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Key Points:
- First systematic, integrated heat flow and magnetic study of a submarine arc volcano highlights multiscale convection cells
- Deep circulation structurally controlled, with recharge through the caldera floor and discharge at the caldera walls and postcollapse cones
- Shallow circulation is characterized by recharge zones in close proximity to the sites of present-day diffuse and focused discharge

Supporting Information:
- Supporting Information S1

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Heat Flow and Near-Seafloor Magnetic Anomalies Highlight Hydrothermal Circulation at Brothers Volcano Caldera, Southern Kermadec Arc, New Zealand

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Abstract Brothers volcano is the most hydrothermally active volcano along the Kermadec arc, with distinct hydrothermal fields located on the caldera walls and on the postcollapse volcanic cones. These sites display very different styles of hydrothermal activity in terms of temperature, gas content, fluid chemistry, and associated mineralization. Here we show the results of a systematic heat flow survey integrated with near-seafloor magnetic data acquired using remotely operated vehicles and autonomous underwater vehicles. Large-scale circulation is structurally controlled, with a deep (~1- to 2-km depth) central recharge through the caldera floor and lateral discharge along the caldera walls and at the summits of the postcollapse cones. Shallow (~ 0.1-0.2 km depth) circulation is characterized by small-scale recharge zones located at a distance of ~ 0.1–0.2 km from the active vent sites.

1. Introduction

Brothers volcano is located along the Kermadec intraoceanic arc and is related to subduction of the Pacific Plate beneath the Australian Plate (Figure 1), with the corresponding opening of the Havre Trough back-arc complex in response to the separation of the Kermadec Ridge from the Colville Ridge ~5 Ma ago (Wright, 1994). Brothers volcano is one of three caldera volcanoes that form the active volcanic arc front between 37°S and 34°S (Wright, 1994; Wright & Gamble, 1999). It is part of a silicic volcanic complex (de Ronde et al., 2005) with an elongated shape that covers an area of approximately 13 × 8 km^2 and includes a ~3-km-wide caldera with 300- to 500-m-high walls (Embley et al., 2012). The orientations of regional faults and basement structures are consistent with rifting of the Havre Trough (de Ronde et al., 2017), indicating strong tectonic control on Brothers volcano, which may have formed by eruptions within a graben structure delimited by the regional faults (Embley et al., 2012).

Constructional volcanism progressively occurred in the southern part of the caldera, forming a ~2-km-wide and 350-m-high symmetrical postcollapse cone (Upper Cone), largely undissected. A smaller cone (Lower Cone) overlaps the northeast flank of the Upper Cone (Figure 1). The geochronological and stratigraphic relationships between the two cones are not fully established (Embley et al., 2012), but their relative positions suggest that the Lower Cone is younger than the Upper Cone (de Ronde, Humphris, Höfig, Reyes, et al., 2019). The cones are characterized by lavas and volcaniclastic material of dacitic composition, confirmed by the International Ocean Discovery Program (IODP) drill sites (see the supporting information) U1528 and U1531 (de Ronde, Humphris, Höfig, & the Expedition 376 Scientists, 2019).

There is not a continuous well-defined ring fault system in the Brothers caldera, but steep and nearly vertical scarps are interpreted as normal faults associated with the collapse of the caldera through piston-like subsidence (Embley et al., 2012). The caldera walls are characterized by abundant volcaniclastics, including ubiquitous breccia recovered at IODP drill sites (see the supporting information) U1527 and U1530 (de Ronde, Humphris, Höfig, & the Expedition 376 Scientists, 2019). The caldera floor is characterized by hummocky terrane, likely derived by slump material from the walls and the cones, with small-amplitude sediment waves likely formed by downslope sediment flow (Embley et al., 2012). Multichannel seismics suggest that the caldera is filled with volcaniclastic sediments and intercalated lavas between the caldera floor and the underlying basement (de Ronde et al., 2017). A short core recovered at IODP site U1529 (see the supporting information) is also characterized by dacitic composition (de Ronde, Humphris, Höfig, & the Expedition 376 Scientists, 2019).

