Caldera-forming processes and the origin of submarine volcanogenic massive sulfide deposits

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ABSTRACT

Certain volcanogenic massive sulfide (VMS) ore deposits form in submarine calderas. This association is well known, but the link between caldera formation and the origins of the deposits remains poorly understood. Here we show that the size and location of a VMS deposit within a submarine caldera may be determined by how and when the caldera formed. These spatial-temporal conditions control development of the hydrothermal system associated with the VMS deposit. We propose that caldera opening along outward-dipping faults promotes magma degassing, seawater influx, and high-temperature leaching, resulting in a metal-rich hydrothermal fluid. These outward-dipping faults are considered to provide critical pathways for ore-forming fluids responsible for some caldera-hosted VMS deposits and may also be fundamentally important for the formation of many other caldera-hosted ore deposit types.

Keywords: calderas, volcanogenic massive sulfide deposits, fluids, subsidence.

INTRODUCTION

Calderas are circular volcanic depressions formed by evacuation and eruption of magma from a subsurface reservoir. Calderas represent one of the most important ore-forming environments on Earth. The subsurface magma provides a large source of heat and magmatic volatiles to drive hydrothermal systems. The structural permeability afforded by caldera faults focuses hydrothermal upflow. The accumulation of significant thicknesses of pyroclastic deposits within the caldera is an important source of stratigraphic permeability, which can be exploited by mineralizing solutions. These features make calderas outstanding exploration targets, and a range of ore deposit types including porphyry Cu, epithermal, polymetallic veins, and volcanogenic massive sulfide deposits are found in calderas (Elston, 1994; Rytuba, 1994).

In this paper we use the example of volcanogenic massive sulfide (VMS) deposits to illustrate how specific caldera-forming processes may be key factors in the formation of economic mineral deposits. Volcanogenic massive sulfide ore deposits form in submarine settings as a result of seawater circulating through a subsurface hydrothermal system that is heated by an underlying magmatic source (Franklin et al., 1981; White and Herrington, 2000). Many large VMS deposits, which are rich in zinc, lead, and copper, are associated with silicic volcanic rocks in extensional and transtensional environments (Sillitoe, 1982). In these tectonic zones, some VMS deposits show a close spatial and temporal association with silicic submarine calderas (Ohmoto, 1978). Analyzing the genetic links between these two phenomena provides clues about how, when, and where such mineral deposits form in a caldera setting. Such links have important and surprising implications for understanding the formation of VMS deposits in both modern and ancient settings and can shed new light on the formation of other caldera-hosted mineral deposit types. For volcanologists, this synthesis demonstrates the practical importance of understanding caldera-forming processes, and, for exploration geologists, it provides further insight into the controlling factors on the location and timing of formation of large orebodies.

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SPATIAL CONTROLS

Although calderas may collapse as simple pistons (Smith and Bailey, 1968), they frequently subside in more complicated ways (Troll et al., 2001). Recent field and experimental work (Branney, 1995; Roche et al., 2000; Kennedy, 2000; Kennedy et al., 2000) has shown that the principal caldera ring faults, which form as a result of magma-chamber evacuation, dip vertically or outward and may have a comparatively small diameter relative to the topographic rim of the caldera. A second set of faults, associated with late-stage peripheral extension, normal faulting, and downsagging as the caldera collapses, dip inward and are located on the margins of the caldera (Fig. 1A). These two fault sets provide an ideal fracture system for fluid circulation. In the VMS model, the heat from the magma chamber drives fluids up the subsidence-controlling inner faults, while cold seawater is drawn down along the outer faults. These fluids deposit ores where the main fault intersects the seafloor or permeable pyroclastic rocks in the area of maximum subsidence (Fig. 1). Such deposition is observed at Myojin Knoll caldera, Japan, where a large VMS deposit is actively growing above the main caldera fault (Fiske et al., 2001). In areas of extension and transtension, the main caldera faults may not be circular, but instead form a series of connecting linear or arcuate structures (Kennedy, 2000; Kennedy et al., 2000). When these structures intersect, the fracture system will be better developed than in other areas of the caldera. These intersections are therefore favorable sites for hydrothermal circulation and for the formation of mineral deposits (Fig. 1B).

