Hydrothermal Discharge During Submarine Eruptions

THE IMPORTANCE OF DETECTION, RESPONSE, AND NEW TECHNOLOGY

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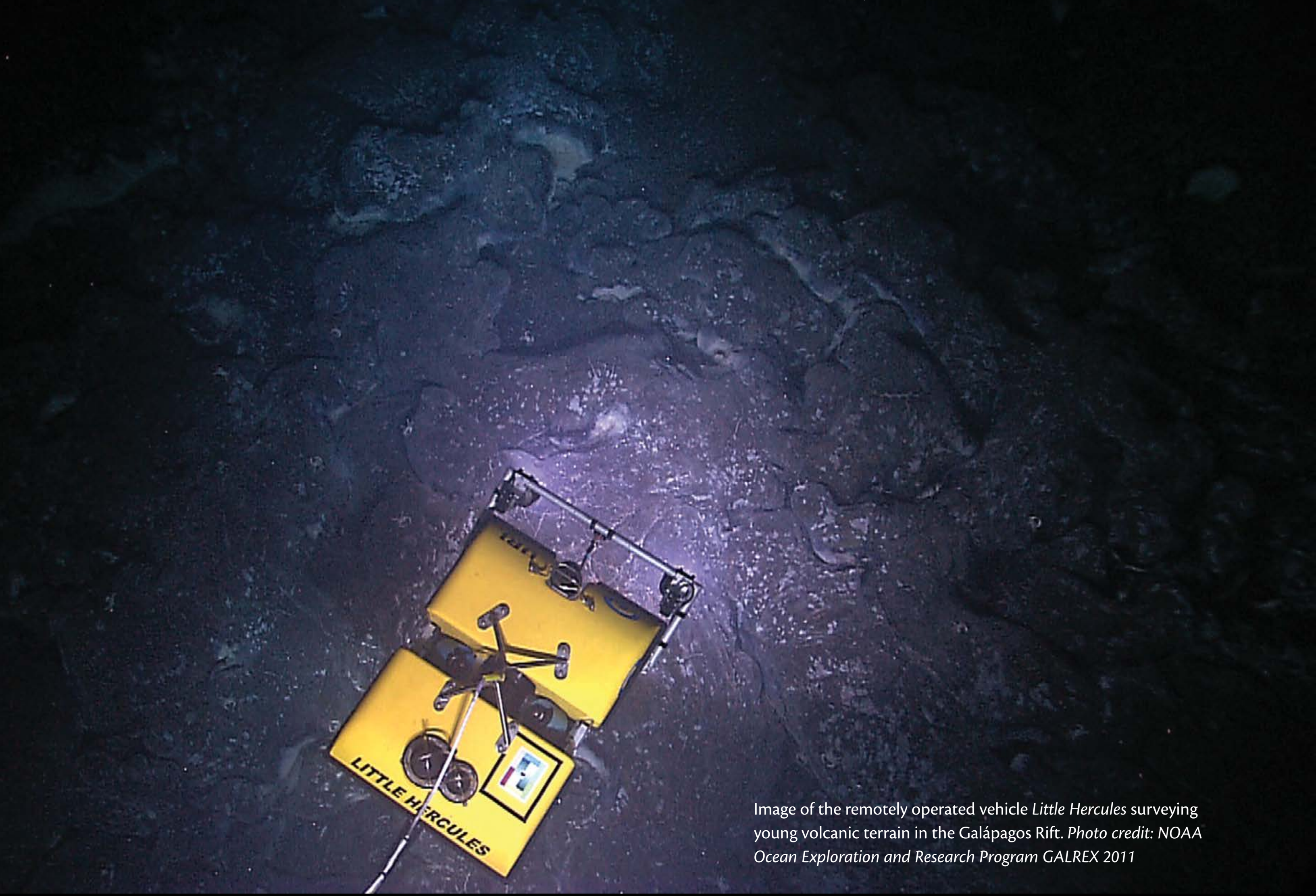

Image of the remotely operated vehicle *Little Hercules* surveying young volcanic terrain in the Galápagos Rift. *Photo credit: NOAA Ocean Exploration and Research Program GALREX 2011*

ABSTRACT. Submarine volcanic eruptions and intrusions construct new oceanic crust and build long chains of volcanic islands and vast submarine plateaus. Magmatic events are a primary agent for the transfer of heat, chemicals, and even microbes from the crust to the ocean, but the processes that control these transfers are poorly understood. The 1980s discovery that mid-ocean ridge eruptions are often associated with brief releases of immense volumes of hot fluids ("event plumes") spurred interest in methods for detecting the onset of eruptions or intrusions and for rapidly organizing seagoing response efforts. Since then, some 35 magmatic events have been recognized and responded to on mid-ocean ridges and at seamounts in both volcanic arc and intraplate settings. Field responses at mid-ocean ridges have found that event plumes occur over a wide range of eruption styles and sizes, and thus may be a common consequence of ridge eruptions. The source(s) of event plume fluids are still debated. Eruptions detected at ridges generally have high effusion rates and short durations (hours to days), whereas field responses at arc volcanic cones have found eruptions with very low effusion rates and durations on the scale of years. New approaches to the study of submarine magmatic events include the development of autonomous vehicles for detection and response, and the establishment of permanent seafloor observatories at likely future eruption sites.

THE IMPORTANCE OF BEING EARLY

Based largely on geophysical mapping in the North Atlantic by Heezen et al. (1959), mid-ocean ridges (MORs) were identified as the central element of plate tectonics (Hess, 1960) and the location where Earth's oceanic volcanic crust is formed (Dietz, 1961). These discoveries on the Mid-Atlantic Ridge began the development of a conceptual paradigm positing MORs as sites of crustal accretion and magmatism. Further exploration found that episodic injections of mantle-derived magma also occur along subduction zones and at mid-plate "hotspots." In each of these areas, seafloor eruptions accrete new oceanic crust, repave the seafloor, and sustain hydrothermal circulation and its associated ecosystems. Many studies have described the aftermath of eruptions and attempted to constrain the areal limit of erupted lavas by various means, but observations of the geophysical, chemical, and biological interactions that occur between the inception of magma intrusion and the end of lava cooling are far scarcer.

