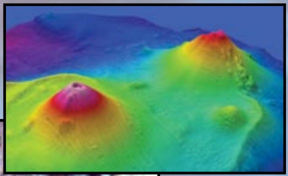
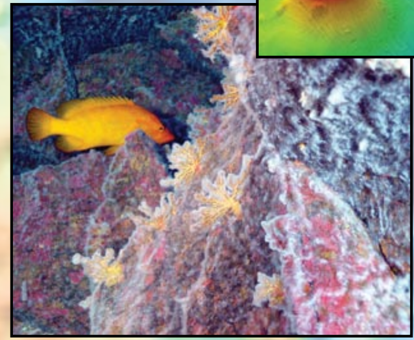
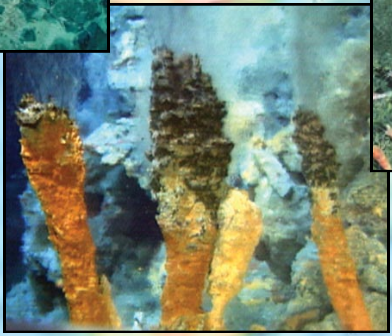


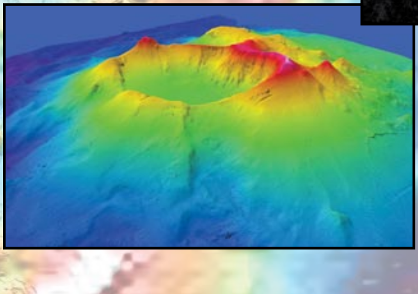


# Exploring the Submarine Ring of Fire

## Mariana Arc - Western Pacific

BY ROBERT W. EMBLEY, EDWARD T. BAKER, DAVID A. BUTTERFIELD, WILLIAM W. CHADWICK JR., JOHN E. LUPTON, JOSEPH A. RESING, CORNEL E.J. DE RONDE, KO-ICHI NAKAMURA, VERENA TUNNICLIFFE, JOHN F. DOWER, AND SUSAN G. MERLE





Sampling an erupting volcano at 550-m depth, discovering roiling pools of liquid sulfur at 400-m depth, watching tropical fish swimming amid fields of black smoker vents, and encountering a blizzard of liquid carbon dioxide globules rising from fractured lava flows at 1600-m depth all sound like wishful thinking or scenes from a science fiction movie. But, we had the good fortune to observe these and other previously unseen phenomena between 2004 and 2006 during a series of expeditions to the Mariana arc in the western Pacific. We describe here several of the most interesting sites, along with their geologic and oceanographic contexts.

Some 70% of Earth's volcanism is submarine, and most of it occurs along the 65,000-km-long mid-ocean ridge (MOR) where new oceanic crust is created (Figure 1, green lines). The volcanic rocks accreted at the MOR are almost entirely basaltic in composition and typically erupt at water depths between 2000 and 4000 m. The fundamental role of Earth's primary accretion boundaries in creating the ocean basins has provided a strong rationale for detailed studies of the MOR since the 1960s. The discovery of hydrothermal activity and associated deep chemosynthetic life on MORs in the late 1970s (see Haymon et al., this issue) provided additional impetus for this research.

Although the MOR remains an important research area, the past decade has seen new attention focused on the submarine volcanism that creates volcanic arcs along subduction zones landward of oceanic trenches. Most of these intra-oceanic arcs (ocean-ocean collisions) and island arcs (ocean-continent collisions) occur in the western Pacific (Figure 1). Subduction zones process oceanic crust and upper mantle in a broad, deep zone that has been called the "subduction factory" (Stern, 2002). These subduction factories are the primary agents for recycling oceanic crust back into Earth's mantle and returning mantle volatiles to the oceans (Figure 2). Although seafloor drilling is now providing access to the uppermost portions of subduction zones, seismological and chemical studies are critical to understanding the deep regions. The lavas and

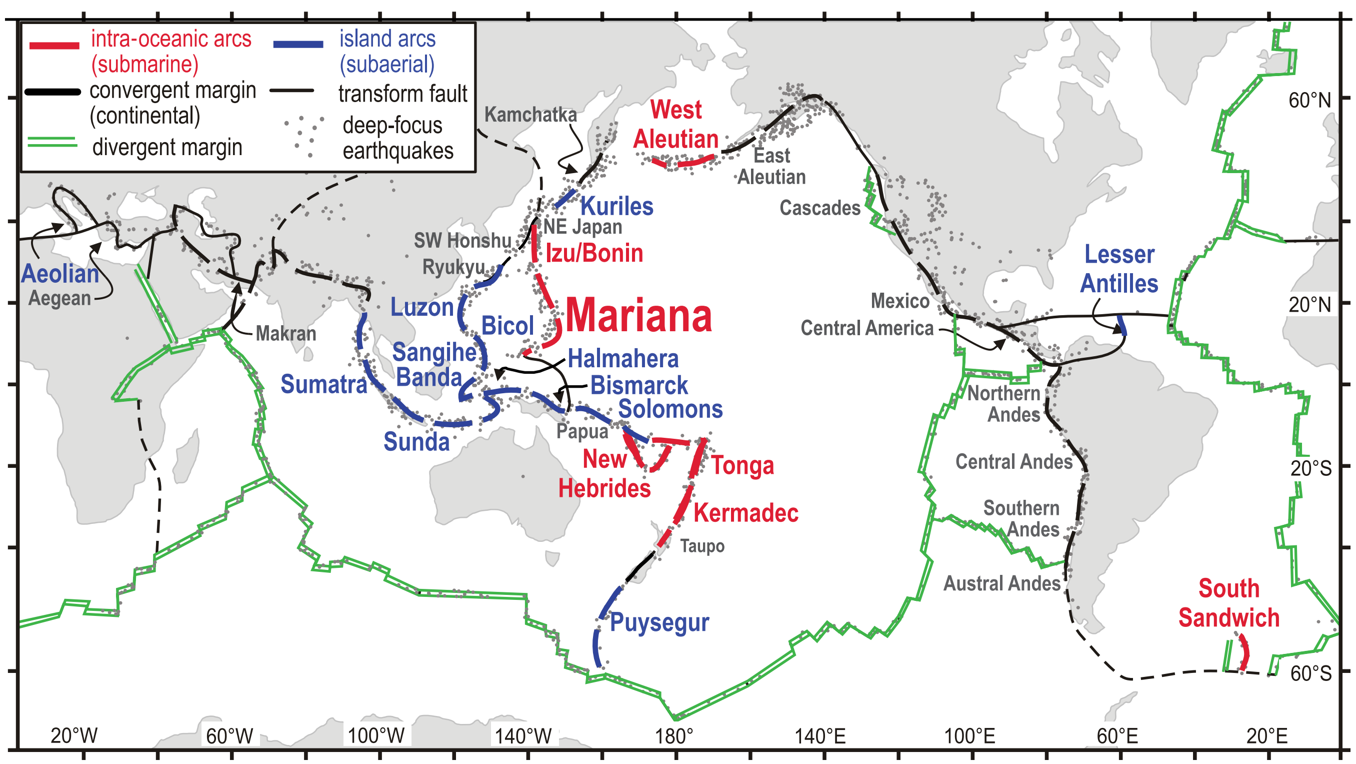


Figure 1. Locations of intra-oceanic arcs, island arcs, and other plate boundaries. *Modified after de Ronde et al. (2003)*

