

3 VHMS CONCEPTUAL MODEL AND EXPLORATION GUIDELINES

3.1 VHMS CONCEPTUAL MODEL

3.1.1 Introduction

There appears to have been relatively little exploration effort made to locate VHMS deposits in Southern Africa, with a few notable exceptions such as in the central zone of the Damara belt and the Barberton and Murchison greenstone belts. Probably almost no application of the lithogeochemical approach to exploration for these deposits has ever been undertaken. It is believed that much more exploration effort has been put into the more variable biggertonnage Sedex-model family of base-metal deposits. A full understanding of both the VHMS and Sedex conceptual models in the mid-1970s came at a time of peak activity in exploration. These exploration activities were especially concentrated in the Proterozoic northwestern Cape terrain, where after a waning interest in sustained base metal exploration in South Africa was seen. In addition, EM technology has since advanced considerably from the mid-1970s (Cain, 1994).

Falconbridge initiated lithogeochemical exploration programmes in the greenstone belts of Botswana (Tati and Matsitama) from 1978 to 1981 and Zimbabwe (Bulawayo, Gatooma-QueQue-Hartley and Bindura-Shamva) from 1980 to 1982 with the primary focus on gold rather than VHMS deposits (Cain, 1994). Funds were in extremely short supply with Falconbridge, especially for VHMS exploration, and budget cutbacks were frequent. No long-term initiatives to apply and test the Canadian approach on a grass-roots basis were really possible.

The Murchison Cu-Zn deposits in the Limpopo Province, some AAC prospects in the Barberton greenstone belt of Mpumalanga, the closed Prieska Zn-Cu mine of the Northern Cape, the Cactus Cu-Pb-Zn mine in Zimbabwe and Elbe and Ochiase in Namibia, appear to be the only deposits in Southern Africa indicated as VHMS deposits. Their apparent paucity is in strong contrast to favourable geological environments. This suggests that a more pro-active exploration effort for VHMS deposits is warranted, because they are an important source of zinc (Cain, 1994).

3.1.2 Regional Setting

The Archaean Canadian and Palaeozoic (Caledonide) Norwegian VHMS deposits occur in submarine, predominantly mafic volcanic piles, e.g. greenstone belts and ophiolite-type successions (viz. Besshi and Cyprus subfamily).

Brunswick No 12 (Bathurst), British Columbia, Buchans (Newfoundland) and true Japanese Kuroko deposits also occur in submarine volcanic sequences, which comprise of bimodal mafic to felsic compositions, on continental crust; with marine sediments usually comprising more than 40% of the total succession. Mineralisation in VHMS deposits is always a result of sub aqueous exhalation, commonly by 'black smokers', of metal-rich hydrothermal solutions derived from fractionation of predominantly calc-alkaline magmas.

VHMS deposits occur throughout the geological record as:

- 'Primitive' Archaean greenstone-belt-hosted types (mainly the younger aged belts of circa 2,7 Ga, e.g. Abitibi belt of Canada);
- Proterozoic, Palaeozoic and Mesozoic types, less common; and
- Cainozoic, modern island-arc types, typified by true Kuroko-style deposits, very common in Circum-Pacific or Alpine tectonic terrain.

Primary features of VHMS deposits include (Figure 6):

- Massive ore 'lenses' (A zone) underlain by carrot-shaped, tapering 'stringer' ore zones of variable character (B2 zone);
- Characteristic depositional structures and textures; mineralogical and metal zoning;
- Alteration with constant geometric form is ubiquitously developed in immediate footwall of massive or in stringer ore as crosscutting pipe-like zones (B1 zone); and as
- Extensive stratigraphic conformable zones (C zone) on a huge (often tens of kilometres strike) scale parallel to the sea floor. These different stratigraphic layers can range from altered highly permeable layers (C zone) to the thin exhalite layer directly above the massive sulphide lens.

