A SUBMARINE MAGMATIC-HYDROTHERMAL SYSTEM AT BROTHERS VOLCANO, KERMADECS

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SUMMARY –Secondary minerals in dredge samples from the Brothers Volcano include silicates, silica polymorphs; Na-Al, Ca, Ba and Ba-Sr sulphates; Fe, Cu, Zn, As and Pb sulphides; Fe and Mn oxide/oxyhydroxides and native S. The variety and range of mineral compositions indicate deposition in different parts of a submarine hydrothermal system characterised by differences in temperature (ambient seawater to >300^{o}C), fluid compositions, degree of magmatic-hydrothermal water-rock interaction and degree of seawater influence. Secondary minerals originate from a partly exhumed waning hydrothermal system/s (NW caldera); the main upflow of a relatively well-established active magmatic-hydrothermal system on the seafloor where sulphide-rich chimneys are extant (SE caldera) and a nascent magmatic-hydrothermal system where crack zones localise upwelling acid waters from depth (cone).

1. INTRODUCTION

Active seafloor hydrothermal venting and sulphide deposits were first reported in two southern Kermadec frontal arc caldera volcanoes, Brothers and Rumble II (West), of the Kermadec-Havre arc-back arc system (Fig. 1) by Wright et al (1998). In 1999 a systematic reconnaissance for submarine hydrothermal activity in the southern Kermadec arc found hydrothermal chemical plumes being discharged from at least seven (and possibly two more) of 13 volcanoes (Massoth et al, 2003). The unusually high concentrations of CO_2, sulphur gases and Fe in the seafloor vent discharges are believed to be hybrid mixtures of hydrothermal and magmatic fluids (Massoth et al, 2003). Of the seven hydrothermally active volcanoes, the Brothers volcano is the most active, (de Ronde et al, 2003) having two separate vent sites including high-temperature black smoker venting (Stoffers et al, 1999).

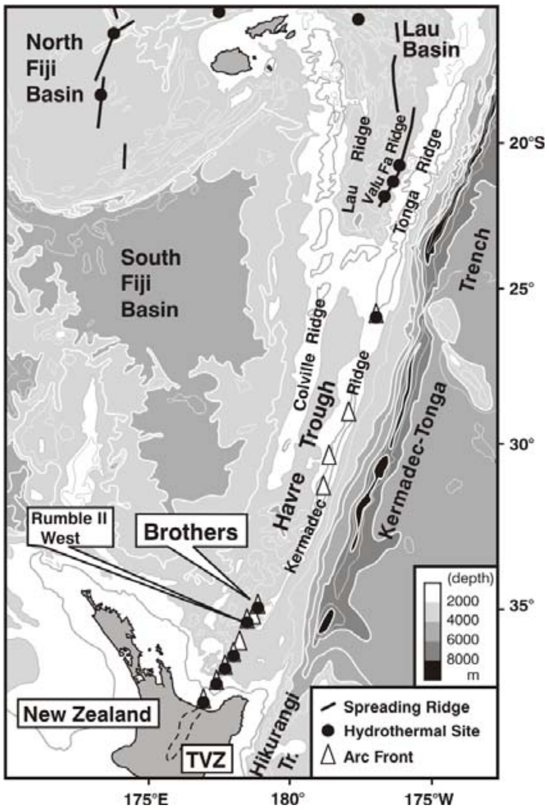


Figure 1- Location of the active arc front, hydrothermal sites and Brothers Volcano in the Kermadec arc (adapted from de Ronde et al, 2004).

In 1996 sulphide-rich samples from a chimney in the Brothers volcano were recovered. These contain chalcopyrite + pyrite + barite ± galena or sphalerite + pyrite + barite ± galena with gold present by as much as 6.1 ppm (de Ronde et al, 2003). In 1998 the Sonne 135 cruise recovered more rock samples (Stoffers et al, 1999) from the NW and SE caldera and cone of Brothers Volcano (Fig. 2) and these are the subjects of this study.

This paper is an initial petrological study of selected 55 samples of lava flows, volcaniclastics, sediments, hydrothermally altered rock and pieces of sulphide chimneys from the Sonne 135 cruise. Samples were petrologically analysed using x-ray diffractometry, transmitted and reflected light microscopy and scanning electron microscopy with an attached energy dispersive x-ray spectrometer.

