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PERSPECTIVES

A look ahead to the next decade at US volcano observatories

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Abstract
Volcano monitoring, eruption response, and hazard assessment at volcanoes in the United States of America (US) fall under the mandate of five regional volcano observatories covering 161 active volcanoes. Working in a wide range of volcanic and geographic settings, US observatories must learn from and apply new knowledge and techniques to a great variety of scientific and hazard communication problems in volcanology. Over the past decade, experience during volcanic crises, such as the landmark 2018 eruption of Kīlauea, Hawai'i, has combined with investments and advances in research and technology, and the changing needs of partner agencies and the public, to transform the operations, science, and communication programs of US volcano observatories. Scientific and operational lessons from the past decade now guide new research and growing inter-observatory and external communication networks to meet new challenges and improve detection, forecasting, and response to volcanic eruptions in the US and around the world.

Keywords Volcano monitoring · Eruption response · Hazard assessment · Risk mitigation · Hazard communication

Introduction

Volcano monitoring tools and scientific understanding of volcanic processes and eruptive histories must keep pace with increasing risk as populations, infrastructure, and economic activities expand farther into volcanic regions in the twenty-first century. With 161 active volcanoes (Ewert et al. 2018), the United States of America (US) is one of the world's most volcanically active nations. Tasked with providing information, forecasts, and warnings about volcanic hazards in the US, the US Geological Survey's (USGS) Volcano Science Center (VSC) operates five volcano observatories to monitor, study, and respond to eruptions. New technology, scientific progress, challenges posed by recent eruptions, and the evolving needs of stakeholders have greatly expanded US eruption monitoring, forecasting, and research capabilities over the past decade. These same forces now combine with lessons from the largest US volcanic crisis since the 1980 Mount St. Helens eruption, the 2018 eruption of Kīlauea, Hawai'i, to inspire continued strategic growth and change in the next decade. This short contribution reflects on major developments at the US volcano observatories in the 2010s and discusses the future of observatory science and operations in the 2020s.

Overview of the US volcano observatories

Since the founding of the Hawaiian Volcano Observatory (HVO) in 1912, four additional observatories have formed and evolved with volcanic activity and changing stakeholder needs (Fig. 1). These are, in chronological sequence of formation: (1) the Cascades Volcano Observatory (CVO) established during the 1980–1986 Mount St. Helens eruption; (2) the Long Valley Observatory (LVO) established in 1982 during volcanic unrest, but whose responsibility has since expanded in 2012 to

