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Ore Deposit Models – 8. Volcanogenic Massive Sulphide Deposits Part I: A Descriptive Model

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Introduction

Viewed from both the economic and scientific perspectives, volcanogenic massive sulphide deposits occupy a unique position of importance among mineral deposit types. Economically, deposits of this type are a major source of copper, zinc, lead, silver and gold, and a range of by-products including tin, cadmium, antimony and bismuth. For example, of the total production from Canadian mines during the period 1977-78, about 30% of the Cu, 63% of the Zn, 27% of the Pb, 58% of the Ag and 8% of the Au was obtained from volcanogenic massive sulphide deposits. From the scientific point of view, problems related to the characterization and genesis of these deposits have attracted the attention of geoscientists more than those of any other deposit type, with the result that in the last twenty-five years more than five thousand articles directly related to volcanogenic massive sulphide deposits have been published. Over the last few years, the flames of scientific, and to some extent economic and political, interest have been further fanned by the discovery of high temperature (350°C) hydrothermal vents on spreading ridges of the eastern Pacific Ocean that are actively precipitating metal sulphides with many similarities to volcanogenic massive sulphide deposits.

With such a history of scientific interest in the subject, even this relatively brief and generalized account of volcanogenic massive sulphide deposits must to some extent constitute a review of the literature, but at the same time, because of its brevity, must be highly selective in its content.

An ore deposit model can be considered to consist of two components. One of

these is a descriptive model which embodies those features of the geological settings, morphology, chemistry, mineralogy, zoning, etc. judged to be characteristic of the deposit type. The descriptive model therefore can be considered to be an idealized example of the deposit type scaled down in degree of detail and complexity from the actual examples on which it is based. The other is a genetic model, which attempts to give a rational and consistent explanation of the characteristics of the deposit type in terms of known or postulated geological processes.

The present article deals only with a descriptive model for volcanogenic massive sulphide deposits. A forthcoming article (Part II) will discuss aspects of genetic models for this ore deposit type. In both articles, emphasis is on generalization and the use of Canadian examples. For more detailed and extensive reviews of the descriptive and genetic models the reader is referred to Franklin *et al.* (1981); Ohmoto and Skinner (1983); Klau and Large (1980); Finlow-Bates (1980); Sangster and Scott (1976); Solomon (1976); Gilmour (1976); Lambert and Sato (1974); Hutchinson (1973); and Sangster (1972).

Terminology

Volcanogenic massive sulphide deposits belong to the larger class of concordant massive sulphide deposits that includes all massive or semi-massive sulphide deposits formed by the discharge of hydrothermal solutions onto the seafloor. Although a complete spectrum of types is represented (Gilmour, 1976), the great majority of individual concordant massive sulphide deposits are readily classified into one of two major groups defined by the chemical, mineralogical, morphological, textural, grade and tonnage characteristics of the deposit itself. However, in naming these major groups, emphasis has been placed on the most common lithologies of the host rocks. Over one part of the spectrum are the *sedimentary exhalative, sediment hosted, or shale hosted* stratiform massive sulphides, which include such famous deposits as Sullivan, Broken Hill, Mt. Isa and Rammelsberg. Over the other part of the spectrum are the *volcanogenic, volcanic-associated, volcanic hosted, or volcanophile massive sulphides*, which are the subject of this article. Many authors correctly object to the term *volcanogenic massive sulphides* because it implies that the deposits themselves are an integral part of the volcanic process, which does not appear to be the case. Rather, they seem to be the product of a specialized type of hydrothermal system that is only occasionally developed in a submarine volcanic environment. However, the term *volcanogenic massive sulphide* has such

wide usage, it is debatable whether it should be dropped. For convenience, the acronym VMS will be used here.

Geological Setting and Distribution

VMS deposits typically, if not exclusively, occur within geological domains which can be defined by the presence of submarine volcanic rocks. Although the immediate host rocks to the deposits are most commonly of direct volcanic origin, such as lavas or pyroclastics, or of indirect volcanic origin, such as volcanoclastics, other sedimentary marine lithologies with no volcanic affiliation, such as shales or greywackes, are by no means rare.

There does not appear to be any preferred tectonic environment for VMS deposits except that, like the submarine volcanic rocks themselves, they are more commonly formed near plate margins (Sillitoe, 1973; Sawkins, 1976). Thus VMS deposits are found at divergent plate margins (ophiolite-associated deposits) which may reflect mid-ocean ridges or spreading backarc basins (e.g., deposits of Cyprus and Baie Verte area, Newfoundland); at convergent plate margins in island arcs or continental margins (e.g., Kuroko deposits of Japan and Spanish-Portuguese Pyrite Belt); associated with intra-plate oceanic islands (Aggarwal and Nesbitt, 1984); and of course in more enigmatic plate tectonic environments such as those represented by Archean greenstone belts.

It is also evident from the above that, since plate tectonic environments are most commonly diagnosed by the petrochemistry of the associated igneous rocks, VMS deposits are not confined to any particular petrochemical type of volcanic rock (Klau and Large, 1980). It has been suggested that there is a preferential association of VMS deposits with the most differentiated phases of a calc-alkaline magma (e.g., Sangster and Scott, 1976; Solomon, 1976). In some cases the importance of calc-alkaline host rocks may have been exaggerated due to confusion over the distinction between real calc-alkaline trends and "pseudo-calc-alkaline" trends superimposed on tholeiitic rocks by the laterally extensive hydrothermal alteration commonly associated with areas of VMS deposits (MacGeehan and MacLean, 1980). In order to scientifically test whether or not VMS deposits are preferentially related to a specific petrochemical type, their spatial distribution should be normalized to number of occurrences per unit area of outcrop of each petrochemical type of volcanic rock. To the author's knowledge, this has never been done.

