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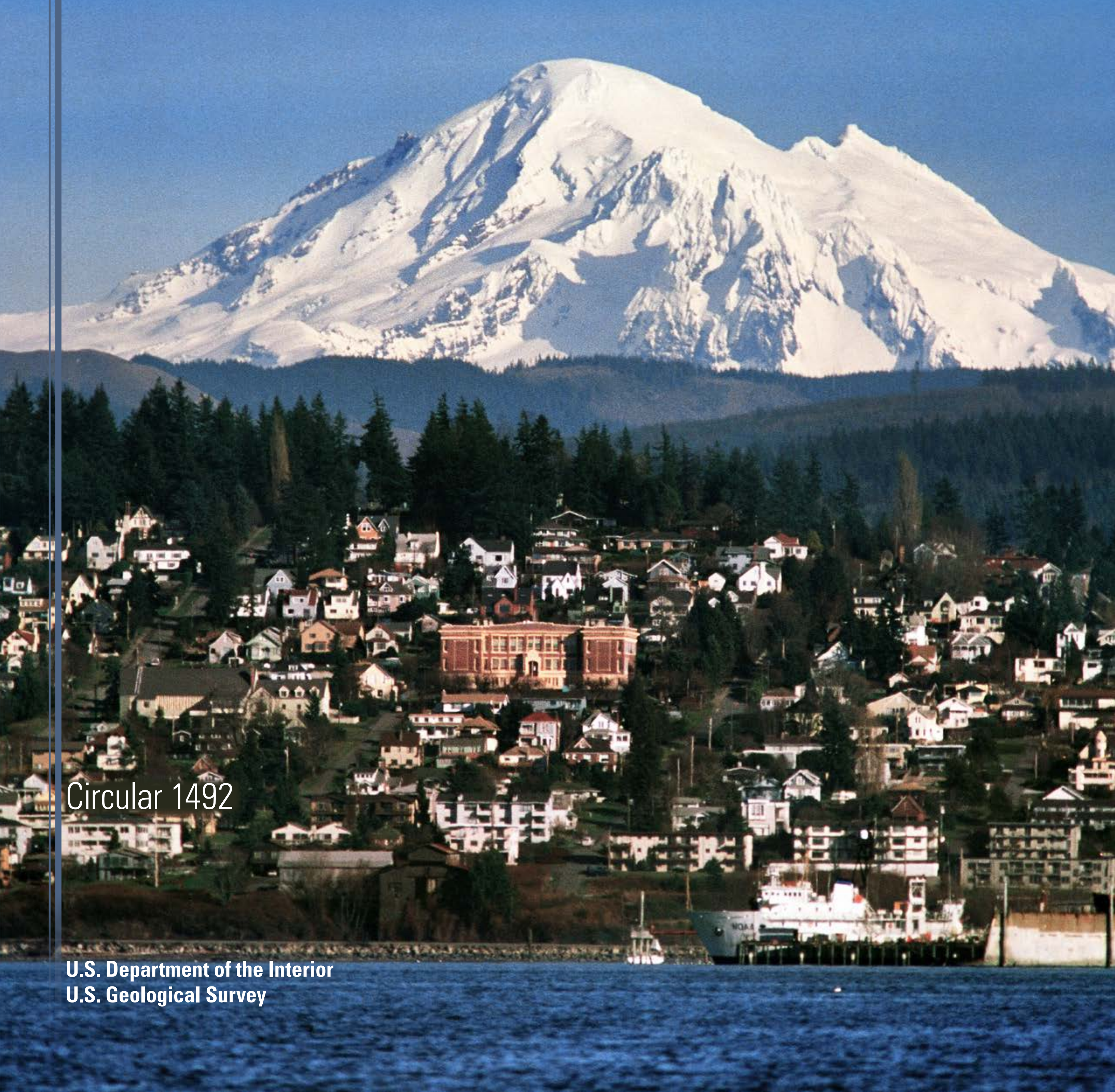
The Volcano Hazards Program: Strategic Science Plan for 2022–2026



Circular 1492

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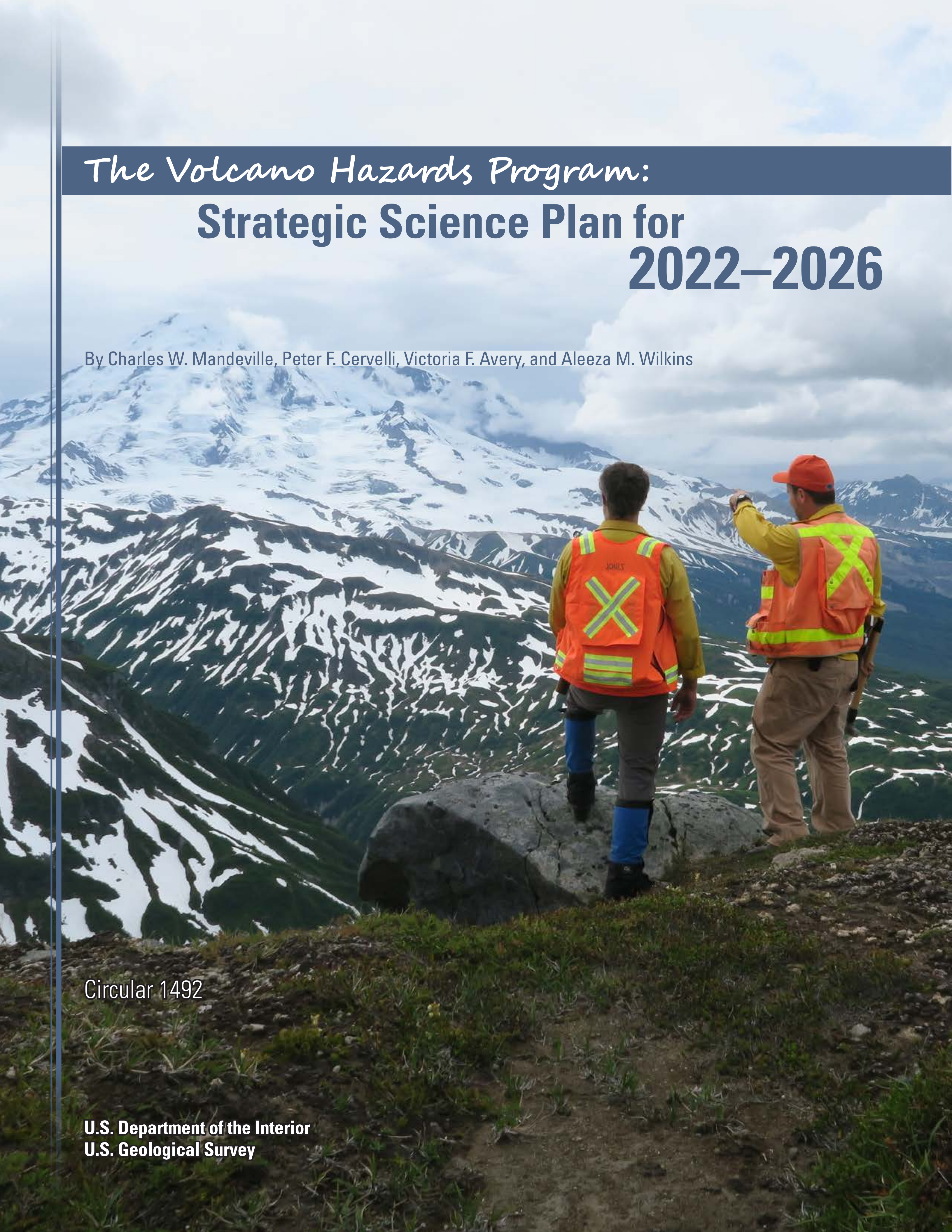
Cover. **Front**—Telephoto view of Mount Baker and the city of Bellingham, Washington, seen from Bellingham Bay. The glacier-covered, 3,286-meter stratovolcano lies about 48 kilometers inland. Photograph by Brett Baunton, © 2008; used with permission.

Back— Fissure 8 (now known as Ahuʻailāʻau) spewing molten lava on June 13, 2018, during the lower East Rift Zone eruption of Kīlauea volcano, Hawaii. Eruption point is from the small cinder cone at right containing four discrete fire fountains. The active lava channel is approximately 30 meters (m) wide at the spillway out of the cone, broadening to 76 m at the bend and 100 m at the far left of the image. Flow direction is from right to left. The maximum flow velocity in the channel just past the islands is 12 m/second (s). Seven standing waves, visible in the middle of the channel starting at the bend, each have a wavelength of ~25 m. In combination, the flow velocity, standing waves, and other parameters suggest a channel depth of ~4 m and thus a bulk effusion rate of ~1,200 m^3/s (340 m^3/s dense rock equivalent) (see Dietterich and others, 2021). Photograph by Dr. Bruce Houghton, University of Hawaiʻi (Manoa); used with permission.



The Volcano Hazards Program: Strategic Science Plan for 2022–2026

By Charles W. Mandeville, Peter F. Cervelli, Victoria F. Avery, and Aleeza M. Wilkins

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Contents

Highlights

Figures

Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic kilometer (km^3)	0.2399	cubic mile (mi^3)
	Flow rate	
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)

Abbreviations and acronyms

ANSS	Advanced National Seismic System
ARRA	American Recovery and Reinvestment Act
AVO	Alaska Volcano Observatory
CalVO	California Volcano Observatory
CNMI	Commonwealth of the Northern Mariana Islands
CONVERSE	Community Network for Volcanic Eruption Response
CSS	Core Science Systems
CVO	Cascades Volcano Observatory
DEM	digital elevation model
dVT	distal volcano-tectonic
EHP	Earthquake Hazards Program
FEMA	Federal Emergency Management Agency
FY	fiscal year

GIS	geographic information system
GPS	global positioning system
HVO	Hawaiian Volcano Observatory
ICS	Incident Command Structure
InSAR	interferometric synthetic aperture radar
ISRO	Indian Space Research Organization
NASA	National Aeronautics and Space Administration
NESDIS	National Environmental Satellite, Data, and Information Service
NHMA	Natural Hazards Mission Area
NISAR	National Aeronautics and Space Administration-Indian Space Research Organization synthetic aperture radar
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
NVEWS	National Volcano Early Warning System
NWS	National Weather Service
SAR	synthetic aperture radar
UAS	unoccupied aircraft system
USAID	U.S. Agency for International Development
USGS	U.S. Geological Survey
UV	ultraviolet
VAAC	Volcanic Ash Advisory Center
VAN	Volcano Activity Notice
VDAP	Volcano Disaster Assistance Program
VHP	Volcano Hazards Program
VONA	Volcano Observatory Notice for Aviation
VSC	Volcano Science Center
YVO	Yellowstone Volcano Observatory
3DEP	3D Elevation Program
24/7	24 hours per day, 7 days per week

Symbols

Ar	argon
€	Euro
C	carbon
CO_2	carbon dioxide
H	hydrogen
HCl	hydrogen chloride
H_2O	water
H_2S	hydrogen sulfide
H_2SO_4	sulfuric acid
He	helium
K	potassium
O	oxygen
Pb	lead
S	sulfur
SO_2	sulfur dioxide
Th	thorium
U	uranium

The Volcano Hazards Program:

Strategic Science Plan for 2022–2026

By Charles W. Mandeville, Peter F. Cervelli, Victoria F. Avery, and Aleeza M. Wilkins

Executive Summary

The U.S. Geological Survey (USGS) Volcano Hazards Program (VHP) Strategic Science Plan, developed through discussion with scientists-in-charge of the USGS volcano observatories and the director of the USGS Volcano Science Center, specifies six major strategic goals to be pursued over the next five years. The purpose of these goals is to help fulfill our mission to enhance public safety and to minimize social and economic disruption caused by volcanic eruptions, through delivery of effective forecasts, warnings, and information on volcano hazards based on scientific understanding of volcanic processes. These six major strategic goals are to—

Goal 1

Continue—and when possible, accelerate—implementation of the National Volcano Early Warning System (NVEWS) to close monitoring gaps on the highest threat volcanoes in the United States and to unify the five USGS volcano observatories into an interoperable system that has capability 24 hours per day, 7 days per week. To support NVEWS, standardize analytical software, acquire new information technology (IT) infrastructure, and add scientific staff to synthesize and interpret real-time and near-real-time data. This builds on investments already made during the American Recovery and Reinvestment Act stimulus of 2009–2010 and the use of one-time infrastructure funding in fiscal year (FY) 2018.

Goal 2

Improve community preparedness for volcanic hazards by updating and standardizing essential components of volcano hazard assessments and providing training to land managers, emergency responders, and State and local communities in the form of tabletop exercises and development of effective emergency response plans. The USGS volcano observatories should build community relationships through briefings, town hall meetings, and use of social media that reaches potentially impacted populations.

Goal 3

Update volcano hazard assessments, which for years have been largely based on paper maps illustrating the zones likely to be affected by ground hazards during a volcanic eruption. A new generation of volcano hazard assessments will take the form of a digital portfolio of products and tools co-developed by the USGS and the end-user community to best address their needs and make the information easier to understand and visualize. The new hazard assessments will incorporate multiple layers of geographic information system (GIS) information and assessments of exposure and risk to population and critical infrastructure. This portfolio of products will include Ash3d model runs for assessing impacts of ashfall in addition to ground-based hazards.

Goal 4

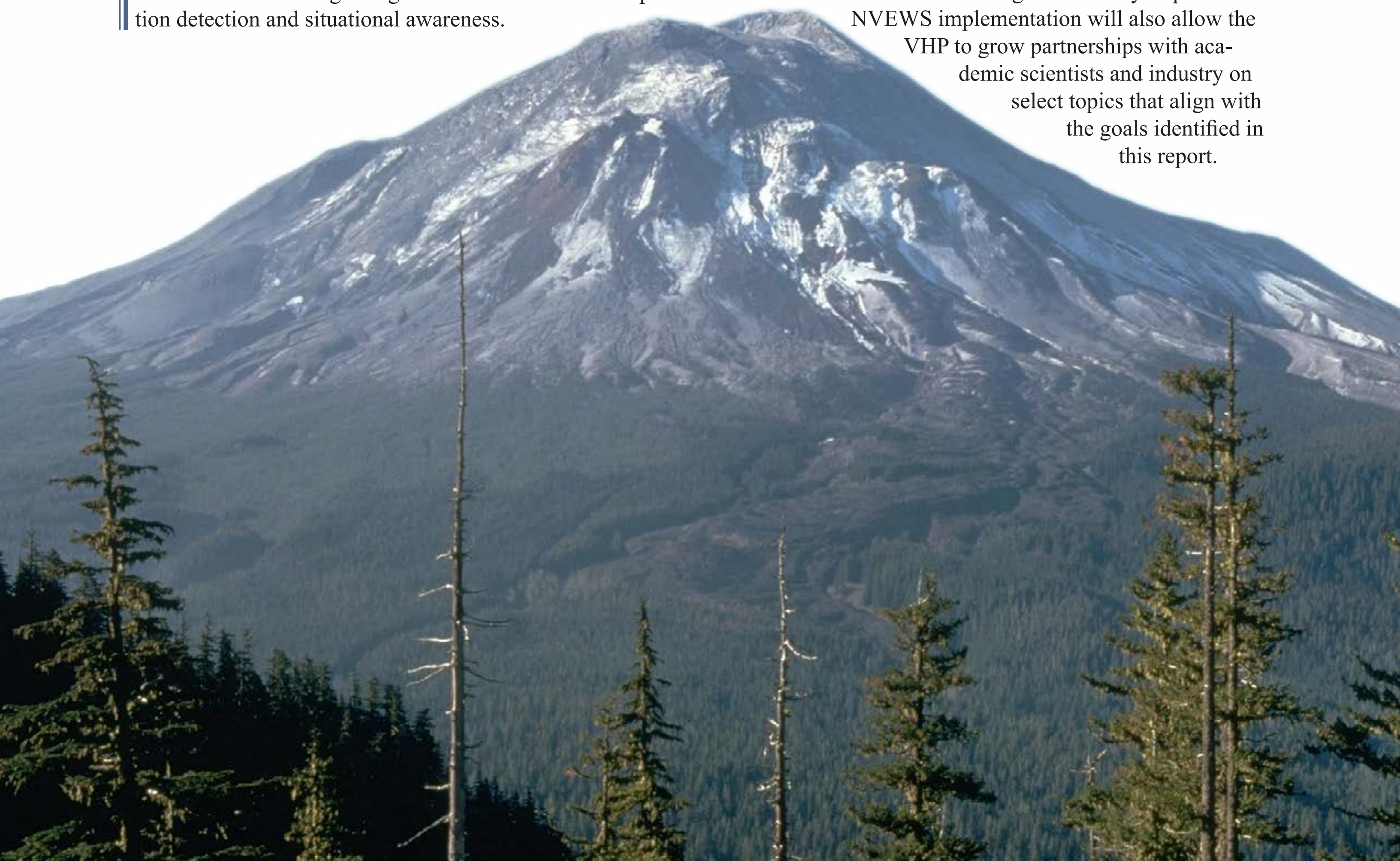
Make observations with new instrumentation and take advantage of advances in real-time gas sensors (for example, MultiGAS, miniaturized scanning differential optical absorption spectrometers, and ultraviolet (UV) cameras), portable gravimeters, and other potential field surveys now possible, some of which are airborne. The VHP must also take advantage of the proliferation of new remote-sensing synthetic aperture radar (SAR) satellites such as the National Aeronautics and Space Administration (NASA)-Indian Space Research Organization (ISRO) SAR mission (NISAR mission) scheduled for launch in September 2023. Other opportunities will arise from improved infrasound networks and more operational use of the World Wide Lightning Location Network for eruption detection and situational awareness.

Goal 5

Rebuild the Hawaiian Volcano Observatory (HVO), which was irreparably damaged during the 2018 eruption of the Kīlauea summit and lower East Rift Zone. The new HVO facility will be located in a less hazardous area (having a much lower probability of lava flow covering the area in the next 200 years) on the University of Hawai‘i Hilo campus and will also house USGS staff from the Pacific Island Ecosystem Research Center. Rebuilding the HVO will eliminate single points of failure and will enable augmentation of the monitoring networks for the Hawaiian volcanoes Kīlauea, Mauna Loa, and Haulālai. In addition, the USGS will build a field operations station within Hawai‘i Volcanoes National Park for final assembly and testing of select monitoring equipment just prior to permanent installation, and to provide general fieldwork support.

Goal 6

Form new partnerships and strengthen existing partnerships, a goal of paramount importance in the next 5 years as the VHP seeks to implement NVEWS. Aiding this effort will be the requirement to leverage resources with other Federal and State agencies that already play a role in volcano monitoring. An additional goal is to form a high-level NVEWS Advisory Committee from Federal partner agencies, and an NVEWS Implementation Committee with members from the scientific community, industry, land managers, and emergency responders that will have a direct role in the design of the NVEWS system and a vested interest in successful implementation. Establishment of an external grants activity as part of NVEWS implementation will also allow the VHP to grow partnerships with academic scientists and industry on select topics that align with the goals identified in this report.



In its effort to advance volcano science and monitoring techniques, the VHP has identified several scientific targets to pursue over the next five years, including:

Target 1

Volcano seismicity, with emphasis on developing better integrated alarm systems that incorporate data from other types of ground sensors, and remote-sensing data. This target will also seek better understanding of the sources of distal volcano-tectonic earthquakes and their relation to volcano unrest and eruption. Other subfields to be explored under this target include better characterization of volcanic tremor, unification and integration of seismology and geodesy, more widespread use of infrasound, and study of uplift at restless calderas.

Target 2

Probabilistic forecasting through refining construction of Bayesian event trees and expert elicitation supported by worldwide databases on volcano unrest and eruptive activity. The VHP will ensure that forecasts include and clearly present the effects of uncertainties in the data and models involved in their creation. Forecasts will be informed from physics-based models of crustal deformation and degassing, pyroclastic density current runout, debris flow dynamics, and ash cloud tracking and ash fallout.

Target 3

Eruption histories and geochronology at the Nation’s threatening volcanoes through application of multiple geochronology techniques including radiocarbon, potassium-argon (K-Ar), $^{40}Ar/^{39}Ar$, uranium-lead (U-Pb), uranium-thorium (U-Th) disequilibrium, U-Th/helium (He), cosmogenic systems, stable isotope records in encapsulating sediments, and paleomagnetic comparison to calibrated secular variation maps to date volcanic deposits and eruption processes precisely and accurately. These dates and rates help the VHP and its partners better understand the fundamental processes that control eruption size, location, frequency, cause, probability, and hazard. Continued success and USGS leadership in this field will require maintaining and improving VHP abilities through staffing, programmatic focus, and laboratory capabilities, including construction of a new laboratory building at Moffett Field, California. Goals for this target in the next five years include improving tephra chronology records through integration of land-based and marine tephra records, publication of geologic maps and eruption histories, and investigations of the time scales of eruption periodicity and duration.

Target 4

Improved physical models of magmatic systems and eruption processes through investigation of the parameters that control eruption style, size, frequency, and duration. These physical models will be used to support probabilistic forecasts of eruptive activity. Models will be developed through numerical simulations that explore the full range of key parameters and through experiments designed to fully capture the range of possible eruption outcomes, with realistic assessments of uncertainties. Experiments will include the determination of water (H_2O)-carbon dioxide (CO_2)-sulfur (S) solubilities in common magma types over a range of temperatures, pressures, and oxidation states. This will allow us to take better advantage of real-time gas measurements with new sensors (for example, MultiGAS, UV cameras, miniaturized scanning differential optical absorption spectrometers, and instruments employing eddy covariance techniques) and integrate those data with petrologic information. Enhancement of the partnership with the Core Science Systems Mission Area of the USGS will allow the VHP to take full advantage of high-performance computing facilities to develop and refine physical models of magma systems and eruptions processes.

Target 5

Improved volcanic aerosol measuring and tracking capability through ground-based and airborne (unoccupied aircraft system [UAS]) measurements of sulfur gas emissions from volcanic point sources. This includes continuing the use of new gas sensors (MultiGAS and UV cameras) already integrated with UAS platforms that have proven successful during the Kīlauea eruption in 2018. The VHP will also continue to take advantage of more formalized partnership with the National Oceanic and Atmospheric Administration (NOAA)/National Environmental Satellite, Data, and Information Service (NESDIS) and NASA to obtain low-latency remote-sensing satellite data from new ozone and sulfur gas detection sensors aboard NOAA- and NASA-operated satellites.

Target 6

Improved modeling and forecasts of lava flow paths to warn potentially impacted communities in a timely manner. Success of the lava flow forecasts, particularly on Kīlauea and Mauna Loa in Hawai‘i, will depend on regular acquisition of new high-resolution lidar data and the generation of accurate digital elevation models. The VHP will continue to collaborate with lava flow modelers of Italy’s Instituto Nazionale di Geofisica e Vulcanologia to bring their lava flow modeling programs into operational use at HVO and make sure they are adaptable to the types of lava erupted in Hawai‘i. Under NVEWS authorization, these models will be available to all the USGS volcano observatories through standardization of software and capability measures.

Introduction

The U.S. Geological Survey (USGS) Volcano Hazards Program (VHP) Strategic Science Plan identifies concrete and realistic goals that advance the VHP's scientific and operational mission, prioritizes them according to their immediate importance and likelihood of success, and recommends how the VHP can best achieve them, either independently or in collaboration with academic, government, and other partners. The plan addresses goals that share three distinguishing characteristics: innovation, importance, and feasibility over a five-year time scale. Although not stressed here, the important day-to-day operations, which have made the VHP (also referred to as "program") so successful and effective since its inception, will continue. The new and innovative work proposed below supplements—rather than supplants—the VHP's existing efforts, which remain essential for fulfilling its primary mission. Pursuing the following major strategic goals will enhance program operations over the next five years:

- **NVEWS implementation—**Continued (and, when possible, accelerated) implementation of the National Volcano Early Warning System (NVEWS) (Ewert and others, 2005, 2018) is planned, including accompanying staffing increases.

- **Improved preparedness—**The VHP will place a major emphasis on preparedness, both for communities at risk, land managers, and emergency responders, and for the VHP itself.

- **Updated volcanic hazard assessments—**To increase the VHP's preparedness to respond to crises, the program will begin the development of a next generation of hazard assessments for the Nation's very high threat and high-threat volcanoes.

- **New observations and instrumentation—**Technological and conceptual advancements enable improved eruption forecasting and warning. Over the next five years, the USGS Volcano Science Center (VSC)[1] will implement new remote and in situ monitoring instrumentation.

- **Rebuilding of the Hawaiian Volcano Observatory facility and its monitoring capabilities—**The 2018 Kīlauea summit and lower East Rift Zone eruption led to the loss of monitoring instruments and critical telemetry nodes and caused irreparable damage to the Hawaiian Volcano Observatory facility. The VSC will utilize fiscal year (FY) 2019 Disaster Supplemental Funds to replace lost monitoring equipment, harden networks, reconfigure data telemetry, and construct a new observatory on the Island of Hawai‘i in a less hazardous area.

- **Expanded partnerships—**The strengthening of existing partnerships and formation of new partnerships with universities and other government agencies is intended to advance volcano monitoring and increase understanding of volcanic processes, and to disseminate useful and effective USGS information.

[1]The line supervision of the five U.S. volcano observatories and their respective scientific, technical, and administrative staff is under the Volcano Science Center, which lies organizationally under the Alaska Region. The Volcano Hazards Program Office provides scientific, administrative, and budgetary leadership to the Volcano Science Center and is one of the programs within the Natural Hazards Mission Area and located at USGS headquarters in Reston, Virginia. The work of the Volcano Hazards Program in terms of volcano monitoring and delivery of timely forecasts and warnings of hazardous activity is executed by the Volcano Science Center (the five observatories under its supervision) and the Cooperative Agreement Partners (the State universities and geological surveys affiliated with the volcano observatories). Appendix 1 shows the relationship between the Volcano Hazards Program and the Volcano Science Center and its observatories.

In addition to setting the strategic goals listed above, the VHP has identified several scientific targets, discussed below, on which it will focus during the next five years to advance volcano science and improve the program's overall monitoring capability and modeling of volcanic systems. These scientific targets include the following:

- **Volcano seismicity**—The VHP will focus on several aspects of volcano seismicity, including our understanding of co-eruptive tremor, distal volcano-tectonic earthquakes, integration of seismicity and geodesy, and more extensive use of infrasound and development of automated alarms.

- **Probabilistic eruption forecasting**—Delivery of timely and accurate eruption forecasts is a core mission responsibility of the VHP, and the program will seek to improve quantitative probabilistic eruption forecasts and assess uncertainties in light of new comprehensive eruption databases and more robust statistics now available.

- **Eruptive histories and geochronology**—Improving our understanding of eruption histories for the Nation's threatening volcanoes will require utilization of multiple age-dating techniques including radiogenic isotopes, cosmogenic isotope exposure ages, stable isotopes, paleomagnetic data, and correlation of marine and land-based tephra records integrated with major element and trace element compositions of volcanic glass and mineral components. Developing more accurate eruptive histories of volcanic centers will inform threat level assessments and also required levels of monitoring.

- **Eruption physics and parameterization**—The program will develop more accurate physical models of volcanic systems, supported by physical data derived from a number of techniques, that have predictive capability supporting the generation of probabilistic forecasts and warnings. Exploration of the full range of parameters that control the appearance and type of eruption precursors, as well as eruption style, size, and duration, will lead to better situational awareness and accuracy of forecasts.

- **Volcanic clouds**—Volcanic ash and gas clouds can impact population centers and critical infrastructure hundreds to thousands of kilometers downwind of the source and pose threats to commercial and military aviation. The VHP will work with its partners to improve warnings and forecasts of ashfall and gas emissions, and characterization of vog (volcanic smog) sources.

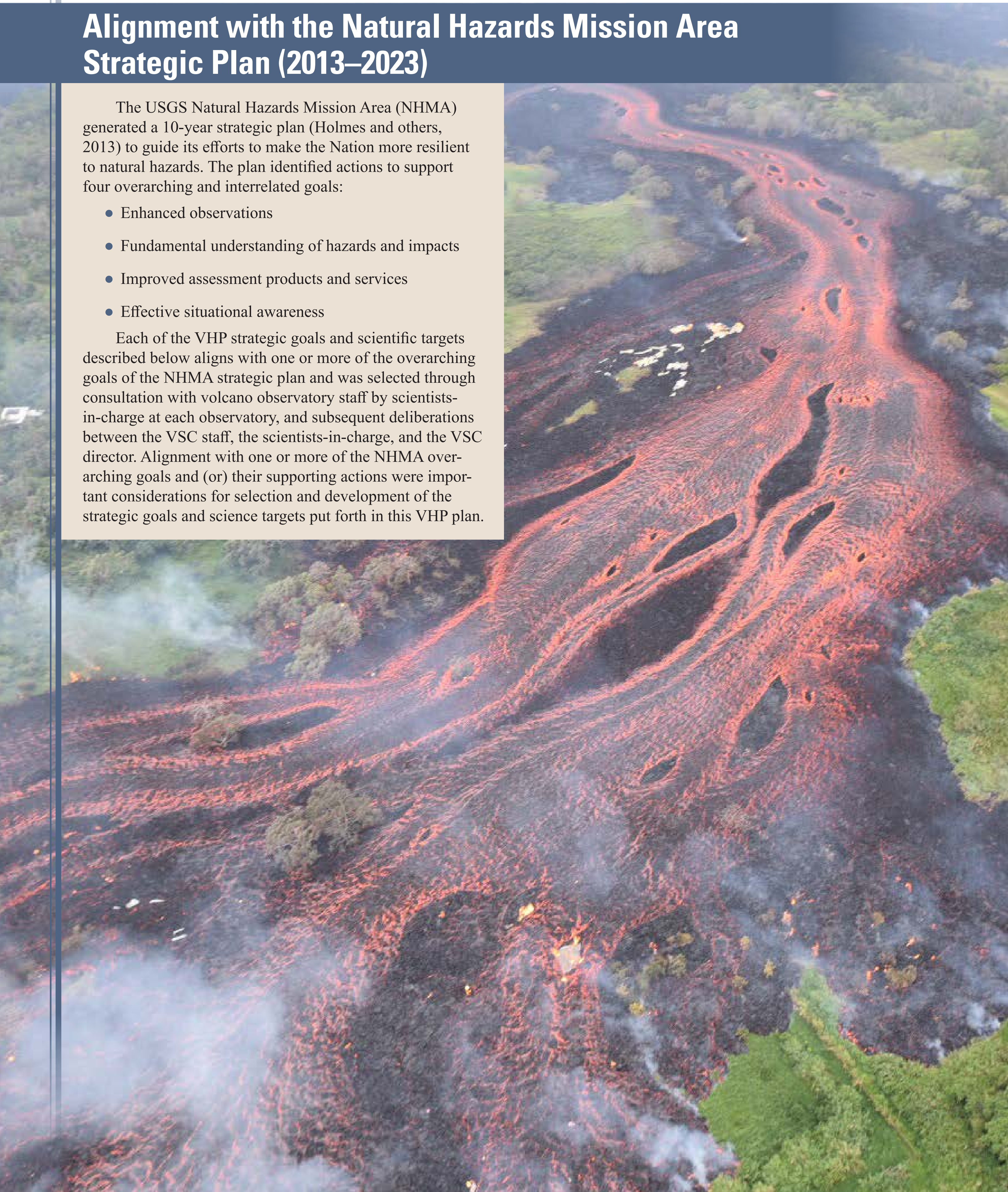
- **Lava flows**—Lava flows from future eruptions of Hawaiian volcanoes will continue to threaten built infrastructure. With this in mind, the VHP is seeking to improve its lava flow modeling and tracking capabilities and adapt existing lava flow modeling software to all lava types. The VHP intends to fully utilize new digital elevation models derived from recent lidar surveys of the Kīlauea summit and lower East Rift Zone and plans to use digital elevation models when they are developed from more widespread lidar surveys to be conducted in the near term over the entire Island of Hawai‘i.

Alignment with the Natural Hazards Mission Area Strategic Plan (2013–2023)

The USGS Natural Hazards Mission Area (NHMA) generated a 10-year strategic plan (Holmes and others, 2013) to guide its efforts to make the Nation more resilient to natural hazards. The plan identified actions to support four overarching and interrelated goals:

- Enhanced observations
- Fundamental understanding of hazards and impacts
- Improved assessment products and services
- Effective situational awareness

Each of the VHP strategic goals and scientific targets described below aligns with one or more of the overarching goals of the NHMA strategic plan and was selected through consultation with volcano observatory staff by scientists-in-charge at each observatory, and subsequent deliberations between the VSC staff, the scientists-in-charge, and the VSC director. Alignment with one or more of the NHMA overarching goals and (or) their supporting actions were important considerations for selection and development of the strategic goals and science targets put forth in this VHP plan.



Alignment with the USGS 21st Century Science Strategy

The VHP Strategic Science Plan aligns with the components of the USGS 21st Century Science Strategy (U.S. Geological Survey, 2021) of providing the Nation with relevant data, improving physical models with predictive capability, and delivering the data in actionable formats through dashboards and decision support applications in several ways, described as follows. First, the program seeks to improve situational awareness of the Nation's active and potentially active volcanoes by increasing the variety of ground-based sensors deployed on them through NVEWS implementation between 2022 and 2026. Second, as part of its NVEWS implementation, the program is increasing the use of artificial intelligence and machine learning in developing automated alarms capable of analyzing real-time monitoring data from multiple instrument types. Third, the increased amount of data generated by a built-out NVEWS will require the program to utilize cloud hosting and computing, in addition to artificial intelligence and machine learning, to be able to efficiently and fully analyze, synthesize, and interpret the data.

The VHP will continue to develop physics-based models of volcanic systems that will increase predictive capacity and the ability to issue accurate forecasts and warnings of hazardous volcanic activity. Alignment with the USGS 21st Century Science Strategy will be achieved through enhancement of existing partnerships and establishment of new partnerships that are relevant to successful NVEWS implementation. Examples include increased cooperation with the National Aeronautics and Space Administration (NASA) and access to the NASA-Indian Space Research Organization (ISRO) Synthetic Aperture Radar (NISAR) mission data streams, and low-latency access to National Oceanic and Atmospheric Administration (NOAA)/National Weather Service wind field and satellite-based remote-sensing data. Other examples include increased collaboration with National Science Foundation-funded investigators from the academic sector or with State geological surveys for leveraging of monitoring resources, subject-matter expertise, and emergency response capability. These partnerships will be particularly important for presently un-instrumented, moderate- and low-threat volcanic fields. Regional seismic networks and satellite-based remote sensing could indicate where campaign instruments should be deployed as a volcanic field reactivates.

Current operational program products that could feed actionable information to the Earth Monitoring, Analysis and Predictions (EarthMAP) initiative of the USGS 21st Century Science Strategy (U.S. Geological Survey, 2021) include (1) the Ash3d physics-based model of ash transport and deposition (Schwaiger and others, 2012), (2) next-generation volcanic hazard assessments, (3) the D-CLAW physics-based model for debris flows and lahars (Iverson and George, 2014; George and Iverson, 2014), (4) Volcano Activity Notices (VANs; see https://www.usgs.gov/natural-hazards/volcano-hazards/notifications), and (5) Volcano Observatory Notices for Aviation (VONAs; see https://www.usgs.gov/natural-hazards/volcano-hazards/notifications).

Volcano Hazards Program Mission Statement and Objectives

The mission of the VHP is to enhance public safety and minimize social and economic disruption from eruptions through delivery of effective forecasts, warnings, and information on volcano hazards based on scientific understanding of volcanic processes. The objectives of the program are to (1) respond to volcanic crises and (2) build capacity that makes such responses more timely, accurate, and effective. Examples of activities under the first objective include monitoring the geophysical, geochemical, and observational signals that indicate volcanic unrest; forecasting eruptions; issuing warnings; and providing information to guide responses by emergency managers. Examples of activities within the second objective include research and development to improve forecasting of eruptions and their hazards and to enhance monitoring technology, and work with emergency managers and communities to improve preparedness.

USGS Volcano Hazards Program Overview

The United States and its territories are home to 161 active and potentially active volcanoes (Ewert and others, 2018), and have experienced a wide range of destructive volcanic phenomena. Within the Natural Hazards Mission Area of the U.S. Geological Survey (USGS), the Volcano Hazards Program (VHP) conducts its mission to enhance public safety and minimize social and economic disruption from volcanic unrest and eruption through delivery of effective forecasts, warnings, and information on volcano hazards based on scientific understanding of volcanic processes. The program does this primarily through the operation of five volcano observatories managed under the Volcano Science Center (VSC), headquartered in Anchorage, Alaska. The locations and areas of responsibility of the five observatories are listed below and shown in figures 1 and 2.

- Alaska Volcano Observatory (AVO)—Anchorage and Fairbanks, Alaska; volcanoes in Alaska, the Commonwealth of the Northern Mariana Islands, and American Samoa.
- California Volcano Observatory (CalVO)—Menlo Park and Moffett Field, California; volcanoes in California and Nevada.
- Cascades Volcano Observatory (CVO)—Vancouver, Washington; volcanoes in Washington, Oregon, and Idaho.
- Hawaiian Volcano Observatory (HVO)—Hilo, Hawaii; volcanoes on the islands of Hawai‘i and Maui, and the Lō‘ihi submarine volcano, southeast of the island of Hawai‘i.
- Yellowstone Volcano Observatory (YVO)—Vancouver, Washington; volcanoes in Wyoming, Montana, Colorado, New Mexico, and Arizona.

Each of the five USGS volcano observatories performs real-time volcano monitoring, conducts core research on how volcanoes work, and establishes eruptive histories and hazards exhibited during past eruptions in order to prepare hazard assessments for each of the Nation’s active and potentially active volcanoes. The trifecta of monitoring, research, and hazard assessment strengthen and complement each other, triggering mutual progress in these endeavors. All three core functions are interdependent in the VHP’s mission. The volcano observatories also raise awareness of volcanic hazards to the public, to emergency response communities, and to State and Federal land managers through active communication and outreach; such outreach includes collaborative co-development and generation of volcano-specific emergency response plans that increase community preparedness and resilience to volcanic hazards. Generation of such emergency response plans ensures that (1) incident command systems, which may be established in an eruption event, benefit from embedded USGS volcano observatory scientists and (2) emergency managers are familiar with USGS forecast and warning products, subject-matter experts, and roles and responsibilities of USGS observatory scientists ahead of volcanic unrest. Each volcano observatory has its own unique and necessary culture, influenced by geographic location, the types of volcanoes monitored and their eruption frequency, and the close relationships developed with the public and with local emergency response partners. However, the VHP is also striving toward more standardization of analytical software and increased interoperability among its volcano observatories. The value of this interoperability was well demonstrated during the recent response to the Kīlauea summit and lower East Rift Zone eruption of 2018. Scientific and technical staff from all five volcano observatories participated in the response, either through travels and temporary work assignments in Hawaii, or in a remote-duty capacity as part of our 24/7 nationwide operations.

In addition to the five volcano observatories, the VHP—in partnership with the U.S. Agency for International Development—operates an international arm of the program called the Volcano Disaster Assistance Program (VDAP), which provides support to volcano observatories around the world, with an emphasis on those in developing countries. When requested by the foreign country, VDAP undertakes a broad swath of activities related to capacity building, equipment donation, and training in diverse fields related to volcanology. VDAP staff provide advice both during remote responses to eruptions and during occasional in-country responses to eruptions. Lessons learned through VDAP activities and responses are then applied to the domestic operations of the VHP (Lowenstern and Ramsey, 2017). VDAP activities reduce risk and vulnerability to volcanic hazards worldwide in many areas where the United States has interests, assets, and operations exposed to volcanic hazards.

The VHP management structure reflects the matrix management of the USGS, with a program office in USGS headquarters in Reston, Virginia. From the program office, the program coordinator sets the strategic science plan and annual program guidance, develops program metrics, coordinates with leadership of other Federal partners, answers data calls from Congress and from USGS and Department of the Interior leaders, manages the VHP’s cooperative agreements, and determines annual Congressionally appropriated funding allocations to the VSC and other USGS organizational units. The VSC has line authority over all five volcano observatories and VDAP, and it thus has the massive responsibility for executing the science plan, conducting volcano monitoring and eruption response, and developing regional, State, and local partnerships. An organizational chart for the VHP is shown in appendix 1.

Strategic Goals

1. National Volcano Early Warning System (NVEWS)

For more than a decade, the concept of a National Volcano Early Warning System (NVEWS) has been a major force driving program plans and efforts. First envisioned in 2003, NVEWS was formulated on the basic principle that the Nation's volcanoes require a level of monitoring commensurate with the threats they pose. Transforming this principle into concrete action first required a thorough assessment of the scope and nature of volcanic threat from each of the 161 active and potentially active volcanoes in the United States. From this assessment, along with a corresponding evaluation of the exposed population and infrastructure, a relative threat ranking of volcanoes ranging from very high threat to very low threat was derived (figs. 1, 2). In 2005, the program completed compiling this relative threat ranking using information available at the time (Ewert and others, 2005), with a subsequent updated ranking published in 2018 using newly available data (Ewert and others, 2018). In 2008, guidelines were established for recommended levels of instrumentation for a volcano of a given threat level (Moran and others, 2008). NVEWS implementation will create new, high-quality data that improve the VHP's ability to warn of volcanic unrest and eruption and to enhance understanding of volcanic processes. Such understanding is essential for effective forecasts.

Since its introduction, NVEWS has received much attention and praise from emergency managers, the academic community, and other stakeholders, both domestic and international. The USGS NVEWS methodology is rapidly becoming the world standard for prioritization of investments in volcano monitoring and related research. For example, the government of Chile was advised by the Volcano Disaster Assistance Program on the importance of establishing a national volcano monitoring system (Lowenstern and Ramsey, 2017), and as of 2020 more than a dozen nations had adopted the method. Congress, too, has shown bipartisan support for the NVEWS initiative. NVEWS legislation was incorporated as Title V of the John D. Dingell, Jr., Conservation, Management, and Recreation Act that was signed into law (Public Law 116-9) on March 12, 2019. This first-ever authorization of NVEWS by Congress, covering the years 2019 through 2023, marks an important milestone for the Volcano Hazards Program that was approximately 15 years in the making. Although authorization does not guarantee appropriations, Public Law 116-9 presents a strong endorsement for the objectives of NVEWS and authorizes the appropriation of $55 million over the 2019–2023 period.

The legislation states that "the Secretary of the Department of the Interior acting through the Director of the USGS shall establish within the USGS a system to be known as the National Volcano Early Warning and Monitoring System to monitor, warn, and protect citizens of the United States from undue and avoidable harm from volcanic activity." The legislation calls upon the USGS to organize, modernize, standardize, and stabilize the monitoring systems of its five volcano observatories in the United States and unify them into a single interoperable system. The overarching objective of this system, to ensure that all the volcanoes in the United States and its territories are monitored at a level commensurate with the threats they pose, will be accomplished through the following activities:

- Upgrading existing networks on monitored volcanoes.
- Installing new networks on unmonitored volcanoes.
- Employing geodetic and (or) other monitoring components (for example, gas and infrasound sensors, visible and infrared cameras, and seismic and gravity sensors) when and where applicable.

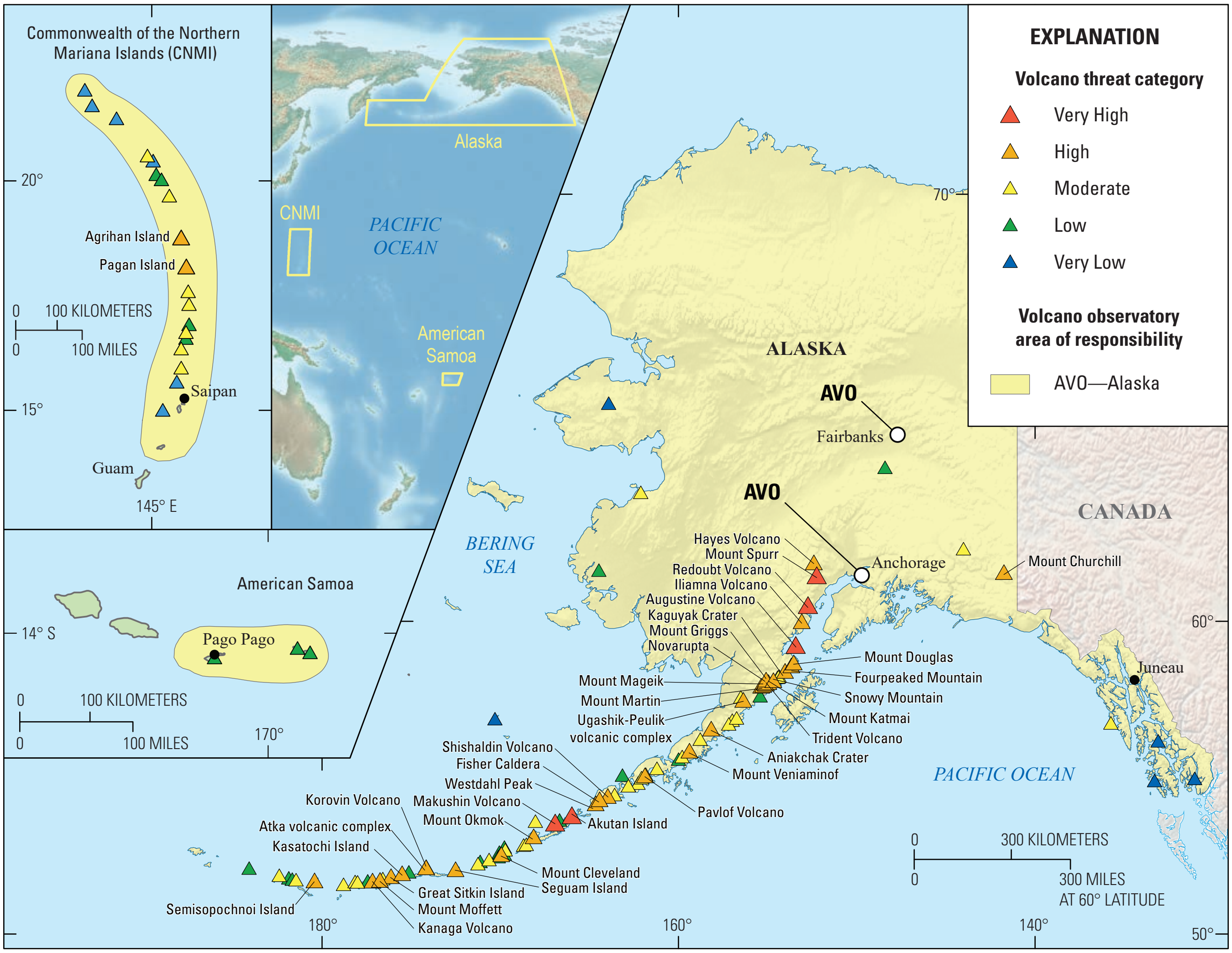
Base from https://www.naturalearthdata.com; WGS 84 Spherical Mercator projection

Figure 1. Map of the Western United States and Hawaii showing active and potentially active volcanoes and their relative threat levels as designated in the National Volcano Early Warning System (NVEWS). Names are included for volcanoes in two threat categories: very high threat and high threat. Also shown are the areas of responsibility for the California, Cascades, Yellowstone, and Hawaiian Volcano Observatories.

The legislation calls for the following system components:

- A national Volcano Watch Office that is operational 24 hours per day, 7 days per week (24/7). The Volcano Watch Office will be merged into the National Volcano Data Center as a cost-saving and efficiency measure.
- A National Volcano Data Center (now referred to as the National Volcano Information Service). The combined National Volcano Data Center-Volcano Watch Office will operate on a 24/7 basis.
- An external grants activity to support research in volcano monitoring science and technology.

Congress has strongly encouraged the strengthening of partnerships and leveraging of resources to achieve measurable progress in the name of public safety. The legislation directs the Secretary of the Interior to establish an advisory committee to assist the Secretary in implementing the system, to be composed of representatives of relevant Federal agencies and members of the scientific community to be appointed by the Secretary. Members of the advisory committee will be leaders from agencies with which Public Law 116-9 directs the Secretary of the Interior to coordinate implementation activities: the Secretary of Transportation, Administrator of the Federal Emergency Management Agency (FEMA), Administrator of the Federal Aviation Administration, and Administrator of NOAA. Other relevant Federal agencies with which the program already partners in volcano monitoring and research will also be invited, including the National Science Foundation and NASA.



Base from https://www.naturalearthdata.com; WGS 84 Spherical Mercator projection

Figure 2. Map of Alaska, the Commonwealth of the Northern Mariana Islands (CNMI), and American Samoa, showing active and potentially active volcanoes and their relative threat levels as designated in the National Volcano Early Warning System (NVEWS). Names are included for volcanoes in two threat categories: very high threat and high threat. The entire region is within the area of responsibility for the Alaska Volcano Observatory (AVO). The CNMI, an unincorporated territory of the United States, lies about 55 kilometers (km) northeast of Guam and extends northward for another 800 km along a chain of 15 islands, most of which have active volcanoes.

Per Public Law 116-9, the VHP also prepared a five-year management plan for establishing and operating the system, which was transmitted to Congress on March 12, 2020 (this was also published as a USGS Open-File Report [Cervelli and others, 2021]). The plan contains the following components:

- Annual cost estimates for modernization activities and operation of the system.
- Annual milestones, standards, and performance goals.
- Recommendations for, and progress toward, establishing new partnerships or enhancing existing partnerships to leverage resources.

The NVEWS five-year management plan describes the USGS strategy to close monitoring gaps on the 34 most threatening volcanoes in the United States with approximately 200 ground-based instruments, during “phase 1” of NVEWS implementation (pending NVEWS specific appropriation), as well as the steps it will take to establish the components of NVEWS listed above should funding be received at the authorized levels. Progress on achieving the monitoring standards proposed in the legislation for the majority of moderate- to low-threat volcanoes and volcanic fields in the Intermountain West of the United States (in Colorado, New Mexico, Arizona, Utah, Nevada, Wyoming, and Idaho) would compose a later “phase 2” of NVEWS implementation, where leveraging of resources from cooperative agreement partners (including State universities and geological surveys), and from Federal agencies operating remote-sensing satellites (NASA, NOAA), will be increasingly important. The five-year management plan complements a less-detailed, 10-year NVEWS implementation plan written in response to Senate report language accompanying FY2017 appropriations (page 38 of Division G of Senate Report 114-218 that accompanied Public Law 115-31): "The USGS is directed to report back to the Committee within 1 year of enactment of this act on the agency's plan to repair, upgrade, and expand monitoring, detection, and warning systems and equipment on high-threat volcanoes." That report was transmitted to Congress on June 19, 2019.

The VHP is not starting from scratch in its network modernization and augmentations efforts. On the contrary, work is well underway. Network modernization was initiated during the 2009–2011 application of $15.2 million of FY2009 American Recovery and Reinvestment Act (ARRA) funds to networks at all USGS volcano observatories. This work has continued opportunistically since 2011. Following the passage of ARRA, the already vetted and published NVEWS plans (Ewert and others, 2005; Moran and others, 2008) offered a clear roadmap to important, well-defined opportunities to advance the Nation's volcano monitoring capabilities. Without NVEWS, and without all the work put into establishing threat rankings and conducting subsequent implementation studies, the VHP would have been an unlikely target for ARRA funding. Instead, the program's "shovel-readiness" led to $15.2 million in ARRA funds that paid for, among other projects, a complete modernization of the seismic network of the Hawaiian Volcano Observatory (HVO) (Okubo and others, 2014) and major improvements to the networks at the Alaska Volcano Observatory (AVO), Cascades Volcano Observatory (CVO), and Yellowstone Volcano Observatory (YVO). Maintaining a list of prioritized "ready-to-go" NVEWS implementation projects from all observatories will be necessary in the next five years. It will also be necessary to establish a formalized and equitable vetting process for determining which NVEWS projects go forward following a potential NVEWS appropriation.

Implementation of NVEWS under the 2019 authorization remains the VHP's principal strategic goal for volcano monitoring. NVEWS will build on modernization efforts already underway. In FY2018, Congress appropriated $14.5 million above the VHP base funding of $28.1 million as "one-time infrastructure funds." Within that total, $13.5 million was used to buy equipment necessary for conversion of 117 analog monitoring stations to digital stations on high-threat volcanoes in Alaska. Completion of analog-to-digital station conversions is a necessary prerequisite to NVEWS buildout in Alaska because the addition of new instruments to these stations (for example, global positioning system (GPS) receivers, infrasound arrays, gas spectrometers, visible and infrared web cameras, and sensitive digital broadband seismometers), will require digital telemetry paths to accommodate new and multivariate real-time data streams. In the summer field season of FY2018, 15 analog stations were converted to new digital stations having digital broadband seismometers and digital telemetry, and in the FY2019 field season, a total of 42 analog stations were converted to digital. In the FY2020 field season, 10 analog stations were converted to digital, despite challenges posed by the COVID-19 pandemic. In FY2021, an additional 27 stations were converted, bringing the total down to 16 analog stations remaining. In addition, $1.0 million in FY2018 one-time funds were applied to continued development and installation of a new lahar detection system on Mount Rainier in Washington, replacing a system installed in 1998 that had reached the end of its expected service.

Augmentation of networks during NVEWS implementation will require a concomitant hiring of scientific, technical, and administrative staff. Augmented networks having a wider variety of ground-based sensors and associated data streams will require analysis by a greater number of scientists of varying specialization (for example, geodesists, seismologists, gas geochemists, and remote-sensing geologists). Moreover, the instrumentation buildout and its long-term maintenance will require an associated hiring of additional field engineers and technicians to service the networks following initial installation with regularly scheduled maintenance visits every 3 to 5 years. Full buildout of NVEWS, assuming full authorized funding of $11 million per year for five consecutive years, will entail the installation of approximately 600 new sensors and the addition of approximately 60 staff members, consisting of about 25 scientists and data analysts, with the remaining positions consisting of engineers, computer scientists, system administrators, and project managers. The timing of hiring and the number of new staff will be dependent on the size of future NVEWS appropriations and whether they are sustained.

Growth and augmentation of the Nation's volcano monitoring networks will continue over the next five years, although the pace of work depends strongly on the size and frequency of NVEWS specific appropriations. Moreover, the VHP faces the concurrent challenge of maintaining existing instrumentation already in place, much of which has aged past its useful lifetime and will require upgrade or replacement in the near future. Progress on all of these fronts will continue to be tracked by the program as part of its annual performance metrics.

National Volcano Early Warning System (NVEWS) Optimization of Monitoring Networks

The U.S. Geological Survey (USGS) prioritizes monitoring, research, hazards evaluation, and community engagement at those volcanoes posing the greatest threat to life and property when they erupt. Many of the most dangerous volcanoes in the United States have only incomplete monitoring networks and obsolete instruments with which to detect the subtle signs of reawakening. Modernizing these networks under NVEWS so that the Nation's volcanoes are monitored at levels commensurate with their threat will create robust sources of real-time data and better situational awareness, and will allow the Volcano Hazards Program (VHP) to improve detection of unrest. These benefits of NVEWS implementation will allow the USGS and its State and university partners to better warn of unrest, lead to greater understanding of underlying volcanic processes, shift eruption response from reactive to proactive, and ultimately lead to more accurate forecasts of eruptive activity.

To increase the monitoring efforts at Mount Rainier, Washington—one of the highest priority volcanoes according to NVEWS rankings—scientists installed a digital broadband seismometer in the Puyallup River valley in the summer of 2017. The USGS VHP and the Pierce County Office of Emergency Management plan to install digital broadband seismometers in the other major river valleys around Mount Rainier. These additional seismometers will improve the volcano monitoring network so that scientists may detect eruption precursors at the earliest stages.

Scientists installing a digital broadband seismometer about 18 kilometers west of the summit of Mount Rainier, Washington, in the Puyallup River valley. Photograph by Rebecca Kramer, USGS.

U.S. Geological Survey (USGS) Cascades Volcano Observatory geophysicists Martin LaFevers and Wes Thelen programming seismic equipment in the enclosure at the Paradise lahar detection station within Mount Rainier National Park, Washington. In addition to addressing the normal challenges of doing fieldwork in remote locations, scientific staff in the Volcano Hazards Program had to contend with personal protective protocols required by the COVID-19 pandemic. Photograph by Liz Westby, USGS.

Recently completed Ohanapecosh lahar detection station in Mount Rainier National Park, Washington, placed beside existing utility service. In September and October 2020 the U.S. Geological Survey (USGS) Volcano Hazards Program installed five new lahar detection stations within the park to improve the new generation lahar detection system. Photograph by Martin LaFevers, USGS.

2. Preparedness

General readiness for volcanic unrest or an eruption crisis requires fortification along many fronts. A fully implemented NVEWS monitoring network is a bulwark against sudden surprises and a primary means of eruption forecasting, but does little to prepare a community for a prolonged period of volcanic unrest. Moreover, even the most prompt and accurate forecasts accomplish nothing unless they reach the right people having the right authority and knowledge at the right time. The worst volcanic disaster in recent history needlessly killed more than 25,000 people when a lahar resulting from the November 13, 1985, eruption of Nevado del Ruiz (fig. 3) inundated the town of Armero and surrounding areas in Colombia with inadequate warning. Better planning and more effective communication with the at-risk population likely could have averted or greatly reduced this tragedy (Voight, 1990, 1996). The disaster at Nevado del Ruiz led to the establishment of the USGS-U.S. Agency for International Development (USAID)-funded Volcano Disaster Assistance Program (VDAP; see Newhall and others, 1997; Lowenstern and Ramsey, 2017). Even though much progress has been made in the 36 years since the Nevado del Ruiz tragedy, and many lessons have been learned from VDAP's foreign volcanic crisis assistance, more domestic preparedness work needs to be done. This circular outlines the ways in which the VHP will continue to improve the delivery of its most timely products to the right stakeholders at the right time.

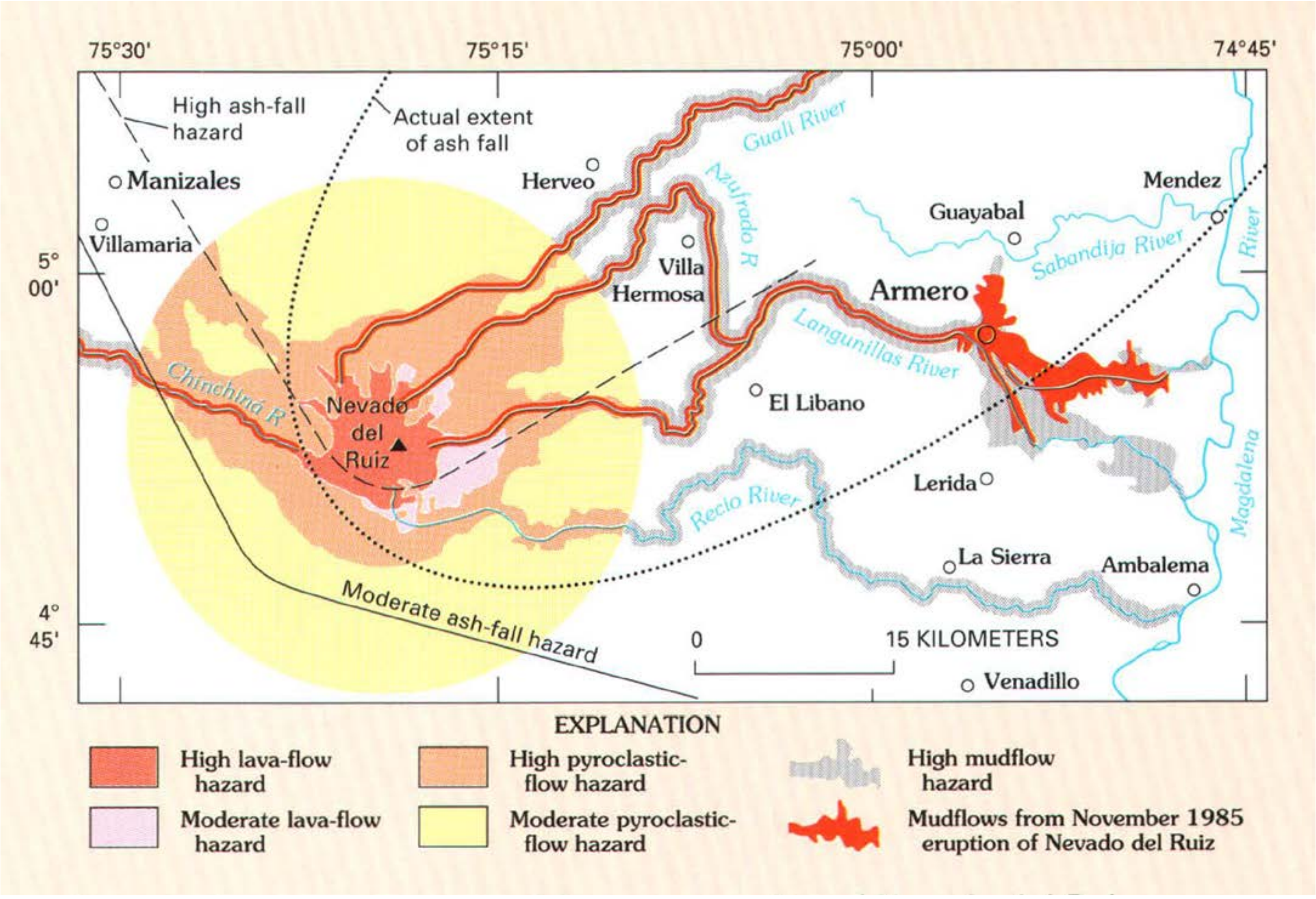


Figure 3. Map showing hazards expected from an eruption of Nevado del Ruiz volcano, Colombia. Such a map was prepared by INGEOMINAS (Colombian Institute of Geology and Mines) and circulated 1 month prior to the November 13, 1985, eruption of Nevado del Ruiz. This map additionally shows the geographic extent of the mudflows (red areas) that killed approximately 25,000 people in that eruption. This tragedy led to the creation of the Volcano Disaster Assistance Program (VDAP) by the U.S. Geological Survey and the U.S. Agency for International Development. From Wright and Pierson, 1992, p. 21.

Over the next five years, the program will work aggressively to increase its role in working with community partners to improve preparedness. Specifically, the VHP will support work to:

1 Define levels of community preparedness akin to the NVEWS-defined monitoring levels. The definitions will be qualitative and subject to evolution over time, with numeric scores derived from expert elicitation. For example, a minimally prepared community might be one where most of the population understands that they live near an active volcano, elementary school students learn about local volcanic hazards, and local governments have contact information for their nearest volcano observatory. This approach would be similar to the NOAA-National Weather Service (NWS) TsunamiReady effort (see https://www.weather.gov/tsunamiready/) with established guidelines for preparedness.

2 Determine the data necessary, create a consistent and codified methodology for producing “next-generation” hazard assessment products, and standardize the creation of these products across all the USGS volcano observatories. This methodology should be suitable for the diverse range of volcano types monitored by the VSC. Once defined, the hazard assessment products will be essential elements of the previously described community preparedness levels.

3 Host training sessions on subjects related to preparedness (for example, Incident Command Systems, probabilistic eruption forecasting, and so forth) for both USGS staff and collaborators in local, State, and Federal government. One important target is to update and improve the FEMA-certified Volcano Crisis Awareness training program for emergency-manager partners, developed by the University of Hawai‘i (Manoa) National Disaster Preparedness Training Center. Exchanges with foreign countries allow local and State officials to gain insight from lessons learned at volcano crises overseas, and to use those lessons to further regional preparedness planning for future domestic crises (Pierson and others, 2017).

4 Continue periodic briefings for local officials, State and Federal emergency managers, and first responders on local volcanic hazards sufficiently often to account for turnover in these professions. Briefings will provide background knowledge on local volcanoes and information about observatory procedures and responsibilities, while also relaying the most current understanding of community vulnerability.

5 Conduct tabletop or functional exercises. These should involve relevant stakeholders, be realistic, and illustrate the complexity and difficulties of an actual volcanic crisis response. Ideally, the exercises should cover a diverse group of volcanoes that, taken together, typify the eruption scenarios most likely to occur (Pierson and others, 2013).

6 Host town hall-style and other engagements with the public (for example, open houses, school visits, or appearances on local radio or television), both during eruption crises and volcanic unrest and during periods of calm. During the Kīlauea 2018 eruption, the HVO led or participated in more than a dozen well-attended public meetings in different towns to discuss activity at the volcano, ash and vog hazards, prognosis for what was going to happen, and other aspects of the 2018 activity. Challenges for USGS scientists included accurate portrayal of uncertainties in how the unrest or eruption could progress, distilling the most helpful guidance to clear and simple suggestions, and staying consistent and allied with cooperating local, State, and Federal emergency authorities. The meetings should raise public awareness of local volcanic hazards and build familiarity and trust with the local volcano observatory.

7 Develop and maintain multi-agency response plans for the most threatening volcanoes. Explore the applicability of "generic" plans for eruption types ranging from prolonged explosive eruptions that threaten large populations to quiet lava effusions far from major towns or infrastructure. Although the type and structure of local governments vary from place to place, many other factors would remain comparatively constant. The response plan that the AVO developed for ash hazards at a large number of Alaskan volcanoes provides a useful starting point for this effort.

8 Use social media and web presence to highlight new or interesting research about community vulnerability or risk studies. Use public websites to increase public preparedness through access to volcano hazard information, warnings and updates, monitoring data, images, video, and graphic products. Use social media to provide situational awareness and educational content to the public through two-way communication between USGS scientists and the public where comments are quickly addressed and questions are readily answered.

A variety of factors influence the prioritization of these goals, including their immediate value to at-risk populations, volcano threat levels, community interest, available funding, and unanticipated opportunities.

The VHP has responsibility for mitigating the harmful effects of volcanic activity within the United States. Core elements of this responsibility—research, monitoring, and communication—are not in doubt, yet the potential fourth element—risk, which is the potential loss of societally important assets caused by volcanic activity—has not been adequately addressed. Even as early as 1985, USGS scientists foresaw the determination of risk as another important aspect of volcano hazards assessment (Tilling and Bailey, 1985). More recently, the USGS scientists and managers have emphasized risk reduction as an important component of the Bureau's (USGS) core mission of preparedness (U.S. Geological Survey, 2007; Holmes and others, 2013; Ludwig and others, 2018), as stakeholder demand for risk reduction has risen. By incorporating the goal of risk reduction into its science, the VHP will be able to deliver enhanced core mission science products to stakeholders in user-centric formats—incorporating fields such as social science and economics—to support stakeholders' efforts to plan more resilient responses to volcanic hazards.

Substantive papers on the topic of volcano risk have been published by USGS scientists (for example, Diefenbach and others, 2015), and the USGS volcano observatories are, in many cases, already practicing risk activities. Starting in 2015, the VHP aided in developing a formal USGS plan to build "internal capacity to advance development and delivery of actionable information for risk reduction" for natural hazards. The effort culminated in USGS Circular 1444, "Science for a risky world—A U.S. Geological Survey plan for risk research and applications" (2018), on which a VHP-supported geologist is second author. The same geologist co-leads the Risk Implementation Team and the USGS Risk Community of Practice, both recommendations of the USGS Risk Plan. The Risk Implementation Team began issuing annual requests for research proposals in FY2019 and FY2020. A VHP geographer received an award from the USGS Risk Community of Practice for the project, "User perspectives on volcanic risk: Evaluating the effectiveness of co-produced risk communication products intended for public outreach," and VHP scientists have been encouraged to submit future risk reduction proposals. Several VHP scientists have also been attending monthly meetings of the USGS Risk Research and Applications Community of Practice since its launch in March 2019. The VHP now explicitly acknowledges determination of risk as part of its portfolio of responsibilities.

3. Volcanic Hazard Assessments

A major focus of the VHP since its inception has been the preparation of volcanic hazard assessments. Such assessments are a critical component of preparedness. Nearly all hazard assessments organize themselves around the hazard-zonation map, which delineates areas threatened by volcanic phenomena, such as lava flows, lahars, and ashfall. Yet, a hazard assessment requires much more than a hazard map. Hazard assessments are based on a wide range of other information to both mitigate risk and define the likely scope of future volcanic activity. Examples of such information include probabilistic forecasts; eruptive history and global analogues; conceptual or numerical models; and location-specific data about potentially affected communities, refined with direct input from their emergency-management officials and other leaders. The VHP's "next-generation" hazard assessments will function best in combination with a portfolio of related and mutually supporting products like online tools, technical reports, and response plans. The portfolio must also be dynamic, evolving both through ongoing discussion with stakeholders and through periodic re-evaluation of community risk.

The VHP has produced a portfolio of volcanic hazard assessment products for various locales, but the character and content of the present assessments vary widely and adhere to no well-established standards. In late 2016, the VHP hosted a Volcano Observatory Best Practices workshop on long-term volcano hazard assessments, in conjunction with U.S. and international partners. Representatives from 20 nations attended the workshop and identified a series of 14 best-practice guidelines for developing hazard assessments and related products (Pallister and others, 2019). These guidelines acknowledge the importance of partnering with stakeholders and endorse the concept of hazard assessments being a portfolio of products created and maintained according to local needs. Over the next five years, the VHP will do the following:

1. Conduct pilot projects to build on and extend the international best-practice guidelines that it helped develop. The pilot projects will produce a next-generation hazard assessment for Mount Baker and one for Kīlauea as examples that will be suitable for all high-threat U.S. volcanoes.

2. Inform next-generation volcano hazard assessments with risk evaluation and stakeholder input. Use geographic information system (GIS) databases, visualization software, computational models, statistical approaches, and other appropriate methods to depict volcano hazards and zones in formats that most effectively convey information and meet user-specific needs.

3. Make long-term assessments more probabilistic to better characterize risk to critical infrastructure and prepare the public. Examples include incorporation of scenario-based Bayesian event-tree analysis in assessments and integration of eruption size-frequency data with forward modeling of ash fallout using tools such as Ash3d (Schwaiger and others, 2012).

4. Seek opportunities to evaluate user needs and the effectiveness of information products, services, and observatory communications by incorporating social and behavioral science insights and more fully engaging partners, stakeholders, and users (Williams and others, 2020).

5. Continue improving USGS public websites to increase access to and dissemination of volcano hazard information, warnings and updates, monitoring data, images, video, and graphic products.

6. Continue to provide situational awareness and educational content to the public via social media (for example, Facebook, Twitter, Instagram, and YouTube). These forms of communication were very effective during the Kīlauea 2018 eruption, as many local residents obtained critical decision-making information this way. The program (USGS Volcanoes), mission area (USGS Natural Hazards) and Bureau (USGS) social media accounts offer two-way communication between USGS scientists and the public where comments are quickly addressed and questions are readily answered.

New Observations from New Instrumentation—Gas Sensors

As magma rises toward the surface of the Earth, the pressure decreases and dissolved gases, like water (H_2O), carbon dioxide (CO_2), sulfur dioxide (SO_2), hydrogen sulfide (H_2S), and hydrogen chloride (HCl), separate from the liquid magma. Just as when opening a bottle of soda, gas bubbles reach the surface first, so a change in the amount and ratio of gas emissions at active volcanoes is a common and important precursor to eruptions. This was well documented by the airborne gas measurements made three months prior to the eruption of Redoubt volcano, Alaska, in 2009 (see Werner and others, 2013).

In years past, the USGS collected gas measurements from fixed-wing aircraft once volcanic unrest had been detected. Such gas measurements represented only one point in time and there was no way to know how much early degassing had already taken place, or if the ratios of different gases, like CO_2 to SO_2 or SO_2 to H_2S, had changed significantly. However, over the past ten years a revolution in the development of real-time continuous gas measurement instruments—such as ultraviolet cameras, MultiGAS sensor packages, and miniaturized scanning differential optical absorption spectrometers—has enabled scientists to measure all gas species and their ratios. Just as analyzing the chemistry of volcanic rock helps volcanologists identify the eruptive history of a volcano, diagnostic gas geochemistry helps the USGS generate eruption forecasts and gives volcanologists an indication of how much magma might be ascending below a volcano. The USGS is now installing these new gas measurement instruments on active volcanoes in the United States to document precursory changes in gas emissions at the earliest stages of unrest.

An ultraviolet camera system designed to measure sulfur dioxide is aimed at Shishaldin volcano, Alaska. Scientists from the U.S. Geological Survey (USGS) Volcano Science Center visited Shishaldin in 2015 to assess ongoing unrest. Their measurements showed magma was degassing from shallow depth, at times causing small explosions that deposited ash on the volcano's flanks. Photograph by Christoph Kern, USGS.

4. New Observations and Instrumentation

The VHP creates and acquires large amounts of geological, geochemical, and geophysical data every day, both from its volcano monitoring networks and from satellites operated by NASA, NOAA, and other Federal partners (including classified assets/National Technical Means accessed through the National Civil Applications Program). VHP-supported scientists also collect data during fieldwork, from USGS laboratories, and from hypothesis-driven experiments. However, many other potentially valuable data types and sources remain underused. Going forward, the VHP will make better use of the following:

1 **Gas sensors.** Until very recently, gas measurements made by the VHP always occurred in campaign mode, yielding no continuous data and no real-time telemetry. In the past few years, however, the VHP and international partners have developed and deployed telemetered instruments to measure gas emissions in active plumes using the continuously recording USGS MultiGAS system (Werner and others, 2017) that measures in-plume concentrations of water (H_2O), carbon dioxide (CO_2), sulfur dioxide (SO_2), and hydrogen sulfide (H_2S); estimates SO_2 emission rates; and determines ratios for a variety of volcanic gas species. The VHP has also deployed telemetered eddy covariance systems for measuring CO_2 emissions in both the Long Valley Caldera and the Yellowstone Plateau volcanic field. Both systems have performed well, even in extreme environments, and when used together they have proven useful for both forecasting and research purposes (Lewicki and others, 2014). The VHP, which integrated the MultiGAS sensor with unoccupied aircraft systems (UAS) for gas measurements during the Kīlauea 2018 eruption response, plans to expand the use of these systems to new areas and will continue to improve their capabilities and robustness. For more information on gas measurement systems, see the highlight entitled “New Observations from New Instrumentation—Gas Sensors.”

2 **Digital telemetry**. Because of new radio-frequency spectrum reallocations by the National Telecommunications and Information Administration and narrower bandwidth constraints, the VHP was required to decommission most of its existing analog telemetry by September 30, 2021, which resulted in an opportunity to replace the noncompliant analog radios with much more capable digital alternatives. Analog telemetry suffers from many random noise sources that irreversibly degrade the transmitted signal. This makes it unsuitable for the new monitoring software that is designed to detect and report low-magnitude seismic patterns that often precede eruptions. New digital telemetry will therefore improve the program’s monitoring capability by accommodating additional types of instruments (continuous GPS, gas sensors, web cameras, and infrasound arrays) and move the program closer to NVEWS completion, while also opening new avenues of research into volcano seismology with better data. In FY2022, the USGS Earthquake Hazards Program (EHP) received Congressional appropriations for expansion of the ShakeAlert Earthquake Early Warning System ("ShakeAlert") in Alaska; therefore, the VHP and EHP may have some limited opportunity for constructing digital telemetry infrastructure in select areas that serve both programs by supporting both ShakeAlert and NVEWS implementations.

3 **Remote sensing**. Using satellite-based remote sensing, the VHP routinely monitors domestic volcanoes—and more than 100 volcanoes around the world in support of VDAP activities—for changes in eruptive activity or extrusion rates. This capability will continue to grow as the next generation of satellites enters service, offering higher resolutions, shorter repeat times, broader spectral ranges, and agile tasking abilities. To take full advantage of these improvements, the VHP must strengthen existing partnerships and create new ones with the agencies—national and international—that launch and operate earth observation satellites. For example, VHP’s relationship with Italy’s Instituto Nazionale di Geofisica e Vulcanologia and Agenzia Spaziale Italiana has already resulted in access to high-quality SAR data from the COSMO-SkyMed constellation of satellites, and promises other significant, near-term benefits such as academic pricing for interferometric synthetic aperture radar (InSAR) products. Figure 4 depicts a pair of COSMO-SkyMed radar intensity images of Bogoslof volcano in Alaska, illustrating the great utility of such data. In addition to pursuing international partnerships, the VHP will also strive for stronger ties with NASA and NOAA to leverage shared remote-sensing expertise and improve data exchange. The VHP will make full use of SAR images of U.S. volcanoes from the NISAR mission, scheduled for launch in September 2023, for change detection. VHP scientists have also been serving on the NISAR Science Planning Team. In 2013, the VHP stationed a volcanologist/remote-sensing expert among the analysts at the National Civil Applications Program facility in Reston, Virginia. This arrangement has been a great success, and VHP aims to reinforce and expand its utilization over the next five years. An additional permanent remote-sensing volcanologist who also specializes in lava flow modeling was added to the staff of the AVO in 2018.

4 **Unoccupied aircraft systems**. Although fraught with regulatory challenges, UAS offer a promising and largely untapped potential for data collection at volcanoes, especially those too dangerous or remote to approach via crewed aircraft. Examples of data collection by means of UAS include gas sampling, aerial photography and photogrammetry, radar, lidar, thermal and multispectral measurements, and even sample collection by aircraft

Cosmo-SkyMed SAR View of Bogoslof Volcano

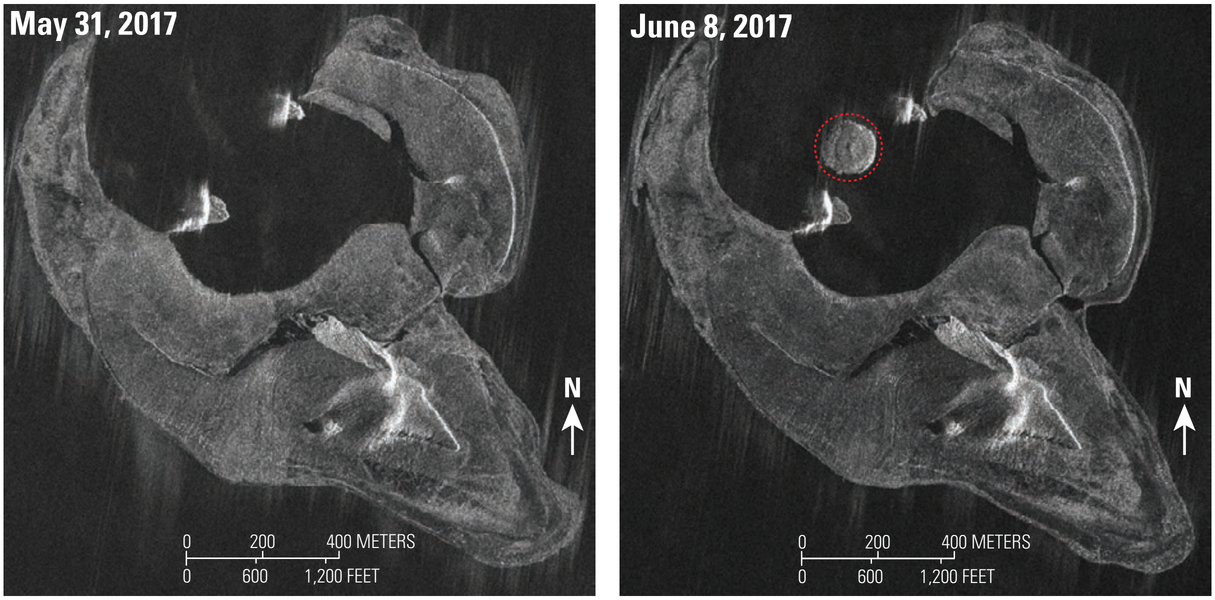


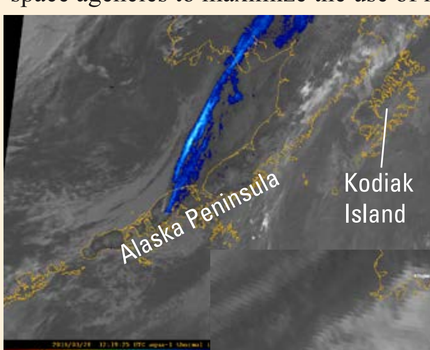
Figure 4. X-band radar data from the Italian Space Agency's Cosmo-SkyMed earth observation satellite system show the appearance of a new lava dome (within the dashed red circle in June 8 image) emerging from the sea at Bogoslof volcano in Alaska. Radar offers several advantages over observations at visible wavelengths, including the ability to see through clouds and steam and to operate without ambient light. The volcano's present shape differs significantly from its pre-eruption form. The Alaska Volcano Observatory has tracked Bogoslof's often violent evolution since the recent eruption began in early December 2016. This information tells much about the nature and kind of the ongoing volcanic processes, which both advances our basic understanding of volcanism and improves the timeliness and accuracy of our forecasts. Image credit: Michael Poland (U.S. Geological Survey) and Kim Angeli (National Civil Applications Program, U.S. Geological Survey).

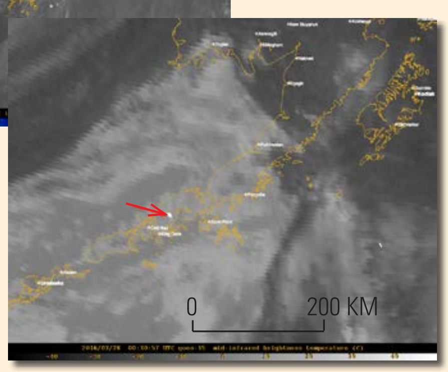
capable of hovering to collect samples and carry sample payloads (for example, rotor-wing aircraft and quadcopter platforms). UAS capabilities, like speed, range, flight duration, and payload, vary over a large scale, as do their costs: from multi-million dollar UAS platforms for military defense to small, inexpensive (~several hundred dollars) quadcopters that provide video surveillance. UAS have two general modes of operation: remotely piloted flight and autonomous flight along a programmed route, the latter of which enables missions flown beyond line of sight. The VHP successfully utilized UAS platforms during the response to the Kīlauea eruption of May 3 to August 4, 2018 (see Highlight, p. 22), clearly demonstrating the great utility of UAS platforms in future eruption responses. The critical value of this technology necessitates having additional UAS pilots within the VSC and expanding the use of UAS at all the USGS volcano observatories. In 2019, the VSC began enlarging its pool of remote pilots as well as its fleet of UAS platforms and sensors enabling UAS capabilities at three USGS volcano observatories. There are currently eight UAS pilots in the VSC (five at HVO, one at CVO/VDAP, and two at the California Volcano Observatory (CalVO). However, in early 2020 a temporary UAS grounding was imposed by the Department of the Interior (Secretarial Order 3379) prohibiting the use and procurement of UAS as well as additional remote pilot training programs. Emergency waivers have been granted to allow mission-critical UAS work and pilot proficiency training, as required. One example of such work is the initial 2019 sampling of the newly formed lake at Kīlauea's summit crater, followed by sampling in 2020 (under the emergency waiver). Once the order is lifted, the VSC will continue to expand its UAS capabilities and use of this technology for routine monitoring, crisis response, and scientific investigations. The VHP supports ongoing work with industry collaborators to develop ruggedized, multi-parametric, long-endurance UAS for use at hazardous stratovolcanoes.

5 **Potential-field geophysics**. Except for very low frequency measurements made over active lava tubes to estimate their cross-sectional area, the VHP does not, at present, use potential-field geophysics (for example, gravity and magnetics measurements) for routine monitoring of volcanoes. Acknowledging the

Volcano Remote Sensing

Satellite remote sensing is vital to volcano monitoring and eruption response in the United States and its territories, including the remote Aleutian Arc of Alaska. This volcanic arc extends 2,400 kilometers—about the same as the distance between Washington, D.C., and Denver, Colorado. Satellite data allow U.S. Geological Survey (USGS) scientists at the Alaska Volcano Observatory to quickly characterize eruptions, and they complement real-time geophysical data recorded by ground-based instruments installed on Aleutian Arc volcanoes. In fact, for about 20 active volcanoes in Alaska that currently have no ground-based instrumentation, remote-sensing imagery provides one of the most important means of eruption detection. For example, during the March 2016 eruption of Pavlof volcano, the USGS was able to update alert levels with information gained from satellite imagery showing both the ash plume and intense thermal activity at the vent (see figure below). Information from these data sources informs the USGS that an eruption is in progress. The USGS can use the data to generate forecasts of ash fallout by initializing its Ash3d volcanic ash dispersion model. Satellite data also allow for a shared view of the eruption between USGS scientists and their colleagues at the National Weather Service. The USGS will continue to work with the National Aeronautics and Space Administration and international space agencies to maximize the use of new satellite capabilities, which will further improve remote monitoring of the Aleutian Arc and all other U.S. volcanoes.





Satellite imagery of the Alaska Peninsula-Kodiak Island segment of the Aleutian Arc during eruption of Pavlof volcano in March 2016. Red arrow in the lower image points to intense thermal activity at the vent, and blue in the upper image represents the ash plume drifting to the northeast. Lower image is from the GOES-15 satellite; upper image is from the MODIS instrument on the Aqua-1 satellite. Images provided by Michelle Coombs, USGS.

utility of magnetotelluric measurements for detecting hot fluids, the VHP intends to use such methods more frequently in future years. Recent magnetotelluric work at Long Valley, California (Peacock and others, 2016), shows how potential-field geophysics can, in some circumstances, delineate the location and extent of magma bodies and the active hydrothermal system. At present, the VHP owns only about half a dozen gravimeters, and half of these are obsolete. Gravity and geodetic measurements complement one another well. While gravity cannot distinguish the free-air effect of ground deformation from the change in mass at the source of deformation (for example, an intrusion), geodesy senses only volume change and tells nothing about changes in mass or density. Taken together, however, gravity and geodetic data collected at the same place and time can constrain some of the most important parameters necessary for physical models of volcanic systems: mass, density, source depth and location, and possibly even source shape. The VHP recommends seeking opportunities for expanding the collection and use of gravity data within the program.

5. Rebuilding the Hawaiian Volcano Observatory Facility and Its Monitoring Capabilities

The 2018 eruption of Kīlauea's summit and lower East Rift Zone was the largest and costliest volcanic event in the United States since 1980. This eruption led to the loss of numerous ground-based sensors including continuous-GPS instruments, digital broadband seismometers, web cameras, and telemetry infrastructure components. Numerous magnitude-5-plus earthquakes accompanying the collapse of the summit caldera caused irreparable damage to the main HVO facility. During the eruption response, HVO staff had to establish new temporary quarters at the University of Hawai‘i (Hilo) and later at the General Services Administration-surplused Customs House facility in Hilo Harbor, and had to establish a new data center in Kawaihae on the west side of the Island of Hawai‘i. The HVO staff subsequently moved out of the Customs House facility into the Iron Works Building in Hilo. The Iron Works Building cannot accommodate the entire HVO staff, however, and additional staff space is currently provided in the warehouse facility at Kea‘au. The Iron Works Building is only intermediate-term (36 months) office space and not a viable long-term solution for HVO because this building lies within a tsunami-hazard zone. In addition to requiring a new permanent facility, HVO will need a forward-operating field station within Hawai‘i Volcanoes National Park.

HVO must also reconfigure, re-route, and stabilize the telemetry and communications network for new and (or) replaced ground-based sensors that provide critical real-time monitoring and situational awareness. Single points of failure will be eliminated in the redesign and re-routing of the telecommunications network, so that there are redundant paths

Unoccupied Aircraft Systems (UAS) in the Kīlauea 2018 Eruption Response

The 2018 eruption and summit collapse of Kīlauea volcano provided the U.S. Geological Survey (USGS) Hawaiian Volcano Observatory (HVO) an unprecedented opportunity to utilize unoccupied aircraft systems (UAS) extensively for eruption monitoring and response. The HVO made use of UAS from the inventories of the USGS Volcano Science Center, the USGS National UAS Project Office, and the Department of the Interior Office of Aviation Services. UAS were used to monitor the summit and the lower East Rift Zone and provide a stream of quick-turnaround data products to scientists and emergency managers. UAS equipped with visual and thermal cameras flew over active lava flows to gain situational awareness; they also patrolled for overflows, chokepoints, or potential lava breakouts, and they measured lava flow velocity for characterizing eruption rates. With assistance from colleagues at the National Aeronautics and Space Administration (NASA) Ames Research Center, video from UAS was livestreamed to the State of Hawaii Emergency Operations Centers, Hawaii County Civil Defense, and the Federal Emergency Management Agency (FEMA) Incident Management Assessment Team, funded through FEMA mission assignments. These livestreams supported real-time critical decision making in hazard mitigation and evacuation efforts.

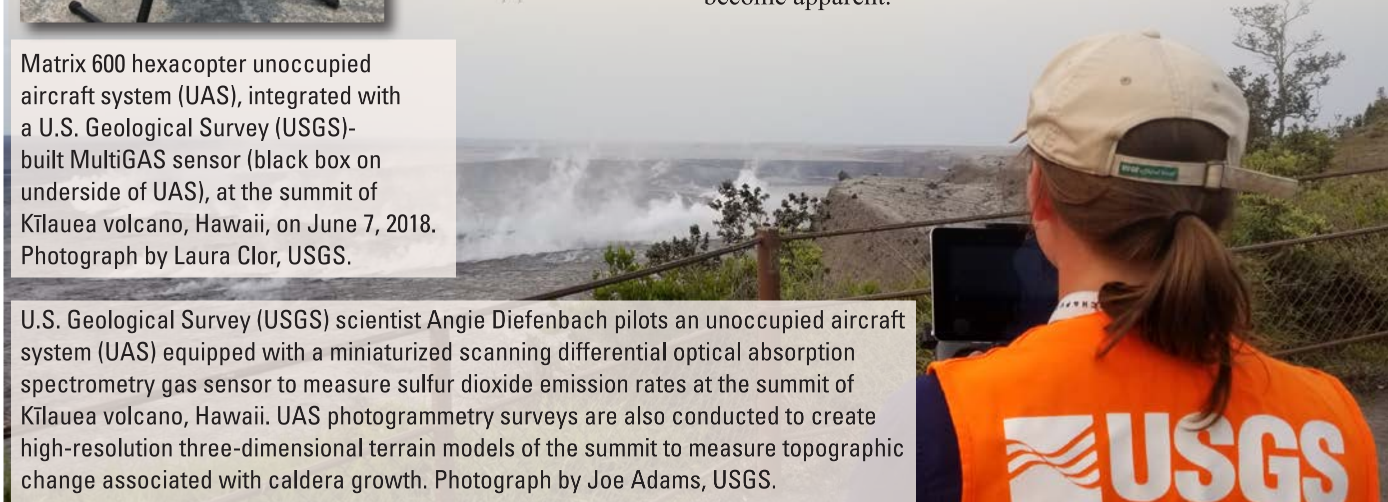
UAS photogrammetry surveys were conducted to (1) create very high resolution (1 meter) digital elevation models and orthophotos for Federal property damage assessment, (2) map lava boundaries, (3) monitor lava-flow advance rates and erupted volume, and (4) provide updated topography for lava-flow inundation modeling in the lower East Rift Zone. At the summit, a time-series of digital elevation models captured caldera growth, including rate and volume of collapse, and orthophotos were used to map fractures and the fall fields of volcanic ballistic projectiles.

UAS were also integrated with novel instruments for operational airborne monitoring of volcanic gases and particulate aerosols. These include two USGS-developed instrument packages that provided fundamental monitoring data throughout the eruption. One instrument assessed airborne sulfur dioxide emission rates using miniaturized scanning differential optical absorption spectroscopy, and another measured in-plume abundances of water, carbon dioxide, sulfur dioxide, and hydrogen sulfide using MultiGAS (Multiple Gas Analyzer System). In addition, researchers from the University of Leeds (United Kingdom) used novel instrumentation to measure and collect aerosol particles from the eruptive fissure plumes and laze plumes that were generated as active lava flows entered the ocean. These aerosol data can help address the question of chemical evolution of volcanic plumes and support studies of the impacts of volcanic emissions on human health.

Imagery and data from the UAS operations were used by the National Park Service to evaluate damage to facilities in Hawaiʻi Volcanoes National Park, including roads, trails, and buildings, and to assess conditions for work within the summit area. Operations within the park and the lower East Rift Zone were closely coordinated with Park Service and Civil Defense personnel and conducted with strict safety oversight. The public also benefited from the high-resolution imagery and video that showed what was happening in closed, hazardous areas.

The extensive use of UAS in this eruption response has proven to be a critical asset in USGS response for any eruption in the contiguous United States, Alaska, and the Commonwealth of the Northern Mariana Islands, and in foreign countries supported by the Volcano Disaster Assistance Program. The added value of UAS in future eruption response efforts will likely be augmented as new UAS pilots from the Volcano Science Center are trained, other sensors are integrated, and other data needs supporting an ongoing response become apparent.

Matrix 600 hexacopter unoccupied aircraft system (UAS), integrated with a U.S. Geological Survey (USGS)-built MultiGAS sensor (black box on underside of UAS), at the summit of Kīlauea volcano, Hawaii, on June 7, 2018. Photograph by Laura Clor, USGS.



U.S. Geological Survey (USGS) scientist Angie Diefenbach pilots an unoccupied aircraft system (UAS) equipped with a miniaturized scanning differential optical absorption spectrometry gas sensor to measure sulfur dioxide emission rates at the summit of Kīlauea volcano, Hawaii. UAS photogrammetry surveys are also conducted to create high-resolution three-dimensional terrain models of the summit to measure topographic change associated with caldera growth. Photograph by Joe Adams, USGS.

for access to real-time data and for preservation of data flow to the observatory and to the combined NVEWS-authorized National Volcano Data Center and Volcano Watch Office—the National Volcano Information Service. This redesign and rebuild of the HVO telecommunications system and real-time volcano monitoring capability will be done in accordance with NVEWS standards and will extend the monitoring networks further down the active rift zones on each of the Hawai‘i active volcanoes, including the highest-threat Kīlauea, Mauna Loa, and Hualālai.

6. Partnerships

The VHP has long used extensive partnerships to leverage resources and expand its capabilities in a variety of scientific specialties and applications. Partnerships are in place with State government agencies and with several universities to support volcano research, monitoring, and communications through formal cooperative agreement awards. The VHP has informal partnerships (non-funded) with other State agencies and academic institutions engaged with the VHP for overall volcano knowledge and situational awareness. Each USGS volcano observatory also maintains working relationships with Federal, State, and local emergency management and land managing entities for preparedness, and with various educational institutions for outreach. Now that the USGS is authorized to design and implement NVEWS, it will be increasingly important to strengthen existing partnerships where and when applicable and to establish new partnerships with other Federal, State, and local emergency-response agencies that have resources, expertise, and public safety-related missions having a vested interest in NVEWS completion.

Significant internal and external partnership plans are described as follows:

1 **Internal USGS Partnerships.**
The VHP has collaborative interaction with numerous mission areas and programs within the Bureau (for example, with the geothermal project within the Energy and Mineral Resources Mission Area, with the High Performance Computing Program of the Core Science Systems (CSS) Mission Area, with UAS projects in several programs and missions areas, and with the National Civil Applications Program and the Earth Resources Observation and Science Centers of the National Land Imaging Program of the CSS Mission Area). In this section, two productive partnerships of the VHP within the Bureau are highlighted—one with the Earthquake Hazards Program (EHP) of the Natural Hazards Mission Area (NHMA) and one with the 3D Elevation Program (3DEP) of the CSS Mission Area. The VHP will continue to work collaboratively whenever possible with the EHP, in particular the Advanced National Seismic System (ANSS) and National Earthquake Information Center. As the EHP builds out ShakeAlert in California, Oregon, and Washington and expands to Alaska in the future, there may be opportunities to share new data-telemetry paths for both NVEWS and ShakeAlert expansion. Likewise, NVEWS will add instruments in many ANSS regional networks in the Western States, Alaska, and the Commonwealth of the Northern Mariana Islands (CNMI), which will benefit both programs. The proposed second phase of NVEWS implementation, focused on Intermountain West volcanic fields in Arizona, New Mexico, Idaho, Wyoming, and Colorado, will need to leverage ANSS regional seismic networks operated by State universities and by the National Earthquake Information Center in areas not covered by a regional network. Implementation of NVEWS in California will need to be a joint effort between VHP and EHP because the volcanoes in California are currently being monitored by ANSS regional networks, and augmentation of the volcano monitoring networks in California will involve installation of other ground-based sensors on what are already ANSS networks. To facilitate this cooperation, VHP should share its plans for NVEWS implementation in California with the EHP, so that joint permitting and (or) re-permitting can be efficiently achieved for ANSS sites where additional ground-based volcano monitoring instrumentation will be installed.

The VHP has partnered with 3DEP in the CSS Mission Area’s National Geospatial Program for over eight years to obtain high-quality lidar data over the Island of Hawai‘i, Long Valley Caldera, Mount Shasta, Newberry volcano, Glacier Peak, Mount Hood, Crater Lake, Three Sisters volcanoes, Mount St. Helens, Mount Adams, and Redoubt volcano, and to obtain interferometric synthetic aperture radar (InSAR) data in Alaska. As opportunities arise, the VHP will continue to answer yearly 3DEP target solicitations and participate in co-funded lidar acquisitions through 3DEP that deliver high-resolution lidar data to the VHP at a fraction of the cost.

2 **National Science Foundation-funded Community Network for Volcanic Eruption Response.**
The VHP has actively engaged and fully participated in the National Science Foundation (NSF)-funded Community Network for Volcanic Eruption Response (CONVERSE) effort aimed at increasing coordination between Federal agencies (for example, USGS, NASA, NOAA-NWS, and the Smithsonian Institution’s Global Volcanism Program; https://volcano.si.edu) involved in volcano monitoring and members of the academic volcano science community (funded as principal investigators by NSF) seeking to advance fundamental understanding of magma genesis, ascent to the surface, and eruption. This coordination network presents an opportunity for the USGS volcano observatories to interact meaningfully with their academic colleagues. It also provides a forum at which the USGS can educate partners about its legally defined roles and responsibilities for providing timely warnings and forecasts of hazardous volcanic

activity. CONVERSE additionally allows the USGS to elaborate how subject-matter expertise is introduced within the Incident Command Structure (ICS) that would likely be established in the event of a volcanic crisis in the United States. Through participation in CONVERSE meetings, the USGS has educated the academic volcano science community that the embedding of subject-matter experts in an ICS is a direct result of the VHP's efforts to co-develop individual volcano emergency response plans with the relevant land management agency (for example, National Park Service, U.S. Forest Service, Fish and Wildlife Service, and Bureau of Land Management, or State agencies) before any volcanic unrest begins. As NVEWS grows, the greater academic community can assist the USGS in its eruption forecasting and response mode, but this assistance must be coordinated through the USGS because of its role in the ICS. The ultimate effective application of NSF Rapid Response Research (RAPID) funds must be coordinated with the scientist-in-charge of the relevant VHP volcano observatory and a potential proposal review panel that would be set up during the response. The panel would vet critical data that needs to be collected as part of the response, versus opportunistic science studies that can be delayed until after the crisis ends.

3 **NVEWS External Grants Activity.**
NVEWS legislation authorizes the USGS to establish an external grants activity in volcano science. If appropriated, this would greatly accelerate the formation and long-term development of CONVERSE because it would allow the USGS to issue targeted requests for proposals to the greater academic and private-sector research community, complementing the foundational, hypothesis-driven research funded by the NSF. It is anticipated that the USGS grants activity will be more focused on operational volcano monitoring technologies and instrumentation development, which the NSF typically does not support. Such a USGS grants activity will be beneficial to the entire volcano science community and will provide the USGS an opportunity to better tap the community's capabilities and specialties in advance of an eruption response through knowledge of past performance of grant-based research funded by the VHP. It will also grow the number of potential partner institutions and specialists that can be engaged in future eruption responses and in the development of new monitoring technologies. Beyond 2026, implementation of the second phase of NVEWS with focus on moderate- to low-threat volcanoes in the volcanic fields of the Intermountain West will require leveraging of resources from new partners, including State geological surveys and State universities, to further studies of those volcanic centers.

4 **NVEWS Implementation Committee.**
Partnerships are integral to the success of NVEWS. In addition to establishing the high-level advisory committee called for in the NVEWS legislation, NVEWS implementation plans call for instituting an effective mechanism for working-level coordination with partners. Thus, the establishment of a NVEWS Implementation Committee will be a very high priority in the next five years (Cervelli and others, 2021). The committee will be composed of entities either directly involved in NVEWS operations (for example, university cooperators) or those essential to its success, such as land managers and emergency managers. The committee's scope includes the respective roles and responsibilities of the committee members, as follows: data acquisition and analysis, dissemination of volcano hazard information products such as alerts and warnings, emergency response to eruptions, and the development of plans for access to Federal lands for the installation and maintenance of volcano monitoring instruments. The Implementation Committee would also be capable of forming working groups composed of subject-matter experts external to the committee to optimize design of NVEWS. Working group membership would include staff from the five USGS volcano observatories and their cooperative partners, as well as new partnerships established with academia, industry, and State and Federal agencies as needed. The committee would suggest topics for USGS external grant proposal solicitations and internal VHP activities. The Implementation Committee would oversee the long-term implementation, operation, and maintenance of NVEWS.

5 **Volcano Disaster Assistance Program.**
In 2016, the VHP celebrated the 30th anniversary of the VDAP partnership with the USAID Office of Foreign Disaster Assistance (now reorganized into the USAID Bureau of Humanitarian Assistance)—a partnership that has helped save thousands of lives and hundreds of millions of dollars in U.S. assets (Newhall and others, 1997; Lowenstern and Ramsey, 2017). VDAP responds to volcanic crises around the world at the invitation of affected nations, and during more frequent quiet periods engages in knowledge transfer and infrastructure development. This work directly benefits the VHP by expanding its crisis-response experience and by acting as a global research and development testbed for novel methods and emerging technology (for example, UAS, Multi-GAS, miniaturized scanning differential optical absorption spectroscopy, and event-tree exercises). Moreover, VDAP advances the VHP's domestic mission through leadership in eruption forecasting and in working with partners to develop best practices in hazard assessment and other aspects of volcano research and monitoring.

6 **National Oceanic and Atmospheric Administration.** The mission of the VHP intersects with several line offices and operational forecasting units of NOAA, including NWS; the NOAA Tsunami Program; the National Environmental Satellite, Data, and Information Service (NESDIS); and the Office of Oceanic and Atmospheric Research. Therefore, continued partnership and coordination with NOAA will be essential to the success of NVEWS implementation. In the descriptions that follow, the importance of partnerships with specific subunits within NOAA is stated where we address certain hazards such as ash clouds, eruption plumes, vog, and tsunamis. The volcano monitoring networks operated by the VHP provide the earliest possible warnings of volcanic unrest and possible escalation to eruption on monitored volcanoes. However, once an ash-forming eruption injects volcanic ash into the atmosphere and threatens the aviation sector, a timely and coordinated response is made by the USGS and the NOAA-NWS Volcanic Ash Advisory Centers (VAACs). This USGS-NOAA partnership can greatly contribute to improved ashfall forecasts and ash-cloud tracking because fundamental data on wind fields, and eruption plume heights measured with NWS instruments, provide better constraints on the source parameters the VHP utilizes in its Ash3d model runs. Therefore, expedited access to, and sharing of, critical data become paramount to both agencies in successfully fulfilling their mission to provide warnings and forecasts to the public and the aviation sector. In the next five years, the VHP should enhance partnerships with specified subunits of NOAA described below as a means to improve the timeliness and accuracy of its warnings and forecasts.

As the VHP implements NVEWS, it should enhance existing partnerships with the NOAA-NWS Tsunami Warning Centers to create better situational awareness and detection of volcanogenic tsunamis. Networks will be upgraded and modernized in the CNMI, American Samoa, and the Aleutians, where tsunamis resulting from volcano flank collapse and great earthquakes are likely to occur. A series of discussions have already begun between the VHP and NOAA Tsunami Warning Center staff about the problem of volcanogenic tsunamis similar to the devastating event originating from flank collapse at Anak Krakatau volcano in Indonesia that resulted in 437 fatalities in December 2018 (Giachetti and others, 2012; Grilli and others, 2019).

The VHP will also continue to work with NOAA-NWS to measure, track, and report the spread of vog in the Hawaiian Islands, CNMI, and Guam. These efforts will require subject-matter expertise, technological resources, and logistical support leveraged from the USGS, NOAA-NWS, and the Department of Defense U.S. Indo-Pacific Command.

Science as a Path to Diplomacy

By providing critical monitoring infrastructure, training, and ongoing consultation, the Volcano Disaster Assistance Program (VDAP) aims to mitigate the risks posed by dangerous volcanoes. Close collaboration with international partners and their stakeholders inevitably results in secondary benefits: friendship, mutual trust, and goodwill. For example, after an unexpected eruption in 2008 at Chaitén volcano in Chile, VDAP assisted with the creation of a seismic network at this previously unmonitored volcano. This led to collaborative research on the volcano's history and hazards, and a shared assessment project to prioritize needs for a national Chilean volcano monitoring system. VDAP scientists were called on to advise the government of Chile at the highest levels regarding volcano hazards monitoring and mitigation. The emergence of Chile's volcano expertise and development of a robust volcano monitoring infrastructure followed, and has also fostered engagement with Argentinean geologists to understand risks from some of the dangerous volcanoes that straddle the Chile-Argentina border. By pursuing a program of science and public safety, VDAP fosters an environment that engenders international cooperation and diplomacy.

In May 2008, heavy rains remobilized ash laid down by the recent eruption of Chaitén volcano, in southern Chile. Though the town of Chaitén (visible in photo) had been evacuated, the floods rendered much of the town uninhabitable. All streets and the nearby airport were buried in 1 to 2 meters of mud, and the city harbor was destroyed. During the eruption aftermath, VDAP assisted Chile with equipment installation and later co-funded an international research effort to understand the history of the volcano and the effects of the eruption on the nearby environment. In addition, VDAP advised the government of Chile on a new national strategy to reduce risk from volcanic eruptions. Satellite photograph from NASA earth observatory through the FORMOSAT-2 satellite, May 26, 2008. The information in this highlight was previously published in U.S. Geological Survey Fact Sheet 2017–3071 (Lowenstern and Ramsey, 2017).

There is already very good coordination between the USGS volcano observatories and the NOAA-NWS-operated VAACs, as ash-forming eruptions pose a hazard to civil and military aviation and require joint forecasts and warnings from the USGS, the NWS, and the U.S. Air Force 557th Weather Wing. As the agency operating ground-based monitoring instruments on volcanoes, the USGS is usually the lead in delineating which volcanoes are exhibiting signs of unrest. The VAACs and the 557th Weather Wing subscribe to USGS Volcano Activity Notices (VANs) and Volcano Observatory Notices for Aviation (VONAs). The VHP has also provided operational access to NOAA and the 557th Weather Wing staff to run Ash3d. This physical model for ash-cloud tracking and ashfall forecasts relies upon updated wind-field data from NOAA.The USGS benefits from the Doppler radar and satellite-based remote-sensing assets operated by NOAA for measurement of eruption plume heights and remote-sensing tracking of ash clouds and gases. Improvements to the USGS-NOAA partnership could result in expedited access to satellite remote-sensing data, Doppler radar measurements of plume heights, and larger UAS systems already operated by NOAA that could be integrated with real-time gas sensors developed by the USGS.

Collaborative Partnerships

Fostering collaborative partnerships with other government agencies and academic institutions allows the U.S. Geological Survey (USGS) Volcano Hazards Program to meet research goals in a way that is mutually beneficial as well as cost effective. It is important to continue such partnerships in order to advance innovative research and avoid potential duplication of effort. In the summer of 2015, USGS Alaska Volcano Observatory scientists joined a research cruise with the National Science Foundation (NSF) GeoPRISMS program. While the goal of the NSF expedition was to collect samples from a variety of volcanic settings in the Aleutian Islands, the USGS was also able to service 28 seismic stations on five remote volcanoes that had not been visited since the installation of the stations in 2005. During the cruise, USGS scientists shared logistics expertise with NSF-funded principal investigators who had no previous experience at these Aleutian volcanoes. Leveraging resources and staff expertise on this research cruise allowed partners to extend their time in the field, jointly conduct fundamental research on the magmatic systems that supply these volcanoes, share helicopter access for volcanic gas sampling, and strengthen collaborative spirit.

Geologists at the summit of Kanaga volcano, Alaska, during the 2015 western Aleutians field campaign by the U.S. Geological Survey Alaska Volcano Observatory, the National Science Foundation GeoPRISMS program, and the Deep Carbon Observatory. Photograph by Dr. Elizabeth Cottrell, Smithsonian Institution.

Scientific Targets

The following section contains a series of proposed research targets that, over the five-year scope of this plan, can advance and support the strategic goals defined above. For each of the targets, grouped by theme, specific action items are identified that will strengthen the VHP's capabilities, making the program better able to achieve its primary mission of enhancing public safety and minimizing the social and economic disruption from volcanic activity.

Most if not all of the research targets described below depend on high-quality data for their successful execution. Yet, in many cases, these data do not currently exist, a fact that creates a necessary condition for the plan's overall success of an expanded and enhanced data-collection capability (for example, operational real-time gas emissions data from several U.S. volcanoes). Meeting this condition requires continued growth and improvement of the Nation's volcano monitoring networks, which matches almost exactly the needs for NVEWS completion. Thus, for much of the VHP, the distinction between investment in monitoring infrastructure (that is, NVEWS implementation) and investment in research largely vanishes, replaced by a convergence where better monitoring data inspire fresh and novel research. When such research comes to fruition, it can both deepen our understanding of volcanic processes and make our volcanic hazard forecasts timelier and more accurate.

The reader should not consider the order in which the individual research targets are discussed below as meaningful. Prioritization must occur eventually given the reality of limited resources, but the authors leave these decisions to discussions between the program coordinator and the VSC director, and to subsequent generation of and adherence to the requirements put forth in the annual VHP section of the NHMA guidance document for science center directors.

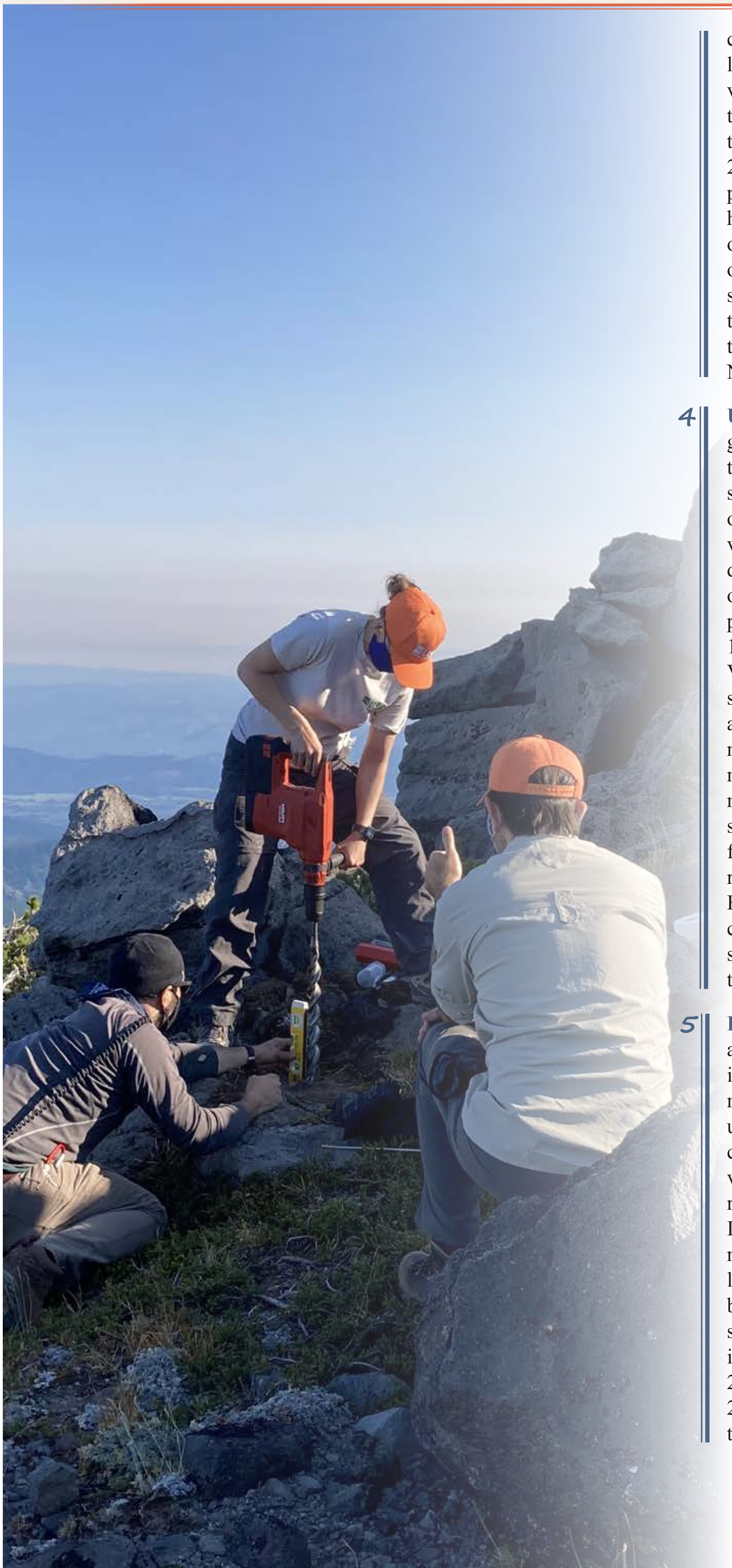
Volcano Seismicity (NVEWS and Hazard Assessment Goals)

The VHP is a world leader in the interpretation of volcano seismology and its application to eruption forecasting. The VHP has already achieved remarkable success in advancing understanding of the character and causes of “non-traditional” seismicity (that is, seismicity generated by processes other than brittle failure), which is common at volcanoes. This work has inspired the VHP to take on the following ambitious goals:

1 **Develop Integrated Alarm Systems.** Running in real time and in parallel with seismic acquisition software, seismic alarms analyze incoming data by searching for unusual signals that may indicate a change in a volcano’s behavior. Such alarms have evolved from simple threshold-exceedance detectors to algorithms capable of identifying coherent patterns appearing on multiple instruments across a volcano’s seismic network (Hotovec-Ellis and Jeffries, 2016). At present, the USGS volcano observatories commonly operate several multi-parameter alarms, as was done during the AVO response to the eruption of Bogoslof volcano in 2016–2017 with data from the World Wide Lightning Location Network, seismic instruments, infrasound arrays, and satellite-based remote sensing (Coombs and others, 2018). The VHP has already made some progress toward integrating the different alarms into a single system, but much work remains, especially the effort needed to include alarms that operate on non-seismic data. Over the next five years, the VHP aims to design and implement a truly integrated alarm system suitable for all the U.S. volcano observatories. This may require the application of additional scientists and (or) postdoctoral fellows toward the effort. Such a system would justify and leverage NVEWS infrastructure and markedly improve detection and forecasting capabilities.

2 **Better Understand Distal Volcano-Tectonic Earthquakes.** Swarms of distal volcano-tectonic (dVT) earthquakes have been shown empirically to be early warnings for some volcanic activity and are attributed to pressurization of hydrothermal fluids, which activate nearby faults in a process analogous to how the deep injection of waste water from oil wells can result in induced seismicity (White and McCausland, 2016). Over the next five years, it is important that research improves understanding of the processes responsible for dVT earthquakes and how to distinguish the swarms that lead to eruptions from those that do not.

3 **Characterize Volcanic Tremor.** The significance and origin of the different types of volcanic tremor that are observed remain poorly understood despite some recent progress (Chouet and Matoza, 2013). Tremor at vol-



canoes can arise from the flow or movement of steam, liquid water, magma, or other fluids, which often leads to vexing ambiguity during precursory unrest. Co-eruptive tremor at Bogoslof (an un-instrumented volcano at the time) was recorded by distant seismometers during its 2016–2017 eruption, and recent research shows great promise toward being able to determine eruption plume height and possibly event magnitude from characteristics of co-eruptive tremor (Haney and others, 2020; Fee and others, 2017). Over the next five years, the VHP should seek to develop methods of distinguishing the different types of tremor and determining the causative fluid as the tremor occurs, particularly as networks improve through NVEWS implementation.

4 **Unify Seismology and Geodesy.** Bridging the spectral gap between seismology and geodesy, both instrumentally (at high fidelity) and intellectually (having both simultaneously for interpretation), would improve our monitoring capability and the way we think about volcanic processes. Modern seismic instruments can detect signals (for example, tilt) that occur over seconds or days, while the latest GPS processing techniques can provide three-dimensional position measurements at 1 Hz (once per second). Over the next five years, the VHP will promote research to interpret and explain the signals from magmatic processes that express themselves across the spectrum from thousands of hertz to permanent offsets. The resulting insights will likely result in major advances in how to interpret the linkages between magma ascent, inflation of crustal magma reservoir systems, and eruptions, further improving the ability to forecast the timing and magnitude of eruptions. Likely recharge of magma into the subsurface reservoirs at Kīlauea following the 2018 eruption presents a significant opportunity to close this gap, as the quality of the seismic and geodetic networks at Kīlauea is optimal for this type of integrated study (Flinders and others, 2020).

5 **Embrace Infrasound.** More than 10 years ago, Moran and others (2008) identified infrasound sensors as an important part of a well-monitored volcano's instrumentation network. Since then, infrasound has proven useful for detecting explosions, many of which have created significant ash clouds—such as at Bogoslof volcano in 2016–2017 (Coombs and others, 2018)—at remote volcanoes lacking ground-based instruments. Infrasound also promises the means to quickly locate new lava-fountaining vents on basaltic shield volcanoes like Mauna Loa. On the research front, the availability of both seismic and airwave data from the same event has spawned a new and fruitful line of inquiry into the physics and hazards of volcanic explosions (Matoza and Fee, 2014; Matoza and others, 2018; Fee and others, 2017, 2020; Lyons and others, 2020). As NVEWS implementation proceeds, the VHP will include infrasound sensors

in the standard suite of instruments deployed at new or upgraded networks at individual volcanoes, and also will improve regional infrasound arrays when and where applicable.

6 **Research Uplift at Restless Calderas.** Many large calderas, including Yellowstone, experience occasional episodes of uplift over large areas (>1,000 square kilometers), which often occur with (or are punctuated by) elevated swarm seismicity. The ultimate cause of the uplift can be difficult to identify definitively, and possibilities include (1) fluids within the largely meteoric water portion of the upper-crust hydrothermal system, (2) mixtures of meteoric water and fluids exsolved from crystallizing rhyolitic magma, and (3) brines and magmatic water ± CO_2-rich fluids exsolved from rhyolitic to basaltic magmas at the interface of the magmatic-hydrothermal system (Dzurisin and others, 2012; Lowenstern and Hurwitz, 2008; Lowenstern and others, 2015). However, many researchers now suggest the uplift is the result of increases in the rate of basaltic magma intrusion at depth in these large systems, on the basis of high CO_2 emissions that can be identified as magmatic in origin (Werner and Brantley, 2003; Lowenstern and Hurwitz, 2008; Dzurisin and others, 2012; Lowenstern and others, 2015) and high heat flux required to keep the Yellowstone magmatic-hydrothermal system active for hundreds of thousands of years (6.4 gigawatts; Friedman and Norton, 2007). Curiously, some calderas typically subside after an episode of uplift, which can be attributed either to a decrease in the rate of basaltic magma intrusion in the depths of the system or to a permanent loss of exsolved magmatic fluids or pressurized hydrothermal fluids due to seal failure at a zone of structural weakness that is marked by faults or intersections of fault zones with caldera-rim faults (Dzurisin and others, 2012; Wicks and others, 2006, 2020). However, other calderas behave almost monotonically. For example, over the last 44 years, geodetic measurements of Long Valley Caldera have recorded more than 75 centimeters (cm) cumulative uplift as of 2014 (Hill and others, 2014), and 83 cm as of 2017 (Hildreth, 2017) with negligible countervailing subsidence (Hill and others, 2014). Over the next five years, the VHP will address the puzzle of caldera uplift through a multiyear and multidisciplinary effort to better identify and track the fluids—if any—that may be the cause of uplift and associated earthquake swarms at Yellowstone. Key factors toward making advances in understanding the ultimate causes of uplift and subsidence in the Nation's large caldera systems will be the following:

- Development of longer time series of gas flux and chemical data, completely integrating—

  1. stable and radiogenic isotopes of gas and fluid samples;
  2. deformation measurements from continuous GPS, leveling, and InSAR; and
  3. gravity and microgravity measurements used to discern the nature of the fluid or fluids causing ground deformation (that is, magma, gas, and thermal waters, or combinations of them).

- Better characterization of the variation in the nature of the crust beneath the caldera, exploiting all geophysical techniques available (for example, seismic tomography, gravity measurements, and electromagnetic surveys).

- Development of more advanced four-dimensional numerical simulations of heat and mass flow in porous, non-isotropic, nonelastic media. Such simulations can incorporate—

  1. observational measurements from all sensors deployed in the field,
  2. more frequent InSAR scenes,
  3. results from laboratory experiments, and
  4. fundamental thermodynamic and rheologic properties data from all relevant rock and magma types at various strain rates.

In addition to its scientific merit, making progress on this topic could also improve public safety in areas prone to phreatic or hydrothermal explosions, which at present appear to occur without recognized precursors. Accomplishing this work will require collaboration among experts spanning the breadth of the earth sciences, and close partnerships with Yellowstone National Park and the other parts of the YVO consortium. This work can be undertaken at two of Earth's largest and most dynamic caldera systems (Yellowstone Plateau volcanic field and Long Valley Caldera) and will advance all six of the VHP's strategic goals.

Probabilistic Eruption Forecasting (Preparedness and Hazard Assessment Goals)

To meet its mission requirements, the VHP strives to identify and forecast which episodes of unrest will culminate in eruptions, and for those volcanoes that do erupt, to predict the eruption style and duration, the volume of erupted material, the regions most likely to be affected, and when possible, the risk to population and infrastructure. Under ideal circumstances, having sufficient data about past eruptions and present unrest, along with a combination of statistical methods and physical modeling, we can in many cases estimate these quantities to first approximation bounds (Anderson and Poland, 2016; Neal and others, 2019). Even in real-world conditions, using the same means, we can often provide upper and lower bounds.

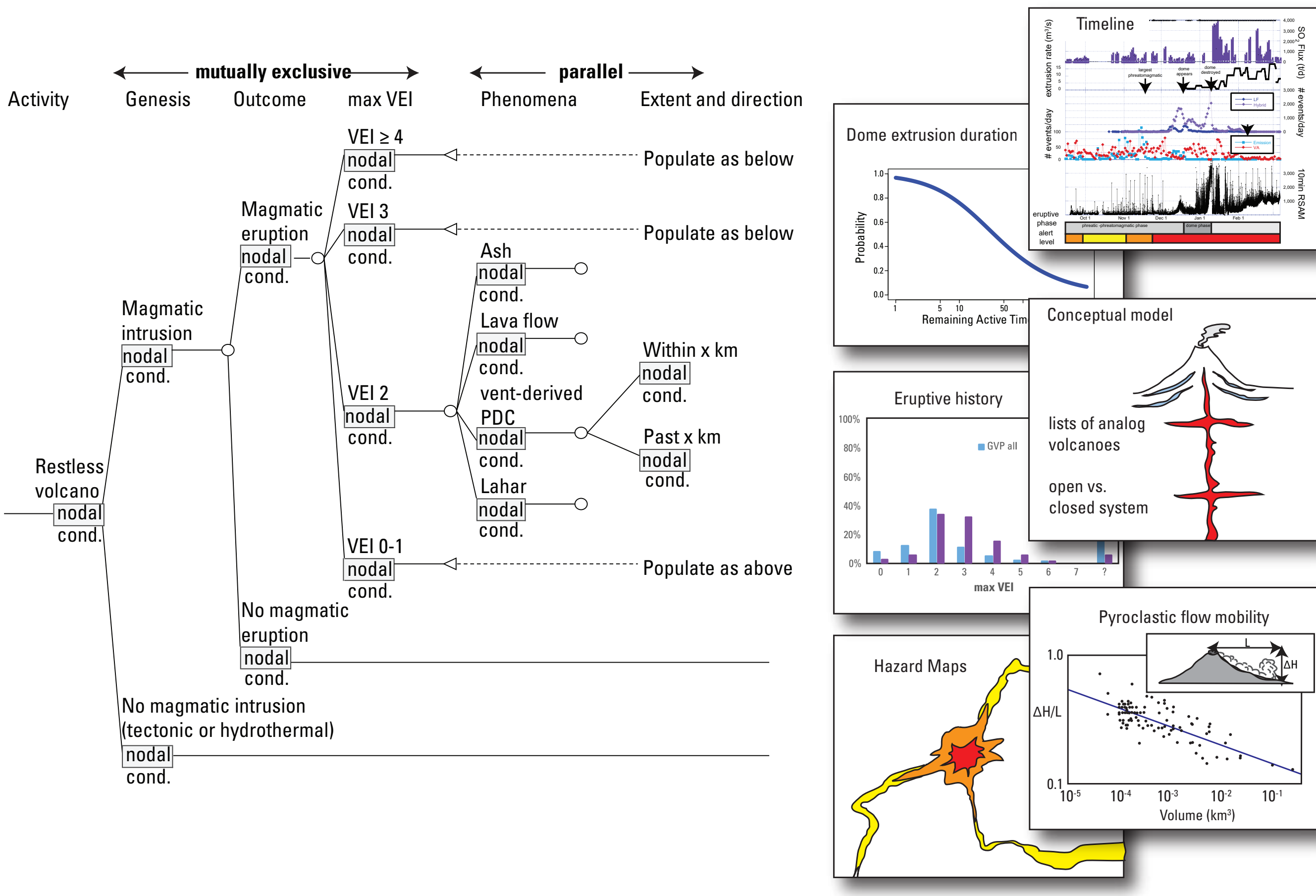


Figure 5. An example of a probabilistic volcanic event tree. The probabilities for mutually exclusive branches (those on the left) must sum to 1, meaning that the events represented by the branch set must be mutually exclusive. Event tree analysis is “Bayesian” in two senses: first, each event probability is conditional on the preceding event in the tree sequence; and second, conditional probabilities are updated as more evidence or information becomes available. Pyroclastic density current outcome event is denoted by PDC. Supporting data and products utilized in expert elicitation are shown as six inset diagrams on the right. Abbreviations and symbols: cond., conditional; GVP, Global Volcanism Program; km, kilometer; km^3, cubic kilometer; LF, low frequency seismic event; m^3/s, cubic meter per second; min RSAM, minimum real-time seismic amplitude measurement; t/d, ton/day; VA, distal or deep volcano-tectonic seismic event; VEI, Volcanic Explosivity Index; %, percent; ΔH/L, ΔH is the vertical height traversed by a PDC from source to the end of the runout distance, L; #, number of. Graphic provided by Heather Wright, U.S. Geological Survey.

Over the past few years, VDAP and other VHP-supported scientists have introduced statistical methods for assigning probabilities to potential volcanic events based on a combination of trends and characteristics of monitoring data, eruptive history, and statistical data on past eruptions at similar analogue volcanoes worldwide. This work has shown that such a combined approach can be helpful in the absence of complete information (that is, under realistic conditions). This approach grew out of pioneering applications of probability trees that USGS scientists used successfully during the 1980 Mount St. Helens and 1991 Pinatubo eruptions. In the intervening decades, volcano monitoring instruments have been improved and have proliferated, applied statisticians have created models well-suited for volcanic phenomena, global volcanological databases have grown, and interest in probabilistic forecasting methods has spread. Seeing this timely opportunity, VDAP began a pilot project in 2015 with the intention of creating databases of past volcanic events around the world and creating methods for organizing these data into a form suitable for event-tree analysis of the possible outcomes from volcanic unrest (Clemens and Simmons, 1998). Event trees depict possible scenarios of evolving unrest with a series of bifurcating branches, with the limbs representing the possible outcomes from a question like “Is new magma present?” (see figure 5 for an example of an event tree). The specific threats posed by the volcano under investigation determine the range of possible outcomes, while the probabilities assigned to these outcomes come from data about previous eruptions at that volcano and at analogues, from physical constraints imposed by geography, and from expert elicitation. Event-tree analysis can also estimate risk, by including data about vulnerability, population density, and infrastructure.

These methods have recently proved useful at multiple foreign volcanic crises (Wright and others, 2018; Syahbana and others, 2019), and during the 2018 eruption at Kīlauea. Further development of volcano databases and related probabilistic methods will undoubtedly improve both our forecasting capability and accuracy. Toward this end, the VHP will undertake the following actions over the next five years:

1. **Database Integration.** The Earth Observatory of Singapore and the Smithsonian Institution's Global Volcanism Program maintain databases containing information regarding volcanic eruptions and monitoring data, respectively. Other databases focused on specific volcanic hazards (for example, seismic swarms and lava domes) already exist or are in development, and consortia such as Incorporated Research Institutions for Seismology and University NAVSTAR Consortium archive extensive seismic and geodetic monitoring data. The VHP, through VDAP, will partner with the operators of these disparate databases to improve the exchange of data and to create tools for greater dissemination of volcano data and improved volcano forecasts.

2. **Creation of Forecasting Tools.** As databases become more integrated, it will be increasingly possible to create tools that serve decision makers and facilitate the generation of eruption forecasts during volcanic unrest. The VHP will aim to make such tools available for use at USGS observatories and to partners around the world. These tools should utilize "open-source" volcano data that has been released by the relevant international volcano observatories. The VHP should improve access to basic forecasting tools (for example, publication of generic event-tree templates and publication of global statistics pertinent to volcanic phenomena).

3. **Clarifying Uncertainties.** The VHP will develop and test methods for conveying uncertainty about forecasts or model results, in understandable terms, to our main partners and the public. At present this remains one of our biggest communications challenges, and it continues to grow as our products become more quantitative. Even specialists can easily misconstrue a comparatively simple graph depicting scalar probability values with error bars if it is presented poorly—for example, having unclear axis labels, excessive jargon, or needless and confusing use of color. A partnership with the Earthquake Hazards Program to address issues associated with the communication of risk and of the timeliness and accuracy of early warning in a way that helps promote public safety seems wise. Although the timescales available for alerting the public to impending volcanic crises versus ground shaking from earthquakes differ, we both have the same challenges in ensuring that the public takes the appropriate protective actions, and our audiences often overlap.

4. **Expanding Training and Experience.** The VHP should strive to expand the collective experience of its staff in eruption forecasting and in the use of forecasts in mitigation through increasing participation of personnel from all observatories in crisis responses, domestic and foreign. VDAP staff are currently in discussion with HVO staff about observatory-wide training in event-tree generation during times of volcano quiescence, advocating the development of long-term event trees as a preparatory tool in advance of volcanic crises. We should extend this opportunity to our observatory partners, especially scientists from institutions and agencies that receive cooperative agreement awards for volcano monitoring and hazard assessment tasks.

Eruptive Histories and Geochronology (Preparedness and Hazard Assessment Goals)

Detailed knowledge of a volcano's eruptive history is essential for understanding the likelihood, size, and scope of future eruptions. Over the last 30 years, the VHP has collected an enormous body of information on this topic while also publishing comprehensive geological maps, eruptive history reports, hazard assessments, and response plans on many of the most hazardous U.S. volcanoes. Requirements for these studies include whole-volcano geologic mapping and field-based studies of all erupted products, including effusive, intrusive, and explosive deposits. Study of debris-flow deposits is also necessary and an integral component of a volcano's event history, whether the debris flow is caused by eruptive activity or not. Field-based studies of the deposits must also be integrated with comprehensive laboratory studies of deposits and events that are informative not only of processes that cause eruptions, but also of processes that cause the more common non-eruptive unrest. Key to these studies is the capability to date eruptive materials with adequate accuracy and precision to reveal the timing and duration of unobserved past events. VHP geochronologists employ a range of methods (radiocarbon, potassium-argon (K-Ar), $^{40}Ar/^{39}Ar$, uranium-lead (U-Pb), uranium-thorium (U-Th) disequilibrium, U-Th/helium (He), cosmogenic systems, and paleomagnetic comparison to calibrated secular variation maps) to date a wide variety of volcanic processes precisely and accurately (for example, Wright and others, 2015). These dates and rates help the VHP and its partners better understand the fundamental processes controlling eruption size, location, frequency, cause, probability, and hazard. The VHP leads the global volcano science community in producing comprehensive eruptive histories; this position of leadership requires maintaining and improving VHP's abilities through attention to staffing, programmatic focus, and laboratory capabilities, including construction of a new laboratory building at Moffett Field, California. Targets for the next five years include the following:

1 **Refine Tephra Chronology.** Refine the chronology of regionally extensive marine and terrestrial tephra deposits in the contiguous United States and Alaska. Combine these results with numerical models of tephra fall to create robust estimates of potential future events.

2 **Publish Maps and Eruptive Histories.** Complete the subset of in-progress whole-volcano geologic maps and eruptive history studies currently at the >80-percent level of completion (Alaska: Okmok, Atka, Shishaldin, Emmons, Veniaminof, Augustine, Iliamna, Redoubt, Spurr, Hayes; Continental United States: Rainier, St. Helens, Hood, Newberry, Shasta, Long Valley; Hawaii: Mauna Loa). Select targets for further study, either attractive components for refinement, or as "Laboratory Volcanoes" where additional petrologic and geophysical studies could shed light on magmatic processes. A goal of the Laboratory Volcano studies will be the development of multi-parametric quantitative models useful for forecasting the rate and style of magmatic ascent and eruption. The recent iMUSH (imaging Magma Under St. Helens) study (Hand, 2015; Crosbie and others, 2019) at Mount St. Helens serves as a model for this type of investigation.

3 **Refine Time Scales of Eruption Episodicity and Duration.** Published and unpublished volcano geologic histories show that eruptions can be highly episodic. Millennia of quiescence punctuated by brief periods of frequent eruptions typify some volcanoes, whereas eruptions of 3 to 6 months duration every decade are normal for others; for others still, a few centers have been in semi-continuous eruption through recorded history. Some eruptive and non-eruptive periods appear to follow a fractal pattern (Shaw and Chouet, 1991). Many volcanoes show evidence of recharge from deep source areas into shallow magma reservoirs. In some cases, recharge is recognizably hotter and more "primitive" magma, but in many other cases the recharge is similar to the volcano's typical eruptive products. Such recharge events can trigger eruptions (for example, Sparks and others, 1977; Pallister and others 1992, 1996; Nakamura, 1995; Murphy and others, 1998; Clynne, 1999), but more commonly they sustain the shallow reservoir, preventing or delaying its cooling and crystallization while it generates the background unrest detected by instrumental monitoring networks. A concerted effort to determine the duration of past eruptive episodes will pay dividends in responding to eruptions. Detailed geochronology and paleomagnetic secular variation studies of eruptive products from representative episodes can measure past eruption and hiatus durations. Interrogation of these same deposits for chemical and textural variation of rocks and crystals can reveal the timing and duration of magma recharge and other events in the subsurface magmatic system. Integrating timing and petrogenetic information with volcanic gas measurements, seismicity, and geodetic signals will enable more robust hazard predictions.

Eruption Physics and Parameterization (Preparedness and Hazard Assessment Goals)

Models are the interface between observation and understanding; without models, a scientist's ability to interpret observations from field and laboratory-based investigations relies on pattern recognition alone. Conceptual models of magmatic systems and processes in the shallow crust (for example, schematic diagrams of magmatic systems) aid the interpretation of volcanic unrest by providing a basis for formation of testable hypotheses. Simple quantitative models can allow for estimates of magma depth to be made from analysis of petrologic, seismic, and deformation data.

Statistics-based lahar-inundation models have proven useful for hazard mapping and crisis response; however, such models have significant limitations. More complex quantitative models that incorporate realistic physics, complex rheologies, and multivariate fluid-solid interactions provide a platform for integrating diverse datasets, formally assessing uncertainties in model output, and testing a wider range of hypotheses, as well as presenting a more realistic vision of how volcanoes work. Yet, only rarely are all the necessary input parameters (for example, detailed digital elevation models and hydraulic pore-pressure distribution) available for real-time crisis applications. Over the next five years, the VHP will pursue development of models on three fronts: magmatic systems, eruption processes, and eruptive products as end results of the first two. For example:

1 **Physical Models.** Kinematic (or descriptive) models have inherent limitations and modest objectives, such as identifying the approximate location and strength of a pressurizing magma body. In contrast, physical models of volcanic systems aim to represent the entire system in all its complexity, from processes within volcanoes and the crust to eruptive products. They combine multiple data types, accommodate a variety of error models, and easily support probabilistic eruption forecasting. However, physical models work best with high-quality datasets having good spatial and temporal coverage and resolution, and that—ideally—are from a variety of ground-based instrument types. At present, few volcano datasets like this exist. Where they do, such as at Kīlauea, physical models have constrained the occurrence and rates of magma replenishment (Anderson and Poland, 2016). As NVEWS advances and new data become available, physical models will improve, and, thereby, so will our forecasting ability.

2 **Parameterization.** The VHP will use eruption products to work toward gaining a better understanding of the physical parameters that define and constrain magmatic systems, including (1) their geometries; (2) volumes of stored magma; (3) concentrations of volatiles; (4) high-temperature and high-pressure experimental petrology studies of erupted compositions for best constraints on pre-eruptive pressure (depth), temperature, and oxidation state of magma storage zones; (5) typical time scales of magma ascent; (6) background seismicity and deformation patterns; and (7) the styles of individual eruptive episodes. Such information will have positive effects for both our operational and research goals.

3 **Experimental Determination of H_2O-CO_2-S Solubility in Common Magma Types.** Gases emitted by active volcanoes consist predominantly of H_2O with subordinate CO_2 and sulfur species (SO_2, H_2S), with other components being relatively minor. The VHP has made numerous recent advances (MultiGAS sensors, miniaturized scanning differential optical absorption spectrometers, and ultraviolet (UV) cameras) in the ability to measure compositions of naturally released gases and in the measurement of dissolved volatiles trapped in melt inclusions. However, melt-vapor solubility relationships for sulfur species (SO_2 and H_2S) are not integrated with those for H_2O and CO_2, whose solubilities are relatively well understood (Newman and Lowenstern, 2002; Moore and others, 1998; Dixon and others, 1995; Botcharnikov and others, 2006). Current lack of an integrated hydrogen-carbon-sulfur-oxygen (H-C-S-O) solubility model hinders our ability to interpret the gas signal to assess volcanic unrest, to conduct post-eruptive studies of melt inclusions from erupted magma, and to address broader applications such as how shallow intrusions potentially develop hydrothermal ore deposits (Hedenquist and Lowenstern, 1994).

The working H-C-S-O solubility model would couple direct high-pressure, high-temperature experiments on common magma types with solid thermodynamic interpretations (for example, Dixon and others, 1995). Components of the model would include the ability to calculate gas composition from melt composition, and vice versa, at specified pressures, temperatures, and oxidation states. The model could also include the ability to calculate changes in exsolved gas composition during different magma ascent paths, both in an open system (in which gas escapes) and in a closed system (in which gas stays with the melt), and the effects of fluxing gas at differing proportions and influx compositions through a static magma column (see Burgisser and Scaillet, 2007; Mandeville and others, 2009). An experimentally founded H_2O-CO_2-S solubility model for a common arc magma type such as dacite or rhyolite would be a major contribution to volcano science and the USGS monitoring mission in the NVEWS-authorized era.

4 **VHP Software Repository.** The VHP should establish a program-wide software repository (for example, the USGS GitHub) and (or) nurture a more widespread culture of sharing and code re-use (for example, https://code.usgs.gov/vsc), which presently is less than optimal, to enable model generation. All U.S. Government-developed software resides in the public domain and should be easily accessible to outside researchers and the public. NVEWS legislation also requires the USGS to standardize its analytical software among its volcano observatories and to unite the individual observatories into a comprehensive and unified monitoring system.

5 **Partnership with the Core Science Systems Mission Area.** Establishing a formal partnership with the USGS Core Science Systems (CSS) Mission Area and appropriate university partners will help the VHP solve large-scale numerical problems existing in volcano science that require high-performance computation. The VHP

should also implement regular training sessions on use of high-performance computing resources for new employees and post-doctoral researchers. CSS is eager to attract new projects for its powerful computing resources. CSS has already funded some of the research and development for the program's numerical modeling of ashfall (Ash3d; Schwaiger and others, 2012) and debris flows (D-CLAW; George and Iverson, 2014). Other areas of development that might benefit from CSS partnership in the next five years are the numerical modeling of pyroclastic density currents (pyroclastic surges and pyroclastic flows; see Benage and others, 2016), coupled with small-scale physical experiments on these lethal volcanic hazards.

