1. Introduction

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Volcanogenic Massive Sulfide Occurrence Model

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Overview

Volcanogenic massive sulfide (VMS) deposits, also known as volcanic-hosted massive sulfide, volcanic-associated massive sulfide, or seafloor massive sulfide deposits, are important sources of copper, zinc, lead, gold, and silver (Cu, Zn, Pb, Au, and Ag). These deposits form at or near the seafloor where circulating hydrothermal fluids driven by magmatic heat are quenched through mixing with bottom waters or porewaters in near-seafloor lithologies. Massive sulfide lenses vary widely in shape and size and may be podlike or sheetlike. They are generally stratiform and may occur as multiple lenses.

Volcanogenic massive sulfide deposits range in size from small pods of less than a ton (which are commonly scattered through prospective terrains) to supergiant accumulations like Rio Tinto (Spain), 1.5 Bt (billion metric tons); Kholodrina (Russia), 300 Mt (million metric tons); Windy Craggy (Canada), 300 Mt; Brunswick No. 12 (Canada), 230 Mt; and Ducktown (United States), 163 Mt (Galley and others, 2007). Volcanogenic massive sulfide deposits range in age from 3.55 Ga (billion years) to zero-age deposits that are actively forming in extensional settings on the seafloor, especially mid-ocean ridges, island arcs, and back-arc spreading basins (Shanks, 2001; Hannington and others, 2005). The widespread recognition of modern seafloor VMS deposits and associated hydrothermal vent fluids and vent fauna has been one of the most astonishing discoveries in the last 50 years, and seafloor exploration and scientific studies have contributed much to our understanding of ore-forming processes and the tectonic framework for VMS deposits in the marine environment.

Massive ore in VMS deposits consists of >40 percent sulfides, usually pyrite, pyrrhotite, chalcopyrite, sphalerite, and galena; non-sulfide gangue typically consists of quartz, barite, anhydrite, iron (Fe) oxides, chlorite, sericite, talc, and their metamorphosed equivalents. Ore composition may be Pb-Zn-, Cu-Zn-, or Pb-Cu-Zn-dominated, and some deposits are zoned vertically and laterally.

Many deposits have stringer or feeder zones beneath the massive zone that consist of crosscutting veins and veinlets of sulfides in a matrix of pervasively altered host rock and gangue. Alteration zonation in the host rocks surrounding the deposits are usually well-developed and include advanced argillic (kaolinite, alunite), argillic (illite, sericite), sericitic (sericite, quartz), chloritic (chlorite, quartz), and propylitic (carbonate, epidote, chlorite) types (Bonnet and Corriveau, 2007).

An unusual feature of VMS deposits is the common association of stratiform "exhalative" deposits precipitated from hydrothermal fluids emanating into bottom waters. These deposits may extend well beyond the margins of massive sulfide and are typically composed of silica, iron, and manganese oxides, carbonates, sulfates, sulfides, and tourmaline.

Scope

This VMS deposit model is designed to supercede previous models developed for the purpose of U.S. Geological Survey (USGS) mineral resource assessments (Cox, 1986; Cox and Singer, 1986; Singer, 1986a, 1986b; Taylor and others, 1995). Because VMS deposits exhibit a broad range of geological and geochemical characteristics, a suitable classification system is required to incorporate these variations into the mineral deposit model. Cox and Singer (1986) grouped VMS deposits into (1) a Cyprus subtype associated with marine mafic volcanic rocks, (2) a Besshi subtype associated with clastic terrigenous sediment and marine mafic volcanic rocks, and (3) a Kuroko subtype associated with marine felsic to intermediate volcanic rocks (table 1–1). This terminology was developed earlier by Sawkins (1976) on the basis of probable tectonic settings for each deposit type. Volcanogenic massive sulfide deposits have also been classified according to base metal (Cu-Zn-Pb) ratios (Hutchinson, 1973; Franklin and others, 1981) and ratios of precious metals (Au-Ag) to base metals (Poulsen and Hannington, 1995) in massive sulfides.

More recent attempts to classify VMS deposit types have emphasized compositional variations in associated volcanic and sedimentary host rocks (Barrie and Hannington, 1999; Franklin and others, 2005; Galley and others, 2007). The advantage of these classification schemes is a closer link between tectonic setting and lithostratigraphic assemblages and an increased predictive capability during field-based studies. The lithology-based typology of Galley and others (2007) is shown in table 1–1 with approximate equivalencies to the categories of Cox and Singer (1986). The lithologic groups correlate with tectonic settings as follows: (1) mafic

Table 1–1. Classification systems for volcanogenic massive sulfide deposits.