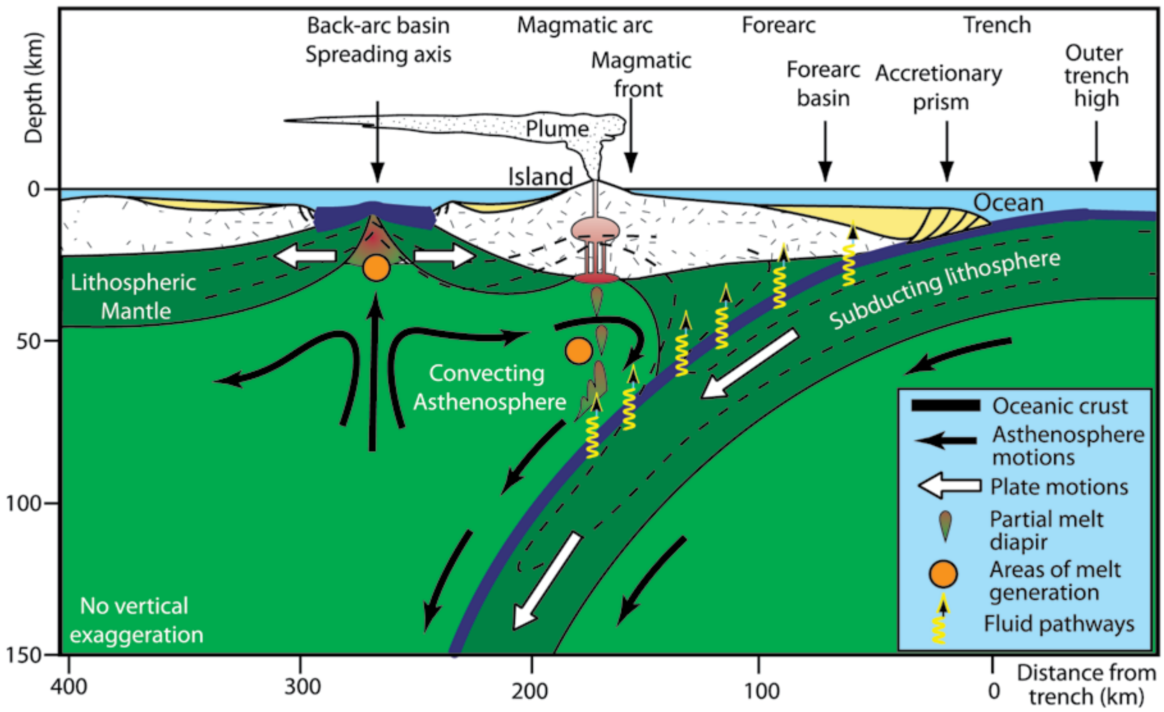



Figure 2. Schematic section through the upper 140 km of a subduction zone, showing the principal crustal and upper mantle components and their interactions. *Modified after Stern (2002)*

fluids sampled at the seafloor, in drill holes, or on tectonically exposed outcrops provide the only direct clues to processes beyond our reach.

The major volcanic-tectonic features of an intra-oceanic subduction zone (Figure 2) are summarized in several review papers (Fryer, 1996; Stern, 2002; Stern et al., 2003), so we provide only a brief synopsis here. The trench is the depression caused by bending and fracturing of the subducting oceanic plate. The forearc is the site of initial interaction between the two plates, marked by fracturing, serpentinization, accretion of sediments, or subduction erosion. The back-arc spreading centers and back-arc rift zones result from seaward migration of the trench and/or plate divergence (Karig, 1971). The magmatic arc lies 100–250 km from the trench axis along a band above the zone of maximum melt generation, whose location is determined by the pressure and temperature of the mantle and the rate of dehydration of the downgoing plate (Stern, 2002). The release of water from the slabs down to depths of 100 km or more decreases the melting point of the mantle and initiates magma accumulations that eventually erupt onto the ocean floor, forming chains of volcanoes. Approximately 75% of all subduction-zone-related submarine volcanoes occur within the Tonga-Kermadec, Izu-Bonin-Mariana, and New Hebrides intra-oceanic arcs (de Ronde et al., 2001, 2003). These and other intra-oceanic arcs account for more than 15% of the total length of Earth's subduction zones (Bird, 2003).

## EXPLORING EARTH'S INTRA-OCEANIC ARCS

Interest in submarine arc volcanoes is increasing. Because these volcanoes are the main portals through which volatiles (primarily $H_2O$, $CO_2$, and $SO_2$) released from the downgoing oceanic plate are returned to the ocean, their output represents an important but as yet unknown part of the oceanic volatile budget. Their volcanic emissions are injected into the ocean at relatively shallow depths, mostly less than 1000 m, providing opportunities to study the interaction of volcanic and hydrothermal chemicals and upper-ocean biological processes. In addition, the wide range of host-rock composition and high gas content produces a chemical variability of hydrothermal emissions much broader than found on

MORs. Finally, because of these systems' isolation from one another (the "point source" nature of their emissions), arc volcanoes sponsor distinct, sometimes unique, hydrothermal fauna from volcano to volcano, resulting in enhanced biogeographical diversity.

The modern era of subduction-zone exploration began in the 1980s with large-scale mapping using then new multibeam and side-scan sonars along with human-occupied vehicles such as the Japanese *Shinkai 2000* and *6500* and the American *Alvin*. Though these pioneering studies of the Izu Bonin (Glasby et al., 2000; Ishibashi and Urabe, 1995) and Mariana (Fryer et al., 1997; McMurtry et al., 1993; Stuben et al., 1992) arcs focused on only a few active sites, they provided impetus for subduction-zone emphasis that began in the late 1990s.

Systematic bathymetric and water-column surveys of the major intra-oceanic arcs were initiated in 1999 along the southern Kermadec arc (de Ronde et al., 2001), expanding to the mid to northern reaches of the Kermadec arc in 2002 and 2004 (de Ronde et al., 2007) and farther north to the Tonga arc in 2003 (Massoth et al., 2005). Similar work on the Mariana arc began in 2003 (Embley et al., 2004; Resing et al., 2003b; http://oceanexplorer.noaa.gov/explorations/03fire/welcome.html), and was followed by in situ studies using remotely operated vehicles in 2004 (http://oceanexplorer.noaa.gov/explorations/03fire/welcome.html), 2005, and 2006 (http://oceanexplorer.noaa.gov/explorations/06fire/welcome.html). These surveys of the Mariana and Tonga-Kermadec arcs were followed by dive campaigns using manned submersibles and remotely operated vehicles (ROVs) to target some of the most active sites. As of 2007, more than 80 dives with submersibles (*Shinkai 6500*, *PISCES V*) and ROVs (*ROPOS*, *Jason 2*, and *Hyper-Dolphin 3000*) have been conducted on more than 26 submarine volcanoes in the Mariana (12), Kermadec (10), and Tonga (4) arcs (Embley and Investigators, 2006; Massoth et al., 2005; Stoffers et al., 2006). In this paper, we highlight the results of 2003–2006 expeditions to the Mariana Arc.

