Monitoring Marine Eruptions

Chapter I of

Recommended Capabilities and Instrumentation for Volcano Monitoring in the United States

Scientific Investigations Report 2024–5062

U.S. Department of the Interior
U.S. Geological Survey

Cover. U.S. Geological Survey Alaska Volcano Observatory scientist J. Lyons prepares to deploy hydrophones (underwater acoustic sensors) in the Bering Sea near Bogoslof Island, Alaska. These instruments were deployed in response to the shallow submarine eruption of 2016–2017. Photograph by A. Van Eaton, U.S. Geological Survey, May 21, 2017. Background image shows a typical view of the 2008–2018 lava lake in the Overlook crater within Halemaʻumaʻu, Kīlauea. Photograph taken from a helicopter by Tim Orr, U.S. Geological Survey, on August 16, 2013.

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By Gabrielle Tepp

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U.S. Geological Survey, Reston, Virginia: 2024

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Suggested citation:
Tepp, G., 2024, Monitoring marine eruptions, chap. I *of* Flinders, A.F., Lowenstern, J.B., Coombs, M.L., and Poland, M.P., eds., Recommended capabilities and instrumentation for volcano monitoring in the United States: U.S. Geological Survey Scientific Investigations Report 2024–5062–I, 7 p., https://doi.org/10.3133/sir20245062I.

ISSN 2328-031X (print)
ISSN 2328-0328 (online)

Contents

Figure

Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	247.1	acre
square kilometer (km^2)	0.3861	square mile (mi^2)

Abbreviations

IMS	International Monitoring System
OBS	ocean-bottom seismometer
RSP	Polynesian Seismic Network
SOFAR	Sound Fixing and Ranging

Chapter I

Monitoring Marine Eruptions

By Gabrielle Tepp[1]

Introduction

Submarine volcanoes produce much of the same seismicity and eruptive activity as subaerial volcanoes and can pose hazards to society. Although they can be monitored with similar techniques and methods as described in other chapters of this volume, their submerged location brings unique challenges. This chapter addresses these challenges and provides recommendations for monitoring volcanoes fully or partly in marine environments to meet the capabilities described in other chapters of this volume.

The United States and its territories host dozens of submarine volcanoes with most (around 60) in the Commonwealth of the Northern Mariana Islands. Approximately 20 of the Northern Mariana Islands submarine volcanoes are known to be hydrothermally active, and 10 have confirmed eruptions since the 1950s (for example, Baker and others, 2008; Tepp and others, 2019a). Nine of those volcanoes were considered by the National Volcanic Threat Assessment (Ewert and others, 2018) to have a combination of eruptive type and summit depth that poses a higher risk of hazardous eruptions, although only one was listed as a moderate (level 3) threat. Other notable submarine volcanoes of interest to the United States that have historically erupted are Axial Seamount off the Washington State coast, Kamaʻehuakanaloa in Hawaiʻi, and Vailuluʻu seamount in American Samoa. All of these, however, have a low risk of hazards because of their depth (greater than 600 meters below sea level) and eruptive type and so are not included in the National Volcanic Threat Assessment. In addition to submarine volcanoes, the submerged flanks of island volcanoes can also be a source of hazardous submarine eruptions—for example, the 1877 eruption of Mauna Loa, Hawaiʻi, in Kealakekua Bay (Wanless and others, 2006).

The most notable submarine eruption in recent times was the 2022 eruption of Hunga Tonga–Hunga Haʻapai in Tonga, which was one of the largest eruptions on Earth in the past 100 years. It created a massive volcanic plume, unprecedented shock waves, and far-reaching tsunami (Lynett and others, 2022). Other recent submarine eruptions in the Pacific Ocean Basin have produced subaerial plumes that reached aircraft heights (Carey and others, 2014) and large pumice rafts that can affect marine traffic and harbors (for example, Jutzeler and others, 2014; Kornei, 2019). These examples illustrate the potential hazards of major submarine eruptions. Yet, submarine volcanoes are largely unmonitored, and many eruptions occur that are unnoticed or only identified hours or days afterward.

Within U.S. territory, submarine volcanoes in the Northern Mariana Islands have been known to produce eruptive activity that can affect society. Reports from fishermen and other marine vessels in the Northern Mariana Islands have noted underwater explosions, sea-surface discoloration, and bubbling water, all of which are known to be signs of submarine volcanic activity. South Sarigan seamount, located about 160 kilometers (km) north of Saipan, erupted in 2010 from greater than 150 meters below the sea surface, resulting in a gas and ash plume that reached more than 11.9 km into the atmosphere (for example, Searcy, 2013; Embley and others, 2014), high enough to affect international air traffic. Precursory and co-eruptive seismicity was detected on the regional Northern Mariana Islands seismic network (Searcy, 2013) and on global monitoring instruments (Green and others, 2013).