Cox and Singer (1986)	Galley and others (2007)	Mosier and others (2009)	This report
Kuroko	Felsic-siliciclastic	Felsic	Siliciclastic-felsic
	Bimodal-felsic[1]		Bimodal-felsic
	Bimodal-mafic	Bimodal-mafic	Bimodal-mafic
Besshi	Pelitic-mafic	Mafic	Siliciclastic-mafic
Cyprus	Back-arc mafic		Mafic-ultramafic

[1] Includes hybrid bimodal-felsic group of Galley and others (2007).

rocks with mid-ocean ridges or mature intraoceanic back arcs; (2) pelitic-mafic rocks with sediment-covered back arcs; (3) bimodal-mafic rocks with rifted intraoceanic volcanic arcs; (4) bimodal-felsic rocks with continental margin arcs and back arcs; and (5) felsic-siliciclastic rocks with mature epicontinental back arcs. A sixth group listed by Galley and others (2007), hybrid bimodal-felsic, is treated here as part of the bimodal-felsic group.

In developing grade and tonnage models for 1,090 VMS deposits, Mosier and others (2009) found no significant differences between grade and tonnage curves for deposits hosted by pelite-mafic and back-arc–mafic rocks and for deposits hosted by felsic-siliciclastic and bimodal-felsic rocks, resulting in their threefold classification of mafic, bimodal-mafic, and felsic subtypes (table 1–1). For the mineral deposit model described in this report, however, the compositional variations in sequences of volcanic rocks and the occurrence of sedimentary rocks in stratigraphic sequences containing VMS deposits are important variables in the identification of geologic and tectonic settings. Furthermore, bimodal volcanic assemblages and presence of sedimentary deposits are discernible map features useful in the assessment of mineral resources. Therefore, we have adopted a fivefold classification slightly modified from Galley and others (2007) for use throughout this report (table 1–1). We prefer the term “siliciclastic-felsic” to “felsic-siliciclastic” because of the abundance of volcaniclastic and epiclastic sediment relative to felsic volcanic rocks in this group of deposits (for example, Iberian Pyrite Belt; Carvalho and others, 1999). This usage is consistent with Franklin and others (2005). The term “siliciclastic-mafic” is used because it encompasses the broader range of noncarbonate sedimentary rocks such as graywackes, siltstones, and argillites associated with this type of VMS deposit (Slack, 1993). Finally, the modified term “mafic-ultramafic” includes both back-arc and mid-ocean ridge environments and acknowledges recently discovered massive sulfide deposits along the Mid-Atlantic Ridge, in which serpentinized peridotites are present in the footwall (for example, Rainbow vent field; Marques and others, 2007).

Purpose

The main purpose of this model is to provide the basis for the VMS component of the next National Assessment of undiscovered mineral resources in the United States. The three-part quantitative assessment strategy employed by the USGS (Singer, 1995, 2007; Cunningham and others, 2008) includes (1) delineation of permissive tracts for VMS deposits, (2) selection of grade-tonnage models appropriate for evaluating each tract, and (3) estimation of the number of undiscovered deposits in each tract. Hence, accurate and reliable data on VMS deposits, especially host lithology, tectonic setting, structure, ore-gangue-alteration mineralogy, geochemical and geophysical signatures, theory of deposit formation, and geoenvironmental features, are critical to the assessment methodology.

We believe that geologic information and quantitative data presented in this report are sufficient to identify permissive tracts for VMS deposits and to guide experts in estimating the number of undiscovered deposits in the permissive tracts. In addition, we have tried to provide comprehensive information to aid in assigning deposits from a tract to a specific deposit model type (siliciclastic-felsic, bimodal-felsic, bimodal-mafic, siliciclastic-mafic, and mafic-ultramafic) so that the correct grade-tonnage curve(s) can be used in assessing undiscovered deposits.

Beyond its importance in the National assessment, we believe that an updated VMS deposit model will be useful to exploration geologists, students and teachers of economic geology, and researchers interested in understanding the origin of this important deposit type in the context of earth history and plate tectonics. Among the latter group is a large international group of scientists studying the distribution, characteristics, and origin of VMS deposits on the modern seafloor.

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