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Palaeozoic volcanic-hosted massive sulphide deposits

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EXPLORATION MODEL

Examples

Eastern Australia: Hellyer, Rosebery, Que River, Hercules, Mt Lyell, Woodlawn, Thalanga, Wilga, Currawong, Balcooma, Mt Chalmers. Other major examples include deposits from the Japanese Green Tuff belt (Kuroko deposits), Norwegian Caledonides and Canadian Bathurst Group, N.B.

Target

- Major deposit size: 15–90 Mt.
- Median deposit size: 1–5 Mt.
- Average grade for Cu–Pb–Zn deposits: 1.0% Cu, 12% Zn, 5% Pb.
- High Ag and Au credits: average 120 g/t Ag and 2.0 g/t Au.

Mining and treatment

- Massive sulphide nature limits dilution effect.
- Stringer zones only mined where high-grade or large tonnage (e.g. Mt Lyell).
- Polymetallic nature may cause recovery problems in fine-grained ores.
- Metamorphosed–recrystallised ores are easier to treat.
- Fe content of sphalerite is moderate to high.
- Pyrite content is high.

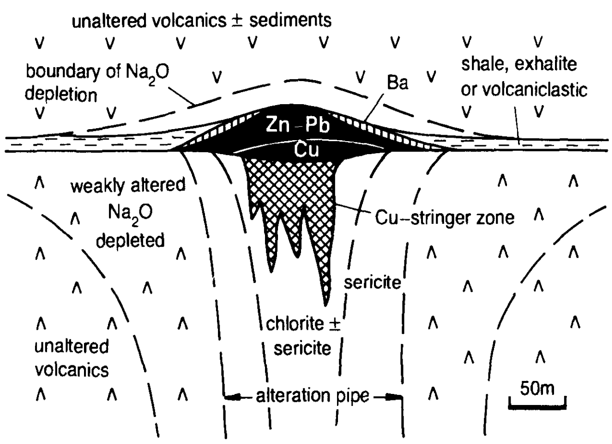

Figure 1. Cross-section of typical mound-style deposit.

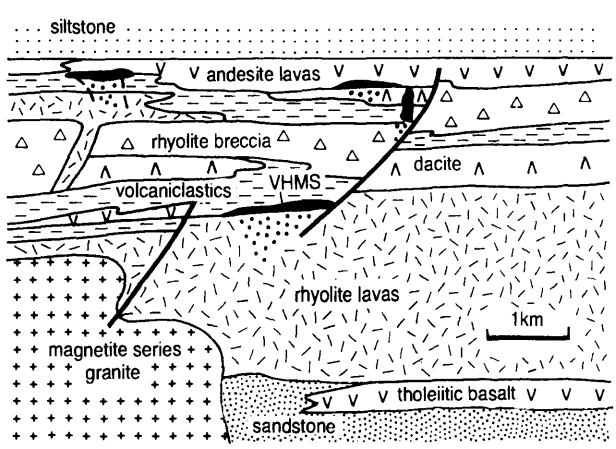

Figure 2. Regional schematic (based on Mt Windsor Province, Queensland).

Regional geological criteria

- Back-arc and inter-arc rift volcanic basins.
- Preferred ages: Cambro-Ordovician and Silurian.
- Calc-alkaline submarine volcanics and sediments.
- Compositional variation: rhyolite–andesite–basalt.
- Proximity to syn-volcanic rift faults.
- Located proximal to volcanic centres (Cu-rich ores) or in distal volcanic facies (Pb–Zn-rich ores).
- Syn-volcanic magnetite-series granites may be present.
- Rhyolite is most common footwall composition.
- Sediment and/or mafic volcanics are most common hangingwall rock types.
- Regional sericite ± chlorite alteration in footwall volcanics.

Local geological criteria

- Ore located in favourable horizon between volcanic units.
- Favourable horizon may be iron-rich exhalite, sulphide-bearing epiclastic, shale or carbonate.
- Ore same age as host volcanic–sedimentary rocks.
- Deposits vary in shape from blankets to lenses, to mounds and pipes.
- Large (1992) recognises ten different styles of VHMS deposits.

Mineralisation features

- Zn–Pb massive sulphide lens is stratiform.
- Massive sulphide may be banded, brecciated or massive and featureless.
- Cu-rich footwall stringer zone is cross-cutting.
- Chlorite, sericite, quartz, barite, carbonate are major gangue minerals.
- Vertical (up-stratigraphy) zonation of Cu, Au→Pb, Zn, Ag, Au→Ba.
- Pyrite is major sulphide mineral plus sphalerite, galena, chalcopyrite ± tetrahedrite, arsenopyrite.
- Magnetite and pyrrhotite are rare except for strongly metamorphosed deposits.