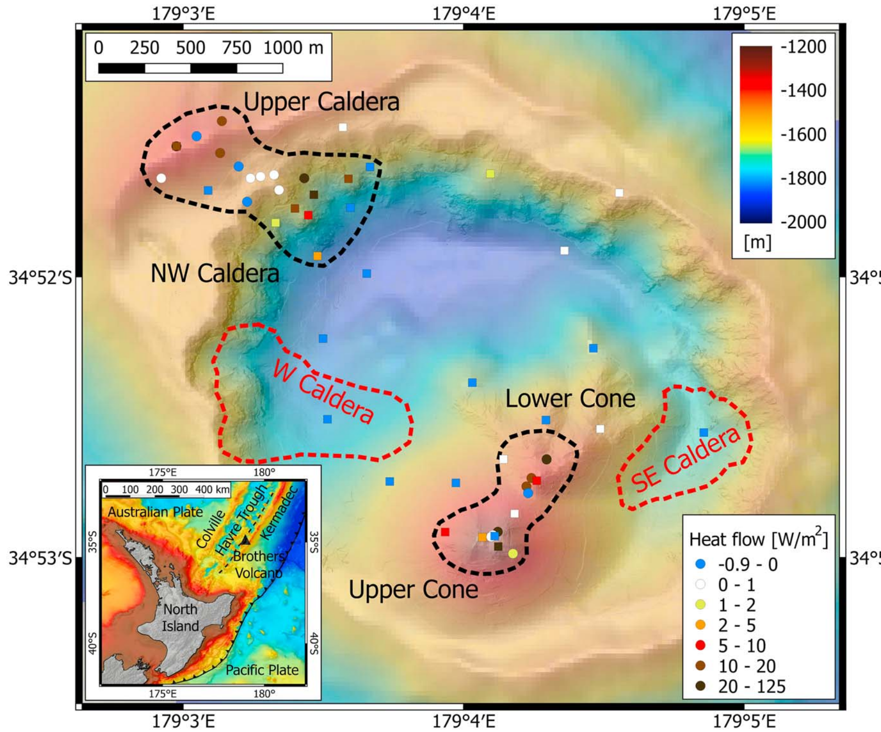

Figure 1. Brothers volcano bathymetry with heat flow stations marked. Squares show data collected using the *Alvin* heat flow probe, whereas circles indicate thermal blankets deployments (see the supporting information). The black dashed polygons show the combined Upper and NW Caldera and the combined Upper and Lower Cone hydrothermal fields, respectively. These polygons are inferred combining locations of observed vent sites with magnetic and heat flow data. The red dashed polygons show the location of the West Caldera and ancient SE Caldera hydrothermal sites, inferred from magnetic data (Caratori Tontini, Davy, et al., 2012). Inset shows the tectonic setting and location of Brothers volcano in the eastern Havre Trough, delimited by the Colville and Kermadec Ridges. The trench location is indicated by the line with teeth on the upper plate, while the dashed black line highlights the location of the active volcanic arc front.

In contrast to hydrothermal systems at mid-ocean ridges (MORs), submarine arc volcanoes are dominated by discharge of magmatic volatiles and acid sulfate fluids (de Ronde et al., 2003). Specifically, the Kermadec arc hosts ~25 hydrothermally active volcanoes with magmatic-hydrothermal signatures (de Ronde et al., 2001, 2007, 2011). Among them, Brothers volcano is the most hydrothermally active (de Ronde et al., 2005, 2011), with present-day hydrothermal discharge occurring mainly on the NW Caldera wall, the recently discovered Upper Caldera site (Humphris et al., 2019), and atop the Upper and Lower Cones (Figure 1). At the NW Caldera and Upper Caldera sites, normal faults are supposed to be the main conduits for hydrothermal circulation, providing enhanced permeability pathways for fluid recharge (Embley et al., 2012). Permeability at the Upper and Lower Cones is likely controlled by higher-porosity zones (de Ronde et al., 2017).

