19. Exploration-Resource Assessment Guides

By John F. Slack

Volcanogenic Massive Sulfide Occurrence Model

Scientific Investigations Report 2010–5070–C

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2012

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Suggested citation:
Slack, J.F., 2012, Exploration-resource assessment guides in volcanogenic massive sulfide occurrence model: U.S. Geological Survey Scientific Investigations Report 2010–5070 –C, chap. 19, 10 p.

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Geological

A variety of geological guides may be used in mineral exploration and resource assessments for VMS deposits. Detailed geological maps clearly provide the critical framework. For regions lacking known deposits, a first-order guide is the age of the volcanosedimentary sequence relative to the ages of sequences elsewhere in the world that contain significant VMS mineralization. The database of Franklin and others (2005) shows time periods in the geologic record during which appreciable tonnages of VMS deposits formed (fig. 4–4). Using these age-based data, globally in the Precambrian major VMS mineralization took place 2.75–2.65 Ga, 2.05–1.85 Ga, and 1.00–0.65 Ga (see also Huston and others, 2010). Volcanosedimentary terranes with ages outside of these time periods, including >3.25 Ga, 2.65–2.00 Ga, and 1.85–1.00 Ga, are less likely to contain large (>30 Mt) deposits. Such gaps in the secular distribution of Precambrian VMS deposits, if not artifacts of erosion or inadequate age control, reflect the evolution of fundamental crustal processes on Earth, especially plate tectonics and related assembly of major continental land masses (see Groves and others, 2005; Condie and others, 2009; Huston and others, 2010). During the Phanerozoic, the greatest tonnages of VMS deposits formed mainly 500–300 Ma (Late Cambrian–Late Carboniferous); no lengthy periods (>50 m.y.) are known that lack significant VMS deposits. Few deposits less than 15 Ma (Middle Miocene) occur on land (Franklin and others, 2005; Mosier and others, 2009), a result of limited obduction of younger marine volcanosedimentary sequences onto the continents.

Within sequences that contain known deposits, key guides are (1) favorable marine volcanosedimentary units including felsic or mafic lavas or tuffs, coarse breccias, and rhyolite domes that host mineralization within the same belt (Lydon, 1996); (2) VMS-type prospects or occurrences including stratabound sulfides and discordant veins; (3) exhalites, especially those containing barite and (or) high concentrations of Cu, Zn, or Pb (Spry and others, 2000); (4) synvolcanic structures such as growth faults, calderas, and fault intersections, which may have focused fluid flow and localized sulfide mineralization; (5) local fine-grained, highly carbonaceous or graphitic sedimentary rocks that record breaks in volcanism and in most cases indicate coeval anoxic or sulfidic bottom waters that prevented seafloor weathering and oxidation of sulfides (Goodfellow and others, 2003); (6) large synvolcanic sills and (or) dikes, which typically occur in the stratigraphic footwall of the deposits, having served as sources of heat to drive the hydrothermal systems (Galley, 1993); (7) abundant chlorite or white mica and their metamorphosed equivalents (including Al-rich minerals), as evidence of VMS-type alteration (for example, Galley and others, 2007); and (8) abundant tourmaline and (or) gahnite (Slack, 1982; Spry and Scott, 1986; Huston and Patterson, 1995). Bonnet and Corriveau (2007) described the diagnostic mineralogy of metamorphosed alteration zones of VMS deposits, highlighting differences in greenschist-facies versus granulite-facies terranes. In the latter settings, which are dominated by gneisses, diagnostic minerals—where not affected by retrograde metamorphism—may include cordierite, diopside, orthopyroxene, garnet, K-feldspar, biotite, and Al-silicates especially kyanite and sillimanite.