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ROBERT W. EMBLEY *(Robert.W.Embley@noaa.gov) is Senior Research Scientist, Pacific Marine Environmental Laboratory (PMEL), National Oceanic and Atmospheric Administration (NOAA), Newport, OR, USA.* EDWARD T. BAKER *is Supervisory Oceanographer, PMEL/NOAA, Seattle, WA, USA.* DAVID A. BUTTERFIELD *is Oceanographer, Joint Institute for the Study of the Atmosphere and Ocean (JISAO), University of Washington, PMEL/NOAA, Seattle, WA, USA.* WILLIAM W. CHADWICK JR. *is Associate Professor, Cooperative Institute for Marine Resources Studies (CIMRS), Oregon State University, PMEL/NOAA, Newport, OR, USA.* JOHN E. LUPTON *is Oceanographer, PMEL/NOAA, Newport, OR, USA.* JOSEPH A. RESING *is Research Associate, JISAO, University of Washington, PMEL/NOAA, Seattle, WA, USA.* CORNEL E.J. DE RONDE *is Geologist/Geochemist, GNS Science, Lower Hutt, New Zealand.* KO-ICHI NAKAMURA *is Researcher (Marine Chemist), National Institute of Advanced Industrial Science and Technology, Tsukuba, Ibaraki, Japan.* VERENA TUNNICLIFFE *is Professor, Department of Biology, School of Earth and Ocean Sciences, University of Victoria, Victoria, B.C., Canada.* JOHN F. DOWER *is Assistant Professor, Department of Biology, School of Earth and Ocean Sciences, University of Victoria, Victoria, B.C., Canada.* SUSAN G. MERLE *is Senior Research Assistant, CIMRS, Oregon State University, PMEL/NOAA, Newport, OR, USA.*

## MARIANA ARC

The Izu-Bonin-Mariana subduction zone has a long and complex geologic history (Stern et al., 2003). The most recent phase of subduction contributing to formation of the present-day Mariana arc began with the initiation of back-arc spreading in the Mariana Trough about seven million years ago (Stern et al., 2003). The remnants of this early island arc are the basement ridges that form the underpinnings of the islands of Guam, Rota, Tinian, and Saipan and their western counterpart, the West Mariana Ridge (Figure 3). The present magmatic arc, which lies west of this older arc (Bloomer et al., 1989), divided the magmatic arc front into three sections (Figure 3). The Southern Seamount Province (SSP) is a chain of volcanically active islands lying west of the "old islands." The Central Island Province (CIP) is dominated by the eight island volcanoes (Anatahan to Uracas) in addition to a few seamounts. The Northern Seamount Province (NSP) is entirely submarine and ends at 24°N where the Marina arc merges with the southern Bonin arc. Six of the nine island volcanoes have had historical eruptions, the most recent being the southernmost island-volcano Anatahan that had its first historical eruption in 2003 (Truesdale et al., 2006). There have also been submarine eruptions at Esmeralda (Stuben et al., 1992), Ruby (Norris and Johnson, 1969), Ahyi (Smithsonian Institution, 2001), and possibly several other less-well-documented sites.

## SUBMARINE RING OF FIRE EXPEDITIONS TO THE MARIANA ARC

There have been surveys of and sampling campaigns at the Mariana subduction zone since the 1960s (Bloomer et al., 1989; Fryer, 1996; Stern et al., 2003), but

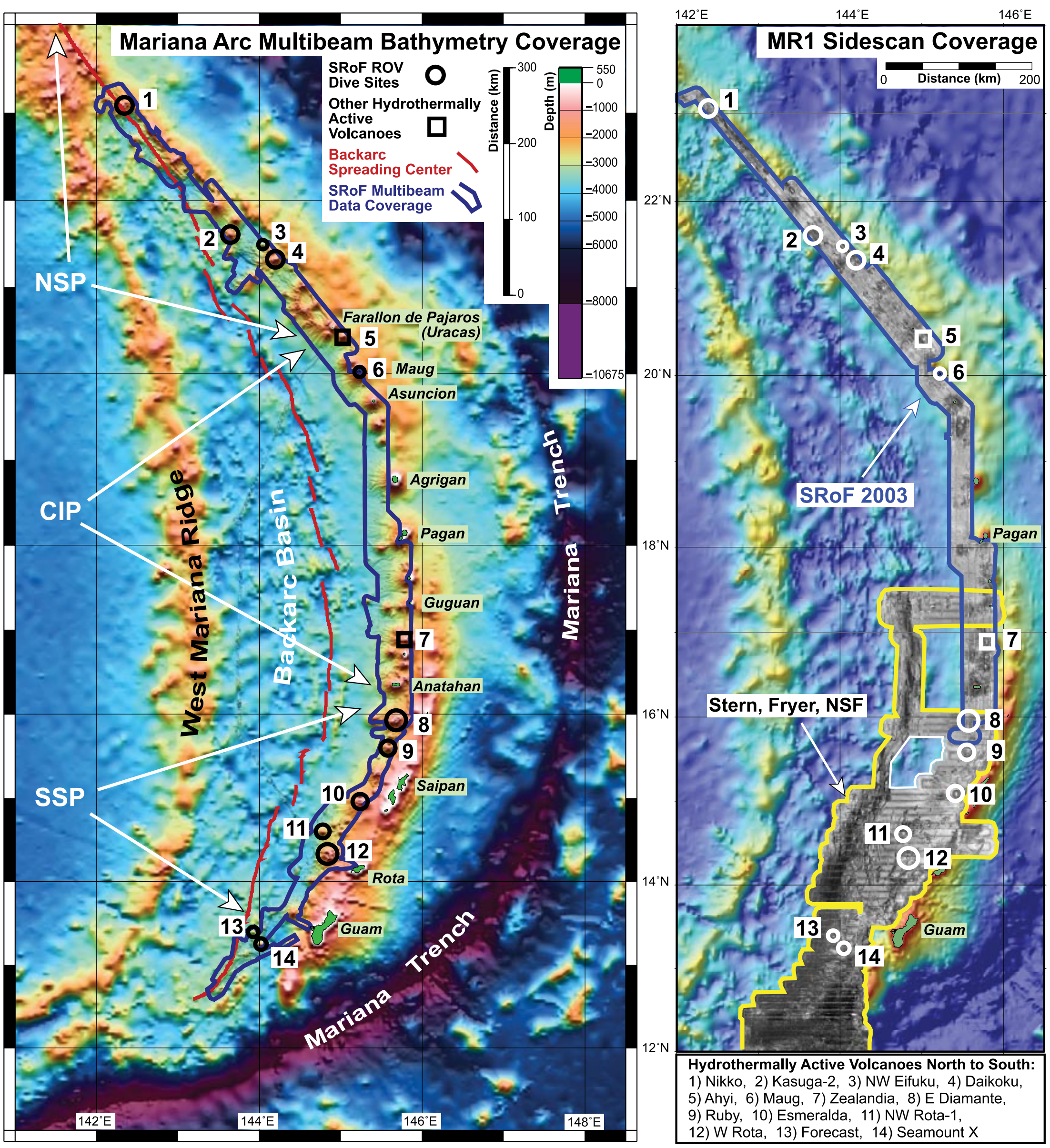


Figure 3. Left panel: Multibeam bathymetry data coverage of the Mariana magmatic arc. The thick blue line indicates multibeam data collected on the Submarine Ring of Fire cruises in 2003, 2004, and 2006. Bathymetric mapping in 2003 and 2004 used the hull-mounted EM300 system (~ 30-m grid cell) on R/V *Thomas Thompson*. Bathymetric mapping in 2006 used the hull-mounted SeaBeam 2000 system (~ 50-m grid cell) on R/V *Melville*. Dives with remotely operated vehicles were made on numbered volcanoes (except for Ahyi [5]) on the Mariana arc, shown in legend below right panel. Right panel: Hawaii Mapping Group *MR1* side-scan sonar coverage at the Mariana arc. The side-scan data resolution is 16 m. The thick blue line indicates side-scan data collected on the Submarine Ring of Fire cruise in 2003. The Fryer and Stern *MR1* data sets were collected in 1997 and 2001, respectively.

even as late as 2003, only a few active submarine hydrothermal sites had been found (Embley et al., 2004; Ishibashi and Urabe, 1995; McMurtry et al., 1993; Stuben et al., 1992). Our 2003 expedition used surface-towed (side-scan) and hull-mounted (EM300) mapping systems to inventory every substantial volcanic edifice from 12°30′ N to 23°30′ N. To identify active hydrothermal sites, we conducted water sampling over 51 volcano edifices, detecting hydrothermal emissions at 21 sites (Embley et al., 2004, and author Baker and colleagues are preparing a paper on more recent work). In 2004, 2005, and 2006 we discovered some extraordinary sites while conducting ROV dives to 12 of these volcanoes (Table 1; Figure 3).

