3. Historical Evolution of Descriptive and Genetic Knowledge and Concepts

By W.C. Pat Shanks III

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Volcanogenic Massive Sulfide Occurrence Model

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3. Historical Evolution of Descriptive and Genetic Knowledge and Concepts

By W.C. Pat Shanks III

Massive sulfide deposits of base metal sulfides are among the earliest metallic ore deposits known and extracted because of their high grade, strong contrast with country rocks, iron staining and gossans at the surface, and their relatively simple mining and extraction. However, understanding the timing and mode of emplacement of these deposits proved much more difficult, and it was not until the second half of the twentieth century that several lines of evidence, not the least being the discovery of hydrothermal activity on the modern seafloor, conspired to convince researchers and explorationists that these deposits form syngenetically at or slightly beneath the seafloor by hydrothermal exhalative processes.

Most workers in the nineteenth century believed massive sulfide deposits, including many that would later be recognized as VMS deposits, formed by fissure-filling and (or) selective hydrothermal replacement. The source of the fluids was controversial, with some researchers favoring lateral-secretion from country rocks and some favoring fluids from granitoid intrusives (Stanton, 1984). Emmons (1909) studied so-called segregated vein deposits in the Appalachians from Newfoundland to Georgia and established that many of the deposits were formed prior to regional metamorphism. He noted the complete gradation from schistose country rock to sulfide-schist laminations to massive sulfide, and concluded that the country rock and interbedded and massive ore are all of the same age. Despite these seminal observations and interpretations, most workers accepted epigenetic theories, and even Emmons switched to a selective-replacement theory for Ducktown ores (Emmons and Laney, 1911). The work of Lindgren (1913) emphasized magmatic hydrothermal replacement theories and was very influential, especially in North America.

In the 1950s, discoveries of stratiform volcanic-hosted massive sulfides in the Bathurst area of New Brunswick opened the door for syngenetic interpretations (Stanton, 1959). These ideas coincided with the emergence of the exhalative theory as applied to massive sulfide deposits of the Norwegian and Irish Caledonides (Oftedahl,1958; Dunham,1964).

Though still controversial in some quarters, the modern era of studies of volcanic exhalative massive sulfides emerged in the 1960s through a combination of new discoveries and new exposures, improved radiometric dating, fluid inclusion studies, new stable and radiogenic isotope studies, work on continental hot springs (White and others, 1963), and, in particular, discovery of modern seafloor hydrothermal activity (Miller and others 1966; Bischoff, 1969; Edmond and others, 1979; Hekinian and others, 1980; Spiess and others, 1980).

