

Investigating the geological evolution of Rumble II West Volcano Using EM300
Bathymetry and TowCam Imagery

Final Draft – May 28th, 2009

Jennie Mowatt
University of Washington
School of Oceanography, Box 357940
Seattle, WA 98195-7940
jemowatt@yahoo.com

Non-Technical Summary

The Kermadec arc, a hydrothermally active region situated on the boundary of the converging Pacific and Australian plates north of New Zealand, is host to a chain of underwater volcanoes, many of which are both volcanically and hydrothermally active. Rumble II West, located at 35°21.200'S, 178°39.100'E, is one of thirteen volcanoes located on the southern 260 km of the Kermadec arc and before this survey, it had yet to be mapped in detail. Rumble II West is important because it supports rare and unique hydrothermal ecosystems and contributes to deep ocean heat and chemical fluxes. In addition, valuable minerals like sulfides and even gold have been dredged from it. Data was collected aboard the R/V Thompson in March 2009. Bathymetric surveys and camera tows of the seafloor were used to determine the geological evolution of Rumble II West. Results from these analyses indicate that Rumble II West is a post-erupted stratovolcano that has undergone multiple caldera formations and ring faulting. In addition, the volcano has experienced tectonic faulting through the main structure, oriented NE to SW, that demonstrates the buildup of geologic stress created by subduction of the tectonic plates that form the arc.

Acknowledgements

I would like to thank the captain and crew of the R/V Thompson, Dan Fornari, Marshall Swartz, Deb Kelley, Mitch Elend, Mike Reed, Miles Logsdon, Fritz Stahr, and the instructors and my fellow classmates of Ocean 444.

Abstract

This study provides an initial characterization of the geological evolution of the submarine volcano Rumble II West using EM300 bathymetry data and TowCam seafloor imagery. Rumble II West is located NE of New Zealand in the Kermadec arc, an underwater volcanic chain that is hydrothermally active with significant emission of sulfur- and volatile-rich fluids. Many volcanoes on the arc have been extensively studied, Brothers volcano in particular, but Rumble II West had only been previously defined through low-resolution mapping and camera imagery. This survey was important because this particular volcano is located in a highly active tectonic region that is rich with hydrothermal systems supporting mineral deposition and deep-sea ecosystems. Data was collected aboard the R/V Thompson during a student research cruise in March 2009. EM300 bathymetry maps and TowCam seafloor imagery data were used in conjunction with a comparative analysis of Brothers volcano (geologically similar to Rumble II West) to derive the geological processes that formed the volcano. It was determined that Rumble II West was initially a stratovolcano that has undergone episodic pyroclastic eruptions from its summit leading to caldera formation and subsequent ring faulting. This is in addition to faulting derived from basement structures striking NE to SW through the caldera, increasing stress on the overall edifice. Orientation of these faults with respect to the Kermadec-Havre trough are not parallel, leading to a fractioning of the plate and induced stress from microplate migrations. This stress is altering the overall regime of volcano production and hydrothermal emissions on the arc.

Introduction

Characterization of submarine volcanism has predominantly been confined to mid ocean ridges and actively venting underwater volcanoes. The Kermadec arc is a region of intense volcanic activity located on the boundary of the converging Pacific and Indo-Australian plates (Figure 1, 2) (Wright 1998). The Pacific plate subducts under the Australian at a shallow angle until it reaches a depth of approximately 50 km; from 50 to 200 km the dip increases to 70°

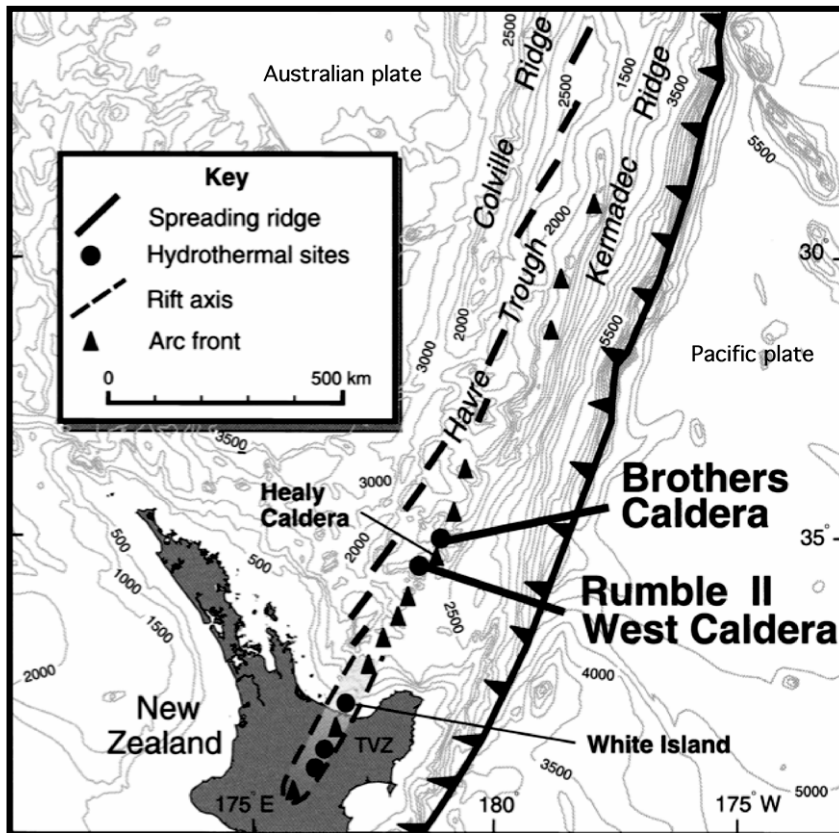


Figure 1. Northeastern New Zealand margin and Kermadec-Havre back arc system. The Kermadec arc is located on the convergence of the Pacific and Australian tectonic plates (Wright 1998).

(Smith 2006). Rates of subduction vary from 6-24 cm/yr^{-1} depending on location along the arc (Smith 2006). Throughout the Kermadec arc, volcanoes are consistently located ~100 km above the subducting slab (Smith 2006). In this zone of the arc, subduction transfers deep fluid and sediments into the Earth's mantle. Fractions of this material are then recycled back

to the seafloor and chemical signatures of this process are manifested both in the diverse rock assemblages as well as the novel fluid compositions including acid-sulfate and hydrothermal fluids mixed with seawater (deRonde 2005).

