched out and attenuated, resulting in several en echelon ore lenses. In very low grade metamorphic areas even large ore bodies tend to be flattened parallel to the schistosity as a result of transportation along shear zones. Deformation thus has a very profound effect on ore body morphology which may be either beneficial or deleterious to the mineability of the deposit.

Weathering and supergene alteration

In the near surface weathering regime, most hypogene mineral assemblages are unstable in the presence of weathering agents such as water-dissolved oxygen, carbon dioxide, and certain ionic species released by the dissociation of sulphides. The action of these weathering agents causes the sulphide body to re-equilibrate electrochemically and promote the formation of more stable secondary sulphide and oxide mineral assemblages. The activity of the weathering agents, being derived mainly from the atmosphere, generally decreases with increasing depth below the surface, This results in a vertically zoned weathered profile (Figure 41). Ideally, the hypogene ore body grades upwards in an oxidized sulphide zone which may be enriched by secondary ore minerals. This zone is followed by a leached oxide-zone, which is capped by a gossan at surface (Blain and Andrew, 1977; Joyce, 1976).

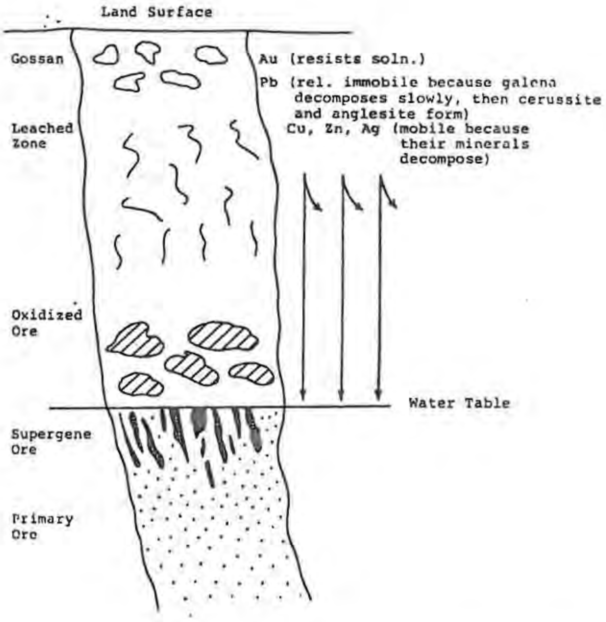


Figure 41: Schematic cross-section of an oxidized pyritic base metal sulphide deposit.
From Joyce, 1976.

In contrast to silicate rocks, most massive sulphide bodies are coherent electronic conductors. The reactions that take place in the weathering environment are for that reason electrochemical reactions between the sulphide conductor and a co-existing aqueous medium (Blain and Andrew, 1977). Supergene alteration is thus essentially an electrolytic process, comprising couples of oxidation-reduction half-cell reactions, each of which involves the exchange of electrons.

As ore bodies are progressively exhumed, their contained sulphide minerals gradually become unstable in the presence of oxygenated groundwater. A point is reached where the Eh of the solutions exceeds the equilibrium Eh value for incipient supergene alteration of the mineral phase (Garrels and Christ, 1965). The mineral may then oxidize with the consequent release of electrons, which are conducted through the ore and consumed elsewhere by a complementary reduction couple. Continued supergene alteration of primary ore occurs as a progression of oxidation half-cell reactions (Blain and Andrew, 1977). In releasing electrons, the oxidizing ore becomes positively polarized and forms an anode. At the top of the conducting ore body, dissolved oxygen in the groundwater is reduced to hydroxyl ions by the consumption of electrons causing a negative polarization and the formation of a cathodic region. Current flow through the ore is matched by external ionic migration through the groundwater. Thus, during supergene alteration, massive sulphide bodies probably behave as very large electrochemical corrosion cells (Blain and Edward, 1977). Figure 42 summarizes the chemical reactions and their interrelations during the early stages of supergene enrichment of a pyrite-chalcopyrite-bornite ore body.

Although supergene copper minerals have been recorded at many Canadian Archaean deposits with gossanous outcrops, the Copper Rand and Henderson No.2 mines at Chibougamau, Quebec (Allard, 1976) and the Detour deposit near Matagami in Quebec (Sinclair and Gasparrini, 1980), are the only deposits documented where substantial parts of the ore have been supergene enriched.

The Detour deposit is not a typical "Noranda-type" massive sulphide deposit, but consists of three zones of stringer-type mineralization. Supergene mineralization is confined to certain sections of these ore zones which in unaltered form consist of veins of alternating irregular bands of quartz, sphalerite, pyrite, chalcopyrite, calcite and dolomite. The veins are anastomosing and occur in sub-vertical fracture systems (Sinclair and Gasparrini, 1980). Mineralization in the B-ore zone has been affected by recurrent faulting which greatly enhanced the permeability of the zone. Alteration in this zone is thus far advanced in comparison to the other zones. The principal supergene minerals are chalcocite, digenite, bornite, and covellite, with varying amounts of native copper and silver. These minerals replace each other in a progressive series with resultant copper-enrichment. The supergene minerals occur as rims around hypogene chalcopyrite and sphalerite, fill fractures in the hypogene minerals, or completely replace the chalcopyrite. Considerable amounts of limonite and kaolin are associated with the ore minerals in the B-zone.

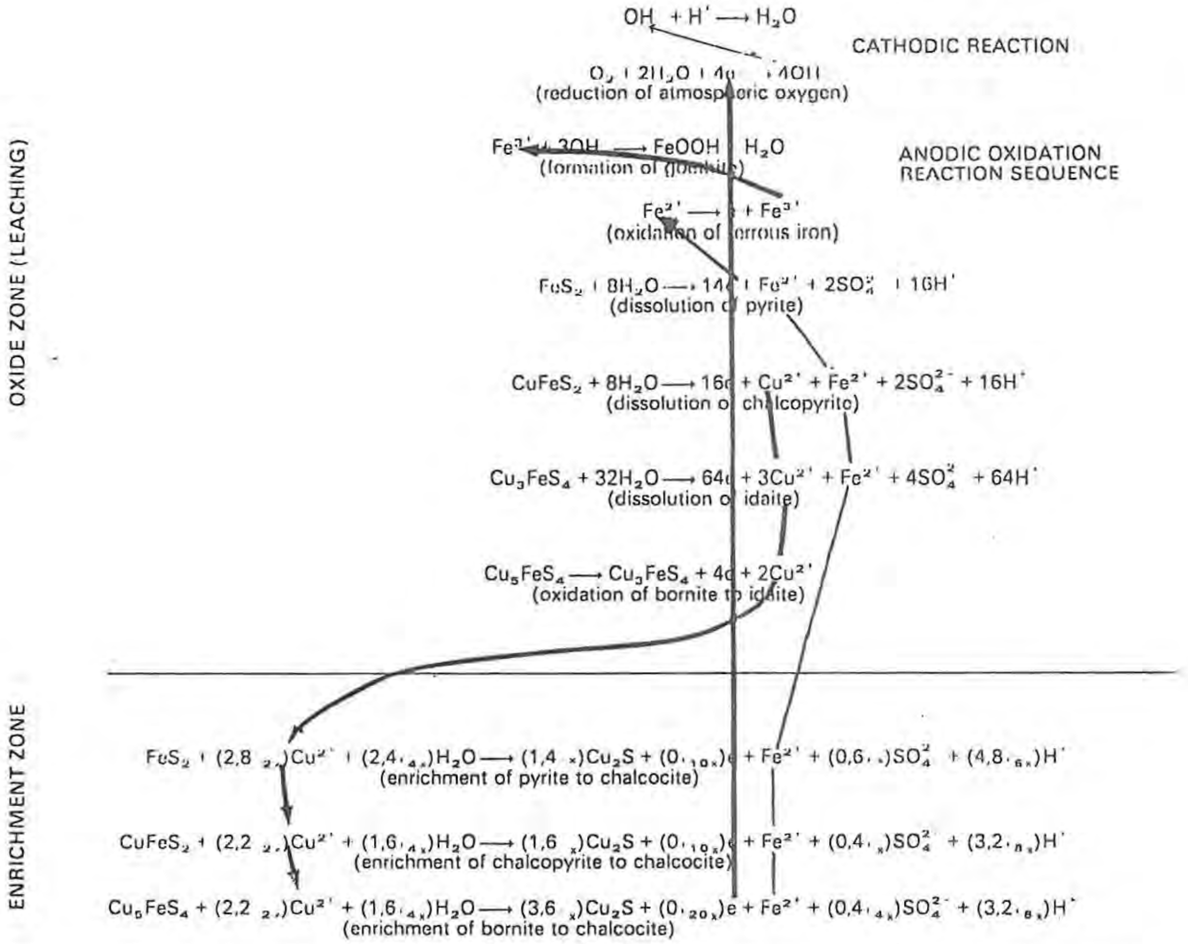


FIG. 42: Chemical reactions and their inter-relations during the early stages of supergene enrichment of pyrite–chalcopyrite–bornite orebodies.

