16. Petrology of Sedimentary Rocks Associated with Volcanogenic Massive Sulfide Deposits

By Cynthia Dusel-Bacon

Volcanogenic Massive Sulfide Occurrence Model

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Importance of Sedimentary Rocks to Deposit Genesis

The importance and percentage of sedimentary rocks associated with VMS deposits differ among the various deposit types, defined by their lithologic settings. Sedimentary rocks are a negligible component in bimodal-mafic type deposits, make up a minor component in mafic-ultramafic type deposits, but are an important component in siliciclastic-mafic, bimodal-felsic, and siliciclastic-felsic type deposits (Franklin and others, 2005). In spite of the differing relative proportions of sedimentary rocks to mafic and felsic volcanic rocks, associated sedimentary lithofacies in the majority of the above VMS settings are all dominated by terrigenous clastic sedimentary rocks, primarily wacke, sandstone, siltstone, mudstone, and carbonaceous mudstone, with lesser amounts of chert, carbonate, marl, and iron-formation (Franklin and others, 2005). The absence of certain sedimentary facies also can provide important paleogeographic constraints. For example, the lack of unconformities or thick epiclastic sedimentary successions between or within the Archean volcanic formations of the Blake River Group that hosts the bimodal-mafic-type VMS deposits of the Noranda district suggests that volcanism was distal from subaerial or above storm-wave-base landmasses (Gibson and Galley, 2007).

The major- and trace-element compositions of sedimentary rocks associated with VMS deposits can reflect the distinct provenance types and tectonic settings of the associated sedimentary basins (Bhatia, 1983; Bhatia and Crook, 1986). Most of the sedimentary rocks were deposited in extensional basins. However, the VMS deposits themselves generally formed within volcanic centers that were located in smaller graben structures within a larger sediment-filled extensional basin (for example, Bathurst; Goodfellow and McCutcheon, 2003; Franklin and others, 2005). Trace-element data for VMS-associated volcanic rocks indicate that most VMS deposits formed during various stages of rifting associated with intra-arc and back-arc development (for example, Lentz, 1998; Piercey and others, 2001; Piercey, 2009). The distribution and thickening of sedimentary strata associated with volcanic and volcaniclastic rocks can reveal the presence of synvolcanic growth faults that formed during rifting. These faults are a key tectonic element in the formation of hydrothermal convection systems that discharged metal-bearing fluids onto the seafloor or into permeable strata immediately below the seafloor to form the VMS deposits (for example, Franklin and others, 2005).

Clastic sedimentary strata, typically carbonaceous argillite, immature epiclastic volcanic wacke, and carbonate units, most commonly occur within the hanging wall succession of VMS deposits (for example, Bergslagen district, Sweden; Allen and others, 1997). Volcaniclastic deposits, defined by Fisher and Schmincke (1984, p. 89) to include “all clastic volcanic materials formed by any process of fragmentation, dispersed by any transporting agent, deposited in any environment or mixed in any significant portion with non-volcanic fragments,” are an important component in most VMS deposits and include both pyroclastic deposits and reworked and redeposited volcanic material that may be intercalated with terrigenous sediment (Franklin and others, 2005). Differentiating between primary volcanic textures and reworked epiclastic textures in such rocks can be difficult.

Sedimentary rocks, including redeposited felsic volcaniclastic strata associated with the felsic volcanic host rocks, can help elucidate the mode of deposition of the felsic volcanic rocks (subaerial or submarine), water depth at the time of the submarine volcanic eruptions and VMS formation, and the stages of extension and subsidence in a continental-margin incipient rift. For example, sedimentary facies associations at the strongly deformed Zn-Cu massive sulfide deposits at Benambra, Australia, indicate that mineralization occurred in the center of an ensialic back-arc or intra-arc basin following fault-controlled subsidence in a mixed subaerial and subaqueous environment with active rhyolitic volcanism, through a marine shelf environment with limestone-volcaniclastic sedimentation, to a moderate- to deep-water environment with mudstone and turbidite sedimentation and rhyolite to basaltic volcanism (Allen, 1992). The massive sulfides formed in siltstone within a proximal (near-vent) facies association of a mainly nonexplosive, moderate- to deep-water submarine volcano composed of turbiditic sediments interleaved with rhyolitic to basaltic sills, lavas, and associated hyaloclastites during the advanced stage of extension and subsidence (Allen, 1992).