Geochemical

Geochemically-based guides for VMS exploration and assessment can be divided into categories that focus on the following sample media: (1) rocks, (2) minerals, (3) stream sediments and heavy mineral concentrates, (4) glacial till, (5) lake sediments, (6) waters, and (7) soils and soil gases. The greatest effort probably has been directed towards rock geochemistry, involving searches for elevated contents of base and precious metals and for favorable indicators of VMS-type hydrothermal alteration. Igneous rocks within prospective belts typically have geochemical signatures that reflect formation in diverse geodynamic settings, including oceanic spreading ridges, rifted arcs and back-arcs, and rifted continental margins. Dominant is tholeiitic to transitional bimodal magmatism; alkaline and peralkaline volcanic rocks are rare by comparison (for example, Piercey, 2007). Within Precambrian terranes, favorable settings for VMS deposits include, but are not limited to, high-temperature rhyolites that have diagnostic compositions including high Zr (>300 ppm), Y/Zr ratios <7, negative Eu anomalies (chondrite-normalized basis [CN]), $(La/Yb)_{CN}$ ratios <7, and $(Gd/Yb)_{CN}$ ratios <2 (Galley and others, 2007, and references therein). In Phanerozoic terranes, compositions of felsic (and mafic) igneous rocks associated with VMS deposits vary greatly, depending on whether the setting is petrologically primitive or evolved, and relative to Precambrian terranes are not as definitive (see Piercey, 2009).

Many studies have focused on compositional variations of the sulfide deposits, altered wall rocks, and associated exhalites as possible exploration guides to ore. The metal ratio 100 Zn/(Zn + Pb) was used by Huston and Large (1987) in the Mount Read volcanics of Tasmania to distinguish VMS deposits and occurrences from sulfide concentrations produced by other types of mineralization. Geochemical vectors proposed for wall rocks surrounding deposits include the "alteration box plot" of Large and others (2001a), which combines the Ishikawa alteration index, 100 (K_2O + MgO)/(K_2O + MgO + Na_2O + CaO), with the chlorite-carbonate-pyrite index, 100 (MgO + FeO)/(MgO + FeO + K_2O); increasing values of both parameters reflect the intensity of alteration in which sericite, chlorite, carbonate, and pyrite replace sodic feldspar and glass in volcanic rocks. This scheme may have advantages over previous approaches, such as those based on chemical gains and losses during alteration (for example, Barrett and MacLean, 1994; Leitch and Lentz, 1994), and is best applied to felsic volcanic rocks in concert with mineralogical and textural data on the analyzed samples. More recently, Piché and Jébrak (2004) devised a normative mineral alteration index that is less-sensitive to lithological variations among samples and better identifies ore-related hydrothermal mineral assemblages.

On a regional scale, hydrothermal fluid flow related to VMS mineralization may form distinctive mineral assemblages and mineral compositions that differ from those produced by greenschist-facies metamorphism, in which hydrothermally altered volcanic rocks preferentially contain abundant Fe-rich chlorite, ferroactinolite, and coarse-grained clinozoisite (Hannington and others, 2003). The loss of Na_2O during VMS alteration is a hallmark of this deposit type, occurring mainly in footwall zones, and by itself may be an effective guide to ore (for example, Hashiguchi and others, 1983; Lydon, 1996; Piercey, 2009). Other proposed vectors for altered wall rocks include increases of Tl, Sb, Ba/Sr, $\delta^{34}S$ values of sulfides, and Mn contents of carbonate towards ore (Large and others, 2001b, and references therein). Lentz (2005) summarized the use of Hg as an exploration guide. Another possible vector is variations in mineralogy and mineral chemistry in wall rocks caused by sulfide-oxide-silicate equilibria produced during metamorphism of the deposits. This process and its exploration applications were first described in detail by Nesbitt and Kelley (1980) and later amplified by Spry (2000), who highlighted the haloes and proportions of Mg- and (or) Zn-rich silicates and Zn-rich oxides that typically increase in intensity with proximity to ore. Compositions of minerals that formed during VMS and later superimposed metamorphic processes have been the focus of many topical studies, including tourmaline (Taylor and Slack, 1984; Griffin and others, 1996), Zn-rich staurolite (Heimann and others, 2005, and references therein), rutile (Clark and Williams-Jones, 2004), and magnetite (Beaudoin and others, 2007;). The presence of high gold concentrations in some deposits was studied by Hannington and Scott (1989) and Hannington and others (1999), resulting in the recognition of low-Fe sphalerite and certain sulfidation equilibria as guides to Au-rich systems. Some terranes, particularly those dominated by mafic volcanic rocks, may provide an enriched source rock control on the formation of Au-rich VMS deposits (Stolz and Large, 1992).

