The abundance of seafloor massive sulfide deposits

ARTICLE *in* GEOLOGY · DECEMBER 2011

Impact Factor: 4.64 · DOI: 10.1130/G32468.1

4 AUTHORS, INCLUDING:

John W Jamieson
Helmholtz Centre for Ocean Research Kiel

Thomas Monecke
Colorado School of Mines

Sven Petersen
Helmholtz Centre for Ocean Research Kiel

The abundance of seafloor massive sulfide deposits

Mark Hannington[1], John Jamieson[1], Thomas Monecke[2], Sven Petersen[3], and Stace Beaulieu[4]
[1]Department of Earth Sciences, University of Ottawa, Ottawa K1N 6N5, Canada
[2]Department of Geology and Geological Engineering, Colorado School of Mines, Golden, Colorado 80401, USA
[3]Leibniz Institute of Marine Sciences, IFM-Geomar, 24148 Kiel, Germany
[4]Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543, USA

ABSTRACT

The possibility of mining seafloor massive sulfide deposits has stirred debate about the sustainable use of this new resource and whether commercial development is worth the risk. Among the outstanding questions is how many deposits might be accessible to deep-sea mining. More than 300 sites of high-temperature hydrothermal venting have been identified since the discovery of black smokers, but significant massive sulfide accumulation has been found at only 165 of these sites. Estimates of the total number of vent fields and associated mineral deposits, based on plume studies and deposit occurrence models, range from 500 to 5000. We have used new deposit occurrence data from 10,000 km of ridge, arc, and backarc spreading centers to estimate the amount of massive sulfide in the easily accessible neovolcanic zones of the global oceans. The total accumulation in these areas is estimated to be on the order of 6×10^8 tonnes, containing ~3×10^7 tonnes of copper and zinc. This is similar to the total discovered copper and zinc in Cenozoic massive sulfide deposits mined on land but is insufficient to satisfy a growing global demand for these metals.

INTRODUCTION

The discovery of submarine hydrothermal vents at the Galápagos Rift in 1977 began a period of intensive seafloor exploration that continues today. Within five years of finding the first black smokers at 21°N East Pacific Rise, more than 50 sites of hydrothermal venting and seafloor massive sulfide deposits were known on the mid-ocean ridges; by the early 1990s more than 150 sites had been discovered (Rona and Scott, 1993). Because the ocean floor covers more than 70% of Earth's surface, many expect the oceans to contain a proportionate amount of the world's mineral resources, comparing the resource potential of seafloor massive sulfide deposits to that of deposits that are now mined on land for Cu, Zn, Pb, Ag, and Au (Rona, 2003; Cathles, 2010). Significant accumulations of metals from hydrothermal vents are found in the oceans, such as the metalliferous sediments in the Atlantis II Deep of the Red Sea (91.7×10^6 tonnes of 2.06% Zn and 0.46% Cu; Guney et al., 1988). Even more metal is contained in manganese nodules. The global resource of copper in nodules has been estimated at ~7×10^8 tonnes (U.S. Geological Survey, 2010), and a number of countries, including China, Japan, Korea, Russia, France, and Germany, are actively exploring for nodules in the Pacific. However, recent developments suggest that the first deep-sea mining of base metals will likely be from the much smaller, higher-grade massive sulfide deposits in the neovolcanic zones of ridges, volcanic arcs, and backarc basins. One commercial company has already been granted a license to exploit massive sulfide deposits in the Bismarck Sea of Papua New Guinea, adding urgency to the debate about deep-sea mining (Hoagland et al., 2010; Van Dover, 2011).

A growing global database of seafloor hydrothermal systems (Beaulieu, 2010) is beginning to provide the first clues to the size of this potential new resource. In previous studies (Hannington and Monecke, 2009; Hannington et al., 2010), we examined the factors controlling the occurrence, distribution, and sizes of seafloor massive sulfide deposits and used these general characteristics to identify areas of the oceans that are permissive for massive sulfide accumulation. Here, we analyze a subset of the best-studied deposits to estimate undiscovered mineral potential in the neovolcanic zones of the global oceans. The analysis follows a routine that is now in widespread use in mineral resource assessments on land (Singer and Menzie, 2010).

