

# Vailulu'u Seamount, Samoa: Life and death on an active submarine volcano

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**Submersible exploration of the Samoan hotspot revealed a new, 300-m-tall, volcanic cone, named Nafanua, in the summit crater of Vailulu'u seamount. Nafanua grew from the 1,000-m-deep crater floor in <4 years and could reach the sea surface within decades. Vents fill Vailulu'u crater with a thick suspension of particulates and apparently toxic fluids that mix with seawater entering from the crater breaches. Low-temperature vents form Fe oxide chimneys in many locations and up to 1-m-thick layers of hydrothermal Fe floc on Nafanua. High-temperature (81°C) hydrothermal vents in the northern moat (945-m water depth) produce acidic fluids (pH 2.7) with rising droplets of (probably) liquid CO<sub>2</sub>. The Nafanua summit vent area is inhabited by a thriving population of eels (*Dysommia rugosa*) that feed on midwater shrimp probably concentrated by anticyclonic currents at the volcano summit and rim. The moat and crater floor around the new volcano are littered with dead metazoans that apparently died from exposure to hydrothermal emissions. Acid-tolerant polychaetes (Polynoidae) live in this environment, apparently feeding on bacteria from decaying fish carcasses. Vailulu'u is an unpredictable and very active underwater volcano presenting a potential long-term volcanic hazard. Although eels thrive in hydrothermal vents at the summit of Nafanua, venting elsewhere in the crater causes mass mortality. Paradoxically, the same anticyclonic currents that deliver food to the eels may also concentrate a wide variety of nektonic animals in a death trap of toxic hydrothermal fluids.**

currents | habitats | hydrothermal | vents | eels

Seamounts, submerged isolated mountains in the oceans, are among the most poorly understood major morphological features on Earth, offering important research targets for ocean sciences. Seamount research, which involves fields as diverse as volcanology, geology, geochemistry, geophysics, physical oceanography, and marine biology, has yielded crucial insights into the absolute motion of the tectonic plates (1), the rheology and state of stress of the underlying lithosphere (2, 3), the chemical make-up of Earth's mantle (4), and the role of hypoxia in benthic animal distributions (5). Seamounts offer unique habitats for nektonic and benthic life, including both microbes and metazoans (6, 7). The topography of seamounts can substantially enhance internal ocean tides, providing powerful "stirring rods" for mixing the oceans (8) and creating local currents that transport nutrients and retain larvae (9) and concentrate commercially important fishes (10).

We report here the initial, integrated results from recent volcanological, biological, and oceanographic explorations of Vailulu'u Seamount (14°13'S; 169°04'W), an active submarine volcano located 45 km east of the easternmost island in the

Samoan archipelago. Our data come largely from three short oceanographic cruises in March–July, 2005. A cruise on the R/V *Kilo Moana* (KM) in April 2005 included 3 days of bathymetric mapping, hydrographic profiling, and geological sampling. Two cruises on the R/V *Ka'imika-O-Kanaloa* (KOK) in March/April and June/July, 2005 used the National Oceanic and Atmospheric Administration submersible *Pisces V* and a remotely operated vehicle, *RCV 150*, for direct observations and sampling. *Pisces V* also deployed and retrieved instruments that measured microbial colonization, currents, water temperature, and turbidity over a 3-month period. This multidisciplinary approach allowed us to observe a dynamic submarine hydrothermal system on time scales of hours to months and permitted the discovery of hydrothermal venting despite very adverse submarine visibility. These discoveries have provided insights into a series of unique biological habitats that are related to complex volcanological, hydrothermal, and oceanographic boundary conditions, the importance of which we are just now beginning to understand.