Asymmetric Caldera Collapse

A common style of subsidence is asymmetric collapse, either as a trapdoor along a single hinge fault or as a series of blocks (Heiken et al., 1986; Wohletz and Heiken, 1992) (Figs. 2A, 2B). Such a trapdoor structure is observed at Noranda, Quebec, where the largest VMS deposit in that district, the Horne, occurs along the most downfaulted side of the structure. Asymmetric calderas may represent structural environments that are particularly favorable for the formation of certain VMS deposits. First, an asymmetric caldera has a principal fault system on one side of the caldera, facilitating fluid flow and concentration of VMS deposits in a narrow zone. Second, the asymmetric profile of the caldera provides a structural basin allowing VMS deposits to accumulate and be preserved. The comparatively great water depth of this structural basin also suppresses boiling of the hydrothermal solution,

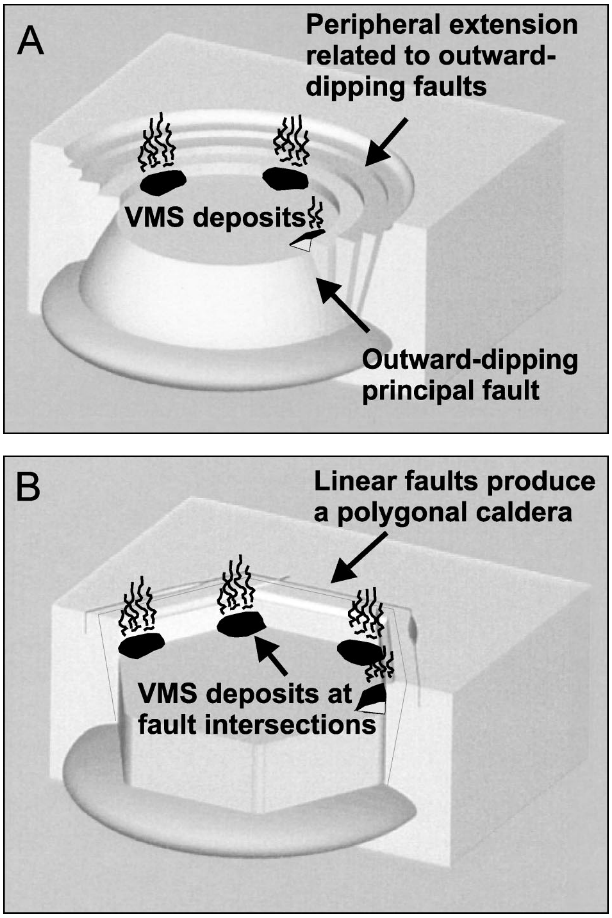

Figure 1. Different styles of caldera subsidence. A: Central block subsides along principal, outward-dipping faults. Volcanogenic massive sulfide (VMS) deposits (black) will be focused in this zone. By contrast, peripheral faults are secondary structures that dip inward. B: Subsidence along polygonal structure. Intersections of individual straight segments focus hydrothermal flow and VMS deposits.

aiding VMS formation. Third, the structural basin promotes accumulation of unwelded, low-density pyroclastic debris and/or silicic lava flows that have been erupted during and after caldera formation. Material that is driven into the basin by mass wasting from the adjacent caldera walls also contributes to the high sedimentation rates (Iisaza et al., 1999; Fiske et al., 2001). Under these conditions, VMS orebodies form subsurface replacement deposits in fragmental rocks. The subsequent eruption of low-permeability lava flows will preserve these mineralized zones. VMS orebodies of this type include the giant Archean Horne deposit (Gibson and Kerr, 1993; Kerr and Gibson, 1993). This type is also observed at the Hunter Mine caldera, Quebec (Mueller and Mortensen, 2002), and may be applicable to the Selbaie, Sturgeon Lake, and Bergslagen deposits as well (Franklin et al., 1981).

In relatively undeformed successions, gravity signatures can aid in the identification of caldera structures. On a Bouguer gravity anomaly map, negative values are suggestive of low-density pyroclastic deposits, which may pond to great thicknesses (>1 km) in structural depressions such as calderas. An asymmetric caldera should exhibit a large negative anomaly on one side, whereas steep gradients associated with the negative anomaly are indicative of a major caldera fault that can accommodate a large ore deposit. Such an orebody might also be manifested as a localized gravity high within the larger negative anomaly.

