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Biogeochemical Observations of the Kavachi Submarine Volcano (Solomon Islands)

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ABSTRACT. An expedition to the Kavachi submarine volcano (Solomon Islands) in January 2015 was serendipitously timed with a rare lull in volcanic activity that permitted access to the inside of Kavachi's active crater and its flanks. The isolated location of Kavachi and its explosive behavior normally restrict scientific access to the volcano's summit, limiting previous observational efforts to surface imagery and peripheral water-column data. This article presents medium-resolution bathymetry of the main peak along with benthic imagery, biological observations of multiple trophic levels living inside the active crater, petrological and geochemical analysis of samples from the crater rim, measurements of water temperature and gas flux over the summit, and descriptions of the hydrothermal plume structure. A second peak was identified to the southwest of the main summit and displayed evidence of diffuse-flow venting. Microbial samples collected from the summit indicate chemosynthetic populations dominated by sulfur-reducing ϵ -proteobacteria. Populations of gelatinous animals, small fish, and sharks were observed inside the active crater, raising new questions about the ecology of active submarine volcanoes and the extreme environments in which large marine animals can exist.

INTRODUCTION

The New Georgia Island Group is the result of a complex tectonic configuration, characterized by subduction of the active Woodlark Spreading Center (WSC) beneath the Solomon Islands intra-oceanic arc. This triple junction is the site of active volcanism, crustal uplift that closely matches subducted bathymetric features from the WSC, and a proposed "slab window" that leaves asthenospheric mantle in direct contact with a thin overlying crust (Mann et al., 1998; J. Chadwick et al., 2009). The Kavachi submarine volcano (8°59'S, 157°58'E) is situated ~30 km northeast of the subduction zone and rises abruptly to the surface from more than 1,000 m water depth (Figure 1). By far the most active volcano in the region, Kavachi is known for frequent phreatomagmatic (denoting explosive water-magma interaction) and subaerial eruptions leading to occasional ephemeral island emergence (Johnson and Tuni, 1987). The remote geographic location and inherent danger of frequent

eruptions has prevented scientists from observing the proximal area of Kavachi's summit crater.

Of the roughly 30 active submarine volcanoes known worldwide, only a few have been observed during or closely following an active eruption, for example, Northwest Rota-1 (W.W. Chadwick et al., 2010), West Mata (Resing et al., 2011), El Hierro (Santana-Casiano et al., 2013), Kick'em Jenny (Devine and Sigurdsson, 1995), and Axial Seamount (W.W. Chadwick et al., 2012, and references therein). Despite these limited studies, active submarine volcanoes are considered important natural laboratories for observing the effects of ocean acidification on marine animals (e.g., Hall-Spencer et al., 2008), with Kavachi being an extreme example of such an environment.

Kavachi erupts nearly continuously. Reports of airborne steam and ash visible from shore are common, and the formation and erosion of multiple islands over the past century indicate the summit is in a constant state of flux (Johnson and

Tuni, 1987). The most detailed investigation prior to this study, which took place during a single day in May 2000, was conducted from an approximate 1 km perimeter surrounding the actively erupting main peak. That study provided insights into the eruptive processes of Kavachi based on conductivity-temperature-depth (CTD) casts and surface imagery (see Baker et al., 2002). A magnitude 8.1 earthquake that shook the entire region in April 2007 prompted the reconnaissance of a conspicuous surface plume following a subaerial eruption visible from a nearby island (Wunderman, 2007). The latest published evidence of activity was obtained by NASA's EO-1 satellite on January 29, 2014 (NASA Earth Observatory, 2014), and it appears similar in behavior to the 2007 eruption.

This study was conducted during a quiescent phase, which allowed for the first closeup look inside and around the shallow summit of Kavachi. Our research team took advantage of this rare lull in volcanic activity to gather geological, biological, and oceanographic observations using relatively simple equipment and methodologies. We report here on our initial results, which include evidence of diffuse-flow venting on a confirmed second peak, a megafaunal community living inside the active crater, and insights into the eruptive processes and magma source characteristics of Kavachi's active volcanism.

METHODS

This work was conducted in January 2015 with operations based out of Gatokae Island, Western Province, Solomon Islands. Approaches to the summit crater were made after several days of observing inactivity from a safe perimeter—normal eruptive activity for Kavachi is audible on the surface, and no such sounds were heard during the course of this expedition. All equipment used was lightweight,

FACING PAGE. Article co-authors Alistair Grinham and Matthew Dunbabin prepare an autonomous surface drifter for deployment over Kavachi's summit crater. Photo is taken looking north toward Vangunu Island, with the volcano's surface plume visible in the middleground where the water changes color from dark blue to light blue-green."