Interpreting the mode of emplacement of deep-marine silicic volcanic rocks, especially those that have undergone significant alteration, metamorphism, and deformation, is controversial, however, and debates regarding the possibility of deep-marine, explosive silicic volcanism have continued for decades. Some studies proposed that ignimbrites in subaqueous environments are confined to shallow-water, near-shore environments at water depths of tens of meters or less because higher confining pressures under deeper water conditions would impede vesiculation and hence explosive eruption (for example, Cas and Wright, 1987; Allen, 1988). Others concluded, however, that considerable volumes of pumiceous tephra were deposited directly into the marine environment at significant depths (>1.4 km) (for example, Fiske and Matsuda, 1964; Busby-Spera, 1984; Cashman and Fiske, 1991; Fiske and others, 2001; Busby and others, 2003). Depositional features of sedimentary rocks, especially volcaniclastic rocks, will play an important role in resolving this controversy for ancient VMS deposits.

Footwall sedimentary, as well as volcanic, strata can be important source rocks for VMS mineralization. For example, in the siliciclastic-felsic setting of the Bathurst district, the hydrothermal convective system that was responsible for forming the deposits extended into the prevolcanic, rift-related terrigenous sedimentary strata that disconformably underlie the volcanic sequence and VMS deposits (van Staal and others, 2003). The primary permeability and porosity of footwall lithofacies affect the movement of hydrothermal fluids and, thus, the distribution and development of semiconformable alteration zones. Regional semiconformable alteration assemblages are pervasive and widespread in permeable volcaniclastic and siliciclastic sedimentary facies of VMS deposits (Gifkins and Allen, 2001).

Differences in the primary permeability and porosity of volcanic and sedimentary lithofacies of VMS host rocks affect the morphology of their footwall alteration zones (Morton and Franklin, 1987; Gibson and others, 1999; Franklin and others, 2005). In VMS settings in which synvolcanic faults cut strata composed of unconsolidated volcaniclastic or siliciclastic rocks with high permeability and porosity, ascending hydrothermal fluids may defuse laterally away from the fault and discharge over a large area. If an aquaclude (such as subsurface, precipitated silica, clay, and minor sulfide minerals; fine-grained argillite; carbonaceous argillite; chert; and flows, sills, and cryptodomes within the volcaniclastic succession) develops within the footwall sequence, the initially poorly-focused discharge may become localized along structural conduits or may form discordant, broad, and locally stratiform footwall alteration zones (Franklin and others, 2005).

Porosity and grain size of sediments play an important role in the prevention of metal-bearing fluids dissipating onto the seafloor. Subseafloor accumulation and replacement provide an efficient mechanism to trap metals and may be responsible for forming large, tabular VMS deposits. Some components of the circulating hydrothermal fluid become trapped in hanging-wall sediments and seafloor precipitates, and elements such as Si (as chert) and conserved elements (Mn, Eu, P, Tl, and base and precious metals) accumulate in these sediments, forming useful vectors to potential ore (Franklin and others, 2005). The subseafloor VMS deposits form as sulfide minerals are precipitated within the preexisting pore spaces and fractures of volcanic or sedimentary rocks or as a result of the replacement of volcanic or sedimentary constituents in a chemically reactive host, such as carbonate (Doyle and Allen, 2003, and references therein). The most favorable sedimentary rocks for such subseafloor deposits are deep-marine, terrigenous clastic rocks such as sandstone and wacke; subseafloor deposition within mudstone lithofacies is uncommon. Therefore, VMS deposits hosted by volcanic successions that are dominated by volcaniclastic and (or) siliciclastic lithofacies are preferred targets (Franklin and others, 2005).

