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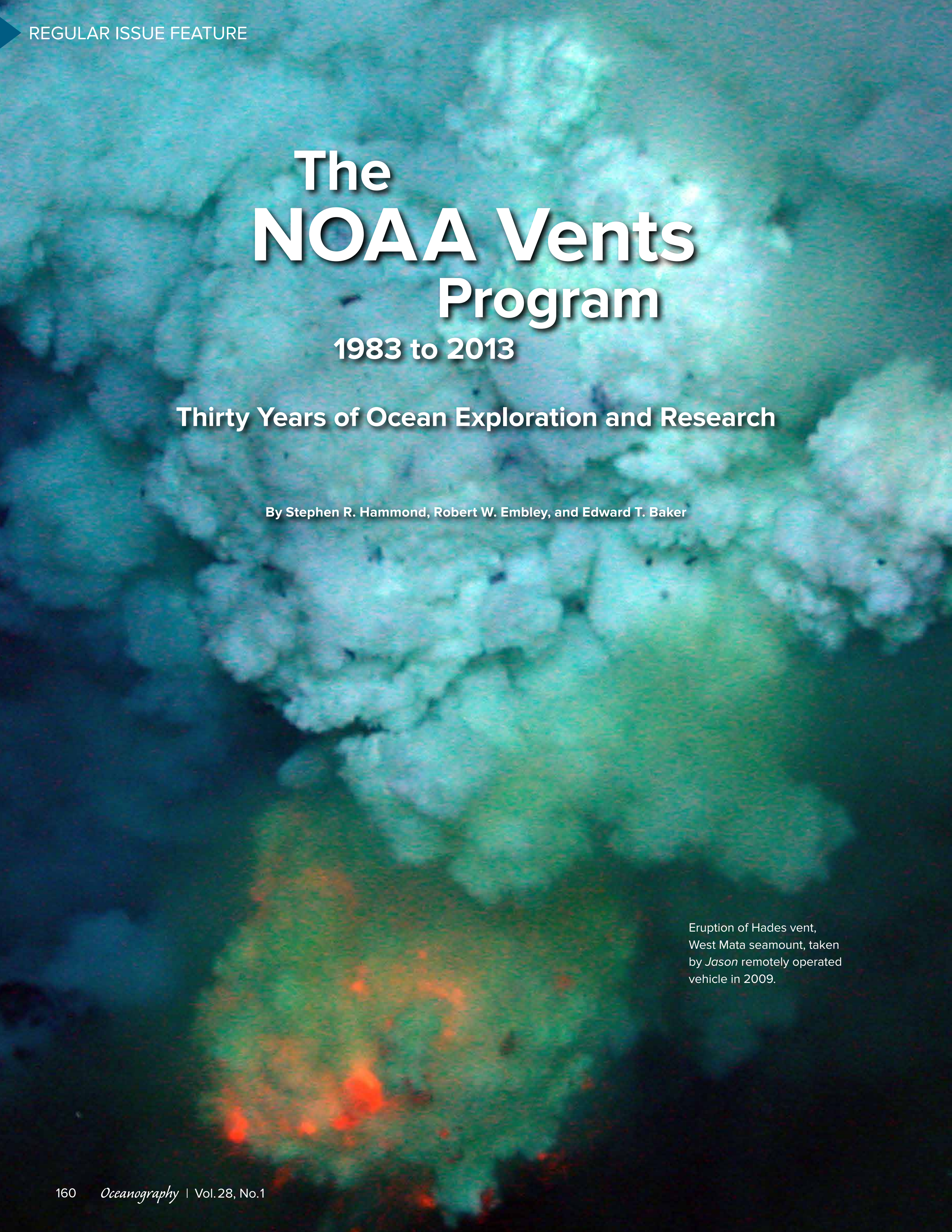
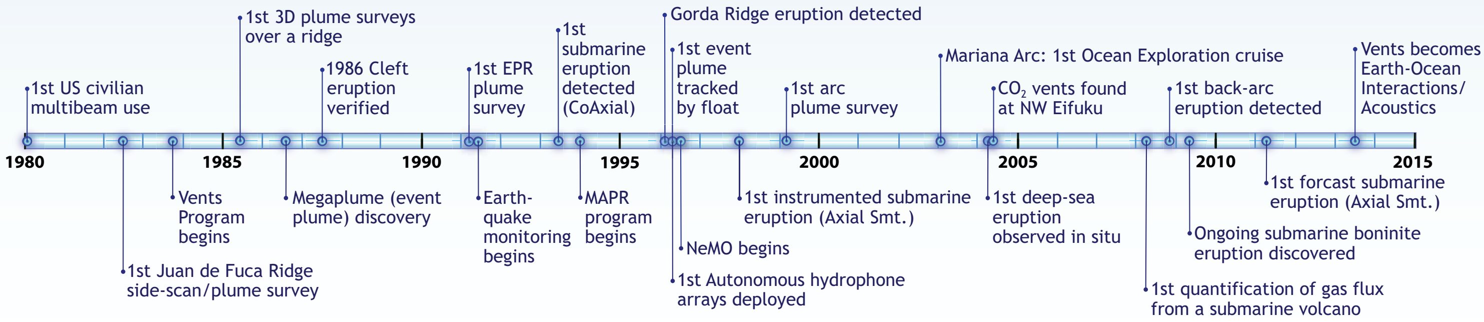
The NOAA Vents Program 1983 to 2013

Thirty Years of Ocean Exploration and Research

By Stephen R. Hammond, Robert W. Embley, and Edward T. Baker



Eruption of Hades vent, West Mata seamount, taken by *Jason* remotely operated vehicle in 2009.



ABSTRACT. Two seminal advances in the late 1970s in science and technology spurred the establishment of the National Oceanic and Atmospheric Administration (NOAA) Vents Program: the unexpected discovery of seafloor vents and chemosynthetic ecosystems on the Galápagos Spreading Center (GSC), and civilian access to a previously classified multibeam mapping sonar system. A small team of NOAA scientists immediately embarked on an effort to apply the new mapping technology to the discovery of vents, animal communities, and polymetallic sulfide deposits on spreading ridges in the Northeast Pacific Ocean. The addition of interdisciplinary colleagues from NOAA's cooperative institutes at Oregon State University and the University of Washington led to the creation of the Vents Program in 1983 at NOAA's Pacific Marine Environmental Laboratory. Within a decade, Vents surveyed the entire Juan de Fuca and Gorda Ridges for hydrothermal activity, discovered the first "megaplume," established multiyear time series of hydrothermal fluid measurements, and, for the first time, acoustically detected and responded to a deep-sea volcanic eruption. With this experience, and partnering with researchers from around the globe, Vents expanded to exploration along the East Pacific and GSC divergent plate boundaries. In 1999, the Vents Program embarked on systematic surveys along volcanic arcs and back-arc basins of the Mariana and Kermadec-Tonga subduction zones. For three decades, the Vents Program focused on understanding the physical, chemical, and biological environmental consequences of global-scale processes that regulate the transfer of heat and mass from Earth's hot interior into the ocean. As the fourth decade began, the Vents Program was restructured into two new programs, Earth-Ocean Interactions and Acoustics, that together continue, and broaden, the scope of Vents' pioneering ocean exploration and research.

INTRODUCTION

The 1977 discovery of deep-sea hydrothermal venting and its associated animal communities (Corliss et al., 1979) changed, in a moment, the relationship between researchers and the ocean floor. Before this discovery at the Galápagos Spreading Center (GSC), marine geologists and chemists focused predominantly on questions of broad spatial and temporal scale: plate movements, crustal properties, and sediment geochemistry. Within the span of a research cruise, the deep sea acquired a human dimension. Fundamental geological and biological processes could be studied during the range and duration of a single submersible dive. Marine biologists founded an entirely unanticipated discipline. The GSC discoveries, along with the discovery of "black smokers" on the East Pacific Rise (EPR) in 1979, quickly became the impetus for collaborative national and international studies of spreading centers throughout the world ocean, an excitement that continues unabated today (Figure 1). In this article, we trace the three-decade development and impact of one program whose work spans almost the entire history of seafloor hydrothermal discovery and research.

Nearly concurrent with the GSC discoveries, the National Oceanic and Atmospheric Administration (NOAA) and the Office of Naval Research had the prescience to install the first US non-classified multibeam bathymetric sonar on the *Surveyor*, one of NOAA's global-class research vessels. In 1980, NOAA's National Ocean Survey (now Service) began the first systematic, high-resolution bathymetric mapping of seafloor spreading centers. At NOAA's Pacific Marine Environmental Laboratory (PMEL), interest in the Northeast Pacific ridges began with cruises of opportunity in 1980–1983 that mapped ridge axial morphology, petrology, and tectonic features (Malahoff et al., 1982; Fornari et al., 1983) and found evidence of hydrothermal venting in near-bottom waters (Massoth et al., 1982) over the Juan de Fuca and Gorda Ridges (Figure 2). During a span of five years, NOAA systematically mapped the Northeast Pacific ridges and their intervening fracture zones (e.g., Malahoff et al., 1981). Relative to the best maps previously available, the new maps revealed intriguing structural complexities. The spreading ridges were revealed as a series of offset segments, and the fracture zones were found to have a multiplicity of fault zones and en echelon pull-apart basins. One of the most interesting discoveries was that of an 8 km × 3 km caldera at the summit of the large volcano that dominates one of the four segments of the Juan de Fuca Ridge (JdFR). Now familiarly known as Axial Seamount, it is the youngest in a string of large submarine volcanoes, the Cobb-Eickelberg Seamount Chain, which extends westward onto the Pacific plate.