relatively low cost, and deployed using small boats. Down-looking images of the seafloor paired with water-column measurements were made using a GoPro camera in a deep-rated housing, battery-powered lights, and a National Oceanic and Atmospheric Administration/Pacific Marine Environmental Laboratory (NOAA/PMEL) Miniature Autonomous Plume Recorder (Walker et al., 2007) mounted on an instrument frame that was raised and lowered with an electric fishing reel. Baited drop-camera recordings were achieved using an autonomous National Geographic Remote Imaging DropCam following methods described by Friedlander et al. (2014). Surface drifters measuring water temperature, light

transmission, and atmospheric $p\text{CO}_2$ were deployed as described by Dunbabin (2016). Total CO_2 flux was calculated using the drifter's measurements of flux per unit area, which was extrapolated to represent the total size of the bubble zone. A downward-looking camera was mounted on the drifter, which logged its position, and after multiple runs through the bubble zone it was possible to estimate the total surface area by noting the appearance and disappearance of bubbles on camera footage.

We measured bathymetry with a Lowrance HDS-5 echosounder (50/200 kHz). IVS Fledermaus software was used to manually remove soundings that qualitatively deviated from a

general trend depicting the volcano, similar to swath editing in multibeam sonar processing. This “cleaned” point-cloud (~85,000 soundings; see online supplemental Figure S1) was then used to create three individual continuous curvature spline surfaces, each with unique spatial extent and resolution. This multisurface approach was necessary in order to accurately represent varying degrees of data density over the study area, with the most soundings concentrated at the summit caldera, and the least at the foot of the volcano (Flinders et al., 2014). The three surfaces (100 m study-wide, 35 m volcano-focused, and 7 m summit-focused) were then blended to create a single individual surface for visualization. Blending constraints ensured that within each specific area, only the highest resolution surface would be used.

Scuba divers collected rock and bacterial samples by hand. Major and trace element analyses were conducted using a Perkin Elmer Optima 3100 XL inductively coupled plasma atomic emission spectrometer (ICP-AES) and a Thermo X-Series 2 quadrupole inductively coupled plasma mass spectrometer (ICP-MS; Kelley et al., 2003). The Marine Geological Sample Laboratory at the University of Rhode Island prepared the sample slides. Bacterial DNA was extracted using PowerSoil® DNA Isolation Kit (MO BIO Laboratories, Carlsbad, California), polymerase chain reaction (PCR)-amplified using universal 16S rRNA gene primers (27F: AGR GTT YGA TYM TGG CTC AG, 1100R: GGG TTN CGN TCG TTG) and cloned with pGEM-T Easy (Promega, Madison, Wisconsin). After removal of vector and primer sequences, all clones were imported into the software package mothur (<http://www.mothur.org>) to screen for putative chimeras and generate an initial alignment against a SILVA-based reference set (SEED version 119). Quality screened and aligned 16S rRNA clones were then imported into the ARB environment (<http://www.arb-home.de>), manually curated, and added to the master ARB tree (tree_SSURefNR99_1200_slv_123).

