10. Exhalites

By John F. Slack

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

Suggested citation:
Slack, J.F., 2012, Exhalites in volcanogenic massive sulfide occurrence model: U.S. Geological Survey Scientific Investigations Report 2010–5070 –C, chap. 10, 6 p.

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Geometry and Spatial Distribution

The term exhalite refers to “exhalative” chemical sedimentary rock, following the first usage by Ridler (1971). Exhalites are stratiform beds or lenses of rock that are spatially associated with VMS deposits (Sangster, 1978; Franklin and others, 1981; Spry and others, 2000; Peter, 2003). Most workers consider exhalites to record the precipitation of mainly amorphous Fe ± Mn ± Si ± S ± Ba ± B phases from VMS-related hydrothermal vents and plumes (Peter and Goodfellow, 1996; Peter and others, 2003a; Grenne and Slack, 2005). Exhalites characteristically occur in proximal settings within hanging-wall strata above the sulfide deposits, and (or) as marginal aprons at approximately the same stratigraphic level. Distal exhalites, hundreds of meters or more along strike from VMS deposits, also may be present, although discerning their genetic relationship to specific sulfide horizons can be difficult. Less common are exhalites occurring in footwall sequences below the sulfide zones. Some siliceous beds such as the Main Contact Tuff in the Noranda district of Quebec (Kalogeropoulos and Scott, 1989) and the Key Tuffite in the Matagami district of Quebec (Liaghat and MacLean, 1992) have been interpreted as exhalites; however, based on studies of modern VMS systems, it is likely that these beds did not form by plume fallout but instead by widespread diffuse venting and related silicification of tuffaceous units on the seafloor or in the shallow subsurface.

Modern exhalites have been found in the vicinity of several VMS systems. Examples of proximal exhalites include those on the Mid-Atlantic Ridge (see Metz and others, 1988). Modern distal exhalites are represented by the Fe ± Mn sediments that surround many seafloor VMS deposits (TAG; German and others, 1993) and by far-field metalliferous sediments such as those in the Bauer Deep and on the East Pacific Rise (Heath and Dymond, 1977; Barrett and others, 1987; Hein and others, 1997; Koski and others, 2003b). In ancient settings, Algoma-type iron formations (Gross, 1996) likely formed through fallout from neutrally buoyant plumes in distal environments, relative to VMS systems, and are recognized in both Precambrian and Phanerozoic volcanic sequences (see Goodwin, 1973; Peter, 2003). Manganese-rich umbers like those in the Cretaceous ophiolite on Cyprus probably have a similar origin (Robertson and Hudson, 1973; Ravizza and others, 1999). A caveat here is that detrital sulfide-rich turbidites or similar reworked sulfidic sediment, deposited far from a VMS deposit as on the modern Mid-Atlantic Ridge (Metz and others, 1988), does not reflect fallout from a hydrothermal plume.

Most exhalites are tabular in form and conformable to bedding within enclosing volcanic or sedimentary strata (Spry and others, 2000; Galley and others, 2007). Common thicknesses range from a few centimeters to as much as several meters. In many cases, proximal exhalites are thickest directly above sulfide zones and become progressively thinner with increasing distance from a deposit. Distal exhalites tend to have uniform thicknesses over strike lengths of tens to hundreds of meters, except in areas of inferred uneven seafloor topography and where affected by postdepositional faulting or folding. A very thick (20–30 m) proximal exhalite forms a tabular layer directly above pyritic massive sulfide at the Bald Mountain deposit in Maine, where a bowl-shaped graben structure promoted the accumulation of both thick sulfide zones and overlying Si-Fe deposits (Slack and others, 2003). At the United Verde deposit in the Jerome district, Arizona, an exhalative jasper approximately 30 m thick overlies the massive sulfide deposit (Lindberg, 2008, fig. 3). An even thicker exhalite occurs at the Baiyinchang deposit in western China, forming a mound-shaped lens 30–50 m thick above altered rocks in the hanging wall sequence (Hou and others, 2008). Such thick exhalites may have played an important role during evolution of some VMS deposits by confining heat and hydrothermal fluids in the subsurface, which in turn promoted subseafloor sulfide mineralization and related zone refining (Barriga and Fyfe, 1988; Slack and others, 2003). Based on modeling studies, Schardt and Large (2009) suggested that cap rocks aid in the formation of Zn-rich deposits by preventing the dissolution of anhydrite and Zn sulfides by late hydrothermal fluids. In some cases, siliceous cap rocks above VMS deposits did not form by exhalation onto the seafloor but instead by epigenetic replacement in the subsurface (Jones and others, 2006).