## FIRST OBSERVATIONS OF A DEEP SUBMARINE ERUPTION

NW Rota-1 volcano (Figures 4 and 5), located about 100 km north of the island of Guam, was chosen for submersible study because of the well-defined hydrothermal plume over its summit (Figure 5) and the unusual chemistry of the plume effluent (Embley et al., 2004; Resing et al., in press). Particulate and dissolved samples indicated a high-temperature reaction between extremely acidic fluids and the host rocks (Resing et al., in press). The first dives using ROV *ROPOS* at the site in 2004 found the summit of the volcano in a state of low-level eruption, spewing out acidic white clouds saturated with liquid sulfur from a small crater near its summit (Brimstone Pit) at a depth of 540 m (Embley et al., 2006). We observed and sampled small lapilli that rained down on the ROV, and we saw colonies of shrimp swarming around diffuse vent sites in the summit area. In 2005, we observed increased activity at Brimstone Pit, with explosive degassing, ejection of volcanic bombs, and elevated temperatures in the eruption cloud (up to 120°C). A 25–30-m shoaling of the volcanic vent (compared to the depth recorded in 2004) provided evidence of rapid construction of a fragmental cone.

A return to this site in 2006 produced even more dramatic results. Over the course of a single week on site, we observed massive degassing (Figure 6a) and explosive eruptions, including frag-

Table I. Characteristics of Mariana arc submarine volcanoes explored by submersible or remotely operated vehicle (with exception of Ahyi and Zealandia). Low T (Low temperature) < ~100°C; High T >~ 100°C.

| Volcano | Summit Depth (m) | Morphologic Type | Rock Types (> $SiO_2$) (R. Stern, *pers. comm.*) | Hydrothermal Vent Type | Comments |
|---|---|---|---|---|---|
| Ahyi | 60 | Cone | Basalt | Low T | Historical eruption |
| Ruby | 178 | Cone | Basalt | Low T | Historical eruption |
| NW Rota-1 | 517 | Cone | Basalt-Andesite | Low T, High Gas | Active eruption 2003–2006 |
| NW Eifuku | 1563 | Cone | Basalt | Low T, High Gas | Liquid $CO_2$ degassing |
| Seamount X | 1228 | Caldera, Cone | Basalt-Andesite | Low T | Diffuse |
| Esmeralda | 53 | Caldera | Basalt-Andesite | Low T | Diffuse |
| Maug | 55 | Caldera, Cone | Dacite | Low T | Iron, diffuse |
| Zealandia | 460? | Caldera, Cone | ? | Low T? | CTD only |
| Minami Kasuga-2 | 293 | Caldera | Basalt | Low T and High T? | |
| West Rota | 303 | Caldera | Dacite | Low T | Extinct or dormant |
| Daikoku | 320 | Cone, Caldera | Andesite | High T, High Gas | Liquid sulfur pool, > 200°C |
| East Diamante | 145 | Caldera, Cone | Dacite | High T | 242°C, smokers at 345 m |
| Nikko | 383 | Cone, Caldera | Andesite | High T, Gas | Liquid sulfur, > 200°C, degassing |

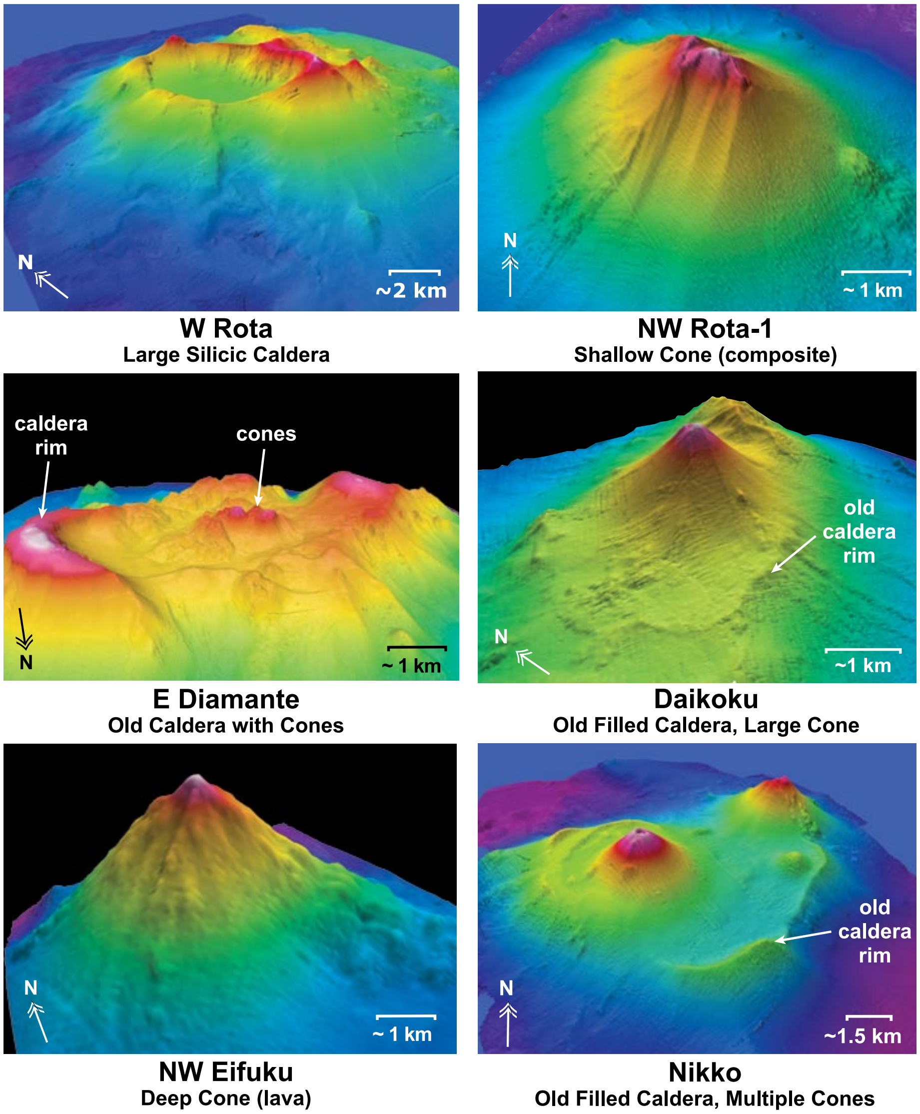


Figure 4. Three-dimensional bathymetry of selected Mariana volcanoes from multibeam data. All images are two times vertically exaggerated. Depth ranges for the volcano images are: NW Eifuku, 1563–3400 m; NW Rota, 1517–3400 m; West Rota, 303–3225 m; East Diamante, 145–2390 m; Daikoku, 320–2500 m; NW Eifuku, 1563–3400; Nikko, 383–2795 m.

mentation of erupted volcanic bombs (Figure 6b) and flashes of glowing red magma in the vent (Figure 6b, inset); these are described in a paper being prepared by author Chadwick and colleagues. The damping effect of the seawater allowed a close approach to the site that would have been impossible on a subaerial volcano during an eruption of comparable intensity. Unprecedented sample collections of gases, solids, and aqueous solutions at the NW Rota-1 eruptive site provide unique access to complex magmatic and hydrothermal processes (Butterfield et al., 2006). We were also able to document the effects of the eruption on the local biology and oceanographic environment. For example, the semi-continuous supply of volcaniclastic material from the eruption and the periodic collapse of the cinder cone produced zones of turbid water around the flanks of the volcano down to ~ 2000-m depth. As far as we know, this is a unique signature of active submarine eruptions on arc volcanoes (Baker et al., 2002; Embley et al., 2006). The specialized shrimp populations living on the summit of the volcano (Limen et al., 2006) (Figure 6c) take advantage of microbial mats thriving on the periphery of the eruption area, and they also dine on organisms that fall victim to the toxic clouds wafting up from the eruption site (Figure 6c, top panel). At present, we are unsure whether this population colonized the site as a specialized eruption fauna or if it represents the survivors of a population decimated by the eruption onset.