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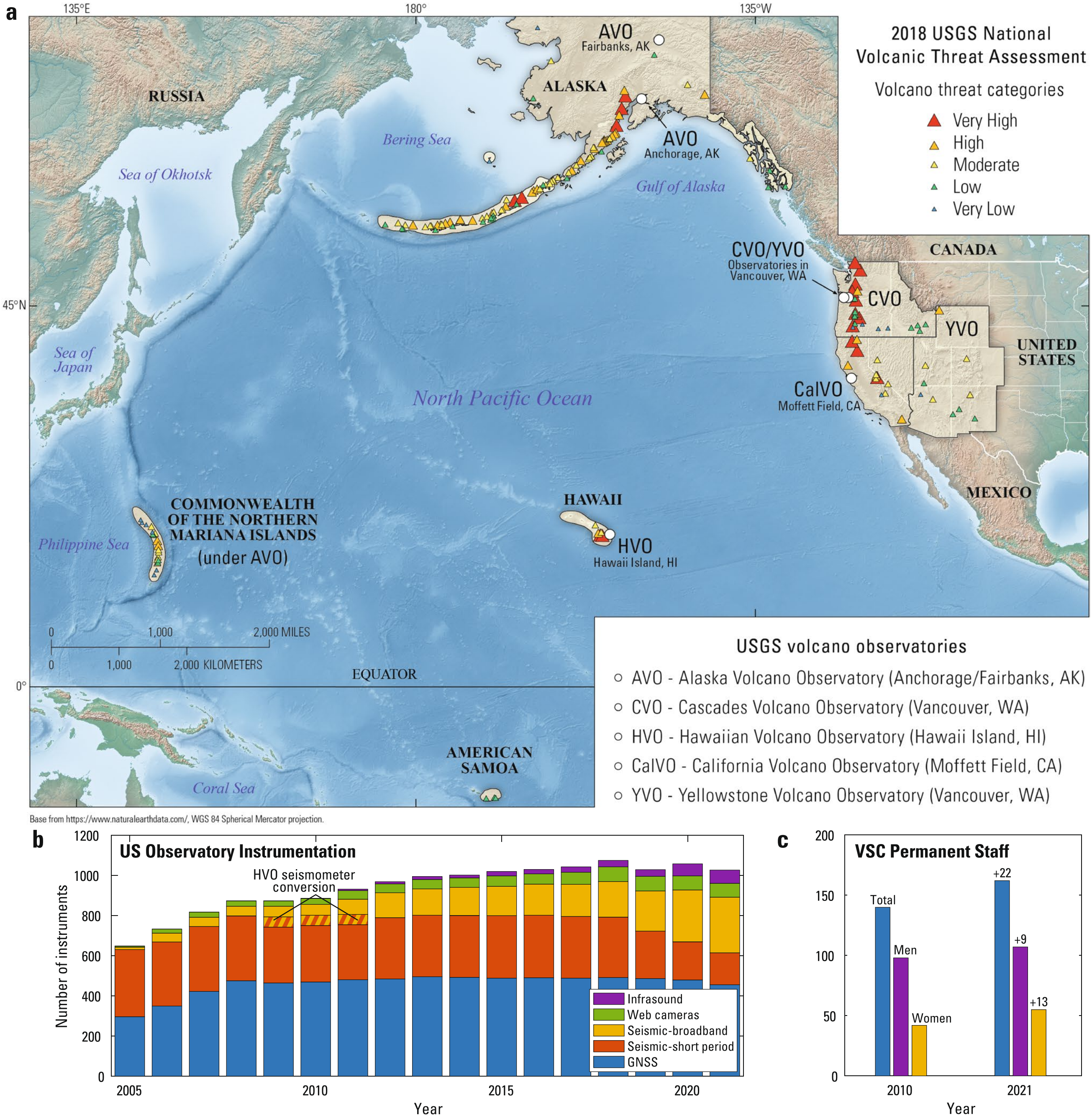

Fig. 1 **a** Map of US volcanoes, color-coded by threat ranking (Ewert et al. 2018), and observatory regions of responsibility. **b** Selected monitoring instrumentation used by US observatories over time. After rapid network expansion in the late 2000s, the past decade has focused on upgrading instrumentation, including recent conversion of the seismic network from mostly analog short period to digital broadband systems, real-time GNSS processing, and the growth of infrasound and web camera networks. Web cameras comprise all USGS telemetered web cameras, including both optical and thermal cameras. All counts are approximate due to metadata uncertainty. **c** VSC staff in 2010–2021 with gender breakdown. The 2010 total includes staff from the USGS National Research Program who were transferred to USGS VSC in 2017

cover California and Nevada as the California Volcano Observatory (CalVO); (3) the Alaska Volcano Observatory (AVO) established in 1988; and (4) the Yellowstone Volcano Observatory (YVO) established in 2001.

In 2012, to close regional gaps and deepen relationships with local partners, each observatory was formally assigned geographic responsibilities for volcano monitoring and eruption response. YVO's responsibility expanded to cover the Intermountain West and AVO and HVO assumed roles in the Northern Mariana Islands and American Samoa, respectively. All observatory operations involve partnerships with other federal agencies, state geological surveys, and universities, and all observatories work closely with emergency managers and other government agencies such as the National Weather Service, the Federal Aviation Administration, and the federal land managers, to prepare for and respond to volcanic eruptions. Observatories have led interagency coordination committees and response planning efforts for volcanoes and regions (Yellowstone Volcano Observatory 2014; Alaska Volcano Observatory et al. 2017; https://www.usgs.gov/volcano/coordination-plans). VSC staff also support international volcano observatories through the Volcano Disaster Assistance Program (VDAP, established in 1986).

Like many government volcano observatories around the world, USGS balances fundamental research and operations to directly support public safety (cf. Pallister et al. 2019; Chevrel et al. 2021; Lowenstern et al. 2022). By integrating these tasks, the US observatories have made seminal contributions to volcano science and risk reduction, including innovative monitoring tools, real-time public data streams, and foundational models of magmatic and volcanic processes. Collaboration with international observatories and the academic community (e.g., World Organization of Volcano Observatories, International Association of Volcanology and Chemistry of the Earth's Interior [IAVCEI]) has served to advance global volcano science and exchanged international state-of-the-art data, knowledge, and tools (Pallister et al. 2019; Lowenstern et al. 2022). Critically, while each US observatory has a distinct focus, blend of staff expertise, and relationships with local partners, all offices combine resources for research and operations as the entire USGS VSC.