Strike lengths vary greatly depending on several factors, but in areas of good outcrop and (or) coverage by drill core, some exhalites are known to extend for several kilometers or more. Such laterally extensive exhalites are well documented in the Løkken district of central Norway, where beds of sulfide- and silicate-facies iron formation (“vasskis”) and jasper have been traced at the same stratigraphic levels for 3–5 km

(Grenne and Slack, 2005), as well as in the Bathurst district of New Brunswick, Canada, where some beds of oxide-carbonate-silicate iron formation extend >10 km along strike (Peter and Goodfellow, 1996). More commonly, however, field exposures limit the map continuity of exhalites to only a few hundred meters.

Mineralogy and Zoning

Diverse mineral facies of exhalites have been recognized, the most common of which are oxide, carbonate, sulfide, silicate, and sulfate, each being based on the predominant type of mineral component. Figure 10–1 shows simplified cross sections of VMS deposits and different types of related exhalites, their morphologies and facies, likely origins, and examples. Exhalites may be divided into the following types:

6. oxide facies, consisting of jasper, hematite iron formation, and magnetite iron formation;
7. carbonate facies, which includes one or more Fe-Mg-Ca-Mn carbonates such as siderite, ankerite, dolomite, calcite, rhodochrosite, and kutnahorite;
8. silicate facies, comprising iron-rich minerals (such as greenalite and stilpnomelane), magnesian minerals (such as talc and chlorite), manganese-rich minerals (such as spessartine garnet), and boron-rich minerals (such as tourmaline);
9. sulfide facies, chiefly composed of pyrite and (or) pyrrhotite with only minor base-metal sulfides (chalcopyrite, sphalerite, galena); and
10. sulfate facies, which comprises barite and, in a limited number of deposits, anhydrite and gypsum.

Another facies type is chert and metachert, a widespread exhalite composed mainly of microcrystalline quartz that, in some deposits, forms a cap rock above the massive sulfide body (Gemmell and Large, 1992; Slack and others, 2003; Jones and others, 2006). Other exhalite facies that contain abundant fluorite, apatite, gahnite, or Zn-staurolite are uncommon to rare in the geologic record. Although proximal exhalites containing appreciable chalcopyrite and(or) sphalerite may occur within several hundred meters of a VMS deposit, because of chemical and hydrodynamic processes during plume fallout, distal pyrite- and pyrrhotite-rich sediments may instead be a reflection of euxinic (sulfidic) bottom waters (Grenne and Slack, 2005).

Vertical and lateral mineralogical zoning occurs in many exhalite units. Typical are multiple layers or laminations composed of different proportions of hydrothermal components, in many cases intermixed or alternating with detrital material including pelagic clay and locally-derived volcaniclastic sediment. Layers may vary in thickness from <1 mm to as much as 1 m; many exhalites display fine-scale laminations of alternating mineral facies (see Spry and others, 2000; Peter and others, 2003b). Lateral zoning of minerals is not as well documented but is known in some districts, such as the Bathurst camp, New Brunswick, where siderite is most abundant near VMS deposits within a major iron formation unit of the Brunswick belt (Peter and Goodfellow, 1996), and a variety of constituents including carbonate, stilpnomelane, and apatite are most abundant in iron formations proximal to sulfide deposits of the Heath Steele belt (Peter and Goodfellow, 2003).

Base-metal sulfide minerals may show a zoning pattern in oxide-facies exhalites. Studies of modern seafloor precipitates from hydrothermal plumes indicate that proportions and grain sizes of such sulfides tend to decrease with increasing distance