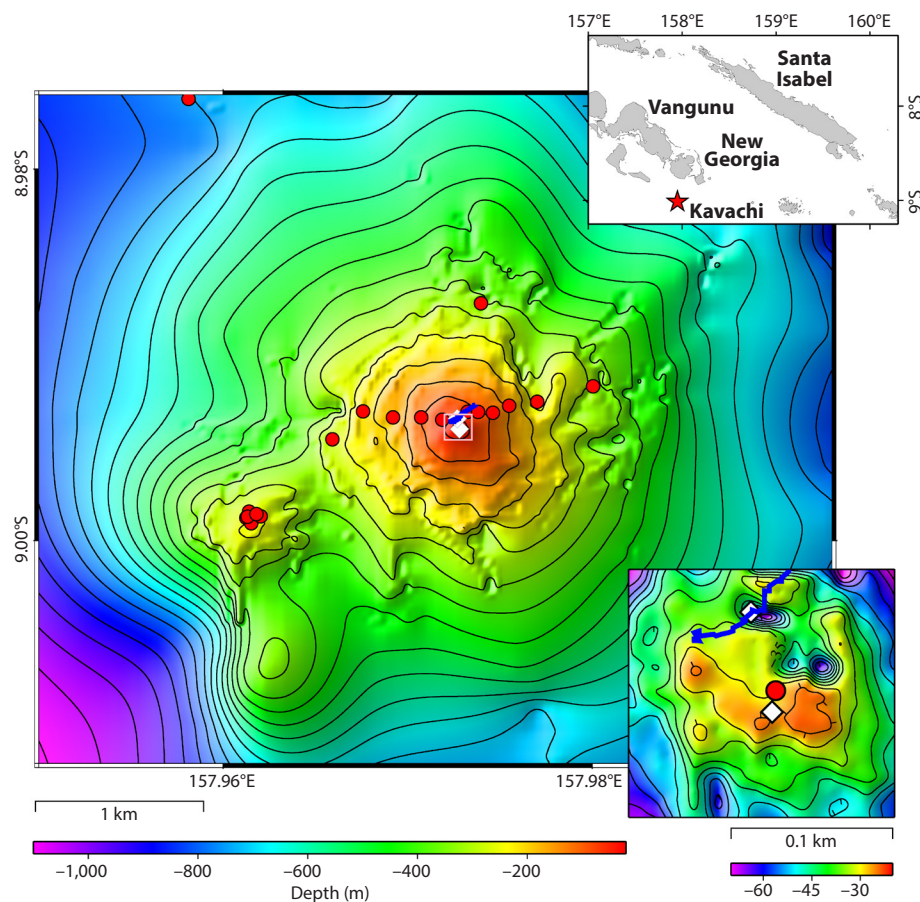


FIGURE 1. Bathymetry of Kavachi and the summit crater (inset, lower right). Red circles indicate locations of water column profiles and benthic imagery. White diamonds locate baited drop cameras deployments. The blue line delineates the path of a surface drifter that measured temperature and atmospheric CO_2 . The contour map and the inset at lower right were created from approximately 85,000 depth soundings visualized and edited as a three-dimensional point-cloud using IVS Fledermaus. The inset map at upper right was created with Generic Mapping Tools (v 4.5) using data available from Marine Geoscience Data System's Global Multi-Resolution Topography Data Synthesis (v 3.1). A map with ship tracklines used to create this plot is provided in online supplemental Figure S1.

Based on the location of Kavachi clones within the tree, we chose an additional 32 related sequences from the ARB database for further phylogenetic analysis, including representatives from *Campylobacter* (Campylobacteraceae) and *Sulfuricurvum* (Helicobacteraceae) as outgroups. Where possible, 16S sequences from pure cultures were included. Phylogenetic analysis was conducted using rapid bootstrapping (1,000 inferences) and subsequent maximum likelihood search within RAXML (v. 8.2.4) under a GAMMA model of rate heterogeneity and general time reversible (GTR) substitution matrix. Sequence data are deposited in GenBank under the accession numbers KU761314-KU761325.

RESULTS

Edifice Morphology

The summit of Kavachi has an oblong, pockmarked crater measuring approximately 120 m × 75 m with a length-wise strike of 115° and a rim rising to an average of 24 m depth (Figure 1).

The deepest soundings on the peak are ~70 m water depth and indicate asymmetrical terrain surrounded by almost uniform flanks with 18° slopes that descend to depths greater than 1,000 m. We confirm the existence of a “southwest extension,” or secondary summit, located 1.3 km southwest of the main summit; it rises to 260 m, and there is a narrow col between the peaks (Figure 1). Previously published bathymetric maps suggested the existence of this feature, but lacked the resolution to define it (Exon and Johnson, 1986; Johnson and Tuni, 1987; Baker et al., 2002). Bottom imagery was collected at five sites on the Southwest Extension, with one image presenting evidence of chemolithoautotrophic bacteria commonly associated with hydrothermal venting (Figure 2B).

Hydrothermal Plumes

Opportunities to sample hydrothermal plumes associated with actively erupting submarine volcanoes are often limited by safety concerns. Those that have

been observed are enriched in suspended particulate matter, ³He, and sulfur, and exhibit depressed pH values (Walker et al., 2008). Video recorded by a scuba diver around the outside of the crater rim reveals widespread, vigorous gas bubbling originating from the shallowest regions surrounding orange, cloudy hydrothermal plume water inside the crater that almost completely obscures visibility (Figure 2A). The diver who recorded this footage reported physical discomfort from caustic water contacting his skin when he approached the outer line of bubbles. Optical backscatter and oxidation-reduction-potential (ORP) signals were observed directly over the summit crater, and a minor ORP signal was seen to the north of the Southwest Extension summit at a depth of approximately 220 m. Minor ORP signals can indicate diffuse venting sources on the seafloor (Baker et al., 2016), and given our visual confirmation of bacterial mats on the summit of the Southwest Extension, it is reasonable to assume that