These active sites are characterized by two different types of hydrothermal activity (Baker et al., 2012). Type I is characterized by extensive areas of high-temperature (up to 320 °C) venting of relatively gas-poor, moderately acidic fluids at the NW and Upper Caldera sites, where Cu-/Au-rich sulfide chimneys are commonly found. Patches of diffuse venting mark the boundaries of these focused vent sites. By contrast, Type II is characterized by lower-temperature (≤120 °C) diffuse venting of gassy, very low pH (to 1.9) acid-sulfate fluids at the summits of the Upper and Lower Cones, where native sulfur chimneys and extensive Fe oxyhydroxide crusts occur (de Ronde et al., 2005, 2011). Additional hydrothermal vents (Figure 1) also occur on the West Caldera walls (Baker et al., 2012; Caratori Tontini, Davy, et al., 2012), and a largely extinct site is located at the SE Caldera (de Ronde et al., 2005; Baker et al., 2012; Caratori Tontini, Davy, et al., 2012).

Brothers volcano represents an excellent example of a submarine arc hydrothermal system, and for this reason, it was recognized by the IODP as the top candidate worldwide for arc volcano drilling, to investigate the formation of mineral deposits along arcs and the subseafloor volcanic architecture of these volcanoes. Here we report the results of geophysical and heat flow studies that were carried out in preparation of the IODP Expedition 376 (May–July 2018), focusing our discussion on the Upper Caldera, NW Caldera, Upper Cone, and Lower Cone vent sites, because these sites were the targets of the drilling campaign. Specifically, we analyze high-resolution near-seafloor magnetic data in conjunction with conductive heat flow measurements to investigate hydrothermal circulation at Brothers volcano.

The combination of these detailed data sets for the first time provides a unique opportunity to investigate the geometry and temporal evolution of hydrothermal circulation at a submarine arc volcano. We find that crustal magnetization shows the integrated expression of hydrothermal alteration over time, whereas heat flow reflects present-day active, but transient, fluid flow. Multiscale convection cells exist at Brothers volcano, with deep circulation (~1- to 2-km depth) structurally controlled by a central recharge through the caldera floor, whereas lateral fluid discharge occurs along the caldera walls and at the summit of the postcollapse cones. Shallow circulation (~0.1- to 0.2-km depth) is characterized by small-scale recharge zones in close proximity to the sites of active diffuse and focused venting.

2. Geophysical Surveys

2.1. Heat Flow Surveys

Measurements of conductive heat flow are an essential tool to test models of subseafloor hydrothermal fluid circulation. In a standard model cold seawater enters recharge zones and percolates down to the reaction zone above the magma chamber at depths ~1–2 km (Alt, 1995), where it is heated up to temperatures ~350–400 °C. This hot fluid becomes extremely buoyant and flows up to the seafloor in the discharge zones (Lowell et al., 2013). Extreme spatial variability in the heat flow pattern indicates convection of hydrothermal fluids is the dominant mechanism of magma cooling, with limited background contribution coming from thermal conduction (e.g., Johnson et al., 1993; Stein et al., 1998). The spatial scale of the heat flow anomalies also provides a good indication of the geometry and depth of hydrothermal circulation (e.g., Fisher et al., 1990). Furthermore, while discharge zones are commonly characterized by large mass flow with some spectacular manifestations such as black smokers, recharge zones are invisible because the mass flow is very slow and occurs over large areas. However, they can be identified as zones of very low to negative heat flow.