In 1982, a collaborative expedition between NOAA and academic researchers surveyed the JdFR using a new deep-towed digital 30 kHz side-scan sonar system (Crane et al., 1985). Thermistor arrays suspended below the side-scan unit detected several hydrothermal plumes along the ridge. This and other information (e.g., Normark et al., 1982) enabled discoveries of active hydrothermal systems along each of the surveyed JdFR segments during the first *Alvin* submersible dives in the Northeast Pacific in 1984 (Figure 2).

ESTABLISHING THE NOAA VENTS PROGRAM

Initial studies of the hydrothermal vent fluids sampled at the GSC and the EPR concluded that those discharges must be pervasive along the global network of seafloor spreading centers, and thus a fundamental contributor to the ocean's geochemical cycle (Edmond et al., 1979). These fluids introduce ocean nutrients such as iron and sulfur compounds, global tracers such as ^3He, and biologically important gases such as carbon dioxide (CO_2), methane, and hydrogen. Widespread scientific attention was immediately focused on the chemosynthetically and microbially sustained ecosystems that live exclusively in proximity to both the warm and hot chemical-rich hydrothermal vent fluids. Another prominent early interest in hydrothermal vents was the mineral resource potential of the often spectacular chimney-like structures and mounds that form when dissolved metals in hot hydrothermal fluids precipitate as they exit vent orifices. In addition to the usually predominant sulfides of iron, copper, and zinc, some chimneys included appreciable quantities of more valuable elements, such as gold and silver.

These discoveries provided an unambiguous opportunity for NOAA, established with the overarching goal of being the United States stewardship agency for Earth's ocean. This responsibility requires an understanding of natural ocean processes and their effects on marine life and resources, both biological and mineralogical. Consequently, in 1983, NOAA established the interdisciplinary team of ocean scientists that soon became known as the Vents Program. (In an unusual break from government tradition, "Vents" has always been simply a descriptor, not an acronym.) Its mission was to systematically explore, discover, and, ultimately,

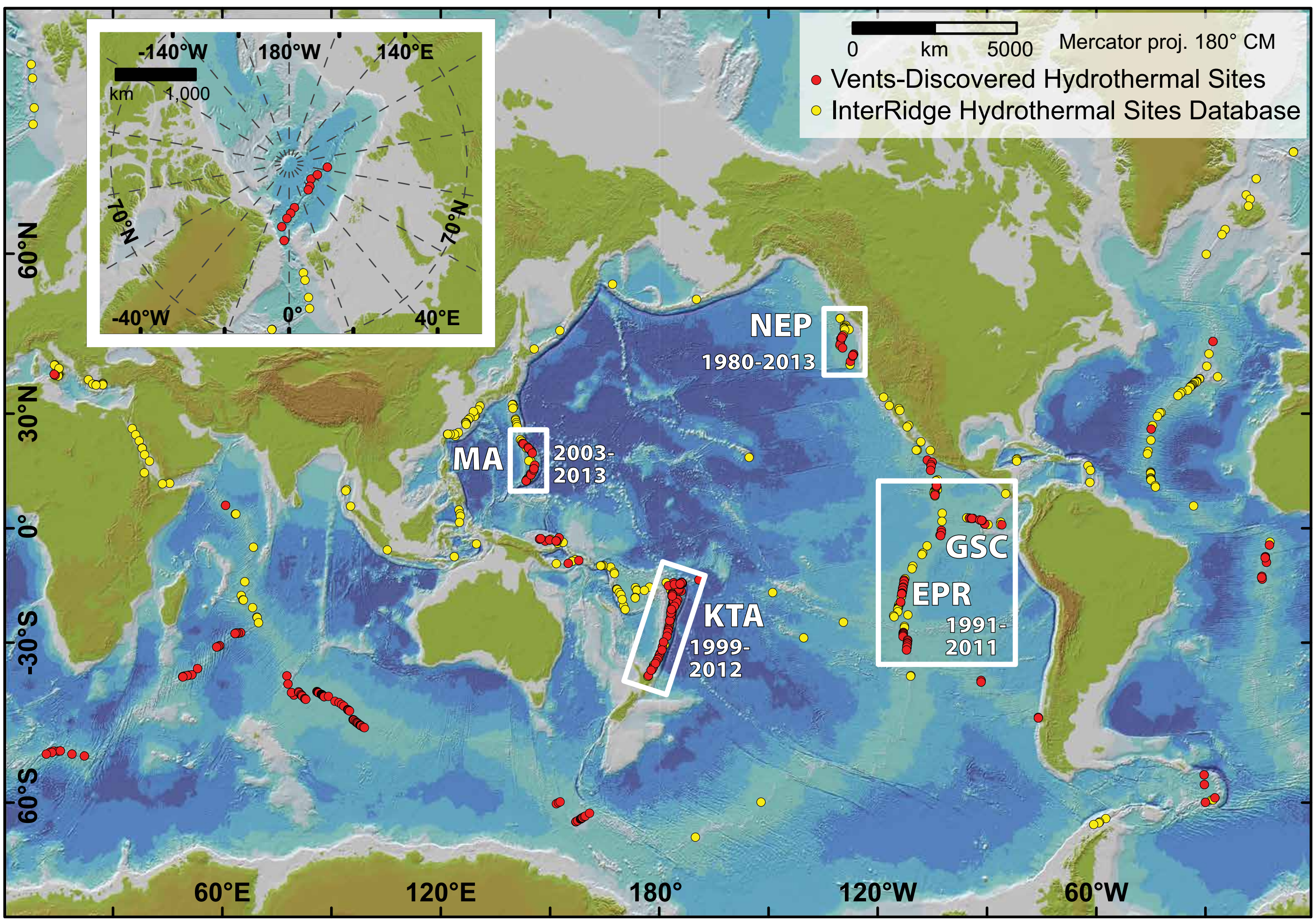


FIGURE 1. Confirmed (visually) and inferred (from plume data) vent locations from the InterRidge database. About 50% (red circles) of all sites were discovered with National Oceanic and Atmospheric Administration (NOAA) Vents Program participation, and about half of those were found by various collaborators using Vents Miniature Autonomous Plume Recorders (MAPRs) deployed on conductivity-temperature depth instruments (CTDs), dredges, rock cores, and other deep-towed instruments. The white boxes indicate regions and time intervals of long-term research interest for Vents. NEP = Northeast Pacific. GSC = Galápagos Spreading Center. EPR = East Pacific Rise. KTA = Kermadec-Tonga arc. MA = Mariana arc.

characterize the environmental impacts of submarine volcanism and its associated hydrothermal activity on the ocean at scales from local to global.

With a mandate to build a pioneering oceanographic exploration and research program, NOAA set about creating an achievable and long-term program plan. The core team consisted of geological, geophysical, physical, and chemical oceanographers from PMEL, PMEL's cooperative institutes at Oregon State University (the Cooperative Institute for Marine Resources Studies) and the University of Washington (the Joint Institute for the Study of the Atmosphere and Ocean), and NOAA's Atlantic Oceanographic and Meteorological Laboratory. Additionally, the program also initiated critical, long-standing partnerships with ocean scientists from universities and governmental agencies, foreign and domestic.

Recognizing the scale of its mission, the Vents Program institutionalized several fundamental operating principals. One was the need to maintain an interdisciplinary approach in which scientific questions were to be designed by consensus and studied using complementary tools. Because the objectives were aimed at fundamental planetary-scale processes, the program required a phased, long-term (initially decadal, eventually multidecadal) operational approach. And finally, given the realities of governmental funding, it would be necessary to leverage the available resources. In the first decade, this strategy meant working in the Northeast Pacific on NOAA vessels. Later, it meant building collaborations with National Science Foundation (NSF) investigators and international researchers with access to their own ships and other seagoing assets.