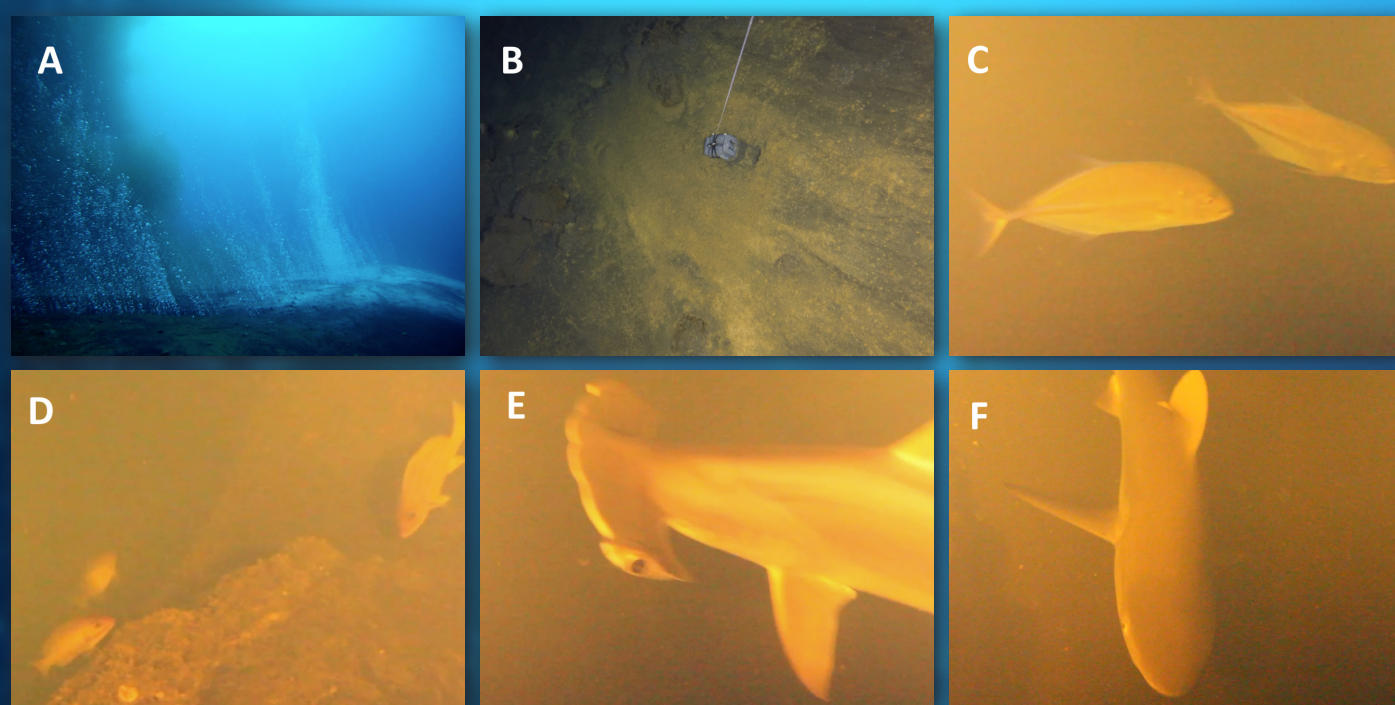


FIGURE 2. (A) Oblique view of a line of bubbling gas along the outer edge of Kavachi’s crater with orange, cloudy plume fluids in the background. (B) Downward-looking view of a microbial mat on the summit of the Southwest Extension. (C) Bluefin trevally, (D) snapper, (E) hammerhead shark, and (F) a silky shark observed using a baited drop camera deployed inside the crater.

this minor anomaly may be associated with this source.

A surface drifter measuring atmospheric CO_2 and water temperature at 0, 2, and 5 m depths measured ΔT values of $>13^\circ\text{C}$ above ambient (approximately 29°C) over the crater, which persisted down-current from the main summit (Figure 3). A $>300\%$ step increase in atmospheric CO_2 concentration occurred in the surface water over the bubble zone, indicating bubbling gas from the summit contained large concentrations of CO_2 (other gases were not measured). The measured unit area flux rate was $19.5 \text{ kg m}^{-2} \text{ d}^{-1}$, and assuming a similar rate across the whole surface bubble zone, the total flux rate was 153 t d^{-1} . This estimate lies within the lower range of previously reported studies (Burton et al., 2013). The increased availability of dissolved CO_2 within the bubble zone provides a labile carbon source for chemolithoautotrophic communities surrounding the venting site.

Our observations align with those made in 2000 by Baker et al. (2002), who concluded from their perimeter survey that Kavachi's hydrothermal discharge

disperses and/or escapes to the atmosphere almost immediately upon reaching the surface. We were unable to constrain the pH of vented fluids directly inside Kavachi's crater, but a pH of 6.1 was measured in a single water sample collected within the surface plume. This compares to pH values ≤ 5 measured within the craters of other active submarine volcanoes (Staudigel et al., 2006; Kiliyas et al., 2013), and aligns with observations of acidic (possibly pH <1.0) hydrothermal fluids driven by high concentrations of CO_2 and SO_2 at the NW Rota-1 submarine volcano (Resing et al., 2007). We therefore characterize the plume inside of Kavachi's crater as a discrete "extreme" environment: hot, caustic, and particulate-laden.

Biology of the Active Crater

Seamounts serve as unique and important biological habitats that support increased biomass and biodiversity of benthic and pelagic species (Rogers, 1993; Stocks and Hart, 2007). Volcanically active seamounts, defined as those exhibiting fluid/gas venting or active eruption, are of particular interest as they offer chemosynthetic energy pathways for microbial

communities to exploit. Non-vent-specific benthic scavengers, deposit feeders, and filter feeders can utilize chemo-synthetic biomass to support up to 100% of their nutritional input (MacAvoy et al., 2002). Plumes originating from hydrothermal vent fields are known to support increased microbial biomass, which may sustain higher trophic levels in the water column (Bennett et al., 2013; Dick et al., 2013; Burd and Thomson, 2015).