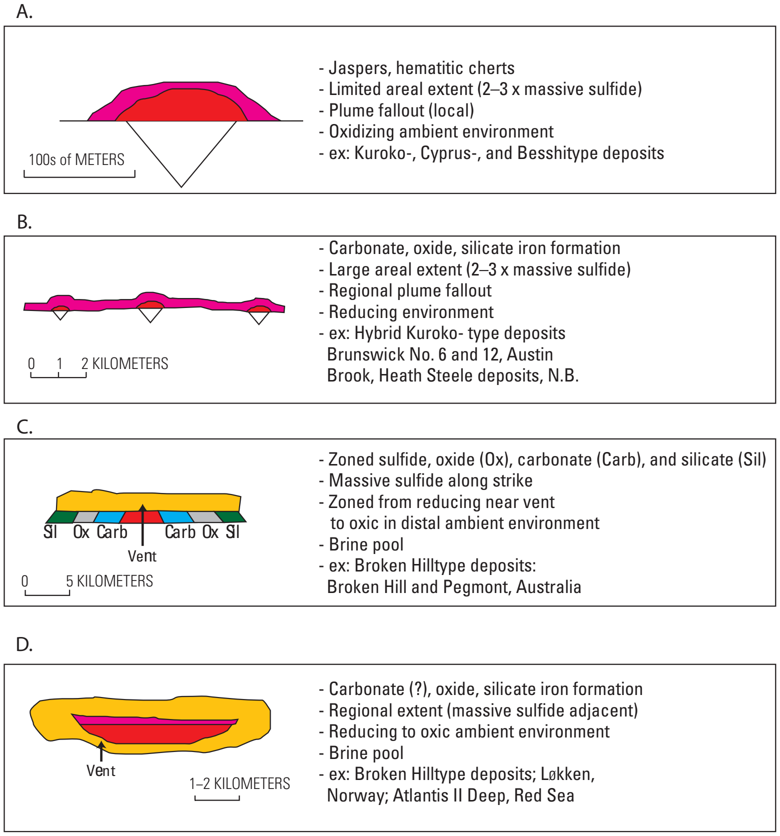

Figure 10–1. Simplified cross sections of volcanogenic massive sulfide deposits showing different types and morphologies of exhalites, with examples. *A*, Proximal jasper and hematitic chert overlying mound-like deposit. *B*, Proximal and distal (regionally extensive) iron formation occurring immediately above and along strike from deposits. *C*, Zoned iron formation, grading outward from inner sulfide-facies to carbonate-facies to oxide-facies to silicate-facies. *D*, Iron formation occurring immediately above a sheetlike deposit. Modified from Peter (2003).

from a vent site and that at distances of >1 km from a vent any sulfides present are volumetrically very minor in small grains <10 µm in diameter (Feely and others, 1994; German and Von Damm, 2003). Noteworthy are very large “superplumes” or “event plumes” in modern seafloor-hydrothermal systems (Baker, 1998), which could have formed widespread exhalite deposits in the ancient geologic record.

Protoliths

Owing to postdepositional effects of diagenesis and metamorphism, original hydrothermal components of exhalites may be largely or totally removed by such processes. In the case of oxide-facies iron formation, primary phases are widely believed to have been amorphous ferric-oxyhydoxide based on their occurrence in modern hydrothermal settings, including in plumes and plume-derived sediment (for example, Peter and others, 2003a). A similar precursor is inferred for the iron-rich component of jasper, with the quartz component being derived from amorphous silica of predominant seawater origin (Grenne and Slack, 2005). Crystalline hematite that occurs in ancient VMS-related jasper and iron formations is considered a product of diagenesis and (or) metamorphism, because in modern settings hematite only forms from moderate-temperature (>115 °C) fluids (Hein and others, 2008), whereas in plume settings the ambient temperatures of iron precipitation are much lower (typically <10 °C) and thus below the stability of hematite. Magnetite iron formation, where unrelated to diagenetic or metamorphic transformation of hematite, is likely to have originated by subseafloor alteration of primary ferric oxyhydroxide by nonredox processes (Ohmoto, 2003). Discerning the primary phase(s) in silicate-facies exhalites is more difficult because their stability is governed by a complex set of parameters including temperature, pH, fO_2, fCO_2, etc. (see Klein, 2005). Especially challenging is determining the protolith of spessartine-quartz rocks (coticules; Spry, 1990), which may have precursors of Mn-rich carbonate and clay, or Mn-oxyhydroxide and clay, depending on physicochemical conditions on and near the paleoseafloor (Slack and others, 2009, and references therein). Protoliths of various types of carbonate-, sulfide-, and sulfate-facies exhalites are generally considered to be similar or identical to the presently observed mineral assemblages for samples at or below lower greenschist grade metamorphic conditions.

Geochemistry

Many geochemical studies have been carried out on exhalites both to evaluate their origin and to determine possible use in mineral exploration. The former goal has focused recently on attempts to constrain the redox state of coeval bottom waters during deposition of protoliths to the exhalites (see Goodfellow and others, 2003), especially for Precambrian seafloor-hydrothermal systems (Slack and others, 2007, 2009). Exploration applications have been proposed by many workers, but few studies provide compelling guidelines, in part because of the need for extensive outcrops or drill cores in order to establish a thorough sampling distribution relative to a known hydrothermal source. Gale and others (1997) analyzed Archean exhalites in the Canadian shield for rare earth elements (REE) and suggested that the presence of positive Eu anomalies, in shale-normalized diagrams, indicates proximity to a VMS deposit. Detailed studies by Peter and Goodfellow (2003) showed that the highest Fe/Mn ratios in chlorite, stilpnomelane, siderite, and sphalerite along the Heath Steele belt occur near the B Zone sulfide deposit and that use of a hydrothermal sediment index, based on bulk compositions of exhalites, can be an effective guide to known sulfide mineralization. Grenne and Slack (2005) also showed that in seafloor-hydrothermal jaspers of the Løkken district, Norway, As/Fe and Sb/Fe ratios both decrease systematically away from an inferred major VMS vent site. Modern analogs of such Fe-Mn-Si exhalites show a range of bulk compositions including variations in REE and trace elements related to varying proportions of hydrothermal, hydrogenous, and detrital components (see Mills and Elderfield, 1995; Koski and others, 2003a).

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