A primary obstacle to the advancement of our knowledge of submarine eruptions is that conventional monitoring methods cannot detect and/or locate them on most of the deep seafloor. Land-based seismic networks detect only large earthquakes in the ocean basins and, except in ideal circumstances (e.g., The 1996 Loihi Science Team, 1997), have crude locating capability. A farther-reaching (hundreds to thousands of kilometers) and more precise tool is long-range hydroacoustic detection of the seismicity associated with eruptions (Tolstoy and Ewing, 1950). Seismic waves generated by earthquakes and eruptions convert to acoustic *T*-waves at the seafloor-ocean interface and then refract to horizontal ray paths, enabling the *T*-waves to enter the sound channel (Fox et al., 1993). Only in the last 20 years has precise identification of the time and location of individual, low-magnitude earthquakes and explosions associated with underwater eruptions been available from regional hydrophone networks (e.g., Fox et al., 1993; Cowen et al., 2004; Embley and Lupton, 2004; Dziak et al., 2007, 2011b, 2012). Hydroacoustic networks are few, however, and the seafloor is remote and difficult to reach, so the number of eruptions discovered or detected and subsequently inspected is low. Our knowledge of crust-ocean interaction during an eruption remains limited.

Hints of previously unsuspected crust-ocean interaction first appeared in the mid-1980s and early 1990s, when serendipitous observations and rapid-response cruises began documenting eruptions that produced not only new lava but also massive transfers of heat, chemicals, and biota from the solid Earth to the deep ocean (e.g., see summaries by Baker, 1995; Lupton et al., 1999; Cowen et al., 2004; Baker et al., 2011). Some of these discharges have been confirmed as chemically distinct fluids that rise hundreds of meters to form discrete, stable, spheroidal eddies. These event plumes, or megaplumes (Baker et al., 1987), range over a factor of 100

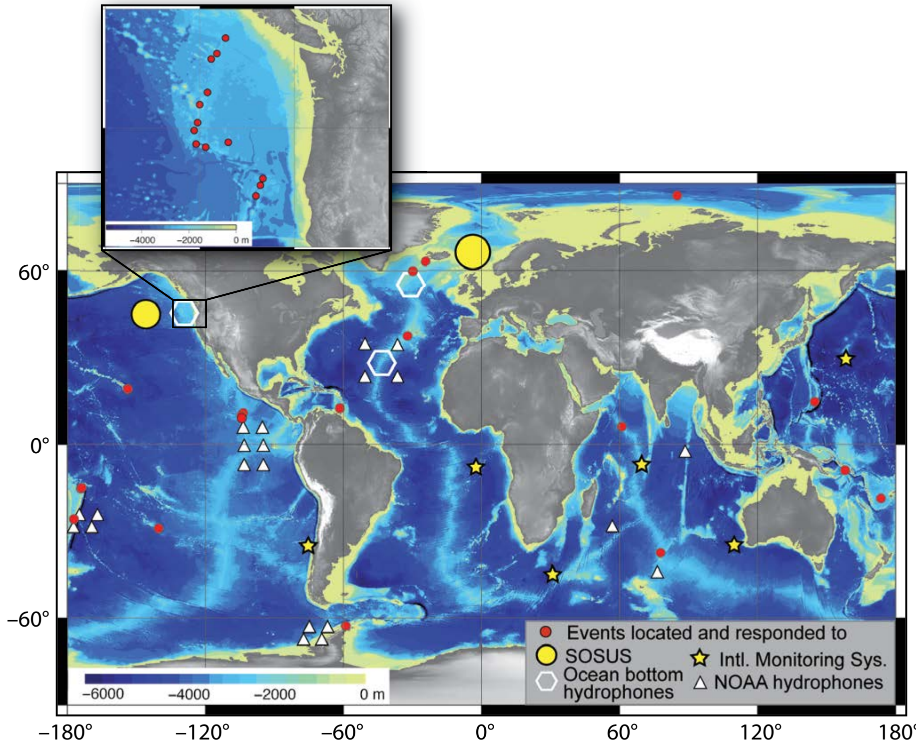

Figure 1. The global and (inset) Northeast Pacific distribution of detected "events" responded to since 1986; red dots indicate earthquake *T*-phases recorded by hydrophone, seismic waves recorded by land-based seismometers, or eruptions serendipitously discovered. The locations of real-time (yellow symbols) and self-recording (white symbols) submarine hydrophones are also shown. SOSUS = Sound Surveillance System array.

in volume (1–150 km^3), yet maintain a distinctive and consistent chemical signature. The collection of thermophilic microbes from event plumes (Summit and Baross, 1998) and post-eruption seafloor venting (Holden et al., 1998) implies that eruptions also transfer biota from the crust to the ocean.

Almost three decades after the recognition of eruption-linked hydrothermal discharges, a convincing theory of their formation still eludes us. We do not know if the fluid discharge that accompanies MOR eruptions is instantaneously altered seawater or water that is suddenly released from storage networks in the crust or magma chamber. We do not know the chemical conditions that produce the hydrothermally unique and uniform composition of these fluids, nor how these processes vary in space or time during an eruption. Recent discoveries of long-lasting, low-mass-rate eruptions at submarine arc volcanoes (e.g., Embley et al., 2006; Chadwick et al., 2008; Resing et al., 2011) offer a research opportunity not likely possible on MORs: sustained observations of ongoing eruptions.

Because of the unpredictability in time and space of seafloor eruption events, systematic study will be always a challenge. Progress will be slow until we are able to emulate terrestrial volcano studies by gathering detailed observations during an eruption, or as soon as possible after one commences.