Rock Names

Bimodal-mafic-type VMS deposits (for example, Noranda, Canada; Gibson and Kerr, 1993) are associated with terrigenous sedimentary rocks that are dominated by immature wacke, sandstone, and argillite, with local debris flows; hydrothermal chert is also common in the immediate hanging wall to some deposits. Mafic-ultramafic type VMS deposits (for example, Troodos, Cyprus; Constantinou and Govett, 1973) generally contain <10 percent sedimentary rocks consisting primarily of sulfidic, reduced, or hematitic-oxidized argillite, chert, and (or) tuff (Franklin and others, 2005).

Siliciclastic-mafic-type VMS deposits occur in mature, oceanic, back-arc successions in which thick marine sequences of clastic sedimentary rocks and intercalated basalt are present in subequal or pelite-dominated proportions (Slack, 1993). Examples are in the Besshi and Shimoakawa districts of Japan (Banno and others, 1970; Mariko, 1988) and the Windy Craggy deposit of British Columbia, Canada (Peter and Scott, 1999). Sedimentary rocks characteristic of a pelitic lithofacies include argillite, carbonaceous argillite, subordinate siltstone, marl, and carbonate (bioclastic and chemical) (Franklin and others, 2005). Other associated clastic rocks may include arenite, arenite conglomerate, and turbiditic slate and sandstone. Metachert, magnetite iron-formation, coticule (fine-grained quartz-spessartine rock), and tourmalinite occur in or near many metamorphosed Besshi-type deposits and may have originated as a result of premetamorphic hydrothermal alteration or chemical precipitation synchronous with massive sulfide deposition (Slack, 1993).

Bimodal-felsic type deposits, such as those in the Paleoproterozoic Skellefte district, Sweden (Allen and others, 1997) and the mid-Paleozoic Finlayson Lake district, Canada (Murphy and others, 2006; Peter and others, 2007), formed within incipiently-rifted, continental-margin arcs and related back arcs and contain only about 10 percent terrigenous sedimentary strata (Franklin and others, 2005). Felsic volcanic rocks constitute the dominant lithology (35–70 percent of volcanic strata) with basalt making up 20–50 percent (Franklin and others, 2005). Submarine felsic volcaniclastic rocks are common in these districts and many of the felsic volcanic deposits were reworked by sedimentary processes. Common sedimentary rock types (or in many cases, the inferred sedimentary protoliths of metasedimentary rocks) intercalated with the volcanic rocks include rhyolitic tuffaceous siltstone and sandstone, carbonaceous siltstone and mudstone, feldspathic and quartzofeldspathic turbidite, sandstone, volcanic breccia-conglomerate, and volcaniclastic rocks with a lime matrix; limestone is rare by comparison.

Siliciclastic strata constitute up to 80 percent of the rocks associated with siliciclastic-felsic-type deposits, which form in a mature epicontinental back-arc setting, examples being the Iberian Pyrite Belt, Spain and Portugal (Carvahlo and others, 1999; Tornos, 2006), and Bathurst, Canada (Goodfellow and others, 2003). Franklin and others (2005) define a siliciclastic sedimentary lithofacies as one consisting predominantly of wacke, sandstone, argillite, siltstone, and locally iron-formation or Fe-Mn-rich argillite. Associated lithologies include felsic volcaniclastic rocks and minor flows, domes, and their intrusive equivalents (about 25 percent) and mafic flows, sills, and minor volcaniclastic rocks (about 10 percent). Argillaceous and carbonaceous sedimentary rocks and their phyllitic or schistose equivalents, as well as Fe-, Mn-, Ca-, and Ba-rich chemical sedimentary rocks, are common in the hanging wall of this deposit type (Franklin and others, 2005). Typical sedimentary rock types in the Iberian Pyrite Belt are shale (black, dark gray, green, and purple) graywacke, quartzwacke, impure quartzite, siliceous chemical sedimentary rocks (jasper or chert), and radiolarite; minor limestone occurs as lenses and nodules (Carvahlo and others, 1999).