Caldera Subsidence and Water Depths

The spatial position of the VMS deposit in the caldera may affect its composition and economic potential. Silicic submarine calderas that host VMS deposits occur in rifted-arc, forearc, and backarc tectonic settings (Halbach et al., 1989; Smith et al., 1990; Ishibashi and Urabe, 1995). In these environments, water depths tend to be shallower compared to other settings where VMS deposits are found (e.g., mid-ocean ridges). If a caldera subsides hundreds to thousands of meters during collapse, water depths may vary from very deep at the bottom of the caldera to very shallow outside the caldera's margin. Depending on the local water depth and hydrostatic pressure, VMS mineralizing solutions may undergo different amounts of boiling. For example, VMS solutions that emerge from the principal caldera fault at the bottom of a deep asymmetric caldera may undergo little or no boiling. These hydrothermal solutions and VMS deposits will be enriched in copper and zinc (Herzig and Hannington, 1995). Other solutions emanating from faults at structurally higher levels within the caldera, or even outside the caldera, are subjected to greater boiling at shallower water depths, and the resultant VMS deposit may be enriched in elements such as gold and mercury (Gibson et al., 1999; Hannington et al., 1999) (Fig. 2B). At Noranda, VMS deposits rich in zinc and copper occur within the core of the subsidence structure interpreted as a deeper-water environment, whereas VMS deposits enriched in gold may have formed in a shallower water environment along the downfaulted structural margin of the asymmetric subsidence structure (Kerr and Gibson, 1993; Gibson and Watkinson, 1990).

When calderas subside in a piecemeal fashion, the subsidence is characterized by horst and graben structures at different water depths (Fig. 2). These faults may serve as conduits and facilitate eruption of pyroclastic material followed by lavas. Subsequent mineralizing solutions along the same structures can focus VMS deposits in the porous pyroclastic strata, with an impermeable cap provided by the overlying lavas or sediments. Such structures have been observed at Hunter Mine caldera (Mueller and Mortensen, 2002).

TEMPORAL CONTROLS

Spatial relationships between caldera-forming faults and VMS mineralization are important for the development of potentially large VMS orebodies. The timing of caldera formation may also be critically important. VMS formation is favored at two stages: (1) during and immediately after caldera collapse and (2) during postcaldera resurgence.

Structural Opening from Caldera Collapse

During caldera collapse, large-scale structural pathways are created instantaneously. At this stage, the magmatic system can be considered open to heat and mass transfer. The orientation of the principal caldera faults will determine, in part, the openness of the system. If the faults dip inward, they will tend to close as the caldera block or blocks subside. If the faults dip outward, however, they will tend to open the system progressively during subsidence.

Structural opening will have three important consequences for hydrothermal upflow and the formation of a VMS deposit. First, the magma reservoir is subject to enhanced degassing as volatile-rich magma is depressurized. The released magmatic fluids are able to contribute large quantities of ore metals (e.g., Cu, Au) to the hydrothermal fluid (Yang and Scott, 1996, 1999). Thus, large magmatic inputs of metals can be envisaged under these conditions.

Second, strongly convecting hydrothermal cells are initiated immediately after the caldera collapses. Seawater can circulate freely owing to the enhanced structural permeability, and consequently heat transfer from the magma is efficient. The end result is that huge volumes of rock are leached, creating a metal-rich hydrothermal fluid (Ohmoto, 1978). The high-temperature leaching process lowers the

$^{18}O/^{16}O$ isotope ratio in rocks where fluid flow is highest, i.e., along caldera ring faults. Several detailed oxygen isotope studies have demonstrated that the pattern of ^{18}O depletion is circular and focused in a comparatively narrow zone at the margin of the caldera or underlying pluton (Cathles, 1993; Huston, 1999; Larson and Taylor, 1986).