The objectives of study are to: (1) identify minerals deposited from hydrothermal vents and hybrid fluids in the seafloor (2) determine the temperature, fluid types and interaction processes among the different fluids and between the fluids and rock associated with the formation of these minerals and (3) set up a petrological working model for the Brothers Volcano submarine hydrothermal system that may be used to further understand submarine hydrothermal activity and provide insight to conditions associated with massive sulphide deposition in arc-type hydrothermal systems.

2. STUDY AREA

The Kermadec-Tonga trench and Hikurangi Trough (Fig. 1) mark the collision zone between the Pacific and Australian plates. The plate boundary changes from a simple oceanic island arc with a distinct back-arc basin (Havre Trough) in the north, to a continental margin arc system in the south, within the Taupo Volcanic Zone (TVZ) of the North Island (Gamble et al, 1996). Apart from volcanism, the TVZ is a region of extensive active hydrothermal activity (Browne, 1978).

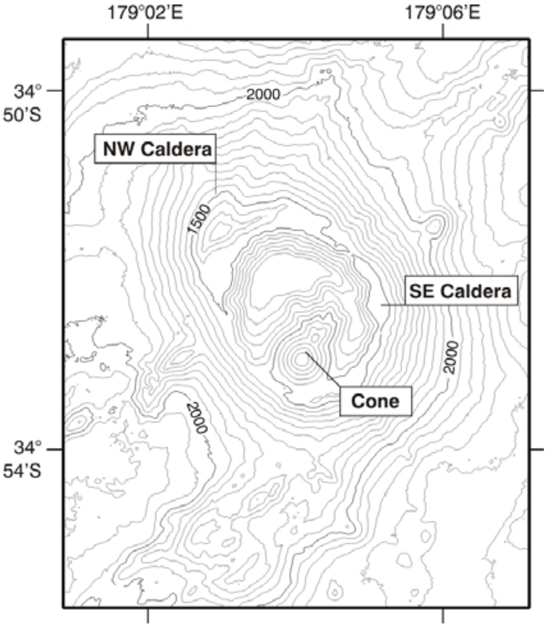


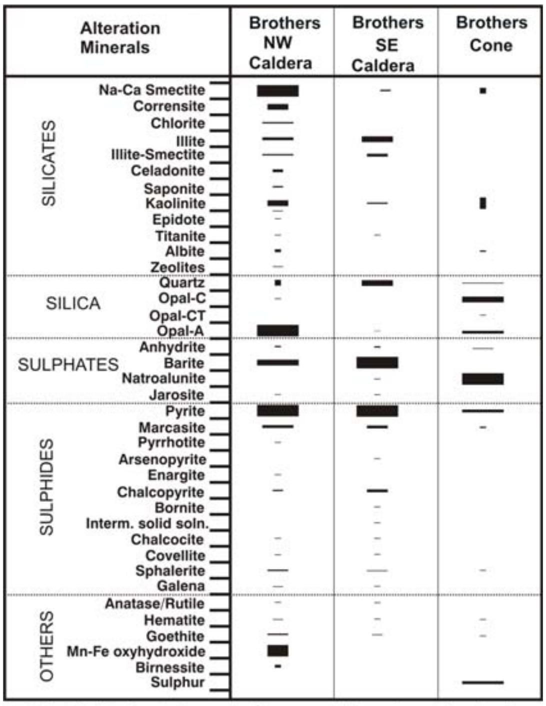
Figure 2- Topographic map of the Brothers Volcano caldera showing the location of sampling sites.

The Brothers Volcano is one of a chain of at least 12 major stratovolcanoes in the 1200 km long, mostly submarine Kermadec subduction system at 26°S to 36°20'S (Wright and Gamble, 1999). The dacitic Brothers volcano is a 7-9 km diameter submarine caldera volcano with its summit at 1350 m water depth. The central cone in is ca. 2 km wide and 350 m high and partly coalesces with the SE caldera wall (Fig. 2). The caldera is 3-3.5 km wide with steep caldera walls 350-450 m from the caldera floor (Wright and Gamble, 1999).