THE NORTHEAST PACIFIC: A NATURAL LABORATORY FOR MID-OCEAN RIDGE STUDIES

In 1984, the new Vents Program began systematically searching the water column above Northeast Pacific ridge axes for evidence of hydrothermal venting. Faced with the task of finding ship-sized vent fields scattered along hundreds of kilometers of oceanic ridges using the traditional oceanographic method of "drilling holes in the water" with a CTD (conductivity-temperature-depth) sensor package, the Vents explorers developed a new technique. Two-dimensional views of hydrothermal plumes could be imaged by steaming the NOAA Ship *Discoverer* slowly forward above the axial zone of the Cleft segment of the JdFR while winching a sensor package up and down in the bottom few hundred meters of the water column (a now widely used technique commonly known

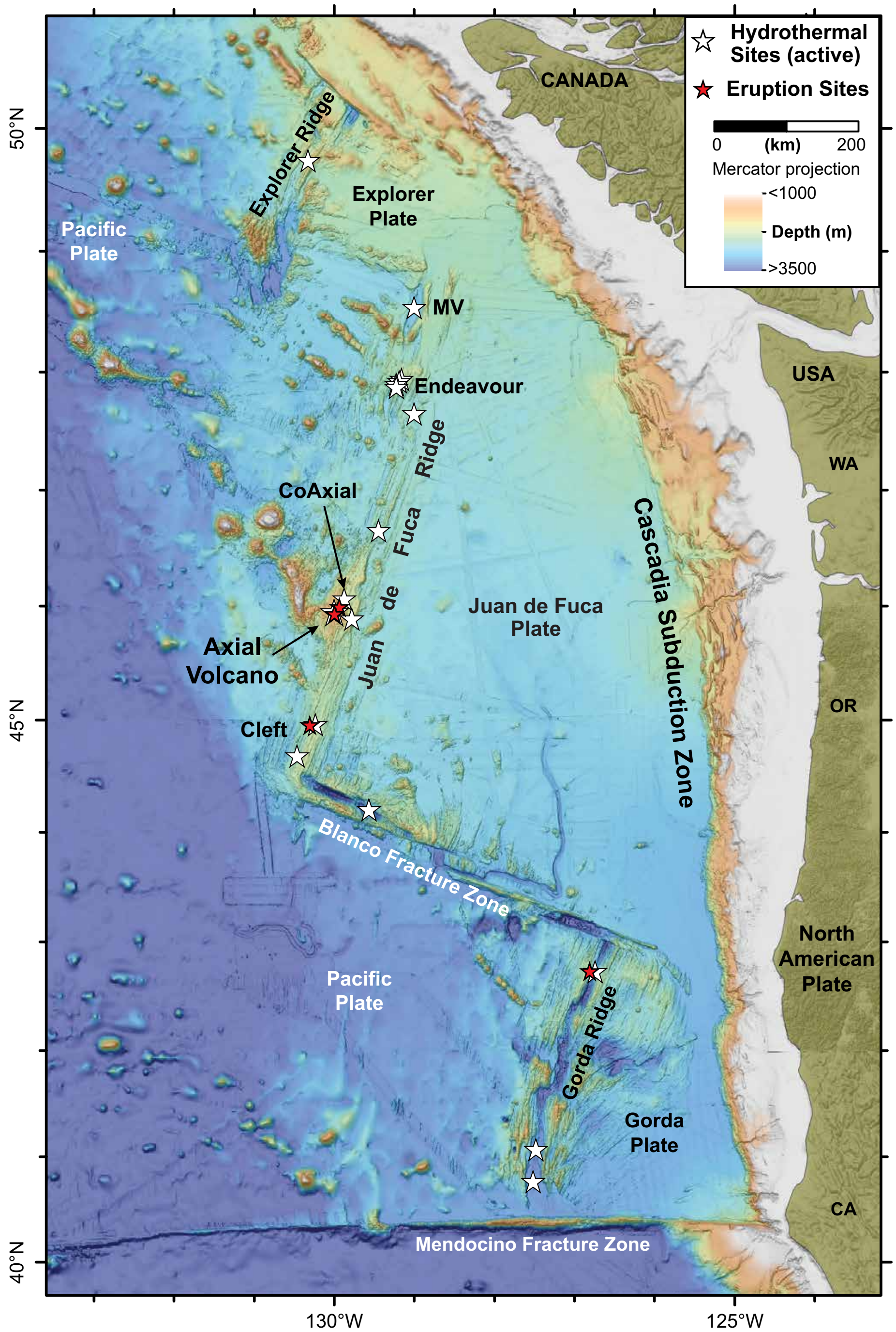


FIGURE 2. Northeast Pacific hydrothermal and submarine eruption sites. White stars are known hydrothermal sites, more than half of which were discovered by Vents researchers. Red stars indicate submarine eruptions detected and verified by the Vents Program. Some sites (e.g., Axial Seamount and Endeavour Segment) have multiple sites that cannot all be resolved at the scale of the map.

as a "tow-yo"; Baker et al., 1985). This strategy greatly improved the efficiency of hunting for new vent sites, which had previously depended on using geological evidence and intuition.

The mineral potential of hydrothermally emplaced sulfide deposits spurred interest in the Gorda Ridge. The only North American spreading center within the newly created (1984) US Exclusive Economic Zone, Gorda Ridge was chosen for coordinated exploration and research by the Gorda Ridge Task Force, staffed by scientists from NOAA, the United States Geological Survey, and Oregon State University. In 1985, water column profiles, multibeam sonar mapping, and dredging were used in one of the first systematic geologic and hydrothermal investigations of an entire first-order (i.e., bounded by fracture zones) spreading center segment.

Between 1984 and 1989, Vents mapped the overall distribution of venting on the entire JdFR with a series of along-axis tow-yos. New deep-tow side-scan sonar vehicles provided the highest resolution seafloor imagery and resolved volcanic features such as lava flows, fractures, faults, and craters. Complementary finer-scale explorations used a deep-sea camera system designed and constructed by the Engineering Development Division of PMEL. This advanced package included an integrated CTD, real-time low-light video, a 35 mm film camera, and high-resolution downward-looking and forward-looking (obstacle avoidance) sonars (Figure 3a). The manned submersibles *PISCES IV* and *Alvin* provided opportunities to further ground truth the sonar imagery and collect samples for biologic and chemical analyses. During this period, Vents began to develop a strong interdisciplinary team of collaborators, including specialists in basalt geochemistry, sulfide mineralization, gas chemistry, benthic ecology, and microbiology, to complement PMEL's in-house expertise (Johnson and Embley, 1990; Embley et al., 1994). These collaborations, a number of which have been active for decades, were a hallmark of Vents and a key factor in the success of the program.

Discovery of Megaplume Leads to Research on Seafloor Volcanic Events

In 1986, during a Vents survey for hydrothermal activity along the Cleft segment, scientists encountered an unanticipated hydrothermal plume some 20 km in diameter and more than 1 km thick. The signal was so unusual that the scientists on board initially thought their instruments were faulty! This, the first of a new class of plumes (Figure 4), was dubbed a "megaplume" or "event plume" to distinguish it from the familiar "chronic" plumes caused by (more or less) steady-state hydrothermal discharge. This serendipitous discovery was hypothesized to result from a seafloor-spreading event, that is, the magmatic injection of a vertical dike of magma at the mid-ocean ridge and subsequent eruption of lava onto the seafloor (Baker et al., 1987; Lavelle, 1995).

To test the eruption hypothesis, during 1987–1989, Vents deployed deep-towed camera surveys to search for recent lava flows. Shiny black lavas devoid of sediment, circumstantial evidence of a recent eruption, were imaged. But had this eruption occurred at the time of the event plume? Comparing the various camera and sonar tracks over the new lava zone revealed another important puzzle piece—some patches of the new lava imaged by the camera system were actually small pillow lava mounds that appeared on a few "swaths" of a 1987 multibeam map but not on the original map completed in 1982/1983 (Figure 3b). This evidence constrained the lava emplacement to between 1983 and 1987, and thus strongly favored the eruption hypothesis (Chadwick et al., 1991). Since 1986, an additional 14 confirmed event plumes have been observed at four separate eruption sites, (three in the Northeast Pacific and one in the Northeast Lau Basin), with less-conclusive evidence for event plumes at as many as five other locations around the world (Baker et al., 2011). The eruption hypothesis had been confirmed, but a convincing explanation of how such immediate and immense transfers of heat and chemicals from crust to ocean occur remains unknown (e.g., Rubin et al., 2012). This transference remains an important gap in our understanding of a fundamental Earth process: the creation of ocean crust by dike injections.

Concurrently with geological mapping at the eruption site (Figure 3c,d), Vents was building a unique multiyear database of plume and vent fluid chemistry to document changes that could be related to local geologic activity. A nine-year time series (1983–1991) of vent and plume samples from the Cleft segment yielded the first estimates of annual average flux of hydrothermal Mn and Fe (Massoth et al., 1994). Four years of vent fluid sampling (1988, 1990–1992) by submersibles and remotely operated vehicles (ROVs) yielded data indicating that the 1986 eruption caused a boiling event, which released vapor-enriched fluids through 1988 followed by a transition to brine-enriched fluids by 1990 (Butterfield and Massoth, 1994). This discovery was the first report of major changes in vent fluid composition over the time scale of years (Figure 5). Over time, this systematic process of vent fluid evolution was confirmed at other places where magmatic events were discovered.