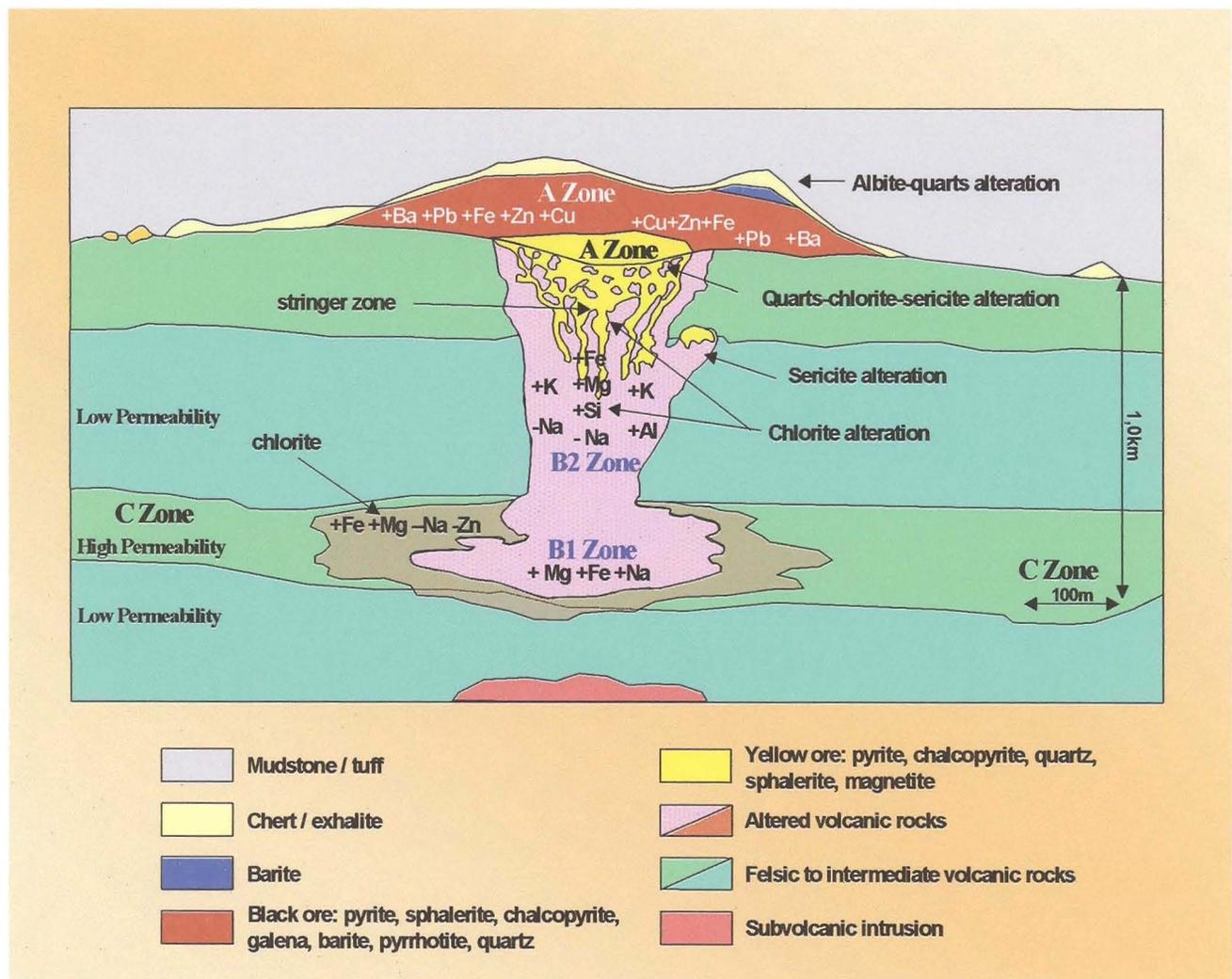


Figure 6. VHMS conceptual model (modified after Large et al, 2001)

These features may often be modified by subsequent metamorphic episodes and polyphase deformation, which impart secondary ore textures and affect metal distribution and shape (Franklin *et al.*, 1981 and Vokes, 1969).