Third, an open system allows a sudden, massive influx of seawater, perhaps even permitting seawater direct access to the underlying magma reservoir. As a result, the magmas that are erupted also may show ^{18}O depletions. This effect has also been suggested at the subaerial Yellowstone caldera, which has been subject to influx of meteoric waters (Hildreth et al., 1984). Another mechanism to produce ^{18}O-depleted magmas is the assimilation (Taylor, 1977; Bacon et al., 1989) or melting (Bindeman and Valley, 2000) of rocks at the roof and walls of the magma reservoir below the caldera. Because these rocks represent an interface between the reservoir and a surrounding envelope of hydrothermal circulation (Giggenbach et al., 1990), they are most susceptible to high-temperature hydrothermal alteration, which decreases their $^{18}O/^{16}O$ ratio. These processes may produce regional ^{18}O depletions in the volcanic rocks that are erupted from the caldera.

Effects of Postcaldera Resurgence

Once a caldera has formed, large hydrothermal systems also can develop during resurgence when magma is injected at shallow levels, providing a renewed heat source, magmatic input of volatiles and metals, and new structural pathways (Fig. 2C). In resurgent systems, inward-dipping faults will tend to be opened, while outward-dipping faults close; this structural situation is reversed from that during caldera collapse. Thus, loci of mineralization may shift from the main outward-dipping faults to inward-dipping structures associated with resurgence in the central parts of the caldera.

SUMMARY

The development of productive ore-forming systems within an asymmetric caldera with steep or outward-dipping faults involves a number of different stages. An asymmetric caldera begins to subside, and the magmatic-hydrothermal system is opened and exposed along the main outward-dipping caldera faults (Fig. 2A). This opening causes enhanced magma degassing and large influxes of seawater or local meteoric water that may interact directly with the magma reservoir. An initially deep hydrothermal system becomes connected to the surface by the caldera faults and migrates rapidly upward (Fig. 2B). Metals are supplied to the hydrothermal fluid by magma degassing and by leaching from volcanic rocks at high temperatures. Simultaneously, the hydrothermal system is recharged through the peripheral faults. The largest orebodies in VMS deposits are developed in porous pyroclastic sequences adjacent to caldera-bounding faults. The sizes and compositions of the VMS deposits will be determined, in part, by their structural position and the water depth in the caldera. In postcaldera time, hydrothermal systems may be reactivated near the center of the caldera as a response to magmatic resurgence, which creates open fluid pathways along previously sealed inward-dipping faults (Fig. 2C).

CONCLUDING REMARKS

Emerging models of caldera-forming processes are providing novel ways to understand spatial and temporal relationships between caldera structures and ore deposits. The style of caldera subsidence and the principal caldera faults control the locations where a mineral de-