Alteration

- Some deposits have zoned alteration pipes below massive sulphides.
- Stratabound alteration zones are commonly developed in the footwall and extend along strike for 2–6 km.
- Hangingwall alteration is weakly developed or non-existent.
- Common alteration zonation toward ore is ser→ser–py→ser–chl–py→chl–py→qtz–py.

Deposit geochemical criteria

- alteration halo is defined by Na_2O depletion and MgO enrichment.
- Alteration index [AI = $100(MgO + K_2O)/(Na_2O + CaO + MgO + K_2O)$] is vector toward ore (AI = 30–>100).
- Ore 100Zn/(Zn+Pb) = 60 to 80.
- As, Sb, Hg, Tl as trace elements in Zn ores.
- Bi, Te, Mo, Co as trace elements in Cu ores.
- $\delta^{34}S$ sulphides have narrow range, commonly 0 to 15‰.
- Mean $\delta^{34}S$ value is 17‰ less than contemporaneous SW sulphate.
- Pb isotopes form tight cluster for individual deposits that may lie on growth curve or reflect heterogenous U/Th/Pb source area ratios.

- $\delta^{18}O$ depletion haloes approaching orebodies.
- $\delta^{18}O$ and $\delta^{13}C$ indicate majority of ore fluid is seawater.

Surficial geochemical criteria

- Stream sediment anomalies important in discovery of Que River, Woodlawn and Wilga.
- Most deposits have strong Pb soil anomalies.
- Zn and Cu show dispersed soil anomalies.
- Gossans present at Mt Lyell, Mt Morgan, Rosebery, Woodlawn, Thalanga, Balcooma, Mt Chalmers.
- Gossan trace elements: Au, Se, Te, As, Sb, Bi, Cd, In, Tl, Hg, Sn and Ba.

Geophysical criteria

- Regional magnetics define major volcanic units, structures and alteration.
- Regional gravity and magnetics may define position of related magnetite-series granites.
- Ores have no magnetic signature.
- EM important in discovery of Que River, Hellyer, Wilga.
- Most deposits have strong EM responses.
- Cu-rich ores have best EM response
- Zn-rich, Cu-poor ores have a very weak or non-existent EM response.
- IP defines ore zone and pyritic alteration halo.

Fluid chemistry and source

- Ore fluids 200–350°C, 2–10 wt% NaCl
- pH 3–5.5.
- Reduced conditions in ore fluid, $H_2S > SO_4$.
- Metals precipitation by cooling and mixing with sea water.
- Source of fluid: seawater ± magmatic input.
- Source of metal: Zn, Pb, Ag leached from volcanics; Cu, Au may be magmatic or leached.
- Zonation in deposits is caused by zone-refining process as hot fluids pass up through the sulphide mound.

Comments on genesis

- Comparison with black smoker systems substantiates previous conclusions that most VHMS deposits are synvolcanic seafloor deposits.
- Seawater depths of 800–4000 m are necessary to form deposits.
- Models for seafloor sulphide formation:
- sulphide mounds develop above hydrothermal vents and grow by upward zone refining of metals;
- sulphide sheets or lenses may form in seafloor brine pools adjacent to vents;
- synvolcanic sub-seafloor replacement to form stratiform massive sulphides.
- Stringer zones and sulphide pipes form by replacement and/ or vein-fill processes in sub-seafloor hydrothermal vent.
- A less-favoured model invokes syntectonic replacement unrelated to volcanism.

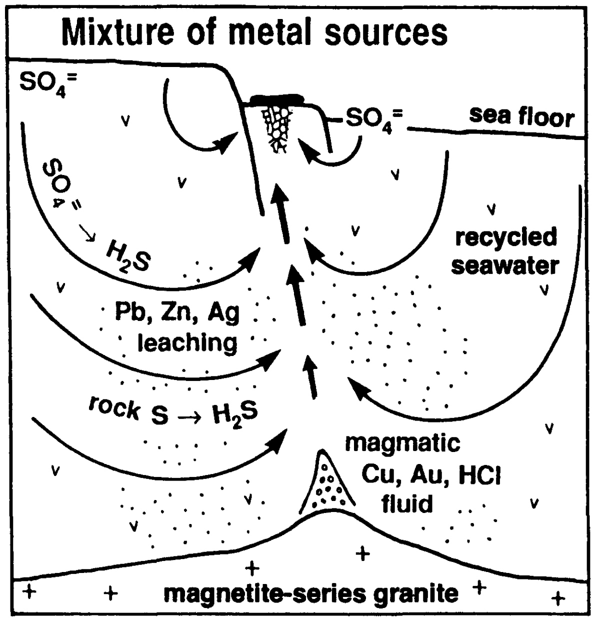

Figure 3. Possible sources of metals for VHMS deposits.