We don't know how long NW Rota-1 has been active (but at least three years, from 2003 to 2006) or will remain so. However, its characteristics are similar to Strombolian activity on land (i.e., high gas flux and low magma throughput; discussed in Chadwick paper mentioned above), which can be very long-lived. If it remains active, this site will continue to be a unique underwater laboratory for studying the physical, chemical, and biologic processes associated with an active submarine volcano and the effects of these processes on the surrounding ocean.

## Shallow Hydrothermal Activity at East Diamante Volcano

East Diamante volcano is an entirely different type of volcano than NW Rota-1, with a longer and more complex geologic history. It is an elongate structure (east-west) with a distinct but partially eroded caldera and a cluster of younger dacite cones in the center (Figure 4). The hydrothermal plume exhibited an intense optical backscatter signal, which originated from the primary hydrothermal site located on the easternmost portion of the central cone complex (Figure 6d). At this site, we observed the shallowest black-smoker system discovered to date at a depth of 345 m. A forest of more than a dozen active and extinct chimneys grows from a well-defined east-west fracture system on the eastern side of the easternmost cone (Figure 4). The fluid temperature was as high as 242°C, which is within 2°C of the boiling temperature of seawater at this depth. Because the boiling point of seawater decreases rapidly above this depth, this site is at the upper depth limit for a high-temperature hydrothermal system. Surprisingly, however, the sulfide chimneys contain a complex suite of sulfide, oxide, and sulfate minerals including pyrite, sphalerite, chalcopyrite, hematite, and barite (de Ronde et al., 2004).

Diffuse hydrothermal venting occurs over much of the eastern cone complex and overlaps with the deeper part of the photosynthetic zone. A white, filmy microbial mat is found coating rocks covered with encrusting red and green algae up to at least 190 m (Figure 6e). Although there have been a number of studies of shallow-water venting where there is overlap between chemosynthesis and photosynthesis (Tarasov et al., 2005), the proximity of this overlap zone to a deeper high-temperature vent field is unusual and underscores the importance of submarine arc volcanoes for studying the ecology and evolution of vent communities over a wide depth range.

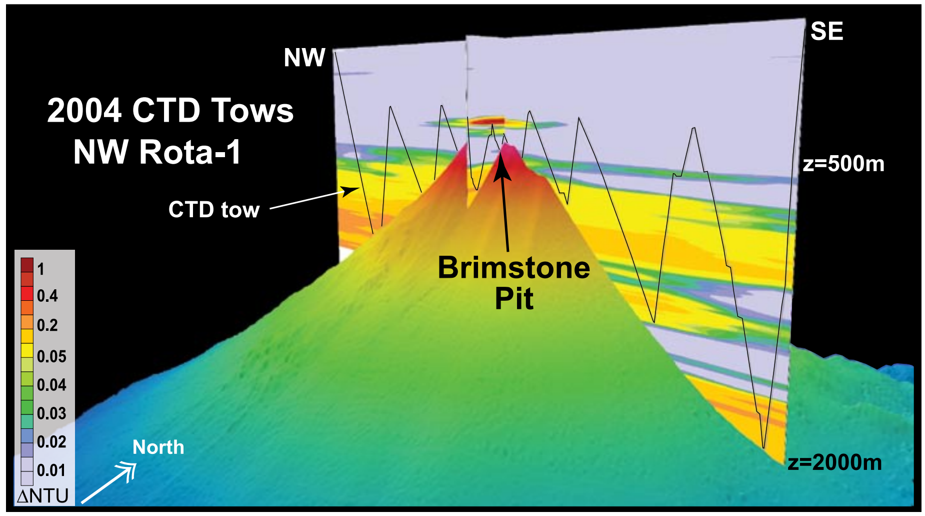


Figure 5. Two-dimensional CTD "tow-yo" profiles of hydrothermal plume turbidity superimposed on three-dimensional bathymetry of NW Rota-1. The longer of the two tows extends more than 7 km from southeast to northwest. Color bar on left is in nephelometric turbidity units (NTU) above background, an optical measurement of the particles in the water. The plume lying above the summit is the eruption plume of Brimstone Pit. The deeper plumes on the flanks are caused by suspended volcaniclastic material originating from Brimstone Pit.

## Liquid Carbon Dioxide at 1600 m

The third unique site was discovered in 2003–2004 near the summit of a small volcano called NW Eifuku (Figure 4). At a depth of 1605 m on the southern flank of the volcano, globular, milky gray droplets of liquid $CO_2$ (Figure 6f, inset) rise through white "smoke" of $CO_2$-rich fluid (Lupton et al., 2006) (Figure 6f). Liquid $CO_2$ was first discovered in the Okinawa Trough in 1989, where it is associated with blankets of thick sediment (Sakai et al., 1990). However, the NW Eifuku site is the first observation of liquid $CO_2$ emission from a bare-rock basaltic system in an active magmatic arc setting (Lupton et al., 2006). Temperature measurements and analyses of the white-smoker fluids (~ 105°C) showed that they are within the supercritical portion of the $CO_2$ phase diagram. These fluids contain the highest concentration of $CO_2$ yet measured at any seafloor hydrothermal vent system (Lupton et al., 2006).

Dense colonies of mussels occur within 100 m of the site (Figure 6g, top), and thick mats of orange-red oxyhydroxide lie further out on the periphery (Figure 6g, lower left inset). In 2004, we observed numerous clumps of filamentous microbial material rolling down the slopes, probably due to the very high primary production of the mats on the steep slopes. The combined presence of almost pure liquid $CO_2$ and extensive mussel communities living in low-pH waters (Figure 6g, lower right inset) produced by the $CO_2$-dominated hydrothermal system at NW Eifuku make this an important natural laboratory, especially for the controversial topic of carbon sequestration in the ocean and for the impact of ocean acidification on marine ecosystems.