3.1.3 Tonnage and Grade Considerations

VHMS deposits are an important source of the world's base metals, especially zinc (Appendix B). A short summary of typical average tonnage and grades of VHMS deposits are listed in Table 2.

Table 2. Average and median tonnage and grade of VHMS deposits (Cain, 1994).

Country	Region	Size Mt.	Zn %	Pb %	Cu %	Ag g/t	Au g/t
CANADIAN	Abitibi belt [n = 52]	9,2	3,43	0,07	1,47	31,7	0,81
	Bathurst camp [n = 29]	8,7	5,43	2,17	0,56	60,03	0,47
WORLD	(2) MEDIAN 50 percentile	1,5	2,0	0,0	1,3	13,0	0,16
	10 percentile [n = 432}	18,0	8,7	1,9	3,5	100,0	2,3

As in the case with MVT base-metal deposits, the VHMS family is not characterised by large tonnages on the whole. It does, however, like MVT deposits, also often occur in clusters. Unless a fairly systematic and meticulous approach is adopted with respect to its detection (and exploitation), there is always the possibility of smaller orebodies being 'missed', as clustering is common laterally – with deposits occurring in 20 to 40 km diameter range at a specific stratigraphic level/horizon. Vertical stacking of smaller deposits is also known; this being fairly common in Falconbridge's Millenbach mining district (Riverin and Hodgson, 1980 and Cain, 1994).

3.2 COMMON EXPLORATION GUIDELINES FOR VHMS DEPOSITS

The common, more important broader guides for locating VHMS deposits, mostly applied in conventional exploration, are discussed in the following paragraphs under the relevant subheadings.

3.2.1 Tectonic Controls

Lydon (1984) suggested that preferred geotectonic environments for VHMS deposits are near plate margins. Ophiolite associated deposits may reflect mid oceanic ridges or spreading back arc basins at divergent plate margins for example the deposits of Cyprus and Newfoundland. The Kuroko deposits of Japan and the Spanish-Portuguese pyrite belt, on the other hand, are associated with convergent plate margins in island arcs and continental margins. Intra-plate oceanic islands or more enigmatic plate tectonic environments also host deposits, such as those represented by Archean greenstone belts (Lydon, 1984). With the above-mentioned statements, is it essential to recognise geochemical associations related to extensional tectonism in continental areas.

A magmatic heat source is necessary below each complex to start the convecting seawater system. Deposits occur in clusters near subaqueous volcanic vents and/or 'black smokers'. Gravity can detect vertical tectonic domains in pristine environments. Transform offsets (and triple junctions) may control gross distribution of mineralisation.

At low metamorphic grade the ore bodies are flattened, with plunge:strike ratios often 3:1. At higher grades plunge:strike ratios increase to 10:1 (giving them a small surface area; therefore making them difficult to detect by mapping) (Lydon, 1988).

Detailed studies of metal zoning in deformed bodies, may assist in the understanding of style of mineralisation (e.g. Geco deposit in Canada – possibly

relevant to the Prieska Zn-Cu mine, the Upington belt and Elbe in Namibia) (Stowe, 1983).

It is however important to note that the Areachap Group has undergone upper amphibolite metamorphism and extensive polyphase deformation and late shearing (Stowe, 1983 and Geringer, 1994). This leads to the proposal that the figure of the conceptual model is not a section view, but a plan view for the Areachap area. If this plan view is taken and shearing is added to it, it becomes obvious that target generation may be very difficult (Stowe, 1983).

