17. Petrology of Metamorphic Rocks Associated with Volcanogenic Massive Sulfide Deposits

By Cynthia Dusel-Bacon

Volcanogenic Massive Sulfide Occurrence Model

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Importance of Metamorphic Rocks to Deposit Genesis

Metamorphic rocks associated with VMS deposits are described in terms of their metamorphic rock names, metamorphic mineral assemblages, and metamorphic facies. A succinct definition of a metamorphic facies, provided by Turner (1981, p. 54), states it to be "a set of metamorphic mineral assemblages, repeatedly associated in space and time, such that there is a constant and therefore predictable relation between mineral composition and bulk rock chemical composition." Table 17–1 shows relationships among the various metamorphic facies and characteristic metamorphic mineral assemblages that develop in four principal bulk compositions during conditions of a given metamorphic facies. Locations of the most common metamorphic facies in pressure (P) and temperature (T) space are shown in figure 17–1.

The majority of ancient VMS deposits have been affected by regional metamorphism and deformation. Analysis of metamorphic grades reported by Mosier and others (2009) for 1,090 VMS deposits from throughout the world indicates that of the 819 deposits for which data were available, only 3 percent were reported as being unmetamorphosed. The rest were metamorphosed under the conditions of the following metamorphic facies (in decreasing frequency of occurrence): 62 percent greenschist facies; 13 percent contact metamorphism; 11 percent amphibolite facies; 7 percent sub-greenschist, prehnite-pumpellyite, or pumpellyite-actinolite facies; 2 percent blueschist- or eclogite-facies; 1.5 percent zeolite facies; and 0.5 percent granulite facies.

Coarse-grained suites of distinctive, upper greenschist- to amphibolite-facies minerals, including chloritoid, garnet, staurolite, kyanite, andalusite, phlogopite, and gahnite (zincian spinel), and upper amphibolite- to granulite-facies minerals such as sillimanite, cordierite, orthopyroxene, and orthoamphibole can define VMS hydrothermal alteration zones (for example, Morton and Franklin, 1987; Bonnet and Corriveau, 2007, and references therein). Aluminous minerals (garnet, chloritoid, staurolite, or the Al_2SiO_5 polymorphs kyanite, andalusite, and sillimanite) commonly occur close to high-temperature alteration pipes (Carpenter and Allard, 1982;

Sillitoe and others, 1996; Galley and others, 2007), reflecting residual enrichment of alumina during premetamorphic hydrothermal leaching of alkalis under high fluid/rock conditions. Using visual identification of distinctive metamorphic minerals and their modal abundances, and determining the unaltered composition of the precursor rock, alteration vectors can be constructed on major-element ternary diagrams that identify the configuration of the fossil hydrothermal alteration zones in VMS systems (Bonnet and Corriveau, 2007). Immobile major and trace-element whole-rock data can indicate whether the aluminous metamorphic minerals resulted from premetamorphic seafloor alteration/metasomatism of the protolith or from primary protolith composition (for example, Barrett and MacLean, 1999). The mineral chemistry of some alteration-associated metamorphic minerals, such as the Fe/Zn ratio of staurolite, also can serve as a vector to ore (Spry and Scott, 1986a). Because many of these metamorphic minerals are refractory during sedimentation, they have the potential to occur in heavy mineral separates collected in till-covered areas and, consequently, are valuable exploration aids for VMS districts (for example, Averill, 2001).

Estimation of pressure and temperature (P/T) conditions calculated from silicate, carbonate, and sulfide mineral assemblages in a given deposit can help determine the relationship between base-metal mineralization and metamorphism, specifically whether metamorphism pre- or postdated ore genesis. The pyrrhotite (sphalerite-pyrite) thermometer of Froese and Berman (1994) has been used by some workers to estimate peak metamorphic temperatures of sulfide assemblages, but Currie and others (2003) found that their results using this thermometer were unsatisfactory and speculated that partial inversion of pyrrhotite from hexagonal to monoclinic form had disturbed the distribution of FeS. The sphalerite geothermometer, based on the FeS content of sphalerite coexisting with pyrite and pyrrhotite, was used in the 1950s through the 1970s, but it is not reliable. However, the FeS content of sphalerite in pyrrhotite-sphalerite-pyrite assemblages can be useful for constraining pressure during metamorphism, with the caveat that care must be taken in order to characterize sphalerite paragenesis and identify sphalerite compositions that record peak metamorphic conditions and not later retrograde effects (Toulmin and others, 1991).

