6. Physical Description of Deposit

By John F. Slack

6 of 21

Volcanogenic Massive Sulfide Occurrence Model

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Contents

Definition 105
Dimensions in Plan View 105
Size of Hydrothermal System Relative to Extent of Economically Mineralized Rock.....................105
Vertical Extent 105
Form/Shape...106
Host Rocks 108
References Cited...108

Figure

6–1. Different forms and styles of volcanogenic massive sulfide deposits.............................107

6. Physical Description of Deposit

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Definition

In the following description of VMS deposits and their physical features, a deposit is defined as a mineral occurrence that has sufficient size and grade(s) to be economically profitable to mine under favorable circumstances (Cox and others, 1986).

Dimensions in Plan View

Typical dimensions of VMS deposits are in the range of 100–500 m. Small deposits may be only tens of thousands of square meters in plan view, whereas giant deposits can have dimensions of several square kilometers. The unmined Windy Craggy deposit in British Columbia, Canada, at depth is approximately 200 m wide and 1.6 km long (Peter and Scott, 1999), with a dimension of 0.3 km^2; the Kidd Creek orebody in Ontario, Canada, is approximately 500 m wide and at least 2,000 m long (downdip mining extent) and has a minimum dimension, vertically restored, of 1.0 km^2 (Hannington and others, 1999). The Besshi deposit on Shikoku, Japan, is 3,500 m by 1,800 m, thus covering an area (reconstructed prior to deformation) of 6.3 km^2 (see Slack, 1993); the dimension of the original deposit, prior to erosion, was much greater. Such large variations in the dimensions of VMS deposits reflect diverse parameters, such as: the nature and duration of seafloor and subseafloor hydrothermal activity; seafloor topography; permeability of footwall strata; structural and (or) volcanic controls on mineralization; postore deformation including shearing, folding, and faulting; extent of erosional preservation; and mining cutoff grades.

Size of Hydrothermal System Relative to Extent of Economically Mineralized Rock

The diverse nature of VMS systems results in large size ranges for envelopes of altered rock surrounding economic orebodies. Highly focused fluid flow in some deposits has produced alteration of limited volumetric significance to footwall stringer zones that typically contain only minor sulfides; hence, it is uneconomic to mine such deposits. However, many deposits have alteration haloes that in plan view extend well beyond the width of the orebody, including the Ordovician Brunswick No. 12 deposit in the Bathurst district of New Brunswick (Goodfellow and McCutcheon, 2003) and the Paleoproterozoic Chisel deposit in the Snow Lake district of Manitoba (Galley and others, 2007), where haloes are two or three times wider than the economic parts of the deposits. Even larger is the alteration zone surrounding the Western Tharsis deposits in Tasmania, Australia, being about 800 m in diameter compared to the maximum orebody width of about 150 m (Large and others, 2001). These dimensions do not consider the sizes of laterally extensive stratabound alteration zones, such as those occurring within footwall strata immediately below the sulfide ores, or in much deeper, so-called semi-conformable alteration zones that in some cases extend a kilometer or more from the projected economic margins of the deposit (Galley, 1993). Such zones may also occur in the stratigraphic hanging wall of deposits (for example, Noranda district), probably reflecting hydrothermal systems that were generated by synvolcanic but postore intrusions (see Franklin and others, 2005).

Vertical Extent

The nature of postore deformation determines whether the vertical extent of a VMS deposit is equivalent to its original stratigraphic thickness or its length. For relatively undeformed deposits, typical vertical extents (thicknesses) are on the order of tens of meters; extents of >250 m occur in a few deposits of this type, such as San Nicolás in Mexico, Tambo Grande in Peru, and Sibay in Russia (Johnson and others, 2000; Tegart and others, 2000; Herrington and others, 2005). The greatest vertical extents occur in tabular and sheetlike deposits that dip steeply to vertically, for which their extents reflect original deposit lengths and not thicknesses. Examples include the Besshi deposit in Japan (1,800 m; Sumitomo Metal Mining Company, Ltd., 1970) and the Kidd Creek orebody in Canada (>2,000 m; Hannington and others, 1999). Vertical extents of feeder zones also vary greatly, but they generally are less than 100 m, although some deposits have much thicker feeder zones (restored to predeformation geometries) on the order of several hundred meters, such as Hellyer, Tasmania (Gemmell and Large, 1992), Podolsk, Russia (Herrington and others, 2005), and Rio Tinto, Spain (Tornos, 2006).