Introduction

Eastern Australian Palaeozoic volcanic-hosted massive sulphide (VHMS) deposits have been a major source of Cu ± Au (e.g. Mt Lyell and Mt Morgan) and a significant source of Pb–Zn–Ag (e.g. Rosebery, Hellyer, Woodlawn and Thalanga) over the last one hundred years. There is a wide range in variability or style of Australian Palaeozoic VHMS deposits, including mounds, pipes, sheets, layered deposits, stacked deposits, stockwork and disseminated deposits, and cyclic layered deposits. Although these various styles show a range of features, there is a consistent theme which strongly suggests that they all belong to the one genetic group of ore deposits.

Distribution and age

Most VHMS deposits in Australia (24 of 30) occur within the Palaeozoic volcanic belts of eastern Australia (Table 1). The major VHMS districts are (1) the Mt Read Volcanics and correlates (Cambro-Ordovician) in Western Tasmania, host to Hellyer, Que River, Rosebery, Hercules and the Mt Lyell deposits; (2) Mt Windsor Volcanics and correlates (Cambro-Ordovician) in Queensland, host to Thalanga, Liontown, Reward, Balcooma and Dry River South, (3) the Goulburn to Cooma volcanic belt (Silurian) in southeastern New South Wales, host to the Woodlawn and Captains Flat deposits, and (4) the Enano Group volcanic sequence (Silurian) in the Benambra district of northeastern Victoria, host to the Wilga and Currawong deposits. In addition to these four volcanic belts, individual deposits occur in the Rockhampton district of Queensland, hosted by the Devonian Capella Creek Beds (Mt Morgan deposit), the Permian Berserker Beds (Mt Chalmers deposit), and the Permian mafic volcanics (Devlin Creek deposit).

Metal content and classification

A classification of VHMS deposits, based on the Cu ratio 100Cu/(Cu+Zn) and the Zn ratio 100Zn/(Zn+Pb), was devised by Solomon (1976). Australian VHMS deposits fall into the following groups:

(1) Cu deposits (Cu ratio >60, Zn ratio >60)—the Mt Lyell deposits, Mt Morgan, Mt Chalmers, Balcooma, Mt Ararat and Reward;
(2) Zn–Cu deposits (Cu ratio <60, Zn ratio 90 to 100)—Wilga, Currawong and Devlin Creek;
(3) Zn–Pb–Cu deposits (Cu ratio <60, Zn ratio 60 to 90)—Rosebery, Hercules, Que River, Hellyer, Thalanga, Liontown, Dry River South, Woodlawn and Captains Flat.

The Zn–Cu-type deposits are restricted to the Silurian, whereas the Cu type and Zn–Pb–Cu type occur sporadically throughout the time span from Cambrian to Permian.

Tonnage and grade

Australian Palaeozoic deposits vary in size from 1 Mt to >90 Mt (Table 1). The most common size range is 2–5 Mt for an individual deposit, but nine deposits exceed that range: Prince Lyell (90 Mt), Mt Morgan (50 Mt), Rosebery (19.4 Mt), Woodlawn (17.7 Mt), Hellyer (17 Mt), Currawong (9.5 Mt), Thalanga (6.8 Mt), Lyell Blow (5.6 Mt) and North Lyell (5.1 Mt) (Large 1992). The polymetallic Zn–Pb–Cu deposits display the best overall grade, with an average of 11.8% Zn, 4.7% Pb, 1.0% Cu, 117 ppm Ag, 2.0 ppm Au. By comparison, the Cu-type deposits average much lower grades of 0.2% Zn, 0.0% Pb, 1.3% Cu, 8 ppm Ag, 1.6 ppm Au.