3.2.2 Tuffaceous Exhalites

'Tetsusekiei' (Kuroko) and the Main Contact Tuff (Noranda) are examples of tuffaceous exhalites occurring on the seabed over a wide lateral area of smokers (Kalogeropoulos and Scott, 1989). Whether these rocks are truly tuffs needs to be questioned, but that there are chemical sediments related to the black smoker process has been observed at the active black smokers (Binns and Scott, 1993). These cherty exhalites 'host' the massive sulphide lenses. Composition can be variable from hematitic (true Kuroko) to pyrrhotitic (Noranda). Silica (sericitic chert) is very common. Silica facies, through to sulphide (pyrite) to carbonate-facies (dolomite) banded iron stone formations are known (Franklin *et al.*, 1981). Thickness varies from millimetre to one-metre proportions in undeformed situations; they are therefore difficult to detect by conventional mapping and may easily be 'missed'. Massive pyrite 'blows' may occur; these being a frequent source of (geophysical, gossans and geochemical) 'red herrings' (Large *et al.*, 2001).

The exhalative horizon comprises an important element in the model geometry mentioned above. The segment forms one of the long arms of a tipped-over letter 'H' (Large *et al.*, 2001).

3.2.3 Ore Mineralogy and Geochemistry

The main ore minerals are sphalerite, chalcopyrite and galena. Pyrite and pyrrhotite (magnetic) are the dominant sulphides with which the ore minerals are associated. Generally the ore contains more Zn than Cu, percentage wise. The orebody can vary from massive, more than 60 % sulphides to stringer ore, which may vary from disseminated to semi-massive in texture.

The by-products: Ag, Au, Cd (Sn, Se, Te and Bi) and also Zn spinel (gahnite) and cassiterite may be important in exploration (in discriminating barren pyritic zones from massive base-metal sulphides in gossans and stream sediments) (Theart, 1985). Barite, gypsum or anhydrite are present in some younger deposits for example the Prieska Zn-Cu mine where rhodonite has been reported (Theart, 1985 and Wagener and Van Schalkwyk, 1986).

Zonation: Massive, banded sphalerite-pyrite-rich ore (\pm pyrrhotite) often overlies chalcopyrite-rich massive (\pm magnetite) and stringer ore. Higher Au and Ag contents are present in the stringer zones (Lydon, 1988).

Pyrrhotite, galena and sphalerite are deformed during deformation, but pyrite tends to remain brittle (Vokes, 1969). A rough positive correlation exists between sulphide granularity and metamorphic grade (Lydon, 1988).

The detection of a Hg halo around Millenbach partially aided in its discovery by lithogeochemical sampling of regional and core samples (Riverin *et al.*, 1980).

3.2.4 Mineralogy and Metamorphism of Alteration Zones

“Rock/water interaction during sub-seafloor geothermal activity causes the congruent dissolution of many major and trace elements from volcanic piles, their transport by hydrothermal fluids and their subsequent precipitation in similar ratios in often more felsic successions”. “Cumulatively, this results in a compositional gap in a typical basalt-rhyolite suite being spanned by a continuum of altered rock compositions” (Lydon, 1988). This is reflected by

changes in gross mineral paragenesis in the footwall successions hosting the VHMS deposits (Large, 1992).

Most host successions to VHMS deposits have undergone stages and grades of metamorphism as a result of their occurrence in plate-margin (end consumptive–beginning extensional/accretive) zones.

Chlorite, sericite, albite, carbonate, anthophyllite, staurolite, andalusite, kyanite, sillimanite, garnet and cordierite are commonly indicative of metamorphosed alteration zones in volcanic and volcanoclastic successions. Precursor hydrothermal ‘conditioning’ is responsible for the predominance of seemingly aberrant aluminous silicate mineralogy (more typical of metapelitic rocks) in volcanic rocks of basaltic to rhyolitic composition – even at low metamorphic grades (Large *et al.*, 2001). At the Prieska Cu Zn deposit, it is suggested that the gedrite bearing felses (comprising in increasing order of abundance: tourmaline, phlogopite, albite and gedrite) represent the metamorphic equivalent of the Mg-Fe rich chlorite core of the alteration pipe (Theart, 1985).

With a trained eye, alteration mineral suites can be recognised in the field or in hand specimens, though this usually requires tedious petrographic investigations.

The interpretation of lithogeochemical sampling and whole rock analysis of major and selected minor and trace elements is a much quicker method of confirming alteration signatures in hydrothermal plumbing systems related to massive sulphide deposition.