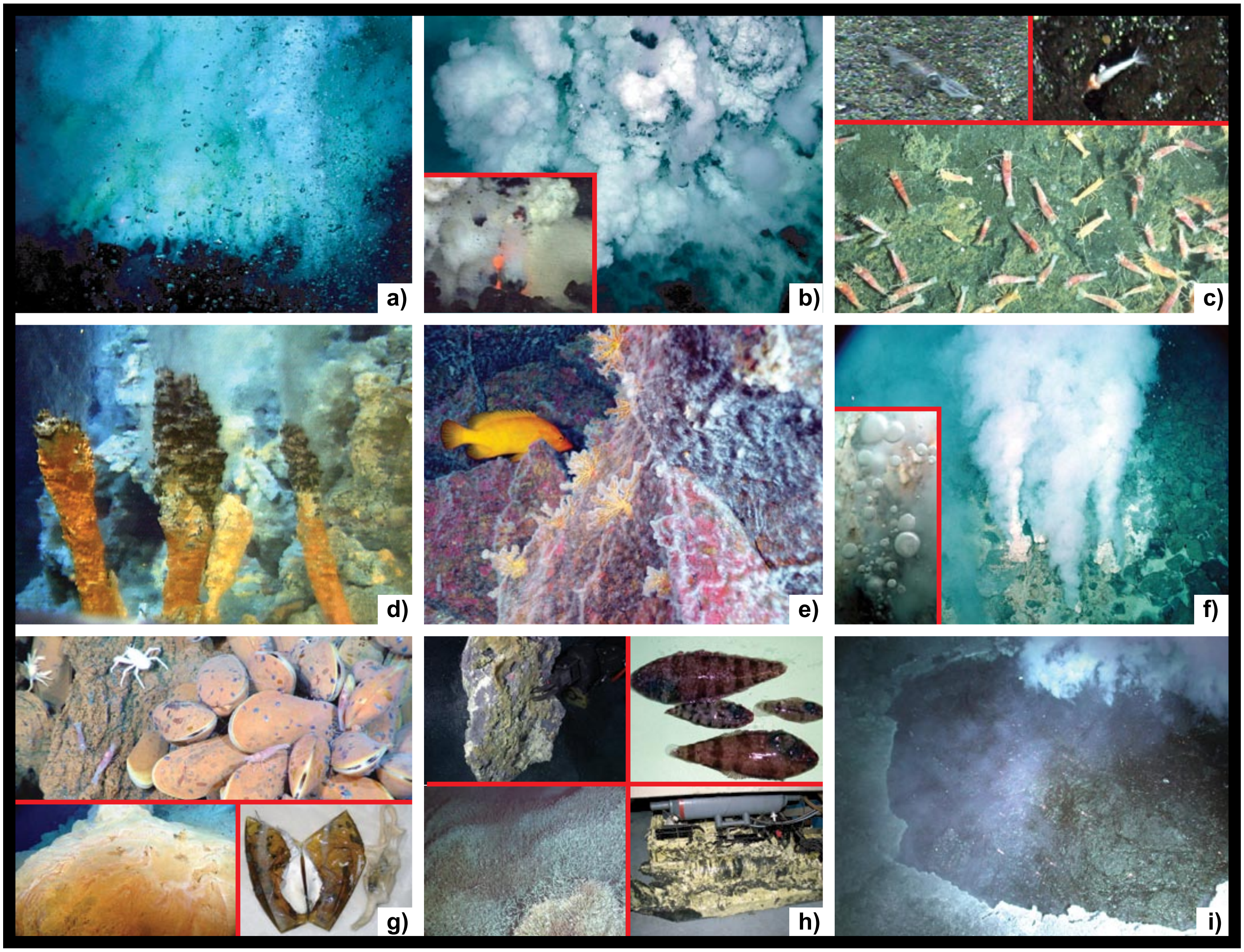


Figure 6. The underwater images of Mariana volcanoes shown here were taken by digital still cameras on remotely operated vehicles *ROPOS* and *Jason 2*. Figure 3 shows locations of volcanoes, and Figure 4 shows bathymetry. **(a)** NW Rota-1 eruption. Gases exsolving from lava that has just erupted on the seafloor at Brimstone Pit. Sheets of $CO_2$ bubbles are evident in advance of the surging hot lava, and bright-yellow, sulfur-rich plumes originate from the lava itself. The $CO_2$ bubbles "pulsed" whereas the sulfur plumes were directly correlated to lava extrusion. Image is ~ 1.5 m across. **(b)** NW Rota-1 eruption. Example of the erupting volcanic vent of Brimstone Pit with abundant ash and degassing bombs falling out of the resulting volcanic plume. Image is ~ 2 m across. Inset: Video frame grab shows glowing red lava jetting out of the vent during the final dive at the site. Image is ~ 20 cm across. **(c)** NW Rota-1 volcano. Bottom panel: Close-up view of shrimp near the summit. The reason for the difference in color is not yet clear; however, one possibility is that the longer it has been since the shrimp last molted, the more material (could be sulfur or bacteria?) they accumulate on their carapaces. Image is ~ 50 cm across. Top panel: Carcasses of squid (left) and fish (right) lying on seafloor near summit of volcano, probably killed by the high amounts of sulfite in the volcanic plume. **(d)** East Diamante volcano. Small (~ 30-cm) actively venting spires on top of chimney in Black Forest vent field located on the eastern side of the cone complex within the caldera. The chimneys themselves are about 7-m tall. The fluids are venting at 242ºC and expelling gray, mineral-rich smoke into the ocean. **(e)** East Diamante volcano. Chemosynthetic microbial mats cover encrusting red algae and coral on volcanic cone. Hydrothermal vent and coral reef communities overlap in the depth range of approximately 188–205 m. Image is about 100-cm across. **(f)** NW Eifuku volcano, Champagne vent. The white-smoker chimneys are ~ 20-cm across and ~ 50-cm high, and venting fluids measure 103ºC. White flocculent mats and elemental sulfur coatings surround the chimneys, and liquid $CO_2$ droplets rise from the seafloor. Inset: Close-up of $CO_2$ droplets adhering to camera lens. **(g)** NW Eifuku volcano. Top panel: Vent mussels *Bathymodiolus* were so dense in some places on the slopes near the Champagne site that they obscured the bottom. The mussels are ~ 18 cm long. Galatheid crabs and shrimp graze on bacterial filaments on the mussel shells. Lower panel: At left, yellow and orange microbial mats form a "bioreactor" mound with a thin crust and small chimneys on top. The crusty outer coating acts as a thermal blanket to elevate the internal temperature from diffuse venting and help retain reduced microbial nutrients. This mound is approximately 1-m across. At right, the low-pH environment around the Champagne site causes the mussel shells to dissolve so fast upon death that the shell (the white material) is nearly gone before the clam meat (on right) decays. The brown organic cover protects the shell from dissolution while the mussel lives. **(h)** Daikoku and Nikko volcanoes. Lower left: Extensive tracts of tubeworms include a diverse assemblage of other biota (white crabs, flatfish, and shrimps) near summit of Nikko cone. Image is > 3 m across in foreground. Upper left: *Jason 2* holds up a large piece of sulfur crust (~ 50-cm across), common at both Daikoku and Nikko volcanoes. Lower right: While trying to extract a sample of the sulfur crust, *Jason 2* inadvertently broke through the crust, and molten sulfur enveloped the lower part of the vehicle. Upper right: Four tonguefish samples. The larger fish from Nikko (~ 10-cm long) are almost twice as long as their counterparts on Daikoku. **(i)** Daikoku volcano. Convecting pool of black liquid sulfur near summit. Area shown is ~ 4.5-m long and ~3-m wide. The crust (foreground) is formed by contact of liquid (187°C) sulfur with seawater, but vigorous degassing at back of pool continuously re-ruptured the crust, creating a standing wave its surface.

### The Molten Sulfur Ponds of Daikoku and Nikko Volcanoes

Daikoku is a large cone constructed over an older, elongate caldera that has been almost entirely filled by subsequent volcanic activity (Figure 4). The cone rises over 700 m from its base at 1050-m depth and has a 200-m-diameter summit crater that is breached on the northwest. High concentrations of sulfur in the hydrothermal plume here suggested a location where chemosynthetic activity could thrive. The initial dives in 2004 and 2005 found extensive diffuse venting where tubeworms and associated fauna colonized around rock outcrops, plus a dense population of small snails and a new species of flatfish (Dower et al., 2006) on the sedimented summit just outside the breach in the crater wall (Figure 6h, upper right). This crater's slope was paved with sulfur crusts over a large area (Figure 6h, upper left). In addition, a whitish, slowly rising effluent cloud rose out of a deep pit crater within the larger crater, somewhat reminiscent of the plume from Brimstone Pit observed in 2004, but much less intense.