Nature of volcanic districts

Deposits occur within the submarine portion of volcanic belts that consist of a series of complex volcanic centres with related volcaniclastic and epiclastic facies. Important aspects are:

- The volcanic package enclosing the VHMS deposits is dominated by rhyolite (usually 60–80 per cent of pile) with lesser andesite, dacite, basalt and sediment.
- The mineralised volcanic suite consists of calc-alkaline volcanics.
- The major VHMS-bearing belts have a thick pile of rhyolitic volcanics in the base of the volcanic succession, including lavas, volcaniclastics and subvolcanic intrusives. The rhyolite sequence, which may vary in stratigraphic thickness from 1 to 3 km, either overlies a sedimentary package or its base is obscured by younger intrusive granites.
- Recent studies on physical volcanic architecture of the VHMS districts indicate that the volcaniclastic and epiclastic sequences include porous mass flows, pumiceous sandstone, siltstone, breccia and turbidites (Allen 1992, McPhie & Allen 1992). Peperitic units are also encountered at Mt Morgan and Mt Windsor (Messenger 1994, Doyle 1994).
- A mixed sequence of sediments and volcanics commonly overlies the rhyolite sequence and forms the upper part of the volcanic pile. The volcanics may be bimodal (e.g. rhyolite–andesite at Mt Chalmers), but more commonly exhibit a polymodal character (e.g. dacite, andesite, rhyolite and basalt in the Trooper Creek Formation of the Mt Windsor Volcanic pile).
- Massive sulphide deposits are generally located toward the base of the polymodal volcanic–sedimentary sequence or at the top contact of the basal rhyolite pile.
- In the Mt Read and Mt Windsor volcanic belts there are at least two important stratigraphic levels of mineralisation. In other belts only one mineralised horizon has been confidently recognised.

Form and shape of deposits

Although a complete spectrum of shapes and forms is exhibited by the Australian deposits (Large 1992), it is possible to group them into three main types:

- ***Lens and blanket deposits:*** low aspect ratio with dominant zinc-rich massive sulphide lens and subordinate stringer zone. Examples are Rosebery, Thalanga, Liontown, Dry River South, Woodlawn. Generally these deposits are of the Zn–Pb–Cu and the Zn–Cu type.
- ***Mound deposits:*** high aspect ratio, narrow and elongate massive sulphide with a well-developed stringer zone and alteration system, directly beneath the mound. Hellyer (Zn–Pb–Cu type) and Mt Chalmers (Cu type) are good examples.
- ***Pipe and stringer deposits:*** cross-cutting massive sulphide pyrite–chalcopyrite pipe or stringer zones with little or no stratiform Zn-rich sulphide lenses. Examples are Prince Lyell, Lyell Blow, Highway, Mt Morgan, which all are Cu type and contain significant Au credits.

The regional distribution and the shape of the massive sulphide ores have been related to fluid focusing along syn-volcanic growth faults. In the Mt Read volcanic belt the Mt Lyell, Hercules and Rosebery deposits are located adjacent to structures representing major rift faults associated with the development of the volcanic arc (e.g. Large 1990). On a local scale, syn-volcanic growth faults have controlled fluid movement and the location and shape of deposits such as Hellyer (McArthur 1989), Mt Chalmers (Large & Both 1980), Thalanga and Reward (Gregory et al. 1990, Berry et al. 1992) and Mt Morgan (Taube 1986).

Ore and gangue mineralogy

Considering the diverse morphology and metal ratios, Australian VHMS deposits contain a restricted range of major and minor opaque minerals. In addition to the major phases of pyrite, chalcopyrite, sphalerite and galena, ubiquitous minor phases

Table 1. Total resource, tonnage and grades data for Australian Palaeozoic VHMS deposits over 1 Mt in size (after Large 1992 and Beams 1995).