Current models of hydrothermal circulation are mostly constrained by heat flow surveys at MORs (e.g., Johnson et al., 2010; Salmi et al., 2014) and show that circulation can be highly localized around vent systems with annular zones of recharge in close proximity to the upflow zones, supporting pipe-like numerical models (Coumou et al., 2008; Fontaine & Wilcock, 2007). However, multiple scales of convection cells may exist involving different circulation depths. Specifically, a common distinction is made between shallow and deep circulation (Fisher et al., 1990; Stein et al., 1998). This nested system of fluid circulation pathways is a reflection of the different scales characterizing the permeability distribution in complex volcanic settings, where deep circulation (~1- to 2-km depth) is usually focused through structural elements such as faults or large-scale fractures, whereas shallow circulation (tens to hundreds of meters depth) is characterized by isotropic recharge zones encircling areas of focused fluid discharge, where permeability is homogeneously distributed in porous media.

2.2. Magnetic Surveys

Submarine volcanic rocks are often strongly magnetic because of their significant content of Fe-Ti oxide mineral content, such as titanomagnetite. Hydrothermal alteration processes can transform these primary magnetic minerals into less magnetic, or nonmagnetic, minerals, such as pyrite, effectively reducing the magnetization to negligible values (e.g., Ade-Hall et al., 1971; Fujii et al., 2018; Rona, 1978; Watkins & Paster, 1971; Wooldridge et al., 1990). For example, studies of the magnetic signature of fossil hydrothermal systems in ophiolites have clearly shown how areas of reduced crustal magnetization are associated with the mineralized stockwork zones (e.g., Hall, 1992; Johnson et al., 1982; Richards et al., 1989).

For this reason, high-resolution magnetic surveys are an essential tool to model the pattern of subseafloor hydrothermal circulation, especially when heat flow measurements are sparse or not possible. Thus, to resolve magnetic anomalies at the scale and depth of the hydrothermal systems and to counteract the natural decay of the magnetic field with depth, near-seafloor data collected by deep-submergence vehicles such as autonomous underwater vehicles (AUVs) or remotely operated vehicles (ROVs) are required. Near-seafloor high-resolution magnetic surveys of basalt-hosted hydrothermal vent sites at MORs or back-arc basins (e.g., Caratori Tontini et al., 2014; Caratori Tontini et al., 2016; Fujii et al., 2015; Tivey et al., 2014; Tivey & Dyment, 2010; Tivey & Johnson, 2002) and at submarine arc volcanoes (Caratori Tontini, Davy, et al., 2012; Caratori Tontini et al., 2012, Honsho et al., 2013; Szitkar et al., 2015) have revealed well-defined magnetic "burnholes," that is, discrete zones of reduced crustal magnetization in and around areas of active and extinct vent sites, inferred to represent hydrothermal upflow zones.

3. Methods and Results

3.1. Heat Flow Data

We conducted a systematic heat flow survey (see the supporting information) using a combination of 10 thermal blankets (Johnson et al., 2010; Salmi et al., 2014; Tivey et al., 2016) and the 0.66-m *Alvin* heat flow probe. We acquired data at 52 stations collected in 2017 during the research cruise SO253 with the R/V *Sonne* using the ROV *Quest 4000* (dives #413 and #414) and in 2018 during the research cruise TN350 with the R/V *Thompson* using the ROV *Jason* (dives #1037–1041). The heat flow stations are spaced ~100 m apart (on average) at the Upper and NW Caldera and Upper and Lower Cone hydrothermal sites (Figure 1). A coarser grid with a ~500-m spacing was acquired on inactive areas on the caldera floor, on some of the caldera walls, and on the flanks of the Upper and Lower Cones, respectively. Rough topography with very limited areas of flat terrain, the ubiquitous presence of talus, lack of sediment (for the heat flow probe), and a commonly insufficient distance from active discharge zones so that thermal equilibrium could be reached by the instruments limited the choice of stations that could be occupied at Brothers volcano.