Table 17–1.   Characteristic minerals for principal rock composition types in the various metamorphic facies. Modified from Blatt and others (2006).

[Al, aluminum; Ca, calcium; Mg, magnesium]

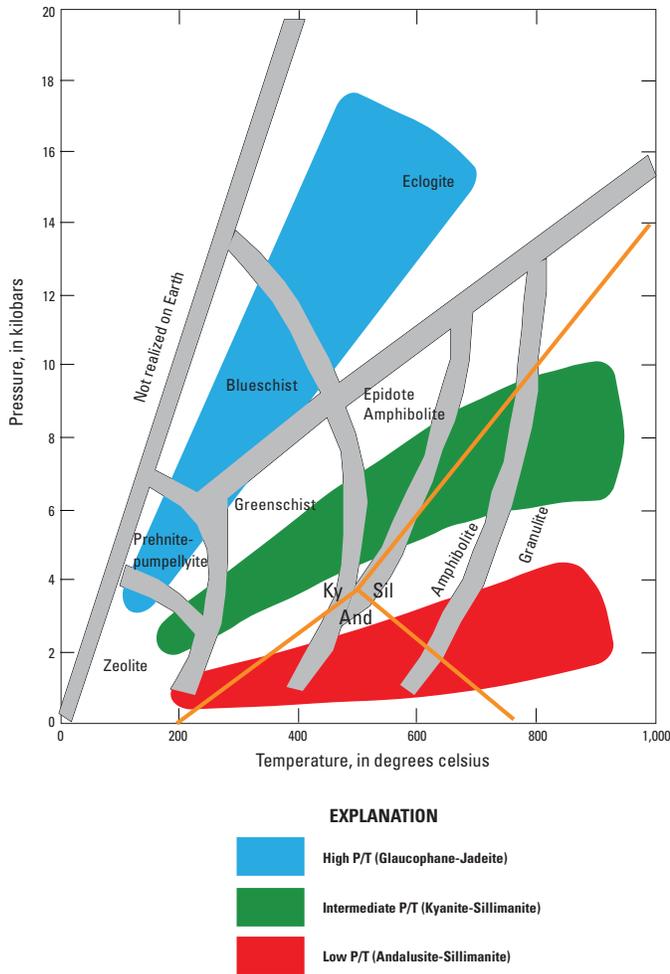| Facies	Mafic rocks	Ultramafic rocks	Pelitic rocks	Calcareous rocks
Zeolite	Analcime, Ca-zeolites, zoisite, albite	Serpentine, brucite, chlorite, dolomite, magnesite	Quartz, clays, illite, albite, chlorite	Calcite, dolomite, quartz, talc, clays
Prehnite-pumpellyite	Chlorite, prehnite, albite, pumpellyite, epidote	Serpentine, talc, forsterite, tremolite, chlorite	Quartz, illite, muscovite, albite, chlorite, stilp-nomelane	Calcite, dolomite, quartz, clays, talc, muscovite
Greenschist	Chlorite, actinolite, epidote or zoisite, albite	Serpentine, talc, tremolite, brucite, diopside, chlorite, magnetite	Quartz, plagioclase, chlo-rite, muscovite, biotite, gar-net, pyrophyllite, graphite	Calcite, dolomite, quartz, muscovite, biotite
Epidote-amphibolite	Hornblende, actinolite, epidote or zoisite, plagioclase, sphene	Forsterite, tremolite, talc, serpentine, chlorite, magnetite	Quartz, plagioclase, chlorite, muscovite, biotite, graphite	Calcite, dolomite, quartz, muscovite, biotite, tremolite
Amphibolite	Hornblende, plagioclase, sphene, ilmenite	Forsterite, tremolite, talc, anthophyllite, chlorite, o thopyroxene, magnetite	Quartz, plagioclase, chlorite, muscovite, biotite, garnet, staurolite, kyanite, sillimanite, andalusite, graphite, ilmenite	Calcite, dolomite, quartz, biotite, tremolite, forsterite, diopside, plagioclase
Granulite	Hornblende, augite, orthopyroxene, plagioclase, ilmenite	Forsterite, orthopyroxene, augite, hornblende, garnet, Al-spinel	Quartz, plagioclase, orthoclase, biotite, garnet, cordierite, sillimanite, orthopyroxene	Calcite, quartz, forsterite, diopside, wollastonite, humite-chondrodite, Ca-garnet, plagioclase
Blueschist	Glaucophane, lawsonite, albite, aragonite, chlorite, zoisite	Forsterite, serpentine, diopside	Quartz, plagioclase, muscovite, carpholite, talc, kyanite, chloritoid	Calcite, aragonite, quartz, forsterite, diopside, tremo-lite
Eclogite	Mg-rich garnet, omph cite, kyanite, rutile	Forsterite, orthopyroxene, augite, garnet	Quartz, albite, phengite, talc, kyanite, garnet	Calcite, aragonite, quartz, forsterite, diopside
Albite-epidote	Albite, quartz, tremolite, actinolite, chlorite	Serpentine, talc, epidote or zoisite, chlorite	Quartz, plagioclase, tremo-lite, cordierite	Calcite, dolomite, epidote, muscovite, chlorite, talc, forsterite
Hornblende hornfels	Hornblende, plagioclase, orthopyroxene, garnet	Forsterite, orthopyroxene, hornblende, chlorite, Al spinel, magnetite	Quartz, plagioclase, mus-covite, biotite, cordierite, andalusite	Calcite, dolomite, quartz, tremolite, diopside, fors-terite
Pyroxene hornfels	Orthopyroxene, augite, plagioclase, garnet	Forsterite, orthopyroxene, augite, plagioclase, Alspinel	Quartz, plagioclase, orthoclase, andalusite, sillimanite, cordierite, orthopyroxene	Calcite, quartz, diopside, forsterite, wollastonite
Sanidinite	Orthopyroxene, augite, plagioclase, garnet	Forsterite, orthopyroxene, augite, plagioclase	Quartz, plagioclase, sillimanite, cordierite, orthopyroxene, sapphirine, Al-spinel	Calcite, quartz, diopside, forsterite, wollastonite. monticellite, akermanite