Recent advances and future directions of the US observatories reflect long-term research and innovation punctuated by opportunities and challenges posed by volcanic crises. In particular, the 2018 eruption of Kīlauea Volcano, Hawai‘i, was a landmark event that affirmed the past decade of developments at US observatories while exposing key challenges for the next decade. Over a 3-month period, lava from the most destructive eruption in Hawai‘i in the past 200 years buried homes and infrastructure on the volcano’s flank, while simultaneous extensive caldera collapse at the volcano’s summit caused damage from ground-shaking and ash emissions (Fig. 2a; eruption summarized in Neal et al. 2019; see Bulletin of Volcanology Collection, Patrick et al. 2020). We therefore illustrate the current state of US observatories through the framing of monitoring and response before, during, and after the 2018 Kīlauea eruption.

Advances and challenges in the past decade: the lead-up and response to the 2018 Kīlauea eruption

Prior to 2018, expansion and upgrade of US volcano monitoring capabilities with new ground-based instruments had greatly improved our ability to detect, forecast, and characterize volcanic unrest, hazard, and eruptions throughout the US (Fig. 1b). The augmentation of ground-based networks to include digitally telemetered broadband seismometers, real-time processing of GNSS data streams, local and regional infrasound arrays, web cameras, and continuous gas monitoring had strengthened surveillance at highest-threat volcanoes in the US (Ewert et al. 2018), improved the reliability of eruption forecasting and detection (Coombs et al. 2018; Neal et al. 2019; Power et al. 2020, and provided more real-time, public scientific data for the global volcano research community (see 2016–2017 eruption of Bogoslof volcano, Alaska, Bulletin of Volcanology Collection, Waythomas et al. 2019). The Kīlauea crisis response built upon this decade of progress, demonstrated by early detection and characterization of eruption precursors for forecasting (Neal et al. 2019), syn-eruptive expansion of instrumentation (Shiro et al. 2021), and multiparametric studies of volcanic plumbing system and eruption dynamics now resulting from these data (e.g., visual-infrasound lava channel dynamics, Fig. 2b; Lyons et al. 2021).

Similarly, rapid growth in remote sensing technology and adoption of unoccupied aircraft systems (UAS) were both instrumental in the Kīlauea eruption response. New optical, thermal, and synthetic aperture radar (SAR) satellites have improved our ability to detect ground deformation, rapidly quantify topographic change, map eruptive deposits, and detect and characterize thermal signals and ash clouds at high temporal and spatial resolution (e.g., Coombs et al. 2018; Poland et al. 2020; Schneider et al. 2020; Poland and Zebker, 2022). In the Kīlauea crisis, daily acquisitions of optical and SAR imagery with resolutions to ~ 25 cm tracked the inaccessible lava flows and collapsing summit caldera for both rapid hazard assessment and longer-term research (Zoeller et al. 2018; Anderson et al. 2019). Miniaturized, cell-enabled, and high-definition optical and thermal cameras and lidar improved real-time observations and airborne mapping for assessing activity and hazards (Patrick et al. 2019; Dietterich et al. 2021). In their first major application by USGS at a US volcano, UAS surveys documented eruptive activity on an on-demand basis around the clock, enabling high-resolution video and mapping for orthoimagery and digital surface models (Fig. 2b; Neal et al. 2019; DeSmither and Diefenbach 2021). These UAS datasets, including volcanic gas and aerosol measurements, supplied critical data, such as updated terrain data and lava effusion