In some terranes the bulk geochemistry of VMS-related exhalites can be used as vectors to massive sulfide deposits. This approach is best used for exhalites that are exposed in outcrops and (or) drill cores, such that a stratigraphic continuity can be inferred and applied to sampling programs and interpretations of data. In most cases, however, exhalites cannot be traced along strike with confidence, thus limiting their usefulness as direct vectors to VMS deposits. In the Bathurst district of New Brunswick, Canada, exhalites are well exposed at two main stratigraphic levels, both of which have been intersected in numerous drill cores. These exhalites, consisting of different facies of iron formation (sulfide, carbonate, silicate, oxide), served as the focus of detailed mineralogical and geochemical studies of both the Brunswick and Heath Steele belts (Peter and Goodfellow, 1996, 2003; Peter and others, 2003a, b). These studies have produced the most complete databases known for laterally extensive exhalites related to ancient VMS mineralization, and they provide the best framework for evaluating the use of exhalite geochemistry in targeting high-temperature hydrothermal centers and, by inference, massive sulfide orebodies. Based on data for the Heath Steele exhalites, Peter and Goodfellow (2003) constructed a composite diagram showing idealized mineralogical and compositional zonations for proximal to distal settings relative to a single VMS source deposit. Among many identified parameters, some proposed as diagnostic of proximal exhalites (<500 m from massive sulfide) are the presence of chalcopyrite, sphalerite, and (or) galena; high concentrations of Cu, Pb, Zn, Ag, As, Au, Bi, Cd, Hg, In, Sb, Sn, and Tl; and high Fe/Ti, Ba/Ti, and Eu/Eu* ratios where Eu/Eu* is the magnitude of the Eu anomaly. Peter and Goodfellow (2003) used these compositional parameters, together with others (for example, P/Ti), to define a hydrothermal sediment index, which shows the consistently highest values at and near the three largest VMS deposits in the Heath Steele belt. Exhalative jasper related to VMS mineralization in the Løkken district of Norway, which can be traced along strike for 4–6 km, show a pattern in which As/Fe and Sb/Fe ratios increase towards the massive sulfide deposit (Grenne and Slack, 2005). In other terranes where exhalites may not be laterally extensive, favorable indicators of proximity to VMS deposits include the presence of base-metal sulfides (chalcopyrite, sphalerite, galena), elevated contents of trace metals such as Cu, Zn, Pb, and Tl, and positive Eu anomalies (Gale and others, 1997; Peter, 2003). Miller and others (2001) reported on the discovery of the West 45 deposit in Queensland, Australia, which was found in part by identifying a large positive Eu anomaly in a sample of exhalative jasper.

Other sample media have been used with varying success in VMS exploration. Stream sediments constitute parts of many regional-scale exploration and assessment programs, based on the delineation of geochemical anomalies that reflect erosion of sulfide-bearing rock from known deposits (for example, Slack and others, 1990; Telmer and others, 2002; Leybourne and others, 2003). Heavy mineral concentrates have been used less frequently, in part because of the much longer time required to obtain a sample (by panning), and because some sulfides like sphalerite are not mechanically strong and thus rarely survive as large grains for recovery in panned concentrate surveys. Heavy indicator minerals nevertheless may be useful in programs that focus on glacial dispersion trains (Averill, 2001) or on gahnite, spessartine garnet, or other resistant minerals that are common recorders of VMS-type mineralization (Spry and others, 2000). Bulk till geochemistry has been used in exploration programs for over 50 years, being most effective when integrated with surficial geology, especially till stratigraphy and ice flow patterns (for example, McMartin and McClenaghan, 2001); interpretations are constrained by the typically great dilution of deposit-related geochemical signatures by glacial materials and by occurrences of multiple till sheets. Lake sediments have been used in some regional geochemical surveys (McClenaghan and others, 1997); aqueous geochemical methods and applications are summarized by Leybourne (2007). Soil geochemical surveys (for example, Cameron and others, 2004) are generally limited in scope to localized targets that already are delineated by favorable geological features or geophysical anomalies. Comparative studies of conventional bulk versus selective leach methods suggest that the former technique is superior (Hall and others, 2003). Reconnaissance soil surveys have not been as widely used, although some large, unexposed VMS deposits have been found by this approach, such as Bald Mountain in northern Maine (Cummings, 1988). Soil gases have also proven useful because of their mobility in the vadose zone and glacial overburden (McCarthy and others, 1986; Kelley and others, 2006).