## Results and Discussion

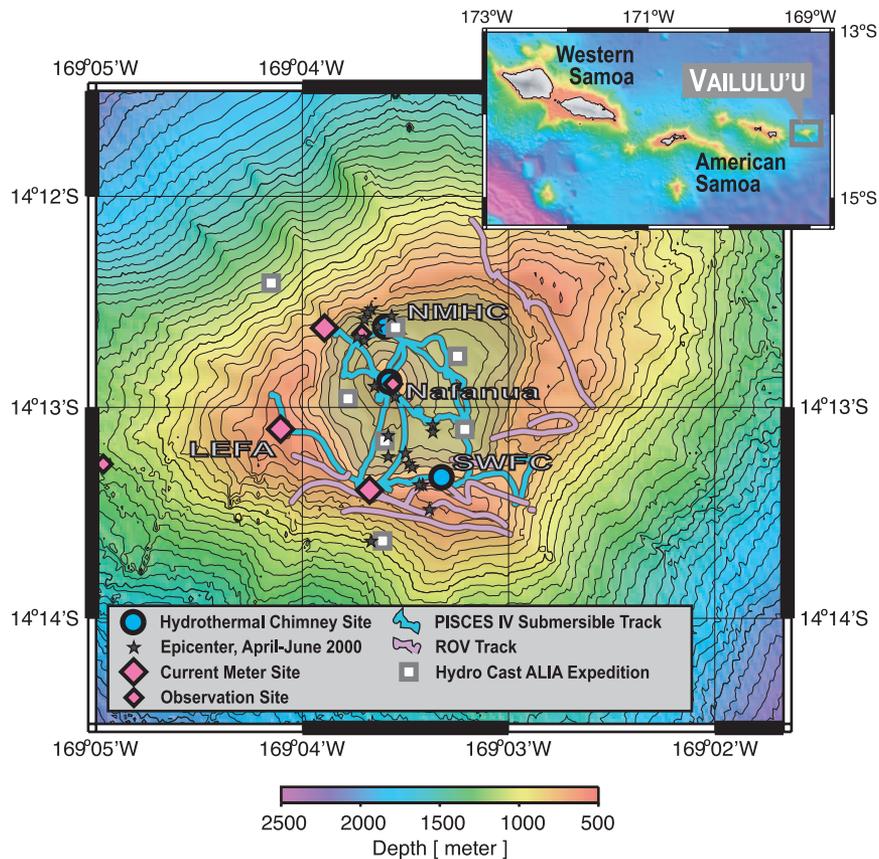
Three previous expeditions in 1999–2001 showed that Vailulu'u volcano is seismically and hydrothermally active, with an average of four local earthquakes per day and hydrothermal fluxes that rival those of black smokers at midocean ridges (11–14). The return to Vailulu'u in 2005 revealed a new, 300-m-high volcanic cone that had grown in the crater of Vailulu'u from 1,000-m water depth and that forms a new central summit, named Nafanua. Nafanua's summit depth of 708 m is well above the two major breaches of Vailulu'u crater ( $\approx 750$  m water depth). Continued growth at this rate could bring the summit close to the sea surface within decades, even though no evidence of active lava flows were observed from the submersible (Fig. 1). Nafanua is formed dominantly of very large pillow lavas, and it displays lava drainage-related collapse features on its summit, indicating high mass eruption rates. The lavas contain very large vesicles, indicating substantial degassing during eruption, but there is very little production of volcanoclastics evident within the crater and no evidence for explosive volcanism. Submersible dives along the crater wall indicate the presence of abundant volcanoclastics in the pre-Nafanua summit eruptives, however, suggesting that Vailulu'u has had clastic eruptions previously. Indeed, crater morphology and the presence of pillow breccias

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Abbreviation: NMHC, North Moat Hydrothermal Complex.

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**Fig. 1.** Bathymetric map of Nafanua and the summit crater of Vailulu'u. Inset indicates the location of Vailulu'u east of the Samoa archipelago. Hydrothermal sites include the NMHC, the summit of Nafanua, and the South Wall Hydrothermal Complex (SWHC). The region colored green within the crater at depths >800 m indicates the Moat of Death, where the ocean floor is littered with fish and invertebrate carcasses. Note that all data coverage is indicated by submersible and ROV tracks. Monitoring locations include temperature recorders, exposure experiments, and/or light back-scattering sensors (nephelometers). Time series conductivity-temperature-depth measurements were made at the NMHC site and NW of the crater.

in the crater walls suggest that Vailulu'u may once have had a central summit that was substantially shallower than Nafanua. This summit subsequently collapsed to form the crater that ultimately provided the foundation for Nafanua. Extrapolation of Vailulu'u's upper slopes suggests that such a Nafanua precursor may once have come very close to the surface.