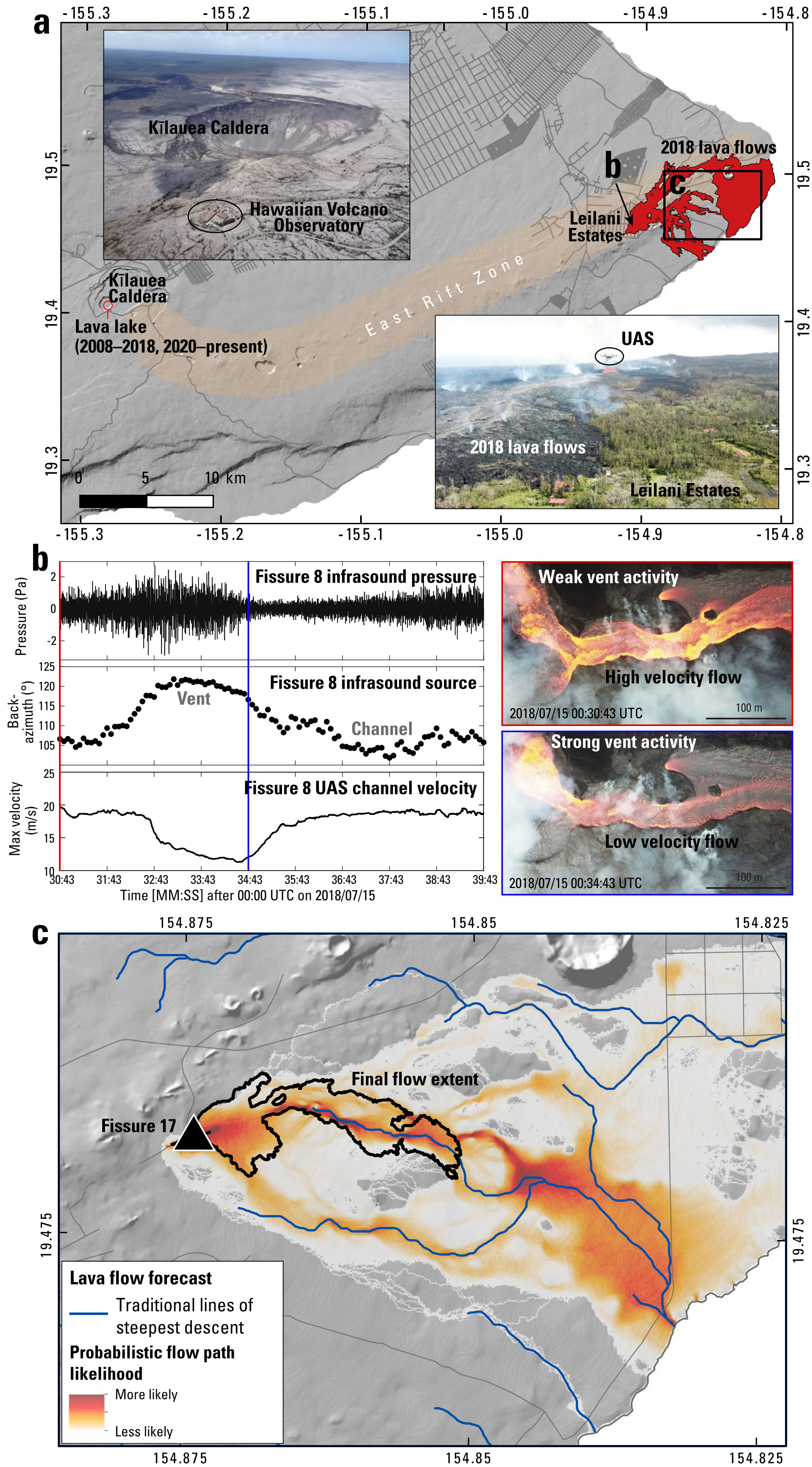

Fig. 2 2018 Kīlauea eruption examples of improved eruption observations and hazard assessment. **a** Kīlauea summit and East Rift Zone map with images of the summit caldera collapse (evacuated Hawaiian Volcano Observatory, HVO, in the foreground) and an unoccupied aircraft system (UAS) survey of the lava flows in Leilani Estates. **b** Integration of novel infrasound and UAS video analysis of magnitude, source location, and channel velocity of the main 2018 vent (fissure 8, Ahuʻailāʻau) capturing short-period changes in effusion rate (pulses) (redrafted after Lyons et al. 2021). **c** Probabilistic lava flow forecasts in 2018 used DOWNFLOW (Favalli et al. 2005) to model the likelihood of different flow routes from new vents (e.g., fissure 17; Neal et al. 2019), building on the traditional use of steepest descent lines (Kauahikaua et al. 2017)

rates, for hazard modeling during response and now inform studies of volcanic processes (e.g., Kern et al. 2020; Dietterich et al. 2021; Mason et al. 2021).

