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The 1996 Gorda Ridge event detection and response activities: historical perspective and future implications

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Abstract

Ridge axis magmatic events, including diking and eruptive phases, are episodic perturbations that trigger a sequence of interrelated and rapidly evolving geophysical, chemical and biological processes associated with the formation of ocean crust. Access to the US Navy's SOund SUrveillance System (SOSUS) in 1993 via PMEL-NOAA's T-Phase Monitoring system launched the scientific community from mere reliance on serendipitous encounters of magmatic events to their remote detection at the initiation of an event's distinctive seismic signature and subsequent 'directed' rapid and follow-up field responses. This capability offers exceptional opportunities to observe and quantify covariation among related seismic and hydrothermal processes and to provide basic new constraints on maturing models of submarine volcano-hydrothermal systems.

The detection of a seismic swarm on the northern Gorda Ridge on 28 February 1996 prompted a multi-cruise response to investigate any new lava flows and event- and chronic-style hydrothermal discharge associated with suspected dike intrusion and eruptive activity. The results of these studies are described in the 12 papers composing this special issue on the detection of and response to mid-ocean ridge magmatic events. The successes and limitations of the Gorda Ridge event response series as well as previous event response efforts clearly demonstrate the need for greater pre-event coordination and preparation. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

The intrusion of a magma dike into the neovolcanic zone of a mid-ocean ridge has been described succinctly as the irreducible, or "quantum", event in the accretion of

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the upper ocean crust (Delaney et al., 1994). Over the last decade, the community of mid-ocean-ridge researchers has come to recognize the profound importance of transient intrusive and extrusive volcanic events on seafloor geological, chemical, and biological processes. Consequently, the interest in real-time and long-term examination of diking and related phenomena has grown sharply in recent years.

Ridge axis diking/eruptive events are episodic perturbations that trigger a sequence of interrelated and rapidly evolving physical, chemical, and biological processes associated with the formation of ocean crust. Dikes and lava flows develop rapidly and instantly alter the local hydrothermal flow regime. Volcanic activity produces hydrothermal discharge with a distinct geochemical signature, and triggers specific microbial and macrobiological responses in the adjacent crust and overlying water-column. Significant change in a variety of processes can be expected to take place over limited time spans. In effect, diking-eruptive events offer short-term natural "experiments" unachievable in the laboratory. Observing and quantifying covariation among related processes provides basic new constraints on presently immature models of submarine volcano-hydrothermal systems. Furthermore, knowledge of the effects and duration of short-lived events will augment our ability to characterize temporal variability in longer-term, seemingly more stable systems.

The first encounters with mid-ocean ridge diking/eruptive events were serendipitous, facilitated by intensive studies over specific areas of the global ridge system. In 1986 and 1987, the discovery of massive but short-lived discharges of hydrothermal fluid over the Cleft segment of the Juan de Fuca Ridge suggested the occurrence of a seafloor spreading events (Baker et al., 1987, 1989). This hypothesis was supported by subsequent mapping of large pillow mounds and lava flows dated to the mid-1980s (Embley et al., 1991; Chadwick and Embley, 1994). Because much of the seafloor investigation at the Cleft site was conducted only years after the 1986 and 1987 discoveries of the megaplumes, the significance of such "event plumes" was not fully appreciated until the field work had been completed. For example, there was no explicit study of microbial activity at the Cleft site, although V. Tunnicliffe and R.W. Embley (pers. comm.) noted flocculated deposits similar to the microbial flocs associated with later eruptions (Haymon et al., 1993; Juniper et al., 1995). Nonetheless, continuing geological, geochemical, and biological studies conducted at Cleft built a strong circumstantial case linking diking/eruptive events and event plumes (Embley and Chadwick, 1994) and laid the groundwork for a theory of the chemical evolution of hydrothermal fluids following an eruption (Massoth et al., 1994; Butterfield and Massoth, 1994).

A second serendipitous opportunity to study an eruptive/diking event occurred in 1991 when an Alvin expedition happened upon the immediate aftermath of an eruption at 9°N on the East Pacific Rise (Haymon et al., 1993). Unlike at Cleft, the availability of detailed pre-eruption geological maps facilitated the formulation of models of volcanic and hydrothermal interactions (Haymon et al., 1993). Continuing studies since 1991 have documented significant changes in the chemical (Lilley et al., 1992; Von Damm et al., 1995) and biological (Lutz et al., 1994) effects of the eruption, refining the ideas of hydrothermal chemical evolution developed at Cleft. Perhaps the most remarkable observation was that of the "snowblower vents" geysering plumes of microbial debris from the seafloor, the most provocative illustration of a "deep hot biosphere" ever noted. No event plumes were detected after the eruption, although only a few water column profiles were collected (Macdonald et al., 1992).