New Technology Leads to Event Detection and Rapid Response

The event plume discovery was an important catalyst in creating a new perspective on ridge-crest processes. Ridges were now seen as dynamic environments, shaped not only by processes occurring on the time scale of seafloor spreading but also over days. Consequently, to fully understand the ocean environmental impacts of submarine volcanism would require detection and observation of episodic volcanic events while they are active. Because of the detection limits of land-based seismometers, the small earthquakes associated with submarine

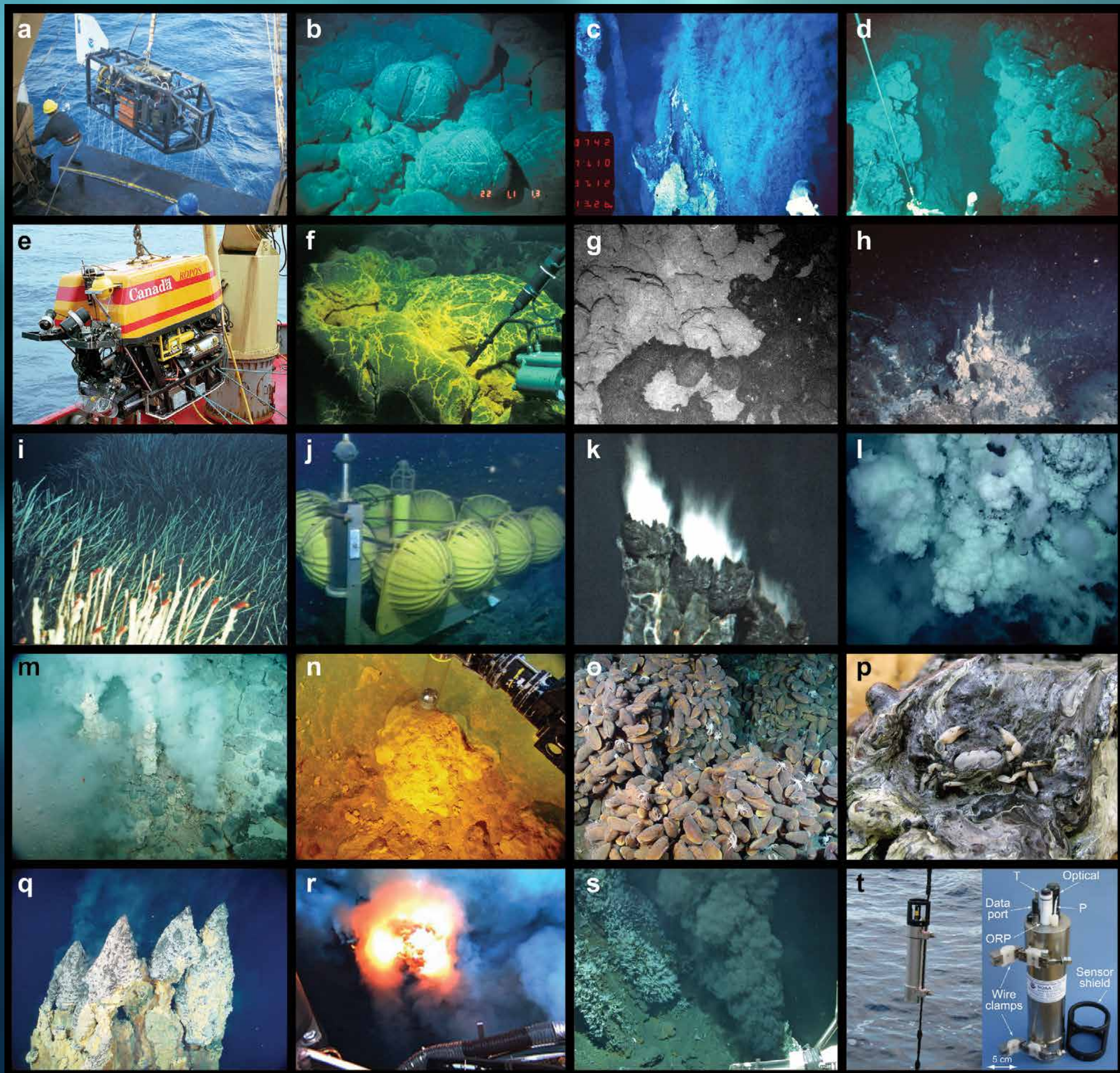


FIGURE 3. Selected photos of seafloor sites and instruments used by the Vents Program. (a) Towed camera system with real-time imagery developed by NOAA Pacific Marine Environmental Laboratory (PMEL) engineers and used from 1987 to 1995 to map hydrothermal systems on Juan de Fuca Ridge. (b) Presumptive lava mounds from the 1986 North Cleft eruption, photo taken with *Alvin*'s still camera. (c) Vigorous black smoker (Pipe Organ vent) at North Cleft, taken with *Alvin* submersible still camera. (d) Eruptive fissure, North Cleft, taken with *Alvin* still camera 1988. (e) *ROPOS* remotely operated vehicle (ROV) on deck of the NOAA Ship *Discoverer*, ~1992. (f) Vivid yellow microbial mats stained by iron precipitation, photographed by *ROPOS* about three weeks after an eruption in July 1993. (g) Black glassy lava from a 1996 Gorda Ridge eruption contrasts with older sediment-coated lavas, taken with Woods Hole Oceanographic Institution towed camera system. (h) First view of ASHES vent field on Axial Seamount, 1984 *Alvin* photograph. (i) Tubeworm field photographed in 1997 by *ROPOS* before its destruction during the 1998 eruption. (j) Pressure gauge and hydrophone package (VSM) stuck in 1998 lava flow, photographed by *ROPOS*. (k) El Guapo vent photographed by *Jason* ROV in Axial caldera; white color is from light reflected through boiling, vapor-rich fluids (~350°C). (l) One of the first observations of ash and gas plumes erupting from the submarine volcano NW Rota-1 (Mariana arc), photo by *Jason* ROV digital still camera. (m) Champagne vent with vigorous flow of supersaturated CO_2 fluid and liquid CO_2, NW Eifuku Seamount, Mariana arc, taken in 2004 by *ROPOS* digital still camera (DSC). (n) Thick carpet of iron-rich microbial mat being sampled from summit of NW Eifuku Seamount by *ROPOS* DSC in 2004. (o) Dense mussel beds near Champagne vent, NW Eifuku Seamount, taken in 2004 by *ROPOS* DSC. (p) Crab "fossilized" in elemental sulfur, Nikko Seamount, sampled by *Jason* ROV in 2006. (q) Five Towers vent field, shallowest black smoker (345 m) discovered to date, East Diamante Seamount, Mariana arc, *ROPOS* DSC photo 2004. (r) Explosive eruption of boninite lava at West Mata Seamount, NE Lau basin, *Jason* ROV photo, 2009. (s) A 360°C black smoker, Mata Ua Seamount, NE Lau basin, taken with *QUEST 4000* ROV digital still camera in 2012. (t) Miniature Autonomous Plume Recorder (MAPR) on cable and close-up of the instrument.

eruptions could only be detected by submarine hydrophones. In 1991, Vents was successful in its request to use military hydrophone data, and in 1993, the data began to be acquired in real time.

Amazingly, in June 1993, only a week after acquiring the real-time data link, a swarm of earthquakes was detected on the CoAxial segment, a little known section of the JdFR (Fox, 1995). Over the next 23 days, more than 676 events of magnitude M ≤4 were recorded. During the course of the swarm, the locations of the events were observed to migrate to the north, presumably as magma was progressively intruded along the strike of the rift. A hastily arranged diversion of an underway Canadian cruise while the seismic swarm was active provided observations that confirmed the presence of an event plume (Figure 4). The era of ridge-crest "detection and response" efforts had begun.

Fortuitously, the CoAxial eruption coincided with the availability of a new seafloor asset. For almost a decade, Vents had depended primarily on *Alvin* for conducting seafloor exploration and sampling. As *Alvin*'s availability declined, Vents looked to alternative submarine vehicles, such as ROVs. A team of Canadian colleagues had purchased a high payload, deep-diving ROV, but did not have access to a suitable vessel. In 1992/1993, Vents entered into a partnership to help develop the vehicle, known as *ROPOS* (Remotely Operated Platform for Ocean Sciences), for use in the Northeast Pacific Ocean on NOAA vessels (Figure 3e). By 1993, *ROPOS* was ready for a challenge no one had expected: the first-ever submarine eruption detection and response cruise.

The first dive at the CoAxial eruption site immediately discovered a pristine lava flow still venting warm water (Figure 3f). The successful series of ROV dives that followed demonstrated, for the first time, that a rapid-response cruise offered a means for addressing previously unknown global-scale processes and their impacts on ocean environments. A follow-up expedition with NSF collaborators using *Alvin* then collected direct evidence of a subsurface microbial biosphere in the upper portion of the ocean crust, an idea long conceptualized (e.g., Deming and Baross, 1993) but scarce in support (Butterfield et al., 2004).

Access to real-time hydrophone data was a singular technological advance that led directly to the discovery and the beginning of previously hypothesized deep-ocean geological processes (Dziak et al., 2007). Utilization of hydrophone data continues to the present and now also incorporates systematic efforts focused on detection and study of marine mammals (Mellinger et al., 2007).

The success of the CoAxial response galvanized the ridge crest community to create a formal "time-critical studies" program. The NSF RIDGE Program committed to funding "rapid-response" efforts as soon as possible upon the detection of the next eruption in the Northeast Pacific. Vents agreed to provide ship time and to provide the staging facility for seagoing gear. This agreement proved timely, as the next event was detected and located in February 1996 on the northern Gorda Ridge, off southern Oregon (Figures 2 and 3g). A large earthquake swarm triggered an event response that included a week on the NOAA Ship *MacArthur* and additional time on Oregon State University's research vessel *Wecoma* (Cowen and Baker, 1998).

