Determining geological relationships that lead to the locations of focused and diffuse vents on the Brothers Volcano, using seafloor imaging and EM300 multibeam bathymetry

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Non technical summary

Brothers volcano is an underwater active volcano located approximately 400 km off the coast of New Zealand. Brothers volcano is thought to be one of the most hydrothermally active volcanoes in the region hosting at least three active hot spring fields. Two of these have been preliminarily explored; one hosting black smoker chimneys and the other highly acidic white smokers.

The aim of this project was to describe the geological features that lead to the formation of the black and white smoker fields. Brothers volcano was mapped using a sonar system on the R/V Thompson during a University of Washington student cruise in March 2009, and the seafloor was directly imaged with a towed underwater camera. Camera tows were conducted at two sites, on the northwest caldera and at the cone. The images were classified on a scale of 0-5 (with 5 being 100% coverage) depending upon the geological features present. Distinct mappable units included sediment, talus, lobate flows, scarp faults and hydrothermal deposits. Analyses of these data show that tectonic faults and volcanic talus deposits are the primary factors which determine the location of the fields. This study of Brothers volcano provided rare direct seafloor imagery and documented increased activity in hydrothermal venting from previous years. Brothers volcano is an unique area of study due to three distinct types of hydrothermal venting being found in a relatively small region.

Abstract

Brothers volcano is part of the Kermadec arc, a back arc extensional zone of the north east coast of New Zealand. The volcano is one of the most active volcanoes in the entire arc. Active hydrothermal venting has been observed at both the cone and northwest caldera locations. The goal of this project was to map and explore the geological features that control the location of white and black smoker vents at these two locations, respectively. The seafloor was imaged using TowCam (WHOI) sled and bathymetry was collected using the SIMRAD EM300 multibeam mapping system on board the R/V Thomas G. Thompson during a University of Washington student cruise, March 8-12th, 2009. At Brothers the relationship between talus flows and faults primarily control venting locations and styles. The North West caldera venting is controlled via ring faults in the caldera wall and by talus providing a permeable substrate from which venting can occur. Venting at the cone appeared to be more robust than noted in previous years. Over 60% of the planet volcanism occurs under in the ocean, yet due to limited studies, little is known about these systems. This project provides a foundation to begin to understand these dynamic and unique systems, from which life is able to thrive fueled by volcanic gases.

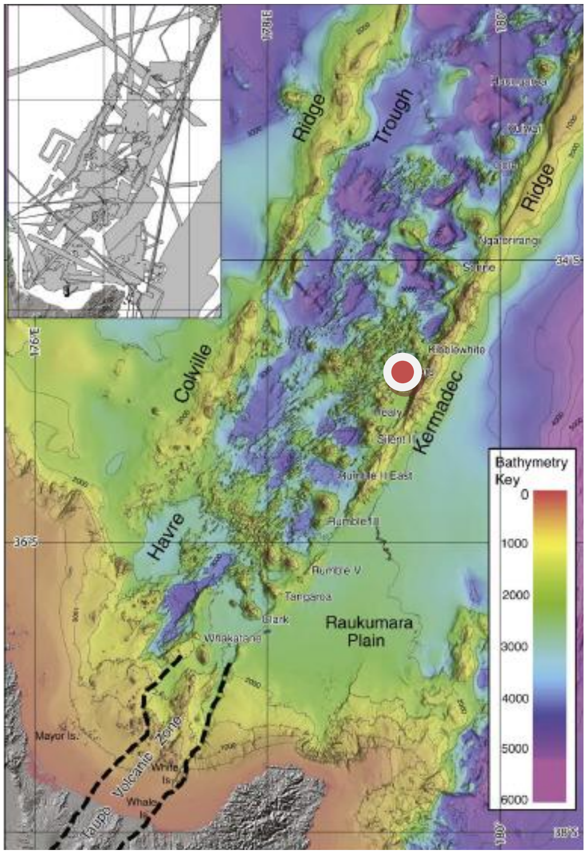


Figure 1: Composite of all available bathymetric data for the Southern Havre trough and satellite derived topography. Brothers Volcano circled. From Wysoczanski et al, 2009.

The Kermadec arc is the southern expression of the Lau-Havre-Taupo complex, which is an arc-backarc extensional zone. The arc is a site of active volcanism with over 45 volcanic centers (de Ronde, 2007); many of these centers host active hydrothermal venting. The arc-back arc extension and Havre trough are formed by the westward subduction of the Pacific-Australian plate boundary (Figure 1, Wysoczanski et al, 2009). The entire arc system can be observed for 2700 km between Fiji and the North island of New Zealand. The present day motion is caused by convergence of the Tonga-Kermadec trench and associated movement of various microplates. This movement is leading to the convergence of the Kermadec arc and extension of the Havre trough (Wysoczanski et al, 2009). The ridges and trough associated with the arc-back arc extension are depicted in figure 1, with the Colville and Kermadec ridges surrounding the Havre trough. The structural fabric of the Havre trough (figure 2) can be simplified into three distinct regions; cross arc chain, central southern Havre trough and basal plateau (Wysoczanski et al, 2009). Brothers volcano is situated in the central southern Havre trough with structural fabric known as constructional-volcanic.

The Kermadec arc, until recently, was not well studied. The NZAPLUME I and II (1999 and 2002) cruises, along with the NOAA Ocean Explorer, New Zealand American ring of fire

Figure 2: Conceptual diagram of the structural fabric of the southern Havre Trough. From Wysoczanski et al, 2009.

expedition, led to the discovery of numerous vent sites present in this volcanic arc. Brothers volcano, located at the northern extremity of the Southern Kermadec Arc (SKA), has an elongate edifice, with a northwest to southeast major axis that is 13km long. The structure is dominated by a caldera that reaches water depths of 1836 m. The caldera floor has a diameter of 3x3.5km (figure 3) punctuated by an emerging cone and associated satellite cone. The caldera floor is surrounded by steep sided, fault-bounded walls which rise by 290-530 m above the seafloor (Lavelle et al, 2008).