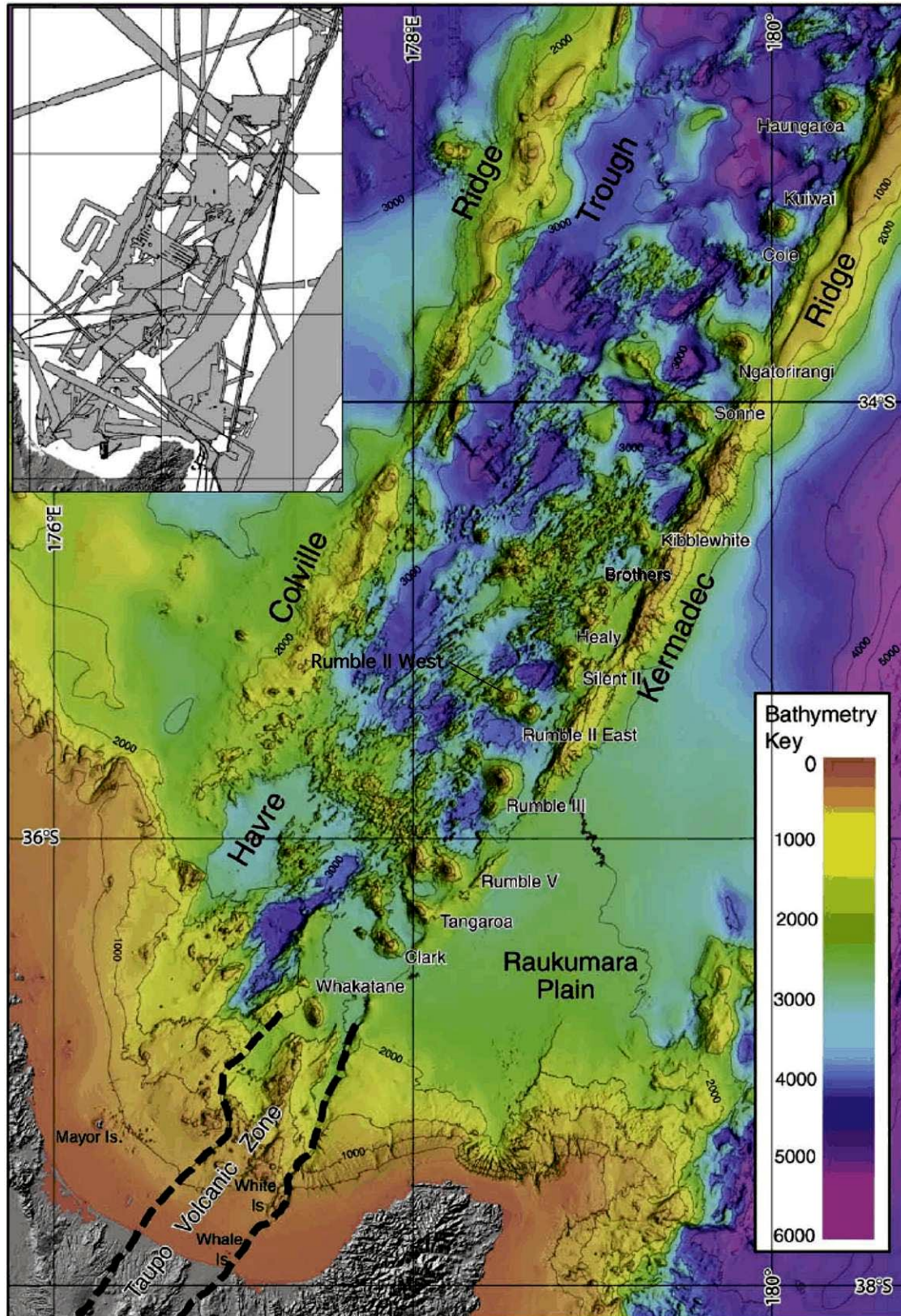


Figure 2. Bathymetric map of all available multibeam data for the Southern Havre Trough. Inset indicates the tracks and areas of individual surveys whose data comprise the map. Areas that are not covered use satellite data configured to fit the edges of multibeam dataset (Wycoszanski 2009).

This paper presents recent results from new high-resolution bathymetric surveys of the Rumble II West volcano and camera imagery of a transect on the seafloor. These data were analyzed against the already well-studied and geologically similar Brothers volcano to characterize the formation and geological evolution of Rumble II West. This was an important survey because it allows for a better understanding of the processes that shape the Kermadec arc and in turn impact chemical and heat fluxes in the ocean via hydrothermal emissions.

Rumble II West is one of approximately thirteen volcanoes located along the southern 260 km of the Kermadec arc (deRonde 2001). It is one of two volcanoes included in the Rumble II complex (Rumble II East being the other), and comprises one of six Rumbles in the arc (Figure 3). The Kermadec arc is a unique region compared to many other volcanically and hydrothermally active vents sites, typically found on mid-ocean ridges (MORs], because of its setting, diversity of rock types, intensity of venting and fluid compositions. Much of the arc is located in a relatively shallow environment (< 2 km) rich with hydrothermal activity, as compared to MORs that are commonly deeper and generally less active (deRonde 2001). Of the volcanoes found on the southern Kermadec arc, seven were determined to be hydrothermally active (Figure 3) (deRonde 2001).

Because of the influence of subduction-derived products at the arc, rock compositions are widely variable. Basalt is the most common rock type found along the volcanic arc but compositionally more evolved rocks that include dacite, rhyodacite, andesite and even fragments of sulfur have been recovered (deRonde 2001, 2005). These rocks occur as pillow lavas, talus, lobate, lapilli and tephra (deRonde 2005). Because this hydrothermal system is located at relatively shallow depths, (220-1350 m), boiling is common and venting temperatures are generally less than the 400°C temperatures found at MOR hot springs (deRonde 2007). Fluid

chemistry is altered during phase separation, enhancing mineral deposition (deRonde 2001, 2007). Rock-buffered fluids released from basalts are generally reducing, in contrast to fluids that have interacted with dacite-rhyodacite rocks that are more oxidized (deRonde 2001). The presence of native sulfur is theorized to reflect greater oxidizing conditions in the subsurface (deRonde 2001). Dredging in 1996 at the Brothers and Rumble II West sites recovered gold-bearing massive sulfides and native sulfur, which produced some of the first evidence for hydrothermal systems in the Kermadec arc (deRonde 2001). High gold concentrations make these sites attractive for their exploitation of base metals by the mining industry.

In addition to alteration of the crust in the immediate vicinity of the vents, hydrothermal vent systems also impact the ocean. Hydrothermal plumes in the Kermadec arc rise 220-700m off of the seafloor to water depths of 1150 m (depending on the summit height of the chimney orifice) where they inject black smoke into the water column that is eventually dispersed by tides and currents (deRonde 2001). Plumes generally consist of Fe, Mn, He and S particulate matter