Deposit	*Age*	*Size (Mt)*	*Cu (%)*	*Pb (%)*	*Zn (%)*	*Au (ppm)*	*Ag (ppm)*	*Status*
Cu type								
Prince Lyell	Cambrian	90.0	0.9	nr	nr	0.3	2.0	Current mine
Mt Morgan	Devonian	50.0	0.7	nr	0.1	4.7	6.0	Past producer
Lyell Blow	Cambrian	5.6	1.3	nr	nr	2.0	61.0	Past producer
North Lyell	Cambrian	5.1	5.3	nr	nr	0.4	33.0	Past producer
Mt Chalmers	Permian	3.6	1.8	0.2	1.0	2.0	15.0	Past producer
Lyell Comstock	Cambrian	2.4	2.4	nr	nr	0.7	5.2	Past producer
Balcooma	Cambrian	2.1	3.3	nr	nr	0.5	19.0	Prospect
Crown Lyell III	Cambrian	2.1	1.4	nr	nr	0.3	4.1	Past producer
Royal Tharsis	Cambrian	1.5	1.5	nr	nr	0.5	2.8	Past producer
Cape Horn	Cambrian	1.4	1.4	nr	nr	0.4	3.3	Past producer
Highway	Cambrian	1.2	5.5	nr	nr	1.2	6.5	Current mine
Crown Lyell OC	Cambrian	1.1	1.4	nr	nr	0.5	3.9	Past producer
Mt Ararat	Cambrian	1.0	2.7	nr	nr	0.6	9.0	Prospect
Zn–Cu type								
Currawong	Silurian	9.5	1.7	0.9	4.3	1.3	38.0	Prospect
Wilga	Silurian	4.0	3.0	0.4	6.2	0.5	23.0	Past producer
Zn–Pb–Cu type								
Rosebery	Cambrian	19.4	0.7	5.0	16.2	2.9	155.0	Current mine
Woodlawn	Silurian	17.7	1.7	3.8	9.9	1.4	80.0	Past producer
Hellyer	Cambrian	17.0	0.3	7.0	13.0	2.3	160.0	Current mine
Thalanga	Cambrian	6.8	2.2	3.9	12.4	0.6	99.0	Past producer
Captains Flat	Silurian	4.2	0.7	6.0	10.0	1.7	55.0	Past producer
Dry River south	Cambrian	3.4	1.0	3.6	10.1	0.7	77.0	Prospect
Que River	Cambrian	3.1	0.6	7.5	13.5	3.4	200.0	Past producer
Hercules	Cambrian	2.6	0.4	5.2	16.7	2.7	159.0	Current mine
Liontown	Cambrian	2.0	0.5	2.3	6.6	0.9	50.0	Prospect

nr—not recorded (generally known to be less than 0.1% in the case of Pb)

are tetrahedrite, arsenopyrite, bismuth sulphosalts, cassiterite and electrum. Magnetite and pyrrhotite occur as major minerals in some Archaean Zn–Cu-type deposits (e.g. Scuddles, Gossan Hill), but are present only as minor minerals (<1 wt%) or are completely absent from the Palaeozoic VHMS deposits. Cu deposits commonly contain molybdenite, bismuthinite, various bismuth sulphosalts, bismuth tellurides and gold tellurides. Zn–Pb–Cu deposits are enriched in arsenopyrite, tetrahedrite, tennantite, boulangerite and bournonite. The dominant non-sulphide/oxide gangue minerals are sericite, chlorite, talc, barite, quartz, and various carbonates. Barite is a common constituent in the upper parts of the massive sulphide lenses of all the Zn–Pb–Cu deposits. Barite is also a common gangue mineral in the Cu-type deposits, where it may be relatively abundant in the upper parts of the Cu-rich pipe and later Zn–Pb lenses (e.g. Mt Chalmers, Large & Both 1980; Reward, Beams et al. 1989). Barite is rare in the Zn–Cu group (e.g. Wilga).

Metal zonation

The upward-zoning sequence from Fe to Fe–Cu to Cu–Pb–Zn to Pb–Zn–Ba is now universally accepted for VHMS deposits (e.g. Sangster 1972, Sato 1972, Large 1977, Solomon & Walshe 1979, Franklin et al. 1981, Eldridge et al. 1983, Huston & Large 1989). Mound-shaped deposits, such as Mt Chalmers and Hellyer, and the thick lenses appear to exhibit the most distinct metal zonation pattern, whereas the blanket and sheet deposits (e.g. Rosebery, Woodlawn, Wilga) show more complex zonation patterns. The Cu-rich pipes and stringer-dominated deposits (e.g. Prince Lyell, Mt Morgan) are poorly zoned.

Alteration

Although the degree, extent, shape and zoning of hydrothermal alteration associated with Australian VHMS deposits are quite variable, there are some distinct patterns which are important for both their genetic and exploration implications. The most significant aspects are that:

- Stratabound or semi-conformable footwall alteration is more common than alteration pipes.
- Alteration pipes, especially those with significant Cu stringer mineralisation, have a central zone of intense chlorite alteration. In some cases silica alteration overprints the chlorite alteration immediately below the thickest

development of massive sulphide (e.g. Hellyer). The sericite/chlorite ratio generally increases outwards so that the chlorite pipe is surrounded by a sericite-rich envelope. Patchy carbonate alteration may extend from the outer edge of the chlorite zone through the sericite zone (e.g. Rosebery, Hellyer, Mt Chalmers).