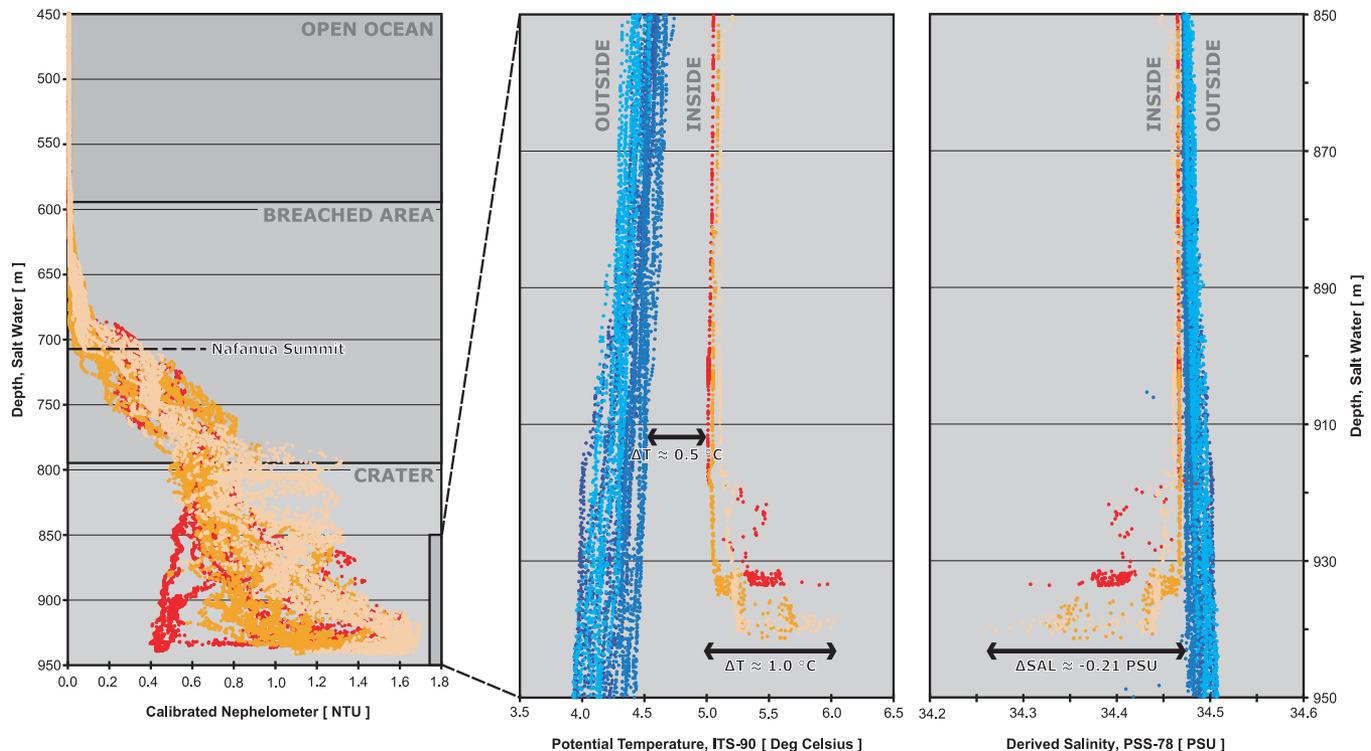
Nafanua lavas are petrographically and chemically similar to lavas previously dredged from many locations on the volcano. Samples collected from Nafanua by submersible and from a single dredge haul suggest that Nafanua is petrographically quite homogeneous and made up of olivine-phyric alkali basalts. However, Pb isotope data for one sample ( $^{206}\text{Pb}/^{204}\text{Pb} = 19.367$ ;  $^{207}\text{Pb}/^{204}\text{Pb} = 15.628$ ;  $^{208}\text{Pb}/^{204}\text{Pb} = 39.732$ ) define a new isotopic end member composition for Vailulu'u lavas relative to samples analyzed previously from the crater and flanks of Vailulu'u (15). Without relative ages of the previously analyzed basalts, it is impossible to determine whether this variation is caused by natural scatter or by a systematic temporal evolution in the source regions of Vailulu'u lavas. There is no evidence for a geochemical hiatus between Nafanua and other basalts from Vailulu'u.