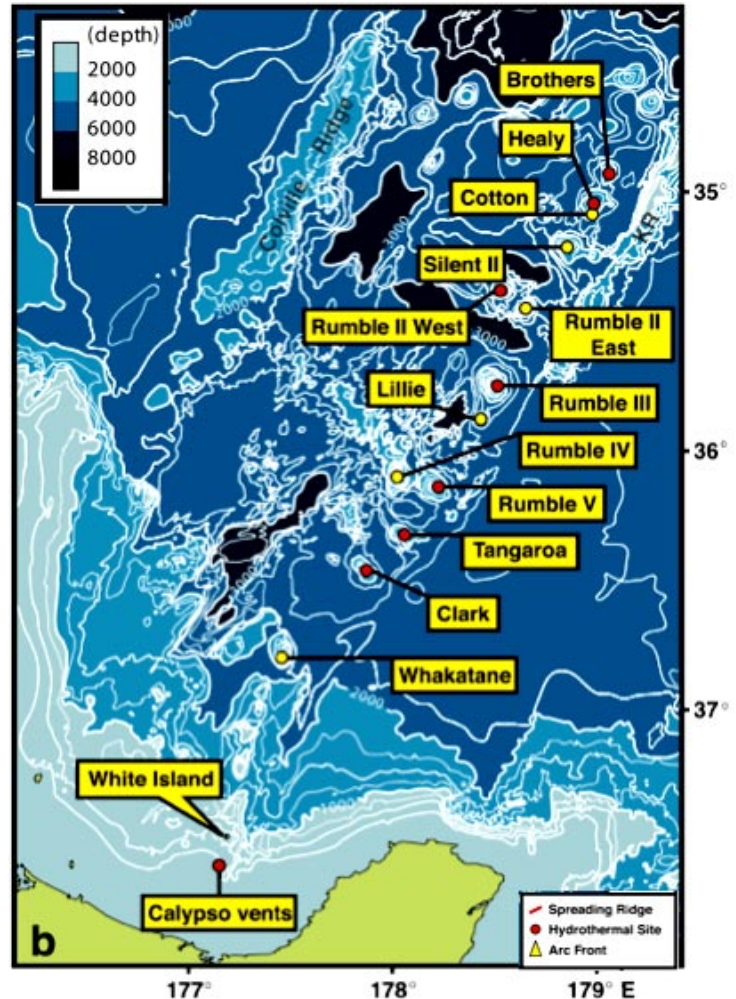


Figure 3. Volcanoes of the southern Kermadec arc. Rumble II West and Brothers are located in the upper half. (deRonde 2001)

The concentrations of CO₂, H₂S and He gases released from vents, in addition to particulate matter, are orders of magnitude higher than those typically found at MORs (deRonde 2001, 2007).

The closest equivalent in size and structure to Rumble II West on the Kermadec arc is Brothers volcano. Brothers is located approximately 105 km north of Rumble II West (also on the Australian plate) and is the closest equivalent in size and structure of volcanoes on the arc (Figure 4). It has been extensively surveyed, making it ideal for providing comparison to the less studied volcano Rumble II West. The edifice of Brothers is 13 km long by 8 km across and is located in 2300 m water depth. The caldera walls reach ~ 400 m high. It has a cone (~350 m high, 1.5-2 km wide) protruding through the center of its caldera.

There are two distinct, active vent sites within its caldera, one on the NW interior wall and one on the cone near the southern rim. The NW caldera site is comprised of two large hydrothermal fields composed of vents and sulfide deposits, each ~600 m by ~50 m and located between 1600-1650 m (Figure 4). Vents at this site are active black smokers, releasing plumes from 1650 m that rise to 1540 m (deRonde 2005). Camera tows conducted in 1998 imaged the black smokers near the summit of the caldera and hydrothermally altered rocks and sulfide talus present (deRonde 2005). The cone site is comprised of diffuse venting at 1195 m spread over a few hundred meters (deRonde 2005). The highest intensity of this venting has been observed at 1150 m and 1200 m (deRonde 2005). The NW caldera chimneys are determined to be older than those at the cone but it has been put forth by deRonde that activity at both sites may be waning based on comparison studies from previous years (2005).

Tectonic processes are active in Brothers' basement fractures and influence faults striking 30° to 55°. This is consistent with Havre-Trough rifting and indicates 1st order extensional

tectonic control (deRonde 2005). This geologic feature directly impacts intracaldera structures like the cone and hydrothermal processes. The intersection of major caldera ring faults and the basement ridge form a rhombic arrangement that controls the progressive collapse of the caldera. Basement fractures striking under the NW caldera site control the location of the maximum caldera collapse (deRonde 2005). This in turn supplements active venting (mainly diffuse) within the innermost ring of the caldera (deRonde 2005).

Although numerous volcanoes in the arc have been well studied, Rumble II West had not been well examined prior to this survey. Earlier low-resolution bathymetric maps indicated a strato-volcano (Wright 1998). It was evident that there was a cone in the center of the caldera with possible basement faulting running across the entire edifice structure, similar to the construction of Brothers. This study first examined the geological evolution of Rumble II West through interpretation of its morphology and direct seafloor imagery in order to gain a better understanding of the processes that shape this volcano. Results from Rumble II West were then compared with observations from Brothers, to analyze the geologic evolution of these dynamic systems.

Methods

Investigation of Rumble II West was conducted aboard the R/V Thompson during March 2009. Bathymetry data were collected using the Simrad EM300, a hull-mounted multibeam echo sonar consisting of 135 beams that formed a “swath”. To collect data, a synchronous ping was sent out in an arc that reflected off the seafloor and the travel time was then extrapolated to calculate the depth. Track lines were planned assuming a swath coverage of ~2X the water depth

and a 2 km average overlap that varied with depth. Eight track lines were run continuously over the volcano and surrounding flanks at approximately 10 knots to provide

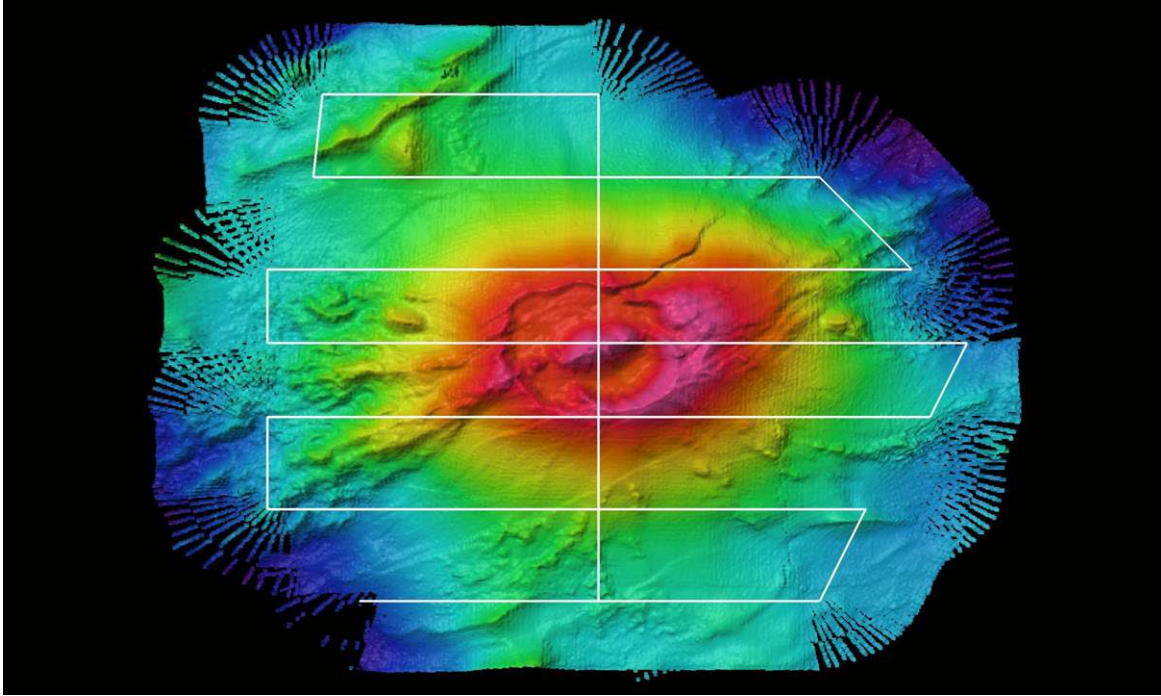


Figure 5. EM300 tracklines run over the Rumble II West volcano.

comprehensive coverage of the site (Figure 5). Water depths ranged from 1180 to 3000 m. Prior to collection, a CTD cast was conducted to provide sound velocity data, which were incorporated into the EM300 data acquisition systems. Raw data from the EM300 were uploaded into the CARIS processing program (<http://www.caris.com>) where flawed data, or “outliers”, were edited out to accurately render seafloor bathymetry. Bathymetry data were gridded at 30 m resolution and the corrected data were then visualized in Fledermaus (<http://www.ivs3d.com/products/fledermaus/>) for use in later interpretation.