Monitoring of submarine volcanoes is best accomplished with marine-based instrumentation, which is also useful for monitoring small island volcanoes that may not have the land area necessary for comprehensive subaerial monitoring. The primary marine-based instrumentation used for submarine volcanoes includes ocean-bottom pressure sensors to assess sea-floor deformation, ocean-bottom seismometers (OBSs) to detect seismicity, and both moored and ocean-bottom hydrophones to detect submarine explosions. Other sensors offer important monitoring data, such as turbidity, temperature, and chemistry of hydrothermal emissions. Marine-based instruments are typically deployed in campaign-style networks with no real-time telemetry owing to cost considerations and technical limitations. However, when necessary, marine instruments can be operated in real time using cables to transmit data to land-based facilities; other technologies for this purpose are in use or in development, such as acoustic transmission from the instrument to a moored buoy (Matsumoto and others, 2016) and a winch-based system with a satellite antenna that is part of the instrument mooring (Matsumoto and others, 2019). Emerging technologies for marine-based monitoring may be considered as part of a future monitoring plan. These technologies include ocean gliders and floats with on-board hydrophones that have been used to record earthquakes and submarine eruptions (for example, Matsumoto and others, 2013; Sukhovich and others, 2015) and fiber-optic cables that have been used as strainmeters to detect earthquakes (for example, Marra and others, 2018; Lindsey and others, 2019). Land-based instruments and satellites can also provide some capability for monitoring submarine volcanoes, but they provide more limited observations than marine-based instrumentation.

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Recommended Capabilities

Regional-Scale Monitoring of Submarine Eruptions

To provide for public safety from submarine volcanoes, it is important to monitor for submarine volcanic unrest and to detect eruptions, even at volcanoes far from monitoring instrumentation. Remote monitoring of submarine volcanic activity is best accomplished with hydroacoustic and seismic signals, although infrasonic and atmospheric acoustic signals are sometimes detected from submarine eruptions that breach the sea surface (for example, Tepp and Dziak, 2021). Hydroacoustic signals (hereinafter referred to as T-phases) can be produced directly in the water column by explosions, or they can be generated by the conversion of a seismic signal at the seafloor (for example, Talandier and Okal, 1998). Importantly, T-phases can propagate much farther than seismic signals owing to the comparatively low attenuation of sound in water and the deep-ocean waveguide known as the Sound Fixing and Ranging (SOFAR) channel. T-phases from volcanic activity have been detected at distances exceeding 15,000 km and even from different ocean basins (for example, Johnson and others, 1963; Metz and others, 2016).

Beginning in the 1950s, hydrophone arrays operated by the Department of Defense recorded at least a dozen submarine eruptions (for example, Dietz and Sheehy, 1954; Dziak and Fox, 2002). Currently, the Comprehensive Test Ban Treaty Organization operates several cabled hydrophone arrays around the world as part of its International Monitoring System (IMS) that monitors for nuclear explosions. These arrays transmit data in real time, and some have data publicly available for volcano monitoring purposes, such as the Wake Island (U.S.) arrays. Hydrophone arrays (fig. I1) operate similarly to infrasound arrays and can be used for finding bearings to volcanic activity at regional distances. IMS data have also been used in numerous research studies of submarine volcanoes (for example, Green and others, 2013; Metz and others, 2016; Tepp and others, 2019b), which demonstrates the potential benefit of such systems to monitoring.

Land-based instruments have also been used for real-time monitoring of submarine volcanoes. The longest operating and most successful network in this regard is the Polynesian Seismic Network (RSP; for example, Talandier and Kuster, 1976; Talandier, 2004), which was specifically designed to optimize T-phase detection. The seismic-station recording parameters and locations are based on T-phase characteristics and propagation physics. The RSP has detected volcanic activity throughout the Pacific Ocean Basin, including activity of submarine volcanoes in the Northern Mariana Islands. The IMS hydroacoustic network also contains some land-based seismic stations that have been optimized for T-phase detection in the same way as the RSP (for example, Okal, 2001). Non-optimized land-based seismic networks can also detect submarine volcanic activity, including typical seismic phases and T-phases. For example, the Northern Mariana Islands seismic network recorded precursory seismicity and eruptive activity from South Sarigan seamount in 2010 (Searcy, 2013); an earthquake swarm, major eruption, and large landslide at NW Rota-1 Seamount in 2009; and explosive eruptions from Ahyi seamount in 2014 (Tepp and others, 2019b). Typically, land-based seismic monitoring is most successful when sensors are located within 30 km of the submarine activity, which allows for the detection of most seismic phases. More distant seismometers may only detect strong seismic phases or some T-phases.