Extensive microbial mats in and around the active crater were visually distinct, with dense orange- and white-colored regions observed on the external flanks down to approximately 100 m water depth. Orange-colored bacterial samples colonizing scoriaceous tephra collected from the summit at $\sim 24 \text{ m}$ depth on the outside of the crater rim were used for 16S rRNA clone library analysis. In total, 12 clones were retrieved with an average length of 1,050 base pairs. Phylogenetic analysis (Figure 4) revealed that all clones were related to *Sulfurimonas* (Epsilonproteobacteria, Campylobacterales, Helicobacteraceae), a genus known for growing chemolithoautotrophically using sulfur and CO_2 in low-pH hydrothermal systems (Yanagawa et al., 2013). In general, Kavachi clones were related to sequences found in other iron/sulfur-rich hydrothermal systems, including the East Pacific Rise and Lau Basin. Kavachi clones fell into one of three distinct groups within the *Sulfurimonas*. Group 1 was related to several pure culture isolates, although the only highly similar sequence (99% identity) was an uncultured environmental clone retrieved from the Arctic Ocean in 2002. The closest relative of group 2 (95% identity) was a single clone retrieved from particulate detritus associated with the tubeworm *Ridgeia piscesae*, while the closest relative of group 3 was from iron-rich hydrothermal sediments. These *Sulfurimonas* clones may represent unique diversity within the genus, possibly restricted to Kavachi and similar submarine volcano systems. Given the presence of *Sulfurimonas* in clone libraries, it is possible that the

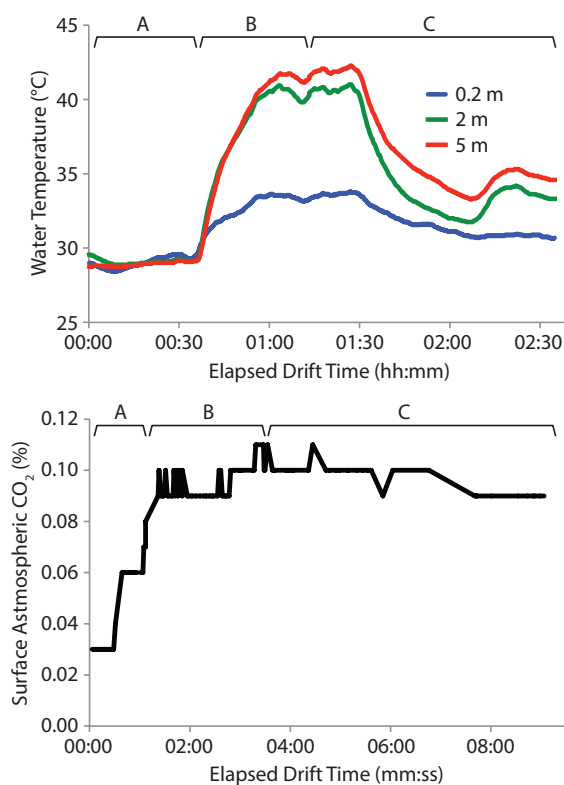


FIGURE 3. Autonomous drifter data collected over Kavachi's active crater. (top) Water temperature at three depth intervals. (bottom) Atmospheric CO_2 measured at the surface over roughly the same transect as the temperature drifter. Sections delineated by (A) are upcurrent of the crater, (B) are directly over the crater, and (C) are downcurrent.