Measured heat flow values ranged between −0.9 and 125 W/m^2, with the hot stations (i.e., those >1 W/m^2) measured inside the areas enclosing the Upper and NW Caldera and Upper and Lower Cone hydrothermal sites, as might be expected. Cold stations (i.e., those <1 W/m^2), including negative values, were also measured in localized spots inside these areas, for example, in a flat area on the NW Caldera rim, between the Upper Caldera and NW Caldera vent fields, on a circular depression on the summit of the Upper Cone, and along the flank between the Upper and Lower Cones. A larger region including the caldera floor and the lower flanks of the Upper and Lower Cones is also characterized by consistently negative, low-amplitude heat flow values.

3.2. Magnetic Data

High-resolution magnetic data were collected between 2007 and 2018 using different deep-submergence vehicles (see the supporting information). The first survey was conducted from the R/V *Sonne* in 2007 during the ROVARK cruise using the AUV *ABE* (dives #202–210) and then in 2011 while aboard the R/V *Tangaroa* during the NZASMS11 cruise using the AUV *Sentry* (dive #92). The magnetic data from *ABE* and *Sentry* were collected with an average line spacing of 50 m at an average altitude of ~50 m above the seafloor (Caratori Tontini, Davy, et al., 2012; Caratori Tontini, de Ronde, et al., 2012). An additional survey over the Upper Caldera vent field, including additional parts of the caldera rim, was also performed in 2018 at the end of the *Jason* dive #1041, after completing the heat flow measurements.

The magnetic anomalies from *ABE*, *Sentry*, and *Jason* were inverted (e.g., Parker & Huestis, 1974; Caratori Tontini et al., 2008; Caratori Tontini, Davy, et al., 2012) to determine the pattern of crustal magnetization that is then interpolated into a common grid (Figure 2). Crustal magnetization values are in the range [0–10] A/m, which is consistent with the range of measured magnetizations for dacitic lavas observed at IODP drill sites U1527 and U1531 (de Ronde, Humphris, Höfig, & the Expedition 376 Scientists, 2019). Low crustal magnetizations are found on the caldera floor and in the area enclosing the active Upper Caldera, NW Caldera, and West Caldera hydrothermal sites and that of the extinct SE Caldera site. Intense crustal magnetization is observed over the Lower Cone, whereas the Upper Cone is characterized by reduced values of crustal magnetization.

4. Discussion

The heat flow pattern (Figure 1) shows intense spatial variability, with hot stations in close proximity to cold stations (distance <100–200 m, down to less than 20 m on the Upper and Lower Cones). Large values of heat

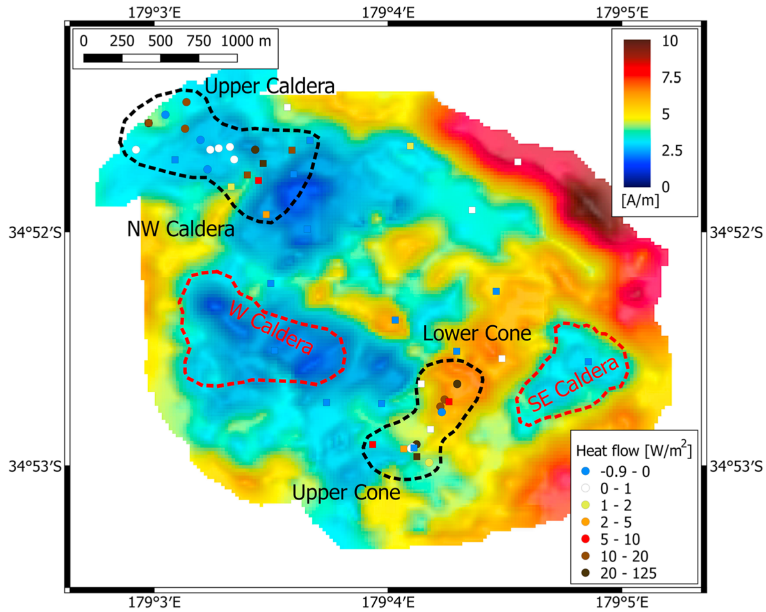

Figure 2. Brothers volcano surface crustal magnetization with heat flow stations, obtained from inversion of near-seafloor magnetic data (see the supporting information). Polygons description in Figure 1.