3. RESULTS

The rocks recovered from the Brothers Volcano are dominated by volcanics, including dacite and rhyodacite with relatively minor andesite lava flows. Other samples include ignimbrites, volcanic sandstone with abundant fresh glass (80%) and hydrothermally altered fragments (20%) cemented by opal A and sulphides; and pieces of sulphide-rich chimneys. Primary minerals in the volcanics include glass, plagioclase, clinopyroxene, titanomagnetite, apatite and rare zircon and orthopyroxene. The intensity of alteration of volcanics, as indicated by the amount of primary minerals replaced, ranges from near-complete (100% of primary minerals replaced except for apatite and rare zircon) to moderate (50-60% of primary minerals still extant).

Thirty-eight minerals and mineraloids were identified in the 55 analysed samples. The most common alteration minerals are illitic clays including well-crystalline illite and interlayered illite-smectite, chlorite, corrensite, Na-Ca-Mg-(Fe) smectites including saponite and nontronite, celadonite, kaolinite, opal-A, zeolites including Na-clinoptilolite and stilbite, barite ranging from pure barite to Sr-bearing barite, pyrite, marcasite, chalcopyrite, sphalerite ranging from pure ZnS to Fe-bearing ZnS, leucoxene, hematite and goethite. Less common are: epidote, titanite, albite, quartz, opal-C including lussatine and lussatite, opal-CT, anhydrite, natroalunite, pyrrhotite, arsenopyrite, enargite, bornite, intermediate solid solution in the Cu-FeS system (iss), chalcocite, covellite, galena, anatase/rutile, birnessite and native sulphur. The distribution of these minerals in the NW and SE caldera and cone are shown in Fig. 3.



Note: length of bar denotes increasing frequency, thickness increasing abundance

Figure 3- Relative frequency and abundance of secondary and hydrothermal minerals found replacing rock and depositing in vugs and fractures in the NW caldera, SE caldera and cone of Brothers Volcano.

The secondary minerals occur as replacement of original volcanic rocks, precipitated from waters or sublimated from vapour as in native sulphur, or deposited after recovery from the sea. Most of the silicate minerals occur as alteration products of the rock whilst most of the sulphides, sulphates and oxides/oxyhydroxides are found only in vugs and veins or form part of the chimney samples. The most common vein and vug fills include opal-A, smectites, zeolites, quartz and opal-C. Pyrite, goethite, anatase/rutile and hematite also replace titanomagnetite, glass and ferromagnesians. Barite alters ferromagnesians in some samples but is mainly precipitated from hydrothermal waters. Kaolinite often replaces earlier illitic clays and chlorite; and in one sample from the cone, natroalunite. Natroalunite from the cone, associated with sulphur has a platy morphology (Fig. 4) typical of alunite formed from magmatic-hydrothermal solutions (Arribas et al,. 1995).

Jarosite ($KFe_3[SO_4]_2[OH]_6$) and tamarugite ($NaAl[SO_4]_2 \cdot 6H_2O$) are deposited after the rock had been recovered from the sea and stored under humid conditions. Euhedral laths of jarosite (<70 µm) form around the edges of marcasite ± pyrite. Tamarugite, which is water-soluble, only occurs in rock that has been completely replaced by natroalunite, opal and pyrite.

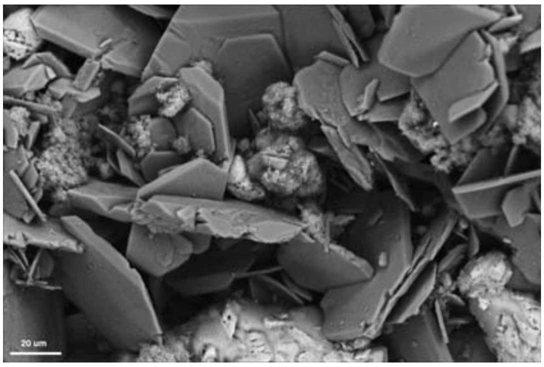


Figure 4- Scanning electron back-scattered image of magmatic-hydrothermal platy natroalunite from the Brothers Volcano cone.