GLOBAL DISTRIBUTION OF SEAFLOOR MASSIVE SULFIDE DEPOSITS

Almost all seafloor massive sulfide deposits have been found at the plate boundaries, where there is a strong spatial and temporal correlation between magmatism, seismicity, and high-temperature hydrothermal venting (Fig. 1). The plate boundaries have a total strike length in the oceans of 89,000 km, including oceanic spreading centers (64,000 km) and submarine volcanic arcs and backarc basins (25,000 km; Bird, 2003; de Ronde et al., 2003). Although most of the deposits have been found on the mid-ocean ridges (65%), many also occur along the volcanic arcs (12%) and at backarc spreading centers (22%).

The global incidence of seafloor hydrothermal activity is closely linked to the magmatic budgets of each of these different settings. This accounts for the general correlation between spreading rates and the incidence of hydrothermal vents on the mid-ocean ridges (Baker et al., 1996). On fast-spreading ridges, such as the East Pacific Rise (full spreading rates of >8 cm/yr), the eruptive fissures occupy narrow axial grabens (~1 km wide), which are the most common locations for hydrothermal vents. However, because the eruption rates are so high, lavas commonly disrupt the flow of hydrothermal fluids and bury sulfide deposits that are localized along the fissures. As a result, the deposits at fast-spreading ridges tend to be abundant but small. The largest sulfide accumulations are found on slow-spreading ridges, where volcanism is episodic and alternates with long periods of intense tectonic activity with few eruptions (Fouquet, 1997; Hannington et al., 2005). Slow- and intermediate-rate spreading centers, such as the Mid-Atlantic Ridge and Central Indian Ridge (1–4 cm/yr and 4–6 cm/yr, respectively), are characterized by lower rates of magma supply but greater structural control on hydrothermal upflow. They have wide (up to 15 km) and deep (up to 2 km), fault-bounded axial valleys where eruptions occur only very rarely, or at intervals of thousands of years or more, and hydrothermal activity may be long-lived (e.g., Hannington et al., 2005).

Submarine hydrothermal systems in subduction-related environments are generally similar to those at the mid-ocean ridges in terms of the processes of seafloor mineralization. However, volcanic arcs and backarc spreading centers are characterized by a range of different crustal thicknesses, heat flow regimes, water depths, and magma compositions that lead to important differences in the compositions of the hydrothermal fluids and the mineralogy of the massive sulfide deposits (Hannington et al., 2005). The numbers of vents at the volcanic fronts of the arcs remain poorly known, as the volcanoes are still being discovered. On the Mariana and Kermadec Arcs, which are the most completely surveyed, hydrothermal plumes have been found in the summit calderas of approximately one-third of the arc volcanoes (de Ronde et al., 2003, 2007). However, the majority of the high-temperature vents and the largest sulfide deposits, so far, have been found at spreading centers in the adjoining backarc basins (e.g., Lau Basin, North Fiji Basin).