Figure 17-1. Pressure/temperature diagram showing the principal eight metamorphic facies; the Al_2SiO_5 polymorphs kyanite (Ky), andalusite (And), and sillimanite (Sil) (after Holdaway, 1971); and the three major types of pressure/temperature facies series (after Spear, 1993).

Another important piece of information that can be gleaned from the study of metamorphic rocks associated with VMS deposits is the identification of metamorphic protoliths (parent rock types). In many instances, it is difficult to see through the metamorphic overprint of the deposits and host rocks, but knowledge of the protolith assemblages is essential to reconstruction of the lithologic association at the time of mineralization and, in turn, the tectonic setting of the deposit. Trace elements and rare earth elements (REE) known to be immobile during low- to moderate-grade metamorphism (below upper amphibolite- to granulite-facies conditions) include Nb, Ta, Zr, Ti, Cr, and Y. These immobile elements are especially useful for identifying the magmatic compositions of metamorphosed igneous rocks associated with VMS deposits and for providing important information on the heat flow and tectonic environment of VMS formation (see Lentz, 1998;

Barrett and MacLean, 1999; Piercey and others, 2001; Piercey, 2009).

Finally, exploration of VMS ores within regionally metamorphosed and deformed sequences can be financially advantageous for the following reasons: (1) metamorphic recrystallization and concomitant increase in grain size and purity of the sulfide minerals (and in some cases nonmetallic minerals, such as kyanite within alteration zones) make their liberation and concentration easier and less costly; (2) ores typically are thicker in the hinge zones of folds, thus facilitating mining methods; and (3) selective mobilization during metamorphism can result in local enrichment of metal grades (Vokes, 1969, 2000; Marshall and others, 2000; Gauthier and Chartrand, 2005).

Rock Names

Depending on metamorphic grade, common rock types associated with VMS deposits that were derived by the metamorphism of mafic rocks are greenschist (chlorite-rich schist), greenstone, metagabbro, metadiabase, and amphibolite. Rocks derived by the metamorphism of sedimentary rocks include argillite, slate, phyllite, quartz-mica schist, metagraywacke, metaconglomerate, quartzite, limestone, marble, and calc-silicate. Quartzofeldspathic or mafic gneiss can be derived from either sedimentary or igneous protoliths.