The number of minerals found in the NW caldera (Fig. 3) of the Brothers Volcano is partly due to the large number of samples obtained and analysed from this site. The number of minerals also represents a wide range of hydrothermal temperatures, depth zones and fluid compositions in the NW caldera relative to the SE caldera and cone regions. Apparently there have been several hydrothermal regimes in the NW caldera that had been intermittently cooled and inundated by seawater. This is exemplified by samples where rock altered to fine crystals of epidote + titanite + illite (associated with waters that had equilibrated with the rock at about 240 ± 20^{o}C), is later inundated by cation-leaching and near-acid-SO_4 waters that further altered the rock to illite + anhydrite + sulphides. With further cooling of the system and with seawater incursion, opal-A, zeolites and corrensite are deposited.

Volcanic sandstones from the NW caldera also show evidences for exhumation of parts of a hydrothermal system/s during or just before the volcanic eruptions that deposited dacitic glass. The unearthed hydrothermal mineralogy (now detrital) is similar to the assemblages shown in Fig. 3 for the NW caldera except for the presence of detrital prehnite. Opal-A and Fe-sulphides cement the glass and hydrothermal rock fragments suggesting a rejuvenation of hydrothermal activity after volcanic eruption/s.

Within the SE caldera, quartz, illitic clay, barite and chalcopyrite are more abundant than in the NW caldera. Mn-Fe oxyhydroxides, including goethite and birnessite, epidote, titanite, chlorite, albite and zeolites are absent. Natroalunite, bornite and Cu-Fe-S intermediate solid solutions are present in the SE caldera but not in the NW. The differences in mineralogy between the NW and SE caldera may be an artefact of sampling, as mentioned previously. However the mineral assemblages in the SE caldera indicate that the samples originate near a magmatic-hydrothermal upflow zone as discussed below.

The Brothers cone samples contain minerals that are reminiscent of acid-SO_4 alteration in subaerial active craters of volcanoes including native sulphur, tridymite, natroalunite and kaolinite (Reyes et al, 2003) and abundant of lussatite. Unlike subaerial volcanic craters however, natroalunite and kaolinite are not pervasive in the Brothers cone sample but instead are confined in 100 µm wide fractures. Furthermore, these fractures are later cross-cut by younger fractures filled with smectite, opal-A, pyrite and lussatine. The numerous cross-cutting interrelationships among the fractures and fracture-fills suggest that the upflow of magmatic fluids from depth in the Brothers cone is intermittently quenched and diluted by seawater influx during rock fracturing.

4. DISCUSSION

The major gangue minerals, sulphides and oxides/oxyhydroxides in the Brothers volcano span a range of temperatures (Browne, 1978; Barton and Skinner, 1979; Velde, 1977; Reyes, 1990; Vaughan and Craig, 1997) from near ambient seawater to >300^{o}C (Fig. 5). The influence on secondary mineralogy of seawater, magmatic fluid influx, degree of hydrothermal water-rock interaction, reduction-oxidation potential (R_H= log[H_2/H_2O]; Giggenbach, 1997) and temperature vary with time and space. Where hydrothermal water compositions have equilibrated with the rock, altering fluid are neutral pH or "mature" and the alteration assemblage referred to as neutral pH. "Immature" cation-leaching acid waters occur when equilibration between water and rock has not yet been attained (Giggenbach, 1997).

As shown in Fig. 5 the influx of magmatic-hydrothermal fluids initiates a cycle of hydrothermal activity. Magmatic influx is manifested in the (1) sulphide-rich chimney samples from the SE crater where chalcocite, bornite, iss, chalcopyrite and pyrite are found, (2) the presence of native sulphur and platy natroalunite in the cone samples (Fig. 4) and (3) occurrence of vein enargite (Hedenquist et al, 1998) in a rhyodacitic sample in the NW caldera. The last example was probably partly exhumed from a deeper level in a hydrothermal system that had already partly waned. The fluids that deposited natroalunite in the cone and pyrite + bornite + chalcopyrite in the SE caldera are highly oxidised and contain relatively high H_2S as illustrated in a log(P_{H2}) vs log(H_2S) activity diagram at 350°C (Fig. 6).