There also does not appear to be any preferred time distribution for VMS deposits, which range in age from about 3.5 Ga in the Pilbara Block of Australia to the

modern sulphide deposits of the East Pacific Rise. Hutchinson (1973) pointed out that there are definite age span groupings for VMS deposits which, as Sangster (1980a) observed for Precambrian deposits of North America, correspond to periods of deposition of thick, supracrustal accumulations, and should not be considered as marking unique metallogenic phenomena. Therefore, again, it is more than likely that these age-frequency peaks would disappear if the number of deposits were normalized to area of volcanic outcrop of given age ranges.

However, there is no doubt that within submarine volcanic domains of the same age and petrochemical type there is a strongly preferred spatial distribution of VMS deposits. For example, 83 economic VMS deposits are known in 2.65-2.73 Ga volcanic belts of the Canadian Shield, but only two are known in compositionally similar volcanic belts of the same age in Australia (Franklin *et al.*, 1981). Similarly, on a smaller scale within a single volcanic belt or domain, VMS deposits are not evenly distributed. For example, out of the nine essentially similar volcanic complexes identified by Goodwin and Ridler (1970) in the Abitibi Belt, only four contain significant VMS deposits. Characteristically, within most volcanic domains VMS deposits tend to occur in spatial groups or clusters, separated from one another by lithologically similar rocks that may contain only a few, isolated, small VMS deposits. Sangster (1980b) calculated that the average area occupied by a typical cluster was about 850 square kilometres, equivalent to a circular area of about 32 km in diameter, and that it contained an average of 12 deposits and 94 million tonnes of ore.

Within each cluster most of the deposits tend to occur within a single stratigraphic interval, which occupies only a fraction of the total stratigraphic interval occupied by the host volcanic edifice as a whole. This most productive stratigraphic interval is often referred to as the *favourable horizon*, and it is particularly evident in the Noranda (Spence and de Rosen-Spence, 1975), Matagami (Roberts and Reardon, 1975; MacGeehan, 1978) and Bathurst (Davies, 1980) areas of Canada and the Green Tuff Belt of Japan (Lambert and Sato, 1976). Figure 1 illustrates the case in the Noranda area, where it can be seen that a large proportion of the deposits occur close to a single stratigraphic horizon. This concentration of VMS deposits in such a small stratigraphic interval is even more remarkable if one takes into account that below the stratigraphic interval illustrated in Figure 1 there are more than 16,000 m of both felsic and mafic volcanic rocks that contain no evidence of VMS deposits (Franklin *et al.*, 1981).

Within the stratigraphic confines of the favourable horizon and the lateral confines of a cluster, the localization of individual VMS lenses seems to be strongly related to structural controls in the substrate and positive or negative topographical features of the ocean floor (see below). Sangster (1972) and Scott (1978) noted that the distribution of deposits in the Noranda and Hokuroku mining camps, respectively, appeared to be controlled by sets of linear fractures. Solomon (1976) deduced that 50 per cent of VMS deposits are spatially associated with felsic volcanic rocks, and even in areas of dominantly mafic volcanic rocks, the VMS deposits themselves show a propensity of association with rhyolite domes or felsic fragmental rocks. Knuckey (1975) suggested that many of the individual ore lenses of the Millenbach mine, Noranda, as well as the rhyolite domes and their feeder dykes, with which some but not all ore lenses are spatially related, are associated with synvolcanic faults with vertical displacements. In a more general perspective, Hodgson and Lydon (1977) proposed that many VMS deposits are associated with the fracture systems produced by resurgent calderas or subvolcanic intrusions.

Cumulatively, the evidence cited above does not suggest a simple relationship between VMS deposits and submarine volcanism *per se*. If VMS deposits were simply a direct and integral product of submarine volcanism, then possibly a more or less uniform stratigraphic distribution

of the deposits, combined with a preferred spatial association with volcanic vents, could be expected for every submarine volcanic edifice of a specific petrochemical type. Instead, there is obviously a very selective distribution of VMS deposits which, regardless of the petrochemical magma type, occur only in a minority of submarine volcanic edifices. Furthermore, within these mineralized edifices VMS deposits tend to be relatively common. In contrast to the lack of distinct control by petrochemical type of volcanism, the spatial relationship of the deposits to synvolcanic faults, rhyolite domes or topographic depressions, caldera rims or subvolcanic intrusions, suggests that the deposits are closely related to particular hydrologic, topographic and geothermal features of the ocean floor that only infrequently combine to give the specific configuration that is necessary to form VMS deposits.

Architecture of VMS Deposits

The idealized architecture of a VMS deposit is depicted in Figure 2. The typical deposit consists of a concordant lens of massive sulphide, composed of 60 per cent or more sulphide minerals (Sangster and Scott, 1976), that is stratigraphically underlain by a discordant stockwork or stringer zone of vein-type sulphide mineralization contained in a pipe of hydrothermally altered rock. The upper contact of the massive sulphide lens with hanging wall rocks is usually extremely sharp, but the lower contact is usually gradational into the