In addition to the EM300, a TowCam deep-sea digital camera was utilized to image the seafloor. The system took 3.3 megapixel color pictures once every 12 seconds for the duration of

a tow (a maximum of 7 hours). During the camera tow, the ship traveled at $\frac{1}{4}$ - $\frac{1}{2}$ knot. The tow traversed through 5 waypoints along the peak of the cone (Figure 8).

Images were later manually and individually examined for geologic unit type and percent coverage on a scale of 0-5, 5 representing 100% coverage. Geologic units used to describe coverage were talus, lobate, sediment, massive flow, pillow lavas and rubble. Representative images of units found at Rumble II West are shown in Figure 7 and descriptions of each unit are located in Table 1. In addition, images were also examined for presence or absence of biology, hydrothermal deposits and flocculent. The data were input into an excel spreadsheet along with the image number, date, time and position from the ship's navigations data.

Table 1. Description of geologic units used to describe ground coverage during TowCam transect.

Type	Description	Size
Talus	Blocky pieces typically surrounded by others like it, occasionally sedimented	~ 20-40 cm across
Sediment	Fine grained, usually scattered with ash	Grain sized, \square 1-5mm
Lobate	Heavily sedimented, flattened but rounded pieces	~ 40–50 cm
Flow	An altered piece of single rock spread out over a distance	Usually spread out over a distance larger than the camera frame (\square 120 cm)
Pillow lavas	Rounded, usually un-sedimented blocks	~ 60-100 cm across
Rubble	A mix of many types (usually sediment, debris and blocks too small to be considered talus)	Varied using above sizes.

Subsequently, TowCam data were examined and used to create a geological swath map that detailed the dominant geologic coverage over the course of the tow (Figure 6).

Results

The summit of Rumble II West is comprised of an interior cone surrounded by a post-eruptive caldera 950 m high. The caldera summit lies in 1200-1400 m of water, and has a basal depth of ~3000 m with a footprint of 17-22 km. The edifice has a diameter of 2.5-3 km with a caldera 250 m high except where it is broken by a prominent fault on the NE rim (Figure 8). Volcaniclastic deposits dominate the flanks of the volcano although Wright observed older lava flow fronts on the lowermost eastern slope and younger flows on the western-southwestern flank (1999).

The central cone is approximately 1.5-2 km in diameter and 350 m high (see Figure 8). It was found to host extinct vent fields but it remains unconfirmed that hydrothermal activity persists on the cone or within the caldera (deRonde 2001). The camera tow across the cone revealed a predominantly talus and sediment covered environment, on slopes and flat ground respectively. Ash was documented in numerous images but did not appear to be recent (Figure 7). A transect outlining the geological units seen over the course of the camera tow can be seen in Figure 5. Talus was generally blocky pieces approximately 20-40 cm across, surrounded by similar blocks. It was one of the most dominant ground covers along with sediment and was typically found on slopes. Sediment was the other dominant ground cover and often had ash scattering over it. Grain size was not possible to determine as no samples were taken but it generally appeared as a fine-grained dark grey substrate with white ash. Lobates were rare along the tow and were ~ 40-50 cm across and often heavily sedimented. Flows usually spanned outside of the camera frame and appeared as heavily sedimented, altered sheets of rock. Pillow lavas were rounded, generally unsedimented, reaching 60-100 cm across and rare throughout the tow. Rubble was considered any substrate that was outside the size range and description of the

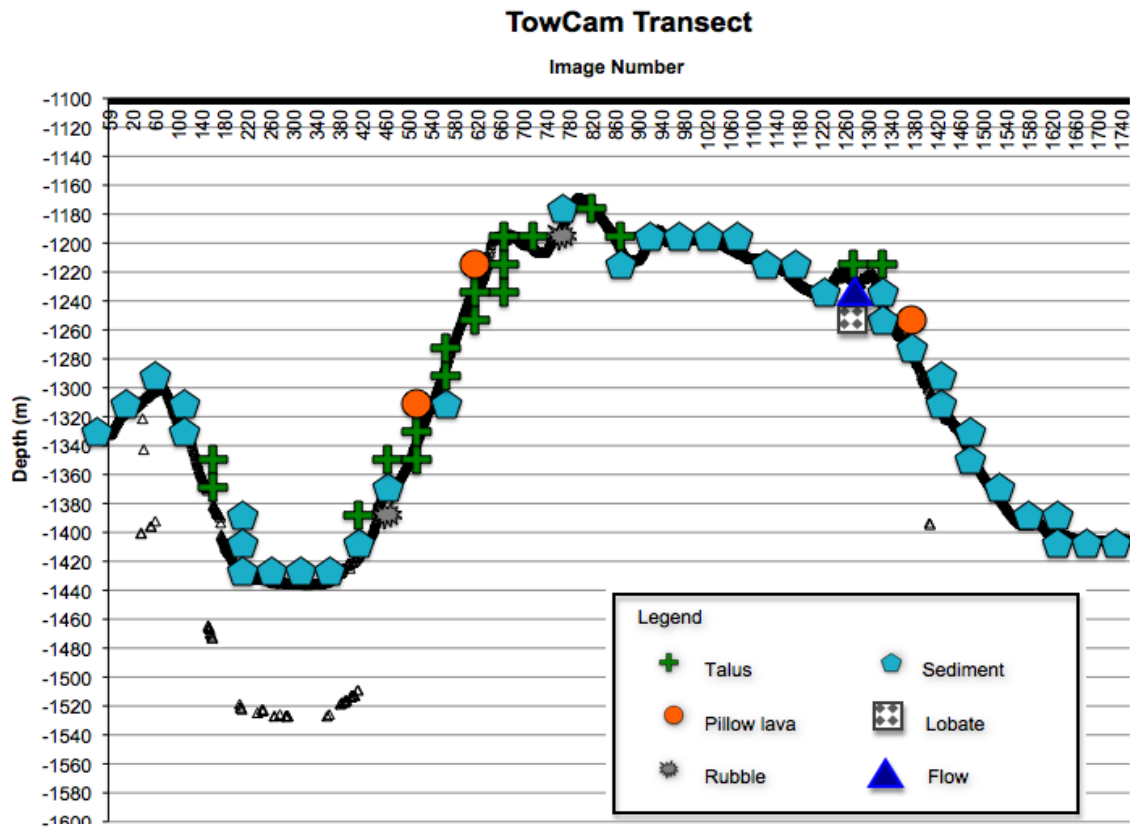


Figure 6. Geologic swath map displaying dominant bottom coverage observed of TowCam transect across the cone. Note transect traverses from east to west.

above-mentioned geologic types. Biology was found to be varied and generally present throughout the camera tow indicating that few if any major events have occurred on the cone recently (Figure 9). Highly mobile species included fish and an octopus while sedentary species included hard and soft corals. Biology was most commonly found on top of the cone.