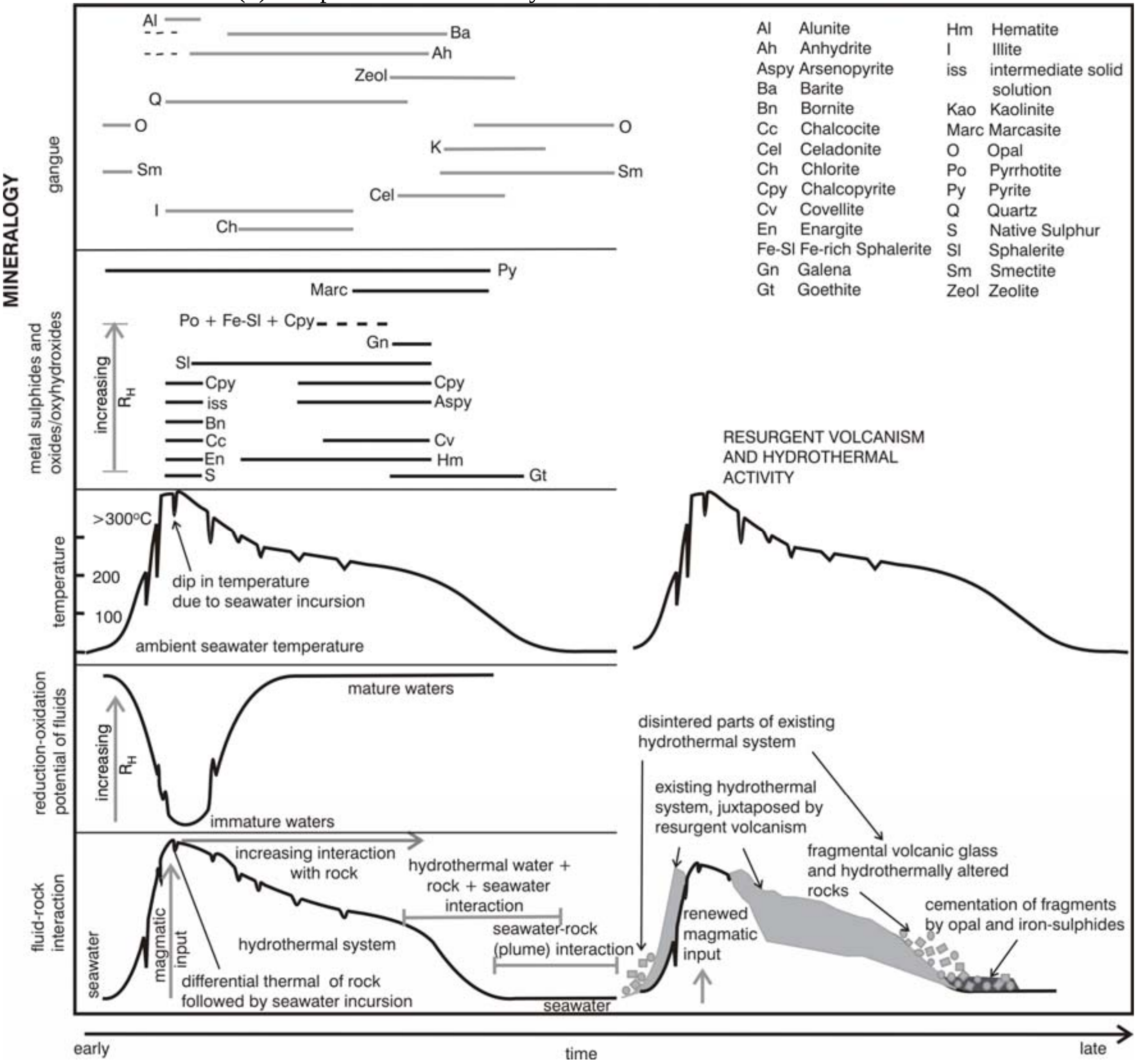


Figure 5- Factors affecting the deposition of metal sulphides, oxides/oxyhydroxides and silicate gangue minerals in the Brothers Volcano including time, temperature, degree of water-rock interaction (mature-immature), reduction-oxidation potential, of the fluids (R_H = log H_2/H_2O) fluid types and the interaction among different fluids and the rock. Mineral temperature ranges are plotted. See text for explanation.