Form/Shape

The geometry of VMS deposits may preserve original hydrothermal shapes or alternatively reflect varying degrees of postore deformation such as folding, faulting, and shearing (see Large, 1992). In areas of no or minimal deformation, possible deposit forms include sheets, layers, lenses, mounds, pipes, and stockworks (fig. 6–1). Sheetlike deposits are characterized by high aspect ratios in which the lengths of sulfide zones exceed thicknesses by an order of magnitude or more. Examples include the Besshi deposit on Shikoku, Japan, which has approximate dimensions of 3,500×1,800 m and a typical thickness of <30 m (Slack, 1993, and references therein), and the Thalanga deposit in Queensland, Australia, having a strike length of approximately 3,000 m and a thickness of 10–20 m in most places (Berry and others, 1992). Such sheetlike geometries, where demonstrably not of deformational origin, may reflect:

- sulfide deposition in a brine pool,
- precipitation from dense high-salinity fluids that migrate to a topographic low,
- accumulation of clastic sulfides eroded from a topographically higher edifice of massive sulfide,
- near-vent (<500 m) precipitation from the buoyant part of a hydrothermal plume (Large and others, 2001; German and Von Damm, 2003),
- coelescence of originally isolated sulfide mounds by mineralization from multiple vent sites (Huston, 1990),
- subseafloor replacement of a permeable volcanic or sedimentary bed (Large, 1992), or
- extensive seafloor weathering of a former sulfide mound (Herrington and others, 2005).

Layers show broadly similar geometries. Lenses have shorter length to thickness ratios and in many cases display irregular shapes with tapered margins; a large deposit of this type is San Nicolás in Mexico, which is 900 m long, >200 m wide, and as much as 280 m thick (Johnson and others, 2000).

Sulfide mounds show a wide range of geometries, commonly with roughly equal widths and lengths (approx. 100–300 m) and much smaller thicknesses, such as the Millenbach deposit in the Noranda district of Quebec (Knuckey and others, 1982). Atypical geometries are those such as the roughly equidimensional massive sulfide mounds like the bowl-shaped Bald Mountain deposit in Maine, which is approximately 370×275 m in diameter and as much as 215 m thick (Slack and others, 2003), and the hourglass-shaped TG3 deposit at Tambo Grande in Peru, which is approximately 500×350 m in diameter and up to about 250 m thick (Tegart and others, 2000). Such roughly equidimensional geometries likely reflect sulfide deposition within a confined space, such as volcanic craters or small grabens. Pipelike deposits, like those at Sibay in the South Urals of Russia (Herrington and others, 2005), Mount Morgan and Highway-Reward in Queensland, Australia (Messenger and others, 1997; Doyle and Huston, 1999), and Baiyinchang in Gansu Province, China (Hou and others, 2008), have thicknesses that are commonly greater than their diameters, typically as a result of subseafloor mineralization involving the replacement of permeable volcanic or sedimentary units by sulfides. The location and geometry of some pipelike deposits like Mount Morgan were controlled by synvolcanic growth faults (Taube, 1986). A modern analog is the Ocean Drilling Program (ODP) site at Middle Valley on the northern Juan de Fuca Ridge, where stacked sulfide mounds occur together with underlying alteration zones and a deep, epigenetic stratiform Cu zone (Zierenberg and others, 1998).