Mineralogy

Given that the vast majority of VMS deposits and their host rocks have been metamorphosed, the mineralogy of (meta)sedimentary rocks associated with the various deposit types rarely preserves the primary clay-SiO_2-feldspar ± hornblende ± pyroxene mineralogy of the sediments and will vary according to metamorphic grade, as discussed in Chapter 17 of this report. Common detrital or matrix minerals present in the sedimentary rocks include quartz, phyllosilicates (for example, illite, kaolinite, chlorite, sericite, biotite, and muscovite, sequentially developed with increasing metamorphic grade), plagioclase, K-feldspar, carbonate minerals, detrital olivine, pyroxene and amphibole, and the metamorphic minerals that replace them (for example, epidote, titanite, ilmenite), and pyrite and (or) organic material/graphite. Magnetite, coticule, and tourmaline are characteristic minerals in chemically-precipitated sedimentary rocks in siliciclastic-mafic-type deposits.

Textures

Textures in sedimentary rocks associated with VMS deposits, where not subsequently modified by dynamothermal metamorphism, include soft-sediment deformation structures, rhythmic turbidite layering, graded beds, crossbedding, thinning or thickening of beds associated with synvolcanic faulting, rhythmic fine-scale banding of carbonaceous and volcanic laminae, bimodal size distribution of reworked volcaniclastic rocks (particularly those containing quartz phenocrysts), and poorly-sorted sedimentary breccias and conglomerates. Clastic textures are also present in the massive sulfide deposits. For example, in the Iberian Pyrite Belt, sedimentary structures such as graded bedding, crossbedding, sedimentary breccias, and slump structures are common in massive, laminated ores (Carvalho and others, 1999).

Grain Size

Grain sizes of the sedimentary rocks intercalated with VMS deposits or those present in the nearby submarine depositional environment range from submillimeter particles in fine-grained mudstones to clasts tens of centimeters in diameter in volcanic and sedimentary breccias/conglomerates within rift basins. Bimodal grain size distributions, particularly of quartz and feldspar, are common in epiclastic rocks derived from the remobilization of crystal tuffs or subvolcanic porphyry intrusions. Metamorphic recrystallization generally results in an increase in grain size, but this increase can be countered by comminution of grains during penetrative deformation and shearing. High-grade, postore regional or contact metamorphism can produce coarse-grained garnet, andalusite, cordierite, hornblende, or other minerals in originally fine-grained sedimentary rocks. Clastic sulfides eroded from chimneys and mounds generally consist of sand- to silt-sized grains in bedded deposits, and cobble- to boulder-sized clasts of massive sulfides occur rarely in debris-flow channel deposits, as discussed in Chapter 4 of this report.

Environment of Deposition

Sedimentary rocks associated with bimodal-mafic type VMS deposits were deposited within an incipiently rifted bimodal volcanic arc above an intraoceanic subduction zone. Sedimentary rocks in mafic-ultramafic type VMS deposits accumulated in a mature, intraoceanic, back-arc and related transform-fault setting or, less commonly, in an oceanic island or late-stage continental back-arc seamount environment (Franklin and others, 2005).