With a decrease in magmatic input and an increase in hydrothermal water-rock interaction (Fig. 5), alteration waters become mature and alteration mineral assemblages change accordingly, with temperature, depth and distance from the main magmatic influx zone. Increasing incursion of seawater further cools the hydrothermal system. The interaction among rock, hydrothermal waters and seawater produces barite, anhydrite, zeolites,

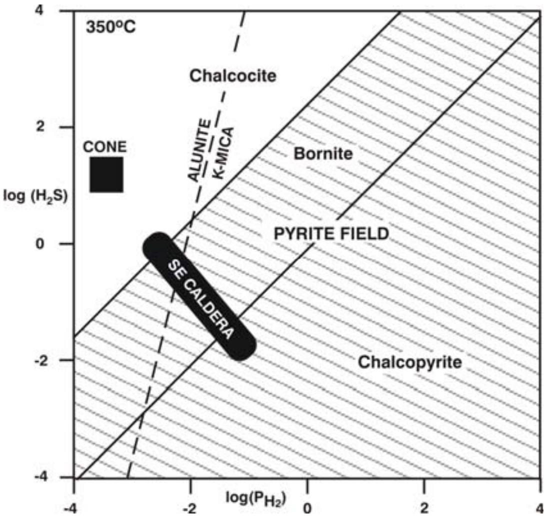


Figure 6- Stability fields of chalcopyrite, pyrite,

bornite, alunite and K-mica at 350°C as defined by $\log(P_{H_2})$ vs $\log(H_2S)$ and the general composition of fluids in the cone and SE caldera. Thermodynamic data are from Bowers et al (1984) and Murray and Cubiciotti (1983).

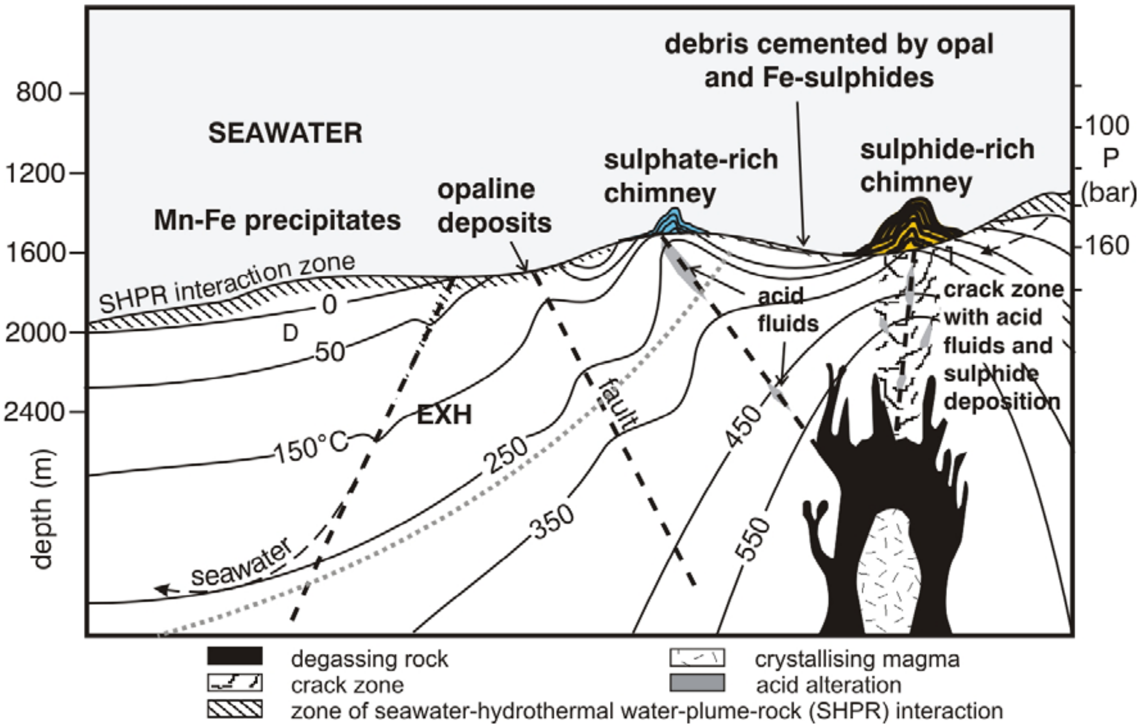


Figure 7- Cartoon of an arc-type submarine volcano such as Brothers Volcano. Chimney sizes are exaggerated. See text for discussion.

