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PERSPECTIVES

Coordinating science during an eruption: lessons from the 2020–2021 Kīlauea volcanic eruption

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Abstract

Data collected during well-observed eruptions can lead to dramatic increases in our understanding of volcanic processes. However, the necessary prioritization of public safety and hazard mitigation during a crisis means that scientific opportunities may be sacrificed. Thus, maximizing the scientific gains from eruptions requires improved planning and coordinating science activities among governmental organizations and academia before and during volcanic eruptions. One tool to facilitate this coordination is a Scientific Advisory Committee (SAC). In the USA, the Community Network for Volcanic Eruption Response (CONVERSE) has been developing and testing this concept during workshops and scenario-based activities. The December 2020 eruption of Kīlauea volcano, Hawaii, provided an opportunity to test and refine this model in real-time and in a real-world setting. We present here the working model of a SAC developed during this eruption. Successes of the Kīlauea SAC (K-SAC) included broadening the pool of scientists involved in eruption response and developing and codifying procedures that may form the basis of operation for future SACs. Challenges encountered by the K-SAC included a process of review and facilitation of research proposals that was too slow to include outside participation in the early parts of the eruption and a decision process that fell on a small number of individuals at the responding volcano observatory. Possible ways to address these challenges include (1) supporting community-building activities between eruptions that make connections among scientists within and outside formal observatories, (2) identifying key science questions and pre-planning science activities, which would facilitate more rapid implementation across a broader scientific group, and (3) continued dialog among observatory scientists, emergency responders, and non-observatory scientists about the role of SACs. The SAC model holds promise to become an integral part of future efforts, leading in the short and longer term to more effective hazard response and greater scientific discovery and understanding.

Keywords Eruption response · Scientific coordination · Scientific advisory committee · Hawaii · CONVERSE

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Introduction

Significant leaps in understanding volcanic eruptions and their consequences often occur during and shortly after well-observed eruptions. For example, the 1980 Mount St. Helens eruption highlighted the hazards from a large flank failure and a lateral blast (Miller et al. 1981), the 1991 eruption of Pinatubo enabled the climatic effects of large eruptions to be quantified (Minnis et al. 1993) and emphasized that secondary hazards such as lahars last far longer than the primary eruptions (Major et al. 1996), and the 2022 Hunga Tonga—Hunga Ha'apai eruption revealed the rich array of waves generated by explosive eruptions (Matoza et al. 2022). Many critical data sets and samples can be collected only during an eruption, and studies of these can lead to more effective hazard mitigation. However, during a crisis, there is the potential to miss science opportunities as priorities focus on public safety and hazard mitigation, and field access for observations and sampling or installation of instrumentation becomes restricted by authorities. Scientists responding to the eruption under the auspices of long-standing formal roles recognized by authorities (e.g., scientists affiliated with a volcano observatory) have less time to interface with scientists from other institutions who are not yet directly involved in the eruption response. To this end, the National Academy of Sciences ERUPT report (National Academies of Sciences, Engineering, and Medicine 2017) highlighted "Develop a coordinated volcano science community to maximize scientific returns from any volcanic event" as one of three grand challenges for the volcano science community.

Among the elements required to advance our understanding of volcanic systems and improve forecasting are a coordinated response by the entire research community to help overcome observational bias (e.g., large eruptions are rare in the historical record and a small number of volcanoes have been the subject of intense study), and developing synergistic partnerships between academic institutions and volcano observatories. The most damaging recent volcanic crisis in the USA, the 2018 eruption of Kīlauea, Hawaii, demonstrated both the opportunities for and challenges of maximizing the scientific returns of volcanic eruptions. The US Geological Survey (USGS) Hawaiian Volcano Observatory (HVO), charged with the eruption response, deployed unprecedented levels of instrumentation for eruption monitoring and made round-the-clock field observations in order to inform their primary mission—to evaluate and communicate hazards and support public safety (Neal et al. 2019). At the same time, there was a flood of requests by non-observatory researchers to obtain rock samples and field access, and/or to deploy equipment. These requests could not be realistically or equitably addressed in near-real time due to both access restrictions and the limited available time of observatory staff and emergency managers. Data collected by scientists during the eruption have produced many important scientific discoveries, (e.g., Neal et al. 2019; Anderson et al. 2019; Gansecki et al. 2019; