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Introduction to Recommended Capabilities and Instrumentation for Volcano Monitoring in the United States

Chapter A 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 Hawaiian Volcano Observatory gas scientist M. Cappos installs a newly calibrated multicomponent gas analyzer system (multi-GAS) at the Sulfur Cone volcano monitoring station on Mauna Loa's Southwest Rift Zone, Hawai‘i. The station is located at an elevation of 11,250 feet (3,430 meters) above sea level; work in these high-elevation environments necessitates extreme caution and diligence. Multi-GAS instruments provide continuous real-time monitoring of major volcanic gas species (water, carbon dioxide, sulfur dioxide, and hydrogen sulfide) and meteorological conditions (wind speed and direction, air temperature, and humidity) and must be replaced every 2 years on average. Monitoring the ratios of different volcanic gases here can help to identify changes to the magmatic system beneath the volcano. The surrounding ground is covered in elemental sulfur that is deposited by the constant degassing of volcanic sulfur gases. Photograph by C. Sealing, U.S. Geological Survey, August 2, 2024. Background image shows a typical view of the 2008–2018 lava lake in the Overlook crater within Halema‘uma‘u, Kīlauea. Photograph taken from a helicopter by Tim Orr, U.S. Geological Survey, on August 16, 2013.

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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)

Abbreviations

DEM	digital elevation model
GNSS	Global Navigation Satellite System
InSAR	interferometric synthetic aperture radar
NTIA	National Telecommunications and Information Administration
NVEWS	National Volcano Early Warning System
SWIR	short-wave infrared
UAS	unoccupied aircraft system
USGS	U.S. Geological Survey

Chapter A

Introduction to Recommended Capabilities and Instrumentation for Volcano Monitoring in the United States

By Ashton F. Flinders, Jacob B. Lowenstern, Michelle L. Coombs, and Michael P. Poland

Introduction

The National Volcano Early Warning System (NVEWS) was authorized and partially funded by the U.S. Government in 2019. In response, the U.S. Geological Survey (USGS) Volcano Hazards Program asked its scientists to reflect on and summarize their views of best practices for volcano monitoring. The goal was to review and update the recommendations of a previous report (Moran and others, 2008) and to provide a more detailed analysis of capabilities and instrumentation for monitoring networks for U.S. volcanoes. This Scientific Investigations Report and its chapters reflect those USGS scientists' views and summaries and will serve as a guide for future network upgrades funded through NVEWS.

Given the well-documented hazards posed by volcanoes to population centers and aviation (for example, Blong, 1984; Scott, 1989; Neal and others, 1997, 2019; Guffanti and others, 2010; Shroder and Papale, 2014; Prata and Rose, 2015; Palmer, 2020), volcano monitoring is critical for ensuring public safety and for mitigating the impacts of volcanic activity. Accurate and timely forecasts are facilitated by well-designed monitoring networks that are in place long enough to allow for background behavior to be recognized and understood. Because precursory signals may be limited and unrest may progress rapidly to an eruption, our goal is to deploy monitoring systems that enable detection of the reactivation of dormant volcanoes as early as possible, allowing for public safety and risk mitigation. NVEWS planning is also informed by the results of Ewert and others (2005, 2018), whereby 161 U.S. volcanoes are currently categorized and ranked commensurate with their relative threat.

In each chapter, author(s) considered the need for some redundancy of instrumentation and telemetry, given the likelihood of occasional equipment failure, particularly in extreme and remote environments. Establishing digital telemetry networks requires advanced planning, sighting, radio-shot testing, and, inevitably, troubleshooting in the field. This is harder to achieve rapidly during a crisis; thus, an important goal for monitoring U.S. volcanoes is to establish digital telemetry backbones with redundancy and extra capacity to absorb additional instruments should a volcano begin to exhibit signs of unrest (fig. A1). The National Telecommunications and Information Administration (NTIA) imposed new regulations in the United States, eliminating the use of older analog radios for many purposes, which had been one previous means for redundant data delivery. However, the resulting conversion from analog to digital systems usefully enables stations to accommodate new and multivariate real-time data streams (for example, Global Navigation Satellite System [GNSS] receivers, infrasound arrays, gas spectrometers, visible and infrared cameras, and broadband seismometers).