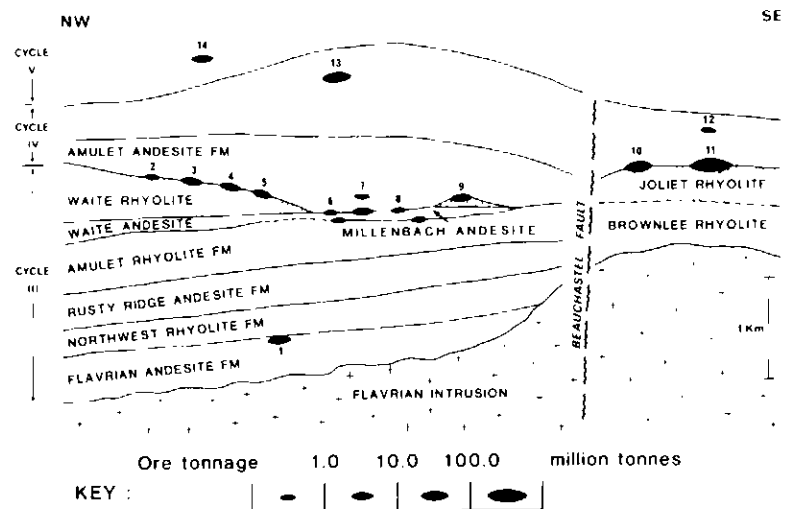


Figure 1 A schematic composite section of the Noranda massive sulphide district, showing stratigraphic relationships in the upper part of the Blake River Group and the stratigraphic positions of major VMS deposits (After Spence and de Rosen-Spence, 1974; Knuckey *et al.*, 1982; Knuckey and Watkins, 1982). Cycles refer to the andesite-rhyolite volcanic cycles of

Spence and de Rosen-Spence, 1975. Key to deposits: 1 - Corbet; 2 - Vauze; 3 - Norbec; 4 - E. Waite; 5 - O. Waite; 6 - Amulet C and F; 7 - Amulet Upper A and Lower A; 8 - L. Dufault No. 1; 9 - Millenbach; 10 - Quemont; 11 - Horne; 12 - Delbridge; 13 - W. MacDonald (Mine Gallen); 14 - Mobrun

stringer zone. A single deposit or mine may consist of several individual massive sulphide lenses and their underlying stockwork zones. The conventional interpretation is that the stockwork zone represents the near-surface channelways of a submarine hydrothermal system and the massive sulphide lens represents the accumulation of sulphides precipitated from the hydrothermal solutions on the sea floor above and around the discharge vent. The characteristics that are illustrated in Figure 2 represent the simplest configuration, in which no complications, such as syndepositional slumping of the massive ore away from its stockwork zone, are taken into consideration.

The morphology of a single massive lens ranges from that of a steep-sided cone to that of a tabular sheet. The majority of cone-shaped deposits appear to have accumulated on the top or flanks of a positive topographic feature, such as a rhyolite dome in the case of the Millenbach deposit, whereas the majority of sheet-like deposits,

such as the Brunswick No. 12 deposit, appear to have accumulated in topographic depressions. Most Canadian deposits have undergone penetrative deformation, so that in extreme cases a deposit may have been stretched into a pencil-shaped body, with the stockwork zone transposed to a position of apparent lateral conformity with the massive sulphide lens.

By far the most common sulphide mineral in the massive sulphide lens is pyrite. Pyrrhotite, chalcopyrite, sphalerite, galena and, more rarely, sulphosalts and bornite comprise the subordinate sulphide species. The most common non-sulphide metallic minerals include magnetite, hematite and cassiterite. Of the gangue or associated minerals that may occur as co-precipitates with the sulphides are quartz, chlorite, barite, gypsum and carbonates.

Textures and structures of the ores are very variable. In the least metamorphosed deposits the massive ore is usually a fine grained mosaic of sulphide grains which increase in coarseness with increasing meta-

morphic grade. In the cone-shaped deposits, massive, rubbly or brecciated textures tend to predominate in the central part of the lens, whereas silt- to boulder-sized sulphide fragments form an apron of clastic sulphide rock that often exhibits spectacular sedimentary structures around the periphery of the lens. Regularly layered or laminated sulphides are more typical of the sheeted deposits. Textures and structures of the most metamorphosed and deformed massive sulphide lenses are more aptly described as gneissose.

Perhaps the most diagnostic features of VMS deposits are the pronounced zonations of chemistry, mineralogy and textures of the ores and the metasomatic changes to the host rock within the hydrothermal alteration pipe. The most obvious and consistent of these zonation patterns is the systematic decrease in chalcopyrite/(sphalerite + galena) ratios, or more simply and conveniently, the Cu/Zn ratio, upwards and outwards from the core of the alteration pipe and the base of the massive