Vents on Vailulu'u and Nafanua produce large fluxes of hydrothermal fluids and particulates that decrease visibility inside the crater to 2–10 m in many areas. Light back-scattering sensor (LBSS) data from hydrocasts document substantial temporal and spatial variability in turbidity. The highest particulate densities were found at water depths >730m, where values were consistently >0.2 nephelometric turbidity units (NTU) and reached 1.6 NTUs (Fig. 2). At 730- to 680-m water depths, turbidity was in the range 0.05–0.4 NTU. We identified three distinct hydrothermal vent

complexes inside the crater (Fig. 1). They are located in a linear array that coincides with epicenter clusters of volcano-tectonic earthquakes that occurred in April-June, 2000 (14).

**Vent Complex I.** The highest temperature vents of the North Moat Hydrothermal Complex (NMHC; see Fig. 1; up to 81°C) were found at the foot of the northern crater wall, where they form a diffuse zone of venting in several contiguous 10-m-sized fields (Fig. 3D) that are covered with sometimes glassy unaltered rock fragments cemented together by iron sulfide crystals (marcasite). Low salinities in the water column above the hydrothermal vents [ $\Delta sal = 0.21$  (practical) salinity unit; Fig. 2] are associated with substantial positive temperature anomalies ( $\Delta T = 1^\circ\text{C}$ ). Such low-salinity fluids are likely to form in a relatively shallow (low pressure) phase-separating hydrothermal system (16) that can separate seawater into two conjugate fluids, a condensed-vapor low-salinity fluid and a residual brine. The less dense low-salinity fluid was sampled, whereas the higher density fluid was not. Seawater from Niskin-bottle samples taken near these vents had a moderately low pH (5.1), whereas fluid collected with a sediment scoop at the point of venting had a pH of 2.7. Some of these high-temperature fields release significant quantities of a buoyant immiscible fluid, most likely liquid  $\text{CO}_2$  [as observed previously in hydrothermal vents near the Okinawa trough (17), in the form of small rising droplets]. This vent field was formed in a portion of the crater that is older than Nafanua and may not be related to the recent eruption episode.

**Vent Complex II.** A major low-temperature vent field was found on the summit of Nafanua, with diffuse venting of hydrothermal



**Fig. 2.** Vertical profiles of light back-scattering sensor (LBSS-) data at the NMHC site showing variability over a 14-h time period (Left). Salinity (Center) and temperature (Right) data are given for hydrocasts outside of the crater (NW of the NW breach, in blue) and the crater at the NMHC site (orange/yellow). Only three representative casts are shown for deployments inside the crater, together with the total range observed outside. Note the temperature inversion and the low salinities at the bottom of the crater site, indicating injection of (“vapor-like”) hydrothermal fluids from a phase-separating reaction zone. Potential temperature is well correlated negatively with potential density, and temperature inversions are mirrored by corresponding low density spikes (data not shown).

waters at temperatures  $\approx 4^\circ\text{C}$  above the ambient temperature ( $\approx 5^\circ\text{C}$ ). The Nafanua low-temperature vent fields are best recognized by the widespread occurrence of 2- to 4-cm-thick hydrothermal Fe-floc that may accumulate to thicknesses of up to 1 m and that even cover lava pillars (Fig. 3A). Nafanua summit vents may be fed from a weak, deep-rooted magma heat source and/or may represent the cooling of this newly emplaced volcano and its feeder system.

**Vent Complex III.** Another type of low-temperature venting (ambient to  $\approx 28^\circ\text{C}$ ) produces centimeter-to-meter-sized Fe-oxide chimneys (Fig. 3B and C). The largest field of this type is located on the inner side of the south crater wall, older than and distant from the cone of Nafanua [South Wall Hydrothermal Complex (SWHC); Fig. 1]. These Fe chimneys are made of a relatively solid substrate that can be penetrated easily by a metal temperature probe.

Low-temperature hydrothermal vents with the presence of microbial mats (Type II) or pencil sized Fe-Finger chimneys (Type III) also were found along the west rift of Vailulu’u, at least down to a depth of 1,700 m.

All of the observed vents expel clear fluids; thus, the origin of particulates in the crater most likely results from oxidation of acidic iron-rich North moat fluids upon mixing with ambient seawater, rather than from the “quenching” of saturated sulfide-bearing solutions more typical of deep-ocean “black smoker” vents.