We note that other USGS and broader national and international hazard programs can leverage NVEWS instrumentation plans. Examples of this include the following:

1. Improved seismic coverage of volcanoes will increase the capability of the USGS Earthquake Hazards Program to detect and locate earthquakes, estimate ground shaking, and provide timely early warnings through the ShakeAlert Earthquake Early Warning System (Given and others, 2018).
2. The National Oceanic and Atmospheric Administration's Tsunami Program will benefit from additional seismic stations, particularly within the sparsely instrumented Aleutian Islands, Northern Mariana Islands, and American Samoa.
3. Infrasound stations can detect signals from landslides, debris flows and lahars, floods, and weather events, providing benefits to the National Weather Service and the USGS Landslide Hazards Program.

Figure A1. Photograph of a U.S. Geological Survey Alaska Volcano Observatory geophysicist orienting a radio antenna toward a monitoring station near Shishaldin Volcano, Alaska. View from southeast at seismic station BRPK. Shishaldin Volcano emits a gas plume, and the edifice is covered with debris from a 2019–20 eruption. Photograph by Allan Lerner, U.S. Geological Survey, August 20, 2020.

How to Use This Report

Magma moving toward the surface interacts with anything in its path, including hydrothermal systems, cooling magma bodies from previous intrusions, and surrounding host rock. These interactions lead to various geophysical and geochemical phenomena that volcano monitoring networks can detect. A primary goal of volcano monitoring is to detect and correctly interpret such phenomena to provide early and accurate warnings of impending eruptions and to forecast ongoing eruptions, which can last days, months, or years.

Effective monitoring of volcanoes is an interdisciplinary endeavor. Varied techniques are useful for tracking different aspects of preeruption unrest, an eruption itself, and its aftermath, all of which contribute to ensuring public safety. In this report, we first describe a core group of monitoring techniques—seismology, infrasound, ground deformation and gravity (geodesy), gas analysis, and hydrology—that have collectively proven effective for detecting precursory and syneruptive signals and for forecasting eruption timing and style. We then present sections on how these traditional technologies can be combined with other approaches to, for example, track surface changes with satellites and deployed cameras (fig. A2), detect lahars with infrasound and seismometers, and detect and track ash clouds and related lightning with satellite- and ground-based systems. Other chapters describe monitoring marine eruptions, the use of unoccupied aircraft systems, and monitoring from boreholes. Each section contains subsections describing specific capabilities and recommended instrumentation and techniques needed to attain those capabilities.

Aside from the practical, logistical, and financial considerations that may interfere with compliance to the recommendations herein, we also stress that there are scientific caveats. We specifically caution against compliance to our recommendations regarding the number of instruments. These numbers are estimated for a generic stratovolcano similar to Mount St. Helens, but significant variation in the characteristics of U.S. volcanoes makes a one-size-fits-all approach impractical. In terms of spatial scale, 5 kilometers from the volcanic center has one meaning for isolated stratovolcanoes with a central vent, such as Augustine Volcano in Alaska, but quite a different meaning for much larger caldera systems, such as Yellowstone Caldera in Wyoming; shield volcanoes and their associated rift zones, such as Mauna Loa in Hawai‘i; and volcanic fields, such as the Clear Lake volcanic field in California.

Desired capabilities should be evaluated on a volcano-by-volcano basis. Not every potential capability is relevant at all volcanoes—for example, there is no need for a capability related to lahar detection at Mauna Loa. Similarly, several volcanoes in the Aleutian Islands are ranked as high threat predominantly because of their hazard to aviation (for example, Semisopochnoi Island and Great Sitkin Volcano; Ewert and others, 2018). The absence of permanent populations near these volcanoes can mean that advanced early warnings are not crucial for evacuation, but timely and accurate detection and notification of explosive eruptions are essential for aviation. Users of this report can determine those capabilities that are considered necessary for a given volcano of interest.

Summary of Recommendations

Summaries of our recommendations for instrumentation are listed in tables A1 (recommended instruments for volcano monitoring), A2 (recommended instruments for special topics), and A3 (recommended instrument cache for rapid response). In table A1, we summarize the recommendations of the chapters in this volume by monitoring levels. As originally defined by Ewert and others (2005), monitoring levels were directly linked to the volcanic-threat rankings. For example, level 1 networks were recommended to monitor very low-threat volcanoes, such as the Golden Trout Creek volcanic field, California; level 2

Figure A2. Photograph of U.S. Geological Survey Hawaiian Volcano Observatory geophysicist A. Flinders (left), volunteer C. Ruggles (middle), and geologist M. Zoeller (right) monitoring the resumption of volcanic activity within Halema‘uma‘u, the crater associated with Kīlauea, Hawai‘i, on January 5, 2023, using digital cameras and a laser rangefinder. Tracking and documenting surface changes during ongoing eruptions with rapidly deployed cameras is a long-standing technique that has greatly benefited from advances in technology. Photograph by U.S. Geological Survey, January 5, 2023.

Table A1. Recommended instrumentation for volcano monitoring in the United States by monitoring level.

[DEM, digital elevation model; GNSS, Global Navigation Satellite System; InSAR, interferometric synthetic aperture radar; km, kilometer; m, meter; SWIR, short-wave infrared]

Monitoring category	Monitoring level (monitoring need and volcano threat level)			
	1 (Minimal monitoring; very low threat)	2 (Limited monitoring for change detection; low threat)	3 (Basic real-time monitoring; moderate to high threat)	4 (Well monitored in real time; high to very high threat)
Seismic	Five seismic stations within 200 km of the volcanic center, including two stations within 50 km	Five seismic stations within 50 km of the volcanic center, including two stations within 10 km	Seven or more broadband seismic stations within 20 km of the volcanic center, including at least two stations within 5 km	Twelve to 25 broadband seismic stations within 20 km of the volcanic center, including at least eight stations within 10 km and four or more stations within 5 km; at least one broadband or strong-motion station within 10 km of the volcanic center. Small-aperture seismic array in places where logistics preclude placing stations high on the edifice
Infrasound	One array with four or more elements within 200–300 km of the volcanic center	At least one broadband infrasound sensor co-located with a three-component seismic sensor within 10 km of the volcanic center, and one array with four or more elements within 200–300 km	At least four broadband infrasound sensors co-located with three-component seismic sensors within 10 km of the volcanic center or 15 km of summit vents (for example, Mauna Loa and Kīlauea summits). At least one array with four or more elements within 15 km of the volcanic center or two arrays within 20 km of volcanic centers and main fissure systems with good azimuthal coverage along the trend of fissures. At least two arrays with six or more elements within 200–300 km of sources and with significantly different back-azimuths to sources	At least four broadband infrasound sensors co-located with three-component seismic sensors within 10 km of the volcanic center. At least two arrays with four or more elements each within 15 km of the volcanic center
Ground deformation and gravity	Baseline deformation measurements using InSAR; establish baseline GNSS and gravity survey networks and repeat surveys occasionally in case future unrest should warrant additional data collection	InSAR images acquired annually or every few years incorporated into automated processing and analysis; GNSS and gravity surveys repeated every several years (depending on logistics); a single, continuous-mode GNSS station within 5–10 km of the deforming source	Five to 10 telemetered continuous-mode GNSS stations, of which four are within 5–10 km of the deforming source and one is outside the area of expected deformation; if conditions permit, two to four borehole tiltmeters within 5–10 km of the deforming source. InSAR processing on at least an annual basis, and GNSS and microgravity surveys (as appropriate) every several years to supplement data collected from continuously operating stations	Sixteen or more continuous-mode GNSS stations, of which at least eight are within 5–10 km of the deforming source and two are outside the area of expected deformation; if conditions are appropriate, four to six borehole tiltmeters within 5–10 km of the deforming source, and one continuous gravimeter. Regular InSAR acquisition and processing, including multi-temporal approaches as conditions warrant. GNSS and microgravity surveys every year to every several years (as appropriate) to supplement data collected from continuously operating stations

Table A1. Recommended instrumentation for volcano monitoring in the United States by monitoring level.—Continued

Monitoring category	Monitoring level (monitoring need and volcano threat level)			
	1 (Minimal monitoring; very low threat)	**2 (Limited monitoring for change detection; low threat)**	**3 (Basic real-time monitoring; moderate to high threat)**	**4 (Well monitored in real time; high to very high threat)**
Gas	Automated daily satellite-based alerts of SO_2 emissions. Ensure existence of gas geochemical data on any existing fumaroles or geothermal springs	Establish a satellite-based SO_2 emission-rates catalog and characterize baseline gas geochemistry and emission rates using airborne and (or) ground-based sampling techniques on a 5- to 10-year schedule	Establish a satellite-based SO_2 emission-rate time series at any volcano with an adequate level of degassing. Characterize baseline gas geochemistry and emission rates using airborne and (or) ground-based sampling techniques on a 3- to 5-year schedule. Conduct continuous monitoring and (or) survey measurements of gas emission rates as appropriate at any volcano with an adequate level of degassing	In addition to level 3 recommendations, characterize baseline gas geochemistry and emissions on a 1- to 2-year schedule
Springs, streams, and volcanic lakes	Compile an inventory of spring, stream, and well sites to identify those with indications of ongoing magmatic influence, such as elevated $^3He/^4He$ ratios, large fluxes of magmatic CO_2, or anomalous heat fluxes. This inventory would ideally include a field visit with sampling, basic measurements (temperature, pH, and specific conductance), and subsequent laboratory analysis for major-element chemistry and isotope ratios, potentially including those of C, O, H, and He	Same as for level 1	Same as for levels 1 and 2, with resampling every 5 to 10 years to gradually define baseline conditions and develop rating curves. Those springs and streams with clear magmatic signals and accessible sites may be targeted for longer term studies with deployed commercial off-the-shelf technology and conductivity, temperature, and depth sensors and autosamplers. Bathymetric and heat-flow mapping, identification of hydrothermal vents, and, in some cases, mapping the three-dimensional distribution of temperature, salinity, and dissolved gas	Where appropriate, characterize variability caused by factors such as tectonic earthquakes and semi-diurnal-seasonal influences (for example, barometric and tidal), including regular sampling surveys along all major drainages. Install instrumentation for multiyear (3–5 year) periods to collect hourly (or better) information on heat flux and magmatically derived solutes. At select volcanoes, continuous real-time monitoring of hydrologic parameters, targeting springs, and (or) streams that are known or likely to be influenced by magmatic processes, including periodic sampling and streamgaging to calibrate sensors and establish rating curves
Tracking surface changes caused by volcanic activity	Collect moderate-resolution baseline imagery and at least 10-m-resolution DEMs to provide a synoptic overview of volcanic landforms, deposits, and thermal features for later comparison. Implement automated hot spot detection and alerting	Same as for level 1	Collect and regularly update high-resolution baseline optical and thermal imagery; acquire a 5-m minimum-resolution DEM and high-spatial-resolution satellite images (<1-m resolution) or stereopair aerial imagery for detailed geologic and hazard mapping; deploy one telemetered ground-based optical camera	Same as for level 3, except baseline DEMs should be at least 1-m-resolution to improve hazards modeling; deploy two telemetered ground-based cameras, and a thermal camera where appropriate; regularly acquire high-resolution stereopairs and orthorectified optical and SWIR satellite and (or) aerial imagery

Table A1. Recommended instrumentation for volcano monitoring in the United States by monitoring level.—Continued