After multiple chance encounters it was clear that future progress would depend on replacing fortune with design. In 1993, the NOAA VENTS Program gained access to the U.S. Navy's SOund SUrveillance System (SOSUS) in the northeast Pacific and began real-time monitoring of acoustic T-waves generated by seafloor seismic activity (Fox et al., 1993/1994; Fox and Hammond, 1993/1994; see also Fox and Dziak, 1998). Since then our ability to detect and locate transient events associated with active submarine volcanoes has been fundamentally improved. As a community, we are no longer dependent on happenstance and serendipity to provide opportunities for in-depth characterization of these elementary events of oceanic crustal accretion.

The first remote detection of a rapidly migrating along-axis submarine earthquake swarm occurred in June, 1993, on the CoAxial segment of the Juan de Fuca Ridge (Fox et al., 1995; Dziak et al., 1995). The seismic events migrated a distance of nearly 40 km between June 26 and 28, 1993, the classic signature of dike intrusion developed from terrestrial observations (for details see Fox, 1995). Four response cruises in the next few months mapped and sampled three event plumes, chronic plumes and vent fluids from two new vent fields, and a still-cooling lava pile (Embley et al., 1995; Baker et al., 1995; Massoth et al., 1995; Butterfield et al., 1997). Particularly interesting was the chemical and biological distinction between the two vent fields, Flow and Floc. The Flow site, located at the terminus of the dike intrusion, featured a new lava mound and a metal-rich hydrothermal effluent where biological activity was sparse. No lava eruption occurred at Floc, about 30 km back along the strike of the dike, but the volatile-rich effluent there supported a rich biological community highlighted by extensive distributions of microbial mats and "snowblower" vents (Juniper et al., 1995) similar to those observed at 9°N (Haymon et al., 1993). Multiple thermophiles have been cultured from these waters that grow optimally at temperatures (80–90°C) considerably higher than the venting fluids (Holden et al., 1998). Time series sampling of vent fluids and plumes at both Flow and Floc has added considerably to our knowledge of the post-eruption evolution of hydrothermal fluids (Butterfield et al., 1997; Baker et al., 1998).

Subsequent to the 1996 Gorda Ridge Event described below, the largest swarm of earthquakes ever observed at a Hawaiian volcano was remotely detected in July/August, 1996, at Loihi Seamount on the flank of the island of Hawaii (Duennebier et al., 1997). Over 4000 earthquakes were detected over a 3 week period by the U.S. Geological Survey's Hawaiian Volcanic Observatory. A rapid response and two followup cruises to Loihi documented for the first time on a hotspot volcano a submarine eruption, the formation of a pit crater, and eruption related greatly enhanced hydrothermal venting. Geophysical and petrologic data from the recent Loihi eruptive episode have provided interesting comparisons and contrasts with the well studied nearby Kilauea volcano (Dunnebier et al., 1997; Garcia et al., 1998).

2. Recent Gorda Ridge event

This special issue of Deep-Sea Research II describes the detection of, and response to, the recent magmatic event observed at the Gorda Ridge near 42.67° N, 126.8°W, within the northeast Pacific SOSUS net. Each paper discusses the Gorda Ridge event results in light of previous event studies, as well as their implications for future response activities.

The paper by Walker and Hammond (1998) provides a historic (1964–1966) perspective on the use of the SOSUS hydrophone arrays to detect and locate seismic and volcanic events along and near the Juan de Fuca and Gorda Ridges. Interestingly, they report a sequence of small T-wave events that may have been associated with a 1965 eruption on Gorda Ridge and which visually resemble the 1993 CoAxial and 1996 Gorda Ridge seismic events.

Fox and Dziak (1998) report that seismicity associated with the 1996 Gorda Ridge event began on 28 February 1996. The early intense seismicity of more than 40 events/h decreased to less than 5 events/h by 13 March. A second episode of seismicity peaked at over 30 events/h on 15 March, three days after the end of the first response cruise. The general nature and level of the seismicity was similar to that of the 1993 CoAxial dike injection and eruption: a rapid series of small earthquakes without a large foreshock. The seismicity also showed some periodicity, as bursts of seismic activity were followed by more quiescent periods.