The Kermadec arc is unique and venting that occurs here is different to other hydrothermal systems within the world's ocean (Massoth et al, 2003). Arc magmas are fractionated to a greater extent and tend to have a greater range in chemical composition than mid-ocean ridges (de Ronde et al, 2001). Host rock type in the Kermadec Arc extends over a range of compositions from basalt to rhyodacite (de Ronde et al, 2005). Brothers volcano is comprised of porphyritic glassy dacite lavas. The low vesicularity of these dacites indicates that effusive emplacement of the lavas rather than pyroclastic eruption is common (de Ronde, 2005). Interestingly, De Ronde et al (2005) conclude that the presence of the caldera and cone signify that the volcanic evolution includes pyroclastic eruptions.

The rock and mineral composition of hydrothermally active volcanoes directly influences the chemistry of vent fluids due to rock-water interactions at high temperatures (Delteil et al, 2002). Brothers volcano hosts the most vigorous and extensive hydrothermal venting yet discovered on the Kermadec arc (de Ronde, 2005). There are four sites that are known to have hosted active venting. These are located on the; northwest caldera, southeast caldera, cone and LaLa (de Ronde. Pers comms. Figure 4). Of these, the cone and northwest caldera are presently regarded as active (de Ronde, 2005). Venting source differs between sites; high-temperature focused black smokers, white smokers and low temperature diffuse vents are present. The cone site is dominated by diffuse venting with white smokers also presents, the northwest caldera site contains 2 m tall black smoker chimneys and the extinct southeast caldera site includes relict sulphide-rich chimneys (de Ronde et al. 2005).

The cone and caldera sites on Brothers volcano are chemically very distinct (de Ronde et al, 2005) with the cone site displaying a much greater concentration of dissolved magmatic gases; CO_2, SO_2 and H_2S. This increase is indicated by a shift of 0.27 pH compared to the surrounding ambient seawater. Also the cone site displays H_2S concentrations of 4250 nM, whereas no H_2S was detected at the northwest caldera (de Ronde et al, 2005). This is of great interest considering the relatively small distance between the two sites (figure 2). Given the close proximity of the two sites along with the observed differences one can conclude that there must be differing sources of hydrothermal vent fluid to the seafloor. De Ronde et al (2005) claimed that the northwest caldera is dominated by evolved seawater with episodic injections of magmatic fluids. In contrast, processes at the cone site are dominated by magmatic-hydrothermal interactions.

Studies regarding the distribution of focused venting at the TAG hydrothermal hypothesized that black smokers are formed by mixing of high-temperature fluid with seawater (Mills, 1995). Anhydrite and sulfide are precipitated first, forming a porous chimney structure. With further sulfide precipitation the chimney becomes impermeable. Once the chimney has become impermeable venting takes on the form of metal-rich acidic fluids expelled directly into the water column (Mills, 1995). White smoker vents are produced by the mixing of black smoker fluid and ambient seawater (Edmond et al, 1995). Previous studies have described significant distribution of talus at Brothers volcano (de Ronde, 2005). These talus beds could provide a surface which would enable formation of white smokers. With black and white smoker and diffuse venting all being observed at Brothers, an ideal platform is provided to relate these hydrothermal structures to geological features.

Numerous hypotheses have been presented speculating about the geological features that result in the occurrence of hydrothermal vents at specific locations. De Ronde et al (2005) suggested that the structure of the caldera and vent systems at Brothers is controlled by intersections of basement faults. The northwest caldera site is located at an intersection of two major conjugate faults (with a strike of 055˚, Figure 3). The orientation of the conjugate faults is consistent with an influence by Havre trough rifting. Faulting at Brothers volcano is controlled by extensional tectonics (de Ronde, 2005). This relationship has been well documented at numerous mid-ocean ridge sites. For example, Delaney et al (1992) proposed that the location of the vents in the Endeavour hydrothermal system on the Juan de Fuca Ridge is controlled by intersections of ridge parallel faults and non ridge parallel faults. These intersecting faults are areas of high permeability, which enable hydrothermal fluids to be channeled towards the surface. This high permeability is brought about by coupled movement along the conjugate faults. Both of these studies document the strong control of faulting on the locations of the vents.

Between 8-12th March 2009 onboard the R/V Thompson TN230 University of Washington student cruise Brothers volcano was mapped and imaged using the hull-mounted Simrad EM300 multibeam system and the TowCam imaging platform (provided by Dan Fornari, WHOI) to determine the geological features that control hydrothermal venting. The goal of this project was to map the location and geological features proximal to sites of active venting and to use these spatial relationships to determine the controls on venting at Brothers volcano.