Monitoring category	Monitoring level (monitoring need and volcano threat level)			
	1 (Minimal monitoring; very low threat)	2 (Limited monitoring for change detection; low threat)	3 (Basic real-time monitoring; moderate to high threat)	4 (Well monitored in real time; high to very high threat)
Lahars	None	None	At least one four- to six-element infrasound array with sensitivity to multiple drainages sited to minimize topographic barriers to potentially active drainages and to provide azimuthal separation between drainages. Two seismometers in or near each drainage of interest, with one in the potential source area and the other in a downstream location but upstream from any population center or infrastructure that could be threatened. The infrasound array could be co-located with one of the seismic stations if conditions are acceptable	Three or more three- to six-element infrasound arrays along each potential flow channel that has high lahar hazard. Include at least one array with four to six elements that has sensitivity to multiple drainages to minimize topographic shielding and to provide azimuthal separation between drainages. At least one seismometer in the source area of each drainage, with additional sensors along each drainage at 1–5 km intervals. Some of these stations may already exist as part of a volcano monitoring network. Web cameras, where possible, to verify surface flow occurrence
Marine eruptions	Minimum of one to three land-based seismic stations optimized for T-phase detection, with distribution determined by the number and location of submarine volcanoes. Short-term (6–12 months) 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 the region	Same as for level 1 as well as bathymetric mapping of submarine volcanoes when possible	Same as for level 2 as well as one to two cabled small-aperture hydrophone arrays with four moorings. Additional optimized T-phase stations and short-term hydrophone deployments, dependent on regional situation and activity levels. Additional monitoring with satellites and other methods as needed for understanding eruption hazards. At least one real-time, marine-based instrument site with a broadband seismometer, hydrophone, and other sensors. Bathymetric mapping of submarine volcanoes every 5–10 years and after periods of volcanic activity	Same as for level 3 as well as at least four real-time marine-based instrument sites with a broadband seismometer, hydrophone, and other sensors. One to two infrasound sensors or arrays on the nearest islands. Bathymetric mapping every 1–5 years and after periods of volcanic activity

Table A2. Recommendations for volcano-threat-level-independent special topics for volcano monitoring in the United States.

[ENTLN, Earth Networks Total Lightning Network; GLD360, Global Lightning Detection Network; GOES, Geostationary Operational Environmental Satellite; km, kilometer; m, meter; NEXRAD, Next Generation Weather Radar; NLDN, National Lightning Detection Network; NOAA, National Oceanic and Atmospheric Administration; UAS, unoccupied aircraft system; USGS, U.S. Geological Survey; WWLLN, World Wide Lightning Location Network]

Monitoring category	Summary of recommendations
Eruption plumes and clouds	Low-latency access to geostationary satellite image products from the GOES and Himawari platforms. Ideally, 5 minutes or less from image collection to USGS availability Access to polar-orbiting satellite image products from NOAA platforms. Ideally, a latency of 30 minutes or less from image collection to USGS availability Real-time data subscriptions and alarms from commercial and academic long-range lightning detection networks. Volcanoes in Alaska, Hawai‘i, and the Commonwealth of the Northern Mariana Islands are covered by the GLD360, ENTLN, and WWLLN networks, as well as moderate coverage from GOES Global Lightning Mapper. Volcanoes in the contiguous United States are additionally covered by the NLDN Deployment of a telemetered, short-range electrical sensor (very high frequency sensor, field mill, or similar) to capture small-scale vent discharges associated with the earliest stages of volcanic plume development Collaboration with National Weather Service and academic partners at the National Severe Storms Laboratory on volcanic cloud product development for the NEXRAD system and for portable radar systems Deployment of a radar system for rapid evaluation of eruptions with potential for ashfall on populated areas and substantial impacts to infrastructure Deployment of ash sensor and collection systems in targeted areas near an erupting volcano (within approximately 10–100 km depending on eruption dynamics and wind field)
Boreholes	Where feasible and appropriate, boreholes would be at least 200 to 300 m deep but also can include shallower boreholes where acquired data could yield important information Any borehole installation would include core recovery to better characterize the volcano’s subsurface structure and eruptive history After borehole installation, boreholes would ideally be fit with appropriate instrumentation, which could include some combination of seismometers, tiltmeters, strainmeters, pore-pressure sensors, temperature sensors, and geochemical sensors Given the substantially higher cost of drilling and installing instrumentation in deeper boreholes (for example, more than 1 km), partnerships with academic and government agencies (for example, the U.S. Department of Energy and the National Science Foundation) would be beneficial
Unoccupied aircraft systems (UAS)	Ideally, at least two accredited UAS remote pilots would be operational at each volcano observatory Ideally, each observatory would have a fleet of UAS platforms and sensors capable of a broad array of volcano monitoring techniques Long-term investment by the Volcano Hazards Program, to encourage expansion of UAS monitoring capabilities, including remote pilot training, procurement, development of platforms and sensors, and field campaign support, would benefit volcano threat preparedness

Table A3. Recommended rapid-response instrument cache for volcano monitoring in the United States.