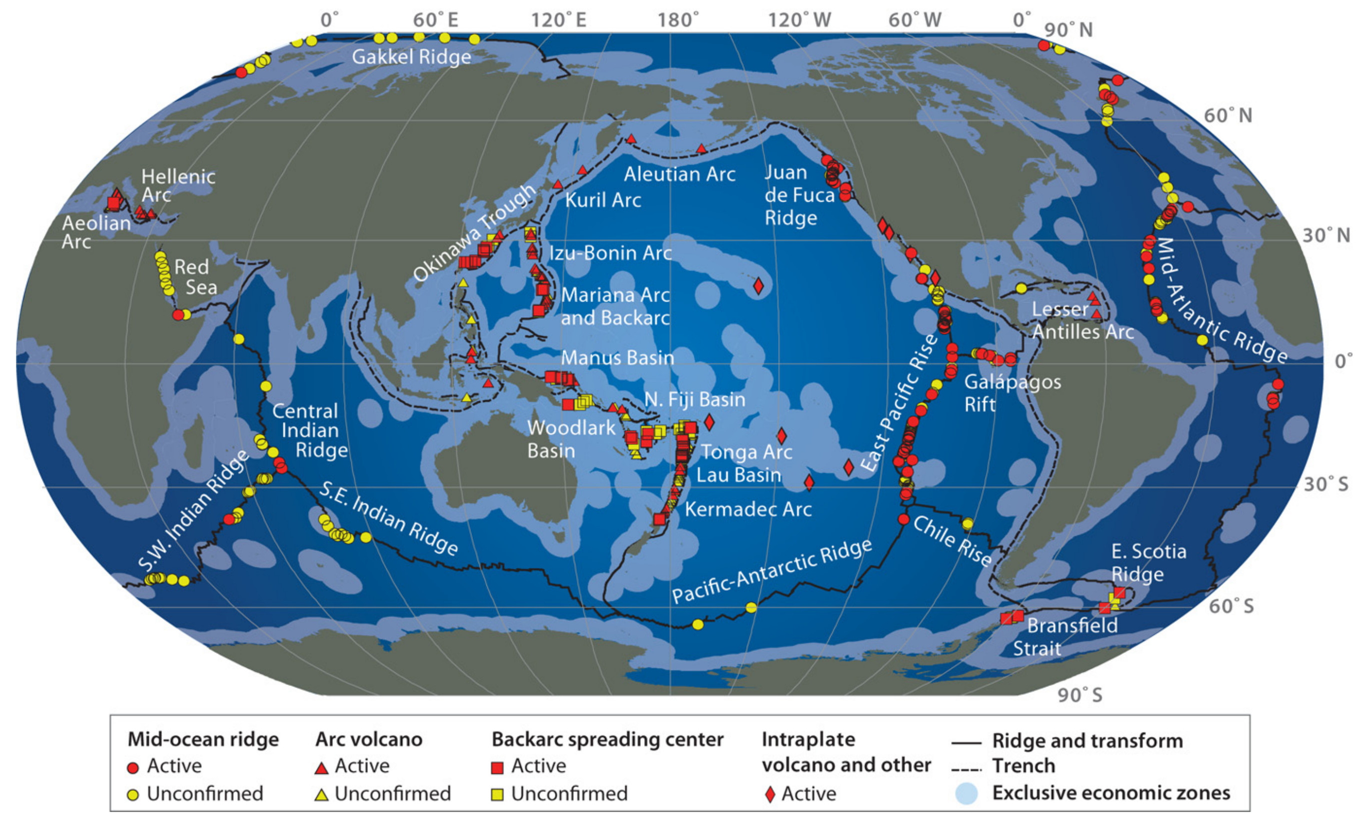

Figure 1. Global distribution of seafloor hydrothermal systems and related mineral deposits. Version 2.0 of the InterRidge Global Database (Beaulieu, 2010) used in this study contains information on 554 sites of seafloor hydrothermal activity (confirmed and unconfirmed) and inactive deposits. About 300 are sites of high-temperature hydrothermal venting; 165 are confirmed sites of massive sulfide accumulation (Table DR1 [see footnote 1]). Credits: S. Beaulieu, K. Joyce, and S.A. Soule (Woods Hole Oceanographic Institution).

ESTIMATING THE GLOBAL ABUNDANCE

To estimate the abundance of seafloor massive sulfide in the neovolcanic zones of the global oceans, we examined deposit densities in 32 control areas of roughly equal size (5° of latitude by 5° of longitude) containing 129 occurrences (Table DR2 in the GSA Data Repository[1]). The areas were chosen to represent permissive geology throughout the oceans and include ~7200 km of ridge and 2800 km of arc and backarc spreading centers. The map scale used for the analysis (1:2,500,000) was chosen so that the quality of the map data was the same in all cases. The measurement of deposit densities in the control areas requires an unambiguous definition of what constitutes a "deposit"; unfortunately, descriptions of deposits in the literature have included everything from a single vent or chimney to a large mound or cluster of vent complexes. In this study, we selected a subset of 106 deposits with reported dimensions of more than 100 m^2 on the seafloor as the minimum unit and clusters of mounds or vent complexes spatially separated from the next nearest cluster by more than 10 km as the maximum unit. Details of the methodology and assumptions are provided in the Data Repository.