Note. In the schematic representation of the enrichment reactions, x refers to a very small number which may alter the balance of reactants and products as electrochemical half-cell reactions.

From Blain and Andrew, 1977.

Sinclair and Gasparrini (1980) relate the general lack of substantial supergene ore bodies in the Canadian Shield to its relative stability since Precambrian times. They hold the opinion that supergene alteration occurred as a fairly widespread phenomenon not long after formation of the deposits, probably as a result of exposure and weathering after the Kenoran orogeny (2560 m.y. B.P.). Supergene ores have however only been preserved in those deposits that were covered by Proterozoic and younger sediments and thus protected from erosion. This supposition is substantiated by the fact that unaltered deposits in the Noranda area have either been denuded by glacial activity and then covered by tillite, or are "blind" ore bodies that has never been exposed to weathering (Boldy, 1979).

Supergene minerals have been described from a number of Japanese Kuroko deposits (e.g. Shimazaki, 1974; J. Sato, 1974) but seem to be only relatively minor constituents of the ore. It seems thus that in the deposits under consideration, supergene alteration does not greatly affect either grades or tonnages, but since even incipient alteration may affect the extractibility of the ore, it should be considered in feasibility studies, and borne in mind during the operational life of the mine.

IMPLICATIONS FOR THE EVALUATION AND EXPLOITATION OF MASSIVE SULPHIDE DEPOSITS

Although a very large amount of literature on the genetic aspects of volcanic-exhalative deposits in general and Canadian and Japanese deposits in particular has been published, only a very few papers consider the more practical aspects and their implications for the mining industry. The following is an attempt to bring theory and practice together and to show how the geological factors under discussion in the previous sections, influence such aspects as ore body delineation, ore reserve estimation, mine development and mining, and ore beneficiation.

Ore body delineation

Drilling is the only effective way to sample an ore body prior to actual mine development, and is therefore used extensively during the delineation and evaluation stages which follow the discovery of a potential ore deposit. It is the most expensive technique used during the pre-development period and should be planned very carefully. The decision to evaluate a deposit is normally taken after a certain amount of drilling to delineate it, has been completed. To obtain maximum benefit from these two programs they should be planned to coincide with each other and should not be treated as separate entities. In other words, the drilling pattern used for the initial exploration drilling must be able to be modified for deposit evaluation drilling without the duplication of any work.

The selection of a drill pattern is to a major extent governed by the expected size, shape, and structural attitude of the mineralized body. In the initial stages,these factors are surmised from the exploration model based on an understanding of the genesis of the deposit, and substantiated by geological mapping, structural interpretation, geophysical surveys, and initial drilling.

The Kuroko deposits of Japan are essentially flat-lying lensoid bodies with their maximum dimensions in the horizontal plane parallel to the regional stratigraphy. These maximum dimensions range in known deposits from 800 by 800 m for the very large Matsumine Mine to 70 by 30 m for the Osaki Mine. Thicknesses are from 8 m to 190 m (see Table 1). These factors, together with strong stratigraphic control, facilitate the exploration of these deposits by the drilling of vertical holes on a wide-spaced regular grid (Figure 43). The intersection of white rhyolite, hydrothermal alteration, and/or disseminated mineralization provides incentive for follow-up exploration procedures: E.M. and I.P. surveys and closer-spaced drilling. Once the presence of massive sulphides has been established, the drilling grid is closed in even further and the lateral and vertical extent of the ore deposit is established (Figure 44).

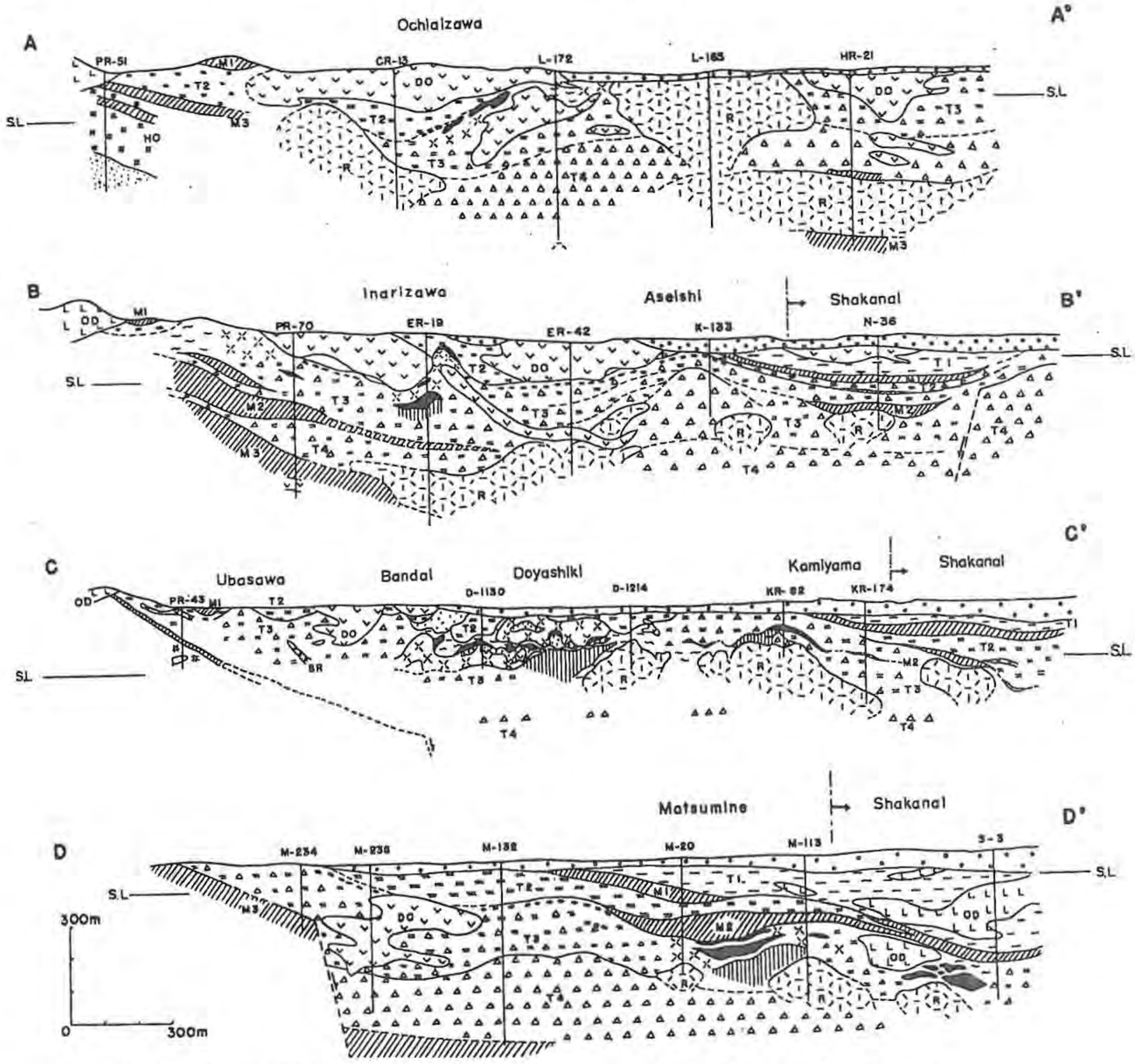
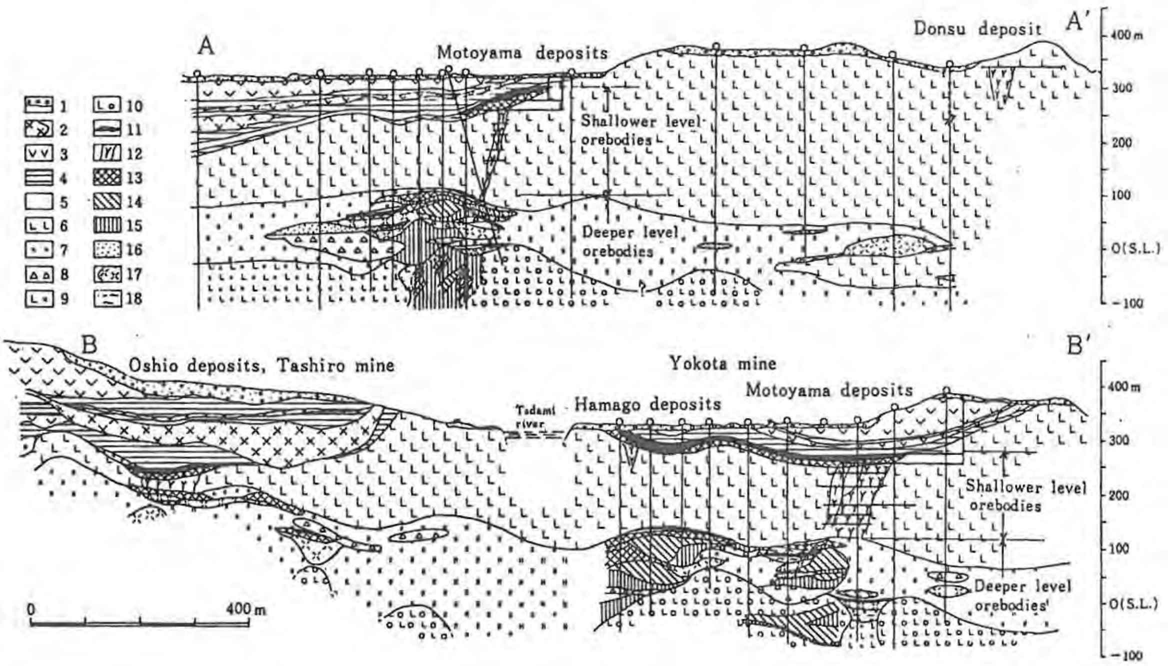