flow in excess of 20 W/m^2 from lateral conductive heat transfer are observed in proximity to hydrothermal vents at the Upper Caldera and NW Caldera and Upper and Lower Cone sites. A very large area of negative heat flow occurs on the caldera floor. These extreme and nonuniform values suggest that convection is the main mechanism of heat transfer at Brothers volcano, with local variations in heat flow values related to local cold and hot spots with respect to a relatively flat background. There is no clear reference value, but a purely conductive heat flow model (see the supporting information), assuming a magma chamber at 2.5-km depth below the seafloor (e.g., de Ronde et al., 2011; Dziak et al., 2008; Gruen et al., 2012), would imply a broad maximum of ~1.3 W/m^2 on the caldera floor with respect to a background value of ~ 0.2 W/m^2 along the caldera walls, which is in contrast to the observations showing minimum (negative) heat flow on the caldera floor.

We interpret the caldera floor as a broad recharge zone, where a spatial scale of ~2 km suggests a similar circulation depth. This implies that the caldera floor is part of a deep circulation cell, where cold fluids slowly percolate through the volcanic products and the basement underneath to reach the reaction zone just above the magma chamber. The main upflow zones defining this deep circulation cell are under the Upper Caldera and NW Caldera and Upper and Lower Cone sites, respectively, where the largest heat flow values are observed. The active discharge (Baker et al., 2012) occurring at the West Caldera vent field would suggest this site could also be included in this large-scale circulation cell. However, no heat flow stations were collected here in proximity of discharge zones to support this hypothesis.

In the active vent areas at the Upper Caldera and NW Caldera and Upper and Lower Cone sites, we found some significant differences between adjacent stations with the presence of localized cold spots, indicating additional recharge zones (Figures 1 and 3). Even if the spacing between stations in our survey does restrict our ability to determine small-scale spatial variations, the contrasting cold and hot spots in close proximity of one another strongly suggests an additional mode of shallow circulation. At the Upper and NW Caldera sites and the Upper and Lower Cone sites, respectively, we can resolve spatial scales of 100–200 m, suggesting that this is also the maximum depth of the shallow circulation system. These localized areas of cold seafloor adjacent to high-temperature vent sites support the model of shallow circulation suggested by Coumou et al. (2008) for hydrothermal vents at MORs, where convection cells self-organize into pipe-like upflow zones surrounded by zones of cold downflow ~100–200 m away. This separation of deep and shallow circulation at Brothers volcano is also supported by observations of mostly diffuse venting at both the Upper and Lower Cone sites and surrounding black smokers of the Upper and NW Caldera sites. Areas of low-

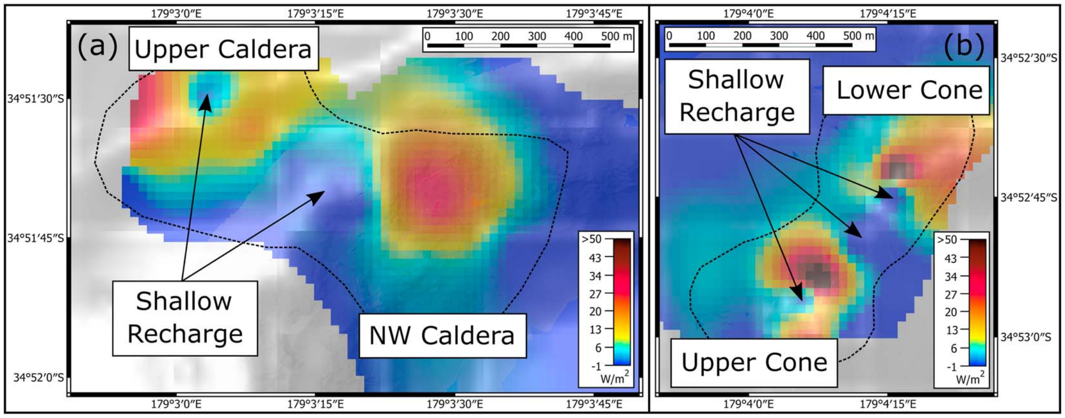

Figure 3. Detailed heat flow pattern (minimum-curvature interpolation of stations in Figure 1) at (a) the Upper Caldera and NW Caldera sites and (b) the Upper and Lower Cone sites, with cold spots interpreted as shallow recharge zones.

temperature diffuse venting imply shallow mixing with seawater, which would promote the formation of discrete circulation cells.