An average of four deposits was included in each of the 5° × 5° control areas; 90% of the control areas have densities of two or more deposits per 100,000 km^2, 50% have densities of six or more deposits, and 10% have densities of ten or more deposits. In this study, we consider only those deposits that are located within the neovolcanic zone. Thus, deposit densities can also be expressed in terms of the linear dimensions of ridge or arc segments between the occurrences (Fig. 2A). As expected from heat fluxes (Baker, 2007) and plume data (Baker and German, 2004), the deposits are farther apart on the slow-spreading ridges (average of 174 km) and closer together on the fast-spreading ridges (average of 54 km). Deposit densities on backarc spreading centers are similar to those on mid-ocean ridges with similar spreading rates; along volcanic arcs the spacing is more closely linked to the spacing of individual volcanoes (de Ronde et al., 2003). The combined average spacing for all 32 control areas is 107 km (Fig. 2B). Based on the cumulative strike length of the oceanic plate boundaries (89,000 km) and an average density of one deposit every ~100 km, the total number of deposits expected in the global neovolcanic zones is ~900. Taking into account the range of deposit densities, the expected number of deposits is at least 500 (90th percentile) and not more than 5000 (10th percentile).

This result obviously has a large uncertainty, but independent estimates of the spacing of hydrothermal vents, at least on the mid-ocean ridges, all arrive at similar numbers. Global heat flux associated with high-temperature convection at mid-ocean ridges ranges from 1.1 to 2.5 × 10^{12} W, with the most commonly cited values close to 1.8 ± 0.3 × 10^{12} W (Elderfield and Schultz, 1996; Mottl, 2003; Sinha and Evans, 2004). A large number of studies have shown that at least 90% of this axial flow is diffuse flow (i.e., 350 °C fluid that has been cooled by mixing with seawater before reaching the seafloor). In order to account for the high-temperature flux (10% of 1.8 ± 0.3 × 10^{12} W), as many as 50,000–100,000 black smokers would be required, assuming heat output of 2–5 MW for a single vent, or a density of at least one black smoker for every 1 km of ridge axis. Large vent fields, with up to 100 black smokers and heat outputs equivalent to 200–500 MW, are expected to account for most of the high-temperature flux. A vent complex of this size would be required only every 50–100 km, amounting to ~1000 large fields on the global

[1]GSA Data Repository item 2011342, supplemental information on the abundance of seafloor massive sulfide deposits, is available online at www.geosociety.org/pubs/ft2011.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