3.3 LITHOGEOCHEMICAL ALTERATION CHARACTERISTICS AS A VHMS EXPLORATION TOOL

Much of the contribution to an understanding of the nature of the footwall alteration was based on the Millenbach deposit, initially, and since extended to a working model for all VHMS deposits (Riverin *et al.*, 1980; Kalogeropoulos and Scott, 1989 and Knuckey *et al.*, 1982).

3.3.1 Cross-Cutting Footwall Alteration

Although contact metamorphism associated with a subvolcanic granodiorite intrusion has resulted in a typical rock (e.g. 'dalmatianite' - conspicuous cordierite/anthophyllite clots impart a spotted texture), normative calculations show that the footwall alteration pipe, developed below the Millenbach massive ore, initially had chloritic cores and sericitic margins (Riverin *et al.*, 1980). A decrease in Na₂O and CaO and increases in Fe₂O₃ (total iron) and MgO contents are now recognised as typical in alteration pipes immediately below the ore lens. This signature was also found at the Prieska Cu Zn deposit (Theart, 1995). It forms the shorter arm of the tipped-over letter 'H' in the geometric model mentioned above (Large *et al.*, 2001 and Franklin, 1981).

Detailed lithogeochemical studies of various Superior Province greenstone belts concluded that Na₂O and CaO depletion and Fe₂O₃ and MgO enrichment are the most typical trends in the crosscutting footwall of economic sulphide deposits (Cain, 1994 and Gemmell *et al.*, 1992).

This crosscutting soda-depleted alteration zone can extend far downwards stratigraphically below stringer ore, on average up to 1 km. The base of the tapering feature may mushroom out into an area characterised by soda enrichment associated with chlorite and albite alteration (Large, 1992).

Na₂O content is the most useful indicator of alteration as background levels show little variation with degree of differentiation (2.9-3.8%). A Na₂O content of less than 1% invariably indicates footwall alteration (Large, 1992).

3.3.2 Hanging Wall Alteration

The hanging wall is commonly lacking sulphides and alteration is of a very low intensity compared to footwall alteration (Large, 1992).

Large (1992) summarised the hanging wall alteration as being sericite- and chlorite-bearing alteration showing the same chemical trends as the footwall zones, but to a lesser degree. An example at Mount Chalmers showed that Na₂O decreases whereas MgO and the alteration index increase, as the ore horizon is approached from the hanging wall side.

Rare earth element (*REE*) patterns of altered volcanic may change in hanging wall alteration zones, with negative Eu anomalies and low Zr/Y ratios compared to unaltered volcanics (Large, 1992).

3.3.3 Regional Conformable Alteration

The presences of very extensive stratigraphically conformable regional alteration zones are typical of VHMS deposits. These are related to the presence of aquifer, cap rock, recharge channel, discharge channel and heat source (intrusions) as favourable criteria in mega-cell hydrothermal plumbing systems (Large, 1992).

Extensive zones of soda depletion well into the footwall of the Sturgeon Lake - Mattabi and Confederation Lake deposits probably represent aquifers, which were leached with respect to Na₂O, CaO, MnO and Zn by hydrothermal fluids, as a typical example (Large *et al.*, 2001).

The conformable alteration zones are always sub parallel to the exhalites of Segment A, and they form the other long arm of a tipped-over letter 'H', shown as Segment C in the overlay to Figure 8. The conformable alteration zones seem to average ± 1 km or so below ore-bearing exhalative zone (Large, 1992).

Care needs to be taken with the 'H' model, when interpreting patterns of soda depletion, to distinguish discharge channels (cross-cutting alteration pipes in the immediate footwall of VHMS deposits) from regional conformable alteration zones sub parallel to the stratigraphy (aquifers). This is particularly the case in strongly tectonised terrain where 'rodding' and/or 'pencilling' can occur to total transposition in extreme cases (probably in the Murchison belt where the 'H' becomes totally flat according to Cain, 1994).