A unique experiment conducted during this response was the first

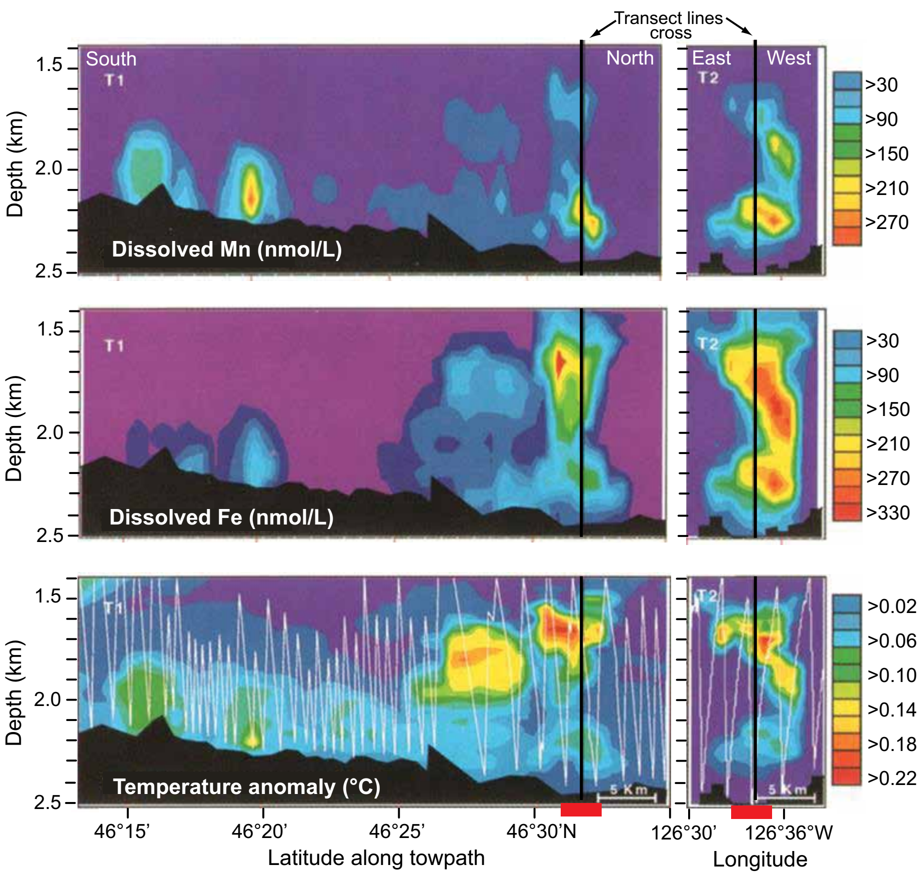


FIGURE 4. Juan de Fuca megaplumes. South-north and east-west perpendicular transects (vertical black lines show their intersection points) of plume chemistry (dissolved Mn and Fe) and hydrothermal fluid temperature anomalies mapped by CTD tows (paths shown by white lines in bottom panel) about two weeks after the 1993 eruption on the CoAxial segment of the Juan de Fuca Ridge. The plume chemistry was measured by a continuous in situ analyzer (SUAVE) developed at PMEL. Red bars near 46°32'N, 126°34'W denote the location of the 1993 lava flow. Two megaplumes (event plumes), rising approximately 1 km above the lava flow, were created by the eruption. *Figure after Massoth et al. (1995)*

successful placement of a ballasted float in an event plume (Lupton et al., 1998). Tracking of the float enabled plume sampling only days after its inception and then 60 days later. Negligible decay of the plume occurred, suggesting that event plumes might have lifetimes on the order of a year, permitting broad dispersal of their entrained chemical and biological cargoes. Other Vents studies of current and plume flow along seafloor spreading centers provided insights into how physical oceanographic factors exert major influences on the dispersal of the larvae of hydrothermal vent animals (Cannon et al., 1995; Lavelle et al., 2012).

The First Instrumented Submarine Eruption at NeMO: The New Millennium Observatory

Buoyed by successes in responding to submarine eruptions, Vents next aimed at a more difficult task: gathering data before and during an eruption. Axial Seamount, the most magmatically robust site on the JdFR, was chosen for this effort (Figure 3h–k). After deploying instruments on the seafloor during the 1996–1997 field seasons, the array was christened NeMO (the New Millennium Observatory), the world's first in situ submarine volcanic observatory. The wait for an eruption was breathtakingly short. In late January 1998, a strong earthquake swarm at Axial Seamount's summit heralded the onset of a volcanic event (Dziak and Fox, 1999). A response cruise 18 days later on *Wecoma* sampled a large plume over the caldera. Two moorings that survived the eruption documented the formation of a hydrothermal plume two hours after the first earthquake and minutes after the onset of caldera deflation (Figure 6). Remarkably, the instruments tracking deflation of the seafloor were partially engulfed in the lava, yet survived to record unique data (Figure 3j). An innovative engineering effort using *ROPOS* enabled recovery of the instruments. Vents scientists had, for the first time, measured the geological and thermal characteristics of a submarine eruption!

The monitoring program at Axial Seamount, conducted by cruises and with deployed instruments, continued after the 1998 eruption. In 2011, just over 13 years later, Axial Seamount erupted again, this time forecast by continuing reinflation of the caldera (Chadwick et al., 2012). Monitoring at Axial Seamount has a bright future because the summit has now been instrumented with a new fiber-optic cable network and is part of NSF's Ocean Observatories Initiative. Event responses occurred after several serendipitously discovered eruptions on other portions of the mid-ocean ridge, but the Northeast Pacific remains the only place on the deep seafloor where it has been feasible to detect, locate, and, most importantly, quickly respond to episodic volcanic events when they occur (Baker et al., 2012).

EXPANSION TO A GLOBAL PERSPECTIVE

After a decade working on the JdFR, the Vents Program had developed tools and techniques to address a global view of hydrothermal venting. This broader approach was necessary because hypotheses formulated on the JdFR could not be tested without surveys and samples from a globally diverse set of geological environments. Three new exploration and research fronts were identified: divergent ridges of varying spreading rates, the as yet unexplored submarine volcanic arcs and back-arc ridges, and cultivation of a global program by engaging US and foreign colleagues and sharing resources and data.

Divergent Plate Boundaries: The Effects of Varying Magmatic Budgets

To explore the influence of fluctuations in the magmatic budget on the distribution and composition of hydrothermal venting, Vents began to look for opportunities to work on the faster spreading ridges of the EPR, where spreading rates vary from ~80 to 150 mm yr^{-1}. Between 1991 and 2005, Vents participated in four cruises that strengthened the correlation between spreading rate (or magmatic

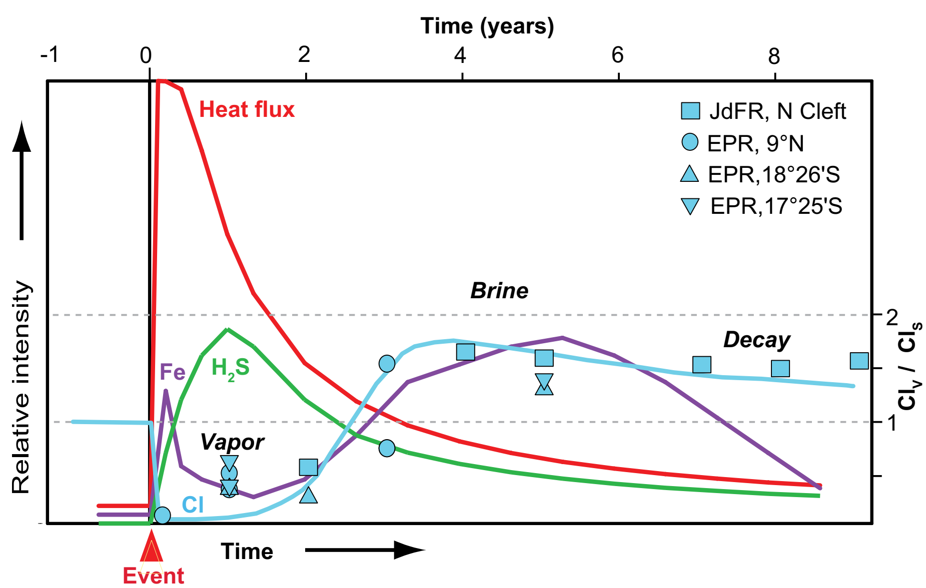


FIGURE 5. The hypothetical response of hydrothermal discharge chemistry to a volcanic event, proposed by Butterfield et al. (1997). Immediately after an eruption, a vapor-rich, but low-chlorinity (Cl) phase produces high heat flux and a spike in dissolved Fe, followed some time later by a rise in H_2S accompanied by a decline in Fe. After the vapor-phase is depleted, a brine-rich phase emerges, with increased Cl and Fe. Eventually the system decays to the pre-eruption chemistry. Cl measurements for a variety of eruption-affected vent fluids (cyan symbols) suggest a time scale of several years duration for the vapor and brine phases (upper time scale), during which the ratio of vent fluid Cl (Cl_v) to seawater Cl (Cl_s) can vary from <0.5 to almost 2 (right-hand scale) (D. Butterfield, NOAA, *pers. comm.*, 2014).

budget) and the spatial density of venting sites (Figure 7), and showed that plume chemistry was strongly influenced by the magmatic state of a ridge segment.