Multiple ring faults are visible within the caldera, with the most pronounced located near the SE wall (Figure 8). These faults are manifested as a series of steps and terraces concentrically located on the interior slope in a concave shape towards the cone. Numerous faults running through the rim of the volcano have impacted the overall structure and continued development of Rumble II West. The main fault strikes through the NE corner of the caldera towards the SW (Figure 8). Former surveys failed to identify the extent of this fault and this survey demonstrates the greater detail at which geologic growth has occurred. Lesser faults were also apparent on the outer southern flanks with a particular forking of faults on the SE rim (Figure 8).

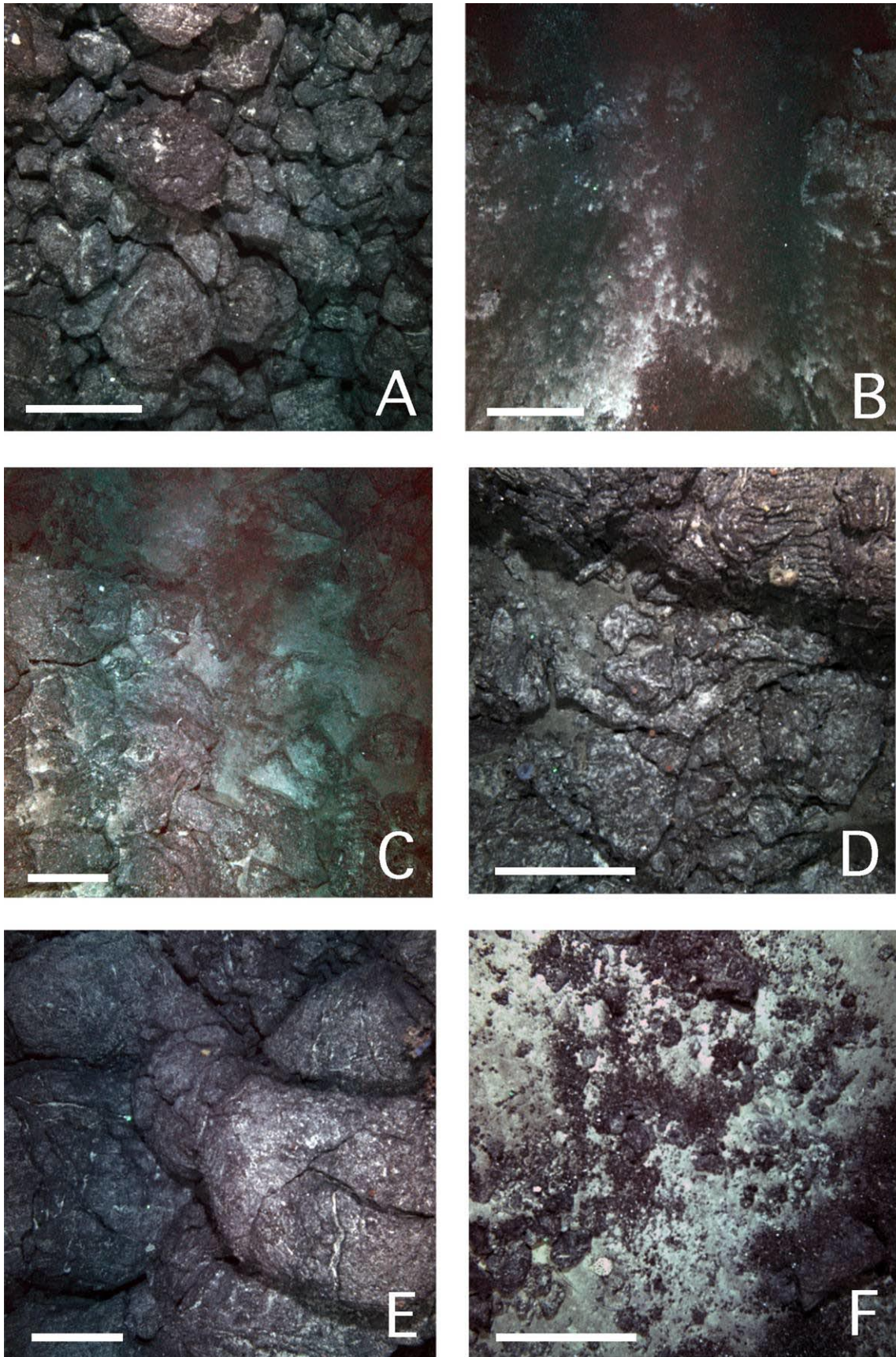


Figure 7. Geologic units used to describe bottom coverage included A) talus B) sediment C) lobate D) flow E) pillow lava and F) rubble (featured with ash coverage here). Scale bars represent 41 cm.