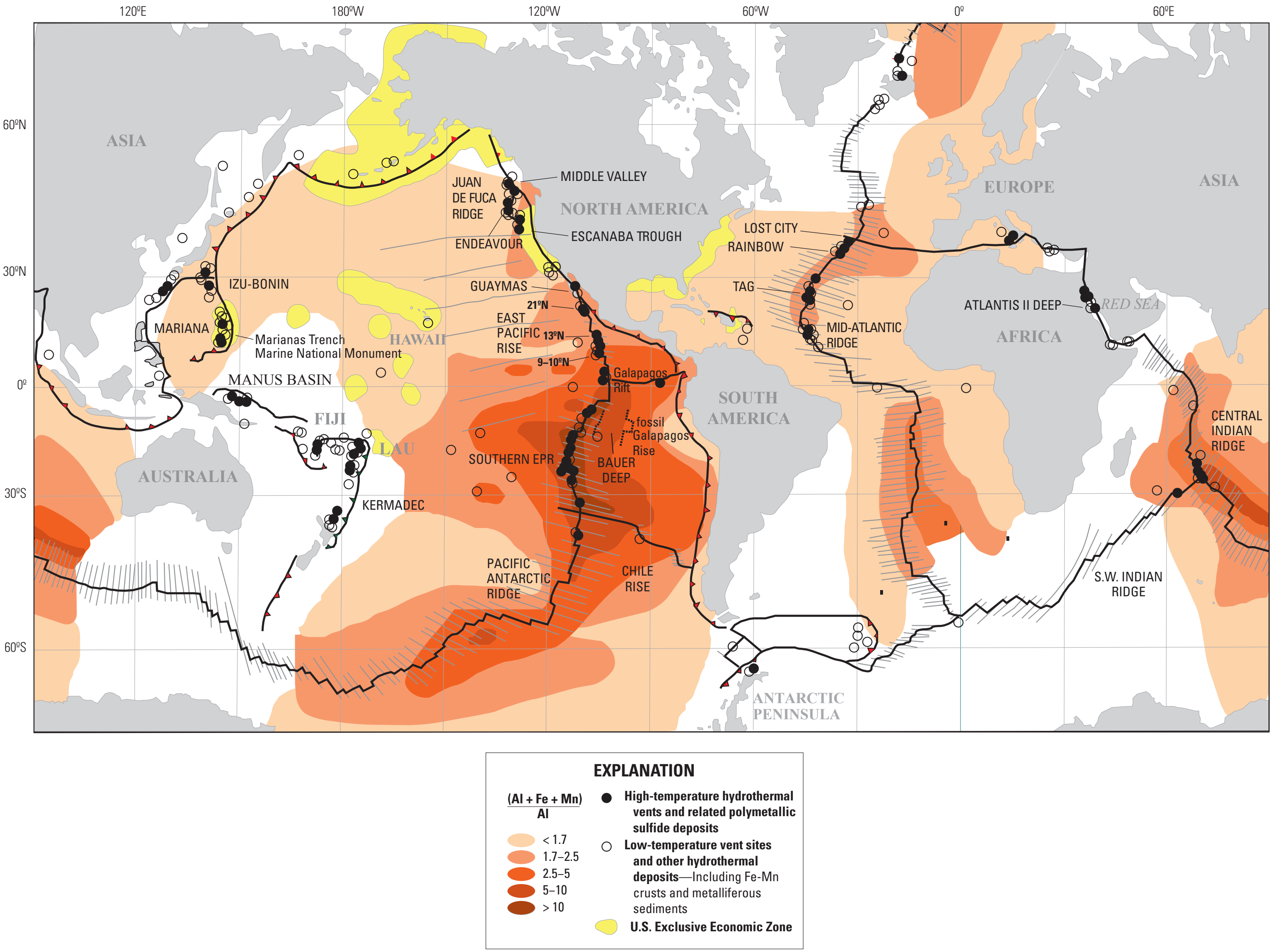
Hydrothermal Activity and Massive Sulfide Deposit Formation on the Modern Seafloor

The recognition of abundant and widespread hydrothermal activity and associated unique lifeforms on the ocean floor is one of the great scientific discoveries of the latter half of the twentieth century. Studies of seafloor hydrothermal processes led to advances in understanding fluid convection and the cooling of the ocean crust, the origin of greenstones and serpentinites, and the origin of stratiform and statabound massive sulfide deposits. Suggestions of possible submarine hydrothermal activity date from the late 1950s when a number of investigators debated the importance of “volcanic emanations” as a factor in the widespread occurrence of manganese nodules and other ferromanganese oxide deposits on the seafloor. For example, Arrhenius and Bonatti (1965), in their classic paper “Neptunism and Vulcanism in the Oceans,” stated the following:

> The origin of authigenic minerals on the ocean floor has been extensively discussed in the past with emphasis on two major processes: precipitation from solutions originating from submarine eruptions, and slow precipitation from sea water of dissolved elements, originating from weathering of continental rocks. It is concluded that in several marine authigenic mineral systems these processes overlap. (p. 7)

Boström and Peterson (1966), in another classic paper, published evidence for extensive and widespread Fe-rich metalliferous sediments on the seafloor with a distribution strongly correlated with the mid-ocean ridges (fig. 3–1). They stated:

> On the very crest of the East Pacific Rise, in equatorial latitudes—particularly 12° to 16°S, the sediments are enriched in Fe, Mn, Cu, Cr, Ni, and Pb.



Distribution of Seafloor Metalliferous Sediment, Massive Sulfide Deposits, and Hydrothermal Vents

Modified after Hannington and others (2007) and Bostrom and others (1969)

Figure 3–1. Map of seafloor tectonic boundaries, metalliferous sediment distribution (modified from Boström and Peterson, 1966), locations of seafloor hydrothermal vents and deposits (modified from Hannington and others, 2005), and distribution of U.S. Exclusive Economic Zones. [Al, aluminum; Fe, iron; Mn, manganese]

> The correlation of these areas of enrichment to areas of high heat flow is marked. It is believed that these precipitates are caused by ascending solutions of deep-seated origin, which are probably related to magmatic processes at depth. The Rise is considered to be a zone of exhalation from the mantle of the earth, and these emanations could serve as the original enrichment in certain ore forming processes. (p. 1258)

At about the same time, the discovery of hot brine pools on the floor of the Red Sea (fig. 3–1) indicated the possibility of direct precipitation of metalliferous sediments (fig. 3–2) from hydrothermal brines on the seafloor (Miller and others, 1966; Bischoff, 1969, Hackett and Bischoff, 1973). This discovery more than any other resulted in a revolution in the field of ore genesis and a reassessment of the origin of massive sulfide deposits.