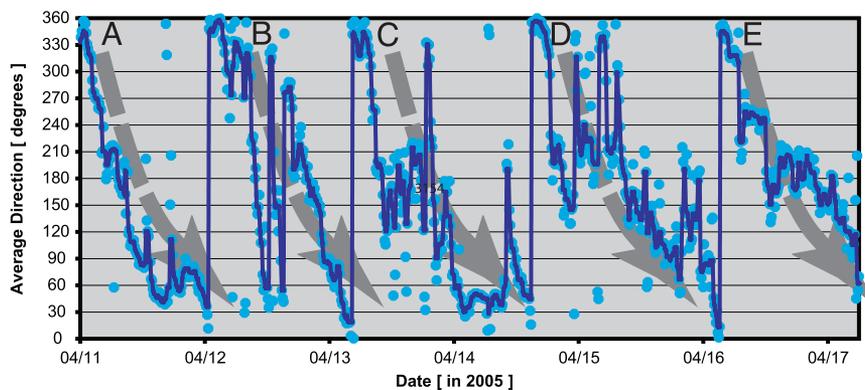
Mixing of hydrothermal fluids and external waters is evident throughout the crater, resulting in extremely variable chemical compositions and particulate inventories. Fe and Mn inventories in crater waters ranged from 11 to 585 nM/liter Fe and 6 to 113 nM/liter Mn, with Fe/Mn ratios that ranged from 0.5 to 14. Dissolved oxygen inside the crater decreased from 3.5 mg/liter at 600 m to 3.0 at the lowest breach level. Within the deeper enclosed crater, values were typically  $\approx 3.0$  mg/liter, but there

was marked local variability, with some locations exhibiting values as low as 2.4 mg/liter. Most conductivity–temperature–depth (CTD) profiles in the crater yielded relatively constant gradients in potential density and temperature (Fig. 2; ref. 12) with significant density and temperature inversions only in the immediate vicinity of the NMHC (Fig. 1). This result shows overall that a stable density structure in the crater is rapidly established, whereas hydrothermal inventories remain poorly mixed. This finding demonstrates the very dynamic nature of this system and that complete homogenization of the crater hydrothermal inventory is not accomplished on the time scale of the 3- to 4-day residence time of water in the crater (13).

Hydrothermal fluids and particulates are expelled from Vailulu’u crater to the open ocean by a complex ventilation process. This process was studied by conductivity–temperature–depth hydrocast deployments inside and outside the crater (with continuous 12-h profiling at two locations) and current meter deployments of up to 3 months on the W Summit (Lefa) and the NW and SW breaches (Fig. 1). Temperature records offer a proxy for vertical water displacement in a thermally stratified water column and document the injection of cold water into the crater through its breaches. Earlier work (12) and evaluation of our more recent conductivity–temperature–depth data suggest that the crater is ventilated by three main forces: (i) hydrothermal buoyancy causes plumes to rise, with the rise-height limited by the steep density gradients in the water column at the depth of the crater rim; (ii) ocean currents bring waters to the volcano predominantly from the SW; and (iii) vertical oscillations of ocean internal tides at the Vailulu’u summit move water up and down with an average vertical heave of 50 m, peaking at almost 100 m during the “spring” portion of the lunar tidal cycle.

The 3-month seafloor current meter deployment at Lefa summit documented anticyclonic water circulation around Vailulu’u, as is





**Fig. 4.** Current meter data from Lefa Summit for the time period from April 4 to 11, 2005. Note that the current directions display an anticlockwise rotation. Five major rotation periods are indicated by vertical lines over a time period of 6 days. Some complete rotations may be accomplished in <2 h, close to the resolution limit imposed by the 20-min sampling frequency of the instrument.

densities near the peak of the volcano, where accelerated currents provide the best feeding conditions for filter feeders and cnidarians and where vagrant predators and scavengers are common (Fig. 3 I–N). The latter included solitary synphobranchid eels and a large (1-m armspan) octopus that we observed on Lefa Summit during several dives (Fig. 3M).