A somewhat ambiguous magnetic pattern (Figure 2) is observed at Brothers volcano where the Upper Cone is characterized by a localized area of low crustal magnetization, yet the Lower Cone shows intense values of crustal magnetization. Given both Upper and Lower Cones are characterized by active venting, this seems to indicate a possible magnetic difference between the two sites. A temporal distinction may exist between the Upper and Lower Cone sites. For example, the Lower Cone has a rougher morphology (Embley et al., 2012) and appears to be built on top of the lower NE flank of the Upper Cone. This would be consistent with a younger age for the Lower Cone (de Ronde, Humphris, Höfig, Reyes, et al., 2019) and therefore for its hydrothermal system. This relative temporal difference could explain the different crustal magnetization observed at these sites, where the hydrothermal system at the Lower Cone has only recently developed, whereby only insignificant volumes of primary titanomagnetites in the host rocks have been affected by water-rock interaction when compared to the Upper Cone, where lower values of crustal magnetization are observed (Figure 2).

The hydrothermal systems of the Upper and Lower Cone sites are also thought to be much younger than that at the Upper and NW Caldera sites (Baker et al., 2012; de Ronde et al., 2005), with the Cone sites interpreted as nascent magmatic-hydrothermal systems (de Ronde et al., 2005, 2011). A much broader area of low crustal magnetization encompasses the Upper and NW Caldera sites, which are instead interpreted as long-lived hydrothermal systems (de Ronde et al., 2005, 2011; Ditchburn & de Ronde, 2017). Our interpretation is that significant demagnetization caused by hydrothermal alteration of the primary titanomagnetites could explain the broad area of low crustal magnetization at the Upper and NW Caldera sites. This area is likely characterized by protracted hydrothermal activity when compared to that of the postcollapse Upper and Lower Cone hydrothermal sites. This is supported by ages for hydrothermal activity at the NW Caldera site exceeding 15,000 years locally, yet the maximum age derived for any mineralization at the Upper Cone site is only a few tens of years (de Ronde et al., 2005; Ditchburn et al., 2012; Ditchburn & de Ronde, 2017).

Figure 2 shows that areas of low crustal magnetization (and hydrothermal alteration) are wider than the spatial scale of heat flow variations and encompass both hot and cold spots (characteristic of shallow recharge zones) at the Upper and NW Caldera sites and at the Upper Cone site. We cannot exclude that areas of present-day recharge could have been characterized by hydrothermal discharge in the past, with corresponding alteration of the primary magnetic minerals of the host rocks. This is also predicted by models of hydrothermal circulation (Gruen et al., 2012). This observation would be consistent with the interpretation of Tivey et al. (2014) that heat flow reflects the present-day active, but transient, thermal environment of fluid flow, whereas crustal magnetization is a broader representation of the static-time averaged effect of hydrothermal alteration, including areas where discharge has occurred in the past (but may not be occurring today). In summary, both active and inactive vent sites show low crustal magnetization, which reflects

