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Hydrodynamic modeling of magmatic–hydrothermal activity at submarine arc volcanoes, with implications for ore formation

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ABSTRACT

Subduction-related magmas have higher volatile contents than mid-ocean ridge basalts, which affects the dynamics of associated submarine hydrothermal systems. Interaction of saline magmatic fluids with convecting seawater may enhance ore metal deposition near the seafloor, making active submarine arcs a preferred modern analogue for understanding ancient massive sulfide deposits.

We have constructed a quantitative hydrological model for sub-seafloor fluid flow based on observations at Brothers volcano, southern Kermadec arc, New Zealand. Numerical simulations of multi-phase hydrosaline fluid flow were performed on a two-dimensional cross-section cutting through the NW Caldera and the Upper Cone sites, two regions of active venting at the Brothers volcanic edifice, with the former hosting sulfide mineralization. Our aim is to explore the flow paths of saline magmatic fluids released from a crystallizing magma body at depth and their interaction with seawater circulating through the crust. The model includes a 3×2 km^2 sized magma chamber emplaced at ~2.5 km beneath the seafloor connected to the permeable cone via a ~200 m wide feeder dike. During the simulation, a magmatic fluid was temporarily injected from the top of the cooling magma chamber into the overlying convection system, assuming hydrostatic conditions and a static permeability distribution.

The simulations predict a succession of hydrologic regimes in the subsurface of Brothers volcano, which can explain some of the present-day hydrothermal observations. We find that sub-seafloor phase separation, inferred from observed vent fluid salinities, and the temperatures of venting at Brothers volcano can only be achieved by input of a saline magmatic fluid at depth, consistent with chemical and isotopic data. In general, our simulations show that the transport of heat, water, and salt from magmatic and seawater sources is partly decoupled. Expulsion of magmatic heat and volatiles occurs within the first few hundred years of magma emplacement in the form of rapidly rising low-salinity vapor-rich fluids. About 95% of the magmatically derived salt is temporarily trapped in the crust, either as dense brine or as precipitated halite. This retained salt can only be expelled by later convection of seawater during the waning period of the hydrothermal system (i.e., "brine mining").

While the abundant mineralization of the NW Caldera vent field at Brothers could not be classified as an economic ore deposit, our model has important implications for submarine metal enrichment and the origin of distinct ore types known from exposed systems on land. Sulfide-complexed metals (notably Au) will preferentially ascend during early vapor-dominated fluid expulsion, potentially forming gold ± copper rich vein and replacement deposits in near-seafloor zones of submarine volcanoes. Dense magmatic brine will initially accumulate chloride-complexed base metals (such as Cu, Fe, Pb and Zn) at depth before they are mobilized by seawater convection. The resulting mixed brines can become negatively buoyant when they reach the seafloor and may flow laterally towards depressions, potentially forming layers of base metal sulphides with distinct zonation of metals.

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1. Introduction

Submarine hydrothermal systems form a variety of economically important mineral deposits, commonly known as volcanogenic massive sulfide (VMS) deposits (Stanton, 1958; Solomon and Walshe, 1979; Scott and Binns, 1995; Petersen et al., 2000; Scott, 2001; Franklin et al., 2005; Hannington et al., 2011). While hydrothermal activity at mid-ocean ridges (MOR) is widespread and most significant in terms of global mass and heat flux (e.g., Stein and Stein, 1994; German et al., 2003; Fisher and Wheat, 2010; Cathles, 2011; Hannington, 2011), hydrothermal systems related to bimodal or felsic magmatism in submarine arcs are considered to be better modern analogues for these fossil ore-forming systems and are being actively explored today (e.g., Hannington, 2014).

Magmatism at MOR systems provides a heat source for hydrothermal circulation, while crystallization of arc magmas releases significant amounts of saline magmatic fluids that strongly interact with the convecting seawater (Yang and Scott, 1996, 2005; Zaw et al., 1996; Solomon et al., 2004a; de Ronde et al., 2014a). For example, the water content of dacitic and rhyolitic melts generated in subduction zone settings ranges from 1 to 6 wt.% (Wallace, 2005; Wysoczanski et al., 2012). In addition, subduction-related magmas are chemically more diverse than MOR basalts and contain higher concentrations of precious metals and volatiles, in keeping with the variable metal inventory of large VMS deposits found today on land (e.g., Binns et al., 1993; Scott and Binns, 1995; Yang and Scott, 1996, 2005; Petersen et al., 2000; de Ronde et al., 2005).

The typically shallower water depths at submarine arc volcanoes compared to MOR settings (e.g., de Ronde et al., 2003b) and the correspondingly lower fluid pressures favor fluid separation into a high-density, high-salinity brine and a low-density, low-salinity vapor (e.g., Bischoff and Rosenbauer, 1987; Fournier, 1987; Foustoukos and Seyfried, 2007; Coumou et al., 2009). Temperature and pressure of phase separation control the partitioning of metal complexing agents such as sulfur or chlorine and, therefore, the preference of dissolved ore metals to enter either the vapor or the brine phase (Heinrich et al., 1999; Pokrovski et al., 2008). Hot, buoyant fluids are preferentially focused into topographic highs on the seafloor (Gruen, 2011; Bani-Hassan et al., 2012), reaching shallower depths before interacting with seawater (e.g., Baker et al., 2003). By contrast, dense brines may sink into depressions on the seafloor, as proposed to explain large, sheet-like massive sulfide ore bodies seen in ancient deposits exploited on land (Solomon et al., 2004a, 2004b).