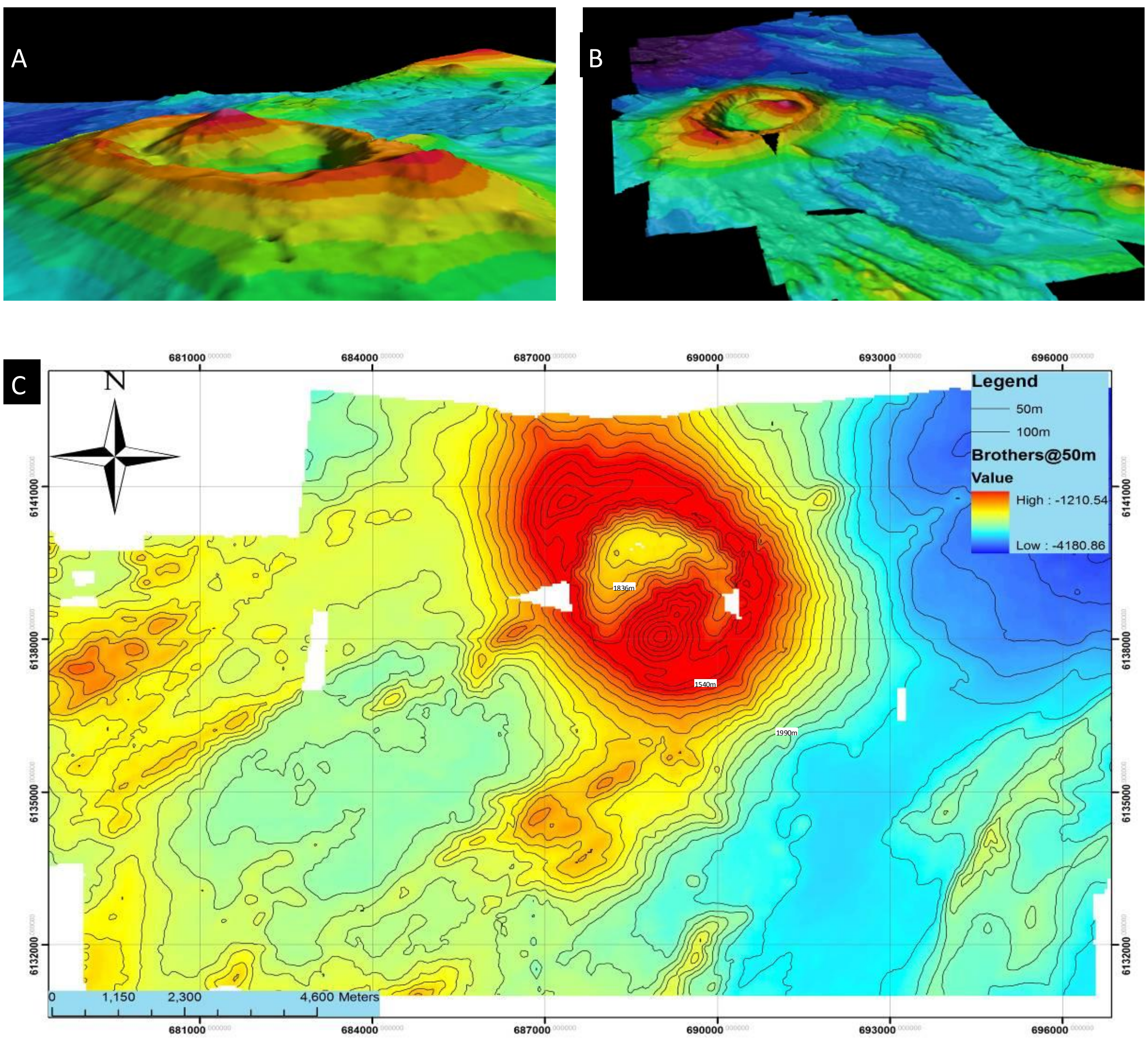


Figure 3: Brothers Volcano. A: Brothers from NE. B: Brothers and surrounding topography from NW, C: Brothers bathymetric map contoured at 50 and 100m. Map projection: UTM zone 60S, WGS84.

Methods

The Simrad EM300 mapping system onboard the R/V Thompson was used to produce bathymetric maps of the volcano and surrounding topography. The EM300 operates at a 30 kHz frequency and transmits 135 pings from a hull mounted transducer, which allows a swath width of two times the water depth. This equates to approximately 3 km swath widths at Brothers volcano, when assuming a water depth of 1500 m. The data were collected on two days to compensate for adverse weather conditions, limiting data quality during the first run. During the planned run of data collection on 3rd March 2009, wind speeds reached 40 knots and the rough sea state meant that data collection was poor. A section of the western caldera wall is missing due to poor quality of returned data. Before data collection an XBT was deployed to determine the sound velocity profile of the water column. Raw data were imported into CARIS Hips and Sips for ping editing and visualized in Fledermaus. Swaths were edited using a configuration file unique to R/V Thomas G Thompson to allow for offsets in the positions of the transducer and GPS. The swaths depicting Brothers volcano were gridded at 40 m, whereas surrounded topography needed to be gridded at 50 m. Grid sizes were determined to ensure that enough pings were received per grid cell to accurately make a representation of that depth.

Seafloor images were obtained using the underwater camera system TowCam (WHOI); two camera tows have been used in this project at the cone and northwest caldera (figure 4). TowCam images where processed using a MATLAB script provided by Adam Soule (WHOI), which combined the images to the TowCam CTD and assigned the images a positional index which could be used post processing to geolocate each image. The CTD was additionally equipped with turbidity and Eh sensors which measure suspended particles and redox potential.

Images were collected at a 12 second frequency with tow speeds generally between ¼ - ½ knot, tows typically lasted 5-6 hours. This frequency allowed overlap between the individual images. In total four tows were undertaken, one at each of the potential sites of hydrothermal activity.

TowCam images were each visually analyzed and classified on a scale of 0-5 depending upon the composition of the image (table 1). Images were classed upon the presence of the following features; talus, lobate, massive flow, pelagic sediment, ripples, scarp, hydrothermal sediment, hydrothermal deposits and biology.

Scale	0	1	2	3	4	5
Weighted percentage (%)	0 (absent)	1-25	26-50	51-75	75-99	100 (complete coverage)

Table 1: TowCam image classification parameters

Image examples of the units used are shown in figure 3, with the corresponding image classification given in the plate summary. Post image classification, composition profile maps were produced for both the cone and northwest caldera tow (Figures 6 and 8).