Isotopic

Among numerous stable and radiogenic isotopic systems, oxygen isotopes hold the greatest promise for direct application to mineral exploration and resource assessments for VMS deposits (for example, Miller and others, 2001). Oxygen isotope haloes have been delineated around many deposits. In one of the earliest studies, Green and others (1983) documented systematic oxygen isotope variations in part of the Hokuroku district of Japan, finding an overall pattern in which whole-rock $\delta^{18}O$ values correlate with alteration assemblage, irrespective of precursor lithology; in the footwall of the Fukazawa deposit, the values show a progressive increase of approximately 8 per mil from the outer zeolite zone to the inner chlorite-sericite zone. A similar regionally-based zonation was identified in the West Shasta VMS district of California by Taylor and South (1985), including the vicinity of a synvolcanic pluton that likely was the heat source that drove the seafloor-hydrothermal system. Comparable results were obtained in regional oxygen isotope studies of the Noranda district in Quebec (Paradis and others, 1993), the Panorama district in Western Australia (Brauhart and others, 2000), the Iberian Pyrite Belt of Spain (Lerouge and others, 2001), and the Sturgeon Lake region of Ontario (Holk and others, 2008). An exception is the Palmeiropolis deposit in Brazil, which lacks an oxygen isotope contrast between hydrothermally altered wall rocks and unaltered host rocks, possibly due to isotopic homogenization during pervasive metamorphic fluid flow (Araujo and others, 1996). Detailed studies of individual feeder zones have confimed the characteristic patterns described above, such as at the Bruce deposit in Arizona (Larson, 1984) and the Kidd Creek and Geco deposits in Ontario (Huston and others, 1995; Araujo and others, 1996). From exploration and assessment perspectives, detailed whole-rock oxygen isotope studies can define zones of hydrothermal downflow and upflow within a volcanic pile and use the latter upflow zones as a guide to undiscovered deposits in the region (Holk and others, 2008).

Geophysical

A diverse suite of geophysical methods has been used in VMS exploration both on regional and local scales. Ford and others (2007) highlighted the most effective methods, which are electromagnetic, magnetic, electrical, and gravimetric. In regional programs and in areas lacking detailed geologic maps, airborne surveys that combine electromagnetic and magnetic measurements can yield valuable information on geological features that are permissive for the occurrence of VMS deposits, including structures, intrusive bodies, and alteration zones (for example, Keating and others, 2003). Major contrasts in density, magnetism, and electrical conductivity of VMS deposits, relative to their volcanosedimentary host rocks, provide the foundation for these surveys. Many deposits have been discovered during airborne or ground electromagnetic surveys, some of the most notable being the giant Kidd Creek orebody in Ontario (Bleeker and Hester, 1999), the large Heath Steele and Brunswick No. 6 orebodies in New Brunswick (Keating and others, 2003), and the large Crandon deposit in Wisconsin (May and Schmidt, 1982). However, the electromagnetic (EM) method has two major drawbacks: First, that distinct anomalies may also be produced by unmineralized features including sulfide-free carbonaceous or graphitic sedimentary rocks and water-saturated overburden. A second limitation is the difficulty of delineating electromagnetically a Zn-rich deposit because of the poor conductivity of sphalerite relative to other sulfide minerals (Bishop and Emerson, 1999). If not deeply buried, deposits that contain appreciable magnetite or pyrrhotite generate distinctive magnetic anomalies, both from airborne and ground surveys. Magnetic data also can be useful for delineating large subvolcanic intrusions and, by inference, the locations of undiscovered VMS deposits, based on the premise that such intrusions provide the heat sources that drive stratigraphically higher hydrothermal systems (Galley, 2003; Galley and others, 2007).