Figure 43: East-west cross sections through the Hanaoko Kuroko Belt showing initial exploration drill holes. Sections are between 500 and 1000 m apart. From Takahashi and Suga, 1974.



1: Quaternary sand and gravel, 2: Basalt dike, 3: Patchy tuff, 4: Mudstone, 5: Soap stone, 6: Rhyolite (R_I), 7: Tuff, 8: Rhyolite (R_{II-III}), 9: Patchy rhyolite (R_{IV}), 10: Perlitic rhyolite (R_D), 11: Stratiform Kuroko, 12: Network-disseminated ore, 13: Oko, 14: Siliceous Oko, 15: Keiko, 16: Hematite-quartz layer, 17: Gypsum ore, 18: Clay bed.

Figure 44: Geological cross-sections through the Yokota Mine Area showing evaluation and exploration drill holes. Vertically "stacked" deposits necessitate deep drilling.
From Hirabayashi, 1974.

Massive sulphide deposits in the Canadian Shield have in general undergone some form of structural deformation. Deposits are thus, except for the undeformed Noranda deposits, either steeply plunging rod- or blade-shaped, or inclined tabular bodies. As a result, drilling has to be much more directional than in the case of the Kuroko deposits. This is complicated by the generally poor exposure of the Precambrian rocks in the Canadian Shield due to Pleistocene till cover and widespread swamps and lakes. The poor exposure led to the development of sophisticated geophysical equipment and techniques which are used extensively both in exploration and in the delineation of ore deposits. The massive nature of the ore facilitates the use of electromagnetic and induced polarization methods which are capable of providing information on the dip, strike and even the plunge of "blind" deposits. Due to the common occurrence of magnetite and pyrrhotite in the deposits, magnetic surveying is also used extensively, and since it is far less expensive than ground E.M. methods, it is commonly used to outline possible targets for E.M. surveying.

The Rod No.1 and No.2 ore bodies of Stall Lake Mines Limited are elongated lenses of massive sulphides set in an envelope of pyritic rhyolitic tuff. Figure 45, a vertical longitudinal projection of the ore zones, illustrates the procedure followed in the delineation of this deposit.

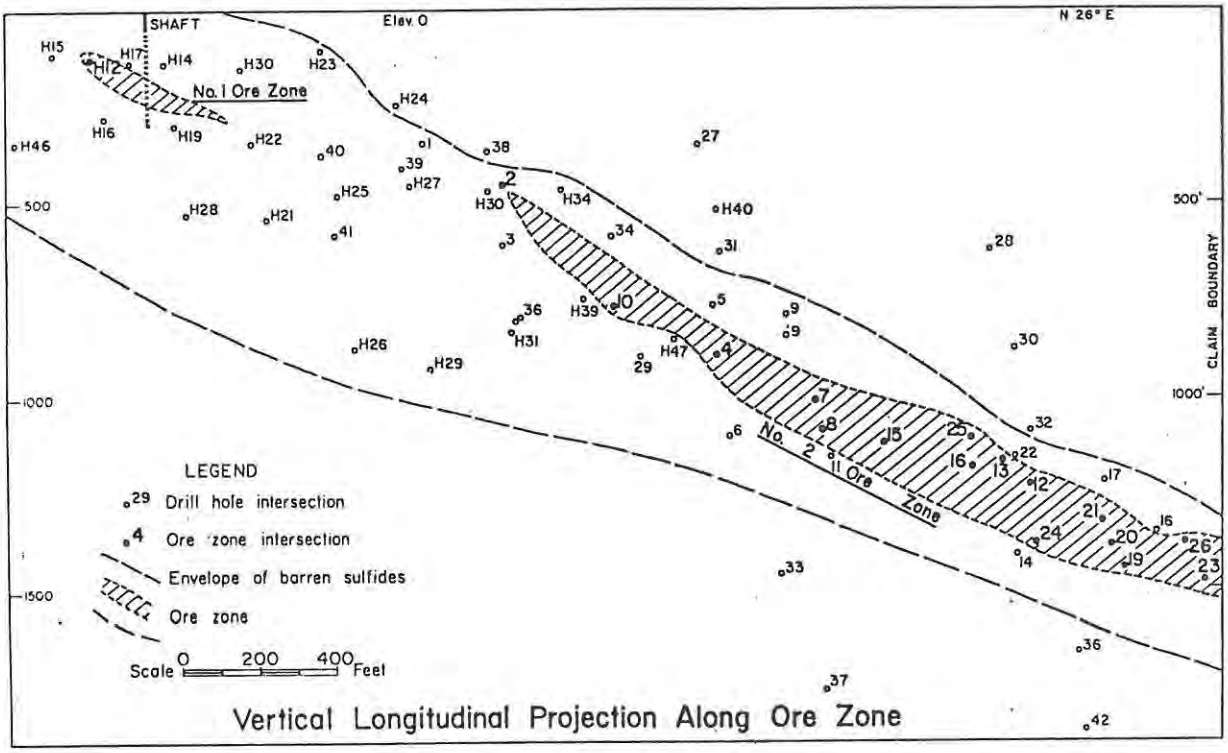


Figure 45: Vertical longitudinal projection along the Rod No.1 and No.2 ore zones, Stall Lake Mines Limited.
From Coats et al., 1970.