A CONCISE HISTORY OF EVENT DETECTION AND RESPONSE

Since 1986, there have been responses to at least 35 suspected magmatic "events" after their discovery or detection on the seafloor (Figure 1, Table 1). Eruption evidence, in the form of hydrothermal discharge (especially event plumes) or visually fresh lavas (especially those collocated with datable depth changes or radiometrically dated to be weeks to months old when collected), was observed at 22 of these events. Serendipity, the fortuitous discovery of an ongoing or recent eruption, and land-based seismic networks provided evidence for the earliest documented eruptions. These methods resulted in such discoveries as the first event plumes (Baker et al., 1987), associated fresh lavas (Embley et al., 1991), and seafloor depth changes (Chadwick et al., 1991) on the Cleft segment of the Juan de Fuca Ridge; eruption-like seismic events at 58°54'N on the Reykjanes Ridge (Nishimura et al., 1989); and a still-smoking eruption at 9°50'N on the East Pacific Rise (EPR; Haymon et al., 1993). The latter was the first to be radiometrically dated using short half-life (138 days) ^{210}Po, showing

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Table 1. Detection and response history of seafloor volcanic or tectonic events.
Additional events have been acoustically detected but did not trigger air or sea response efforts.

Event	Location (lat, long)	Event date (**Confirmed**, *Estimated*)	Detection type	Days to first response	Response tools	Event plume? New lava? Radiometric dating?	Essential References
Juan de Fuca Ridge/ Cleft Segment	44.9, −130.3	*August 1986*	Serendipity	1–4d?	CTD	Y, Y, N	Baker et al. (1987) Chadwick et al. (1991) Embley et al. (1991)
Juan de Fuca Ridge/ Cleft-Vance Segment	45.2, −130.15	*August 1987*	Serendipity	~ 20?	CTD	Y, N, N	Baker et al. (1989)
Macdonald Seamount	−29, −140.42	*October 1987*	Serendipity	0	CTD, rock samples	N, Y, Y	Rubin et al. (1989)
North Fiji Ridge	−18.83, 173.5	*December 1987*	Serendipity	few?	CTD	Y?, N, N	Nojiri et al. (1989)
Kick'em Jenny Volcano, Caribbean	12.3, −61.63	**December 29, 1988**	Land seismic	~ 120	HOV	N, Y, N	Devine and Sigurdsson (1995)
Macdonald Seamount	−29, −140.42	*January 1989*	Serendipity	0	CTD, HOV	N, Y, N	Huber et. al. (1990)
Reykjanes Ridge	59.83, −30.0	**May 21, 1989**	Land seismic	~ 14	Air-drop sono-buoys, XBTs	N, N, N	Nishimura et al. (1989)
Reykjanes Ridge	63.1, −24.5	**October 30, 1989**	Land seismic	5	CTD, camera	N, N, N	Olafsson et al. (1991)
East Pacific Rise	9.83, −104.3	*April to December 1991*	Serendipity	0?	CTD, HOV, camera	N, Y, Y	Haymon et al. (1993) Rubin et al. (1994)
Juan de Fuca Ridge/ CoAxial segment	46.5, −129.6	**June 26, 1993**	SOSUS	14	CTD, HOV, ROV	Y, Y, N	Fox (1995, and references therein)
Blanco Transform Fault	44.2, −129.7	**January 9, 1994**	SOSUS	18	CTD, ROV	N, N, N	Dziak et al. (1996)
Boomerang Seamount, Southeast Indian Ridge	−37.43, 77.8	*November 1995*	Serendipity	150	CTD	N, Y, Y	Johnson et al. (2000a)
Gorda Ridge/North Gorda segment	42.6, −126.78	**February 28, 1996**	SOSUS	11	CTD, ROV, camera, SOFAR float	Y, Y, Y	Cowen and Baker (1998, and references therein)
Loihi (Hawaiian hotspot)	19, −153.86	**July 17, 1996**	Land seismic	30	CTD, HOV, sonobuoys	N, Y, Y	The 1996 Loihi Science Team (1997) Garcia et al. (1998)
Juan de Fuca Ridge/ Axial Seamount	45.93, −130.0	**January 25, 1998**	SOSUS	In situ instruments; 18	CTD, HOV, ROV, in situ instruments	Y?, Y, N	Dziak and Fox (1999) Embley et al. (1999) Baker et al. (1999)
Gakkel Ridge	85.63, 85.0	*January to September 1999; September 2001*	Land seismic	~ 600	CTD	Y?, Y, N	Tolstoy et al. (2001) Schlindwein et al. (2005) Sohn et al. (2008)
Juan de Fuca Ridge/ Endeavour	47.9, −129.4	**June 8, 1999**	SOSUS	In situ instruments	In situ temperature	N, N, N	Johnson et al. (2000b) Bohenestiehl et al. (2004)
Kavachi Volcano, New Georgia Group Forearc	−9.0, 157.96	*May 2000*	Serendipity	Ongoing eruption	CTD	N, Y, N	Baker et al. (2002)
Blanco Transform Fault	44.33, −130.2	**June 2, 2000**	SOSUS	In situ instruments	In situ temperature	N, N, N	Dziak et al. (2003)

AUV = autonomous underwater vehicle. CTD = conductivity, temperature, depth sensor. HOV = human-occupied vehicle. OBS = ocean bottom seismometer. ROV = remotely operated vehicle. SOFAR = Sound Frequency and Ranging channel. SOSUS = Sound Surveillance System array. XBT = expendable bathythermograph.

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Table 1. Continued...