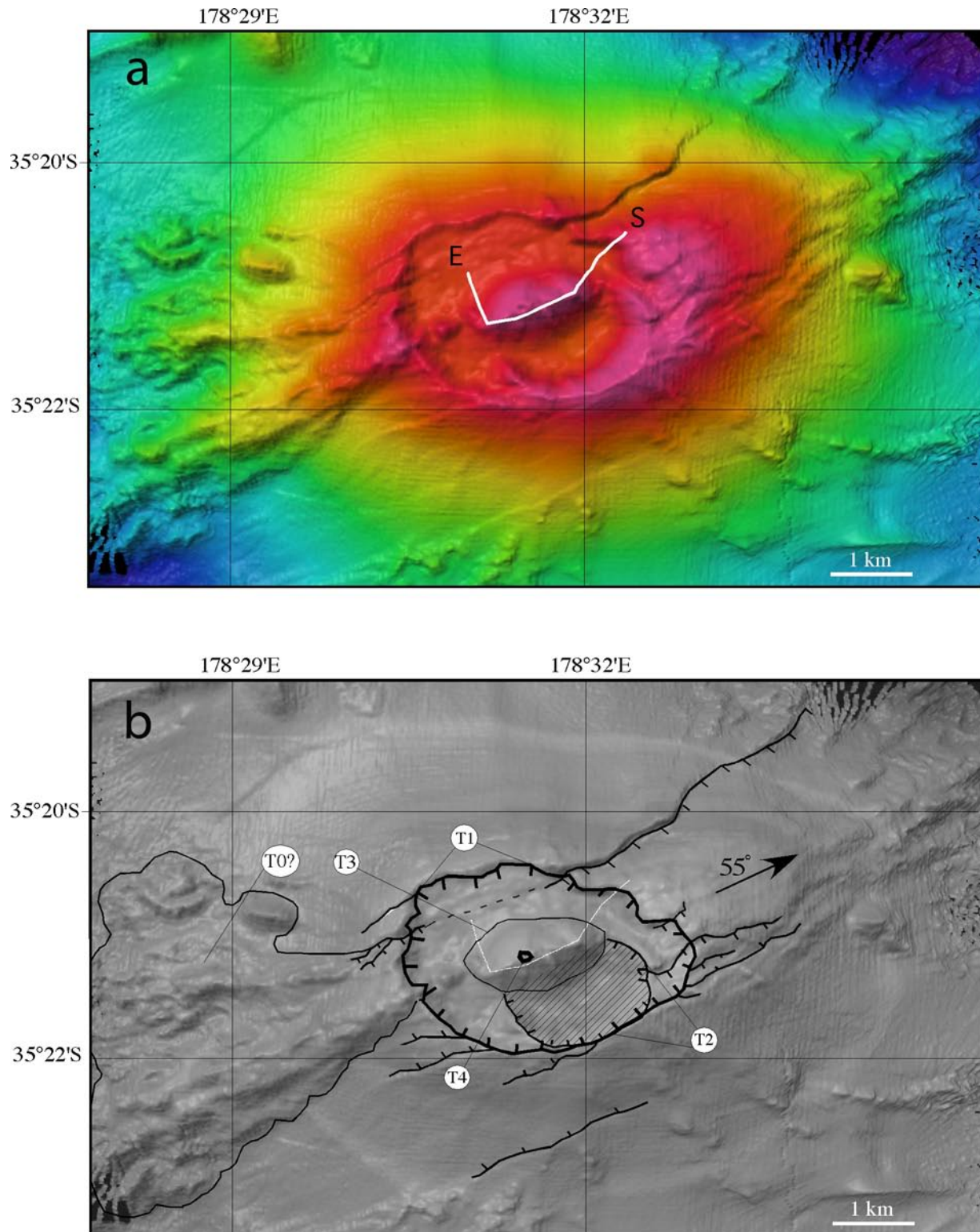


Figure 8. a. TowCam course traveled across Rumble II West. Map is gridded at 30 m resolution. b. Morphological breakdown of evolution of Rumble II West volcano. At time T0?, it's hypothesized that effusive flows occurred down the SW flank of the volcano. At T1, the caldera erupts. At T2, secondary dome forms and subsequently erupts or collapses creating a second caldera and ring faults. At T3, the central cone grows and forms, intersecting T2 caldera. At T4 (most recently), cone caldera formation begins.

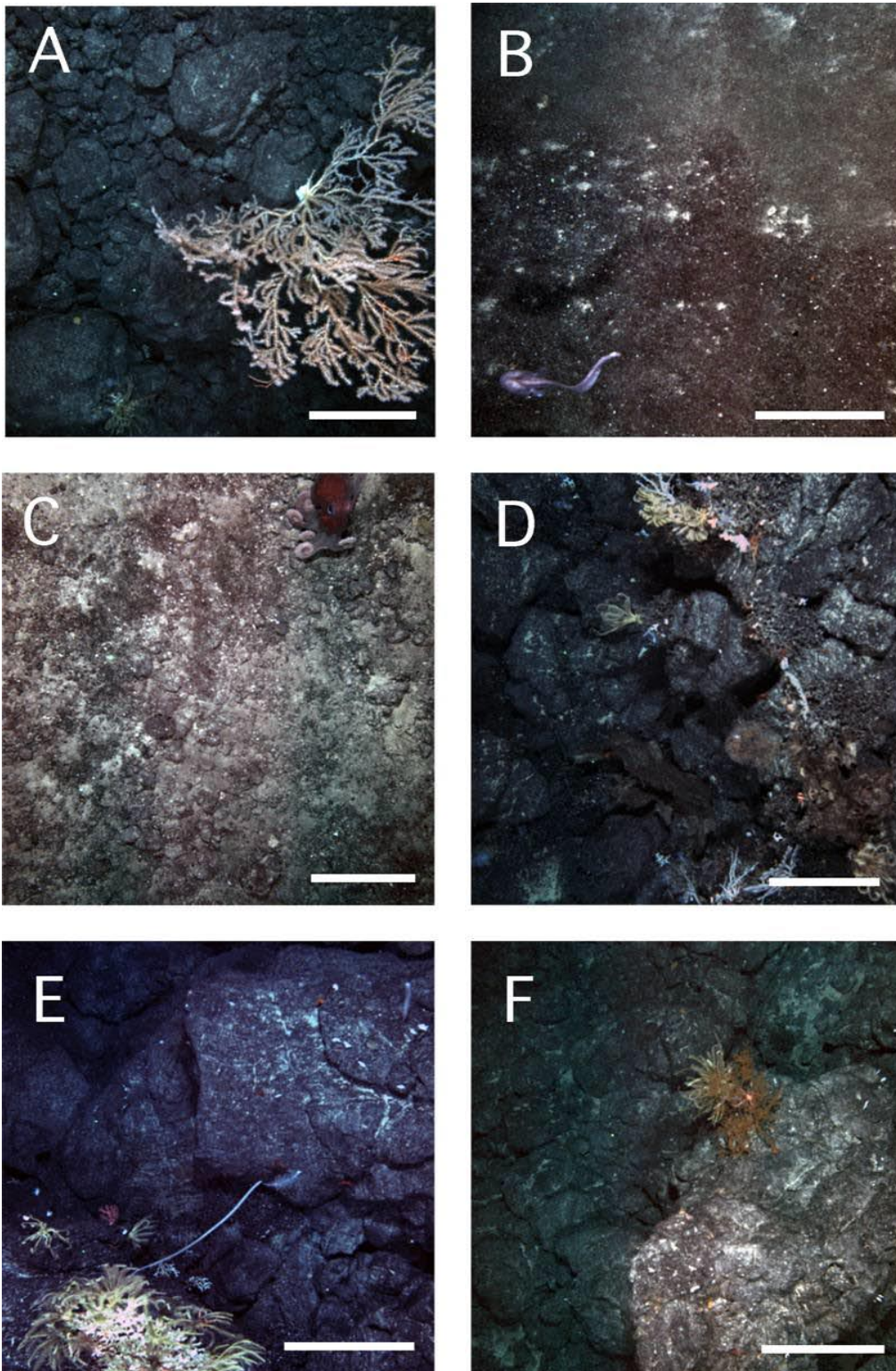


Figure 9. Plate of various biology imaged during transect of TowCam including a) coral b) fish c) octopus d and e) assemblages of corals f) single coral. Scale bars represent 41 cm.

Discussion

The geologic evolution of Rumble II West follows an ordered sequence of events and is described visually in Figure 8b. The structure began as a stratovolcano with a massive peak. Over time, pressure built and it likely underwent a pyroclastic eruption, covering its flanks in talus and scattered ash deposits (detailed as T1 in Figure 8b). This eruption/caldera collapse is evidenced by the steep walls of the caldera (~60-70°) (indicative of an ejection of material). Following this event, a new dome grew on the south side of the caldera, which subsequently erupted, creating the secondary caldera and ring faults seen currently (T2). The next volcanic formation was the rise of the central cone (T3) that overlaps the T2 caldera. The cone is currently undergoing the most recent evolutionary event at its peak- another caldera formation roughly 100 m across (T4). At time T0?, massive flows occurred on the southwest flanks, spreading 3-4 km laterally to the west. This may have occurred prior to the T1 caldera formation because the flow did not penetrate the caldera, only traveling down the outer flank. Faulting throughout the edifice may have occurred at any time in this sequence. The largest fault, running through the northeast T1 caldera rim, and many of the smaller faults on the southeastern T1 caldera rim occurred post eruption of the T1 caldera however whether they pre- or post-date the T2, T3 and T4 events is impossible to determine.