Stockworks generally occur in the stratigraphic footwall of sulfide-rich deposits and represent the feeder zone through which hydrothermal fluids rose towards the paleoseafloor (see Lydon, 1984; Franklin and others, 2005). Thicknesses vary from tens of meters to hundreds of meters in a few deposits. Where relatively undeformed, such stockworks commonly have an inverse funnel shape; others form a pipelike structure. Examples of classic VMS stockworks occur in the Kuroko, Noranda, Jerome, and Rio Tinto districts of Japan, Quebec, Arizona, and Spain, respectively (Franklin and others, 1981; Tornos, 2006; Gibson and Galley, 2007). Less commonly, stockworks are stacked and occur at two or more stratigraphic levels, such as in the Que River and Mount Lyell deposits in Tasmania, Australia (Large, 1992). Some stockworks have been selectively mined for copper, such as Jerome in Arizona (Gustin, 1990), Limni in Cyprus (Richards and others, 1989), and Rio Tinto in Spain (Nehlig and others, 1998). The stockwork of the giant Kidd Creek orebody in Canada is also economically important, as it has been mined for decades (see Hannington and others, 1999). Examples of modern stockworks that have been discovered on and beneath the seafloor include the Galapagos Rift (Ridley and others, 1994), Middle Valley (Zierenberg and others, 1998), and TAG (Petersen and others, 2000).

Deformed VMS deposits typically are folded, faulted, and (or) sheared. Folds within such deposits vary from broad open structures such as those at Eskay Creek, British Columbia, and Caribou, New Brunswick, Canada (Roth and others, 1998; Goodfellow, 2003), to isoclinally folded layers as at Tizapa, Mexico, and Kudz Ze Kayah, Yukon, Canada (Lewis and Rhys, 2000; Peter and others, 2007), to complexly folded lenses such as at Stekenjokk, Sweden, and Elizabeth, Vermont (Zachrisson, 1984; Slack and others, 2001). In the Bathurst district of New Brunswick, Canada, the sulfide deposits have undergone several periods of pervasive deformation, which is especially well-documented in the large Brunswick No. 12 and Heath Steele orebodies (van Staal and Williams, 1984; de Roo