Event	Location (lat, long)	Event date (Confirmed, *Estimated*)	Detection type	Days to first response	Response tools	Event plume? New lava? Radiometric dating?	Essential References
East Pacific Rise	8.6, −104.2	**March 2, 2001**	Hydrophones	684	CTD	N, N?, N	Bohnenstiehl et al. (2003)
Lucky Strike, Mid-Atlantic Ridge	37.3, −32.3	**March 16, 2001**	Hydrophones; land seismic	~ 100 (?) and ~ 465	HOV	N, N, N	Dziak et al. (2004)
Gorda Ridge/ Jackson Segment	42.15, −127.05	**April 3, 2001**	SOSUS	8	CTD, camera	N, N, N	Fox et al. (2001c)
Juan de Fuca Ridge/ Middle Valley	48.78, −128.64	**September 6, 2001**	SOSUS	~ 28	CTD	N, N, N	Davis et al. (2004)
Carlsberg Ridge	6, 61	*July 2003*	Serendipity	~ few	CTD	Y, N, N	Murton et al. (2006)
East Pacific Rise	10.75, −103.65	*July 2003*	Serendipity	60+	HOV	N, Y, Y	McClain et al. (2004) van der Zander et al. (2005)
Northwest Rota-1 Volcano, Mariana Arc	14.6, 144.76	*March 2004; ongoing*	Serendipity	Ongoing eruption	CTD, ROV	N, Y, Y	Embley et al. (2006) Chadwick et al. (2008, 2011a)
Juan de Fuca Ridge/ Endeavour (overlap)	48.13, −129.1	**February 8, 2005**	SOSUS	7	CTD, camera	N, N, N	Dziak et al. (2007) Hooft et al. (2010)
East Pacific Rise	9.83, −104.3	*June 2005 to January 2006*	Serendipity	~ 90	CTD, camera, in situ OBSs	N, Y, Y	Tolstoy et al. (2006) Cowen et al. (2007) Rubin et al. (2008) Soule et al. (2007) Fundis et al. (2010)
Bransfield Strait, Antarctica	−62.7, −59.0	*December 2005 to December 2007*	Hydrophones	?	CTD	N, N, N	Dziak et al. (2010)
Juan de Fuca Ridge off-axis	44.42, −128.5	**March 30, 2008**	SOSUS	20	CTD	N, N, N	Merle et al. (2008)
Gorda Ridge/ North Gorda Segment	42.83, −126.67	**April 23, 2008**	SOSUS	1	CTD	N, N, N	Merle et al. (2008)
Northeast Lau Spreading Center	−15.4, −174.27	*November 2008*	Serendipity	~ few	CTD, ROV, AUV	Y, Y, Y	Baker et al. (2011) Rubin et al. (2009)
West Mata Volcano, Lau Basin	−15.1, −173.75	*May 2009; ongoing*	Serendipity	Ongoing eruption	CTD, ROV, AUV	N, Y, Y	Resing et al. (2011) Rubin et al. (2009)
Juan de Fuca Ridge/ Axial Seamount	45.93, −130.0	**April 6, 2011**	Serendipity	In situ instruments; 120	CTD, ROV, AUV, in situ instruments	N, Y, Y	Butterfield et al. (2011a) Chadwick et al. (2011) Haxel et al. (2011)
Monowai Volcano, Tonga-Kermadec Arc	−25.89, −77.19	*Ongoing*	Land seismic	Ongoing eruption	CTD, ROV	N, Y, N	http://www.volcano.si.edu/reports/bulletin; Chadwick et al. (2008) Leybourne et al. (2010)

AUV = autonomous underwater vehicle. CTD = conductivity, temperature, depth sensor. HOV = human-occupied vehicle. OBS = ocean bottom seismometer. ROV = remotely operated vehicle. SOFAR = Sound Frequency and Ranging channel. SOSUS = Sound Surveillance System array. XBT = expendable bathythermograph.

that it occurred just weeks before its discovery by scientists diving in *Alvin* and continued off and on for nine months (Rubin et al., 1994).

In June 1993, the National Oceanic and Atmospheric Administration (NOAA) Pacific Marine Environmental Laboratory attained real-time access to the US Navy Sound Surveillance System (SOSUS) in the Northeast Pacific (Fox et al., 1993). This Cold War submarine-tracking network became the first hydrophone array to provide accurate and immediate location of even low-level (as low as 2.5 magnitude) seismicity in the Northeast Pacific. Only days after monitoring began, the arrival of acoustic *T*-waves from the CoAxial segment of the Juan de Fuca Ridge led to the first real-time recording of a submarine dike injection (Fox et al., 1995). The first CoAxial response cruise arrived on site only two weeks later, discovering three event plumes, new vent fields, and a still-cooling lava flow (see the summary by Fox, 1995). This detection initiated the era of deep-sea response cruises, largely under the auspices of investigators involved in the National Science Foundation (NSF) Ridge Interdisciplinary Global Experiments (RIDGE) program, its successor Ridge 2000 (http://www.ridge2000.org), and the NOAA Vents Program (http://www.pmel.noaa.gov/vents).

Of the 23 events cataloged between 1986 and 2001 by Cowen et al. (2004), 15 occurred on northeast Pacific spreading ridges where research cruises routinely occur and SOSUS monitoring is available. The only non-Northeast Pacific ridge in that catalog with a dated eruption of lavas on the seafloor was the *Alvin*-discovered 1991–1992 eruption sequence at 9°50'N on the EPR (Haymon et al., 1993). Since then, the global catalog of detected events has expanded to include many segments of the global MOR, back-arc ridges, and volcanic arcs.

On MORs, dated intrusions or eruptions have been detected at spreading rates that vary from ~ 90 mm yr^{-1} (the Northeast Lau Spreading Center) to 11 mm yr^{-1} (the Gakkel Ridge). On the Northeast Lau Spreading Center, a suite of event plumes was released during a small eruption in 2008 (Baker et al., 2011). On the Gakkel Ridge, teleseismic evidence for an eruption was first recorded in January 1999 (Tolstoy et al., 2001) near 85°E, and explosive eruptions (Schlindwein et al., 2005) and massive hydrothermal plumes (Edmonds et al., 2003) were found there in 2001. Remotely operated vehicle (ROV) investigations sampled "zero-age" lava in 2007 at the same location (Sohn et al., 2008). On the slow-spreading (30 mm yr^{-1}) Carlsberg Ridge, an event-plume-like feature extending over ~ 70 km was discovered in 2003 (Murton et al., 2006). The only sites with documented multiple eruptions are the 9°50'N site on the EPR, which erupted again in 2005–2006 (Tolstoy et al., 2006; Soule et al., 2007; Rubin et al., 2008; Fundis et al., 2010), and Axial Volcano on the Juan de Fuca Ridge, which erupted in 1998 (Embley et al., 1999) and 2011 (Butterfield et al., 2011a; Chadwick et al., 2011b).