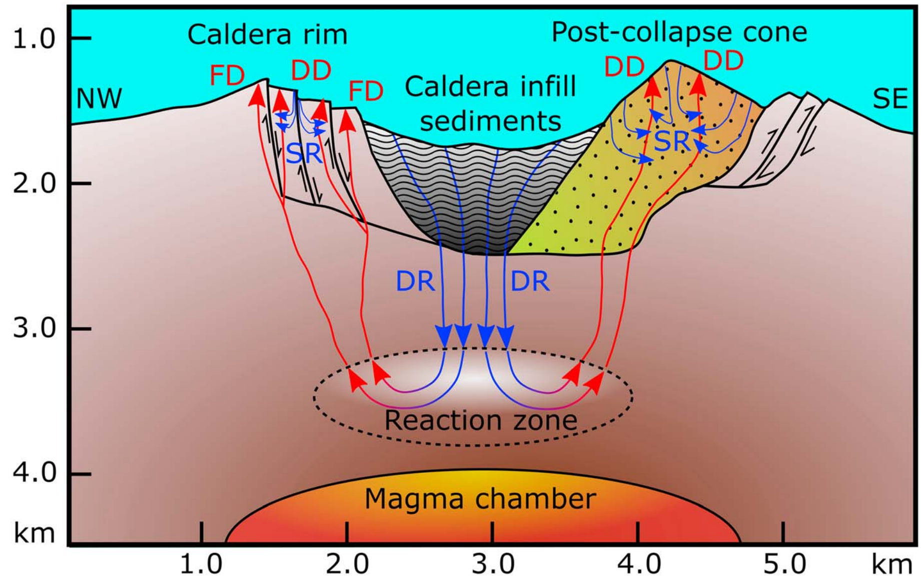

Figure 4. Conceptual model of hydrothermal circulation at Brothers volcano along a NW-SE oriented multichannel seismic line Bro-3 (de Ronde et al., 2017), with recharge (blue arrows) and discharge (red arrows), deep recharge (DR), shallow recharge (SR), focused discharge (FD), and diffuse discharge (DD). Black arrows indicate the caldera faults and structures (Embley et al., 2012), original caldera floor, and geometry of postcollapse cone from seismic interpretation (de Ronde et al., 2017, de Ronde, Humphris, Höfig, Reyes, et al., 2019).

alteration processes occurring over thousands of years, while the heat flow data are a proxy for shorter hydrological processes that can change over decadal scales.

The joint interpretation of heat flow and magnetic data suggests an integrated conceptual model for fluid circulation at Brothers volcano, as shown in Figure 4. Brothers volcano is a multiscale convection system, with both deep and shallow circulation cells. The large-scale, deep circulation is controlled by the structural setting of Brothers caldera, where slow protracted downflow is driven by the relatively permeable sediments and/or volcaniclastics that occupy and infill the caldera floor. By contrast, focused upflow occurs along large-scale faults and fractures along the caldera walls and within the relatively permeable Upper and Lower Cones. Shallow convection cells with small-scale recharge zones of cold seafloor are found at all these hydrothermal sites, where diffuse venting caused by mixing with cold seawater in these shallow layers dominates the Upper and Lower Cone sites and coexists with focused venting at the Upper and NW Caldera sites.

5. Conclusions

For the first time we have created an integrated model of hydrothermal circulation at a submarine arc volcano by combining two detailed geophysical data sets of heat flow and magnetics. Specifically, we hypothesize that crustal magnetization is the integrated expression of hydrothermal alteration processes over time scales of thousands of years, whereas heat flow reflects present-day active, but transient, fluid flow. Brothers volcano is dominated by two scales of hydrothermal circulation. Deep circulation is inherently related to the structural setting of the caldera, with downflow through the caldera floor toward the reaction zone and upflow occurring along the caldera walls and the postcollapse cones. Shallow circulation is compatible with the model of self-organized pipe-like structures observed at MORs. This shallow circulation system explains the evidence of diffuse venting dominating the Upper and Lower Cone sites and occurring at the NW and Upper Caldera sites in between the areas of black smokers. Our results provide fundamental underpinning geophysical information for future interpretation of results from the IODP drilling expedition recently conducted at Brothers volcano (de Ronde, Humphris, Höfig, Reyes, et al., 2019). This model provides also a general framework to understand hydrothermal circulation at arc volcanoes and is applicable to other submarine calderas worldwide.

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