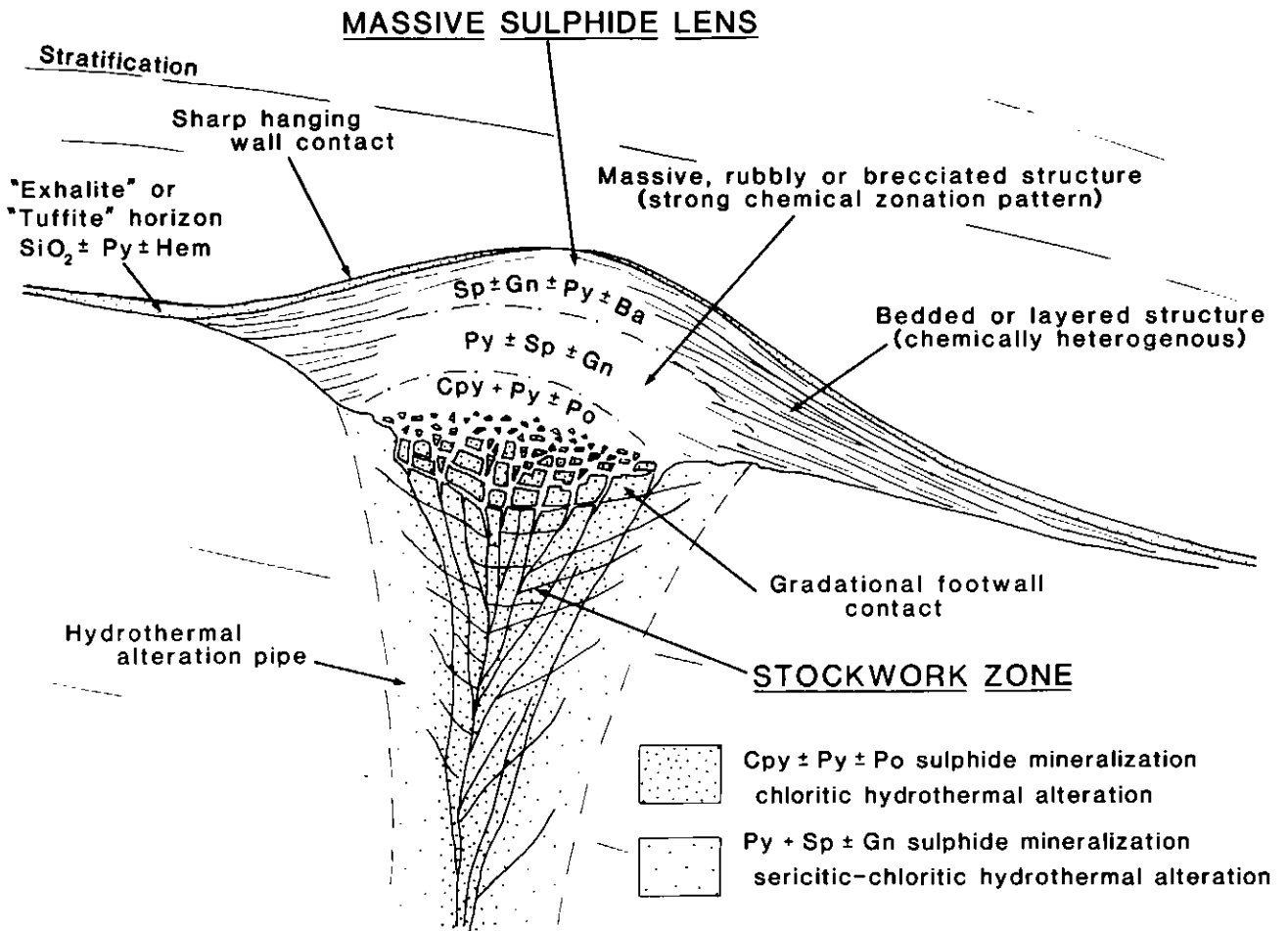


Figure 2 Essential characteristics of an idealized volcanogenic massive sulphide deposit

sulphide lens (Fig. 2). Of the other metallic minerals, pyrrhotite, magnetite and bornite (if present) tend to be concentrated in the core of the stockwork zone and central basal part of the massive sulphide lens, corresponding to the zone of highest Cu/Zn ratios. Barite, when present, generally occurs with the greatest sphalerite and galena concentrations in the outermost zone of the massive sulphide lens. Pyrite, though generally ubiquitous throughout the sulphide zonation pattern, tends to achieve its maximum modal relative proportion where sphalerite becomes predominant over chalcopyrite. In many cases a thin, bedded, pyritic or hematitic, siliceous *exhalite* or *tuffite* horizon forms a veneer over the top of the sulphide mound and extends as a stratigraphic marker laterally away from the deposit. This sedimentary horizon is thought to largely represent chemical precipitation from the waning stages of hydrothermal activity during volcanic quiescence. In some deposits there is a spatial association of magnetite-hematite iron formation (e.g., Bathurst, New Brunswick area) or manganese oxide formation (e.g., Iberian pyrite belt), with clusters of VMS deposits. These widespread metal oxide sediments usually occur somewhat stratigraphically higher than the favourable horizon, but the exact genetic relationship between the sulphide and oxide deposits is not clearly understood.

Hydrothermal Alteration of Host Rocks

Within and surrounding the stockwork zone there is generally a pronounced zonation in the intensity and type of metasomatism produced by the hydrothermal alteration of the host rocks, which to some extent corresponds to the abundance of the sulphide veining. The most detailed documentation of metasomatic effects has been recorded for deposits of the Abitibi Belt. At the Millenbach (Riverin and Hodgson, 1980; Knuckey *et al.*, 1982) and Corbet (Knuckey and Watkins, 1982) deposits of the Noranda area, the alteration pipes consist of inner chloritized cores surrounded by sericitized peripheries. The chloritic core is characterized by major additions of iron and magnesium and by depletions of calcium, sodium and silicon, reflecting the destruction of the feldspar component of the original felsic or mafic volcanic rock during the process of chloritization. Potassium tends to be depleted in the chloritic zone but is enriched in the surrounding sericitic zone. Otherwise, the metasomatic changes of the sericitic zone are less intense gradational continuations of those of the chloritic core zone. This gradational change, reflecting mainly a change in intensity of metasomatism from the "fresh" footwall rocks inwards to the core of the alteration pipe, gives the

impression that the complete zonation pattern is due to a single metasomatic gradient imposed by the ore-forming solution. In this connection it is interesting to note that Riverin and Hodgson (1980) pointed out that the same metasomatic zonation pattern occurs in the alteration selvages of individual sulphide veins in the stockwork zone of the Millenbach deposit. An extreme form of this metasomatic progression may be the talc-actinolite assemblage described by Roberts and Reardon (1978) at the Mattagami Lake deposit, which these authors suggest was formed as a result of the removal of a major amount of Al by the hydrothermal solutions.