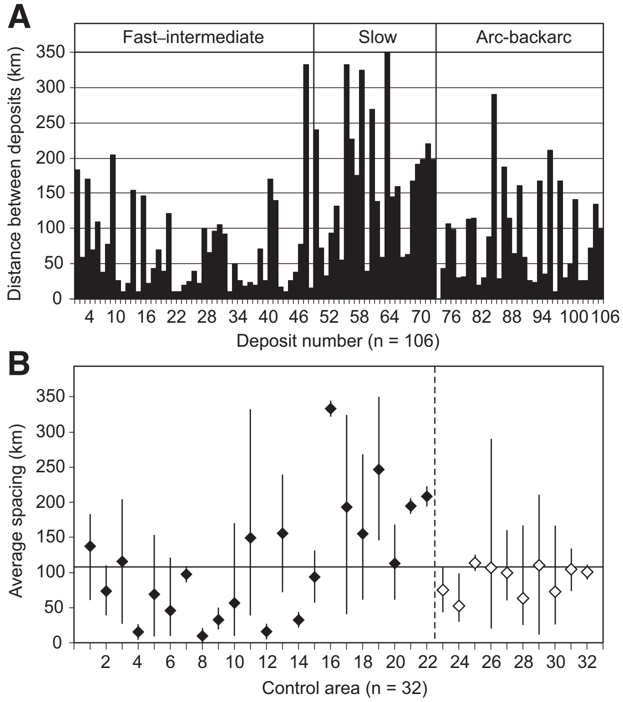

Figure 2. Seafloor massive sulfide deposit densities. A: Distances between adjacent deposits along 10,000 km of ridge, arc, and back-arc spreading centers. Data are included only for those deposits or clusters of deposits more than 10 km apart (n = 106). B: Mean deposit densities (average spacing) in each of the 5° by 5° control areas listed in Table DR2 (see footnote 1); ranges are the minimum and maximum distances between adjacent deposits in each control area. Closed symbols—mid-ocean ridges; open symbols—arcs and back-arc spreading centers. The horizontal line indicates the combined average value for all 32 control areas (107 km). Details are provided in the GSA Data Repository (see footnote 1).

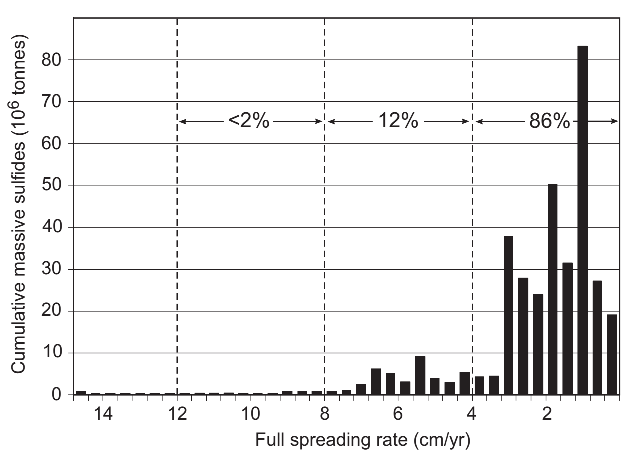

Figure 3. Expected distribution of seafloor massive sulfide deposits on the mid-ocean ridges as a function of spreading rate. The proportion of massive sulfide at different spreading rates is estimated from the length of the ridge segments (Carbotte and Scheirer, 2004), the deposit density as a function of spreading rate, and the expected sizes of the deposits (see the Data Repository [see footnote 1]). The total length of ridges represented in this plot is 53,000 km; the expected number of deposits (n = 537) have a total estimated tonnage of ~3.6 × 10^8 tonnes. The large proportion of massive sulfide expected on the slow-spreading ridges reflects the cumulative length of the slow ridges plus the large sizes of the known deposits.

mid-ocean ridge system. Estimates of the length of ridge needed to continuously power a single hydrothermal system (<10 km to 333 km; Baker, 2007) confirm that the spacing of the vent fields is likely quite regular. This is supported by the spatial density of hydrothermal plumes detected in the water column, which range from one plume every 200 km on slow-spreading ridges to a high of one every 25 km on fast-spreading ridges (Baker and German, 2004). The plume studies suggest that only 16% of the ridge length is hydrothermally active at any given time at a global average spreading rate of 4 cm/yr (Baker et al., 1996). Thus, inactive portions of the ridge may host deposits that are thousands of years old and not captured in the plume data. Including both active and inactive deposits in Figure 2 is considered to provide a more reliable record of metal accumulation at the seafloor than the plume surveys, even though a better inventory of inactive deposits is still required.

From an estimate of the number of deposits in the global neovolcanic zones, we can place some constraints on the total sulfide accumulation by assuming a mass distribution similar to that of the known deposits (Hannington et al., 2010). Unfortunately, the sizes of most deposits are incompletely known; many reported dimensions include large areas of discontinuous sulfide outcrop or barren substrate between chimneys and mounds, thereby overestimating the sizes of the deposits. Significant deposits with explored dimensions on the order of 5000 m^2 or more have now been found in most of the settings considered in this study, and in several cases drilling information is available to judge the continuity and thickness of sulfide outcrops. Four deep drill holes that penetrated the Bent Hill deposit and Ocean Drilling Program (ODP) mound at Middle Valley (ODP Legs 139 and 169) indicate a combined tonnage of 1–1.5 × 10^7 tonnes (Zierenberg et al., 1998). At the large TAG mound on the Mid-Atlantic Ridge, 17 holes drilled to a maximum depth of 125 m indicate 2.7 × 10^6 tonnes of massive sulfide in this deposit (ODP Leg 158; Hannington et al., 1998). Data from extensive drilling of the Solwara 1 deposit in the Eastern Manus Basin (146 holes to a maximum depth of 20 m) have been used to estimate a resource of 2.1 × 10^6 tonnes in a chimney zone covering 90,000 m^2 (Lipton, 2008). Using the drilling data as a guide, we estimated the tonnages of the best-mapped deposits from the outcrop areas in the global database (see Table DR1). These data are the basis for a first-order tonnage model for seafloor massive sulfide deposits presented in Hannington et al. (2010).