Early drilling on the Rod claims group (Coats et al., 1970) investigated a single station cross-over obtained during a semi-detailed electromagnetic survey. The twelfth hole (H12) drilled on a fairly regular grid intersected massive sulphides (15,5 ft. at 3,88% Cu, 1,50% Zn) in a small elongate lense (Figure 45). Drill holes H15 and H17, located 100 ft. on either side of H12, returned 6,2 ft. of 1,64% Cu and 3,6 ft. of 5,12% Cu and 1,17% Zn, respectively. These two holes indicated the strike length of the economic mineralization to be less than 200 ft. Despite the subsequent drilling of some 36 inclined holes, no further significant values were intersected, and the property was relinquished.

In 1965 the claims were optioned by Falconbridge Nickel Mines Limited (Coats et al., 1970). An exploration model based on the remapping of the claims, new geochemical and geophysical surveys, and experience gained elsewhere in the district, indicated the possibility of further economic mineralization down-plunge of the No.1 ore zone. Nine vertical holes were planned in three sections spaced to test the ore horizon at 500 ft., 1000 ft., and 1500 ft. below surface. These were located along the plunge direction as indicated by mineral streaking lineations recorded on outcrops. The fourth hole in the series (No.4, Figure 45) intersected 20,8 ft. of 6,80% Cu, 1,55% Zn and was the first indication of a new mineralized zone. Subsequent holes tested the down-dip and down-plunge extent of economic mineralization, with borehole collars being stepped back on each following section to accommodate the increased depth due to the plunge of the body. Two sections were extended in both the up- and down-dip directions to indicate the limits of the pyritic envelope and to test for en echelon bodies (Figure 45).

An increasingly popular approach to drill hole planning in exploration and ore body delineation is to devise a mathematical simulation model that can be tested in a series of computer runs until an optimum pattern is found. Koch and Link (1971) describe the general principles of mathematical simulation. The approach is to assume certain natural variables - the number of ore bodies and their size, shape, orientation, location and value. Controllable variables, viz. drill-hole locations, azimuths, inclinations, lengths and costs, are then assigned. Alternative assumptions about the natural variables and alternative patterns for the controllable variables are considered in all of their most probable combinations until the optimum drill pattern and spacing is established. Malmqvist et al. (1980) recently applied such a computer simulation model to the exploration for deep-seated massive sulphide deposits in the Skellefte district of Sweden. They found that even a very simple model using a single homogenized host rock, was able to predict optimum exploration targets.

The main advantage of simulations is that the cost-effectiveness of a certain procedure can be taken into consideration. Care should however be taken in applying the chosen model to a specific area. Detailed knowledge of the local geology is necessary to ensure that the model, based on much broader statistical data, is compatible. Simplified geological patterns that lead to a statistically sound drilling grid may ignore some basic structural or lithologic control in the specific area. For example, the grid may coincide with a periodicity created by folding or hydrothermal activity which places the ore bodies exactly between drill holes, or cause holes to intersect only in fold hinges where both the grade and thickness of ore may be exaggerated.

Another approach to the quantification of drill hole spacing is through the use of geostatistics. The variogram function deals with regionalized variables that have specific distance and directional characteristics, and can be used once the geological data base becomes large enough to support meaningful statistical relationships. It is thus mainly useful in the later delineation stages and in the estimation of ore reserves. The variogram function (actually the semi-variogram or variogram/2) is usually plotted on a graph and may fit any of a number of theoretical models described by various authors (e.g. Matheron, 1971; Royle et al., 1974; David, 1977).

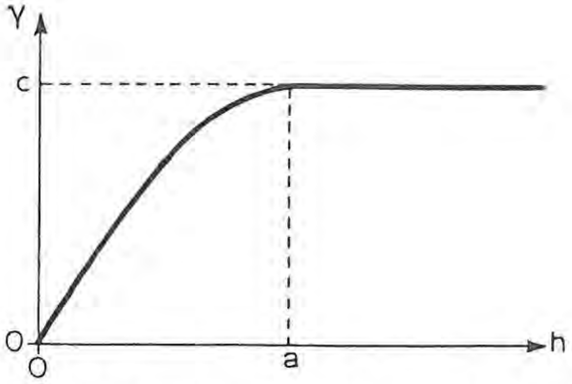


FIG. 46 The 'ideal' shape for a semi-variogram—the spherical model.

from Clark, 1979.

The spherical model (Figure 46) is the most useful in determining the range of influence of samples and thus the optimum borehole spacing. The variogram function ($\gamma(h)$) in Figure 46 is dependent upon the distance between samples (h). Samples further apart than the distance a (or the "range" of the semi-variogram) have no mutual influence and behave in a random manner as is indicated by the flat "sill" (C) of the semi-variogram. The optimum spacing between drill holes in a particular direction is thus indicated by the "range" - any closer sampling would show the correlation, but would be unnecessarily close. It is however doubtful that geostatistical methods can be applied to volcanogenic massive sulphides without major adjustments since it is implicit in the technique that there should be no significant geological trends in the deposit under consideration. Ubiquitous zonation in most massive sulphide deposits cause trends in both the vertical and horizontal sense. Experimental semi-variograms of a Spanish massive sulphide deposit, for example, shows pure "nugget effect" (random behaviour) for minor component lead and zinc, and a parabola for copper, implying polynomial trend (Figure 47).

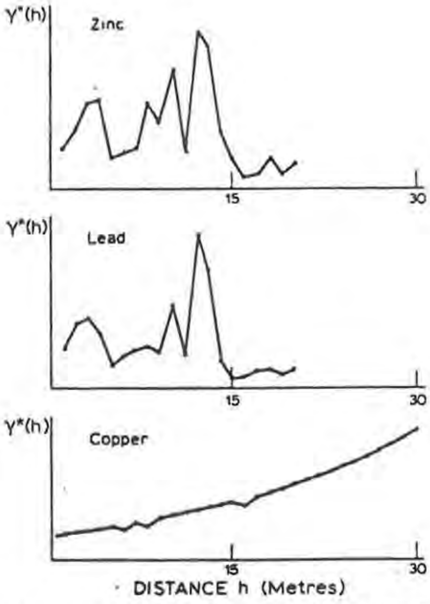


FIG. 47 Experimental semi-variograms for a complex base-metal sulphide deposit.

From Clark, 1979.

Another important procedure in the pre-development stage is the obtaining of representative bulk sample for metallurgical testing. Here most massive sulphide deposits prove to be somewhat problematical. Factors,such as the presence of multiple ore bodies, each different from the others, ore body zonation in individual bodies, differences in ore textures and structures between one part of a body and another, together with weathering and supergene alteration,should be considered when a site is chosen for bulk sampling and/or trial mining.

Ore Reserve estimation

Cox (1968) defined ore as ".... a natural aggregate of one or more minerals, which may be mined and sold at a profit or from which some part may be profitably extracted". The emphasis in this and in other definitions of ore is on the profitability of the venture, which implies a reliable measure of the quantity, quality, and amenability of the ore. For this reason ore reserve computations are made during all stages of the life of a mine, from discovery to robbing pillars and closing. As stated by Popoff (1966) reserves are computed to ".... determine the extent of exploration and development; distribution of values; annual output; probable and possible production life of the mine; method of extraction and plant design; improvements in extraction, treatment, and processing; and requirements for capital, equipment, labour, power and materials." From this it is obvious that ore reserve computations are the most fundamental,and the most responsible and irreplaceable tasks performed during the commercial life of a mineral deposit.

The reliability of ore reserve calculations depends principally on the accuracy and completeness of the knowledge of the geology of the ore deposit. This governs the choice of computation method with its implicit assumptions accepted for interpreting the variables; ore boundaries, metal value and distribution, specific gravity, etc.