Working with various US and foreign colleagues between 1991 and 1998, Vents explored for hydrothermal venting on three cruises at fast-spreading ridges: the northern EPR 8°40'–11°50'N (100 mm yr^{-1}), and the southern EPR at 14°–19°S and 28°–32°S (up to 150 mm yr^{-1}). The northern EPR cruise occurred only six months after the 1991 eruption, discovered during earlier *Alvin* dives, and found that plumes in the vicinity of the eruption were derived from a young, evolving hydrothermal system with high ratios of volatile components (such as hydrogen and hydrogen sulfide) to heat and metals (Lupton et al., 1993). This observation was important because it afforded a way to identify sites of ongoing or recent eruptions by means of water column measurements. Cruises on the superfast-spreading EPR confirmed this finding. Areas with a high proportion of volatile-rich plumes coincided with the occurrence of recent magmatic activity, implying that magmatic intrusions and eruptions on a superfast-spreading ridge are more frequent, and thus perhaps smaller volumetrically, than those on more slowly spreading ridges (Urabe et al., 1995; Baker et al., 2002). The 28°–32°S study also demonstrated the first rigorous correlation between hydrothermal plumes and ridge areas where axial inflation was relatively high and fracture density was relatively low. These correlations suggested that hydrothermal venting is most active where the apparent magmatic budget is greatest, and recent eruptions have largely paved over the pre-eruption fracture network.

To further the relationship between venting and spreading rate (a proxy for the magmatic budget), Vents was funded by NSF and the NOAA Office of Exploration and Research (OER) to study an entirely different sort of mid-ocean ridge, one where the magmatic budget is strongly increased because of interaction with a mantle "hotspot." This cruise, in 2005/2006, and a follow-up cruise in 2011, found that the GSC has significantly fewer high-temperature vent sites than mid-ocean ridges with similar spreading rates, a characteristic first suggested by work along the Reykjanes Ridge (near the Iceland hotspot) and later confirmed at other ridges influenced by the Amsterdam-St Paul and Ascension hotspots (Baker et al., 2008). The apparent deficit in high-temperature venting remains an enigma.

Convergent Plate Boundaries: Arcs and Back-Arcs

Through the first two decades of hydrothermal exploration, little attention was paid to sources on convergent margins, even though those plate boundaries extend for some 23,000 km and host volcanic arcs, forearc rifts, and back-arc basin spreading ridges (Figure 1). Hydrothermal discharge along volcanic arcs fundamentally differs from that along mid-ocean ridges and back-arc basin spreading centers in its reflection of the complex source history of fluids arising from subduction zones. This variability notably includes vent fields, considered the best modern analogues of volcanogenic massive sulfide deposits currently exploited on land, particularly the gold-rich variety. Additionally, hydrothermal vent sites in volcanic arc settings range from depths of thousands of meters to the sea surface, thereby broadening the reach of their environmental impact well

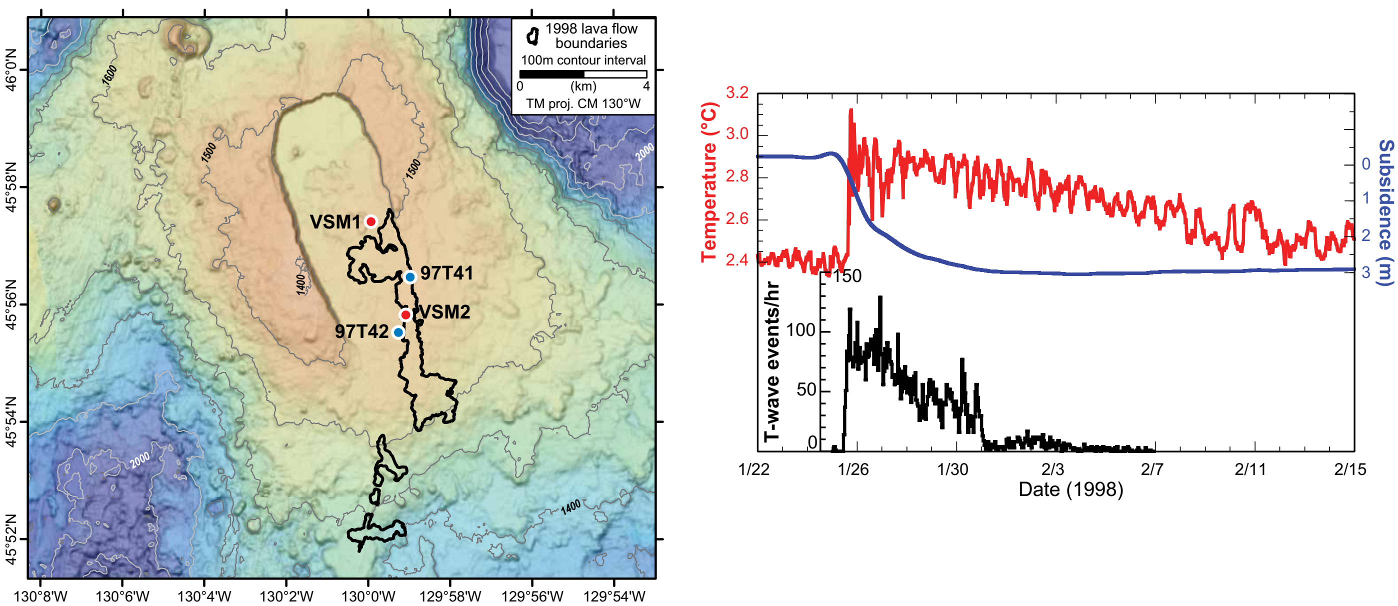


FIGURE 6. Seafloor deflation, near-bottom water temperature, and T-phase swarms recorded during the 1998 Axial eruption, the first submarine eruption monitored by in situ instrumentation. The map shows locations of volcanic system monitors (VSMs, red), temperature moorings (blue), and the black outline of the lava flow. The graph shows the numbers of earthquakes recorded as T-wave events (black line), the subsidence (deflation) of the seafloor (blue line), and the temperature signal (red line) during and following the eruption.

beyond that typical of spreading ridges.

In 1999, Vents teamed with the New Zealand research institute GNS Science to conduct the first systematic survey of the hydrothermal state of submarine arc volcanoes. Only two submarine arc volcanoes, both on the Izu-Bonin arc, had been previously sampled for vent fluids. The 1999 cruise covered only 260 km of the Kermadec arc, yet found seven of 13 volcanoes to be hydrothermally active. As deduced from plume samples, the arc volcanoes showed remarkable chemical diversity ranging from metal-rich to gas-rich, demonstrating that volcanic arcs could be an abundant, yet unexplored, source of hydrothermal discharge, chemosynthetic ecosystems, and mineral resources (de Ronde et al., 2001).

Subsequent cruises conducted during 2002–2007 along the Kermadec-Tonga arc with New Zealand and Australian scientists and ships brought the total to 57 volcanic centers surveyed, 30 of which were found to be hydrothermally active. These discoveries spurred Vents to begin exploration of the Mariana arc (Figure 8), the second longest (after Kermadec-Tonga) interoceanic arc (Embley et al., 2007). Supported by OER, in 2003 the first comprehensive exploration of the Mariana arc covered 1,370 km and identified 76 volcanic edifices grouped into 60 "volcanic centers," including at least 26 (20 submarine) that are hydrothermally or volcanically active (Figures 3l–q and 8). Follow-up cruises with ROV assets were conducted between 2004 and 2010. Based on work in the Kermadec-Tonga and Mariana arcs, Vents estimated that intraoceanic arcs could contribute ~10% of the global hydrothermal budget. Chemically, however, the impact may be even more significant. Many important volatile species, for example CO_2, are often more highly concentrated in arc fluids than in mid-ocean ridge fluids (Lupton et al., 2008).

In 2008, Vents commenced exploration of the northern Lau Basin, which hosts the volcanically active Tofua arc (offset to the west from the Tonga arc), back-arc spreading centers, and multiple discrete volcanoes between the arc and back arc. During cruises between 2008 and 2012, Vents discovered at least 22 active hydrothermal systems, including active eruptions on a back-arc ridge (where event plumes were observed; Baker et al., 2011) and at West Mata Volcano (Resing et al., 2011; Figure 3r,s), defining this area as perhaps the most concentrated region of volcanic activity on the planet (Figure 3r,s).

The Vents Program's work along volcanic arcs has provided glimpses into a diversity of seafloor volcanic activity far greater than seen along mid-ocean ridges (Embley et al., 2008; Figure 3l–s). Eruptions lasting for years have been imaged and monitored at volcanoes on the Mariana (NW Rota-1; Figure 3l; Chadwick et al., 2008) and Tofua (West Mata; Embley et al., 2014) arcs (Figures 1 and 3r). Acoustic monitoring, visual observations, and plume sampling by Vents at NW Rota-1 has led to the characterization of a submarine pyroclastic eruption (Chadwick et al., 2008; Figure 9) and the first estimate of annual CO_2 supply from a submarine volcano, amounting to ~1% of that from all subaerial volcanoes (Dziak et al., 2012a).

Another, non-erupting, volcano on the Mariana arc, NW Eifuku, is also a major CO_2 source, venting a blizzard of liquid CO_2 droplets directly from the seafloor (Lupton et al., 2006; Figure 3m–o). This discharge provides an ideal laboratory for studying the effect of CO_2 acidification on the local ecosystem. Another completely unexpected discovery was pools of liquid sulfur ringed by lush animal communities found on Daikoku and Nikko volcanoes of the Mariana arc and Macauley Cone of the Kermadec arc. These pools, up to several meters in diameter, act as condensers of gases that derive from the underlying magmas (de Ronde et al., 2015). The volcanic vents beneath these lakes provide a steady outflow of hot gases that continuously generate molten sulfur. Further exploration along other interoceanic arcs and the longer length (14,800 km) of island arcs (whose volcanoes are largely subaerial) will ultimately be needed to refine the global chemical and thermal contribution of arcs, as well as their role in the biogeography of vent-endemic animals.