A similar configuration of a sericitic halo to a chloritic core is reported for other deposits in the Abitibi Belt (Lickus, 1965; Sakrisson, 1966; Spitz and Darling, 1973, 1975). Elsewhere in the world, chloritization of the central part of the hydrothermal alteration pipe is the most common form of alteration, and for many deposits this core is surrounded by an outer zone of potassium enrichment, though the main potassic mineral is not necessarily sericite (e.g., Walford and Franklin, 1982; Rui, 1973; Lydon, 1984). In deposits that have been metamorphosed above the stability of chlorite, the major magnesium and iron addition to the alteration pipe is reflected by a cordierite-anthophyllite assemblage in the core zone, as in the Flin Flon-Snow Lake (Froese, 1969; Whitmore, 1969; Walford and Franklin, 1982) and Manitouwadge (Pye, 1960; James *et al.*, 1978) areas of Canada and the Kvikne mines of Norway (Morton, 1972).

A strong silica metasomatism is characteristic of the upper part of the alteration pipe of some deposits, particularly the Kuroko deposits of Japan (Shirozo, 1974; Urabe *et al.*, 1983) and the VMS deposits of Cyprus (Lydon, 1984). Silica, and chlorite also form the predominant non-sulphide fraction of the massive sulphide lens, and occur as cross-cutting veins, as a matrix cement to sulphide grains or as distinct lithological lenses. This silica and chlorite, and in some cases even talc (Costa *et al.*, 1983; Aggarwal and Nesbitt, 1984), represent hydrothermal minerals whose components were supplied directly by the hydrothermal solutions. In considering metasomatic processes, these hydrothermal precipitates must be distinguished from similar minerals whose modal increase is due to the redistribution of components of the host rocks during hydrothermal alteration (e.g., the release of quartz during chloritization of a plagioclase feldspar).

Generalizations about wall-rock alteration beyond this point do not seem warranted at this stage of scientific accomplishment, as the documentation and understanding of wall-rock alteration associated with VMS

deposits is one of the areas that require much more research. There are many documented examples in which the alteration mineralogy of the stockwork alteration pipe clearly departs from the "normal" chloritic core and sericitic periphery. At the Mattabi mine, for instance, the main alteration minerals of the feeder pipe are siderite, chloritoid and andalusite, with chlorite and sericite occurring only as irregularly distributed pods (Franklin *et al.*, 1975), but in this case the footwall succession itself is unusual in that it consists of a thick sequence of epiclastic rocks containing 10%-15% dolomite.

A relatively recent development that has important consequences for mineral exploration is the increasing recognition that in several mining areas a laterally widespread zone of rock alteration occurs stratigraphically below the favourable horizon. In the Mattabi-Sturgeon Lake area, the footwall epiclastic horizon appears to have been depleted in sodium over an outcrop area some 8 km long and 1 km wide (Franklin *et al.*, 1975). In the Snow Lake area, a conformable alteration zone at least 2 km long and several hundreds of metres thick is marked by a staurolite- and chlorite-bearing rhyolite, reflecting a regional sodium depletion and magnesium and/or iron enrichment (Walford and Franklin, 1983). In the Matagami Lake area, MacGeehan (1978) and MacGeehan and MacLean (1980) concluded that all but the uppermost part of the footwall basaltic sequence had undergone a regional alteration involving addition of silica and sodium, and depletion of iron, magnesium, calcium, titanium, zinc and copper, resulting in secondary albite and epidote-quartz mineral assemblages. These authors noted that the elements mobilized by this regional alteration were exactly those that were enriched in the stockwork alteration zone of the Garon Lake deposit. In the Noranda area, Gibson *et al.* (1983) found that the Amulet Rhyolite formation, which occurs immediately below the most favourable ore horizon, in large part actually consists of mafic flows and flow breccia that have undergone regional alteration consisting of intense silicification in its upper part and epidote-quartz and chlorite-sericite alteration at progressively lower horizons. Gibson (1979) noted that the alteration involved the mobilization of aluminum, iron, magnesium, titanium and zinc, which are those elements that have been enriched in the alteration pipes of the Millenbach deposit.

This continuity of the stockwork alteration pipe into zones of regional alteration serves to complicate the definition and understanding of different metasomatic events. In the Kuroko deposits, Shirozo (1974) and Ijima (1974) distinguished only a single quartz-sericite-chlorite alteration zone im-

mediately underlying the deposits and enclosing the stockwork zone, but described surrounding concentric alteration zones, defined on clay and zeolite assemblages, that continue into the hanging walls of the deposits. Hanging wall alteration has been described for other deposits. With the present state of knowledge it is not possible to make a generalized statement as to whether most of this hanging wall alteration is due to the continuation of the same ore-forming hydrothermal activity after deposition of the hanging wall rocks to the main sulphide body, as in the case of the Corbet deposit (Knuckey and Watkins, 1982), or whether it is due to anomalous effects of normal groundwater circulation in the vicinity of the geochemically and mineralogically anomalous zones of an ore deposit during its long post-depositional burial history, as in the case of some deposits in Cyprus (Lydon, 1984).