Data processing and modeling capacities have advanced in parallel with monitoring data, supporting rapid evaluation, application, and research during the Kīlauea crisis and throughout the VSC. Automated event detection and activity alarms triggered by processing of volcano monitoring data streams are now used to alert staff to events 24/7 (Coombs et al. 2018). Studies of the physics and dynamics of volcanic processes have increasingly paired with numerical and statistical modeling to generate physics-based models of volcanic systems and hazards over the past decade (e.g., Ash3d for ash dispersal, D-CLAW for lahars; Schwaiger et al. 2012; Anderson and Segall 2013; Iverson and George 2014). These tools aid integration of models and geologic and monitoring data into probabilistic eruption forecasting in Bayesian event trees and hazard maps at US observatories and around the world (Marzocchi et al. 2010; Newhall and Pallister 2015). Event-trees and physics-based models developed at USGS, such as HYDROTHERM (Kipp et al. 2008) and Ash3d (Schwaiger et al. 2012), and the DOWNFLOW lava flow code (Favalli et al. 2005) shared by the Istituto Nazionale di Geofisica e Vulcanologia (Italy), were all applied for short-term hazard assessment during the Kīlauea crisis for assessing potential for groundwater-driven explosions, ash dispersal, and forecasting lava flow routes, respectively (Fig. 2c; Neal and Anderson 2020; Neal et al. 2019; Hsieh and Ingebritsen 2019).

The 2018 Kīlauea eruption response and shifting communication needs over the past decade have also influenced new strategies for communication and coordination with partner agencies, emergency managers, and the public. Prior to 2018, HVO had worked closely with local emergency managers and at-risk populations for many years, setting a new standard for direct public engagement during an eruption crisis with regular community meetings during the 2014–2015 Pāhoa lava flow crisis at Kīlauea (Poland et al. 2016; Brantley et al. 2019). However, the rapidly evolving and destructive 2018 eruption required 24/7 observatory representative presence at local and state emergency operation centers to provide real-time information to decision-makers, while also maintaining daily outreach at community meetings and press conferences. This event was also the first time a US volcano observatory used social media as a tool on such a large scale to share scientific observations and hazard information while continually answering questions for followers and quelling misinformation.

The demands of the 2018 eruption response required the local regional observatory model (Fig. 1a) to scale up, whereby staff from other US observatories assisted in the field or remotely with monitoring, analysis, and communication. Past cross-observatory support during crises of the previous decade typically relied on in-person assistance (e.g., Augustine 2006 eruption). However, internet-based collaboration tools have revolutionized communication and moved all data streams, alarms, and response discussions online and accessible on mobile devices. Monitoring, modeling, and communications tools, such as the mobile communication app Mattermost adopted by AVO during the 2016–2017 Bogoslof eruption (Coombs et al. 2018; Waythomas et al. 2019), were rapidly deployed across all observatories to support the Kīlauea response. These greatly facilitated real-time cross-observatory data sharing and discussion among field and remote participants, particularly as HVO lost access to its offices (Fig. 2a). Increasing interoperability of observatory equipment, tools, and expertise was critical to supporting and sustaining the response to such a major event.

Looking ahead to the next decade: applying and building on lessons from the 2018 Kīlauea eruption

Scientific, monitoring, and institutional lessons of the 2018 Kīlauea eruption response and advances in volcanology in the past decade offer a roadmap for US observatory growth in the next decade. Monitoring, hazard assessment, and communication during the Kīlauea crisis were challenged by instrumentation and data processing limitations, uncertainties in understanding the magmatic plumbing system and volcanic processes, limited open-source operational physics-based models and input data for hazards such as lava flows, and evolving communication needs of stakeholders. Following the 2018 crisis, USGS VSC is addressing these gaps and challenges by investing in research, monitoring infrastructure, modeling and hazard assessment methods and products, and focusing on eruption response planning, all with an increased emphasis on interoperability among observatories (see also the USGS Volcano Hazards Program 2022–2026 Strategic Science Plan, Mandeville et al. 2022).