A new frontier in event studies opened in March 2004, when an ROV visit to the hydrothermally active Northwest Rota-1 Volcano on the Mariana arc revealed an ongoing eruption (Embley et al., 2006). Punctuated explosions of glowing rock and gas persisted at the 520 m deep volcano during each of five further cruises from 2005 to 2010 (Chadwick et al., 2008, 2011a), and a continuous hydrophone record from February 2008 to March 2010 documented explosive discharges at 1–2 minute intervals over the entire 26-month record (Chadwick et al., 2011a; Dziak et al., 2011a). Hydrothermal plume clues again led to a discovery, in 2009, of a similar low-effusion-rate eruption at West Mata Volcano in the northern Lau Basin (Resing et al., 2011). This deepest (1,200 m) active eruption ever observed has both explosive and effusive phases. Hydrophones moored for two five-month deployment periods before and after the seafloor observations recorded variable but continuous explosions, proof that West Mata, like Northwest Rota-1, is undergoing a lengthy eruption episode. Monowai Volcano, in the Kermadec arc, has a 30-year history of teleseismic activity (http://www.volcano.si.edu/reports/bulletin), has undergone at least two major reconstruction and collapse cycles since 1998 (Chadwick et al., 2008), and has an active hydrothermal system (Leybourne et al., 2010).

IMPLICATIONS FROM NEW OBSERVATIONS

Even with this increase in the global extent of known eruptions, the sample size remains small, and our knowledge of the magnitude and rate of crust-ocean interaction at the instant of an eruption is almost entirely circumstantial. Presently, only four event plume episodes can be confidently associated with specific eruptions; two were found by chance during regional plume surveys and two were detected by SOSUS. Large event plumes in the Northeast

Pacific (Table 1) were found above thick (up to ~ 75 m), voluminous (up to ~ 50×10^6 m^3), and slowly extruded pillow mounds, whereas small event plumes were associated with the thin (a few meters), small (~ 1×10^6 m^3) 2008 eruption on the fast-spreading Northeast Lau Spreading Center (Baker et al., 2011). The volume of event plumes and lava flows thus appears linked, as the hydrothermal heat in event plumes is linearly correlated with the available heat in the associated lava flows (i.e., by cooling from ~ 1,200° to 2°C; Baker et al., 2011). Event plumes have had a unique and consistent chemical signature (much lower ^3He/heat and Mn/heat and higher H_2/heat than typical black smoker fluids), including a dynamic and complex population of labile hydrothermal constituents (Cowen et al., 1998). The 1998 eruption at Axial Volcano is a fifth example of eruption-concurrent discharge, but limited sampling during the response cruise, 18 days post-eruption, makes confirmation of event plume characteristics uncertain.

The Gakkel Ridge eruption is notable for the discovery of abundant pyroclastic debris at depths exceeding 4,000 m, well below the 3,000 m depth at which steam can no longer form, and consistent with observation of even deeper (but not historical) explosive activity at 6 km water depth in the Hawaiian North Arch lava field (Clague et al., 2009).

Despite the accumulating evidence of crust-ocean interaction at eruption sites, only halting progress has been made on testing the hypotheses proposed for the creation of event plumes. Analysis of events detected by SOSUS in the Northeast Pacific shows that event plume formation is linked to magmatic diking, as recorded by spatially migrating seismicity (Dziak et al., 2007). Candidates for the source of event (or event-like) plume fluids include the release of high-temperature, pre-formed hydrothermal fluid from the crust (Baker et al., 1989; Cann and Strens, 1989; Cathles, 1993; Wilcock, 1997; Lupton et al., 1999) or magma chamber (Nehlig, 1993); the heating of crustal fluid by a cooling dike (Lowell and Germanovich, 1995); or the conversion of seawater to hydrothermal fluid by cooling lava (Butterfield et al., 1997; Palmer and Ernst, 1998; Clague et al., 2009). Each process seems to require important, but apparently improbable, prerequisites. The first two depend on the sudden appearance of discharge and recharge crustal permeabilities several orders of magnitude higher than apparently normal, and/or the stable storage of large volumes of fluids whose chemistry is virtually invariant among all eruption sites. The last hypothesis depends on a rate of lava cooling and water-rock interaction far higher than predicted or derived from available observations.

Testing these hypotheses requires several key measurements that are logistically challenging. Does some kind of massive fluid release accompany all eruptions? Does event plume formation begin before, during, or after an eruption? Are event plumes generated in hours or days? Do multiple event plumes correspond to pulses of an eruption? Solving these puzzles requires water-column measurements and seafloor observations during an eruption, which can only be attained through well-constrained assumptions regarding potential for eruptive activity, proper placement and instrumentation at a seafloor observatory, and a good measure of serendipity.

A major difficulty in studying MOR eruptions is that every dated MOR eruption consists only of brief (hours, days) pulses of magma effusion, though some appear to have experienced multiple short pulses spaced over several months (e.g., Rubin et al., 1994, 2008, 2009). Observations at the arc volcanoes Northwest Rota-1 and West Mata, on the other hand, reveal a strikingly different eruption mode. At Northwest Rota-1, eruptions observed to date are low volume rate (~ 0–0.03 m^3 s^{-1}), have high gas/lava ratio, and exhibit rhythmic eruptive behavior (Chadwick et al., 2008, 2011a; Deardorff et al., 2011). These characteristics are most consistent with a Strombolian eruptive style, in which partially segregated pockets of magmatic gas rising in the volcanic conduit drive episodic explosions. Sheets of CO_2 bubbles and dense clouds of sulfur particles accompany the explosions at these two volcanoes (Butterfield et al., 2011b).