Classification

Most proposals for the classification of VMS deposits have placed emphasis on the geotectonic setting or immediate foot-wall lithology of the deposits, rather than on characteristics of the deposits themselves. Sillitoe (1973) distinguished those deposits that formed at spreading centres and usually had high Cu/Zn ratios from those formed in island arc or continental margin settings that usually had relatively elevated concentrations of Pb, Zn, Ag and Ba. Sawkins (1976) recognized three main types of VMS deposits: 1) Kuroko-type, occurring in felsic, calc-alkaline volcanic sequences of Archean to Tertiary age at sites of plate convergence in ocean areas; 2) Cyprus-type, occurring in low-potassium basaltic volcanic rocks in the upper part of ophiolite complexes at sites of plate spreading; and 3) Besshi-type, occurring in clastic sediments and mafic volcanics but

with no clear-cut plate tectonic setting. However, in general, plate tectonic theory does not account for many of the genetic aspects of mineral deposits (Sangster, 1979).

Klau and Large (1980) used host-rock lithologies as a basis for classifying VMS deposits into deposits associated with: 1) felsic volcanic rocks in Archean greenstone belts; 2) post-Archean calc-alkaline and tholeiitic volcanic sequences; and 3) mafic volcanic rocks. They noted that deposits of similar chemical characteristics overlapped these three divisions. Hutchinson (1973) proposed a three-fold classification of VMS deposits based on their major ore element chemistry: 1) Zn-Cu-types occurring in fully differentiated magmatic suites of tholeiitic and calc-alkaline affinities and predominantly of Archean age; 2) Pb-Zn-Cu-types in intermediate to felsic calc-alkaline volcanic rocks and predomi-

Table I Average grade and tonnage data for volcanogenic massive sulphide deposits of selected areas

Area	Dominant Deposit Type	No. of Deposits	Average Grade and Tonnage						
			Cu %	Zn %	Pb %	(*)	Ag g t	Au g t	million tonnes
Abitibi Belt, Canada	Cu-Zn	52	1.47	3.43	0.07	(47)	31.9	0.8	9.2
Norwegian Caledonides	Cu-Zn	38	1.41	1.53	0.05	(0)	N.A.	N.A.	3.5
Bathurst, N.B., Canada	Zn-Pb-Cu	29	0.56	5.43	2.17	(28)	62.0	0.5	8.7
Green Tuff Belt, Japan	Zn-Pb-Cu	25	1.63	3.86	0.92	(7 ^a)	95.1	0.9	5.8

Notes

- (*) Number of deposits for which data available to calculate average Ag and Au grades.
- (a) Average Ag and Au grade for Green Tuff Belt is average of 27 individual lenses from 7 different deposits.

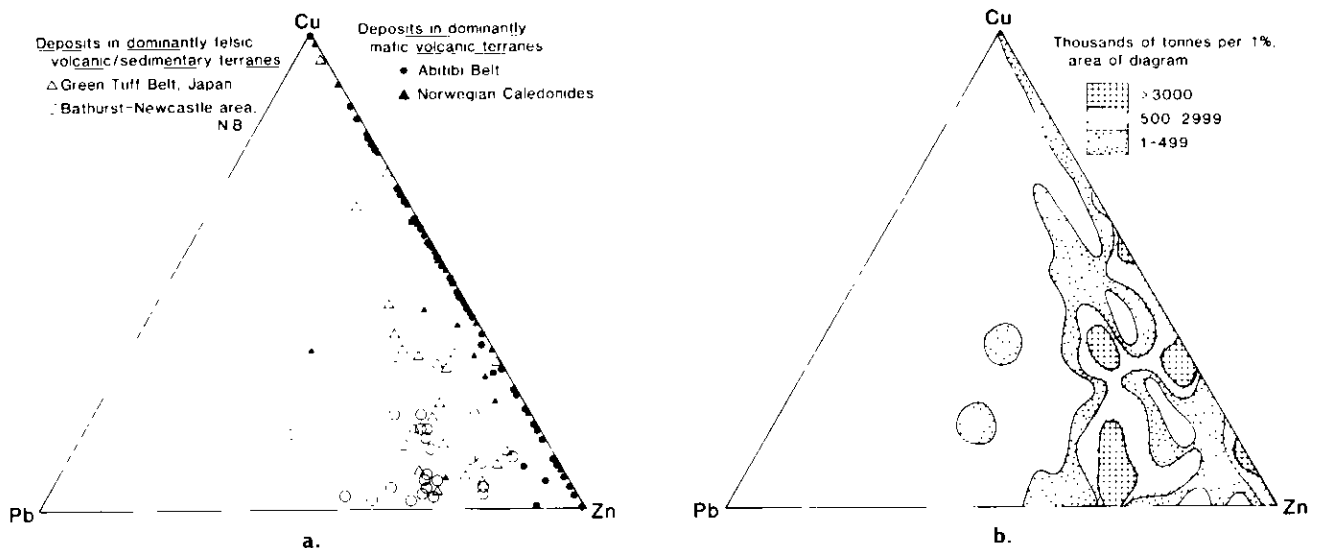


Figure 3 Cu-Zn-Pb ternary diagrams for bulk compositions of VMS deposits of Abitibi Belt, Bathurst area, New Brunswick, Norwegian Caledonides and Green Tuff Belt, Japan, as reported in the literature.

a) Individual mines

b) Data of Figure 3a contoured for thousands of tonnes of contained Cu + Zn + Pb per 1% area of plot

nantly of Phanerozoic age; and 3) Cu-types in poorly differentiated ophiolitic or tholeiitic suites of Phanerozoic age. Solomon (1976) used a very similar classification of 1) Zn-Pb-Cu-types; 2) Zn-Cu-types and 3) Cu types, the terminology reflecting the order of relative abundance of the major ore metals in the deposits.