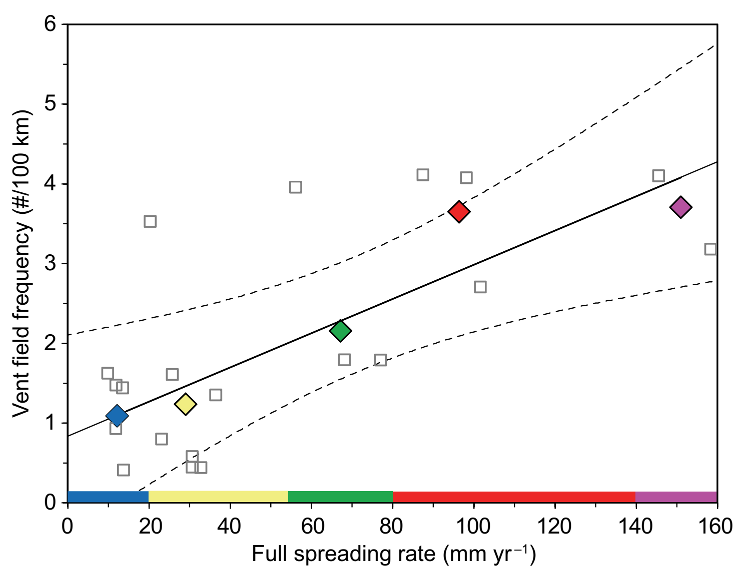


FIGURE 7. Scatter plot of vent field frequency, F_s (number of vent fields per 100 km of ridge axis), versus spreading rate, u_s (mm yr^{-1}). Open squares give values for 20 ridge segments (335–2,060 km long). Colored diamonds show the average values from ridge segments binned in five spreading length categories (colored bars on rate axis) from ultra slow to superfast. Solid black line is the linear regression fit of $F_s = 0.85 + 0.021\ u_s$. Dashed curved lines enclose the 95% confidence intervals for the slope. Vent field frequencies were determined from the InterRidge database, http://vents-data.interridge.org (Beaulieu et al., 2013).

Global Studies Complement Site Studies

The successful monitoring of earthquakes by Vents in the Northeast Pacific since 1993 and the emerging realization that eruptions cause profound changes in hydrothermal circulation within the crust spurred the long-term deployment of hydrophones in the equatorial Pacific, piggybacking on ship time used to service the NOAA equatorial buoy array (Fox et al., 2001). The eastern equatorial Pacific was continually monitored by autonomous hydrophones from 1996 until 2008. The region includes EPR, GSC, Middle America and Peru-Chile trench systems, and the Easter and Juan Fernandez microplates. This effort was the first regional acoustic monitoring of seafloor tectonic/volcanic activity, later expanded to the northern Mid-Atlantic Ridge, Bransfield Strait (Antarctica), the northern Lau Basin, and the southern Indian Ocean (Dziak et al., 2012b).

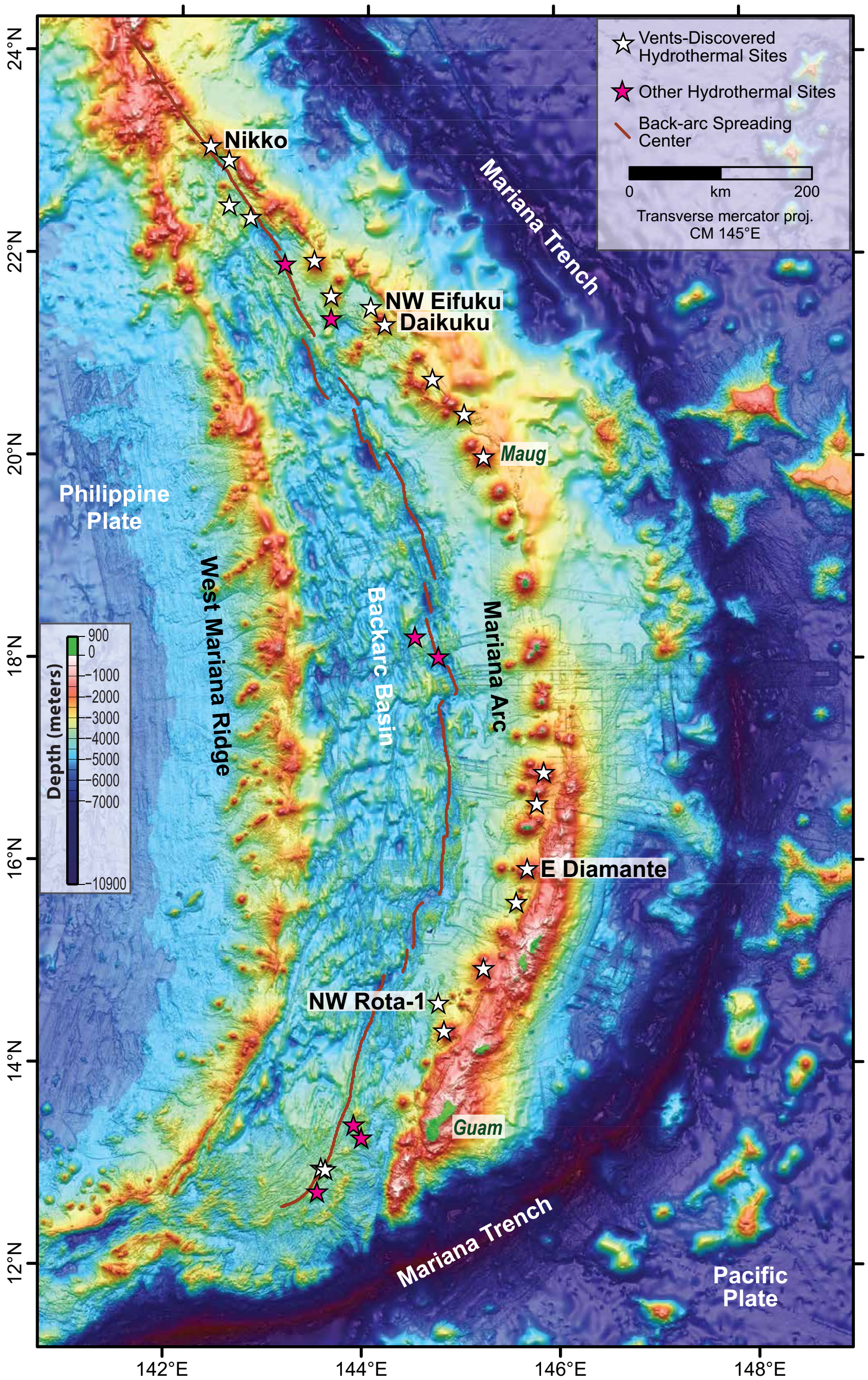


FIGURE 8. Subaerial and submarine volcanoes along the Mariana arc. Islands are solid green shading. White stars are hydrothermal sites discovered by the Vents Program during the period 2003–2006. Red stars are other hydrothermal sites.

Vents has also participated in global programs to map the distribution of hydrothermal plumes on the ocean-basin scale. Beginning in the 1970s, the Geochemical Ocean Sections Study (GEOSECS) and World Ocean Circulation Experiment (WOCE) programs used ^{3}He measurements to map hydrothermal plumes. These plumes identify sources of concentrated and persistent volcanic activity and provide insight into patterns of ocean circulation and mixing. In the Pacific, plumes thousands of kilometers long emanate from the EPR between 10°N and 20°S, the JdFR, Loihi Seamount in the Hawaiian Islands, and the northern end of the Lau Basin (Lupton, 1998). In 2013, another global program, GEOTRACES, resampled the ^{3}He plume that spreads westward from the EPR at ~15°S to measure concentrations of trace metals. Resing et al. (in press) unexpectedly found that hydrothermal dissolved iron, manganese, and aluminum travel westward in ^{3}He-enriched plumes for at least 4,000 km across the South Pacific. Using the ratio of dissolved iron to ^{3}He applicable to mid-ocean ridge hydrothermal emissions, the estimated global hydrothermal ^{3}He flux of 530 mol yr^{-1} yields an iron input of 4 Gmol yr^{-1} to the ocean interior, or ~20% of the riverine supply.

No individual laboratory possesses the resources to fund a global exploration program. Vents interest in exploring ridge and volcanic arc sections around the world depended upon collaborations with US and foreign researchers. In the mid-1990s, Vents recognized another untapped resource: vessels working along ridges and arcs (e.g., collecting petrological samples) but not collecting data in the water column. PMEL Engineering developed a simple plume sensor, the Miniature Autonomous Plume Recorder (MAPR; Figure 3t), which allows any researcher using any wire lowered to the seafloor—such as rock cores, dredges, side-scan sonars—to explore for hydrothermal activity at no cost to the primary cruise objectives. Since then, some 50 partners in the United States and nine foreign countries have conducted over 100 cruises using MAPRs supplied and maintained by PMEL. These cruises have collected data in every ocean by means of some 2,000 vertical profiles and along 14,000 km of towed track line, creating new collaborations to expand the reach of hydrothermal research (Figure 1). About one-quarter of all the vent locations in the InterRidge database (http://vents-data.interridge.org) were discovered using MAPRs.