Satellite and aerial imagery can also be important for detecting submarine volcanic activity that has resulted in discolored water, pumice rafts, subaerial plumes, or other surficial activity. These monitoring methods provide little to no ability for monitoring preeruptive unrest of submarine volcanoes but are useful for identifying and characterizing eruptions that are active or very recently ended.

Figure I1. Photograph from the June 2017 Northern Mariana Islands hydrophone deployment. Four hydrophone moorings, arranged in a diamond-shaped array, were deployed about 110 kilometers northwest of Saipan in about 4,000 meters of water. The large orange spheres are floats that hold the moorings vertical in the water column and allow for instrument retrieval. Old train wheels are used as anchors and the spools of cord connect all parts of the mooring. Deployment operations were done off the motor vessel (M/V) *Peregrine* (Pacific Marine Enterprises) in collaboration with the National Oceanic and Atmospheric Administration (NOAA) and with assistance from the Commonwealth of the Northern Mariana Islands Office of Homeland Security and Emergency Management. The hydrophones recorded signals from submarine volcanoes, earthquakes, and other natural and man-made sources for approximately 1 year (Tepp and others, 2021). Photograph by G. Tepp, U.S. Geological Survey.

Instrumentation

Small-aperture hydrophone arrays are typically deployed with either three or four instruments spaced about 2 km apart (for example, Hanson and others, 2001; Bohnenstiehl and others, 2013). Additional instruments can help refine detection parameters and provide redundancy in case of instrument failure. Each instrument is deployed on a mooring that holds the hydrophone within the SOFAR channel to achieve the best long-range detection capability. These moorings can be self-contained and powered by batteries, with data available only after instrument recovery. To provide real-time monitoring, they must be cabled to a land-based receiving facility or have a telemetry component (for example, satellite buoy); as such, they are costly to operate. Global and regional small-aperture hydrophone arrays, such as those in the IMS, typically have sampling rates of 250 samples per second. This covers the expected dominant frequency range for most volcanic signals; however, some types of signals (for example, mass flows or venting) may contain frequencies as high as several hundred hertz, so higher sampling rates are recommended when possible and desired for the expected activity.

Regional-scale (that is, large-aperture) networks cover a large area with wide spacing (several to hundreds of kilometers) between instruments. Although hydrophones and OBSs have been deployed in such network configurations (for example, Dziak and others, 2005), it is costly and difficult to operate in real time with current technology because every individual station may need to be cabled to shore or have another method of telemetry. Thus, only land-based regional-scale networks are recommended for real-time monitoring. To best use land-based seismic networks for submarine monitoring, T-phase-optimized seismic stations, as discussed for the RSP above, should be incorporated into the regular regional network.

Recommendations

The following recommendations would ideally be applied to regions with at least one submarine volcano at or above the given threat level. For regions with submarine volcanoes that have not been assigned a threat level, the levels 1 and 2 minimums are recommended.

Levels 1 and 2.—Detect major submarine eruptions and large earthquakes (magnitude >3) that may indicate significant volcanic unrest, constrain source location or back-azimuth of volcanic signals, and characterize submarine eruption activity to identify potential hazards.

- Minimum of one to three land-based seismic stations optimized for T-phase detection; distribution determined by the number and location of submarine volcanoes.
- Short-term (6–12 month) deployments of two to three non-real-time hydrophones for regions with higher risk, more volcanoes, and (or) sparser or more distant land-based networks.
- Weekly to daily regional satellite monitoring for signs of volcanic activity dependent on risk in region.

Levels 3 and 4.—Characterize baseline seismic and submarine volcanic activity, identify long-term changes in activity, and detect low-level activity in real time.

- One to two cabled small-aperture hydrophone arrays that have four moorings.
- Additional optimized T-phase stations and short-term hydrophone deployments, dependent on regional situation and activity levels.
- Additional monitoring via satellite and other methods as needed for understanding eruption hazards.

Local-Scale Monitoring of Submarine Volcanoes

Local instrument networks are required to provide adequate event detection at high-risk submarine volcanoes. These networks should be largely equivalent to those at subaerial volcanoes. For example, at least four local OBSs or hydrophones would be needed to accurately locate earthquakes at a submarine volcano. Local networks can detect weaker activity than regional instruments, allowing for a more complete characterization of volcanic activity and the possibility of forecasting eruptions.