Of 62 deposits used in the tonnage model, only eight have dimensions indicating sizes larger than 2 × 10^6 tonnes. Three of these have been confirmed by drilling (TAG, Middle Valley, Solwara 1); the others have sulfide outcrop dimensions that are consistent with similarly large tonnages (e.g., Sunrise, Krasnov, Semyenov, Puy des Folles, Zenith-Victory; see the Data Repository). However, the median deposit size is only 70,000 tonnes, and more than a third of the deposits are considered to be smaller than 3000 tonnes. The total amount of massive sulfide in the deposits used in the tonnage model is ~5 × 10^7 tonnes, ~70% contained in the largest 10% of deposits. Using these data, an estimate of the cumulative tonnage of seafloor massive sulfide in the global neovolcanic zones can be made by populating the tonnage model with the estimated numbers of deposits discussed above.

If we assume that there are ~1000 deposits with a minimum size of 100 tonnes, a maximum size of 1 × 10^7 tonnes, and the size distribution given by Hannington et al. (2010), the total amount of massive sulfide in the neovolcanic zones of the global oceans is on the order of 6 × 10^8 tonnes. The largest 10% of deposits would contain ~4 × 10^8 tonnes. Because the slow-spreading centers account for ~60% of the total ridge length and host the largest deposits, they are expected to account for more than 85% of the total tonnage of seafloor massive sulfides at ridges (Fig. 3). The contained metal is more difficult to estimate, owing to the highly variable metal grades of surface samples (Hannington et al., 2010). For a median grade of 5 wt% Cu + Zn, which closely matches that of massive sulfide deposits on land (Franklin et al., 2005), the total amount of metal (Cu + Zn) along the global neovolcanic zones is expected to be ~3 × 10^7 tonnes.

DISCUSSION

The models presented in this paper provide the basis for the first estimate of the abundance of seafloor massive sulfide deposits in the neovolcanic zones and will help translate new deposit occurrence information into more meaningful assessments of the resource potential. The predicted metal content is significant, similar to the amount of discovered metal in Cenozoic massive sulfide deposits on land (1.9×10^7 tonnes). But it is only a fraction of the total past production and current geological resources of massive sulfides in older deposits (~14×10^9 tonnes containing 8.5×10^8 tonnes of Cu + Zn; Franklin et al., 2005). The estimated 3×10^7 tonnes of Cu + Zn in the neovolcanic zones is only slightly more than the annual production of these metals from all land-based mines, including porphyry Cu deposits (U.S. Geological Survey, 2010). Although deep-sea mining is technically feasible, the current debate must consider that any future recovery of metals from seafloor massive sulfides will have to compete economically with these land-based deposits.

An important outcome of the present study is that the predicted amount of metal in massive sulfide deposits in the neovolcanic zones of the world's oceans is far short of the amount of metal delivered to the seafloor by black smoker vents. On the mid-ocean ridges, the mass of hydrothermal fluid heated to black smoker temperatures (at least 350 °C) is on the order of $3–6 \times 10^{13}$ kg/yr (Elderfield and Schultz, 1996). The amount discharged at this temperature, and thus capable of depositing metals on the seafloor, is ~5×10^{12} kg/yr (10% of the total axial flow). Assuming a combined metal and sulfur concentration of 200–500 mg/kg in the high-temperature fluids (Von Damm, 1990), the global flux of metals and sulfur to black smoker vents is ~10^6 tonnes per year. In just a few hundred years, black smokers at the mid-ocean ridges alone transport more metal and sulfur to the oceans than is estimated to occur in all of the massive sulfide deposits in the axial zones of the ridges, arcs, and backarc basins. The fate of the excess metal is unclear, but it has been known for a long time that distal marine sediments are enriched in metals deposited from plumes associated with the axial hydrothermal systems (Bostrom and Peterson, 1966). This plume fallout does not form massive sulfide deposits but may account for a large fraction of the missing metal.