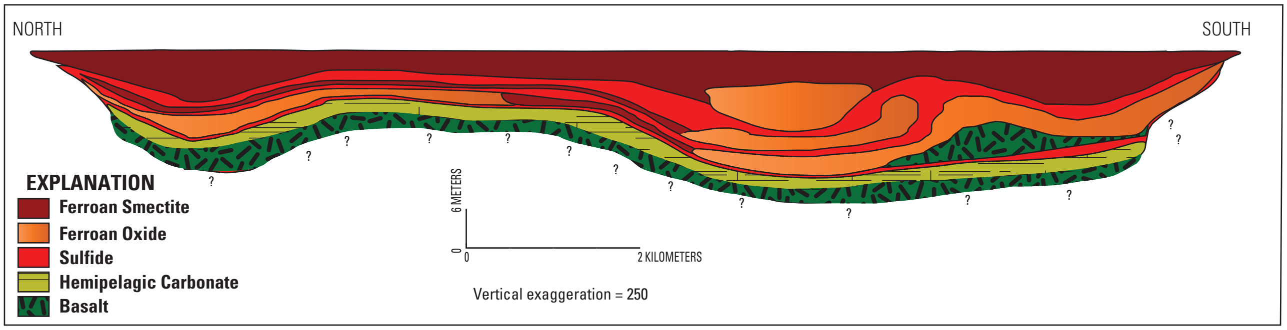
Following the Red Sea discoveries, several lines of evidence from mid-ocean ridge studies and laboratory experiments on basalt-seawater reaction (Bischoff and Dickson, 1975) indicated that seawater circulation through and reaction with ocean crust, owing to convective heating by subseafloor magma chambers, played a dominant role in the formation of ore-depositing fluids. These investigations set the stage for the discoveries of active hydrothermal vents and related sulfide deposits on mid-ocean ridges, island-arc volcanoes, and back-arc spreading centers. Active and inactive hydrothermal vent systems and hydrothermal deposits on the modern seafloor are more abundant than anticipated, especially considering that only a small percentage of the ocean ridge and convergent margins have been explored in detail. Over 300 sites with evidence of significant past or present seafloor hydrothermal activity are now known (Hannington and others, 2005).

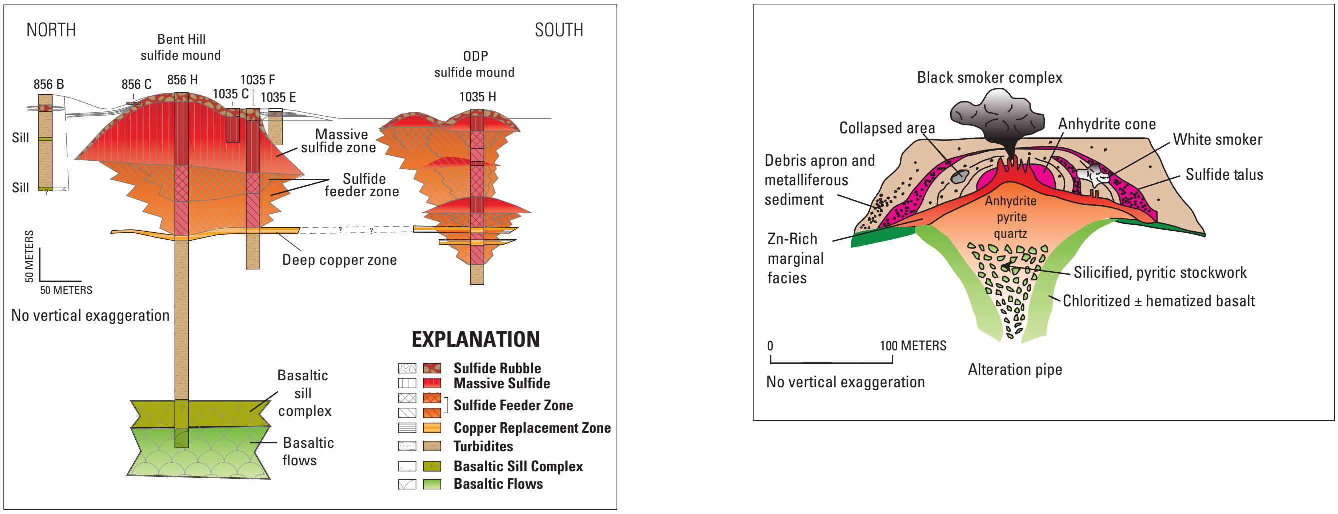
In addition to the Red Sea brine deposits, several large (millions of tons), high-metal-grade deposits are now known on the mid-ocean ridges (fig. 3–2), including the Trans-Atlantic Geotraverse (TAG) site on the Mid-Atlantic Ridge (Humphris and others, 1995), the Middle Valley site (Zierenberg and others, 1998) on the northernmost Juan de Fuca Ridge, and the 12°43’ N site slightly east of the East Pacific Rise (Fouquet and others, 1996).