Cabled networks and instrument arrays are currently in real-time operation at some locations around the world—for example, the Ocean Observatories Initiative network at Axial Seamount (Kelley and others, 2014). Nooner and Chadwick (2016) described a successful forecast of the 2015 eruption of Axial Seamount based on deformation data from the Ocean Observatories Initiative network. OBSs in the network recorded seismicity before, during, and after the 2015 eruption, and earthquakes as small as magnitude 0 were located (Wilcock and others, 2016). Hydroacoustic data were critical for identifying events from the eruption that initiated at the water-seafloor interface rather than below ground, including impulsive signals generated by seawater interacting with lava flows that could provide time and location constraints for effusive events (for example, Caplan-Auerbach and others, 2017; Le Saout and others, 2020). A more limited local cabled observatory (the Hawaiʻi Undersea Geo-Observatory) was deployed at Kamaʻehuakanaloa from October 1997 to April 1998 (Duennebier and others, 2002) and detected seismicity at Kamaʻehuakanaloa (Caplan-Auerbach and Duennebier, 2001) as well as landslides from lava-delta collapses at Kīlauea (Caplan-Auerbach and others, 2001).

Although remote sensing techniques such as interferometric synthetic aperture radar do not work underwater, submarine volcanoes can be mapped with sonar techniques. The resulting bathymetric maps allow for better understanding of changes in the edifice from volcanic activity. For example, comparisons of bathymetric maps produced years apart have identified landslides on Ahyi seamount (Tepp and others, 2019b) and tracked lava cone growth within the summit crater of Vailulu’u seamount (Tepp and others, 2019a).

Instrumentation

All local networks should include OBSs and hydrophones, as well as sensors for hydrothermal activity (turbidity, temperature, and chemistry) and surface deformation. Currently, the best option for transmitting data in real time from marine-based instrument networks is by cables, although other less expensive methods have been tested (for example, Matsumoto and others, 2016, 2019). Short-term (less than about 6 months), non-real-time instruments may be more cost effective for monitoring long-term unrest and lower risk activity. Where possible, local networks may make use of land-based instruments on nearby islands that are close enough (within about 20 km) to detect low-level activity at the submarine volcano.

The Axial Seamount network provides a template for an optimal local submarine volcano network that can inform the design of networks at other volcanoes. It is composed of real-time broadband and short-period seismometers, hydrophones, bottom-pressure sensors, tilt instruments, and various instruments for measuring chemistry and hydrothermal activity (Kelley and others, 2014). The cabled instruments are supplemented by non-cabled instruments for more detailed scientific investigation (Wilcock and others, 2018).

Recommendations

Level 1.—Detect major eruptions and locate large earthquakes (magnitude >4) that could indicate significant unrest that is highly likely to lead to a major eruption.

- No local monitoring recommended; regional marine-based and land-based monitoring is adequate.

Level 2.—Detect and characterize major local eruptions or activity that could indicate significant unrest that could potentially lead to a major eruption.

- One to two land-based seismic stations optimized for T-phases on the nearest island (may be part of regional network).
- Use regional marine-based and land-based monitoring.
- Non-real-time, marine-based instruments deployed during periods of unrest as needed.
- Bathymetric mapping when possible.

Level 3.—Detect and monitor signs of volcanic unrest, including increases in local seismicity and low-level eruptions.

- At least one real-time, marine-based instrument site with a broadband seismometer, hydrophone, and other sensors.
- Additional non-real-time, marine-based instruments deployed during prolonged periods of unrest.
- One to two land-based seismic stations optimized for T-phases on the nearest islands (may be part of regional network).
- Use regional monitoring to supplement local instruments.
- Bathymetric mapping every 5–10 years and after periods of volcanic activity.

Level 4.—Locate local earthquakes, detect signs of volcanic unrest and low-level eruptions, and potentially forecast major eruptions.

- At least four real-time, marine-based instrument sites with a broad-band seismometer, hydrophone, and other sensors.
- Additional non-real-time, marine-based instruments deployed during prolonged periods of unrest.
- One to two land-based seismic stations optimized for T-phases on nearest islands (may be part of regional network).
- One to two infrasound sensors or arrays on nearest islands (may be part of another network), if volcano is shallow enough to produce acoustic waves.
- Use regional monitoring to supplement local instruments.
- Bathymetric mapping every 1–5 years and after periods of volcanic activity.