Numerous studies based on research voyages have highlighted the variable characteristics of submarine hydrothermal activity and seafloor metallogenesis along convergent settings (e.g., Wright et al., 1998; de Ronde et al., 2001, 2003b, 2007; Massoth et al., 2007). However, numerical models investigating the sub-seafloor hydrology of modern arc-related hydrothermal systems are largely lacking in the literature. Here, we use the geological and hydrological constraints obtained from studies on Brothers volcano of the southern Kermadec intraoceanic arc (34.86°S/179.06°E; see Fig. 1) to investigate processes of fluid flow and phase separation in submarine arc volcanoes, using numerical simulations with realistic properties for saline, high-temperature fluids. To obtain a better understanding of the governing parameters for submarine hydrothermal fluid flow, we compare our model results with specific field observations at Brothers. We have not attempted to quantitatively reproduce every detail of seafloor hydrothermal activity at Brothers volcano, as these will mainly be governed by (observationally unconstrained) local variations of lithologies, faults, and other geological features. In this study, we focus on the physical hydrology of the present volcanic structure, including a volcanic cone emplaced into an earlier caldera, but do not consider the complex thermal pre-history of the submarine volcano. Even in a simplified single-stage model, a broad diversity of hydrological regimes develops in our simulations. However, they do allow identification of some first-order processes and principles that control sub-seafloor hydrology and the potential of forming ore deposits associated with submarine arc magmatism.

2. Magmatic–hydrothermal evolution and hydrological constraints at Brothers volcano

Hydrothermal activity at Brothers volcano has been observed on the northwestern inner walls of the caldera (NW Caldera site), along the western caldera wall (W Caldera site), on the NE slope of the larger, main cone (Upper Cone site) and at the summit of the smaller, more degraded cone (Lower Cone site) (Fig. 1A; de Ronde et al., 2005, 2011; Baker et al., 2012; Caratori Tontini et al., 2012). In addition, an older, inactive hydrothermal field was found on the inner slopes of the southeastern caldera wall (SE Caldera site; de Ronde et al., 2005; Caratori Tontini et al., 2012).

At least two major magmatic stages can be distinguished at Brothers volcano (Embley et al., 2012); the first stage includes caldera formation and then collapse of the initial volcanic edifice, with the initial hydrothermal system considered to include magmatic fluids exsolved from an underlying magma chamber (de Ronde et al., 2011). Negative anomalies in total magnetic intensity indicate that extensive, pervasive hydrothermal alteration has taken place especially along the northwestern caldera wall, but also along the southeastern and western caldera walls (Caratori Tontini et al., 2012). Dating of hydrothermal barite from the NW Caldera site using the $^{226}Ra/Ba$ method confirms that hydrothermal activity and associated massive sulfide formation dates back to at least 1200 yrs (de Ronde et al., 2005, 2011). Fluid flow at that time was probably controlled by near-vertical, discontinuous caldera ring faults (Embley et al., 2012), with vent fields migrating from early locations close to the caldera rim to later discharge near the base of the caldera walls (de Ronde et al., 2005). Sulfur isotope analyses of sulfate–sulfide mineral pairs and fluid inclusions indicate formation and trapping temperatures between 240 and 305 °C, consistent with measured vent fluid temperatures of up to 302 °C (de Ronde et al., 2005, 2011).

The second magmatic stage includes at least two episodes of volcanic eruption that post-date caldera collapse, the first forming the smaller, more degraded Lower Cone followed by the younger, larger, less degraded Upper Cone (Fig. 1A; see also Fig. 20 in de Ronde et al., 2005; Embley et al., 2012). Present venting at the Cone sites is diffuse, of low temperature (46–68 °C, with one vent up to 122 °C), with low metal contents in the fluid. Near-seawater salinities of venting fluids indicate high permeability for the cones and sub-seafloor mixing of hydrothermal fluids with seawater (de Ronde et al., 2011). High gas contents as well as isotope (helium, hydrogen, oxygen, and sulfur) signatures and pH analyses, however, suggest a strong magmatic signature, especially for Cone vent fluids (de Ronde et al., 2011). Harmonic tremor measurements confirm a reservoir of gas-laden hydrothermal fluids underlying the cones (Dziak et al., 2008). At the NW Caldera site, present-day venting is focused and characterized by relatively high temperatures (265–302 °C). Salinity variations in the calculated end-member vent fluids indicate that sub-seafloor phase separation is occurring at the NW Caldera site (de Ronde et al., 2011).

Brothers volcano is one of four volcanoes along the Kermadec arc known to host recently deposited sulfide mineralization (de Ronde et al., 2011, 2014b; Leybourne et al., 2012a, 2012b). In general, two types of massive sulfide samples have been obtained from the NW Caldera site: (1) Cu-rich chimneys, related to high vent temperatures (274–302 °C) that contain minor Mo, Bi, Co, Se, Sn, and Au mineralization, and (2) Zn-rich