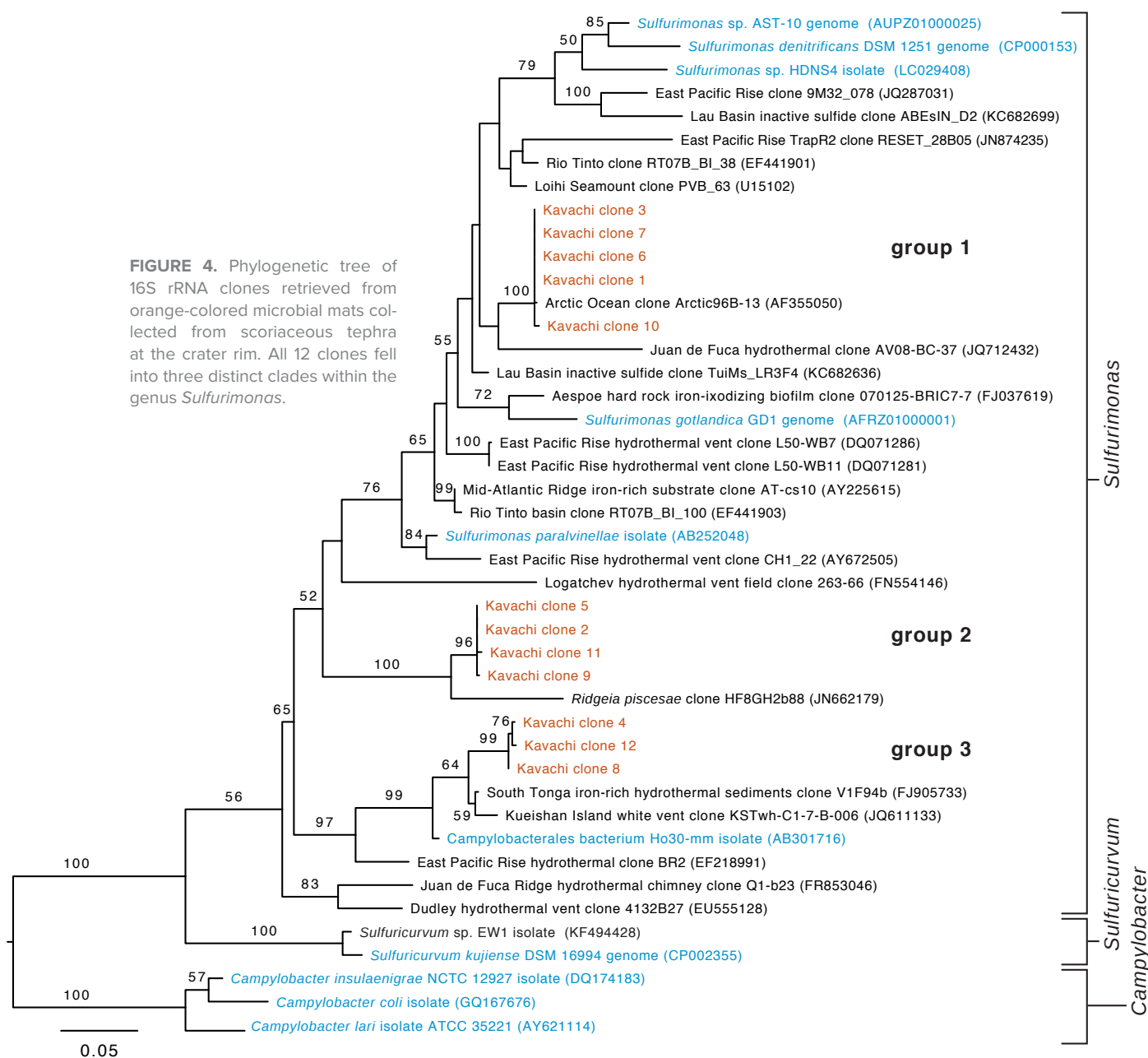
orange-colored microbial mats seen on the peak of the Southwest Extension indicate the presence of diffuse-flow sulfur- and CO₂-enriched hydrothermal fluids on this external feature. However, it is curious that no Zetaproteobacteria were recovered during clone library analysis. Typically, these bacteria are associated with orange-colored mat material in marine hydrothermal systems and indicate active iron oxidation. Organisms such as *Sulfurimonas* are typically associated with white-colored mats indicative of sulfur oxidation. More thorough geochemical and microbiological analyses are

needed to elucidate the role of microbes in geochemical cycling at Kavachi.

Baited drop-camera deployments inside Kavachi's crater at 50 m depth revealed multiple species of fish and zooplankton, apparently associated with active venting processes (Figure 2C–F; online supplemental Video S1). Two species of shark, the scalloped hammerhead *Sphyrna lewini* and the silky shark *Carcharhinus falciformis*, approached the baited camera multiple times in an aggressive pattern; in some cases, sharks appeared to be swimming from greater depths inside the crater. Bluefin trevally,

Caranx melampygus, and a *Lutjanus* sp. snapper were also seen; notably, these groups of fish were impacted the least on reefs following a subaerial volcanic eruption in the Mariana Archipelago (Vroom and Zglicynski, 2011). Appendicularians (pelagic tunicates) drift in abundance throughout recordings from inside the crater, similar to an *Oikopleura* sp. observed in great densities inside a hydrothermal plume at Okinawa Trough (Lindsay et al., 2015). In two other active submarine volcanoes, Vailulu'u Seamount (American Samoa) and Kolumbo (Greece), the craters are dominated by

FIGURE 4. Phylogenetic tree of 16S rRNA clones retrieved from orange-colored microbial mats collected from scoriaceous tephra at the crater rim. All 12 clones fell into three distinct clades within the genus *Sulfurimonas*.



microbial mats and “kill zones” where carcasses of larger animals such as fish are found on the seafloor (Sigurdsson et al., 2006; Staudigel et al., 2006). It is likely that the high crater walls at these sites cause physical entrainment and concentration of vent fluids (e.g., Christopoulou et al., 2016), while Kavachi’s crater is relatively shallow and subjected to high surface currents that allow rapid mixing to occur.