Nikko is the northernmost hydrothermally active Mariana arc volcano visited during the Submarine Ring of Fire expeditions. Its form is similar to Daikoku, although it has two large cones rising more than 600 m from an older caldera base (Figure 4). An intense plume over the summit of the western cone was greatly enriched in Fe, $Mn^{-3}$, $^{3}He$, $CO_2$, and elemental sulfur (Resing et al., 2003a). Dives in 2005 with the *Hyper-Dolphin 3000* ROV into the 250–290-m-diameter summit crater (crater floor averages 460-m deep) discovered a wonderland of extremely dense chemosynthetic life covering most of the crater floor and walls and extending in some places beyond the crater onto the upper flank (Nakamura et al., 2006) (Figure 6h, lower left). The astonishing density of tubeworms, crabs, flatfish, and other organisms is probably supported both by direct seepage of diffuse fluids from below and by gas-rich clouds emitted by numerous vents around the inner crater walls and temporarily trapped within the crater. This volcanic "fog" reduced visibility to a meter or less over large areas of the crater floor. Extensive sulfur crusts, flows, and ornamented chimneys covered the crater floor and the upper flank of the summit. The real surprise was the first observation of liquid sulfur being expelled from a submarine volcano. In 2005, we filmed rivulets of sulfur pouring from a small vent, and in 2006, we found a much larger crusted-over sulfur pond on the upper flank of the southern summit area (Nakamura et al., 2006). The *Jason 2* ROV accidentally broke through the sulfur crust and was "dipped" in molten sulfur, returning to the surface with almost 30 kg of solid native sulfur adhering to its frame (the dive had to be aborted) (Figure 6h, lower right).

We were equally surprised on our return to Daikoku volcano in 2006. More focused venting was found slightly deeper than during the 2004 and 2005 dives, and with further exploration, we discovered a large open pond of liquid sulfur (Figure 6i). Although cold seawater (~ 11°C) froze the surface of the molten sulfur pool (measured temperature of 187°C), vigorous degassing continuously ruptured the crust, which created pulsating waves on the pond's surface.

These sulfur-rich summits of Nikko and Daikoku appear to host remarkable habitats characterized by an unusually high density of chemosynthetic communities. Extensive sulfur deposits were also found on several other Mariana (Embley et al., 2006) and Kermadec (Embley et al., 2005) arc volcanoes. New research directions concerning the concentration of elemental sulfur and its effect on chemosynthetic life at these and other arc volcanoes have emerged from these discoveries.

## IMPORTANCE OF ARC EXPLORATIONS

The sites discussed above offer unparalleled, and in some cases unique, opportunities to observe and monitor extremes in submarine volcanic and hydromagmatic processes. For example, the eruption at NW Rota-1 was the first oppor-

> The sites discussed...offer unparalleled, and in some cases unique, opportunities to observe and monitor extremes in submarine volcanic and hydromagmatic processes.

tunity to observe and sample an active deep-sea eruption site. Event-response efforts focused on the MOR over the past 15 years have provided new insights into the geologic and biologic processes associated with eruptive diking events (Cowen et al., 2004; Delaney et al., 1998; Embley et al., 1995), but these very short-lived events have still not yet been observed directly.

Studies of arc volcanoes could also have broader impacts on societally relevant issues. Recent studies have found that anthropogenic $CO_2$ is measurably increasing the acidity of the upper ocean, and extrapolations show that this increase may soon have potentially serious consequences for the viability of plankton, corals, and other marine organisms that secrete calcium carbonate (Feely et al., 2004). However, little is known about the response of marine life to this increasing acidity. Many of the sites (most notably NW Eifuku) offer the possibility of controlled experiments in a natural laboratory to study these effects over time.

These and other examples illustrate how an increased pace of ocean exploration can improve the science base both for understanding the role of the ocean in the global carbon cycle and for making informed decisions about the use of both living and nonliving ocean resources. Ocean research in the United States has, since the 1970s, been largely driven by focused, hypothesis-driven research funded by the National Science Foundation. The record of discoveries is impressive (National Research Council, 2000). However, the unexpected phenomena discovered during the Submarine Ring of Fire program alone, in just a few years, confirms the potential of this twenty-first century wave of ocean exploration as a mission complementary to hypothesis-driven research, particularly at undersampled active plate boundaries.

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## REFERENCES

Baker, E.T., G.J. Massoth, C.E.J. de Ronde, J.E. Lupton, and B.I.A. McInnes. 2002. Observations and sampling of an ongoing subsurface eruption of Kavachi volcano, Solomon Islands, May 2000. *Geology,* 30:975–978.

Bird, P. 2003. An updated digital model of plate boundaries. *Geochemistry, Geophysics, Geosystems,* 4(3):doi:10.1029/2001GC000252.

Bloomer, S.H., R.J. Stern, and N.C. Smoot. 1989. Physical volcanology of the submarine Mariana and Volcano Arcs. *Bulletin of Volcanology* 51:210–224.

Butterfield, D.A., R.W. Embley, W.W. Chadwick Jr., J.E. Lupton, K. Nakamura, B. Takano, C. de Ronde, J. Resing, S. Bolton, and J. Baross. 2006. Up-close fluid sampling at a deep submarine lava eruption. *Eos Transactions, American Geophysical Union, Fall Meeting Supplement,* 87(52), Abstract V13C-07.

Cowen, J.P., E.T. Baker, and R.W. Embley. 2004. Detection and response to Mid-Ocean Ridge magmatic events: Implications for the subsurface biosphere. Pp. 227–243 in *The Subseafloor Biosphere at Mid-Ocean Ridges*, W.S.D. Wilcock, C. Cary, E. DeLong, D.S. Kelley, and J.A. Baross, eds, American Geophysical Union Monograph 144, Washington, DC.

de Ronde, C.E J., E.T. Baker, G.J. Massoth, J.E. Lupton, I.C. Wright, R.A. Feely, and R.R. Greene. 2001. Intra-oceanic subduction-related hydrothermal venting, Kermadec volcanic arc. *Earth and Planetary Science Letters.* 193:359–369.

de Ronde, C.E J., E.T. Baker, G.J. Massonth, J.E. Lupton, I.C. Wright, R.J. Sparks, S.C. Bannister, M.E. Reyners, S.L. Walker, R.R. Greene, and others. 2007. Submarine hydrothermal activity along the mid-Kermadec Arc, New Zealand: Large-scale effects on venting. *Geochemistry, Geophysics, Geosystems*, doi:10.1029/2006GC001495.

de Ronde, C.E.J., K. Faure, C.J. Bray, D.A. Chappel, and I.C. Wright. 2003. Hydrothermal fluids associated with seafloor mineralization at two southern Kermadec arc volcanoes, offshore New Zealand. *Mineralium Deposita* 38:217–233.

de Ronde, C.E.J., J.R. Hein, R.W. Embley, and R.J. Stern. 2004. Hydrothermal mineralization along the volcanically active Mariana Arc. *Eos Transactions, American Geophysical Union, Fall Meeting Supplement,* 85(47):Abstract V54A-04.

Delaney, J.R., D.S. Kelley, M.D. Lilley, D.A. Butterfield, J.A. Baross, W.S.D. Wilcock, R.W. Embley, and M. Summit. 1998. The quantum event of crustal accretion: Impacts of diking at Mid-Ocean Ridges. *Science* 281:222–230.

Dower, J., V. Tunnicliffe, J. Tyler, K. Juniper, K. Stevens, A. Kouris, and B. Takano. 2006. Observations of flatfish "spas" from three hydrothermally active seamounts in the Mariana Arc. *Eos Transactions, American Geophysical Union, Fall Meeting Supplement*, 87(52):Abstract V32A-05.

Embley, R.W., E.T. Baker, W.W. Chadwick Jr., J.E. Lupton, J.E. Resing, G.J. Massoth, and K. Nakamura. 2004. Explorations of Mariana Arc volcanoes reveal new hydrothermal systems. *Eos Transactions, American Geophysical Union* 85(4):37.

Embley, R.W., W.W. Chadwick Jr., E.T. Baker, D.A. Butterfield, J.A. Resing, C.E.J. de Ronde, V. Tunnicliffe, J.E. Lupton, S.K. Juniper, K.H. Rubin, and others. 2006. Long-term eruptive activity at a submarine arc volcano. *Nature* 441:494–497.