Marine Monitoring for Small Island Volcanoes

Some island volcanoes in the United States have edifices that are largely submerged even though their summits are above the sea surface. Their small sizes limit the ability to install land-based instruments; thus, monitoring of small island volcanoes can benefit from similar techniques used for submarine volcanoes. One example is Bogoslof Island, Alaska, which erupted in 2016–17 (Coombs and others, 2019). Even though the volcano has a large submarine edifice, the small Bogoslof Island had an area of only 0.3 square kilometer (km^2) before the 2016–17 eruption and has maintained an area of approximately 1.5 km^2 to date (2022). This volcano had no local instrumentation during the 2016–17 eruption, and monitoring and understanding of the eruption was improved by the use of submarine monitoring techniques, including a local hydrophone deployed as a rapid-response instrument, the use of regional seismometers and infrasound arrays, and the detection of T-phases (for example, Tepp and others, 2019c). Of note, the local hydrophone recorded mass-flow events that followed a few of the eruptions and that were not recorded seismically, demonstrating one benefit of using hydrophones. Anatahan Island, in the Northern Mariana Islands, is a subaerial volcanic island large enough to host a few local monitoring instruments and provides an example of how marine-based instruments can supplement land-based monitoring for small island volcanoes. During Anatahan Island’s 2003 eruption, seismicity was recorded on regional hydrophones, allowing for additional characterization of the seismicity (Dziak and others, 2005).

Non-real-time OBSs have been used for continuous monitoring of Nishinoshima, a small island volcano in Japan, by switching out the instruments and retrieving data every 6 months (Shinohara and others, 2017). Although this approach does not provide data in real time, it provides a baseline of activity and could be used to detect long-term changes that may reveal an increase or decrease in volcanic activity.

Instrumentation

For small island volcanoes, monitoring networks would ideally rely on land-based instruments, with marine-based instruments used as needed to upgrade networks to the recommended monitoring capabilities outlined in other chapters of this volume. Marine-based monitoring should focus on OBSs but may include other geophysical, hydrothermal, or geochemical sensors. Marine-based instruments may also be deployed on a short-term basis to improve characterization of baseline activity.

Recommendations

Level 1.—Detect major eruptions or activity that could indicate significant unrest.

- Use local land-based and regional monitoring.

Level 2.—Detect moderate eruptions or activity that could indicate major unrest.

- Use local land-based and regional monitoring.

Level 3.—Locate local earthquakes; detect signs of volcanic unrest and low-level eruptions.

- Use local land-based and regional monitoring.
- Deploy short-term (3–12 month), marine-based instruments to improve characterization of baseline activity and to monitor long-term changes, particularly during periods of unrest.

Level 4.—Locate local earthquakes, detect signs of volcanic unrest and low-level eruptions, and forecast major eruptions when possible.

- Use local land-based and regional monitoring.
- Deploy additional marine-based, real-time instruments as needed to complete a network with a level-4-monitoring capability as outlined in other chapters of this volume.

Summary and Other Considerations

This chapter provides recommendations for marine-based monitoring of submarine and small island volcanoes at every threat level. The National Volcanic Threat Assessment (Ewert and others, 2018) lists only one submarine volcano in the United States as a moderate (level 3) threat and a few small island volcanoes as level 3 or 4 threats. Given the relatively poor understanding of submarine volcanic systems, the threat rankings may change in the future as more information about their potential for hazardous eruptions becomes available. Similarly, volcanoes outside U.S. territory may be deemed higher threats and benefit from the recommended monitoring described here.

For marine-based monitoring, special consideration needs to be given to logistics and cost. The recommendations in this chapter aim to balance the high cost of marine-based instruments with the potential societal benefit. Thus, land-based and regional monitoring that requires as few marine instruments as possible are recommended for most cases. The deployment and maintenance of marine-based instruments requires ships with specific capacities, which may present added costs and extra planning time. Scientific research vessels are able to deploy instruments, but usage time may need to be booked years in advance. Developing partnerships with other agencies that operate capable ships (for example, U.S. Coast Guard or U.S. Fish and Wildlife Service) is highly recommended and may allow for reduced costs and more flexibility. Private contractors may also be an option in some cases.

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Moffett Field Publishing Service Center, California
Manuscript approved July 26, 2024
Edited by Linda Rogers and Monica Erdman
Layout and design by Cory Hurd

Tepp—**Monitoring Marine Eruptions**—Scientific Investigations Report 2024–5062–I

ISSN 2328-031X (print)
ISSN 2328-0328 (online)
https://doi.org/10.3133/sir20245062i