Results

EM300 data depicted in figures 3 and 4 show Brothers caldera, the cone and satellite cone and surrounding topography. The white sections are areas where too few pings were recorded for an accurate interpolation of depth to be calculated. The bathymetry (figure 3-C) clearly shows the nature of the very steep-sided interior caldera walls and the much shallower

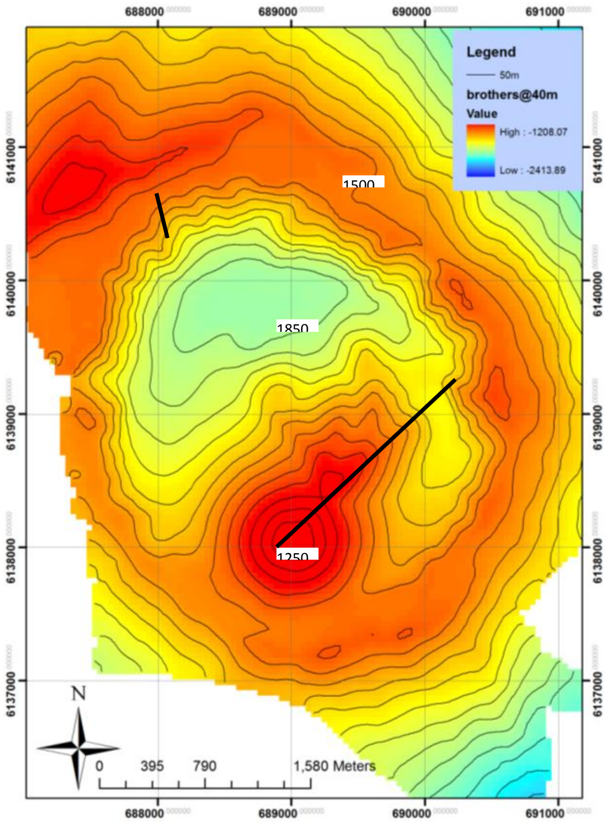


Figure 4: Locations of known hydrothermal deposits and paths of camera tows.

outer flanks of the volcano. The steep caldera walls have been interpreted to mark ring faults that are known to occur at Brothers (de Ronde. 2005). Lineament features are observed trending a direction of north east intersecting the volcano. Several flow like are observed on the northeast flank of the main cone; these are consistent with previous studies.

Sediment was classified based upon the appearance of fine grained particulates. Ripples were generally associated with sediment indicating flow. Rock flows were classified as talus and were identified based upon flow like structures containing similar sized rocks. Lobate flows were classified based upon identification of flat pillow –like volcanic forms. Scarp faults were identified as regions which had a steep increase or decrease in elevation. This change in bottom topography is associated with faults. Vent biology was identified based upon the advice of Tim Shanks (WHOI). Massive flows were classified based upon the identification of flows which appeared to be structurally similar.

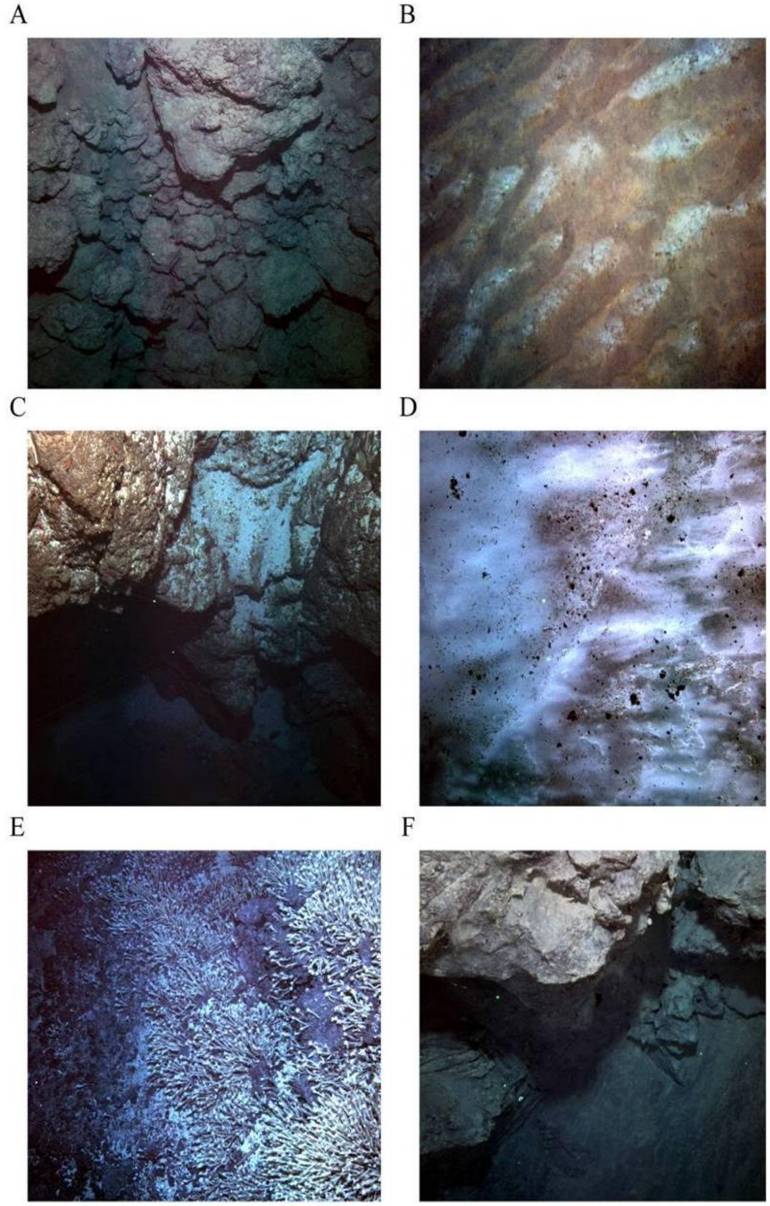
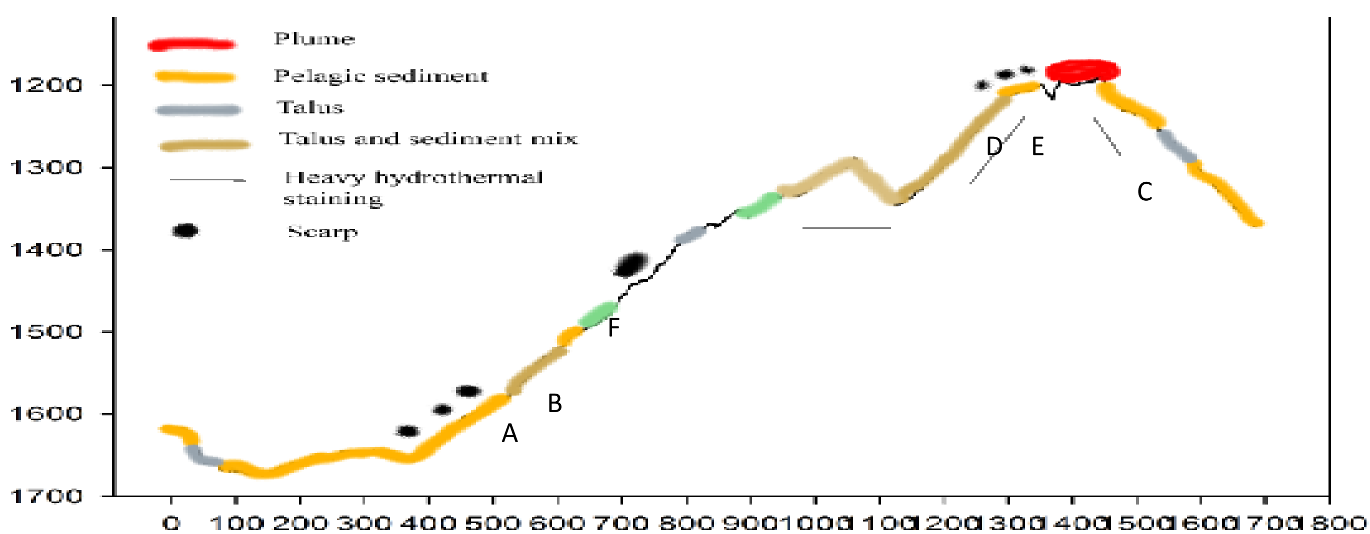