West Mata has provided the deepest and most visibly dramatic eruption activity ever witnessed, and to date is the only location in the deep sea where glowing lava has been observed flowing across the seafloor. Close-range video captured a unique eruption mode: repeated bursting of large (~ 1 m diameter) incandescent bubbles of magmatic gas, releasing large amounts of H_2O, CO_2, and sulfur (Resing et al., 2011). Accompanying these bursts were quieter effusions of pillow lava downslope of the vents. These observations show that gas release during an eruption, even at great depth, can be vigorous and that fragmental deposits and lava flows can form at the same time. Rubin et al.

(2012, in this issue) discuss further details on eruption styles at MORs and volcanic arcs.

The low effusion rate and quasi-continuous eruption of arc volcanoes such as Northwest Rota-1 and West Mata open a new window to eruption studies. In these settings, ROV operations and long-term instrument deployments (Dziak et al., 2011a; Chadwick et al., 2011a) can methodically observe and sample the products of crust-ocean interaction at the seafloor. Although eruptions in this setting are both exhilarating and informative, they represent only a small fraction of the volume of lava delivered to the seafloor every year along MORs, and with a style that is apparently not as punctuated.

NEW DETECTION AND RESPONSE CAPABILITIES

Of the 35 detection and response efforts since 1986, 15 had a serendipitous "response," 20 had a detection-triggered ship or air response, and four also benefited from "instantaneous" responses by in situ instruments. Mounting an unplanned rapid response is an arduous task. The quickest seagoing mobilizations have taken about a week (Table 1). Responses in fewer than 30 days occurred on only 12 occasions, all but three of those on the Juan de Fuca Ridge, which is close to US ports and within the detection range of SOSUS. Available evidence suggests that even response delays as short as a week will miss crucial syn- and post-eruption processes. At Axial Volcano in 1998, for example, instruments on the seafloor and moored in the overlying waters captured an eruption sequence (Figure 2). Pressure and temperature monitors embedded on the surface of the new lava flow (Fox et al., 2001a) and temperature sensors ~ 10 m above the flow (Baker et al., 1999) both recorded sharply elevated temperatures

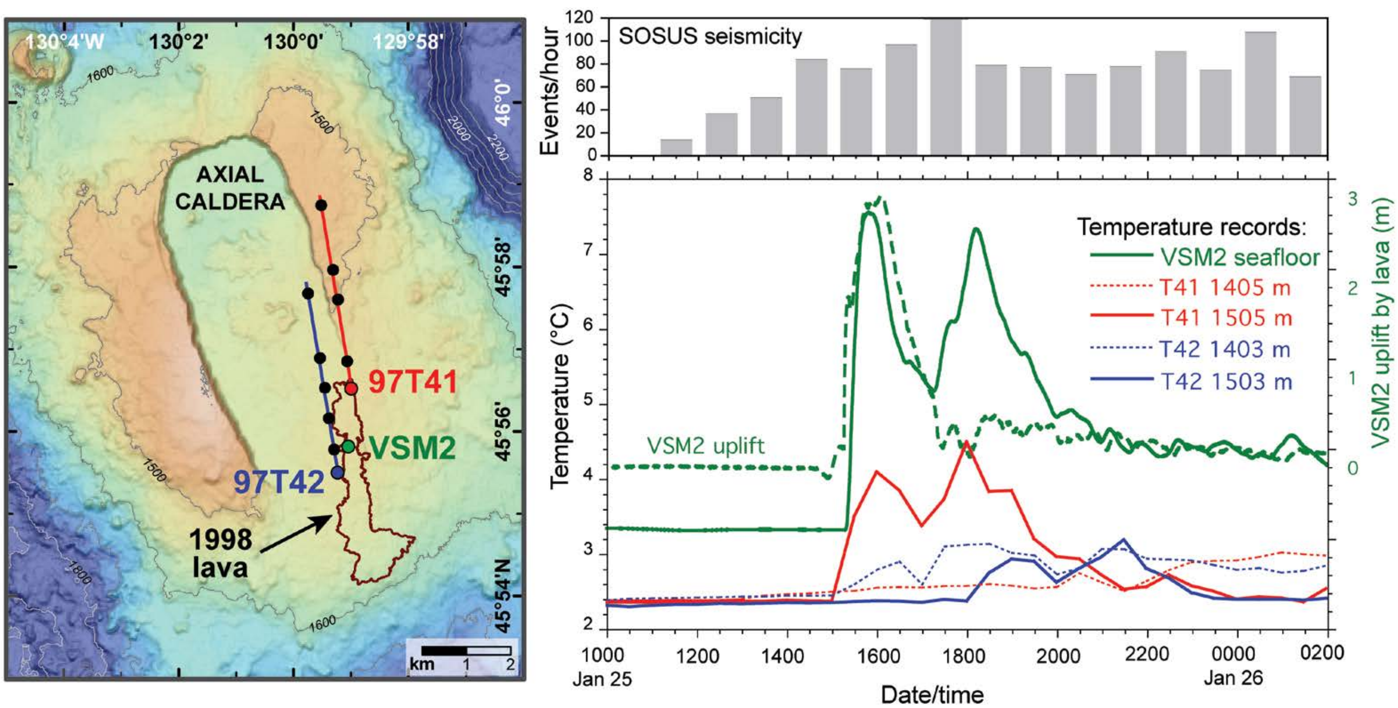

Figure 2. Observations from sensors in place during the 1998 eruption at Axial Volcano on the Juan de Fuca Ridge. These sensors (seafloor Volcanic System Monitor 2 and temperature recorders on moorings T41 and T42, indicated by black dots) document that the eruption of lava and large-scale hydrothermal discharge occurred virtually simultaneously. SOSUS began recording near-continuous seismic activity at 1133 UTC (grey bars). About 3.5 hr later, the VSM2 pressure gauge (green dashed line), entrapped by the lava flow, began an inflation-deflation cycle over the next 130 min. The temperature sensor in VSM2 (green solid line) followed a similar upward-downward cycle and was followed by a second cycle during the next 165 min. A temperature sensor 10 m above the lava on mooring T41 (sampling every 30 min, red dot and lines) underwent a similar cycle set, but at lower temperatures. We attribute these temperature cycles to direct heating from the cooling lava, as the deep sensor on T42 (blue dot and lines), west of the lava flow, showed no temperature increase during the first 3 hr of the eruption. In contrast, the highest-temperature sensor on T42, 115 m above the seafloor, showed an increase concurrent with the VSM2 inflation, well before a similar increase was observed at the highest sensor on T41. This difference is consistent with the westerly currents later observed during the response cruise. For the remainder of the record (until August 1998), the highest temperatures at both moorings were recorded by the shallowest sensors.