opal-A, smectite (including Na-Ca smectite, nontronite, corrensite and saponite), celadonite, pyrite + marcasite, hematite and goethite. Where temperatures further cool to ambient seawater conditions and material from the plume dispersed (e.g., Mills, 1995; Massoth et al, 2003), Fe-Mn oxyhydroxides (including goethite and birnessite) and smectite deposited (Fig. 7).

Resurgent volcanism disinterred parts of a pre-existing hydrothermal system as exemplified by volcanic sandstones from the NW caldera (Fig. 5) where silica-rich hydrothermal fluids, emanating from renewed hydrothermal activity at depth, have cemented the volcanic and hydrothermal rock fragments with opal-A and pyrite (Fig. 7).

5. PETROLOGICAL MODEL

Figure 7 is a cartoon showing an arc-type submarine volcano, like Brothers, with the rock surface at a depth of about 1600 m. Faults provide direct pathways from the crystallising magma and other parts of the magmatic-hydrothermal system to the seafloor. Unlike subaerial magmatic-hydrothermal systems like Nevado del Ruiz (Giggenbach et al, 1990) and Cagua (Reyes at al, 2003) it is postulated that a "crack zone" instead of a vapour conduit extends from the crystallising magma to the surface. The crack zone is created when cold seawater comes initially in contact with rock heated by rising hot fluids and magma. In the initial stages of the crack zone, when the magmatic-hydrothermal system is just being established as in the Brothers Volcano cone, magmatic gases condense and form acid SO_4 waters that deposit platy alunite in ca. 100 µm cracks.

Sulphide-rich chimneys with barite are deposited within the main upflow zone of a magmatic-hydrothermal system, once the crack zone has been partly sealed from seawater inundation by secondary mineral deposition. The sulphide-rich chimney is exemplified by samples from the Brothers SE caldera.

Farther away from the main upflow of magmatic-hydrothermal fluids, it is possible that sulphate rich chimneys form where slightly more mature hydrothermal fluids upflow along faults to the seafloor (Fig. 7). At the same time that the sulphate chimneys are being deposited, subsurface rocks below the chimney are replaced by slightly acid to near-neutral waters to illitic clays, anhydrite, quartz, pyrite, arsenopyrite, sphalerite and galena. Samples from this zone were collected from the NW caldera. The region enveloped by dotted lines in Fig. 7 and referred to as EXH represent the region of the hydrothermal system that had been exhumed during resurgent volcanism. After deposition of volcanic shards and hydrothermal fragments, renewed hydrothermal activity at depth produce opal-A cement, associated with pyrite, on the seafloor surface.

Alteration composed of Fe-Mn oxyhydroxides, corrensite deposition and kaolinite alteration occur along the zone of seawater-hydrothermal fluids-plume-rock interaction zone (SHPR in Fig. 7).

In summary, the secondary mineralogy of dredged samples from the Brothers Volcano originate from an active but partly exhumed and waning hydrothermal system/s (NW caldera); the main upflow of a relatively well-established active magmatic-hydrothermal system on the seafloor where sulphide-rich chimneys are extant (SE caldera) and a nascent magmatic-hydrothermal system where crack zones localise upwelling acid waters from depth (cone). The high H_2S and oxidising conditions indicated by the alteration mineralogy and the superposition of several hydrothermal regimes within the Brothers Volcano caldera is more reminiscent of active hydrothermal areas in andesitic systems such as in the Philippines and Latin America (Giggenbach et al, 1990; Reyes et al, 2003) than hydrothermal systems in the TVZ.

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