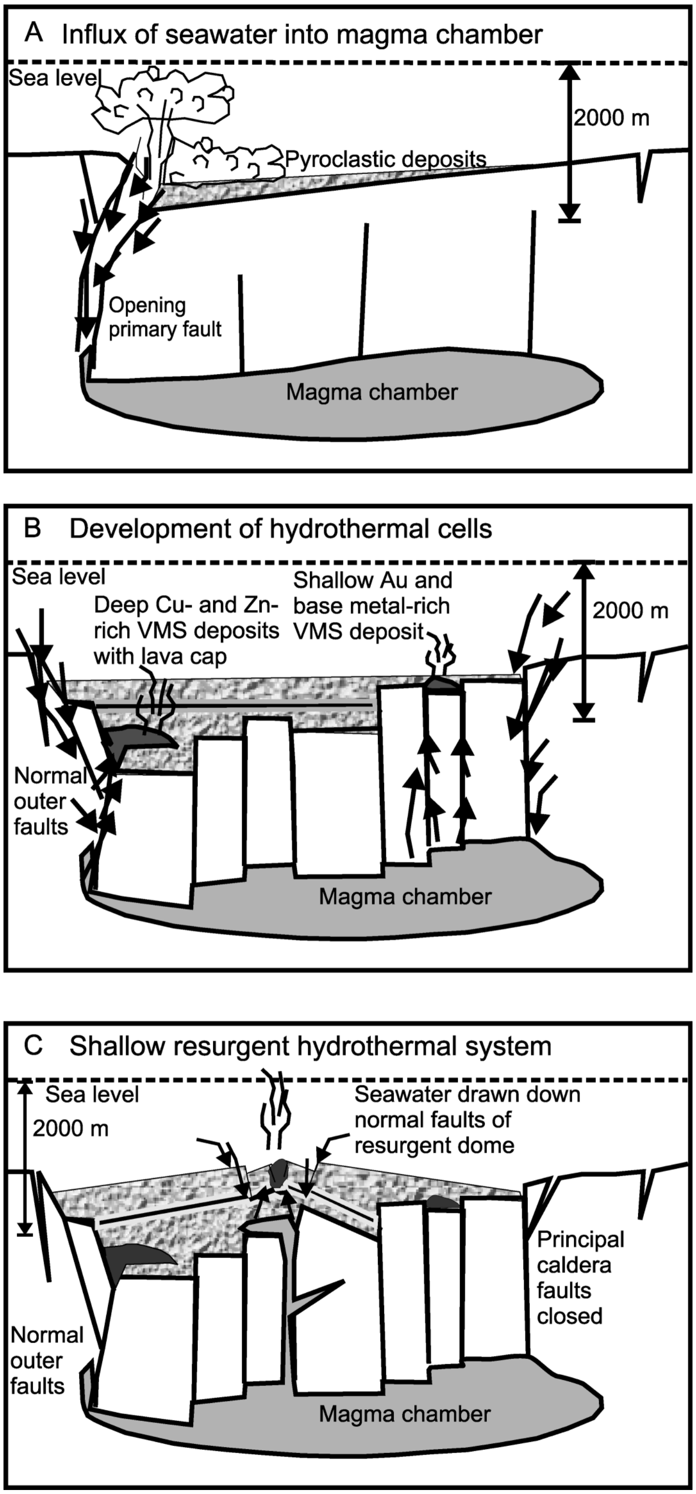

Figure 2. Conceptual view in space and time of caldera-related submarine magmatic-hydrothermal system. A: Asymmetric collapse of caldera exposes underlying magmatic-hydrothermal system. Magma degasses while seawater flows into system. Erupted magma ponds within asymmetric basin. B: Cold seawater flows downward through peripheral inward-dipping faults, while mineralizing fluids heated by magma move up outward-dipping caldera faults. Upflow and downflow generate hydrothermal convection cell that is controlled by caldera structure. Subsidence along series of faults causes piecemeal collapse of caldera and allows hydrothermal flow in number of localities. As result, volcanogenic massive sulfide (VMS) deposits may form at different water depths, depending on how much individual fault block has subsided. C: Renewed magmatism causes resurgence and intrusion into roof rocks above main magma reservoir. As result, roof rocks are uplifted. Outward-dipping caldera faults close while tensional faults associated with uplift form in center of caldera. This new structural configuration permits VMS deposits to develop in central parts of caldera.

posit forms, whereas the timing of caldera collapse allows upward migration of the hydrothermal system and the initiation of a mineralizing event. For exploration purposes, the largest caldera-related mineral deposits will form synchronously or immediately after caldera formation and will be associated with a principal caldera fault. Such faults may be recognized by rapid changes in the thicknesses of pyroclastic deposits, steep gravity contours, or circular patterns of ^{18}O-depleted rocks. Clearly, not all deposits will fit these criteria, but the ideas developed here are a genetic approach to better comprehend the development and evolution of many different ore deposit types in caldera settings.

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REFERENCES CITED

Bacon, C.R., Adami, L.H., and Lanphere, M.A., 1989, Direct evidence for the origin of low-^{18}O silicic magmas: Quenched samples of a magma chamber's partly-fused granitoid walls, Crater Lake, Oregon: Earth and Planetary Science Letters, v. 96, p. 199–208.

Bindeman, I.N., and Valley, J.W., 2000, Formation of low-$\delta^{18}O$ rhyolites after caldera collapse at Yellowstone, Wyoming, USA: Geology, v. 28, p. 719–722.

Branney, M.J., 1995, Downsag and extension at calderas: New perspectives on collapse geometries from ice-melt, mining, and volcanic subsidence: Bulletin of Volcanology, v. 57, p. 303–318.

Cathles, L.M., 1993, Oxygen isotope alteration in the Noranda mining district, Abitibi greenstone belt, Quebec: Economic Geology, v. 88, p. 1483–1511.