(up to several degrees above ambient) for ~ 6 hr, presumably monitoring the initial lava emplacement and cooling. Additional temperature sensors on the moorings—one anchored within the flow itself—documented the appearance of a > 100 m thick plume within minutes of the start of the 72-minute-long sheet flow eruption. By the time ship-based sampling began 18 days later, the thickest (~ 500 m) and most concentrated plume was found some 20 km southwest of the moorings. This tantalizing glimpse of the rapid emergence of eruption-generated discharge encourages our quest for better methods to study and sample these fundamental processes associated with oceanic crust formation and the chemical and biological exchanges related to it. It also underscores the importance of long-term monitoring and development of suites of in situ sensors that can capture samples and record key physical, chemical, and biological data during an event.

Because seafloor eruptions are unpredictable, globally distributed, and (at least on MORs) fleeting, their study poses a daunting challenge. We advocate two approaches. First, increase the global hydroacoustic monitoring network to expand the existing catalog of detected magmatic events. Although rapid responses to more than a few of the detected events will not be feasible, a growing database would greatly improve our understanding of the pattern of eruption frequency and size at MORs and volcanic arcs and identify sites of activity with extended durations. The high frequency of SOSUS-detected seismic events with volcanic characteristics (Table 1) hints at perhaps more magmatic activity than we presently appreciate. Such a database might also identify locations where eruptions are frequent and thus deserving of more focused and sophisticated monitoring. The second proposal is to establish long-term monitoring networks at a few propitious sites with a reasonable opportunity of capturing an eruption event on decadal or shorter time frames. In the following sections we discuss new detection and response capabilities that make these approaches realistic.

Expanding Hydroacoustic Monitoring

The success of SOSUS spurred the development of moored autonomous hydrophones that could expand the very restricted ranges of permanent hydroacoustic networks. Autonomous hydrophones were first deployed successfully around the northern EPR in 1996 (Fox et al., 2001b), and have since monitored spreading ridges in the Atlantic, Indian, and Southern (Bransfield Strait, Antarctica) Oceans (e.g., Smith et al., 2002; Royer et al., 2008; Dziak et al., 2010). By providing detailed catalogs of the spatial-temporal distribution of seismicity on ridges and volcanic arcs, moored hydrophones have greatly increased the database of *T*-wave earthquakes, from both volcanic and tectonic sources.

A significant drawback to existing moored arrays is the absence of real-time information, precluding a prompt response to a detected event. This deficiency led to the addition of hydrophones to profiling floats and ocean gliders. The QUEphone, or Quasi-Eulerian hydrophone, is a new-generation free-floating autonomous hydrophone with a built-in satellite modem and a GPS receiver (Matsumoto et al., 2006). Because it does not have station-holding capability, its main value to response efforts is its potential for rapid deployment by aircraft. Ocean gliders offer a more structured monitoring strategy, as they can be preprogrammed to follow, and repeat, a horizontal and vertical course. Low instrument noise and buoyancy-based drive systems make gliders ideal acoustic monitoring tools, able to navigate around seafloor obstacles and resurface every few hours to transmit data. Matsumoto et al. (2011) demonstrated this capability by flying a glider around West Mata Volcano and recording the broadband volcanic explosion sounds.

For multiyear, high-quality hydroacoustic monitoring, however, we envision the development of three-dimensional arrays of moored hydrophones, linked acoustically to a central communications mooring that can report events on demand, on schedule, or on detection of a defined acoustical signal. With emerging technology, arrays with spatial scales small enough to communicate acoustically (horizontal scales < ~ 5 km) could monitor the seismic environment of an entire MOR segment (linear scale ~ 200 km). With proper planning and geological foresight, such arrays could be deployed at several key locations throughout the global ocean to compile hydroacoustic statistics at sites of varying geologic characteristics. Detection-triggered alerts could inform ships of opportunity about nearby events.

Establishing Seafloor Volcano Observatories

Although scattered hydroacoustic arrays will accelerate our understanding of event frequency and distribution, they will not solve the event-targeted sampling problem. Accomplishing that objective requires "boots on the ground"—sophisticated seafloor systems to observe and sample eruptions. Because of the inherent complexity and cost of seafloor observatories, possible sites must meet two stringent requirements: accessibility to power and communications, and a high probability of magmatic activity. NSF's Ocean Observatories Initiative (OOI) is now undertaking just such a vision. For many years, OOI has been planning a large-scale cabled network (the Regional Scale Nodes or RSN) along the boundaries of the Juan de Fuca Plate (OOI, 2006; http://www.oceanobservatories.org). The only ridge-crest node of this network will be installed on the summit of Axial Volcano. The end result will be the most advanced volcano observatory on the seafloor: a monitoring network of instruments with completely new capabilities for real-time communication, long-term observations and sampling, and virtually unlimited power and bandwidth.