ACKNOWLEDGMENTS

Support for this research was provided by a Natural Sciences and Engineering Research Council of Canada grant to Hannington. The InterRidge Database is supported by the International Seabed Authority and by the InterRidge program for ridge-crest studies. The manuscript benefited from constructive comments provided by three anonymous reviewers.

REFERENCES CITED

Baker, E.T., 2007, Hydrothermal cooling of midocean ridge axes: Do measured and modeled heat fluxes agree?: Earth and Planetary Science Letters, v. 263, p. 140–150, doi:10.1016/j.epsl.2007.09.010.

Baker, E.T., and German, C.R., 2004, On the global distribution of mid-ocean ridge hydrothermal vent-fields: American Geophysical Union Geophysical Monograph 148, p. 245–266.

Baker, E.T., Chen, Y.J., and Morgan, J.P., 1996, The relationship between near-axis hydrothermal cooling and the spreading rate of mid-ocean ridges: Earth and Planetary Science Letters, v. 142, p. 137–145, doi:10.1016/0012-821X(96)00097-0.

Beaulieu, S.E., 2010, InterRidge Global Database of Active Submarine Hydrothermal Vent Fields, Version 2.0: http://www.interridge.org/irvents (July 2011).

Bird, P., 2003, An updated digital model of plate boundaries: Geochemistry, Geophysics, Geosystems, v. 4, 1027, doi:10.1029/2001GC000252.

Bostrom, K., and Peterson, M.N.A., 1966, Precipitates from hydrothermal exhalations on the East Pacific rise: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 61, p. 1258–1265, doi:10.2113/gsecongeo.61.7.1258.

Carbotte, S.M., and Scheirer, D.M., 2004, Variability of ocean crustal structure created along the global mid-ocean ridge, *in* Davis, E.E., and Elderfield, H., eds., Hydrogeology of the oceanic lithosphere: Cambridge, UK, Cambridge University Press, p. 59–107.

Cathles, L.M., 2010, What processes at mid-ocean ridges tell us about volcanogenic massive sulfide deposits: Mineralium Deposita (published online 24 June), 19 p., doi:10.1007/s00126-010-0292-9.

de Ronde, C.E.J., Massoth, G.J., Baker, E.T., and Lupton, J.E., 2003, Submarine hydrothermal venting related to volcanic arcs: Society of Economic Geologists Special Publication 10, p. 91–110.

de Ronde, C.E.J., Baker, E.T., Massoth, G.J., Lupton, J.E., Wright, I.C., Sparks, R.J., Bannister, S.C., Reyners, M.E., Walker, S.L., Greene, R.R., Ishibashi, J., Faure, K., Resing, J.A., and Lebon, G.T., 2007, Submarine hydrothermal activity along the mid-Kermadec Arc, New Zealand: Large-scale effects on venting: Geochemistry, Geophysics, Geosystems, v. 8, Q07007, doi:10.1029/2006GC001495.

Elderfield, H., and Schultz, A., 1996, Mid-ocean ridge hydrothermal fluxes and the chemical composition of the ocean: Annual Review of Earth and Planetary Sciences, v. 24, p. 191–224, doi:10.1146/annurev.earth.24.1.191.

Fouquet, Y., 1997, Where are the large hydrothermal sulphide deposits in the oceans?: Royal Society of London Philosophical Transactions, ser. A, v. 355, p. 427–441.

Franklin, J.M., Gibson, H.L., Jonasson, I.R., and Galley, A.G., 2005, Volcanogenic massive sulfide deposits, *in* Hedenquist, J.W., et al., eds., Economic Geology 100th Anniversary Volume, Society of Economic Geologists, p. 523–560.