Classification of VMS deposits according to their major ore-element chemistry seems to be the most satisfactory method. Using VMS deposits of the four major metallogenic provinces of the Abitibi Belt, Bathurst-Newcastle area, New Brunswick, Norwegian Caledonides and the Green Tuff Belt, Japan (Table I) as a representative sampling of the VMS class as a whole, Figures 3 and 4 show that two major groups can be distinguished on the basis of bulk Zn/(Zn + Pb) ratios of the deposits. These two groups are termed the Zn-Pb-Cu type and Cu-Zn type, respectively, the terminology reflecting the major ore metal associations. These two groups are not readily obvious from a visual inspection of a Cu-Zn-Pb ternary diagram showing only the distribution of bulk compositions of individual deposits (Fig. 3a), but are easily distinguished if each point is weighted in terms of the tonnes of ore metal contained in the deposit and the points contoured for tonnes of contained ore metal per unit area of the diagram (Fig. 3b). The same is true for histograms showing the frequency-distribution of Zn/(Zn + Pb) ratios of individual deposits (Fig. 4a) compared to a similar diagram showing the amount of contained metal per Zn/(Zn + Pb) ratio division (Fig. 4b). These diagrams show that, by far, most of the ore is contained in VMS deposits that have a bulk Zn/(Zn + Pb) ratio of either between 0.70 and 0.80 (the Zn-Pb-Cu type) or greater than 0.95 (the Cu-Zn type). Deposits outside of these limits contain only a small proportion of the total ore, and hence can be considered to be unusual. An apparent merging of the two groups is to be expected for several reasons, not the least being that because of the strong ore metal zonation characteristic of the deposit type, incomplete preservation, or only partial economic viability of the original complete geological mineral deposit, would bias the metal ratios of the economic ore deposit that have been used in constructing the diagrams.

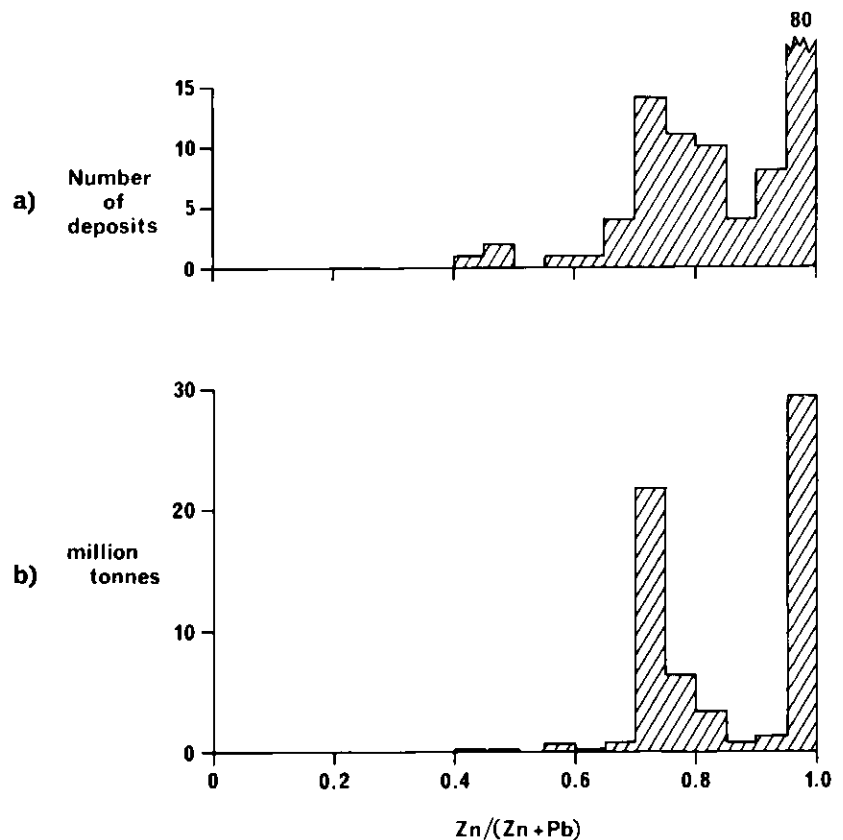
This classification of VMS deposits into just two major compositional groups is thus similar to that proposed by Hutchinson (1973) and Solomon (1976), except that a Cu-type is not recognized and no affiliation to any particular geotectonic setting, volcanic petrochemical suite, or age is assigned to either group. The elimination of the Cu-type is quite justified when it is noted that most deposits which plot near

the Cu apex of the Cu-Pb-Zn ternary diagram owe their position more to the economics of mining than geology when, especially for low grade deposits, the less valuable zinc and lead contents may have been ignored in reporting reserves. For example, none of the Cyprus deposits, often regarded as prime examples of the Cu-type, are devoid of sphalerite, and in some cases Zn contents greatly exceed those of Cu (Lydon, 1984). Most of the deposits described as Cu-types should be considered to belong to the Cu-Zn group.

That this division of VMS deposits into two major groups based on Zn/(Zn + Pb) ratios reflects a natural grouping is emphasized by the high degree of correlation with other features of the deposits. For example, barite as a significant gangue mineral is confined to deposits of Zn-Pb-Cu type; Au/Ag ratios of the Cu-Zn type are usually higher than those of the Zn-Pb-Cu type (Table I); sulphur isotope ratios of the two types clearly form two populations, with ratios of the Cu-Zn type generally being significantly lighter (Fig. 5).