Recent events exemplify the benefits of an observatory rationale. Since the 1998 eruption at Axial Volcano, that site has been the focus of over a decade of time-series measurements conducted by yearly cruises and in situ sensors. Periodic geophysical monitoring has tracked the steady re-inflation of the caldera floor, leading to forecasts of another eruption by 2014 (Chadwick et al., 2006) to 2020 (Nooner and Chadwick, 2009). In July 2011, however, a routine survey cruise to Axial discovered those forecasts to be too conservative: new lava had already flooded the 1998 eruption area (Butterfield et al., 2011a; Caress et al., 2011; Chadwick et al., 2011b). Because key elements of the Pacific SOSUS arrays were offline (Haxel et al., 2011), real-time monitoring was compromised and the eruption went unrecognized for several months until observers discovered new lava on the seafloor. Seafloor instruments recovered from the site in July 2011 recorded the signature of an eruption on April 6, 2011 (Haxel et al., 2011), but a rapid response opportunity went unfulfilled. Follow-on studies of the in situ and remote geophysical records, plus ^{210}Po dating of erupted lavas, will provide constraints on the duration of the eruption

The primary Axial RSN seafloor instrument array features fixed geophysical, biological, and chemical sensors (Figure 3). Although this initial array will provide unprecedented monitoring of the caldera, it will not be capable of either observing eruption-ocean interactions, such as the formation of event plumes or collecting water and rock samples. To test competing event-plume hypotheses will require monitoring both lava emplacement (as was fortuitously recorded at one Axial location in 1998) and the three-dimensional development

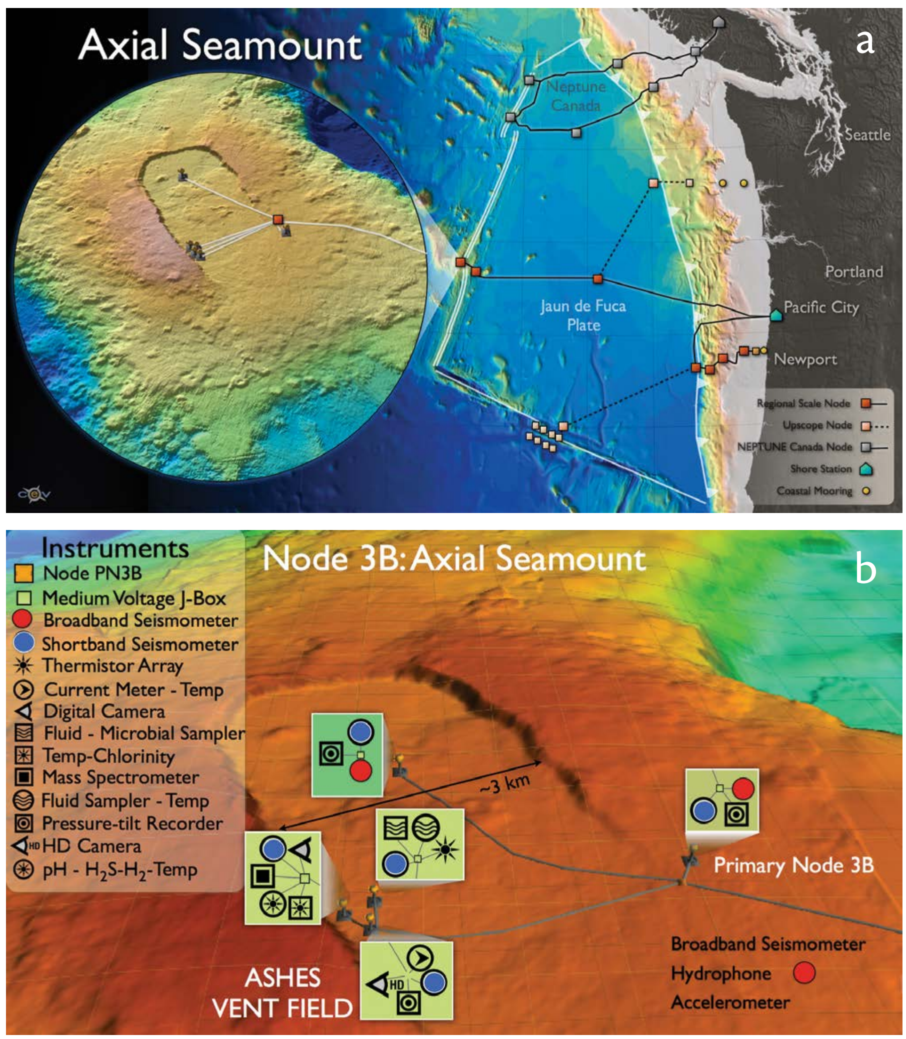

Figure 3. (a) Schematic drawing of the Regional Scale Node array in the Northeast Pacific. (b) Details of the planned instrument array in Axial caldera, Juan de Fuca Ridge. *Images courtesy of Ocean Observing Initiative Regional Scale Nodes and Center for Environmental Visualization, University of Washington*

of hydrothermal plumes above eruption sites (as was only partially observed at two Axial locations in 1998; Figure 2). Existing technology could progressively enhance the Axial node with additional tilt-pressure-temperature sensors, fluid samplers, and instrumented moorings extending at least 500 m above the seafloor. Such an array could compare the onset and duration of plume formation with the emplacement and cooling history of a lava flow, critical measurements needed to test event plume hypotheses.

“FIELD RESPONSES AT MID-OCEAN RIDGES HAVE FOUND THAT EVENT PLUMES OCCUR OVER A WIDE RANGE OF ERUPTION STYLES AND SIZES, AND THUS MAY BE A COMMON CONSEQUENCE OF RIDGE ERUPTIONS.”

Future technological possibilities include autonomous underwater vehicles (AUVs) positioned at powered and networked docking stations within the caldera. AUVs could survey the water column and map the seafloor during and after an eruption, possibly eliminating the need for extensive mooring arrays. The Monterey Bay Aquarium Research Institute mapping AUV has been used since 2007 to collect 1 m resolution bathymetry of Axial's summit (Clague et al., 2007). Repeat surveys were collected immediately after the 2011 eruption was discovered, yielding a high-resolution depth-difference map showing the extent, morphology, and thickness of a new lava flow in unprecedented detail (Caress et al., 2011).

Some deep submarine volcano observatories are already operating. NEPTUNE Canada (http://www.neptunecanada.ca) is the world's first regional-scale underwater ocean observatory network that plugs directly into the Internet, with operating nodes at two hydrothermal sites on Endeavour Segment of the Juan de Fuca Ridge. MOMAR-D, a deep-sea observatory of the European Seas Observatory Network (http://www.esonet-noe.org), is a demonstration mission to deploy and manage a deep-sea observatory at the Lucky Strike vent field on one of the most volcanically active segments of the Mid-Atlantic Ridge.

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