- Where alteration pipes are not developed, chlorite may be concentrated in restricted conformable zones below Cu-rich lenses (e.g. Rosebery) or as a blanket of alteration below the full extent of the massive sulphide (e.g. Woodlawn).
- Major conformable alteration zones occur in the immediate footwall of most orebodies and are dominated by quartz–sericite ± pyrite alteration with patchy development of chlorite and carbonate. These conformable zones extend 50–200 m into the footwall volcanic package and may extend 2–6 km along strike from the orebody.
- Hangingwall alteration is of very low intensity compared to footwall alteration, is commonly lacking in sulphides, and is best developed above the thickest portions of the massive sulphide body. Weakly developed sericite–chlorite–quartz alteration is the most common form and may be developed 10–200 m above the ore position (e.g. Mt Chalmers, Woodlawn, Rosebery). Pipes or plumes of hangingwall alteration (e.g. Hellyer) may be more common than previously recognised.

A number of studies on the chemistry of hydrothermal alteration associated with Australian VHMS deposits have been undertaken (e.g. Petersen & Lambert 1979, Large & Both 1980, Green et al. 1981, Jack 1989, Gregory et al. 1990, Gemmell & Large 1992, McGoldrick & Large 1992). The consistent geochemical patterns are:

(1) Sodium depletion is the most common feature of footwall alteration. Na_2O content generally decreases from 2–4% in unaltered volcanics to <0.5% in the outer sericite–quartz alteration zone and commonly <0.2% in the chlorite-rich alteration.
(2) The extensive stratabound zones of footwall sericite–quartz ± chlorite alteration are characterised by depletion of Na, Ca, and Sr and sporadic enrichment in K, S, Ba and Sc.
(3) Chlorite alteration as pipes or stratabound zones is also characterised by depletion of Na, Ca and Sr and by enrichment in Mg, Fe, Mn and, possibly, S, Ba, Ti and Sc.
(4) At Hellyer, Gemmell & Large (1992) showed that the best chemical indicators of proximity to the centre of the alteration system are alteration index [($MgO+K_2O$)/($Na_2O+CaO+MgO+K_2O$) ∞ 100] (Ishikawa et al. 1976), which increases from 36 to 91, S (increases from 2 to 8%), Ba (increases from 700 to 2300 ppm) and Sr (decreases from 300 to 20 ppm).
(5) Sericite- and chlorite-bearing hangingwall alteration shows the same chemical trends as the footwall zones, but to a much lesser degree. At Mt Chalmers, Na_2O decreases, while MgO and alteration index increase as the ore horizon is approached from the hangingwall (Large 1992).
(6) REE patterns of altered volcanics may be changed in both footwall and hangingwall alteration systems associated with VHMS deposits (Whitford et al. 1988). The most pronounced changes associated with alteration are the development of negative Eu anomalies and low Zr/Y ratios compared to the primary unaltered volcanics.

Genesis of sulphide mound styles

The model for formation of the classic mound-shaped deposits, which can be applied to Australian examples such as Hellyer, Que River and Mt Chalmers, is based largely on the previous studies by Large (1977), Eldridge et al. (1983), Campbell et al. (1984), Lydon (1988) and Huston & Large (1989). An important aspect of the model is the temperature evolution through time of the hydrothermal system, demonstrated at the Hellyer deposit (Khin Zaw et al. 1996) and the Kuroko deposits (Pisutha-Arnond & Ohmoto 1983), from an early intensifying stage, through a thermal maximum, finishing with a temperature decline. This thermal regime has a critical control on base and precious metal transport and deposition, owing to a strong temperature–solubility relationship for the major ore minerals.

The mound deposits develop from deposition of metal sulphides on the seafloor immediately around the hydrothermal vent. Growth of the mound occurs by upward replacement of sulphide assemblages stable at higher fluid temperatures, leading to zone refining, and deposition of the less soluble Cu minerals in the stringer zone and base of the mound, with more soluble Pb, Zn, Ag and Au minerals in the outer and upper parts of the mound (Large 1992). Immature mounds are commonly small, Pb–Zn-rich and poorly zoned (e.g. Hercules) while mature mound deposits are larger and well zoned with a complete spectrum from Cu-rich ores through to Pb–Zn and Au–Ag-rich massive sulphide (e.g. Hellyer). However, an alternative hypothesis, the brine pool model, has been postulated for the Hellyer deposit by Solomon & Khin Zaw (1997).