The specific gravity (S.G.) of an ore is dependent upon the mineral composition and distribution of gangue and ore minerals. For example, in a typical volcanogenic massive sulphide deposit consisting of layered sphalerite (± galena) ore, massive chalcopyrite-pyrrhotite ore, and siliceous stringer ore, each ore type will have a different average S.G. It is obvious that, given identical essays, the pay-metal content per unit volume in the massive ore would be far greater than in the stringer ore, and that it would differ from that of the layered ore, depending on the amount of galena present and/or the amount of interlayered gangue minerals. Dadson (1968) illustrated this problem by referring to a number of examples based on the natural range of specific gravity encountered in massive sulphide deposits (Table 3). He concluded that the specific gravity of a sample is almost as important as the metal assay, and that an average volume-per-ton factor, or an average S.G., for a mine as a whole does not necessarily apply to any of its individual blocks of ore, and almost certainly not to every one of its samples.

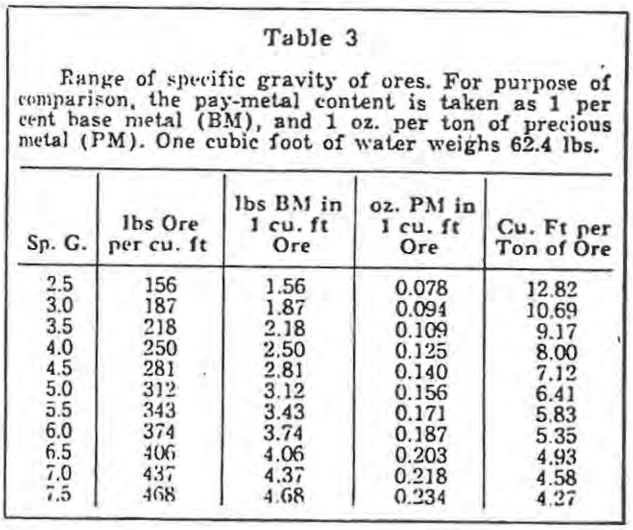


Table 3

Range of specific gravity of ores. For purpose of comparison, the pay-metal content is taken as 1 per cent base metal (BM), and 1 oz. per ton of precious metal (PM). One cubic foot of water weighs 62.4 lbs.

Sp. G.	lbs Ore per cu. ft	lbs BM in 1 cu. ft Ore	oz. PM in 1 cu. ft Ore	Cu. Ft per Ton of Ore
2.5	156	1.56	0.078	12.82
3.0	187	1.87	0.094	10.69
3.5	218	2.18	0.109	9.17
4.0	250	2.50	0.125	8.00
4.5	281	2.81	0.140	7.12
5.0	312	3.12	0.156	6.41
5.5	343	3.43	0.171	5.83
6.0	374	3.74	0.187	5.35
6.5	406	4.06	0.203	4.93
7.0	437	4.37	0.218	4.58
7.5	468	4.68	0.234	4.27

From Dadson, 1968.

The problem of different specific gravities in different parts of the ore body due to ore body zonation is best resolved by weighting each sample not only by the sample length, but also by the S.G. of that specific sample. This can be done by determining the S.G. for every sample in the mine on a routine basis, or less expensively by using an S.G. formula based on the known mineral composition of the ore and on the individual assay value. Söhnge (19) described the derivation and application of such a formula to the complex copper-lead-zinc-silver deposit at Tsumeb, Namibia. This formula (Figure 48) is capable of handling any combination of ore and gangue minerals in the Tsumeb ore body and can easily be adapted to suit the more simple mineralogy of most volcanogenic massive sulphide deposits. It is in fact known from personal experience that a similar formula, based on the sulphur content of individual samples, is used successfully at the Matchless Mine, a volcanogenic, massive pyritic copper-zinc deposit, near Windhoek in Namibia.

Let x = per cent metal in the ore
y = specific gravity of the ore
a = specific gravity of mineral (7·5 for galena)
b = specific gravity of rock (2·8 for dolontite)
c = per cent metal in the mineral (86·6 per cent lead).

Combine n volumes of mineral with one volume of rock:

$$x = \frac{n \,.\, a \,.\, c}{n \,.\, a + 1 \,.\, b}$$

Then $n \,.\, a \,.\, x + bx = n \,.\, a \,.\, c$

and $n \,.\, a(c-x) = bx$

Therefore $n = \dfrac{bx}{a(c-x)}$.

Also, $y = \dfrac{n \,.\, a + b}{n + 1}$

Substituting for n:

$$y = \frac{a \,.\, b \,.\, x + a \,.\, b \,.\, c - a \,.\, b \,.\, x}{bx + ac - ax}$$

$$= \frac{a \,.\, b \,.\, c}{ac - (a-b)x}$$

$$= \frac{\dfrac{a \,.\, b \,.\, c}{(a-b)}}{\dfrac{ac}{(a-b)} - x}$$

or simplified,

$$y = \frac{A}{B - x}, \text{ where } A = \frac{a \,.\, b \,.\, c}{a - b} \text{ and } B = \frac{a \,.\, c}{a - b}$$

Figure 48: The derivation of a specific gravity formula based on the specific gravity of individual minerals and dependent upon the metal assay.
From Söhnge, 1966.

Ore reserve computations can be done by conventional (e.g. Popoff, 1966), statistical (e.g. Koch and Link, 1970, 1971), or geostatistical methods (e.g. David, 1977). "Pure" statistical methods do not seem to be in common usage in volcanogenic massive sulphide deposits, and will therefore not be discussed here.

Due to strong trends inherent in the genesis of volcanogenic massive sulphide deposits, the use of geostatistics in the estimation of ore reserves in these deposits are somewhat suspect. Experimental semi-variograms, as a result, are only valid for small homogenous areas within the ore bodies, i.e. on the scale of single stopes or even only parts of stopes. Should enough data points be available on this scale, a valid theoretical model can be fitted to the experimental semi-variogram. Sample values are then weighted according to the distance between them by means of a "best linear unbiased estimator" obtained through the process of "kriging". This process is described in all the standard works on geostatistics and need not be elaborated here. It is enough to know that in order to use kriging the ore body must be reduced to two dimensions - usually by using a linear measure of grade, e.g. centimetre grams/ton or metre percent - and must be divided into equal blocks. Block values are then assigned within certain statistical confidence limits, and by applying an appropriate S.G. or tonnage factor, can be converted into tonnages and grades. Kriging thus works best on large tabular ore bodies with no significant trends, which effectively rules out most massive sulphide deposits.

Geostatistical ore reserve calculation are done on a routine basis at the Prieska Mine, a volcanic-exhalative massive copper-zinc sulphide deposit, located in the Cape Province of South Africa (Rendu, 1980). The deposit is tabular with a near-vertical attitude measuring 1,8 km along strike and 800 m down-dip, with an average thickness of 9 m. Sampling is done by diamond drilling and by taking chip samples between the hangingwall and footwall along development crosscuts through the ore. Mining is by sublevel, longhole open stoping. Reserves are calculated semi-annually to determine the amount of ore in each stope, incorporating any new data that may have become available; including changes in mining costs and metal prices. The first step in the calculations is to reduce the data to two dimensions. This is done by calculating the average metal values and S.G.'s for each borehole intersection between hangingwall and footwall. The averages are then treated as if they were representative of the ore body at a point halfway down the borehole intersection. Further calculations are then done on a 15 by 15 metre grid on an arbitrary vertical reference plane parallel to the strike of the ore body. To get a measure of the volume of such a 15 by 15 metre block, the distances between the hangingwall and footwall surfaces and the reference plane is obtained by "universal kriging". The average specific gravities and average grades of the 15 by 15 metre blocks centred on grid points are obtained by using "random kriging" (Rendu, 1980). The overall effect of this technique is to "smooth over" any irregularities created by tight parasitic folds, boudinage, and stretching of fold limbs which are features of the high grade metamorphic terrain in which the ore body is located. In fact the strong trends created by these irregularities,and by ore body zonation, are ignored,with the result that ore boundaries are largely unknown. This leads to up to 40% dilution of the ore (Chief Mine Engineer, pers.comm.) due to overbreaking in places, and to the leaving of clean ore behind in others. The problem is further aggravated by sloughing of the side wall formed by the chloritic alteration zone.