Wall rocks (host rocks) typically associated with siliciclastic-mafic-type VMS deposits contain the most distinctive lithologies, which may include metachert, magnetite iron-formation, sericite- and chlorite-rich schist, coticule (fine-grained quartz-spessartine rock), tourmalinite, albitite, and rarely marble. Chlorite- and muscovite-rich rocks, albitite, and magnetite iron-formation commonly form stratabound lenses or envelopes around the massive sulfide ores and can extend to as much as 10 m into the adjacent country rock. Thin, stratiform layers of coticule, tourmalinite, and metachert can extend for some distance into the stratigraphic hanging wall or laterally for hundreds of meters beyond the massive sulfide deposits (Slack, 1993). Characteristic country rock associated with, but spatially more distal to, the siliciclastic-mafic type massive sulfide deposits and their adjacent wall rocks typically include pelitic schist, metagraywacke, and greenstone or amphibolite, depending on the degree of postore metamorphism.

Mineralogy and Mineral Assemblages

Many of the mineral assemblages that developed during seafloor hydrothermal alteration associated with the formation of VMS deposits are similar to those that may form during postore, regional, low-grade (zeolite, prehnite-pumpellyite, and greenschist facies) metamorphism (Franklin and others, 2005). Syngenetic alteration zones are generally semiconformable to the deposits and can extend up to tens of kilometers along strike and below the paleoseafloor to the depths of

subvolcanic intrusions. Semiconformable alteration has been documented in bimodal-mafic successions (for example, Noranda: Gibson and others, 1983), mafic-ultramafic dominated successions (for example, Oman: Koski and others, 2003), and bimodal-felsic successions (for example, Kuroko: Ohmoto and others, 1983) but is poorly documented in felsic-siliciclastic- and siliciclastic-mafic successions (Franklin and others, 2005). Metamorphic minerals developed at low metamorphic grades include chlorite, quartz, epidote, zoisite, clinozoisite, sericite, albite, titanite, and carbonate, depending on protolith composition. In addition to these common, low-temperature minerals, zeolite minerals (for example, analcime, laumontite, celadonite, and heulandite) typically form in the cavities or vesicles of volcanic rocks at zeolite-facies metamorphic grade, generally at temperatures less than about 250 °C. Prehnite-pumpellyite facies conditions are transitional between those of the lower grade zeolite facies and the higher grade greenschist facies and generally occur in temperature and pressure ranges of about 250–350 °C and 2–7 kbar, respectively. Characteristic mineral assemblages of the prehnite-pumpellyite facies that developed in mafic and ultramafic igneous rocks and in pelitic (mud-rich) and calcareous sedimentary rocks are shown in table 17–1.

The distribution of the mineralogical and geochemical characteristics of the low-grade assemblages can be used to identify large-scale, zoned hydrothermal alteration systems around VMS deposits and to differentiate them from superimposed, low-grade, postore regional metamorphic assemblages. Typically, broad zones of semiconformable alteration will show increases in Ca-Si (epidotization-silicification), Ca-Si-Fe (actinolite-clinozoisite-magnetite), Na (spilitization), or K-Mg (mixed chlorite-sericite ± K-feldspar) (Galley and others, 2007). In a simple system, alteration assemblages are distributed with depth from near-surface diagenetic and zeolite assemblages to a spilitic greenschist-facies assemblage, and eventually to an epidote-quartz assemblage. However, in a long-lived, convective hydrothermal system, overprinting of alteration assemblages during progressive alteration and burial occurs (Franklin and others, 2005), complicating the interpretation of alteration or metamorphic textures. Regardless of these complexities, the distribution and relationship of chlorite-rich schists and sericite-rich schists in the wall rocks to VMS deposits can indicate the presence of primary alteration zones that developed during submarine mineralization. For example, Slater and others (1985) suggested that chlorite schists in the Ducktown VMS deposits were metamorphosed chloritic feeder pipes in the footwall to the deposits, and that the sericite-rich schists formed by the metamorphism of alteration zones analogous to those that are common in the hanging wall of Kuroko deposits. Identification of alteration zoning patterns can be difficult, however, given that the alteration pipes may extend beyond the ore deposit and merge laterally and (or) vertically with semiconformable alteration zones, and that the metamorphosed feeder pipes and semiconformable alteration zones can include similar metamorphic mineral assemblages (Franklin, 1984; Morton and Franklin, 1987.) Chloritoid- and staurolite-bearing assemblages can result from greenschist- to amphibolite-facies metamorphism of Al-Fe-Mg-rich alteration pipes or semiconformable alteration zones (Morton and Franklin, 1987; Spear, 1993).