Factors which control variations in VHMS deposits

The spectrum of deposit styles and the reason for their departure from the classic mound style are due to variations in a number of factors relating to the chemistry of the ore fluid, nature of the volcanic pile, and the seafloor environment. These factors include the salinity of the ore fluid, the permeability of the footwall volcanics, composition of the footwall volcanics, the temperature of the ore fluid, the fO_2 and aH_2S of the fluid, and the depth of seawater.

Salinity variation and the brine pool model

Sato (1972) suggested that extensive sheet-style deposits may develop from either (a) high-salinity, low-temperature fluids (120°C, >3m NaCl), which, on venting, form a dense brine that migrates downslope to accumulate in a brine pool, or (b) high-temperature, lower salinity fluids (200°C, 2m NaCl), which, on venting, remain buoyant, resulting in dispersal of fine sulphides in the seawater column, which may then accumulate to form a thin metalliferous sediment. Solomon & Walshe (1979) and McKay & Hazeldene (1987) suggested that sheet-like deposits, such as Rosebery and Woodlawn, formed from low-salinity buoyant plumes, which spread laterally in a shallow-water environment, raining down sphalerite and galena to the seafloor. However, evidence from buoyant black-smoker plumes on the modern seafloor (e.g. Scott 1987) indicates that sheet-style massive sulphide deposits are unlikely to accumulate by this process, because of the low efficiency of precipitation and the rapid dispersal of the fine sulphide particles by seawater currents. Another possible mechanism for developing sheet-style VHMS deposits within mixed sediment–volcanic host sequences, is by stratabound replacement of particular favourable sedimentary horizons adjacent to hydrothermal fissure faults.

Permeability of the footwall volcanics

The nature of hydrothermal fluid discharge up through the volcanic pile and onto the seafloor is principally controlled by the permeability of the footwall volcanic package (e.g. Green 1983). Within relatively impermeable volcanic piles, dominated by massive lava flows, significant fluid flow can only be achieved along major fault structures. Under these circumstances, well-focused fault-controlled fluids give rise to well-developed and zoned alteration pipes, with related pipe-shaped, and commonly high-grade, stringer sulphide zones below the massive sulphide mound.

In permeable volcanic sequences, such as those dominated by epiclastics or submarine mass flow breccias, hydrothermal fluid flow would be less focused (e.g. Morton & Franklin 1987) and would permeate the sub-seafloor volcanics to produce widespread stratabound footwall alteration systems overlain by sheet-style or layered-style massive sulphide deposits (e.g. Rosebery).

Composition of footwall volcanics

Volcanic piles dominated by oceanic tholeiitic basalts commonly underlie Cu–Zn-rich and Pb-poor deposits (e.g. Cyprus-type deposits, such as Devlin Creek) and modern deposits along oceanic spreading centres, whereas piles dominated by rhyolite, andesite and/or sediments commonly underlie the Pb–Zn–Cu type of deposits (e.g. Solomon 1976, Hodgson & Lydon 1977).

Temperature control on ore styles

Thermodynamic studies on the solubility of ore metals (e.g. Sato 1972, Large 1977, Ohmoto et al. 1983) and fluid inclusion research on VHMS deposits (Pisutha-Arnond & Ohmoto 1983, Khin Zaw et al. 1996) have clearly demonstrated that temperature has a major control on the metal distribution and metal content of the deposits. Copper-rich deposits, such as Mt Chalmers, Mt Lyell, Mt Morgan and Balcooma are likely to have formed from hydrothermal systems which maintained output temperatures of 270–350°C over a long period of the history of ore formation, compared to Zn–Pb-rich and Cu-poor deposits (e.g. Captains Flat, Rosebery, Hellyer), where ore fluid temperatures in the range 175–235°C were probably more typical of the main phase of mineralisation.

Depth of seawater

Seawater depth is the primary factor which determines whether or not the rising hydrothermal fluid boils before it reaches the seafloor (Haas 1971). No fluid inclusion evidence has been found to support the concept of ore-fluid boiling in Australian VHMS systems. However, the Cu-stockwork style of deposit at Mt Lyell may have formed due to hydrothermal fluid boiling at considerable depth below a shallow submarine or possibly subaerial volcanic environment. An alternative explanation for extensive sub-seafloor stockwork zones, such as Prince Lyell and the Au–Ag stockwork zone at Que River, is that they formed by interaction of hot hydrothermal fluids with particular permeable, seawater-laden, volcanic horizons (Walshe & Solomon 1981, McGoldrick & Large 1992).