Petrology/Geologic Samples

Three volcanoclastic samples collected from the shallow rim of Kavachi’s crater (~25 m depth) during this recent study encompass a broad range of eruptive textures, including vesicular scoria, dense lavas, and scoriaceous tephra. While the last reported eruption of Kavachi was in 2007, aerial steam columns were reported by shore observers as recently

as mid-November 2014 (author Simon Albert, November 16, 2014). Visual analysis of thin sections of samples indicates that Kavachi’s explosive eruptions are driven by a combination of primary volatile degassing and phreatomagmatic interactions (Figure 5A,B). Major element analysis of bulk samples indicates they are basaltic and relatively mafic at ~6 wt.% MgO. Trace elements (Figure 5C) show patterns typical of arc lavas, although Kavachi Ba/La and Ba/Nb ratios are among the highest of the entire Solomon Island arc, suggesting an extreme composition for the subducted slab-derived fluid (Niu and Batiza, 1997; Schuth et al., 2004; König et al., 2007; Schuth et al., 2009). Ratios of moderately to highly incompatible field strength elements, which are thought to reflect the mantle source composition independent of slab-derived influences, are also among the highest in the Solomon Islands (e.g., Zr/Nb = 93–95), suggesting that the mantle source of Kavachi is highly depleted. Given Kavachi’s position between the trench and the main Solomon volcanic front, the volcano likely taps a forearc mantle that is highly depleted due to prior melting beneath the main arc front volcanoes.

DISCUSSION

Our observations of secondary and tertiary consumers inside Kavachi’s hydrothermal plume contribute to ongoing research into the physiological and behavioral resiliency of marine animals to increased temperature, acidity, and turbidity. This is most relevant in the context of climate change, as well as increased water turbidity and sediment resuspension from deep-sea mining activities. The ecosystem that is supported by the extreme environment of Kavachi’s crater may offer clues to the types of animals that have survived past major changes in ocean chemistry, and those that will thrive in future ocean conditions.

Appendicularians demonstrate a positive response to decreased pH values (Troedsson et al., 2013), which may