Fossil hydrothermal zones are also recognizable by diagnostic mineral assemblages developed in VMS districts that have been metamorphosed under upper amphibolite- and granulite-facies conditions (Morton and Franklin, 1987; Bonnet and Corriveau, 2007). Diagnostic greenschist- and granulite-facies mineral assemblages developed in different

Table 17–2.   Diagnostic mineralogy and major-element geochemistry of greenschist- and granulite-grade metamorphosed alteration products associated with volcanogenic massive sulfide deposits. From Bonnet and Corriveau (2007).

[Fe, iron; Mg, magnesium]

Alteration type	Diagnostic minerals: greenschist facies	Diagnostic minerals: granulite facies	Diagnostic composition	Similar rocks (at granulite facies)
Advanced argillic	Kaolinite, pyrophyllite, andalusite, corundum, topaz	Sillimanite, kyanite, quartz	Al_2O_3, SiO_2	Laterite
Argillic	Sericite, illite, pyrophyllite	Sillimanite, kyanite, quartz, biotite, cordierite, garnet	Al_2O_3, SiO_2, K_2O, Fe_2O_3, MgO	Pelite
Sericitic	Sericite, illite, quartz	Biotite, K-feldspar, sillimanite, kyanite, quartz, cordierite, garnet	K_2O, Al2O3, Fe_2O_3, ± MgO, ± SiO_2	Pelite
Chloritic	Chlorite, quartz, sericite	Cordierite, orthopyroxene, orthoamphibole, phlogopite, sillimanite, kyanite	Fe_2O_3, MgO, ± Al_2O_3, ± SiO_2	Pelite
Carbonate propylitic	Carbonate (Fe, Mg), epidote, chlorite, sericite, feldspar	Carbonate, grossular, epidote, hornblende, diopside, orthopyroxene	Fe_2O_3, CaO	Calc-silicate rock of sedimentary origin, marble or mafic rock

hydrothermal alteration types, as well as in unaltered proto-liths, are given in table 17–2. Bonnet and Corriveau (2007) caution that recognition of sericitic, argillic, and advanced argillic hydrothermal alteration zones in granulite-facies gneissic terranes is severely hampered by the resemblance of their metamorphic mineral assemblages to those developed in unmineralized sedimentary rocks and paleosols that were metamorphosed under granulite-facies conditions (table 17–2); they accordingly recommend that identification of VMS-type hydrothermal alteration be based not only on distinctive meta-morphic mineral assemblages, but also on field observations of relict primary volcanic structures and textures and field indica-tors of hydrothermal activity, such as the presence of meta-exhalites, stockworks, or sulfide mineralization. Recognition of metamorphosed chlorite in footwall alteration pipes is more straightforward and it is commonly expressed as cordierite, orthopyroxene, and orthoamphibole (anthophyllite or gedrite) in the inner alteration zone, where the chlorite may be more Mg-rich, and by talc, phlogopite, or one of the Al_2SiO_5 poly-morphs, in the outer, locally Fe-rich chlorite alteration zone (Morton and Franklin, 1987; Bonnet and Corriveau, 2007).

Most of the upper amphibolite- and granulite-facies, polydeformed alteration systems have been identified in Pro-terozoic and Archean gneissic terranes (Morton and Frank-lin, 1987; Roberts and others, 2003; Bonnet and Corriveau, 2007). The Archean Geco deposit, a bimodal-mafic-type VMS deposit in the Superior province in Canada, is an example of a polydeformed, upper amphibolite-facies deposit in which syngenetic hydrothermal alteration is indicated by zones of abundant sillimanite, anthophyllite, garnet, and cordierite. All of the volcanic rocks in the Geco deposit are metamorphosed to schist and gneiss, and felsic metavolcanic rocks that host the ore consist predominantly of muscovite + quartz ± sillimanite schist, interpreted as metamorphosed sericitic alteration zones (Friesen and others, 1982; Zaleski and Peterson, 1995). In addition to the development of Al-, Fe-, and Mg-rich assem-blages during the metamorphism of alteration zones, plagio-clase-rich rocks associated with some of the orebodies in the siliciclastic-mafic-type Ducktown and Gossan Lead VMS districts have been interpreted as metamorphosed sodic altera-tion zones (Nesbitt, 1979; Gair and Slack, 1984). Mapping of the intensity and distribution of anthophyllite, cordierite, sillimanite, garnet, quartz, muscovite, and staurolite also led to identification of footwall alteration zones and the discovery of the bimodal-mafic Archean Winston Lake deposit, Ontario (Severin and others, 1984; Morton and Franklin, 1987; Thomas, 1991; Bonnet and Corriveau, 2007).