A similar sequence of events has been put forward towards the formation of Brothers volcano by deRonde (2005) and Wright (1999). In the case of Brothers, Wright explains that,

“incremental caldera formation includes (1) a steep and laterally discontinuous ring-fault, (2) a heterogeneous pattern and succession of flank lava flows and volcanoclastic deposits indicating repeated volcanism, (3) the presence of significant

satellite vents and cones, and possibly rift flank volcanism, on the lower edifice flanks, and (4) the occurrence of poorly vesiculated and moderately dense eruptive components”.

This description is readily applied towards observations of Rumble II West. The interpretation of deRonde on Brothers’ formation also confirms that a caldera is generally associated with a volcano that has undergone a pyroclastic eruption and/or magma chamber collapse (2005).

Analysis of Brothers volcano has facilitated a better understanding of the morphology of Rumble II West because they are geologically similar. Both volcanoes rise to depths of ≤ 1500 m of water and have calderas peaking near 1300 m (1350 m at Brothers, 1180 m at Rumble II West). Similar to Brothers volcano, this study documents a cone near the center of the Rumble II West volcano, indicating geologic activity succeeding the collapse event as described earlier. However, at Brothers the cone has active hydrothermal venting at multiple locations (cone and caldera sites). It remains unconfirmed if hydrothermal activity persists at Rumble II West.

Similar to Rumble II West, Brothers also exhibits evidence of faulting in both basement structures and ring faults (Figure 4). These faults are confirmed to impact venting on the cone in addition to aiding further collapse of the caldera. In Rumble II West, the massive fault striking through the caldera and potentially underneath the cone could lead to the beginning or increase of venting in the caldera. Faulting in both volcanoes may provide channels for hydrothermal flow as evidenced by the exit point of the T0? event forming the extension of the major fault on the NE rim of Rumble II West. Brothers volcano may also exhibit a similar exit point on its NW rim extending towards the NE (following the potential fault lines).

Faults at Rumble II West are oriented 55° with respect to the Kermadec-Havre Trough, which is oriented at 30° . The divergence of 25° is creating massive stress between the two systems. This deviation in orientation could be a result of the oblique angle at which the Pacific

and Australian plates are converging. Differences in crustal thickness and buoyancy of the down-going plate may cause rotation and fragmentation to occur, creating microplate wedges that migrate and encourage disorganized spreading (Wysoczanski et al 2009). Prior research by Wysoczanski et al (2009) has demonstrated through a rose diagram the angles at which rift and ridge spreading occurs in the southern Kermadec arc (Figure 10). Faults at Brothers are parallel to the orientation of the trough at 30°. However, comparing Rumble II West with the arc demonstrates that rotational principle as its course lies at 55° (Figure 2).

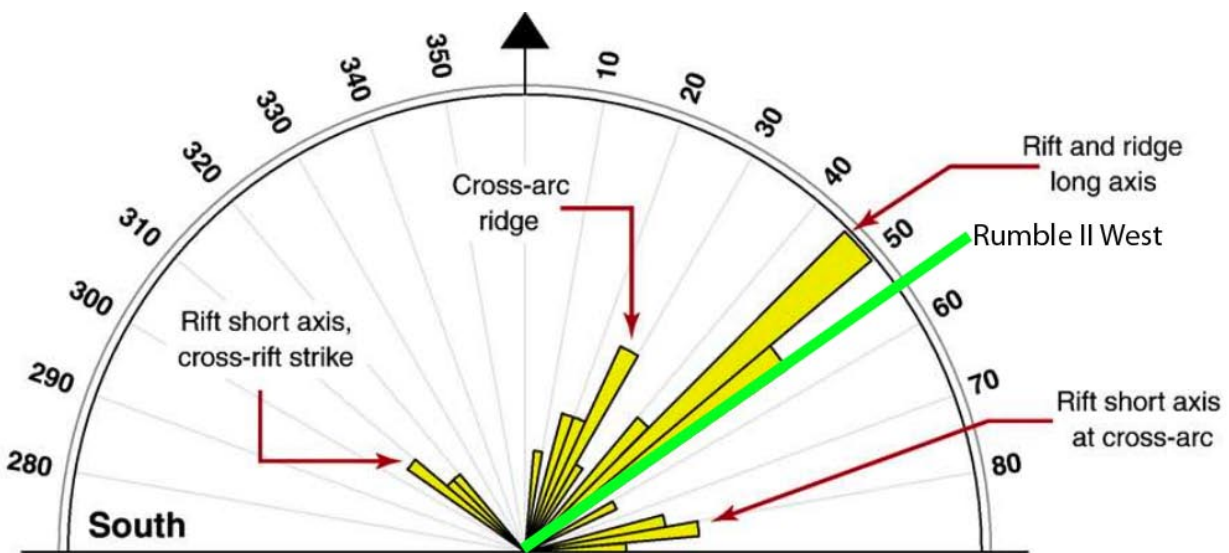


Figure 10. Rose diagram of structural trends in the southern Kermadec arc (adapted from Wysoczanski et al 2009).

Wysoczanski et al demonstrates the pattern of arc and rift regime controlled spreading based on structural orientation and topography of the arc (Figure 11). Zones of the Kermadec arc appear to predominantly fall under one of the two categories that may determine the rotational orientation relative to the arc. Brothers is found to sit over an arc regime whereas Rumble II West is over a rift regime. According to Wright (1999), the arc is migrating trenchward as the Pacific plate subducts under the Australian plate, forming cross-arc chains that