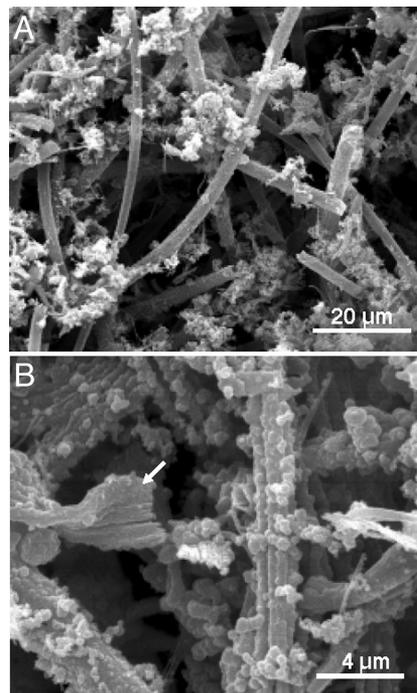
**Habitat Type II.** Nafanua summit experiences large variations in turbidity, alternating from periods of highly turbid water with periods of relatively clear water. It also has favorable conditions for the formation of iron oxide mats. Diffuse, low-temperature vents at this site are inhabited by a thriving population of small cutthroat (synphobranchid) eels, *Dysommia rugosa* (Fig. 3E). These eels occupy nooks and crevices in the pillars and mounds of drained and partly collapsed pillow lava flows and swarm in the water column when disturbed by the submersible. Eels of this species are known from trawl samples in both the Atlantic and Pacific oceans but have never before been studied in their natural habitat. Although they were the only common metazoan animals occupying these low-temperature hydrothermal vents, their isotopic composition ( $\delta^{15}\text{N} = 13.9\text{--}15.9$  permil) and gut contents indicate that they use the vent only as a habitat and are decoupled trophically from the primary production supported by the volcano. The eels do not feed on the chemosynthetic bacterial mats ( $\delta^{15}\text{N} = 2.7\text{--}9.9$  permil) that cover the rocks they live in, but on crustaceans ( $\delta^{15}\text{N} = 14.5\text{--}18.0$  per mil) that may be delivered to Nafanua's summit by the anticyclonic summit currents around Vailulu'u.

**Habitat Type III.** The most turbid crater water occurs at depths >740 m in a moat around Nafanua (including the East pit crater) that displays the most hostile conditions to life. Here, abundant carcasses of midwater fish, squid, and crustaceans littered the seafloor. This region, dubbed the "Moat of Death," has turbid water that is highly acidic in the places we sampled. The only living animals found in this zone were bright red polynoid polychaetes ( $\delta^{15}\text{N} = 11.7\text{--}15.3$  per mil) that swarmed around the rotten fish, squid, and crustacean carcasses ( $\delta^{15}\text{N} = 7\text{--}16$  per mil), where they probably consume bacteria ( $\delta^{15}\text{N} = 0.07\text{--}5.9$  per mil).

**Habitat Type IV.** Vailulu'u also offers a series of environments where the toxic waters of the Moat of Death variably alternate with clean seawater entering through the breaches. Notable examples include those portions of the crater walls lying directly below the southwest and northwest breaches (Fig. 1), where clean seawater enters the crater and permits fish and crustaceans to survive at depths where no life was found elsewhere in the crater. This region may play an important role in trapping life inside Vailulu'u crater. The inside wall of the Southwestern breach supports a very dense population

of small stalked demosponges, *Abyssocladia bruuni* (Fig. 3J). These sponges serve as an excellent indicator of chemical conditions, because they do not occur in the turbid waters where hydrothermal fluids billow upward near the crater walls.

Habitats in the crater itself support low macrobiotic diversity but represent an extreme set of conditions that support life. Thus, eels living on Nafanua summit must withstand frequent inundation by highly turbid waters laden with hydrothermal particulates, but they benefit in turn from the food delivered to them in the vortex of anticyclonic currents. These same currents entrain fish and other nekton into the toxic waters of the Moat of Death where they die and become food, either directly or indirectly, for specialized polychaetes that resist highly acidic and toxic conditions. The exact cause of death for most nekton in this location is uncertain but is probably a combination of the low pH of hydrothermal waters and asphyxiation from the compound



**Fig. 5.** Scanning electron microscope images of Fe floc from Nafanua volcano, Vailulu'u Seamount. (A) Long, hollow filamentous iron oxide tubes interspersed with amorphous iron oxide. (B) Twisted stalks (arrow) resembling structures formed by the Fe(II)-oxidizing bacterium *Gallionella*.

effects of reduced dissolved oxygen and Fe oxide particulates coating gills. Similar cases for mortality of nekton in submarine volcanic settings were reported from Kickem–Jenny seamount, Lesser Antilles (19), and an offshore submarine volcano near Kueishan Island, Okinawa Arc, Taiwan (20).