The similarity of the Gorda Ridge event to the CoAxial event prompted a rapid response cruise and subsequent follow-up cruises. Fortuitously, the NOAA ship McArthur and the UNOLS ship RV Wecoma were available for cruises 10 days and 5 weeks, respectively, after the first seismic events. Thanks to the predisposition of the NSF RIDGE Program and NOAA's VENTS Program towards mid-ocean ridge volcanic event studies, funding for the Gorda Ridge response cruises was secured within days of the start of seismicity. Directed by locations of the T-wave epicenters the first Gorda Ridge Event Assessment Team (GREAT) arrived on station on 9 March, only 10 days after seismicity began. As discussed in Baker (1998), the GR 1 cruise discovered a 15 km diameter event plume, EP96A, centered between depths of 1800 and 2800 m above the shallowest portion of the axial valley axis at $\sim$3100 m. Depth limitations of the McArthur's deep-sea winch precluded sampling of the underlying chronic plume. One month later (7 April to 16 April) GR2 was conducted from the Wecoma equipped with a full-ocean-depth winch and deep-tow camera sled. Systematic efforts to relocate EP96A failed, and only a weak, near-bottom chronic plume remained at the original EP96A site. However, GR2 mapped a distinctly different deep chronic plume to the south of the EP96A site, as well as the edge of a second event plume, EP96B, above the western wall of the axial valley. Near the end of GR2 this suspected event plume was seeded with a neutrally buoyant lagrangian "RAFOS" float. The RAFOS float appeared to successfully track EP96B, traveling some 10 net km to the northwest before surfacing two months later on 10 June at the start of the GR3 cruise (Lupton et al., 1998). Using the NOAA ship Discoverer, cruise GR3 thoroughly mapped a 10-km-diameter event plume centered at the position of the resurfaced float. Chronic venting at the EP96A site had virtually ceased by GR3.

Physical (Baker, 1998) and geochemical data (Feely et al., 1998; Kelley et al., 1998; Massoth et al., 1998) indicate that EP96B and EP96A were distinct plumes whose origins were separate in time and place. Furthermore, nearly identical relationships between hydrothermal temperature anomalies and other parameters such as light scattering (Baker, 1998), particulate Fe (Feely et al., 1998), and dissolved Mn (Massoth et al., 1998), also suggest that the event plume mapped during GR3 was indeed the same plume, EP96B, seeded with the RAFOS float. The contention that the GREAT cruises discovered 2 event plumes directly effects the interpretation of data on nonconservative parameters and processes. If GR3 revisited EP96B, then a two point time series is realized. Consequently, trends in the EP96B geomicrobial Mn data can be considered as a time series (Cowen et al., 1998). However, while the age of EP96A at the time it was sampled during GR1 (days) is well constrained, the age of EP96B at the time it was first sampled at the end of GR2 is less certain. Assuming that the SOSUS system would detect the geophysical processes associated with the formation of even a modest event plume, EP96B would have been $\sim$1month old when sampled near the end of GR2. However, Massoth et al. (1998) present an alternative age derived from an iron partitioning and aggregation model that suggests GR2-EP96B may have been formed only days before it was sampled during GR2, but weeks after the cessation of the SOSUS-detected seismic swarm.

The 1996 Gorda Ridge event is notable for the rapid extinction of chronic venting (Baker, 1998), especially in light of the multiyear duration observed at Cleft (Baker, 1994), 9°N on the EPR (Von Damm et al., 1995), and CoAxial (Baker et al., 1998). Apparent trends in Mn microbial geochemical data also differ from those inferred from previous studies of chronic plumes and from the Cleft segment 1986 and 1987 event plumes (Cowen et al., 1998; Gendron et al., 1993). Inventories of hydrothermal heat (Baker, 1998) and chemicals (Feely et al., 1998; Kelley et al., 1998; Massoth et al., 1998) associated with the Gorda Ridge event plumes are also discussed both with respect to previous events and in the context of relative contributions from event-style versus chronic-style venting. Accurate inventories of the hydrothermal heat and chemicals in an event plume always have been suspect owing to the complexities of mixing and hydrothermal anomaly definition. To overcome this problem, Lavelle et al. (1998) have developed a method to calculate factors for rescaling field-measured integrals of anomalies into the actual anomaly discharge. For example, measured hydrothermal heat in the Gorda Ridge event plumes must be increased by a factor of 2.4 to equal the seafloor discharge.