Figure 5 (above): Cone. A. Talus (coverage=5), B. Pelagic Sediment (coverage=5), C. Lobate flow (coverage=3), D. Heavily hydrothermally stained sediment (coverage=4), E. Barnacles fields ontop of main cone (coverage=5), F. Scarp and truncated flow (coverage=3). Figure 6 (below): Showing the simplified geological composition of the cone tow. With corresponding image locations (Figure 3)



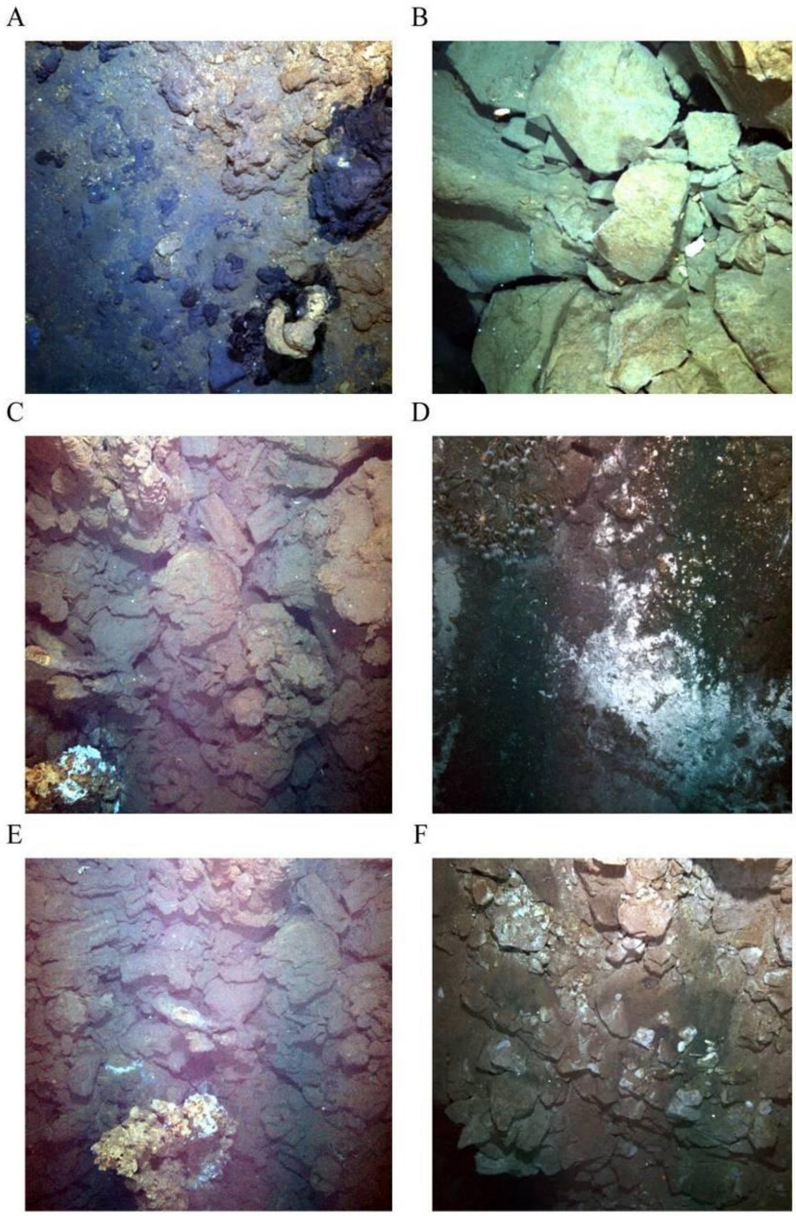
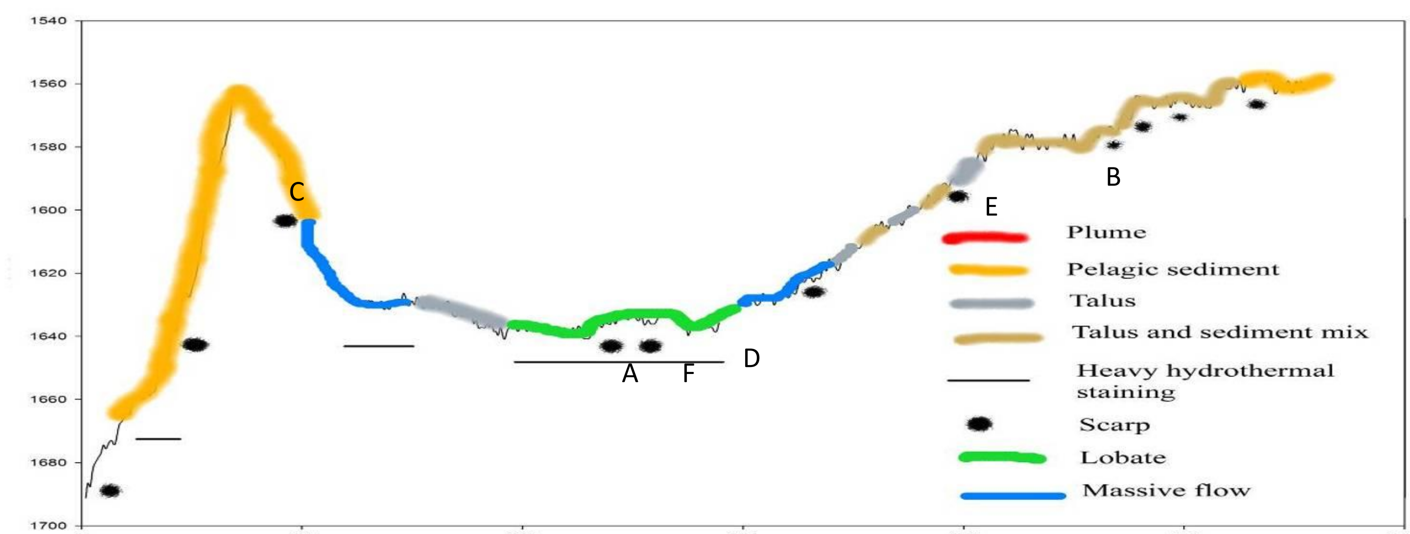