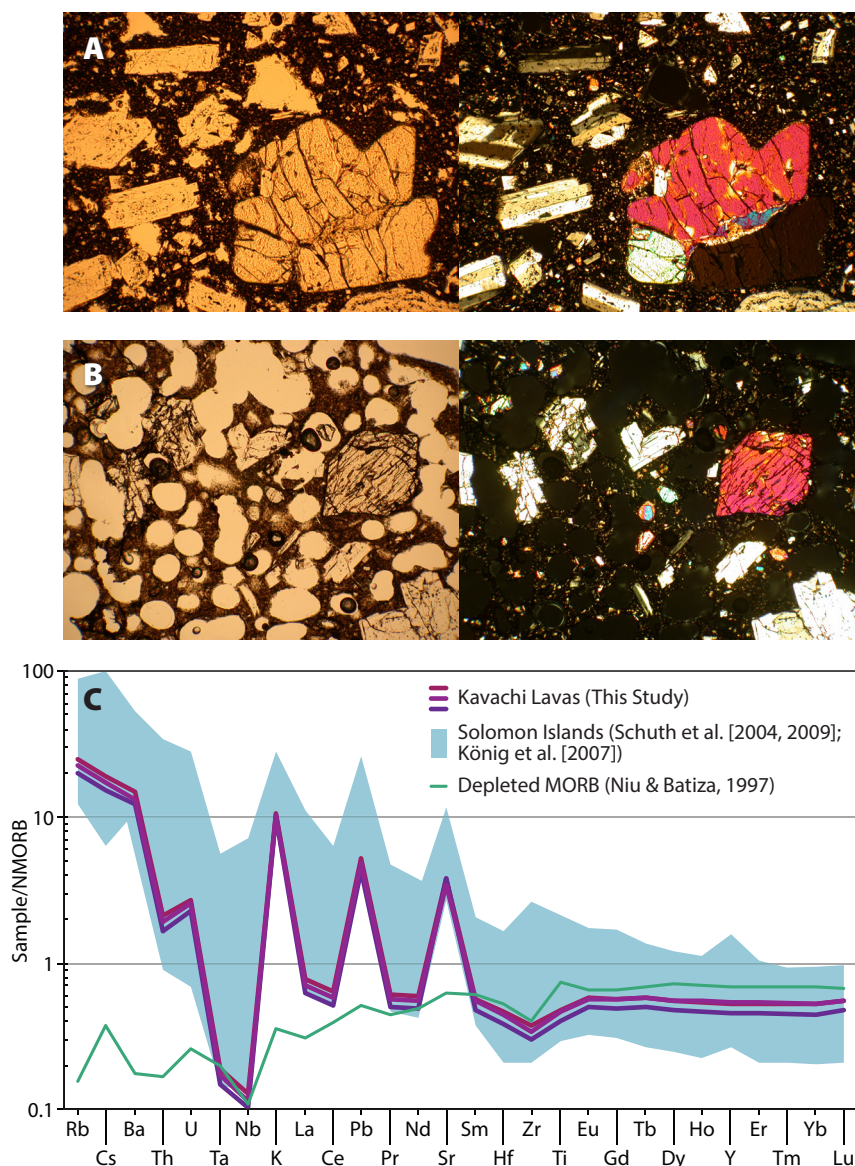


FIGURE 5. (A) Photomicrographs of basaltic lava from Kavachi summit crater with phenocrysts of plag-cpx-ol set in a groundmass of microlite-rich glass. The left image is transmitted light, the right image is crossed polars, and each image is 2.5 mm wide. (B) Photomicrograph of basaltic scoria from Kavachi summit crater with phenocrysts of plag-cpx-ol and abundant vesicles (left image is transmitted light, right image is crossed polars). (C) Normal mid-ocean ridge basalt (NMORB)-normalized trace element diagram after Hofmann (1988). Thick, solid lines are three whole-rock Kavachi lava/tephra samples from this study, and the thin solid line is a highly depleted NMORB for reference. Compositions are normalized to the NMORB of Sun and McDonough (1989). Raw data for the Kavachi Lavas are provided in the online supplemental Table S1.

explain the apparent plume-associative behavior seen among *Oikopleura* sp. Glass tunicates (gelatinous chordates in the same subphylum as appendicularians) were the only observed metazoan living inside the Kolumbo submarine caldera kill zone (Sigurdsson et al., 2006; Carey et al., 2013). Given their apparent resilience to hydrothermal fluids and their unique ability to filter-feed on picoplankton (Bedo et al., 1993; Gorsky et al., 1999; Ribes et al., 2003; Lesser and Slattery, 2015), animals such as *Oikopleura* sp. and glass tunicates could mediate an energy pathway for suspended chemolithoautotroph production into higher trophic levels. While no study has directly investigated oceanic climate change effects on bluefin trevally or snapper, cardinalfish and damselfish exhibit decreased metabolic performance and significant mortality when exposed to temperatures above 32°C (Munday et al., 2009; Johansen and Jones, 2011) and depressed antipredator responses when exposed to increased CO₂ concentrations (Ferrari et al., 2011; Munday et al., 2014). Elevations in water turbidity are a well-established stressor to reef fish (Wenger et al., 2011, 2013; Hess et al., 2015). Sharks and other elasmobranchs demonstrate behavioral thermoregulation with an affinity for warmer temperatures (Schlaff et al., 2014), and while there is evidence suggesting that ocean acidification may have a negative effect on odor tracking in sharks (Dixon et al., 2015), there are also indications of physiological and behavioral resiliency (Heinrich et al., 2014, 2015).

Importantly, Kavachi's hydrothermal plume, seen during the quiescent volcanic phase when these observations were made, is comparatively extreme relative to climate change-driven ocean temperature and acidification effects. Projections to the year 2100 agree on a maximum Δ -0.4 pH and Δ +4°C for surface seawater on a global scale (Field et al., 2014), compared to our estimated Δ -1.9 pH and Δ +13°C between Kavachi's plume and the surrounding surface waters. These extreme conditions, however, may

be representative of ocean basin-scale megaplume events caused by periods of increased volcanism in Earth's geologic history (e.g., Sinton and Duncan, 1997). A further understanding of the physiol-

ogy and behavior of organisms that thrive in these environments could offer new insights into the evolutionary history of marine animals.

of marine animals to rapid changes in their environments, as well as the ability of the ecosystem to recover from an eruptive event. If gelatinous zooplankton, sharks, and other fish species have a par-

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ogy and behavior of organisms that thrive in these environments could offer new insights into the evolutionary history of marine animals.

This study offers rare observations of one of the most active submarine volcanoes in the world. Kavachi's ephemerally active summit area consists of a shallow oblong crater and a small secondary peak to the southwest that exhibits signs of diffuse-flow hydrothermal venting. Mafic basaltic lavas collected from the summit are among the most extreme compositions in the Solomon Island arc, likely reflecting an unusual tectonic position between the trench and the main line of arc volcanoes. Inside the crater, vigorously vented CO₂-rich gas and warm turbid water convect toward the surface and are dispersed by the prevailing currents. Bacteria collected from Kavachi's summit indicate these fluids are enriched in sulfur, and high-temperature and low-pH measurements were made inside the surface plume. Surprisingly, this hostile environment hosts a vibrant ecosystem, including gelatinous zooplankton, reef fish, and sharks. The presence of these animals in such extreme conditions poses new questions centered on the resiliency

ticular tolerance for hot and acidic water, do these groups have a greater chance of surviving human-induced changes to ocean chemistry and periods of increased submarine volcanism on a global scale? What happens to the crater community before, during, and after an eruption, and how often do these cycles occur? Kavachi represents a fascinating natural laboratory for investigating these questions and remains full of mysteries to explore. 📷

SUPPLEMENTAL MATERIAL

Supplemental Figure S1, Table S1, and Video V1 are available at <https://doi.org/10.5670/oceanog.2016.85>.

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