An expanded volcano monitoring network and strategic data management system are key to progress. In 2019, Congress formally authorized the USGS to establish a National Volcano Early Warning System (NVEWS; PL 116–9/S.47 Section 5001) to modernize and integrate monitoring networks across the observatories, establish a data clearinghouse and 24/7 watch capability, and create an external grants program to support research and development (see Cervelli et al. 2021). The USGS is pursuing these NVEWS goals, including prioritizing closing gaps where monitoring instrumentation is insufficient at the highest threat volcanoes in the US (Fig. 1a). The coming decade will see continued expansion and modernization of real-time monitoring networks and application of new geophysical, gas, and other instruments during crises (e.g., Power et al. 2020; Shiro et al. 2021; Thelen et al. 2022). Expanded monitoring also extends to remote sensing tools including UAS. As an example, the USGS is utilizing post-2018 eruption funding to develop domestic UAS capabilities (Nadeau et al. 2020).

Sharing of novel datasets and closer coordination among US observatories and the global volcanology community will improve our collective scientific understanding of magmatic and volcanic systems and hazards. Fully characterizing background activity and unrest at volcanoes and maximizing scientific return during eruptions are necessary to pursue the grand challenges identified in a major 2017 community report on outstanding scientific questions in volcano science ("Volcanic Eruptions and Their Repose, Unrest, Precursors, and Timing;" National Academies of Sciences, Engineering, and Medicine 2017). To facilitate better collaboration between observatory and academic scientists during eruptive crises, a Community Network for Volcanic Eruption Response (CONVERSE) recently piloted a system for sharing data and samples during the 2020–2021 Kīlauea summit eruption (Fischer et al. 2021). Increasing availability of US observatories' monitoring data will complement academic field and laboratory studies to advance understanding of individual volcanic systems and magmatic and eruptive processes. This research will in turn be applied to modeling and forecasting hazards. As an example, new work on magma storage and transport, caldera formation, and lava flow dynamics and forecast modeling is being guided by knowledge gaps about these processes and structures identified in the 2018 Kīlauea eruption (e.g., Anderson et al. 2019; deGraffenreid et al. 2021; Weiser et al. 2022). Additionally, increased awareness of stakeholder needs and international discussions within the IAVCEI Commission on Volcanic Hazard and Risk has inspired a USGS VSC project to improve methods, data, and design to maximize the utility of hazard assessment products (Fig. 2c).

To improve the quality and application of our science, US observatories are also pursuing actions to expand diversity, equity, inclusion, and accessibility (DEIA) in our offices, in our research, and in how we engage with communities. Diversity of USGS staff at volcano observatories does not reflect wider US demographics (Bernard and Cooperdock 2018), but there has been some improvement in gender diversity, for example, in recent years (Fig. 1c). Broadly increasing diversity, equity, and engagement at US observatories, a current strategic USGS goal, will likely benefit their scientific impact and improve hazard communication (e.g., Hong and Page 2004; Maldonado et al. 2015; AlShebli et al. 2018; Nielsen et al. 2018). In the next decade, observatory participation in DEIA programs, such as the Unlearning Racism in Geoscience curriculum (https://urgeoscience.org/), will help to inform observatory science and outreach to more effectively address needs of traditionally underrepresented and indigenous communities.

Conclusions

Future directions envisioned in this review will both advance the science of volcanology and better prepare US volcano observatories for the next volcanic crisis. With investments in monitoring networks, data processing and analysis, geological and geophysical research, and next-generation modeling and hazard assessment, USGS VSC will provide more effective forecasts, alerts, and information on volcanic activity throughout the US. Machine learning and faster processing of real-time data streams will improve alarms and early warning, and shared tools and expertise between observatories will support early detection and characterization of volcanic unrest. US observatory interoperability and collaboration with international observatories and the academic community will support more effective eruption monitoring, response, communication, and research. Future hazard assessments will be informed by more complete understanding of volcanic histories and will be tailored to the needs of, and better communicated to, end users.

To improve eruption response and support of emergency management, US observatories and USGS VSC are drafting and updating plans to better organize local responses and plan for the next large eruption crisis, like that of Kīlauea 2018, that requires significant cross-observatory, USGS, and external support. A silver lining of the COVID-19 pandemic has been development of remote work tools, such as video conferencing and cloud computing, that have significantly increased inter-observatory, international, and academic-observatory communication and knowledge exchange.

The next decade of US observatory science and operations holds great promise. Strategic use of advances in science and technology, integration of new insights into volcanic systems, and strengthened cooperation with partners will all help to achieve the goal of minimizing impacts of future volcanic activity.

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