Figure 7 (above): North West caldera tow. A., B. Talus flow C. Talus flow with extinct sulfide vent chimney, staining D. Heavy hydrothermal staining with barnacle field E. Talus flow with extinct sulfide vent. F. Massive flow. Figure 8 (below): Simplified geological composition units for the cone tow. With corresponding image locations (Figure 3)



Cone and satellite cone

A variety of sediment types and hydrothermal features were found along each tow (figures 5 and 6). One of the predominant features of the cone tow (figure 5) was extensive fields of long neck barnacles. The barnacles were observed at the summit of the main cone, and were the most abundant animals found along the tow-their locations are co-registered with hydrothermal flow. Percentage coverage reached 100% for extended distances (figure 5-E). A large plume was imaged at the summit of the cone based on intense particulates in the water column and a significant perturbation in eH as indicated by the TowCam CTD. An approximate spatial extent of the plume is 168 m given a tow speed of 0.5 knots and an image frequency of 12seconds.

The profile (figure 6) with units labeled for the cone site highlights the dominant geological-hydrothermal features of this area. The dominant geological units of the cone site are a mixture of sediment and talus. A high percentage of heavy hydrothermal staining is associated with mixtures of talus and sediment. Pelagic sediment dominates the bottom of the caldera with well developed sediment ripples on the lower slopes. This sediment is likely to be comprised of high ash content. Flocculent abundance was greatest for the 1st half of the tow and appears to be correlated with pelagic sediment. There is also a peak in flocculent immediately after the plume on the main cone, with the peak lasting about 10 images or approximately 29 m. These and significant Eh hits are consistent with hydrothermal activity in this area. Regions with greatest abundances of talus are limited to the steepest sided slopes, consistent with faulting along the steep walls. The plume is depicted as being on the summit of the cone, with scarp faults appearing to be located immediately before regions of intense hydrothermal activity.