Source of sulphur and metals

The consistent parallel variation of sulphur isotope $\delta^{34}S$ ratios in massive sulphide deposits and coeval marine sulphate deposits, noted worldwide by Sangster (1968), is well demonstrated in the Australian deposits and implicates seawater as a major source of sulphur for these deposits. The large amount of sulphur isotope data now available on the VHMS deposits in the Mount Read Volcanics and the Mt Windsor Volcanics shows patterns that can be interpreted to indicate a combination of reduced seawater sulphate and volcanic rock sulphur sources (Green et al. 1981, Solomon et al. 1988, Gemmell & Large 1992, 1993, McGoldrick & Large 1992).

Two alternative sources have been suggested for the metals in VHMS deposits:

- Leaching from the footwall volcanic pile and related basement rocks by heated seawater convecting above a magmatic intrusive or volcanic magma chamber (e.g. Kajiwara 1973, Spooner & Fyfe 1973, Ohmoto & Rye 1974, Solomon 1976, Large 1977, Solomon 1981, Stolz & Large 1992).
- Direct input of a magmatic volatile phase from the magmatic system that is the source of the volcanism (Urabe & Sato 1978, Henley & Thornley 1979, Sawkins 1976, Stanton 1985, 1990).

A cartoon depicting the possible sources of sulphur and metals is shown in the exploration model. The various styles of Australian VHMS deposits may be considered to be members of a genetic spectrum of deposits which varies from those close to the magmatic source or heat engine (e.g. Mt Morgan, Mt Lyell) and, typically, Cu–Au-rich, through the gamut of Zn–Cu and Zn–Pb–Cu styles, to those in mixed volcanic–sedimentary sequences which are well removed from the volcanic/magmatic centres (e.g. Woodlawn, Rosebery, Hercules). Based on geophysical and geochemical evidence, Large et al. (1996) proposed a model for Mt Lyell which involves mixing between deeply penetrating convective seawater, and Cu–Au–P-bearing magmatic fluid released from a shallow Cambrian granite.

Post-depositional metamorphic and deformational effects

The VHMS ores along with the host volcanic piles have been variably metamorphosed from prehnite–pumpellyite facies (Hellyer) to lower greenschist (Que River), through upper greenschist facies (Rosebery), to amphibolite facies (Balcooma and Dry River south). At Rosebery, the Cambrian VHMS deposit has been affected by later metasomatic processes related to Devonian granite intrusions (Khin Zaw et al. 1997, in press). The VHMS deposits are also variably deformed from shearing, faulting and thrusting (Rosebery) to tight folding (Que River). These later effects have increased the Au tenor of ores and metallurgical viability due to remobilisation and recrystallisation of ore constituents. These later effects often generate controversies as to the timing of ore formation, and have led some workers to interpret a metamorphic origin for the Rosebery deposit (Aerden 1994) and pre-, syn-, and post-depositional origin for the Woodlawn deposit (Glen et al. 1995). At Mt Morgan, Arnold & Sillitoe (1989) considered that mineralisation formed by structurally controlled replacement associated with intrusion of the Mt Morgan tonalite. However, research by Golding et al. (1993, 1994) has showed that the Mt Morgan tonalite is younger than the age of mineralisation, and that the volcanic setting of the deposit, its shape, metal content and isotopic systematics are consistent with original volcanogenic mineralisation that has been annealed by thermal events due to intrusion of the Mt Morgan tonalite.

Successful exploration techniques

Before the 1960s, all VHMS discoveries in Australia were based on outcropping gossans or mineralisation. Of the ten major discoveries since the 1960s, five relied heavily on electromagnetics (Wilga, Currawong, Que River, Hellyer, Dry River South), two on geochemistry (Woodlawn, Reward) and two on geology/gossan outcrops (Thalanga, Balcooma). Modern exploration for VHMS deposits in eastern Australia commonly involves a multidisciplinary approach, using geological mapping to define volcanic facies, and structure and alteration zones accompanied by geochemistry and geophysics to define drill targets. Lithogeochemistry as a vector to ore (e.g. Large 1995) and downhole geophysics (Bishop & Lewis 1992) have become more commonly used tools in recent years.

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