A LOOK TO THE FUTURE

Seafloor research during the past three decades has produced many, often startling, discoveries. Still, we remain at the threshold of understanding how Earth's most widespread and prevalent volcanic activity affects the physical, chemical, and biological environments of the global ocean. Sadly, the ocean remains largely unexplored in both space and time, despite the fact that it makes life on Earth possible. New technologies, especially autonomous sensors and sampling systems, are needed to acquire knowledge of critical ecosystems before environmental changes occurring in many ocean regions overtake our ability to respond to or mitigate them. Bringing the value and excitement of ocean exploration and research to the public, to educators, and to the worldwide community of ocean scientists is an urgent task.

NOAA has begun this task by initiating a science and technology collaboration between PMEL and OER. Extramural collaborations include exciting opportunities with NSF, NASA, the Navy, NOAA Cooperative Institutes, and private organizations such as the Ocean Exploration Trust and the Schmidt Ocean Institute. New technologies already on the horizon hold the promise of dramatically improving subsea navigation and long-term autonomy of subsea vehicles, making large-scale exploration of the ocean more practical, and diminishing the traditional reliance on surface ships.

Beyond science and the promise of new technologies, it will be essential for governments to provide wise stewardship of seafloor environments and their living and nonliving resources. Over the past decade, for example, collaborative exploration in the Mariana arc, located within the United States Exclusive Economic Zone, revealed an unexpected myriad of diverse ecosystems and significant submarine sources of CO_2, all produced and sustained by volcanic activity. These discoveries fostered establishment of the Mariana Trench Marine National Monument in 2009. Without a doubt,

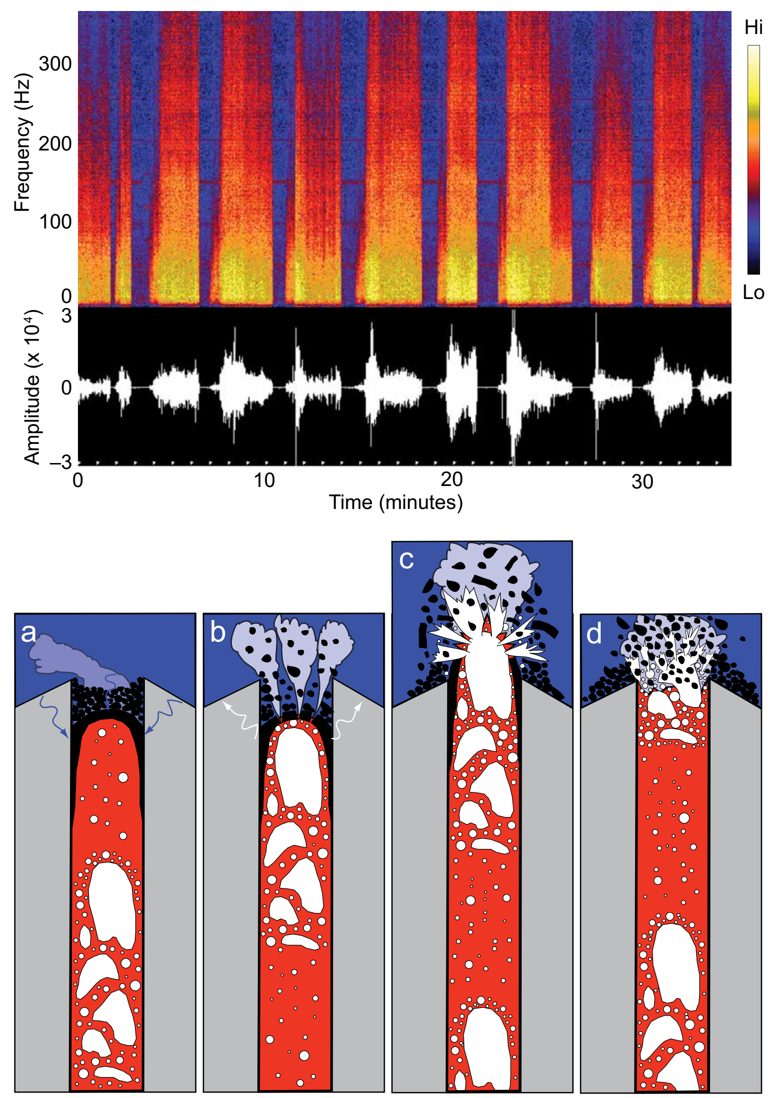


FIGURE 9. Submarine eruption at NW Rota-1 Seamount, Mariana arc. (top) Hydrophone data during an active eruption in 2006. Data displayed as both a time series (in digital units, bottom) and spectrogram (in frequency, top). (bottom) Diagrammatic model for the eruptive activity observed at NW Rota-1 in 2006 (red = magma. White = magmatic gases. Blue = seawater. Black = solidified lava. Gray = older lavas). (a) Between bursts, seawater cools the top of the magma column, forming a solidified cap. (b) When the next gas-rich pocket reaches the cap, it immediately starts to escape. (c) The gas pocket forces the lava cap upward in the vent where explosions destroy it. (d) With the vent uncapped, the eruptive burst proceeds at a higher level until all the gas in the pocket is vented and the activity abruptly ceases, returning to the initial state. *Figure from Chadwick et al. (2008)*

other places and processes yet to be discovered will have similar, or even greater import, and will therefore stand in need of informed governance.

In its fourth decade, the Vents Program is also evolving to address such challenges. In place of a single program, Vents has been restructured and repurposed through division into two distinct but complementary programs. An Acoustics Program continues broad-scale monitoring of ocean seismic events, natural and anthropogenic ocean noise, and marine mammal distributions. An Earth-Ocean Interactions Program builds on the foundation of Vents pioneering submarine volcanic exploration and research and continues to address both naturally occurring processes and those that impact the ocean environment as a consequence of human activities.

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We are especially grateful for the efforts of individuals with whom we worked for a decade or more: **PIs** include D. Butterfield, G. Cannon, W. Chadwick, R. Dziak, R. Feely, C. Fox, W. Lavelle, J. Lupton, G. Massoth, H. Matsumoto, J. Resing, and P. Rona. **Technical Team** members include A. Bobbitt, N. Buck, L. Evans, M. Fowler, J. Gendron, R. Greene, S. Hanneman, J. Haxel, J. Klay, A. Lau, G. Lebon, S. Merle, E. Olson, D. Pashinski, K. Roe, and S. Walker. **Collaborators** include R. Arculus, D. Bohnenstiehl, D. Caress, D. Clague, C. de Ronde, J. Cowen, D. Fornari, J. Franklin, C. German, J. Goslin, J. Holden, J. Huber, J. Ishibashi, I. Jonasson, D. Kadko, R. Koski, M. Lilley, F. Martinez, C. Moyer, L. Mullineaux, K. Nakamura, S. Nooner, M. Park, M. Perfit, J-Y. Royer, K. Rubin, D. Smith, R. Stern, T. Urabe, G. Wheat, and Y. Tamura. **Graduate Students** constituted one of the Vents Program's most important and long-lasting resources because they staffed cruises; developed state-of-the-art sensors; wrote papers; accumulated a wealth of physical, chemical, and biological oceanographic data; and often became long-time collaborators.

The contributions of all these colleagues can best be expressed through an extended bibliography of the Vents Program available at: http://www.pmel.noaa.gov/eoi/bibliography.html. We make special note of E. Bernard, PMEL's Director for virtually the entire duration of the program and a constant and inspirational supporter of the program, and V. Tunnicliffe, our primary collaborator for the biological aspects of hydrothermal systems since the inception of the program. H. Milburn and C. Meinig were the principal engineering leads for the Vents Program's many technical innovations. A multitude of organizations, programs, agencies, and universities, both domestic and international, also provided intellectual and material support that directly contributed to the success of Vents. We are especially grateful for long-term support of the NOAA Office of Ocean Exploration and Research and NSF. Thanks are due as well to the crews of the ships of the NOAA and UNOLS fleets as well as those of our international partners. Without all of these assets, we would not have been able to make the sustained year-to-year observations that are at the scientific heart of the program. This paper was materially improved by the reviews of R. Koski, M. Perfit, and V. Tunnicliffe. Financial support for the paper was supplied by NOAA's Office of Ocean Exploration and Research and NOAA's Pacific Marine Environmental Laboratory (S.R.H.), NOAA's Earth-Ocean Interactions Program (R.W.E.), and the University of Washington's Joint Institute for the Study of the Atmosphere and Ocean through NOAA Cooperative Agreement NA10OAR4320148 (E.T.B). S. Merle and K. Birchfield provided graphics support for many of the paper's figures.

This is PMEL contribution 4214, and JISAO contribution 2321.

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AUTHORS. **Stephen R. Hammond** (stephen.r.hammond@noaa.gov) is Senior Science Advisor, National Oceanic and Atmospheric Administration (NOAA) Pacific Marine Environmental Laboratory (PMEL) and NOAA Office of Ocean Exploration and Research, Portland, OR, USA. **Robert W. Embley** is Marine Geophysicist, NOAA PMEL, Newport, OR, USA. **Edward T. Baker** is Research Scientist and Principal, Joint Institute for the Study of the Atmosphere and Ocean, PMEL, University of Washington, Seattle, WA, USA.

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