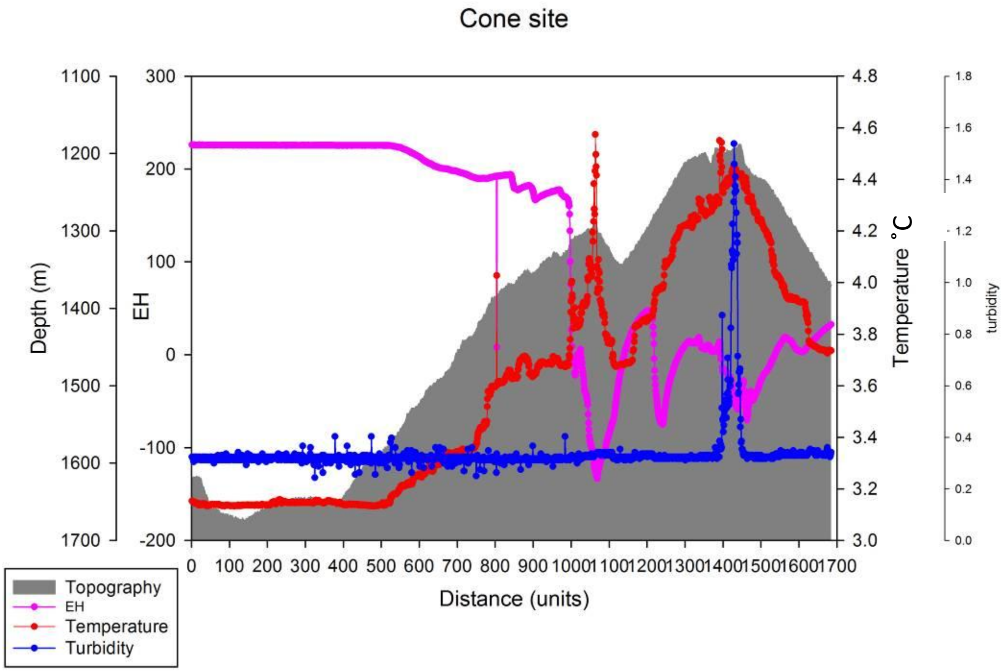


Figure 9: TowCam CTD for the cone. Eh, temperature anomalies and increased turbidity document intense plume activity near the summit of the cone site. With diffuse venting at the satellite cone.

The cone site CTD tow (figure 8), shows less variation than the northwest caldera tow, with the peaks in temperature being more defined and of larger amplitude. There are two temperature peaks located at the upper slopes of both the cone and satellite cone. The temperature spike on the satellite cone is the largest (~1˚C) compared to the gradual increase in temperature on the main cone (~0.8˚C). Eh follows a similar pattern to that observed on the North West caldera, where Eh decrease follows the temperature spikes. The drop in Eh is more substantial on the satellite cone than the main cone, with a 30 mv difference. This indicates that redox potential is greater on the satellite cone. Turbidity is constant throughout the tow apart from a major peak above the cone, which correlates to the period when the camera system was towed through a large plume. The cone CTD data displays much greater negative Eh measurements than the northwest caldera. Venting at the main cone site appears to be more active than in previous years, with visual identification of a white smoker plume at the summit of the main cone.

Northwest Caldera

The Northwest caldera (figures 7 and 8) tow began in the caldera floor at a depth of 1690 and proceeded in a northwestern direction to an end depth of 1560m. The NW caldera had much greater concentrations of talus and lower sediment coverage than the cone. The terrain throughout this tow was very variable, with scarp faults common, this made TowCam imaging difficult. This led to several periods lasting approximately 10-20m of no images of the seafloor. Unlike the cone tow no plume was observed. However, several extinct chimneys were documented, (Figure 7-C and E). Intensive hydrothermal staining was also observed along this tow. Pelagic sediment and rippling was again concentrated along the caldera floor. Further sediment was found on the top of the caldera wall at a depth of 1560m. Scarp faults were

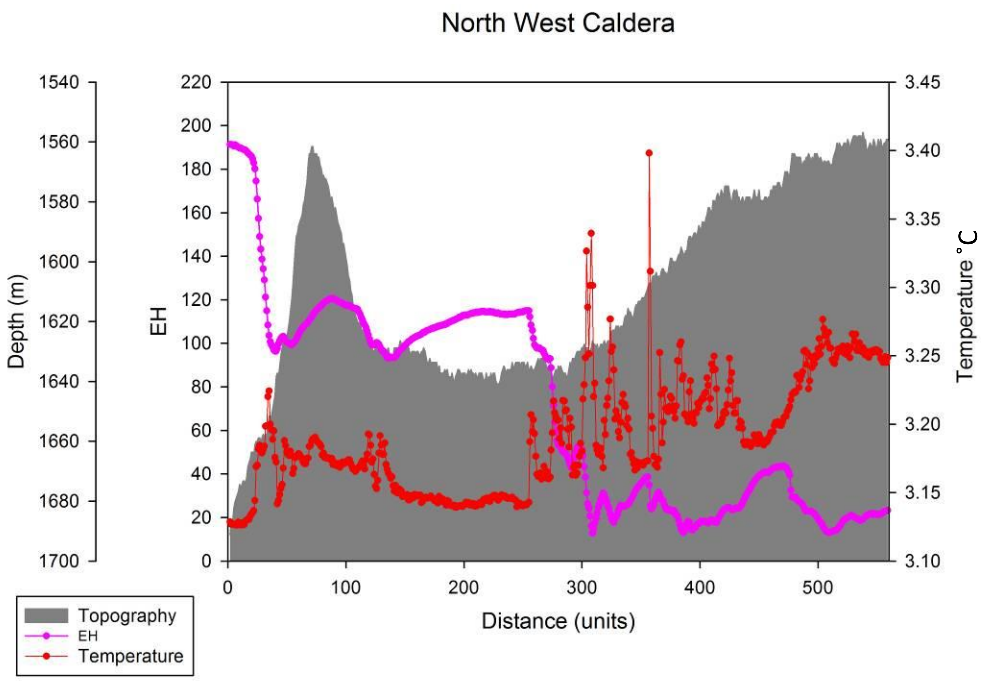


Figure 10: TowCam CTD for the Northwest caldera, temperature increases are associated with progressive decrease in Eh.

observed to be in greater abundance on the northwest caldera than the cone. Heavy hydrothermal staining was less abundant than in the cone tow, with regions of highest coverage at 1640m depth. Extinct sulfide chimneys were observed during the tow associated with the regions of heavy hydrothermal staining.