Embley, R.W., W.W. Chadwick Jr., I.R. Jonasson, D.A. Butterfield, and E.T. Baker. 1995. Initial results of the rapid response to the 1993 CoAxial event: Relationships between hydrothermal and volcanic processes. *Geophysical Research Letters* 22:143–146.

Embley, R.W., C.E.J. de Ronde, G.J. Massoth, I.C. Wright, D.A. Butterfield, M.R. Clark, W.W. Chadwick Jr., J.E. Lupton, A. Malahoff, A.A. Rowden, and others. 2005. Hydrothermal systems on Kermadec arc volcanoes revealed by PISCES V submersible dives. *Eos Transactions, American Geophysical Union, Fall Meeting Supplement,* 86(52):Abstract V44A-04.

Embley, R.W., and Submarine Ring of Fire Investigators. 2006. Geological framework of Mariana hydrothermal systems. *Eos Transactions, American Geophysical Union, Fall Meeting Supplement,* 87(52):Abstract OS34A-01.

Feely, R.A., C.L. Sabine, K. Lee, W. Berelson, J. Kleypas, V.J. Fabry, and F.J. Milllero. 2004. Impact of anthropogenic $CO_2$ on the $CaCO_3$ system in the oceans. *Science* 305(5682):362–366.

Fryer, P. 1996. Evolution of the Mariana convergent plate margin system. *Reviews of Geophysics* 34:89–125.

Fryer, P., J.B. Gill, and M.C. Jackson. 1997. Volcanologic and tectonic evolution of the Kasuga seamounts, northern Mariana Trough: Alvin submersible investigations. *Journal of Volcanology and Geothermal Research* 79:277–311.

Glasby, G.P., K. Izasa, M. Yuasa, and A. Usui. 2000. Submarine hydrothermal mineralization on the Izu-Bonin Arc, south of Japan: An overview. *Marine Georesources & Geotechnology* 18(2):141–176.

Ishibashi, J.-I., and T. Urabe. 1995. Hydrothermal activity related to arc-backarc magmatism in the western Pacific. Pp. 451–495 in *Backarc Basins: Tectonics and Magmatism*, B. Taylor ed., Plenum Press, New York.

Karig, D.E. 1971. Origin and development of marginal basins in the western Pacific. *Journal of Geophysical Research* 76:2,542–2,561.

Limen, H., K. Juniper, V. Tunnicliffe, and M. Clement. 2006. Benthic community structure on two peaks of an erupting seamount: Northwest Rota-1 Volcano, Mariana Arc, western Pacific. *Cahiers de Biologie Marine* 47:457–463.

Lupton, J.E., D.A. Butterfield, M. Lilley, L. Evans, K.-I. Nakamura, J. Resing, R. Embley, E. Olson, G. Proskurowski, W. Chadwick Jr., E. Baker, C. de Ronde, K. Roe, R. Greene, and G. Lebon. 2006. Submarine venting of liquid carbon dioxide on a Mariana Arc volcano. *Geochemistry, Geophysics, and Geosystems,* doi:10.1029/2005GC001152, 002006.

Massoth, G.J., R.J. Arculus, E.T. Baker, D.A. Butterfield, W.W. Chadwick Jr., B.W. Christenson, C.E. J. de Ronde, R.W. Embley, L. Evans, K. Faure, and others. 2005. Plume-vent fluid connections along the Tonga-Kermadec Arc. *Eos Transactions, American Geophysical Union, Fall Meeting Supplement,* 86(52):Abstract V51C-1495.

McMurtry, G.M., P. Sedwick, P. Fryer, D.L. VonderHaar, and H.-W. Yeh. 1993. Unusual geochemistry of hydrothermal vents in submarine arc volcanoes: Kasuga seamounts, northern Mariana arc. *Earth and Planetary Science Letters* 114:517–528.

Nakamura, K., R.W. Embley, W.W. Chadwick Jr., D. Butterfield, B. Takano, J.A. Resing, C.E.J. de Ronde, M. Lilley, J.E. Lupton, and S.G. Merle. 2006. Liquid and emulsified sulfur in submarine solfatara fields of two northern Mariana Arc volcanoes. *Eos Transactions, American Geophysical Union, Fall Meeting Supplement,* 87(52):Abstract V23B-0608.

National Research Council. 2000. *50 Years of Ocean Discovery: National Science Foundation, 1950–2000.* Washington, DC.

Norris, R.A., and R.H. Johnson. 1969. Submarine volcanic eruptions recently located in the Pacific by SOFAR hydrophones. *Journal of Geophysical Research* 74:650–664.

Resing, J.A., G. Lebon, E.T. Baker, J.E. Lupton, R.W. Embley, G.J. Massonth, W.W. Chadwick Jr., and C.E.J. de Ronde. In press. Venting of acid-sulfate fluids in a high-sulfidation setting at NW Rota-1 submarine volcano on the Mariana Arc. *Economic Geology.*

Resing, J.A., G. Lebon, E.T. Baker, J.E. Lupton, K. Nakamura, G. Massoth, and R.W. Embley. 2003a. Geochemical characterization of hydrothermal plumes above hydrothermally active volcanos on the Mariana arc. *Eos Transactions, American Geophysical Union, Fall Meeting Supplement* 84(46):Abstract T32A-0915.

Resing, J.A., G.T. Lebon, E.T. Baker, J. E. Lupton, K. Nakamura, G. Massoth, and R.W. Embley. 2003b. Geochemical characterization of hydrothermal plumes above hydrothermally active volcanos on the Mariana Arc. *Eos Transactions of the American Geophysical Union, Fall Meeting Supplement,* 84(46):Abstract T32A-0915.

Sakai, H., T. Gamo, E.-S. Kim, M. Tsutsumi, T. Tanaka, J. Ishibashi, H. Wakita, M. Yamano, and T. Oomori. 1990. Venting of carbon dioxide-rich fluid and hydrate formation in Mid-Okinawa Trough backarc basin. *Science* 248:1,093–1,096.

Smithsonian Institution. 2001. Ahyi. *Bulletin of the Global Volcanism Network* 26(5). Available online at: http://www.volcano.si.edu/reports/bulletin/ (accessed December 9, 2007).

Stern, R.J. 2002. Subduction Zones. *Reviews of Geophysics,* 40:doi:10.1029/2001RG000108.

Stern, R.J., M.J. Fouch, and S.L. Klemperer. 2003. An overview of the Izu-Bonin-Mariana subduction factory. Pp. 175–222 in *Inside the Subduction Factory*, J. Eiler and M. Hirschmann, eds, American Geophysical Union Monograph 138, Washington, DC.

Stoffers, P., T.J. Worthington, U. Schwarz-Schampera, M.D. Hannington, G.J. Massoth, R. Hekinian, M. Schmidt, L.J. Lundsten, L.J. Evans, R. Vaiomo'unga, and T. Kerby. 2006. Submarine volcanoes and high-temperature hydrothermal venting on the Tonga Arc, southwest Pacific. *Geology* 34:453–456.

Stuben, D., S.H. Bloomer, N.E. Taibi, Th. Neumann, V. Bendel, U. Puschel, A. Barone, A. Lange, W. Shiying, L. Cuizhong, and Z. Deyu. 1992. First results of study of sulfur-rich hydrothermal activity from an island-arc environment: Esmeralda Bank in the Mariana arc. *Marine Geology* 103:521–528.

Tarasov, V.G., A.V. Gebruk, A.N. Mironov, and L.I. Moskalev. 2005. Deep-sea and shallow-water hydrothermal vent communities: Two different phenomena? *Chemical Geology* 224:5–39.

Truesdale, F.A., R.B. Moore, M.K. Sako, S. Koyanagi, P.F. Cervelli, and J.T. Camacho. 2006. Eruption of Anatahan, CMNI: Chronology, volcanology and deformation. *Journal of Volcanology and Geothermal Research* 146(1–3):184–207.