Perhaps the most significant correlation, especially from the point of view of genetic

modelling, is the strong relationship between the deposit type and the dominant lithology for 1 km – 5 km stratigraphically below the deposit. Deposits of the Cu-Zn type occur where the dominant regional footwall lithology is mafic volcanic rocks or their direct sedimentary derivatives, whereas deposits of the Zn-Pb-Cu type occur where the regional footwall succession is composed of dominantly felsic volcanic rocks or mica/clay-bearing sedimentary rocks. Obviously, a corollary to this statement is that deposits of the same mining camp are of the same type. For example, non-intrusive rocks of the Abitibi Belt are comprised of about 70% mafic volcanic rocks, 24% sedimentary rocks (dominantly clastics derived from volcanic rocks), and 6% felsic volcanic rocks (Goodwin and Ridler, 1970). Of the 52 major VMS deposits that occur in the Abitibi Belt, 50 are clearly of the Cu-Zn type (Fig. 3). Similarly, in the Bathurst-Newcastle area of New Brunswick, planimetric measurements of a 1:250,000 scale map (Map NR-3, New Brunswick Department of Natural Resources, 1974) indicates that non-intrusive lithologies of the Tetagouche



Volcanogenic Massive Sulphides

Figure 4 a) frequency distribution of VMS deposits plotted in Figure 3a as a function of bulk Zn/(Zn + Pb) ratio of individual mine

b) Cumulative tonnes of ore metals contained in VMS deposits plotted in Figure 3a as a function of bulk Zn/(Zn + Pb) ratio of individual mine

Group are composed of 53% sediments, 32% felsic volcanics and 15% mafic volcanics. All the VMS deposits of the area are of the Zn-Pb-Cu type. The significance of this correlation will be discussed in Part II.

Conclusion

Volcanogenic massive sulphide deposits are synvolcanic accumulations of sulphide minerals that occur in geological domains characterized by submarine volcanic rocks. The deposits are composed of iron sulphides with subordinate amounts of chalcopyrite, sphalerite and galena. Typically, a deposit consists of a stratiform lens of massive sulphide containing the bulk of the mineralization and a discordant zone of stockwork type sulphide mineralization within hydrothermally altered rocks of the stratigraphic footwall.

The deposits are not confined to a single plate tectonic environment, to a particular petrochemical type of volcanism, or to any particular geological time span. They are not essential products of submarine

volcanism, but are the result of special hydrologic, geothermal and topographic conditions of the ocean floor.

The typical economic deposit may consist of several individual massive sulphide lenses or stockwork zones and contains 1 million tonnes to 10 million tonnes of ore with an average grade of 2%-10% Cu + Zn + Pb. The largest deposits contain in excess of 100 million tonnes of ore. Deposits tend to occur in clusters forming a mineralized district on average 32 km in diameter, and within each cluster individual deposits tend to occur within a single stratigraphic interval.

Characteristically, VMS deposits show a pronounced zonation of ore, gangue and hydrothermal alteration minerals outwards and upwards from the core of the stockwork zone and the base of the massive sulphide lens. VMS deposits are best classified into just two major groups, called the Cu-Zn type and Zn-Pb-Cu type, respectively, which reflects the associations of major ore metals and other geological characteristics.

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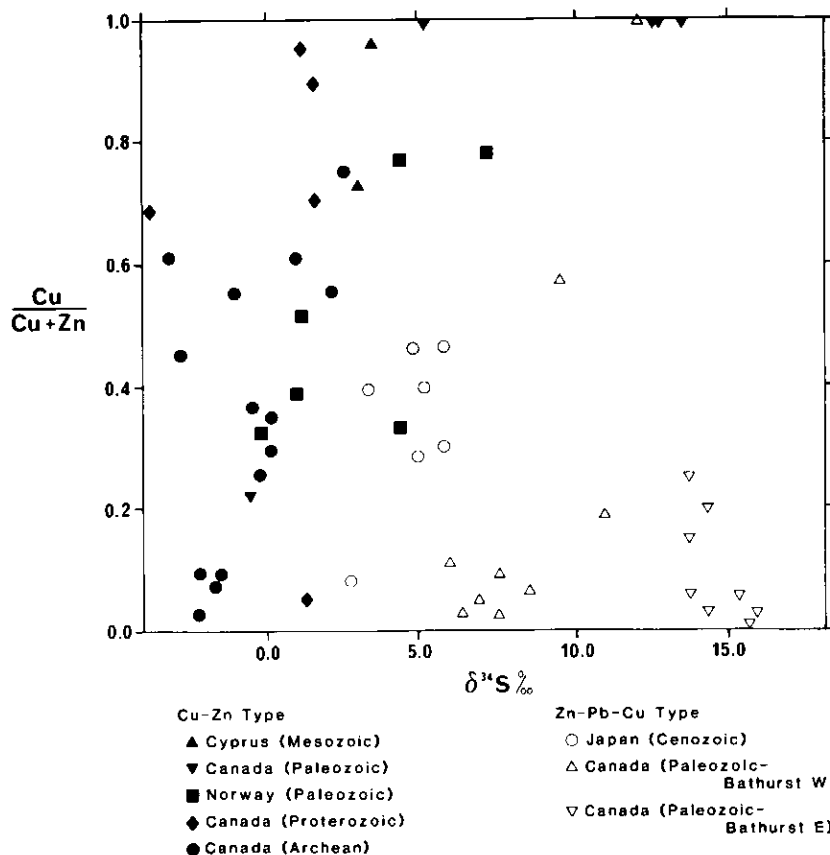


Figure 5 Average sulphur isotope ratios of pyrite from the massive sulphide lenses of VMS deposits plotted against the bulk Cu/(Cu + Zn) ratio of the deposit, showing a clear separation of the two major compositional groups. Sulphur isotope

data compiled from the literature. A minimum of three samples from each deposit was used to derive the arithmetic average for the sulphur isotope ratio

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