To ensure good geological control, most Canadian mines (confirmed by written communications, 1980), prefer conventional methods of ore reserve calculations, and particularly those based on vertical and horizontal cross-sections (e.g. Weeks, 1968; Cairns, 1968; Brooks and Bray, 1968; and Purdie, 1968). The method, described by Popoff (1966), can be easily adapted for manipulation by computer. A common practice is to drill vertical "fans" of holes from underground development at regular intervals, 15 to 30 m. apart. These holes are plotted on corresponding cross-sections and the weighted average assay values are calculated for various grade categories. For example, in Figure 49, a vertical section through the Geco Mine, ore is blocked out according to the combinations of copper and zinc values; denoting "massive" and disseminated" ore. Values carry half-way to the next borehole, the boundary being the acute bisector between the two holes, and also halfway to the adjacent sections according to the "rule of nearest points" (Popoff, 1966). Volumes for each block are thus obtained by multiplying the area of each block by the section interval. Tonnages are derived at by multiplying the volume by a tonnage factor established for each grade category, or in the metric system, by applying an average S.G. for each block.

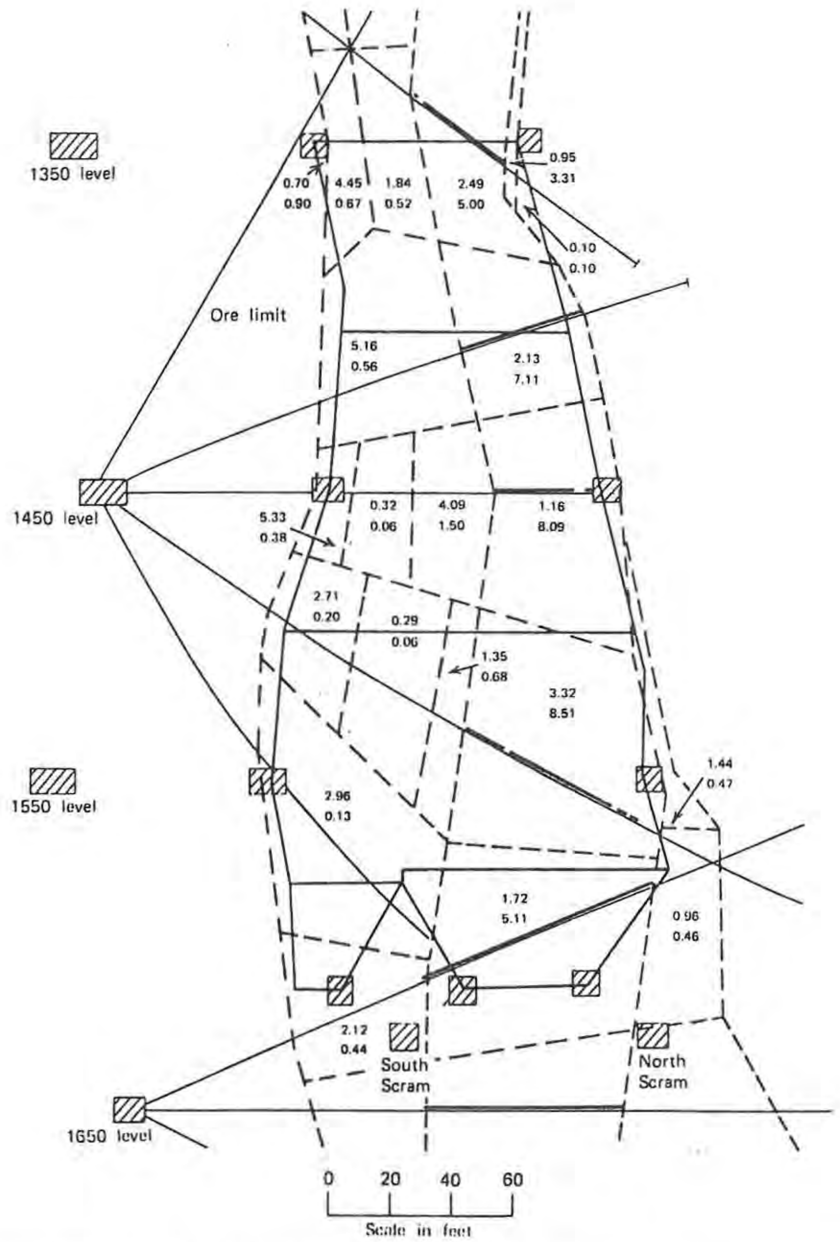


Figure 49: Vertical section through the Geco Mine, Ontario, showing areas of influence assigned to diamond drill holes for tonnage and grade calculations (broken lines). Thick solid lines depict massive sulphides (high grade) and medium solid lines outline mining blocks.
After Brooks and Bray, 1968, from Peters, 1978.

The main advantage of the conventional cross-section method described above, and of other variations of the method (see Popoff, 1966), is that it provides an excellent visual representation of the ore body. Data can be manipulated manually or by computer, and final ore reserves can be adjusted to mining outlines fitted onto the sections for sublevel open stopes (Figure 49), or onto horizontal sections (on a lift-by-lift basis) for cut-and-fill stopes. In this way there is a much closer correlation between predicted and actually mined tonnage and grade. The amount of waste that must be included at nil grade, and the amount of ore that is going to be left behind, is to a major extent known. By accommodating detailed geological interpretation, the cross-sectional method allows the effects of geological factors such as ore body zonation, deformation, and supergene-alteration on tonnage and grade to be considered,and are thus, as far as massive sulphide deposits are concerned, far superior to geostatistical methods as well as to most other conventional methods.

Mining

The role of geology in the selection of a mining method for a specific ore deposit is not discussed in the literature. This is probably because decisions regarding mining methods are taken at corporate management level after the execution of a full feasibility study. These studies involve, apart from geology, also factors like costs, availability of labour and materials, extractibility of the ore, and many others,and are invariably regarded as confidential. However, from the discussion of the geological factors arising from a volcanogenic model, the influence of some of these factors on the selection of a mining method and on the subsequent mining of the deposit, is evident and can be discussed in general.

The size and attitude of the ore body is a result of the mode and duration of ore precipitation and of subsequent structural deformation. These factors obviously govern the selection of a mining method to a large extent. For example, at the very large Kidd Creek deposit (Walker et al., 1975) the combination of factors such as the proximity of a number of sub-vertical, high grade massive sulphide lenses and large disseminated and stringer ore zones,occurring under negligible surficial cover, allowed an open pit operation to be conducted for the upper part of the deposit (Figure 50). Large tabular ore bodies like the Geco Mine (Figure 49) favours the application of sub-level open stoping methods, while small rod-like deposits such as the ones at Stall Lake (Figure 45) probably have to be mined by much more expensive cut-and-fill methods.

Ore body zonation and structural deformation obviously influence the continuity and distribution of the ore and must be kept in mind during mine planning. The Norbec deposit, near Noranda, Quebec (Figure 11) for example, is strongly zoned and as a result was mined in two separate mining blocks (Figure 51). Mining Block 1 consisted of the massive sulphide lense (A-zone) and the higher grade central portion of the stringer or B-zone. Mining Block 2, which was mined subsequent to Block 1, consisted of the remaining lower grade portion of the B-zone. The major portions of both blocks were mined by large open blasthole stopes. The outer fringes were mined by more selective methods in smaller fringing stopes. This strategy ensured a larger income from the high grade material during the early life of the mine when the capital expenditure had to be redeemed. Of even greater importance was that the mill could be set to handle mainly high grade material, and also the majority of the zinc ore. During the second half of the mine life,thus mainly lower grade copper ore was processed. A comparable revenue was however assured due to the lower cost of recovery and lower overhead costs.