Volcanic Clouds (Preparedness and Hazard Assessment Goals)

Far traveling volcanic clouds constitute one of the most disruptive and costly effects of active volcanism, affecting such diverse sectors of society as aviation, public health, and agriculture. For example, ash clouds from the 2010 eruptions of Eyjafjallajökull volcano, Iceland, led to more than 100,000 flights being cancelled, left more than 10 million passengers unable to travel, and cost European businesses up to €2.5 billion (Gabbatt, 2010). Budd and others (2011) estimated the eruption cost the aviation industry alone at least $1.7 billion. The composition and physical characteristics of ash clouds also provide the potential for key insights into the magmatic systems and processes leading to their creation. Over the last five years, VHP research and development created the Ash3d volcanic ash dispersion modeling software (Schwaiger and others, 2012), which has dramatically improved our ability to forecast the propagation of ash plumes through the atmosphere along with the extent and location of the consequent ashfall. Yet many opportunities for continued study of volcanic clouds remain. Research on the following topics should be pursued in the next five years:

1 **Volcanic Aerosols**. The VHP should extend the USGS Ash3d model to enable the forecasting of volcanic gas emissions and aerosols (for example, SO_2 gas emissions and submicron aerosols of sulfuric acid [H_2SO_4]) in addition to ash. Aerosols are formed when volcanic SO_2 gas is converted downwind of the volcano to submicron H_2SO_4 aerosol particles in the presence of atmospheric water vapor and UV radiation from the sun (Pollack and others, 1976; Sigurdsson, 1990; Robock, 2000). Aerosols can damage aircraft and crops and harm livestock, and may be present in volcanic emissions that lack significant or detectable ash content. SO_2 gas and H_2SO_4 aerosols can create respiratory difficulties and exacerbate asthma in humans, although the long-term effects of chronic SO_2 and aerosol exposure remain unknown. Volcanic aerosols often propagate near the ground where they experience complex boundary effects, which will pose challenges for modeling. However, given the persistent SO_2 exposure problems from Kīlauea volcano, developing an internal capability for forecasting the location and concentration of SO_2 emission rates and tracking of H_2SO_4 aerosols should rank highly among VHP priorities.

2 **Satellite Retrievals**. The VHP should continue to collaborate with NOAA/NESDIS to improve satellite-based retrievals of plume properties and chemical constituents that provide important constraints on eruption size, magma composition, vent dynamics, and so forth (Schneider and others, 2015). Incorporating such satellite data in near real-time into ash dispersion models will allow more accurate forecasts of where dangerous concentrations of volcanic ash are present, and thereby reduce the disruption to aviation caused by volcanic eruptions. The VHP should consider creating a formal VHP-NOAA/NESDIS partnership and (or) interagency agreement.

3 **Improved Detection**. The VHP should expand remote detection capabilities for ash-producing eruptions using infrasound observations and lightning alerts from various global lightning location networks. Both of these methods can often pinpoint an explosion or ash plume in space and time, and both can function well at night or in poor weather. Lightning alerts can reach scientists within a minute or two of occurrence, making them especially valuable for prompt notifications of airborne ash. At present, the VHP receives lightning detection notifications from the World Wide Lightning Location Network as a courtesy (that is, at no charge). Given its importance for detection, the VHP will continue to identify and contract for lightning detection service.

4 **Vog**. The VHP should continue interagency and interdisciplinary collaboration with external partners to study the health and economic effects of volcanic smog (vog), ash, and other volcanic gases, ideally to develop mitigation strategies for populations downwind from erupting volcanoes. This activity should be added to the portfolio of VHP forecast, detection, and tracking responsibilities.

5 **Probabilistic Ashfall Maps**. The VHP should use its existing models of ashfall potential, combined with tephra chronology, to create probabilistic ashfall maps for major U.S. volcanoes, or for urban areas threatened by multiple volcanoes. In addition, the VHP should use the cloud to develop GIS-based web applications that produce volcanic ashfall hazard assessments customized for particular users (for example, downwind communities) and scenarios (for example, explosive eruptions of various magnitudes and during various wind conditions at high-threat volcanoes).

Lava Flows (Preparedness and Hazard Assessment Goals)

During the Kīlauea lower East Rift Zone eruption of 2018, the HVO did an excellent job assessing lava flow hazards to threatened communities in the Puna District. HVO produced preliminary lava flow-path forecasts based on steepest descent path modeling for active flow-fronts, new fissures, and channel overflow locations reported from the field utilizing available topographic data and DOWNFLOW (Neal and others, 2019; Favalli and others, 2005). HVO was able to communicate likely flow paths through the generation of lava-flow forecast maps that could be presented to emergency responders and the public.

Mauna Loa, a very active volcano also on the Island of Hawai‘i, threatens even greater population and infrastructure than its neighbor Kīlauea. Historical patterns suggest both a high likelihood of a Mauna Loa eruption in the next few decades and very high lava effusion rates when an eruption occurs (Trusdell and Zoeller, 2017; Trusdell and Lockwood, 2017, 2019, 2020). A repeat of the 1950 Mauna Loa eruption could inundate highly populated resort areas far more quickly than they could be evacuated. For these reasons, we recommend pursuing development of the following models in the next five years:

1 **High-Resolution Digital Elevation Models**. Lava flow models depend on digital elevation models (DEMs), and the quality of the model output depends strongly on DEM resolution and accuracy. Recent acquisitions of high-resolution lidar data on the Island of Hawai‘i, covering both the entire island and focused areas of Kīlauea, will provide exceptional DEMs for modeling the next eruption. Obtaining high-quality DEMs between eruptions that change the topography of active volcano landscapes, via lidar or Structure from Motion (see James and Robson, 2012) where applicable, is a high priority for the VHP over the next five years. Recent experience with the latest generation of lidar data acquisition equipment at Glacier Peak, Washington, shows the feasibility of overcoming the obstacle of penetrating all but the densest vegetation. The arid upper slopes of Mauna Loa present a much easier and potentially less costly target.

2 **Lava Flow Models**. The VHP has invested in a versatile and high-quality software package, D-CLAW (George and Iverson, 2014), for modeling debris flows and landslides. Based on the highly regarded Clawpack (Mandli and others, 2016), which includes adapted mesh refinement, this software should be investigated for its adaptability to lava flow modeling, or at least for testing and validating other models. In parallel with the D-CLAW study, the VHP will also assess other existing lava flow models, such as those developed by the Italian Instituto Nazionale di Geofisica e Vulcanologia for lava flow modeling at Mount Etna, for their efficacy and applicability to the basaltic ‘a‘ā and pāhoehoe flows common in Hawai‘i and elsewhere. Given the frequency of destructive lava flows from volcanoes in Hawai‘i, the potential for lava flows from other volcanoes in the United States, and VDAP’s overseas responsibilities, the VHP should develop a permanent, in-house lava modeling capability that builds on its international leadership in debris-flow and landslide modeling.

Conclusions

The next five years present exciting opportunities for major growth in the U.S. Geological Survey Volcano Hazards Program (VHP), growth that could be exponentially enabled by potential Congressional funding for the National Volcano Early Warning System as outlined in its authorizing legislation, Public Law 116-9. Innovation, prioritization, and ensuring feasibility will remain drivers of our new work, which will build on a solid base of current monitoring, research, and hazard assessment efforts that will converge to propel each other forward. Driving toward new and better research, modeling, monitoring, preparedness, hazard assessments, partnerships, and staffing, as well as rebuilding observatory infrastructure that eruptions have destroyed, will be our strategic focus. Achieving measurable progress in these strategic goals and scientific targets will require coordination and unity of effort among the Program Office, Volcano Science Center (VSC) observatories, and their partner agencies and institutions. Required increased staffing across disciplines in the VHP can be achieved through periodic generation and execution of hiring plans by the VSC, generation of post-doctoral research opportunities that align with these goals and scientific targets, and definition of new tasks with financial support for increased hiring of graduate student and post-doctoral staff in cooperative agreement awards to observatory partners. The result will be a deepening of our understanding of volcanic processes and a strengthened ability to prepare stakeholders for eruptions, leading to volcanic hazard forecasts that are more timely, accurate, and heeded, thus helping to fulfill the VHP's mission to prevent volcanic crises from becoming national disasters.

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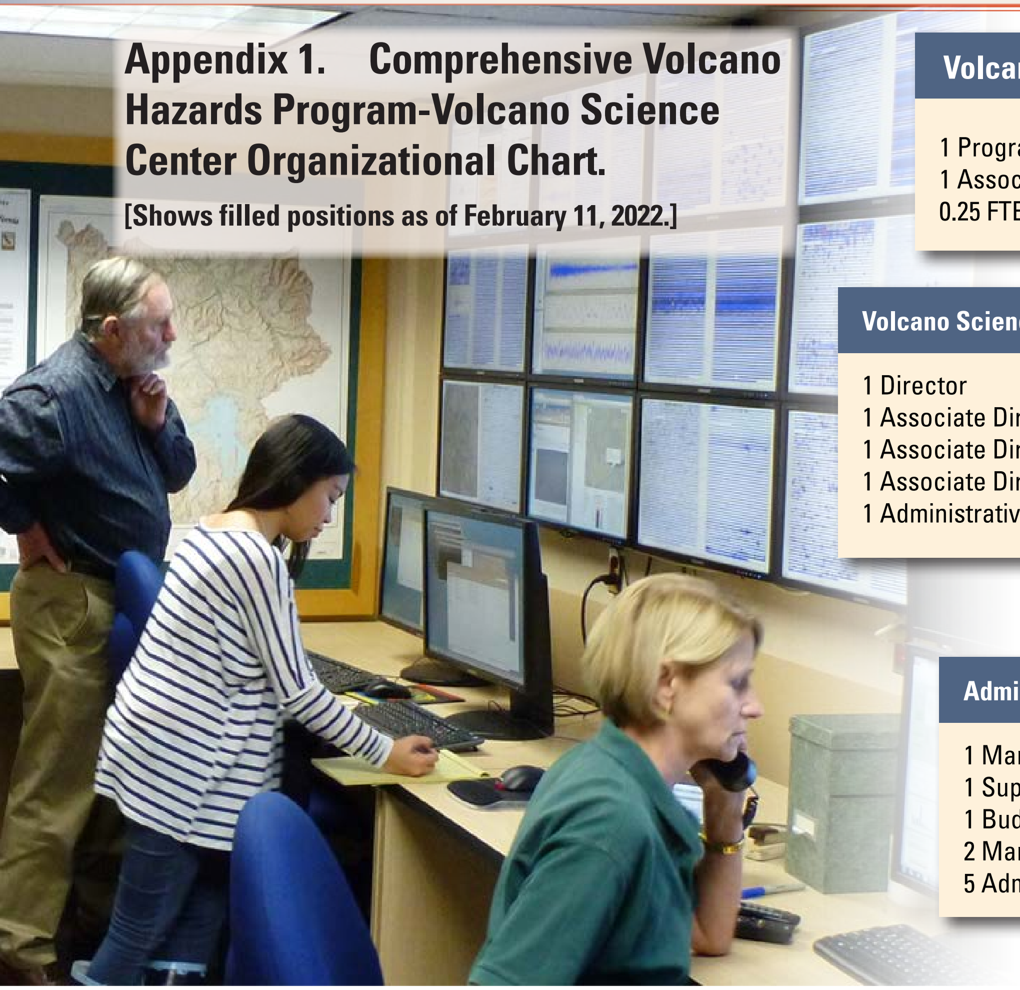
Appendixes 1–3

Appendix 1. Comprehensive Volcano Hazards Program-Volcano Science Center Organizational Chart.

[Shows filled positions as of February 11, 2022.]



Volcano Hazards Program Office

1 Program Coordinator
1 Associate Program Coordinator
0.25 FTE Staff Scientist

Volcano Science Center

1 Director
1 Associate Director for Science and Technology
1 Associate Director for Infrastructure and Operations
1 Associate Director for Monitoring Networks
1 Administrative Officer

Administration

1 Manager/Administrative Officer
1 Supervisory Financial Analyst
1 Budget Analyst
2 Management Analysts
5 Administrative Operations Assistants

Hawaiian Volcano Observatory

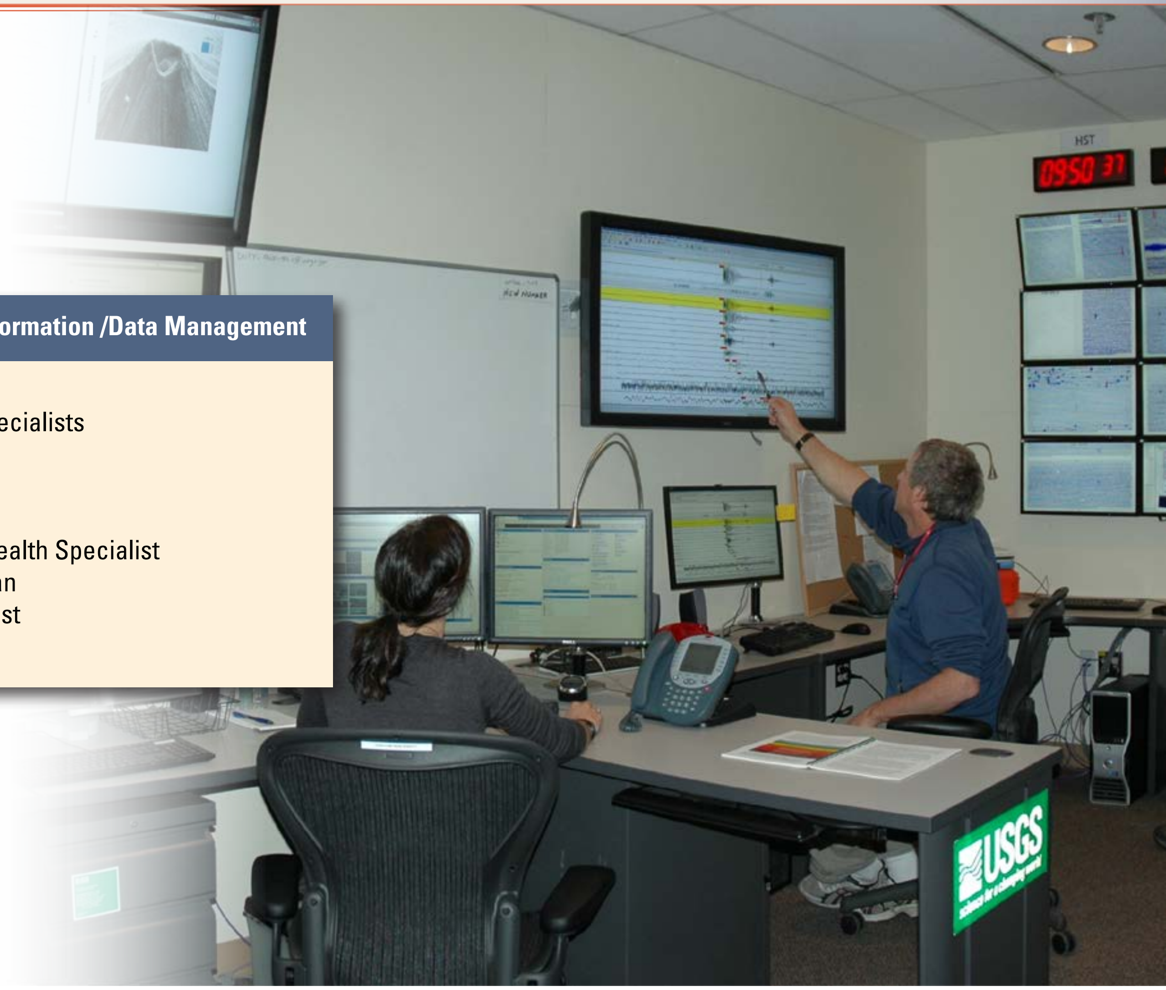
1 Scientist-in-charge
1 Deputy Scientist-in-charge
5 Research Geophysicists
3 Geophysicists
6 Research Geologists
3 Geologists
1 Chemist
4 Physical Science Technicians
1 Supervisory Electronics Technician
1 Electronics Technician
1 Management Assistant

California Volcano Observatory

1 Scientist-in-charge
12 Research Geologists
3 Geologists
4 Research Geophysicists
1 Research Physicist
2 Research Hydrologists
3 Hydrologists
1 Research Chemist
7 Physical Science Technicians

Cascades Volcano Observatory

1 Scientist-in-charge
1 Administrative Officer
6 Research Geophysicists
5 Geophysicists
6 Research Geologists
4 Geologists
2 Research Hydrologists
1 Hydrologist
1 Supervisory Hydrologic Technician
4 Hydrologic Technicians
1 Research Physical Scientist
1 Physical Scientist
3 Physical Science Technicians
1 Research Mathematician
1 Electronics Technician
1 Geographer



Center Infrastructure and Information /Data Management

1 Manager
9 Information Technology Specialists
2 Computer Scientists
2 Geologists
1 Hydrologic Technician
1 Safety and Occupational Health Specialist
1 Physical Science Technician
1 Facility Operations Specialist
1 Maintenance Worker

Alaska Volcano Observatory

1 Scientist-in-charge
7 Research Geophysicists
6 Geophysicists
2 Research Geologists
1 Geologist
1 Research Hydrologist
1 Research Physical Scientist

Yellowstone Volcano Observatory

1 Scientist-in-charge
1 Deputy Scientist-in-charge

Volcano Disaster Assistance Program

1 VDAP Project Chief
2 Research Geologists
9 Geologists
4 Research Geophysicists
4 Geophysicists
2 Physical Science Technicians
1 Computer Scientist

Appendix 2. A Brief Chronology of National Volcano Early Warning System (NVEWS) Legislation and Passage

The U.S. Geological Survey (USGS) Volcano Hazards Program (VHP) has conceptualized and advocated for a National Volcano Early Warning System (NVEWS) as a means to proactively monitor all active and potentially active volcanoes in the United States and its territories at a level that matches the threats they pose. Following completion of the first national volcano threat assessment by the USGS and publication of those results (Ewert and others, 2005), multiple attempts were made by various members of Congress to introduce NVEWS legislation to the Senate and House floors, the earliest occurring in 2009. The list below documents these attempts in chronological order. In 2018, the USGS updated the national volcano threat assessment on the basis of new geological, geophysical, demographic, and hazards exposure data acquired over an approximately 13-year period (Ewert and others, 2018). In 2019, Senators Lisa Murkowski of Alaska and Maria Cantwell of Washington sponsored and included new NVEWS authorization legislation as Title V of the John D. Dingell, Jr., Conservation, Management, and Recreation Act, which the Senate passed by a vote of 92 to 8. The legislation subsequently passed in the House by a vote of 363 to 62 and was signed into law by President Trump on March 12, 2019, as Public Law 116-9, 43 U.S.C. 31k. This NVEWS authorization legislation—which had been in progress for approximately 15 years—is a significant milestone for the USGS VHP and is a strong endorsement by Congress for the monitoring and hazard assessment work currently performed by the VHP. Full implementation of NVEWS will ensure that all active and potentially active volcanoes in the United States and its territories are monitored at levels matching the threats they pose.

Since passage of the NVEWS authorization legislation, the USGS VHP wrote and submitted its NVEWS 5-Year Management Plan to Congress in March 2020, submitted its NVEWS 1-Year Progress Report to Congress also in March 2020, and published its NVEWS 5-Year Management Plan as a USGS Open-File Report (Cervelli and others, 2021). These documents detail the USGS plans for modernizing and upgrading the Nation's volcano monitoring networks into an interoperable system having 24/7 volcano watch capability and are available to the VHP's volcano observatory partners and other relevant Federal agencies.

Attempts to Introduce Legislation

United States Senate, 2009, S. 782: To provide for the establishment of the National Volcano Early Warning and Monitoring System, 111th Congress, 1st Session, 8 p.

United States House of Representatives, 2010, H.R. 4847: To provide for the establishment of the National Volcano Early Warning and Monitoring System, 111th Congress, 2d Session, 8 p.

United States Senate, 2011, S. 566: To provide for the establishment of the National Volcano Early Warning and Monitoring System, 112th Congress, 1st Session, 4 p.

United States Senate, 2015, S. 2056: To provide for the establishment of the National Volcano Early Warning and Monitoring System, 114th Congress, 1st Session, 8 p.

United States Senate, 2017, S. 346: To provide for the establishment of the National Volcano Early Warning and Monitoring System, 115th Congress, 1st Session, 8 p.

Appendix 3. Resources for More Information

Get Volcano Activity Notifications at https://volcanoes.usgs.gov/vns2/

For an overview of the Volcano Hazards Program, visit: https://www.usgs.gov/programs/VHP

For regional questions, contact one of the five USGS volcano observatories below:

- Alaska Volcano Observatory: https://avo.alaska.edu/
- California Volcano Observatory: https://www.usgs.gov/observatories/calvo
- Cascades Volcano Observatory: https://www.usgs.gov/observatories/cvo
- Hawaiian Volcano Observatory: https://www.usgs.gov/observatories/hvo
- Yellowstone Volcano Observatory: https://www.usgs.gov/observatories/yvo

Find us on social media:

Our USGS Volcanoes social media accounts are a great way to learn about what we're doing and to ask us questions. Follow *@USGSVolcanoes* on Facebook, Twitter, and Instagram.

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