Elston, W.E., 1994, Siliceous volcanic centers as guides to mineral exploration: Review and summary: Economic Geology, v. 89, p. 1662–1686.

Fiske, R.S., Naka, J., Iizasa, K., Yuasa, M., and Klaus, A., 2001, Submarine silicic caldera at the front of the Izu-Bonin arc, Japan: Voluminous seafloor eruptions of rhyolite pumice: Geological Society of America Bulletin, v. 113, p. 813–824.

Franklin, J.M., Lydon, J.W., and Sangster, D.F., 1981, Volcanic-associated massive sulfide deposits: Economic Geology, 75th Anniversary Volume, p. 485–627.

Gibson, H.L., and Kerr, D.J., 1993, Giant volcanic-associated massive sulfide deposits: With emphasis on Archean examples: Economic Geology Special Publication 2, p. 319–348.

Gibson, H.L., and Watkinson, D.H., 1990, Volcanogenic massive sulfide deposits of the Noranda cauldron and shield volcano, Quebec, *in* Rive, M., et al., eds., The northwestern Quebec polymetallic belt: A summary of 60 yr of mining exploration: Canadian Institute of Mining and Metallurgy Special Volume 43, p. 119–132.

Gibson, H.L., Morton, R.L., and Hudak, G.J., 1999, Submarine volcanic processes, deposits, and environments favorable for the location of volcanic-associated massive sulfide deposits, *in* Barrie, C.T., and Hannington, M.D., eds., Volcanic-hosted massive sulfide deposits: Processes and examples in modern and ancient settings: Society of Economic Geologists Reviews in Economic Geology, v. 8, p. 13–51.

Giggenbach, W.F., Garcia, P.N., Londoño, C.A., Rodriguez, V.L., Rojas, G.N., and Calvache, V.M.L., 1990, The chemistry of fumarolic vapor and thermal-spring discharges from the Nevado del Ruiz volcanic-magmatic-hydrothermal system, Colombia: Journal of Volcanology and Geothermal Research, v. 42, p. 13–39.

Halbach, P., Nakamura, K., Wahsner, M., Lange, J., Sakai, H., Käselitz, L., Hansen, R.-D., Yamano, M., Post, J., Prause, B., Seifert, R., Michaelis, W., Teichmann, F., Kinoshita, M., Märten, A., Ishibashi, J., Czerwinski, S., and Blum, N., 1989, Probable modern analogue of Kuroko-type massive sulphide deposits in the Okinawa Trough back-arc basin: Nature, v. 338, p. 496–499.

Hannington, M.D., Poulsen, K.H., Thompson, J.F.H., and Sillitoe, R.H., 1999, Volcanogenic gold in the massive sulfide environment, *in* Barrie, C.T., and Hannington, M.D., eds., Volcanic-hosted massive sulfide deposits: Processes and examples in modern and ancient settings: Society of Economic Geologists Reviews in Economic Geology, v. 8, p. 325–356.

Heiken, G., Goff, F., Stix, J., Tamanyu, S., Shafiqullah, M., Garcia, S., and Hagan, R., 1986, Intracaldera volcanic activity, Toledo caldera and embayment, Jemez Mountains, New Mexico: Journal of Geophysical Research, v. 91, p. 1799–1815.

Herzig, P.M., and Hannington, M.D., 1995, Polymetallic massive sulfides at the modern seafloor: A review: Ore Geology Reviews, v. 10, p. 95–115.

Hildreth, W., Christiansen, R.L., and O'Neil, J.R., 1984, Catastrophic isotopic modification of rhyolitic magma at times of caldera subsidence, Yellowstone Plateau volcanic field: Journal of Geophysical Research, v. 89, p. 8339–8369.

Huston, D.L., 1999, Stable isotopes and their significance for understanding the genesis of volcanic-hosted massive sulfide deposits: A review, *in* Barrie, C.T., and Hannington, M.D., eds., Volcanic-hosted massive sulfide deposits: Processes and examples in modern and ancient settings: Society of Economic Geologists Reviews in Economic Geology, v. 8, p. 157–179.