Microbial activity at submarine volcanoes is important because it has a profound impact on the chemical fluxes involved in water–rock interactions, it produces primary biomass from chemical energy provided by the volcano, and these systems may provide some key analogues for life on the early Earth and elsewhere in the solar system. To draw comparisons with other submarine hydrothermal vent systems and to identify geochemically important and environmentally relevant members of the microflora, we inoculated a range of low-organic media with microbial samples from hydrothermal floc, microbial mats, and biofilms from naturally weathered basalt surfaces and from exposure experiments [sterile fragments of rock and basalt glass deployed on the bottom in poly(vinyl chloride) (PVC) collectors]. Inoculations were amended with reduced metals such as Mn(II) or Fe(II). Exposure experiments were deployed at all major monitoring stations (Fig. 1) and recovered after a 3-month exposure.

Vailulu'u and Nafanua provide a substantial source of chemical energy for microbial activity, as evidenced by the massive quantity of microbial mats and associated hydrothermal Fe floc observed in areas of diffuse venting. The hydrothermal floc may reach thicknesses of >1 m in some places on the summit of Nafanua, but it is relatively rich in Fe and lean in organic carbon. Thus, relatively small microbial populations may benefit from an overwhelming amount of inorganic Fe(II) oxidation in the water column. Scanning electron microscopy energy-dispersive x-ray fluorescence showed that the floc is mostly made of Fe oxide particulates (Fig. 5). The hollow filaments are structurally similar to filaments observed previously on rock surfaces from mid-ocean ridges (21); however, the flocs are dominated by relatively amorphous Fe oxides rather than structures easily recognized as microbial, such as tubes and sheaths. At the NMHC, microbial mats were much denser and formed cohesive skins on exposed rocks, at times peeling off in sheets 10- to 25-cm long.

To date, we have identified a series of bacterial isolates with the functional capability of Mn(II) and Fe(II) oxidation. 16S rDNA sequencing shows that the majority of the isolates are  $\gamma$ -Proteobacteria, in particular within the genus *Pseudoalteromonas*. The sequences are 99% similar to *Pseudoalteromonas* sp. previously isolated from submarine basalts (22) and seen in clone libraries derived from microbial mats (23) from Loihi Seamount as well as diverse geochemical environments where Mn(II) oxidation has been shown to commonly occur, such as Guaymas Basin hydro-

thermal vents, the East Pacific Rise, and the Black Sea (23, 24). Intriguingly, some of these Vailulu'u *Pseudoalteromonas* isolates were obtained on media amended with Fe(II), where colonies were selected for the functional capability of Fe(II) oxidation but were found to also oxidize Mn(II). Other species of Vailulu'u Mn(II)-oxidizers include *Marinobacter* sp. and *Shewanella* sp.; these are closely related to isolates previously obtained from basalt surfaces at Loihi Seamount and the East Pacific Rise, respectively. This finding suggests that the organisms isolated from Vailulu'u in this study are environmentally relevant and widely distributed throughout the deep (Pacific) ocean.

## Conclusion

Vailulu'u offers an incredibly diverse and dynamic marine environment where volcanic, hydrothermal, oceanographic, and biological processes are closely interlinked. The growth of Nafanua and its hydrothermal system produces massive quantities of Fe oxide floc with a specific microbial community and hosts a thriving eel population. The complex “breathing” of the crater waters links ocean currents and internal tides to volcanic–hydrothermal venting of the crater. Anticyclonic circulation in the summit region may play a key role in the delivery and entrapment of zooplankton and nekton to the central summit region of Nafanua. Together these factors produce a series of distinct marine habitats that are closely linked spatially but contrast sharply in their biota. This dynamic intersection of lithosphere, hydrosphere, and biosphere offers some exciting puzzles in ecology, oceanography, submarine volcanology and hydrothermalism. If the eels do not use any of the primary production of biomass as a food source, why do they colonize hydrothermal vents in such numbers rather than nearby peaks at similar depths? What is the relationship between the anticyclonic currents in the summit region and the delivery of marine life to the Vailulu'u crater? What and when will be the next volcanic event at Vailulu'u? Is there a way to predict this event? Vailulu'u volcano is vigorously active and unpredictable, like Nafanua, the Samoan goddess of war, the namesake for the most recent volcanic construct in its crater.

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