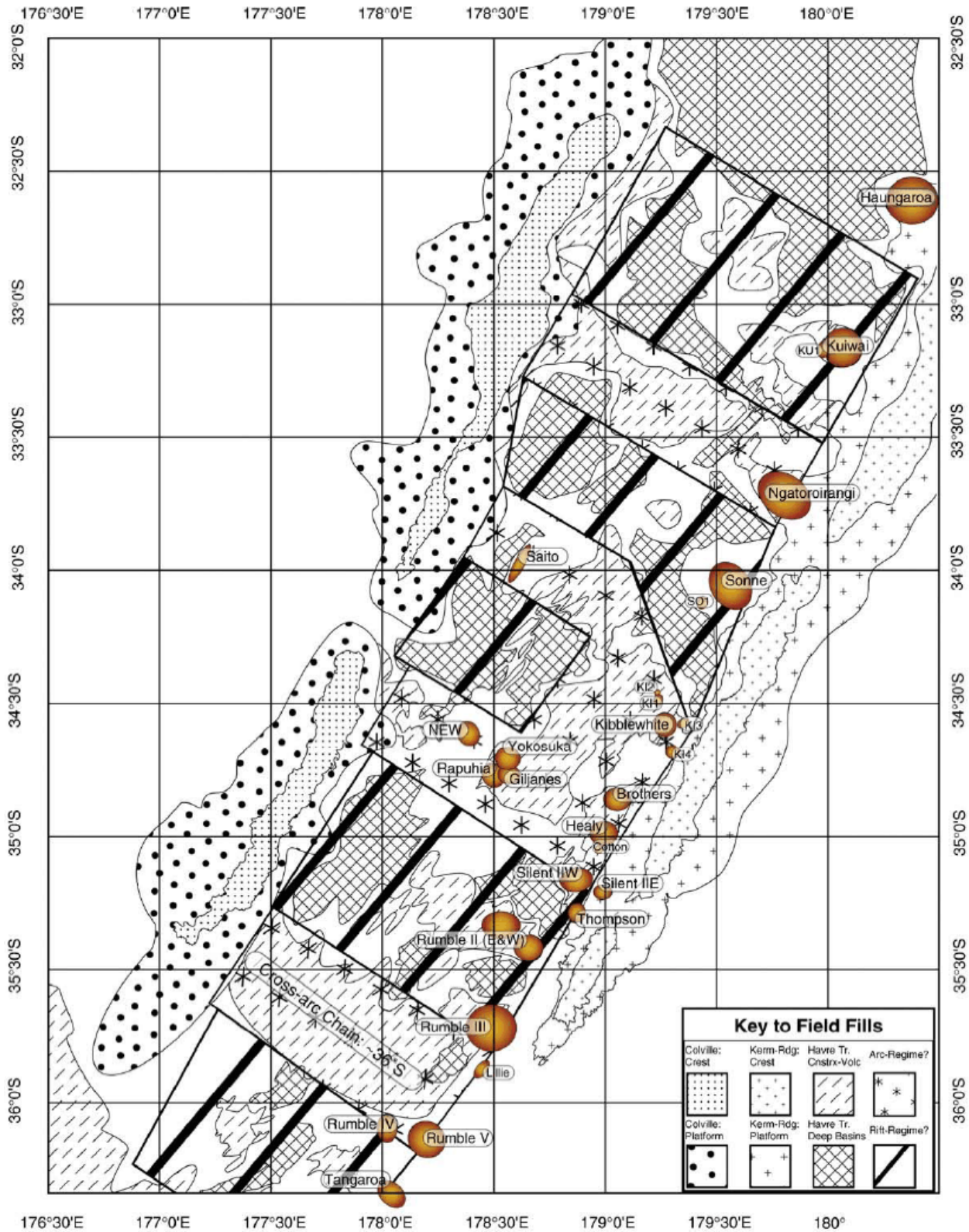


Figure 11. Diagram of structural fabric of the Kermadec arc based on areas of arc regime and rift regime in response to structural orientation and topography (Wysoczanski et al 2009).

are supplemented by rifting described by Wysoczanski et al (2009). This successive dissection of the arc front is creating greater stress fields, especially in rift regimes, that are apparent in the plethora of faulting on Rumble II West.

Conclusion

Rumble II West was investigated through detailed EM300 multibeam mapping and TowCam imagery to better characterize its geology. The volcano has undergone geological evolution by way of multiple pyroclastic eruptions, subsequent ring faulting, volcanic build up of a central cone and further deformation by basement faulting. In addition, faults on Rumble II West are not parallel to those at Brothers or to the orientation of the Kermadec-Havre trough. Tectonic stresses are deforming the arc and dividing it into smaller microplates. This is important because it could lead to the alteration of plate movement in this region. Investigating the interaction of faults and volcanoes relative to the orientation of the trough north and south of Rumble II West would provide better background data towards the function of its tectonic processes.

References

- Delteil, J., Stéphan, J., de Lépinay, B. M., Ruellan, E., 2003, Wrench tectonics flip at oblique subduction. *A model from New Zealand*, *C. R. Geoscience* 335 (2003) 743–750
- de Ronde, C. E. J., E. Baker, G. Massoth, J. Lupton, I.C. Wright, R.A. Feely, R. R. Greene, 2001, Intra-oceanic subduction-related hydrothermal venting, Kermadec volcanic arc, New Zealand, *Earth and Planetary Science Letters*, v. 193, p. 359-369, ISSN 0012-821X, doi: 10.1016/S0012-821X(01)00534-9.
- deRonde, C. E. J., Hannington, M. D., Stoffers, P., Wright, I. C., Ditchburn, R. G., Reyes, A. G., Baker, E. T., Massoth, G. J., Lupton, J. E., Walker, S. L., Greene, R. R., Soong, C. W. R., Ishibashi, J., Lebon, G. T., 2005, Evolution of a Submarine Magmatic-Hydrothermal System: Brothers Volcano, Southern Kermadec Arc, New Zealand, *Economic Geology*, v. 100, p. 1097–1133
- deRonde, C. E. J., Baker, E.T., Massoth, G.J., Lupton, J.E., Wright, I.C., Sparks, R.J., Bannister, S.C., Reyners, M.E., Walker, S.L., Greene, R.R., Ishibashi, J., Faure, K., Resing, J.A., Lebon, G.T., 2007, Submarine hydrothermal activity along the mid-Kermadec Arc, New Zealand: Large-scale effects on venting, *Geochemistry Geophysics Geosystems*, v. 8, Number 7, Q07007, doi:10.1029/2006GC001495, ISSN: 1525-2027
- Graham, Ian J., Reyes, Agnes G., Wright, Ian C., Peckett, Kimberley M., Smith, Ian E. M. Arculus, Richard J., 2008, Structure and petrology of newly discovered volcanic centers in the northern Kermadec-southern Tofua arc, South Pacific Ocean, *Journal of Geophysical Research*, v.113, B08S02, doi:10.1029/2007JB005453
- Smith, Ian E.M. and Price, Richard C., 2006, The Tonga-Kermadec arc and Havre-Lau back-arc system: Their role in the development of tectonic and magmatic models for the western Pacific. *Journal of Volcanology and Geothermal Research*, v.156 p. 315-331, doi:10.1016/j.jvolgeores.2006.03.006
- Wright, I.C., 1997, Morphology and evolution of the remnant Colville and active Kermadec arc ridges south of 33° 30' S, *Marine Geophysical Researches*, v. 19, p. 177-193
- Wright, I.C., and Gamble, J.A., 1999, Southern Kermadec submarine caldera arc volcanoes (SW Pacific): Caldera formation by effusive and pyroclastic eruption, *Marine Geology*, v. 161, p. 207-227, ISSN 0025-3227, doi: 10.1016/S0025-3227(99)00040-7.
- Wright, I.C., P. Stoffers, M. Hannington, C.E.J. de Ronde, P. Herzig, I. E. M. Smith, P. R. L. Browne, 2002, Towed-camera investigations of shallow-intermediate water-depth submarine stratovolcanoes of the southern Kermadec arc, New Zealand, *Marine Geology*: v. 185, p. 207-218, ISSN 0025-3227, doi: 10.1016/S0025-3227(01)00285-7.
- Wysoczanski, R.J., et al., 2009, Backarc rifting, constructional volcanism and nascent disorganised spreading in the southern Havre Trough backarc rifts (SW Pacific), *J. Volcanol. Geoth. Res.*, doi:10.1016/j.jvolgeores.2009.04.004