TowCam CTD data from Northwest caldera tow (figure 10) clearly show that there are two large spikes and several smaller spikes in temperature. The large spikes show temperature increases of 0.35˚C and 0.3˚C with the smaller spikes ranging between 0.1-0.2˚C. Associated with the temperature increases are a drop in the Eh measurement, indicating a more reduced environment indicative of hydrothermal activity. Eh remained at relatively constant level throughout the tow. The large decreases in Eh of approximately 90 mv are associated with the temperature spikes. This indicates that these regions are probably hydrothermal active. Turbidity, which hasn't been plotted for this tow remained constantly low, indicating that no source of focused hydrothermal venting was observed during the tow.

Discussion

Hydrothermal venting at Brothers volcano appears to be vigorous and spatially widespread. Active venting was observed at the cone, through a large and dense plume, other indicators of hydrothermal activity were found during all tows that included documentation of hydrothermal staining, developed barnacle fields and extinct sulfide chimneys.

The major temperature and Eh variations are associated with the pelagic sediment and talus, along with regions of heavy hydrothermal staining. These observations suggest that talus provides a highly permeable structure for hydrothermal fluid to reach the surface. Implying that talus is of fundamental importance to hydrothermal vent location. This agrees with the views of Fornari and Embley (1995) in which they highlight that talus provides a stratigraphic unit that allows a route of horizontal permeability. However, they also speculate that lava flows have an equal if not greater control on hydrothermal venting, especially when lava flows are associated with talus.

Venting at the main cone site appears to be more active than in previous years. The temperature increase and Eh drop at the cone indicates intense diffuse venting. This is also consistent with the presence of large barnacle fields that require venting for nutrient sources. Thick sediments document on the caldera floor substantiate the claim by De Ronde et al that the presence of the caldera and cone signify that the volcanoes evolution includes pryroclastic eruption. This sediment is likely to have high ash content; however would only be able to be confirmed with direct sediment sampling.

Camera tows over the northwest caldera show that there were several 10-20 m lava flows along the caldera wall. Extinct chimneys were documented on talus and in proximal to several temperature spikes and limited changes in backscatter. These relationships are interpreted to indicate that diffuse venting is occurring, however, no sites of focused venting was observed. The plume anomalies which show hydrothermal activity on the northwest caldera site are in agreement with previous studies (de Ronde et al, 2005) in which active black smokers and diffuse venting were discovered. The northwest caldera camera tows depicted a greater variety of geological features than the cone site that could focus hydrothermal venting. These features include talus, scarp faults and lava flows. These features provide important pathways for hydrothermal fluid to reach the surface, historically and currently as evidenced by the association of numerous extinct vent chimneys in this area and by the plume anomalies. De Ronde et al

(2005) linked venting structures at the northwest caldera to a series of ring faults that form around the caldera wall. These provide regions where water can seep into the crust, is heated at depth, and released via hydrothermal vents. Numerous scarp faults were documented along the tows in this study as well, and their presence on the walls suggest that they are likely associated with the caldera wall ring faults as well. Ring faults are believed to occur as a feature of caldera collapse. Scarp faults could lead to the uptake of water like the caldera ring faults and thus lead to hydrothermal activity.

De Ronde et al (2005) outline venting evolution at Brothers, and document that venting is a very dynamic process here. Venting at the cone is believed to be increasing in contrast to a more or less static state at the northwest caldera (de Ronde et al, 2005). The results of this study indicate greater point source venting atop of the main cone than in previous studies as evidenced by the greater extent of the plume observed (168 m), (de Ronde et al, 2005). This increase in venting at the cone could be attributed to a decrease in the venting aperture and focusing of flow (Delaney et al, 1992), due to mineral deposition minimizing the opening. Decreasing the hydrothermal vent opening will lead an increase in subsurface pressure, thus amplifying the flow. It could also be that the system beneath the cone has heated up, however. Heat from magmatic sources is believed to be a major controlling influence on hydrothermal activity in submarine environments (Fornari and Embley, 1995). At Brothers, De Ronde et al, (2005) suggest that magmatic pulses could be common place; this provides an alternative hypothesis for the increased venting documented during this study.

In addition to the importance of ring faulting for providing major channels of hydrothermal flow, documentation of flows, talus, and vent locations in this study also indicate the importance of these features for channeling flow. These observations are consistent with those made by de Ronde et al (2005) that effusive emplacement of lava is important for focusing hydrothermal activity. Fornari and Emberly (1995) highlighted the role of lavas in providing a route for hydrothermal fluid to reach the surface. This hypothesis is supported through the mapping of the geological features.

This research provides one of the few studies into temporal changes at a submarine volcano and presents a foundation for future studies to develop the current models in the formation of hydrothermal vents. Future studies should include documentation of the ages of hydrothermal vents and lava flows to determine the evolutionary timeline. Attempts at deciphering the causes of temporal changes in venting are required. The relationships of vent fluid composition to both micro- and macro-biology is little understood, development in understanding of geological controls is first needed before exploration into any biological effects.

Conclusions

This project characterized the EM300 bathymetry co-registered with geological features from the deep-towed camera system to examine the relationship between geology and hydrothermal flow at Brothers. The distribution of talus and other geological units were successfully mapped for the cone and northwest caldera camera tows providing insights into the factors that control sites of focused and diffuse venting.

Documentation of chimneys and plume signals indicative of flow along the caldera wall, support the hypothesis that hydrothermal venting at Brothers volcano is controlled by a series of ring faults around the caldera wall and by the distribution of permeable talus flows. The talus flows are believed to provide an entry point for the input of water and for hydrothermal fluid output. The processes leading to venting at the cone site could be similar to that of the caldera, with scarp faults playing an important, but possibly less dominant role in hydrothermal forcing.

The unique hydrothermal chemistry of Brothers volcano makes development of the models which define the controlling geological processes a key future research field. This study provides better documentation of two active hydrothermal venting sites and shows that the cone site was more hydrothermally active than in previous years, indicating the dynamical nature of hydrothermally active marine volcanoes.

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