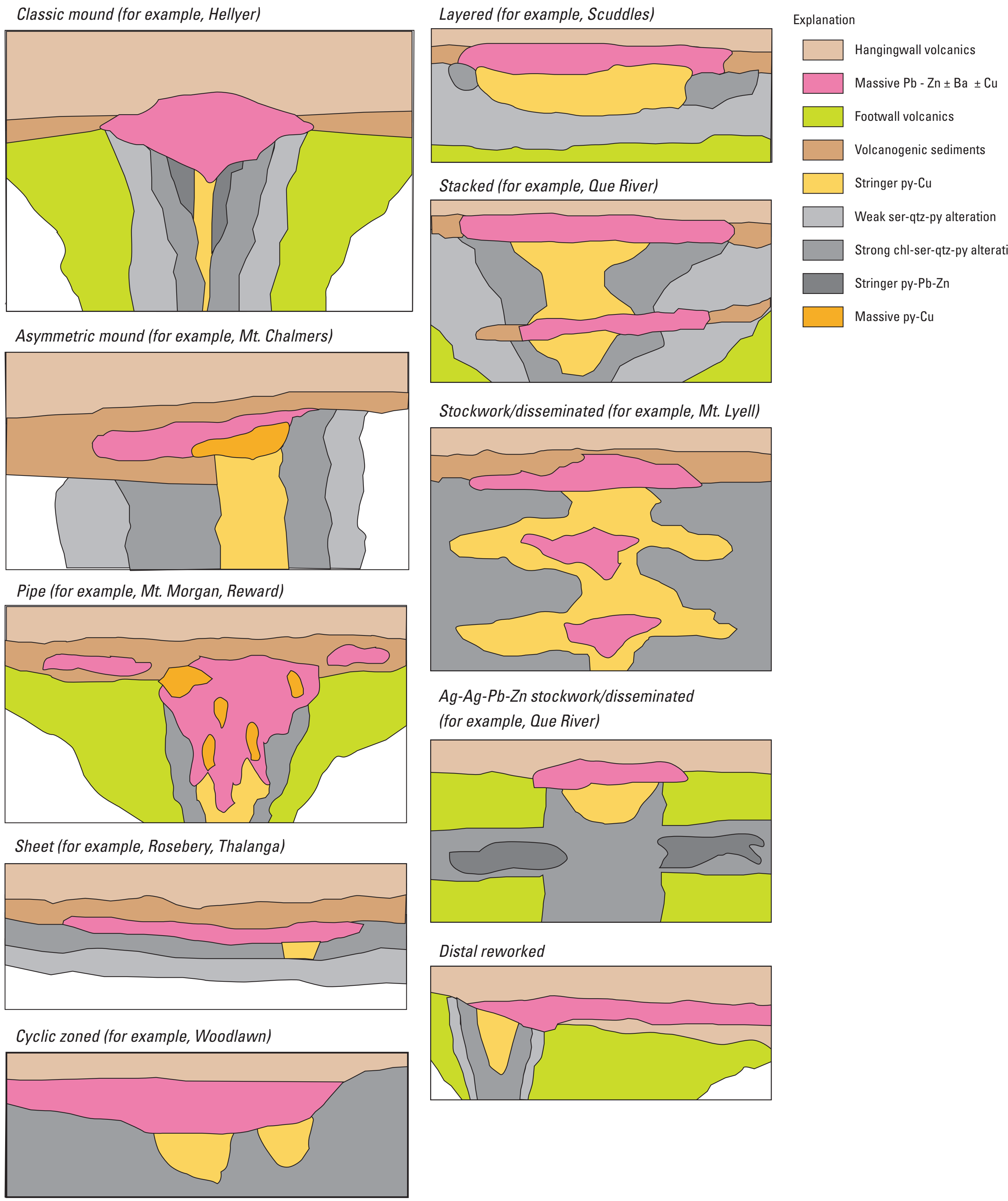

Figure 6–1. Different forms and styles of volcanogenic massive sulfide deposits (with example sites in parentheses). Modified from Large (1992). [Ag, silver; Ba, barium; Cu, copper; Pb, lead; Zn, zinc; chl, chlorite; py, pyrite; qtz, quartz; ser, sericite]

and others, 1991), including the remobilization of sulfides and formation of sulfide breccias (de Roo and van Staal, 2003). Map distributions of deformed deposits can be misleading because in some cases, like in the Ducktown district of Tennessee, what appears to be a simple pattern of one fold generation is actually an intensely folded and sheared group of deposits that experienced multiple deformational events (Slack, 1993, and references therein). Noteworthy are the thickened zones of massive sulfide that characteristically occur in the hinges of tight to isoclinal folds (for example, Brunswick No. 12; van Staal and Williams, 1984), which in many orebodies are of major economic importance.

Highly sheared deposits typically show elongate or dismembered shapes of sulfide bodies and (or) footwall stringer zones, both of which may be offset along shears or ductile faults. Examples include Brunswick No. 12, Ducktown, and Kristineberg in Sweden (van Staal and Williams, 1984; Slack, 1993; Årebäck and others, 2005). As a result of such shearing, and the development of transposed bedding in wall rocks and of complex fabrics within remobilized massive sulfides and feeder zones, it can be difficult to discern primary geometric relations between mineralized zones and volcanosedimentary host strata, including whether the deposits are syngenetic or epigenetic (van Staal and Williams, 1984; Marshall and Spry, 2000). Other products of extensive deformation of VMS deposits include the so-called "durchbewegung structure," comprising fragments of rotated and typically rounded wall rocks in a sulfide-rich matrix, and features such as sulfide-rich veins, mylonites, and piercement cusps (see Marshall and Gilligan, 1989; Duckworth and Rickard, 1993; Marshall and others, 2000). Attenuation and thinning of deposits into the plane of foliation is common and can result in lateral distribution of compositional and mineralogical zoning patterns that were originally vertical, as for example the Silver Peak deposit in Oregon (Derkey and Matsueda, 1989) or many of the VMS deposits in the Foothill metavolcanic belt of California (Kemp, 1982).

Host Rocks

The volcanic and sedimentary rocks that typically host VMS deposits may include lavas, tuffs, shales, siltstones, and (or) sandstones and their metamorphosed equivalents. Sedimentary conglomerates are uncommon to rare. Coarse volcanic breccias and fragmental pyroclastic rocks are the host rocks to many deposits, reflecting proximity of hydrothermal vents to volcanic centers (see Franklin and others, 2005; Galley and others, 2007). In many cases, massive sulfide deposits occur along or near brecciated rhyolite domes, which are well documented in the footwall of many VMS camps such as the Hokoruko district of Japan (Ohmoto and Takahashi, 1983) and the Noranda district of Quebec (Gibson and Galley, 2007).

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