Metamorphic mineral assemblages indicate not only relict VMS-type hydrothermal systems and T and P conditions dur-ing metamorphism, but also the thermal gradient and, hence, the crustal environment in which metamorphism occurred (fig. 17–1). A low geothermal gradient characterizes meta-morphism in subduction zones with high-pressure, blueschist-facies metamorphism (glaucophane + lawsonite or epidote + albite ± chlorite) at low temperatures, and eclogite-facies

metamorphism (garnet + omphacitic pyroxene) at high tem-peratures. Glaucophane-bearing, blueschist-facies assemblages have overprinted the Devonian-Mississippian Arctic deposit in northern Alaska (Hitzman and others, 1986) and the Jurassic–Lower Cretaceous VMS deposits in Cuba (Russell and others, 2000). An example of the high-temperature end of this high-pressure facies series is the amphibolite- to eclogite-facies metamorphism that overprinted the Paleoproterozoic rocks of the Sylarna deposit in Sweden (Grenne and others, 1999).

An intermediate geothermal gradient characterizes metamorphism in continental collisions and orogenic belts (fig. 17–1). Barrovian metamorphic zones, formed under these conditions, are defined by the sequential appearance in pelitic rocks, with increasing metamorphic grade, of chlorite, biotite, garnet, staurolite, kyanite, sillimanite, and sillimanite + K-feldspar. The Ducktown mining district, Tennessee, a siliciclastic-mafic-type VMS deposit in the Blue Ridge meta-morphic province, was metamorphosed under greenschist- to amphibolite-facies conditions in a Barrovian metamorphic series. The known sulfide deposits of this district are restricted to the staurolite-kyanite zones (Nesbitt and Essene, 1982; Slater and others, 1985). Metamorphism occurred during the Taconic (450–480 Ma) orogeny and conditions ranged from chlorite grade in the west to staurolite (-kyanite) grade in the east (Slater and others, 1985). Pyrrhotite, the dominant sulfide, is present as stringers parallel to metamorphic cleav-ages and appears to have formed from pyrite during regional metamorphism; coarse euhedral pyrite porphyroblasts as much as 30 cm in diameter within the pyrrhotitic ore reflect prolonged growth during metamorphism (Brooker and others, 1987). Textural features and variations of sulfides present in the country rocks with increasing metamorphic grade have been interpreted to record significant remobilization of the sulfide constituents during regional metamorphism (Runyon and Misra, 1981; Slater and others, 1985). The bimodal-mafic, Archaen Izok Lake deposit in Northwest Territories, Canada, is an example of a deposit metamorphosed under granulite-facies conditions—the high-temperature end of an intermedi-ate thermal gradient (Franklin and others, 2005).

A steep geothermal gradient characterizes metamorphism in island arcs, ocean ridges, and contact aureoles (fig. 17–1). Characteristic minerals formed in pelitic rocks in this low P/T setting define Buchan metamorphic zones in which biotite → cordierite → andalusite → sillimanite. Synmetamorphic intrusions, including those in extensional settings, are com-monly heat sources for Buchan-type metamorphism. More localized metamorphism in the vicinity of an igneous intrusion can result in a contact aureole of mineral zones around the heat source; minerals developed during contact metamorphism (hornfels) may include the same minerals that formed during regional Buchan metamorphism but, depending on the degree of synplutonic deformation, contact metamorphic minerals may be texturally distinct in lacking a preferred orientation. However, the division between Buchan and contact metamor-phism is artificial in some settings, such as in Maine, where

metamorphic isograds are subparallel to the margins of plutons and metamorphism is best described as regional contact metamorphism (for example, Guidotti, 1989). Mosier and others (2009) list numerous deposits in Kazakhstan (for example, Kusmurun), Uzbekistan (for example, Kuldara), and China (for example, Bieluwutu) that experienced postore recrystallization during contact metamorphism.