The geologic features of siliciclastic-mafic type deposits suggest that the best modern analogues are pyrrhotite-rich sulfide accumulations on and within thick sedimentary sequences overlying oceanic spreading ridges in the northeast Pacific, such as Guaymas Basin, Escanaba Trough, and Middle Valley

(Koski, 1990). In all of these modern-day analogues, eroded material from nearby continental landmasses provides a major component of the clastic sediment. Sedimentary fill in these modern analogues consists of turbidite muds, which may be intercalated with diatomaceous ooze, silt, arkosic sand, and local carbonaceous sediment (Slack, 1993, and references therein). Oceanic basalt and related mafic dikes and sills of MORB composition occur along the spreading ridges and are an important heat source for the hydrothermal circulation. Several tectonic settings contain the above elements: intracontinental rifts, rifted continental margins, oceanic spreading ridges near continental landmasses, back-arc basins, and a spreading ridge that is being consumed by a subduction zone (Koski, 1990; Slack, 1993). Sheet-like metalliferous sediments in the Red Sea also have been suggested as possible modern analogues of the siliciclastic-mafic type deposits (for example, Degens and Ross, 1969; Shanks and Bischoff, 1980; Pottorf and Barnes, 1983). There, hot metal-rich brines and the metalliferous sediments overlie tholeiitic basalt and evaporites and shales; current sedimentation consists mainly of calcareous mud (Shanks and Bischoff, 1980).

Sedimentary rocks associated with bimodal-felsic type deposits accumulated in incipiently-rifted continental margin arc and back-arc settings. The Paleoproterozoic Skellefte district, Sweden, exemplifies the complex and variable paleogeography in which magmatism, base-metal mineralization, and sedimentation have been documented for this deposit type (Allen and others, 1997). Changes in the intensity and location of marine volcanism resulted in subregional disconformities and differential uplift and subsidence that resulted in a complex system of horsts and grabens. Sedimentation in this horst and graben system varied in time and space and included prograding fluvial-deltaic sediments and mudstone and sandstone turbidites. Consequently, the massive sulfides in the Skellefte district are thought to have spanned a range in ore deposit styles from deep-water seafloor precipitation to subseafloor replacements, to shallow water and possibly subaerial synvolcanic replacements (Allen and others, 1997).

Siliciclastic-felsic type VMS deposits formed in a mature continental or epicontinental back-arc setting. Sedimentary rocks associated with this deposit type accumulated in an extending, submarine, fault-controlled basin with restricted circulation and reduced oxidation. Pre- or synvolcanic faults and their intersection with other regional structures played important roles in determining sites of volcanic centers and associated hydrothermal activity within the basins.

Cashman and Fiske (1991) conducted experiments on water-saturated pumice and rock fragments (lithics) and showed that particles settling to the seafloor at terminal velocities will display conspicuous bimodality of particle diameters: pieces of pumice can be five to ten times as large as co-deposited lithic fragments. They also showed that similar material that is erupted into the air and deposited on land has much less well-developed size bimodality, with pumice diameters being generally only two to three times as large as the associated lithics. As pointed out by Cashman and Fiske (1991), these textural differences may be used to infer a subaqueous origin for some of the great thicknesses of non-fossiliferous volcanic deposits in ancient volcanic terranes whose environment of deposition has been uncertain.

Constraints on the water depths of sedimentation associated with VMS deposits can be provided by sedimentologic features of stratigraphic sections above and below the deposits, by fossil assemblages, and by studies of fluid inclusions in the associated massive sulfide minerals. At the bimodal-mafic Bald Mountain deposit in northern Maine, for example, deep-water depositional conditions are suggested by a sedimentary sequence that lacks any wave-generated sedimentary structures; any in situ shallow-marine fauna and even any resedimented shallow-marine fauna; and any evidence for subaerial exposure, erosion, or fluvial sedimentation (Busby and others, 2003). Additional evidence cited by Busby and others for a deep-water environment at Bald Mountain is the presence of carbonaceous mudstones that occur throughout the section, which, typically, although not exclusively, form in deep-water environments >200 m deep (Pickering and others, 1989). These deep-water sedimentologic features are confirmed by fluid inclusion analyses of primary hydrothermal quartz in the Bald Mountain deposit that indicate a hydrostatic pressure corresponding to a paleowater depth of >1.45 km (Foley, 2003).