The geologic context of the Gorda Ridge eruption was successfully investigated using a deep-towed camera, SeaBeam multibeam sonar, and sidescan sonar. Remotely operated vehicles (ROVs) were also employed during two additional cruises: R/V Laney Chouest with the Advanced Tethered Vehicle (August 27–28) and the R/V Thompson with JASON (September 15–18) (Embley et al., 1996). Chadwick et al. (1998) describe the extensive photographic and acoustic imaging of the seafloor used to estimate the area and volume of the new lava flow discovered at the EP96A site during GR 2. Chadwick et al. (1998) use similar data plus T-wave swarm (Fox and Dziak, 1998) and plume (Baker, 1998) data to speculate that a second lava flow may have erupted to the south, spatially coincident with the 15 March earthquake swarm and event plume EP96B. Using a newly developed ^{210}Po–^{210}Pb radiometric technique for dating young lava flows, Rubin et al. (1998) were able to confirm the freshness of the lava and provide eruption ages consistent with the timing of the enhanced T-wave seismicity. Results from other geochemical analyses on the same lava samples lead to the intriguing conclusion that the new lava flow erupted from multiple parent magma sources and melting conditions over a several-week-long interval (Rubin et al., 1998).

Closely monitored eruptive events offer a unique opportunity to investigate MOR hydrothermal systems for improved insight into the habitats and ecology of subseafloor microbial life. Summit and Baross (1998) sampled specifically for high temperature microbes in event plumes EP96A and EP96B during GR 1 and 2, respectively. Large numbers of anaerobic thermophiles were successfully cultured from most of the event plume samples, while none were found in any of the background seawater samples. Cultured strains include new species of heterotrophic thermophilic archaea (Summit and Baross, 1998). Summit and Baross (1998) conclude that the microbes must have been entrained from a subseafloor environment tapped by the event plume source fluids. Juniper et al. (1998) present the first observations of bacterial and viral abundance in event plumes. They find that while bacteria abundance was enhanced by a factor of 2–3 in event plumes relative to ambient seawater, viral numbers were depleted in the youngest event plume (EP96A) but enhanced in the older event plume (EP96B).

3. Conclusions

The papers composing this special issue present new multidisciplinary data on the detection of and response to MOR volcanic events. The results of the Gorda Ridge 1996 event real-time detection and subsequent field responses enlarge a limited data set. Cumulatively, the successes of the three recent remotely detected events (CoAxial, Loihi, and Gorda Ridge) have resolved the community to strengthen its ability to more effectively respond to future events. The value of the SOSUS system is paramount. While the seismic signatures of tectonic versus volcanic events still need refinement, real-time detection of the events is essential in order to respond rapidly enough to observe the initiation of rapidly changing processes. These include the discharge and biogeochemical evolution of event plumes, the creation and evolution of chronic-style venting, and the seismic response of the crust to the dike intrusion. The first use of RAFOS floats in hydrothermal plumes during the Gorda Ridge event response clearly demonstrated their utility in tracking event plumes. Future response studies of the transport and evolution of event plumes will depend on the deployment of readily available RAFOS or similar floats. The deep-tow-camera capability on GR 2 provided rapid verification of an eruption and valuable guidance for subsequent submersible investigations.

Although investigators and agencies were able to launch comprehensive field expeditions within days, constraints on the initial response to the Gorda Ridge event also confirmed the need for greater pre-event planning and coordination. For example, while the availability of the McArthur was a remarkable asset, the unavailability of a full ocean depth winch frustratingly limited GR1's ability to efficiently survey the water column for event and chronic plumes, or to image or sample the seafloor. Other sampling and analytical procedures were also precluded during GR1 and 2 due to the short lead-time. As a community, we have realized that with improved planning and coordination many of these constraints can be eliminated or minimized. To this end the event detection and response community has taken significant steps toward organizing itself: formation of an electronic interactive page on the World Wide Web (http://ridge.unh.edu/edrr) and of the Event Response Coordination Committee (ERCC) (Embley et al., 1997). Community recommendations for pre-event coordination and suggested essential elements for future response efforts have recently been published (Embley et al., 1997). These efforts are fully supported by both the RIDGE and VENTS Programs. This commitment is articulated within the Event Detection and Response element of the RIDGE 1993–1997 Science Plan (RIDGE, 1992), the 1995/96 Program Announcement (RIDGE, 1995), as well as the new 1998–2002 Science Plan (RIDGE, in preparation). These cumulative efforts were already evident during the final preparation of this special issue in the community's predisposition toward responding to the January/February, 1998, seismic event at Axial Volcano, Juan de Fuca Ridge, despite anticipated and realized winter conditions in the northeast Pacific!

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