In addition to deciphering thermal conditions from metamorphic minerals in host rocks, certain sulfide minerals preferentially recrystallize with increasing metamorphic grade. For example, zincian spinel (($Zn,Fe,Mg)Al_2O_4$) can form from either metamorphism of Zn-oxide phases, desulfidation of sphalerite, or the breakdown of Zn-bearing silicates such as staurolite (Heimann and others, 2005, and references therein); pyrrhotite ($Fe_{1-x}S$) can form from higher temperature recrystallization of pyrite (FeS_2). The composition of zincian spinel has been shown to be an effective exploration guide to metamorphosed massive sulfide deposits (Spry and Scott, 1986b; Heimann and others, 2005). However, Heimann and others (2005) demonstrated that the composition of the host rocks and the alteration types present in a given deposit should be considered when choosing the spinel compositions to be used as an exploration guide, especially where the rocks are magnesian.

Deformation and Textures

Basaltic rocks affected by low-grade, seafloor metamorphism generally preserve relict igneous textures, whereas those recrystallized during subsequent regional dynamothermal metamorphism show variable degrees of mineral alignment into planar fabrics. In sedimentary rocks, it may be difficult to differentiate between primary soft sediment deformation on the seafloor and postore regional deformation and folding. The presence of brittle deformational features in a deposit is one indication of postore chilling of the hydrothermal system prior to deformation and, consequently, would argue against deformation being synchronous with deposition of the VMS deposit. Textures, such as aluminous nodules in high-grade quartzofeldspathic gneiss and lapilli or larger block fragments in associated aluminous gneiss adjacent to clearly recognizable metamorphosed lapillistone units with similar sized fragments, are fairly reliable evidence of prior VMS-type hydrothermal alteration (Bonnet and Corriveau, 2007). Detailed thermochronology of the igneous crystallization ages of metaigneous host rocks associated with VMS deposits is required in order to differentiate between host rocks to VMS submarine mineralization and tectonically-juxtaposed lithologies that originated distant from the site of mineralization. Determination of metamorphic cooling ages for various host rock minerals that have a range of blocking temperatures also plays a crucial role in constraining the postore thermal and deformational history of VMS deposits.

Most VMS districts have been affected by fold-and-thrust-belt style deformation because the mineral belts formed in short-lived extensional basins near plate margins, which became inverted and deformed during subsequent basin closure (Allen and others, 2002; Tornos and others, 2002). Examples of folded, faulted, and sheared VMS deposits are given in the section of this report covering physical descriptions of the deposits. As mentioned above, one result of folding, which has the potential to be of great significance for mining operations, is that an originally relatively thin layer of ore can be thickened to economically viable dimensions. The most common explanation for thickening of the sulfide mass is flow of sulfides into fold hinges during deformation. However, some workers have pointed out the controlling effect that could be exerted on fold localization by a mass of sulfides already present in the rocks being deformed (Vokes, 2000).

A discussion of the deformational and metamorphic fabrics and textures developed in sulfide assemblages present in VMS deposits is beyond the scope and focus of this chapter, but excellent overviews are given in numerous publications (for example, Stanton, 1960; Craig and Vokes, 1993; Vokes, 1969, 2000; Marshall and Gilligan, 1993; Marshall and others, 2000).

Grain Size

The grain size of metamorphic rocks associated with VMS deposits generally increases with metamorphic grade and also is dependent on the metamorphic protolith. Likewise, the grain size of associated sulfides in a deposit varies as a function of the primary mineralogy and the extent of metamorphic recrystallization. Primary sulfide minerals of most Zn-Pb-Cu deposits are fine grained and intergrown, whereas those of the majority of Cu-Zn deposits are generally coarser grained (Franklin, 1993). The form and grain size that sulfide minerals take during metamorphic recrystallization depends on the pressure and temperature conditions during metamorphism, the nature of the fluid phase, and the deformational properties of the minerals (for example, Stanton, 1960; Craig and Vokes, 1993). In general, progressive regional metamorphism appears to cause an increase in the grain size of sulfide ores, provided deformation has not been too intense (Vokes, 1969). Very coarse (3–7 cm diameter) garnets are present in a distinctive schist unit at the Elizabeth mine, Vermont. Although the garnets formed as a result of heat supplied during the postore, regional Acadian (Early Devonian) metamorphism, the bulk composition required to produce them came about as a result of pre-Acadian subseafloor metasomatism (Slack, 1999; Slack and others, 2001). Large hornblende crystals, as much as 10 cm long, also are present at the Elizabeth mine (Slack and others, 2001).