Guney, M., Al-Marhoun, M.A., and Nawab, Z.A., 1988, Metalliferous sub-marine sediments of the Atlantis-II-Deep, Red Sea: Canadian Institute of Mining and Metallurgy Bulletin, v. 81, p. 33–39.

Hannington, M., and Monecke, T., 2009, Global exploration models for polymetallic sulphides in the area: An assessment of lease block selection under the Draft Regulations on Prospecting and Exploration for Polymetallic Sulphides: Marine Georesources and Geotechnology, v. 27, p. 132–159, doi:10.1080/10641190802680614.

Hannington, M.D., Galley, A.G., Herzig, P.M., and Petersen, S., 1998, Comparison of the TAG mound and stockwork complex with Cyprus-type massive sulfide deposits, *in* Herzig, P.M., et al., eds., Proceedings of the Ocean Drilling Program, Scientific Results, Volume 158: College Station, Texas, Ocean Drilling Program, p. 389–415.

Hannington, M.D., de Ronde, C.E.J., and Petersen, S., 2005, Sea-floor tectonics and submarine hydrothermal systems, *in* Hedenquist, J.W., et al., eds., Economic Geology 100th Anniversary Volume, Society of Economic Geologists, p. 111–141.

Hannington, M.D., Jamieson, J., Monecke, T., and Petersen, S., 2010, Modern seafloor massive sulfides and base metal resources: Towards an estimate of global seafloor massive sulfide potential: Society of Economic Geologists Special Publication 15, p. 317–338.

Hoagland, P., Beaulieu, S., Tivey, M.A., Eggert, R.G., German, C., Glowka, L., and Lin, J., 2010, Deep-sea mining of seafloor massive sulfides: Marine Policy, v. 34, p. 728–732, doi:10.1016/j.marpol.2009.12.001.

Lipton, I., 2008, Mineral resource estimate, Solwara 1 project, Bismarck Sea, Papua New Guinea: NI43-101 Technical Report for Nautilus Minerals Inc.: http://www.nautilusminerals.com/i/pdf/2008-02-01_Solwara1_43-101.pdf (July 2011).

Mottl, M.J., 2003, Partitioning of energy and mass fluxes between mid-ocean ridge axes and flanks at high and low temperature, *in* Halbach, P.E., et al., eds., Energy and mass transfer in marine hydrothermal systems: Dahlem Workshop Report 89: Berlin, Dahlem University Press, p. 271–286.

Rona, P.A., 2003, Resources of the sea floor: Science, v. 299, p. 673–674, doi:10.1126/science.1080679.

Rona, P.A., and Scott, S.D., 1993, Sea-floor hydrothermal mineralization: New perspectives: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 88, p. 1935–1976, doi:10.2113/gsecongeo.88.8.1935.

Singer, D.A., and Menzie, W.D., 2010, Quantitative mineral resource assessments: An integrated approach: Oxford, UK, Oxford University Press, 232 p.

Sinha, M.C., and Evans, R.L., 2004, Geophysical constraints upon the thermal regime of the ocean crust: American Geophysical Union Geophysical Monograph 148, p. 19–62.

U.S. Geological Survey, 2010, Mineral commodity summaries 2010: http://minerals.usgs.gov/minerals/pubs/mcs/2010/mcs2010.pdf (July 2011).

Van Dover, C.L., 2011, Tighten regulations on deep-sea mining: Comment: Nature, v. 470, p. 31–33, doi:10.1038/470031a.

Von Damm, K.L., 1990, Seafloor hydrothermal activity: Black smoker chemistry and chimneys: Annual Review of Earth and Planetary Sciences, v. 18, p. 173–204, doi:10.1146/annurev.ea.18.050190.001133.

Zierenberg, R.A., Fouquet, Y., Miller, D.J., and Shipboard Scientific Party, 1998, The deep structure of a sea-floor hydrothermal deposit: Nature, v. 392, p. 485–488, doi:10.1038/33126.

Manuscript received 18 May 2011
Revised manuscript received 12 July 2011
Manuscript accepted 13 July 2011

Printed in USA