Disseminated sulfides such as those in footwall feeder zones can be delineated by induced polarization, which targets sulfide grains that are not electrically connected (Ford and others, 2007). Gravity surveys are especially useful for identifying high-density units such as barite-rich exhalites or Zn-rich massive sulfide that otherwise are poor geophysical targets. Radiometric surveys, typically employed in airborne surveys together with magnetic and EM measurements, involve gamma-ray spectroscopy for K, U, and Th that can improve knowledge of basic geology and delineate K-rich alteration zones that surround many deposits (Chung and Keating, 2002). Geophysical techniques that are less widely used in VMS exploration include electrochemical (Cameron and others, 2004), seismic and high-resolution seismic (Milkereit and others, 1996; Adam and others, 2000), oxidation-reduction and spontaneous potential (Hamilton and others, 2004), and various remote sensing methods (for example, Herrmann and others, 2001).

Attributes Required for Inclusion in Permissive Tracts at Various Scales

A permissive tract in mineral resource assessments is defined as an area where geologic features permit the occurrence of one or more deposit types (for example, Singer, 1993). Favorable geology is the most important attribute for identifying a permissive tract. In assessments for VMS deposits, key geologic criteria include:

- presence of a submarine volcanosedimentary sequence having an age that falls within a time period containing numerous VMS deposits with large aggregate tonnages and base metal contents (fig. 4–4);
- evidence of an extensional geodynamic setting and synvolcanic faulting as reflected in distinctive compositions of volcanic and synvolcanic intrusive rocks;
- presence of coarse volcanic breccias or felsic domes indicating proximity to a volcanic center;
- occurrence of exhalites, especially those containing base-metal sulfides or large positive Eu anomalies;
- evidence of VMS-type alteration zones represented by abundant chlorite or white mica, or their metamorphosed equivalents; and
- occurrence of large subvocanic sills as heat sources for the hydrothermal systems.

Also critical in tract delineation are locations of known deposits and prospects, if clearly of VMS affinity. Other positive criteria are anomalously high contents of base metals in stream sediments, presence of abundant indicator minerals such as gahnite or spessartine garnet in panned concentrates, and geophysical data that suggest the occurrence of hydrothermal alteration zones or continuity of favorable units under cover. Previous mineral-resource assessments that use the concept of permissive tracts include those by the U.S. Geological Survey (for example, Cox, 1993; Raines and Mihalasky, 2002) and the British Columbia Geological Survey (Grunsky and others, 1994). Integration of geologic, mineral-occurrence, geochemical, and geophysical data using geographic information systems (GIS) and similar spatial analysis methods provides a robust foundation for assessments (Bonham-Carter and others, 1993; Chung, 2003; Fallara and others, 2006; Nykänen and Ojala, 2007). The importance of mineral prospectivity mapping is discussed by Carranza and Sadeghi (2010), by which the spatial distribution of known VMS deposits in the Skellefte district of Sweden was compared to spatially related geological features, in order to outline recognition criteria for regional-scale VMS prospectivity.

Different map scales can have major influences on the shape and size of permissive tracts. Singer (1993) highlighted the problem of using large-scale geologic maps, which can result in generalization of a given tract, or of arbitrarily enlarging a tract in order to include deposit types that occur in restricted settings. A more detailed analysis of the problem was done by Singer and Menzie (2008), who found that use of more generalized maps tends to favor inclusion of geologic settings that are not permissive for a given deposit type, or of unreported cover sequences with permissive tracts thus producing a misleading appearance of clustered deposits. Singer and Menzie (2008) quantified this problem of map scale by Poisson distribution analysis, showing that, by comparison, a geologic map having twice the detail of a more generalized map will decrease the area of a permissive VMS tract by 50 percent.