Structural deformation of an ore body may be constructive or destructive. Constructive deformation commonly results in an ore body attitude favourable to mining. Examples are sub-vertical tabular bodies like the Geco and Prieska mines, and steeply inclined lenses like the Kidd Creek deposit. Destructive metamorphism commonly affects small or disseminated ore bodies,and through attenuation of fold limbs, boudinage, and/or shearing,creates either a number of en echelon tabular lenses, or a large number of steeply plunging mineralized fold mullions. Problems with ore continuity can be expected during the exploitation of such deposits. Another complication which commonly arises in deformed volcanogenic deposits, is that cross-folding causes flattening and steepening of the ore body plunge. This may interfere with the movement of the broken ore.

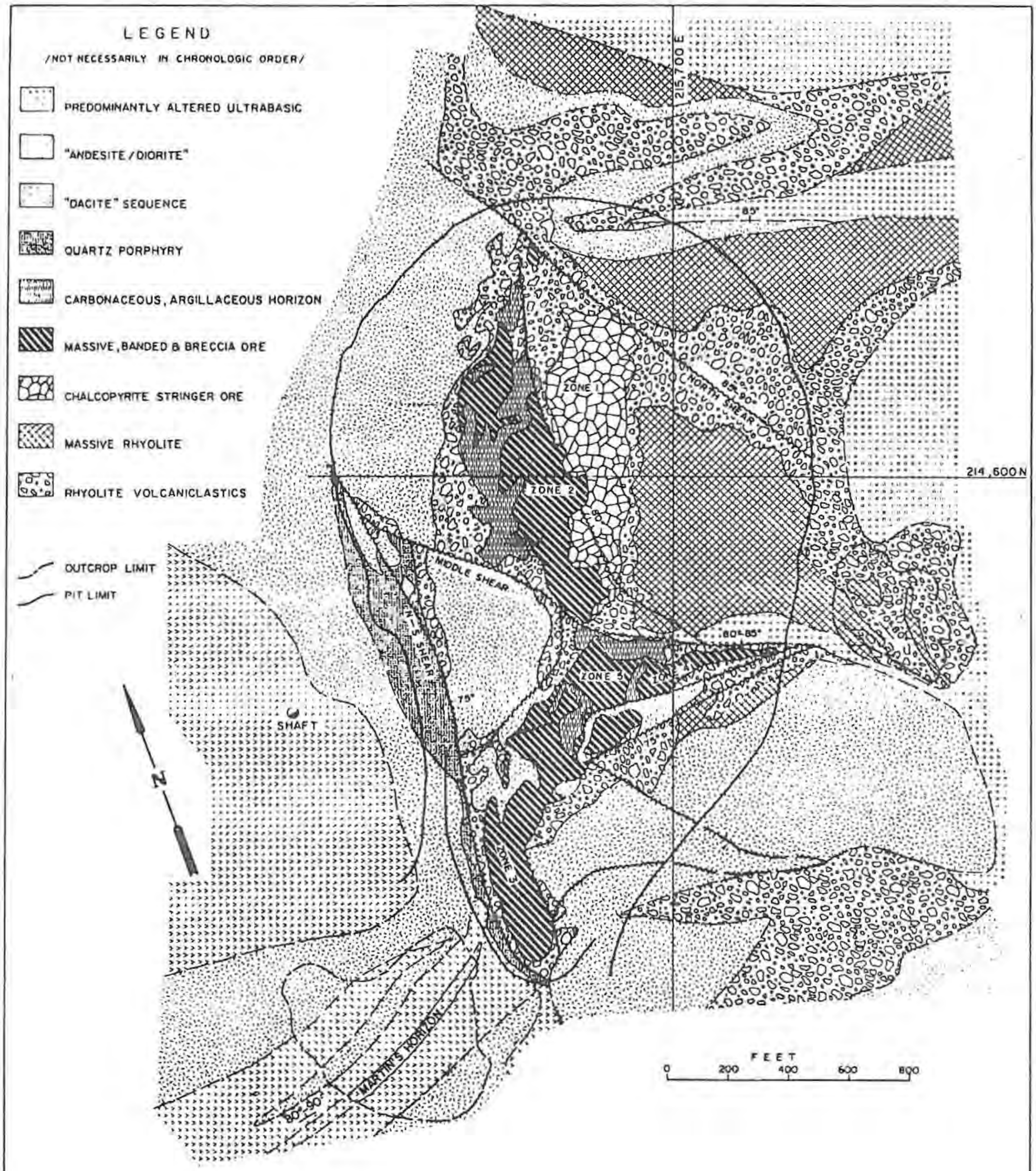


Figure 50: Kidd Creek Mine - surface geological plan and pit limit. From Walker et al., 1975.

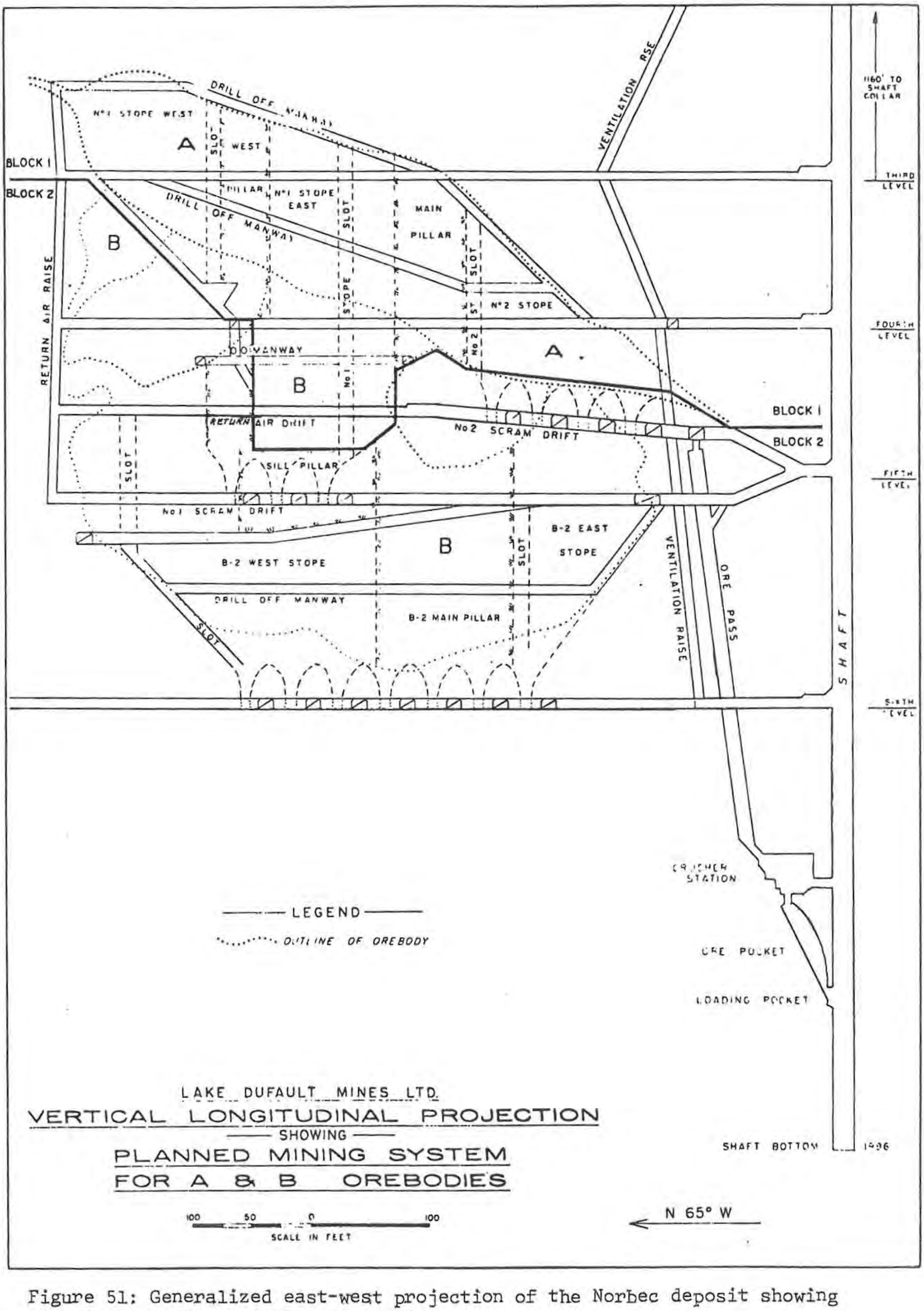


Figure 51: Generalized east-west projection of the Norbec deposit showing the mining outlay and the ore outline.
From Purdie, 1968.