In contrast, stratigraphic evidence from the Mount Chalmers siliciclastic-felsic type VMS deposit—a massive sulfide plus footwall stockwork Cu-Au orebody in Queensland, Australia—indicates a shallow-water depositional setting at the time of mineralization (Sainty, 1992). Fossils identified from the Permian Chalmers sedimentary section consist of brachiopods, gastropods, bivalves, and bryozoans that show limited reworking and trace fossils typical of the Cruziana ichnofacies. These fossil assemblages indicate deposition below the effective wave base and suggest seawater depths of 200–300 m during deposition of the massive sulfides (Sainty, 1992). This shallow depth determination has important implications for the interplay between water depth, boiling of hydrothermal fluids, and the formation of VMS deposits. Ohmoto and Takahashi (1983) proposed that a marine environment with a minimum depth of 1,000 m was necessary to prevent the boiling of ascending hydrothermal fluids that would induce sulfide precipitation and the production of disseminated or vein-type deposits rather than the formation of massive stratiform ores. However, Sainty (1992) suggested that the sedimentologic evidence for a shallow-water depth allows for the possibility that ore-forming fluids may have boiled prior to reaching the seafloor, especially if there had existed constrictions or self-sealing of the fluid channelways, and that boiling may have resulted in the Cu-rich footwall stringer zone and the elevated salinities in fluid inclusions at Mount Chalmers (Large and Both, 1980). Sainty (1992) pointed out that, in spite of likely boiling of hydrothermal fluids at the Chalmers deposit, two massive sulfide lenses were formed, and that this interpretation is consistent with examples from modern massive sulfide systems in which boiling at greater seawater depths, such as at the Explorer Ridge

(1,850 m) and Axial seamount (1,540 m), is accompanied by the deposition of massive sulfides (Kappel and Franklin, 1989; Jonasson and others, 1990).

Carbonaceous shale is a common constituent of most VMS deposits, for example, in the Archean Kidd Creek deposit (Hannington and others, 1999), in the early Paleozoic Bathurst camp (Goodfellow and McCutcheon, 2003), and in the mid-Paleozoic Finlayson Lake district (Peter and others, 2007), the Bonnifield district (Dusel-Bacon and others, 2004), and the Iberian Pyrite Belt (Tornos, 2006). The presence of carbonaceous sediments is important in indicating—in most cases—anoxic, generally deep water conditions. The large tonnage, shale-hosted orebodies of the southern part of the Iberian Pyrite Belt are interpreted to have formed in suboxic to anoxic third-order basins in which upwelling, sulfur-depleted fluids mixed with modified seawater that was rich in biogenically reduced sulfur, leading to the precipitation of massive sulfides on the seafloor (Tornos, 2006). Evidence for this exhalative origin includes a stratiform morphology, an absence of major metal refining, an abundance of sedimentary structures, a lack of sulfates, and a common presence of siderite-rich facies (Tornos, 2006). Carbonaceous units within volcanic piles represent a hiatus in volcanism that is typically characterized by low-temperature hydrothermal activity that was favorable for the generation of massive sulfides. For example, in the Archean bimodal-mafic-type Kidd Creek deposit, carbonaceous sediments occur as interflow deposits throughout the Kidd Creek volcanic complex; carbon isotope data indicate that hydrothermal activity most likely occurred concurrently in several isolated subbasins within a much larger, graben-like setting (Wellmer and others, 1999). Studies of hydrothermal activity at Guaymas Basin, a modern analogue of a siliciclastic-mafic deposit, showed that the presence of abundant sedimentary organic matter (2–4 wt%) in basin sediments strongly influenced mineralogical alteration and the extent of chemical exchange within the oceanic crust, and that abundant C and S species in hydrothermal fluids and mineral deposits at sediment-covered spreading centers also strongly influenced pH, redox, and complexing reactions, which in turn directly constrained metal transport and depositional processes (Seewald and others, 1994, and references therein).

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