Examples of Information Gained from Study of Metamorphic Rocks Associated with Volcanogenic Massive Sulfide Deposits

In their study of the siliciclastic-mafic type massive sulfide deposits of the Vermont Copper Belt, Slack and others (2001) obtained major, minor, and trace-element geochemical data for mineralogically unusual amphibolite-facies wall rocks located within 80 m of the Elizabeth mine orebodies and compared those data to compositions of unaltered metasedimentary and metabasaltic (amphibolite) wall rocks in the district. Bulk-rock contents of immobile elements indicated an exhalative origin for coticule, metachert, and iron-formation. Geochemical data for the other unusual lithologies in the district—quartz-muscovite-carbonate-staurolite-corundum schist and quartz-tourmaline-albite rock—suggested that these rocks are tholeiitic basalts that underwent extensive seafloor alteration and metasomatism prior to Acadian metamorphism (Slack, 1999). Evidence for their basaltic origin consists of high Cr contents and chondrite-normalized REE patterns that are broadly similar to those of unaltered metabasalt from the wall rocks. In addition to high Cr, some rocks are highly enriched in alumina, which Slack and others (2001) attributed to mass loss of other components during extreme premetamorphic hydrothermal alteration. Because the massive sulfides in the Vermont Copper Belt also have very low contents of relatively immobile elements such as Cr, Zr, and REE, Slack and others (2001) concluded that the sulfide bodies lack significant sedimentary or basaltic components and therefore did not form by subseafloor replacement of clastic sediments or mafic volcanics. Instead, they concluded that the massive sulfides originally precipitated by syngenetic-exhalative processes on the seafloor during Silurian and Early Devonian times.

Immobile trace-element and REE whole-rock data have successfully identified the metamorphic protoliths of rocks associated with several other siliciclastic-mafic type VMS deposits. Precursors of chlorite schists and granoblastic albitites from the Gossan Lead deposits, Virginia, were shown to be similar to those of the adjacent unaltered metasedimentary schists, suggesting that the chlorite schists and albitites were derived by hydrothermal metasomatism of clastic marine sediments and not from syngenetic precipitation of chemical exhalites (Gair and Slack, 1984). A clastic marine sedimentary origin was also indicated by trace element and REE ratios for chlorite schists, biotite schists, muscovite schists, and albitites adjacent to sulfide ores of the Ducktown deposits, Tennessee (Gair, 1988; Robinson and Gair, 1992). Geochemical data for chlorite- and biotite-rich schist from wall rocks to the Matchless deposit, Namibia, suggested that these rocks originated as tholeiitic basalt that was subsequently metasomatized (Klemd and others, 1989). Although the majority of the metabasaltic rocks associated with siliciclastic-mafic-type VMS deposits have chemical compositions of oceanic tholeiites, some

greenstones and amphibolites associated with these deposits, including those in the Sambagawa belt of Japan and Windy Craggy, Canada, have trace-element signatures indicative of alkalic, within-plate basalt (Slack, 1993, and references therein).

Thermobarometry of host rocks and sulfides, together with structural studies, have yielded important information regarding the timing of metamorphism, deformation, and formation of sulfide deposits. In a detailed study of the conditions of metamorphism of sulfide deposits and associated host rocks in the Bathurst mining camp, New Brunswick, Currie and others (2003) documented that greenschist-facies metamorphic conditions for the silicate assemblages occurring within, and in the host rocks of, the deposit were identical to those of the sulfide assemblages. This congruence of P/T conditions shows that the deposits formed prior to peak metamorphism during the first metamorphic episode, consistent with a syngenetic origin for the Bathurst deposits. Sphalerite barometry, applied to the appropriate sphalerite-pyrite-hexagonal pyrrhotite assemblages, gave consistent pressures between various structural nappes. Peak metamorphic temperatures, provided by arsenopyrite and chlorite-phengite thermometry, also were consistent between the Bathurst deposits and the structural nappes in which they occur. The narrow range of P/T conditions determined for the Bathurst deposits supports independent structural observations and suggests that the nappes were assembled and internally deformed prior to the first metamorphic episode (Currie and others, 2003, and references therein).

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