Hydrothermal alteration zones with their associated platy micaceous minerals commonly have adverse effects on rock stabilities. Clay zones surrounding the Japanese deposits obviously affect the mining conditions, but sericite-chlorite zones around Canadian deposits are commonly situated in the footwall and thus are of lesser consequence. In highly deformed areas, however, the stratigraphic sequence can be inverted by overfolding, and bad hanging conditions may exist. These are aggravated when the rocks have been subjected to retrograde metamorphism or to supergene alteration.

Geological factors are thus of paramount importance and can only be neglected or ignored to the detriment of the mining venture.

Ore beneficiation

Ore beneficiation (mineral processing, ore dressing, milling) involves the comminution and separation of ore and gangue into concentrated mineral fractions and "tailings", principally by the processes of crushing, grinding, and froth flotation. Milling practice at major mines in Canada is described at length in a special volume of the Canadian Institute of Mining and Metallurgy (Picket ed., 1978), but unfortunately no details are given of ore characteristics and of their influence on the techniques used. These characteristics - grain size, fabric, mineral composition, etc. - are mentioned by Maeshiro (1979) in a treatise on the milling and smelting of Kuroko ores. He states: "Kuroko is a difficult ore to process because of its multimineral content, fine-grained mineral structure, high content of clay minerals and high susceptibility to surface oxidation." These problems led to the development in Japan of several unique methods of extraction, including the "SO_2 and hot water flotation process" described by Maeshiro (1979).

The degree of "liberation", or release of valuable minerals from gangue minerals during comminution, is a function of the grain size and the fabric of the ore. Fine interlocking grains resulting from coprecipitation, cataclastic deformation, or exolution are difficult to liberate. The very fine grinding necessary to achieve complete liberation, is time consuming and costly, and recovery is poor because the very fine mineral particles lose their individual surface characteristics which make selective flotation possible. The ore is then said to "slime". It is thus necessary to establish the "optimum liberation" size; the size which gives the most economical separation, even though a considerable amount of valuable minerals may still be present as "locked grains" within gangue or non-pay ore minerals, and may be discarded in the tailings. The opposite to this is where metamorphic recrystallization has resulted in a polycrystalline aggregate with a large average grain size and straight mineral boundaries. These ores are said to be "free milling". They are easy to separate, and can be ground to the optimum size required for flotation. Kuroko ores tend to be of the former type, and Canadian ores can be either, or any grading or combination in between. This depends on the regional metamorphic grade and the amount of cataclastic deformation that has affected the ore body.

The nature of the gangue minerals are very important. Micaceous minerals and clays, as well as graphite and talc, which are common in the alteration zones of massive sulphide deposits are inclined to float mechanically. Ore minerals may adhere to the micas, graphite, and talc or may become coated with clay and so be lost into the tailings. Complex intergrowths in the ore may also result from metamorphic growth of acicular or platy minerals. These may cause both liberation and flotation problems.

Flotation depends essentially on the surface properties of individual minerals. Most minerals are hydrophyllic (water wetted), but can be selectively coated with a chemical compound so that they become hydrophobic. In a flotation cell a mixture of hydrophyllic and hydrophobic minerals in water is agitated and subjected to a stream of air bubbles blown in from the bottom. Hydrophobic minerals attach themselves to the bubbles and float to the top where they are collected. Hydrophyllic minerals can be tapped at the bottom. The upper size limit of the grains lifted, depends on the size of the bubble, the stability of the froth, and the S.G. of the mineral being floated. It is thus possible to achieve separation of a complex copper-lead-zinc ore by using various reagents to alternately activate and suppress mineral phases in a multistage flotation circuit. Here the presence of incipient surface oxidation of the mineral grains, caused by deep weathering along faults, or by exposure to the air on a stockpile, etc., may cause special problems. When accompanied by the formation of sulphate, common in the presence of pyrrhotite, oxidation impedes or prevents flotation because mineral-reagent complexes formed are unstable, and tend to scale off. Incipient oxidation in the presence of pyrrhotite is especially problematical in copper-zinc ores. Copper minerals, due to the high electronegativity of Cu, break down and go into solution. The copper ions released, react with the surface of sphalerite grains and form layers of CuS. These layers react readily with the xanthate used for copper sulphide flotation, and as a result, a large amount of the zinc minerals is floated off with the copper.

It is evident even from this very brief discussion that a thorough knowledge of the composition, texture and fabric of the ore is necessary before beneficiation can be attempted. Chen and Petruk (1980) recently made a study of the mineralogy of the feed, concentrates, and tailings of the Heath Steele mill in New Brunswick, Canada. They determined the liberation and recoveries of major ore minerals, and characterized the occurrence and distribution of trace elements. The New Brunswick deposits are of Paleozoic age and are Cu-Pb-Zu-Ag deposits, somewhat similar to the Kuroko deposits of Japan. The study by Chen and Petruk showed beyond a doubt that the ore was not ground fine enough at Heath Steele. They established experimentally that grinding to -500 mesh would greatly enhance the liberation and recovery of sphalerite and chalcopyrite which were lost to the tailings as locked grains. Silver recovery would also be enhanced since some of the silver, which occur as inclusions and as interstitial grains, would become liberated with finer grinding. The behaviour of trace elements, both deleterious and valuable, was established. These usually occur with the same minerals, i.e.: Ag, Sb, and Bi in tetrahedrite-tennantite; Co and As in pyrite, arsenopyrite,and cobaltite; and Cd, In,and Hg in sphalerite. Consequently, Ag, Sb, and Bi; Co and As; and Cd, In,and Hg are inseparable in the milling circuits. Thus, the environmentally toxic contributors (As, Hg) cannot be separated from the base metal sulphides. These either go to a concentrate (Hg in Zn) or are pumped onto the tailings (As in pyrite). A thorough mineralogical study thus enhances the effectiveness of the beneficiation process, and at the same time warns of potential pollution hazards. These can then be controlled by the application of appropriate anti-pollution measures.

CONCLUSION

Volcanogenic massive sulphide deposits are important sources of copper, zinc, lead, silver, gold, and other valuable trace elements. They belong to a distinct class of mineral deposit characterised by certain morphological and genetic features.

The size, shape, and metal distribution and concentration are controlled by geological factors which are inherent in the genesis of volcanogenic deposits. These factors, which include primary structural and lithologic control; mode, rate, and duration of metal precipitation; ore body zonation; wall rock alteration; metamorphism and deformation; and supergene alteration, are controlled by the interaction of physical and chemical parameters in the depositional, metamorphic, and weathering environments. A conceptual model based on these parameters and the resulting geological controls, are fundamental in the understanding of these deposits. These factors effectively place "geological confidence limits" into the interpretations and predictions made during ore body delineation, evaluation, and exploitation. Ore reserve estimation procedures which accommodate strict geological control (e.g. cross-section methods) are thus far superior to statistical and geostatistical methods. These place computations within certain "statistical confidence limits", but are incapable of testing the validity of the geological interpretations on which they are based.

A conceptual model, based on theoretic considerations and tested by field observations, also provides grounds for the early prediction of possible problems that could arise during mining and ore dressing. These can be investigated in time and be conpensated for in the mine and mill designs, thereby preventing later adverse effects on the profitability of the venture.

Geological investigation and control should thus be a continuing process throughout the life of the deposit and can be neglected only to the detriment of the mining venture.

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