Iisaza, K., Fiske, R.S., Ishizuka, O., Yuasa, M., Hashimoto, J., Ishibashi, J., Naka, J., Hori, Y., Fujiwara, Y., Imai, A., and Koyama, S., 1999, A Kuroko-type polymetallic sulfide deposit in a submarine silicic caldera: Science, v. 283, p. 975–977.

Ishibashi, J.-I., and Urabe, T., 1995, Hydrothermal activity related to arc-backarc magmatism in the western Pacific, *in* Taylor, B., ed., Backarc basins: Tectonics and magmatism: New York, Plenum Press, p. 451–495.

Kennedy, B., 2000, The nature and origins of caldera structure and morphology, using results from analogue modeling [M.S. thesis]: Montreal, McGill University, 131 p.

Kennedy, B., Stix, J., Vallance, J., and Lavallée, Y., 2000, Caldera asymmetry: Observations and causes from field examples and experimental simulations [abs.]: IAVCEI General Assembly, Bali, Indonesia, 18–22 July 2000, p. 256.

Kerr, D.J., and Gibson, H.L., 1993, A comparison of the Horne volcanogenic massive sulfide deposit and intracauldron deposits of the Mine Sequence, Noranda, Quebec: Economic Geology, v. 88, p. 1419–1442.

Larson, P.B., and Taylor, H.P., 1986, An oxygen isotope study of hydrothermal alteration in the Lake City caldera, San Juan Mountains, Colorado: Journal of Volcanology and Geothermal Research, v. 30, p. 47–82.

Mueller, W.U., and Mortensen, J.K., 2002, Age constraints and characteristics of subaqueous volcanic construction, the Archean Hunter Mine group, Abitibi greenstone belt: Precambrian Research, v. 115, p. 119–152.

Ohmoto, H., 1978, Submarine calderas: A key to the formation of volcanogenic massive sulfide deposits: Mining Geology, v. 28, p. 219–231.

Roche, O., Druitt, T.H., and Merle, O., 2000, Experimental study of caldera formation: Journal of Geophysical Research, v. 105, p. 395–416.

Rytuba, J.J., 1994, Evolution of volcanic and tectonic features in caldera settings and their importance in the localization of ore deposits: Economic Geology, v. 89, p. 1687–1696.

Sillitoe, R.H., 1982, Extensional habitats of rhyolite-hosted massive sulfide deposits: Geology, v. 10, p. 403–407.

Smith, R.L., and Bailey, R.A., 1968, Resurgent cauldrons, *in* Coats, R.R., et al., eds., Studies in volcanology: Geological Society of America Memoir 116, p. 613–662.

Smith, J.R., Taylor, B., Malahoff, A., and Petersen, L., 1990, Submarine volcanism in the Sumisu rift, Izu-Bonin arc: Submersible and deep-tow camera results: Earth and Planetary Science Letters, v. 100, p. 148–160.

Taylor, H.P., Jr., 1977, Water/rock interactions and the origin of H_2O in granitic batholiths: Geological Society of London Journal, v. 133, p. 509–558.

Troll, V.R., Walter, T.R., and Schmincke, H.-U., 2001, Cyclic caldera collapse: Piston or piecemeal subsidence? Field and experimental evidence: Geology, v. 30, p. 135–138.

White, N.C., and Herrington, R.J., 2000, Mineral deposits associated with volcanism, *in* Sigurdsson, H., et al., eds., Encyclopedia of volcanoes: San Diego, Academic Press, p. 897–912.

Wohletz, K., and Heiken, G., 1992, Volcanology and geothermal energy: Berkeley, University of California Press, 432 p.

Yang, K., and Scott, S.D., 1996, Possible contribution of a metal-rich magmatic fluid to a sea-floor hydrothermal system: Nature, v. 383, p. 420–423.

Yang, K., and Scott, S.D., 1999, Possible relations of felsic magmas to ore metals in volcanogenic massive sulfide deposits: Geochemical evidence from the Bathurst mining camp, Iberian pyrite belt, Abitibi belt, and the Hokuroku district [abs.]: Ninth Annual V.M. Goldschmidt Conference, 22–27 August 1999, Harvard University, Cambridge, Massachusetts: Lunar and Planetary Institute Contribution 971, p. 333.

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