[In addition to the instrumentation listed below, the caches should include all associated station infrastructure and equipment to provide power and telemetry for ground-based instruments, including batteries, solar panels, radios, cabling, housing, and mounting equipment, as well as radio repeaters and (or) satellite uplinks to ensure continuous data streams for stations installed in remote areas. DOAS, differential optical absorption spectroscopy; FLIR, forward-looking infrared; FTIR, Fourier-transform infrared spectroscopy; GNSS, Global Navigation Satellite System; Hz, hertz; NOAA, National Oceanic and Atmospheric Administration; ppb, part per billion; ppm, part per million; UAS, unoccupied aircraft system; USGS, U.S. Geological Survey]

Monitoring category	Instrumentation
Seismic	Twelve broadband seismometers; 50–100 node-type seismometers
Infrasound	Twelve infrasound sensors and two four-element infrasound arrays
Ground deformation and gravity	Twelve GNSS receivers
Gas	Three scanning spectrometer systems, one SO_2 camera, and one multicomponent gas analyzer system (multi-GAS) station. Instrumentation for performing periodic field surveys, including one mobile DOAS system, one portable SO_2 camera, one portable multi-GAS system, one field FTIR system, one portable soil-CO_2 fluxmeter, and equipment for direct sampling of fumaroles and springs. For airborne gas monitoring from fixed-wing and helicopter-borne missions, the cache would include one highly sensitive, temperature-stabilized DOAS spectrometer and dedicated in situ instruments that have the capability to measure CO_2 at <1 ppm accuracy and precision and major sulfur gases (SO_2 and H_2S) at <5 ppb accuracy and precision at a 1 Hz sampling rate. In addition, one UAS equipped with multi-GAS and DOAS systems would be available
Springs, streams, and volcanic lakes	No specific instrument recommendations
Tracking surface changes caused by volcanic activity	If deemed appropriate by the observatory; one handheld FLIR camera and (or) one airborne (gimble mount) FLIR. Four telemetered cameras with zoom (two with low-light capabilities)
Eruption plumes and clouds	If deemed appropriate by the observatory; one ground-based Doppler radar system and one or more short range very high-frequency sensors (or broadband) or field mill
Lahars	Eight broadband seismometers and two four-element infrasound arrays
Marine eruptions	Observatories responsible for monitoring volcanoes in marine environments (Aleutian Islands, Northern Mariana Islands, and American Samoa) would ideally pursue partnerships with internal and (or) external partners (for example, USGS Pacific Coastal and Marine Science Center, NOAA, and others), for developing a marine rapid-response instrument cache. Ideally, this cache would include ocean-bottom seismometers, hydrophones, bottom-pressure recorders, and other sensors of opportunity. When possible and appropriate, rapidly deploying multiple land-based seismometers optimized for T-phases on the nearest islands could supplement ocean-bottom seismometers and hydrophones

networks were needed at low-threat volcanoes (for example, Craters of the Moon, Idaho); level 3 networks were designed for moderate-threat volcanoes (for example, Bogoslof Island, Alaska); and level 4 networks were designed for monitoring both high-threat (Yellowstone Caldera, Wyoming) and very high-threat volcanoes, such as Mount Rainier, Washington. Moran and others (2008) opted not to stress a rigid tie between the volcanic-threat rankings and monitoring levels and to allow greater flexibility. In this volume, and in table A1, we also adopt a flexible approach whereby some high-threat volcanoes may warrant level 3, and others may warrant a level 4 monitoring network. USGS Volcanic Hazards Program staff will determine the specific monitoring level required at any particular volcano—a range of scientific, economic, and logistical parameters will be needed to design and implement the appropriate network.

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