In the back-arc extensional environment of eastern Manus Basin, massive sulfide deposits with high concentrations of Cu, Zn, Au, Ag, Pb, As, Sb (antimony), and Ba (fig. 3–2) are hosted by calc-alkaline rocks ranging in composition from basalt to rhyolite. These deposits have been sampled and drilled for exploration purposes (Binns and Scott, 1993), and high grades and significant tonnages have spurred some companies to complete environmental studies, and develop seafloor mining technology, and seek permits in anticipation of mining (Herzig, 1999; Baker and German, 2007; Kunzig, 2009). All of these studies confirm the interpretation of a genetic kinship between modern seafloor deposits and ancient VMS deposits.

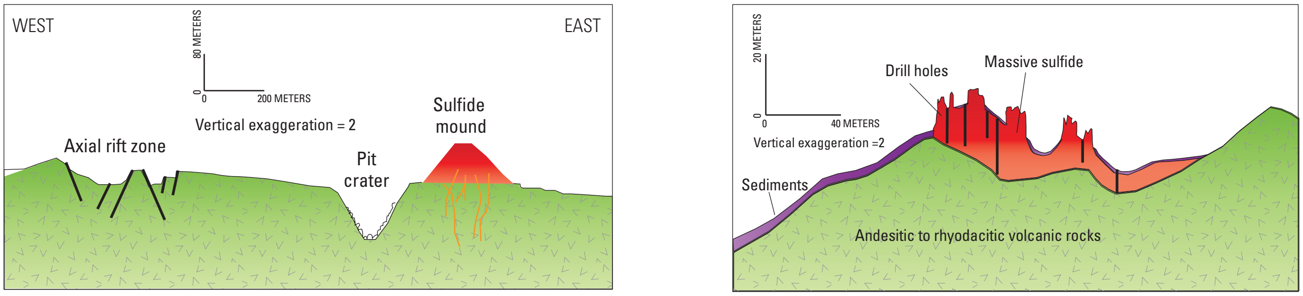
Studies of deposits on the continents have proceeded in concert with seafloor discoveries. Applications of chemical and isotopic methods, interpretations of physical volcanology and tectonic settings, and increasingly sophisticated fluid inclusion studies have improved understanding. The recognition of ophiolites as fossil oceanic crust formed at seafloor spreading centers (Gass, 1968) was accompanied by the realization that associated massive sulfide deposits were syngenetic with their host volcanic strata (Hutchinson, 1965; Constantinou and Govett, 1973). Studies of Kuroko deposits in Japan established them as volcanic exhalitive in origin (Lambert and Sato, 1974; Ohmoto and Takahashi, 1983). Besshi-type deposits were recognized as deformed stratiform deposits (Fox, 1984; Slack, 1993), and deposits from Archean and Proterozoic greenstone belts, especially in northern Ontario, were recognized as volcanogenic (Gilmour, 1965; Franklin and others, 1981).

A. Mineralogic Facies of Metalliferous Sediment beneath the Atlantis II Deep Brine Pool, Red Sea




B. Middle Valley Massive Sulfide System

C. TAG Sulfide-Sulfate Mound, Mid-Atlantic Ridge


D. 12°43'N EPR sulfide mound

E. Solara-1 massive sulfide deposit, Eastern Manus Basin

Figure 3–2. Representative examples of large seafloor massive sulfide deposits. *A*, Cross-section of metalliferous mud facies, Atlantis II Deep, Red Sea (after Hackett and Bischoff, 1973). *B*, Cross-section of Bent Hill and Ocean Drilling Program (ODP) mound massive sulfide deposits, Middle Valley, Juan de Fuca Ridge (after Zierenberg and others, 1998). *C*, Trans-Atlantic Geothermal (TAG) sulfate-sulfide mound, Mid-Atlantic Ridge (after Hannington and others, 1998). *D*, 13°N sulfide mound, East Pacific Rise (after Fouquet and others, 1996). *E*, Solara-1 massive sulfide deposit, eastern Manus Basin (after Baker and German, 2007).

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