Factors Influencing Undiscovered Deposit Estimates (Deposit Size and Density)

Estimates of the size and density of undiscovered mineral deposits are affected by several factors. In one of the earliest studies, Sangster (1980) noted that VMS deposits are characteristically found in clusters, and that for Canadian districts 47 percent of deposits occur in only six clusters (districts). Possible explanations for these clusters of VMS deposits, covering areas averaging 32 km in diameter, include the presence of abundant felsic volcanic rocks and related volcanic centers, and preferential occurrences within inferred submarine calderas (Sangster, 1980). This clustering of deposits was also highlighted by Galley and others (2007), who proposed that the diameter of each group of clustered deposits reflects the extent of regional-scale hydrothermal alteration systems; the distribution of deposits within each cluster relates to synvolcanic fault distribution above subvolcanic intrusions. In the case of the Noranda district, the areal distribution of VMS deposits corresponds closely to the outlines of hydrothermally altered rocks and the Noranda cauldron (Gibson and Galley, 2007). Caution must be used in applying this caldera-based approach to highly deformed terranes, however, because of deformational effects on original geometry (Hollister, 1980) and, hence, on the related density of undiscovered deposits.

In modern settings, average densities of hydrothermal vent fields range from 1.9 to 6.6 sites per 100-km length (Massoth and others, 2007). This range of densities includes data for the back-arc Valu Fa Ridge, the Tonga and Kermadec arcs, and mid-ocean ridges in the eastern Pacific Ocean. The largest deposits on mid-ocean ridges tend to occur where the spreading rate is slow to intermediate and on the shallowest parts of the ridges; calculations based on heat flux suggest the presence, theoretically, of at least one black smoker vent for every 1 km of ridge length, but their distribution is not uniform and large clusters of black smoker vents occur at much greater spacings of about 50–100 km (Hannington and others, 2005). In ancient settings, deposit spacings are related to a variety of processes, yielding an estimated 5-km diameter for the scale of proximal hydrothermal alteration around each deposit (Galley and others, 2007).

A detailed statistical analysis by Mosier and others (2007) provides the most robust foundation for evaluating the density of undiscovered VMS deposits for a mineral-resource assessment. Their study used frequency distributions of deposit densities for 38 well-explored control areas worldwide. Mosier and others (2007) determined that 90 percent of the control areas have more than 100 VMS deposits per 100,000 km^2 and that both map scales and sizes of the control areas are predictors of deposit density. Map scales used to delineate permissive tracts also must be considered because they directly affect the spatial and frequency distribution of deposits and thus deposit densities (Singer, 2008; Singer and Menzie, 2008). For mineral-resource assessments, the most detailed geologic maps therefore should be used in order to maximize the knowledge base for VMS experts when estimating the numbers of undiscovered deposits in a given tract.

Estimates of the sizes of undiscovered mineral deposits rely mainly on statistical data for grades and tonnages for a given deposit type (for example, Cox and Singer, 1986). The largest resources of metals typically are contained in a few giant orebodies, hence very small or low-grade deposits do not greatly affect grade-tonnage distributions. Differences in cutoff grades and other economic factors are not significant, having minimal or at most minor influences on these parameters (Singer, 1993). Detailed statistical studies have documented several key relationships among major types of mineral deposits, including VMS: (1) the distribution of tonnages is approximately lognormal, (2) deposit size is inversely correlated with deposit density, (3) the size of the permissive tract and the size of contained deposits is correlated, and (4) the total amount of mineralized rock is proportional to the size of the median deposit (Singer, 1993, 2008). Relationships derived from statistical studies, including those between sizes of permissive areas and deposit density, can thus be used together with grade-tonnage models as predictors of the number of undiscovered deposits and the total amount of undiscovered metal (Singer, 2008). Also important are craton- and terrane-scale features that likely determine metal endowment, including the occurrence and location of giant and super-giant deposits (Jaireth and Huston, 2010).

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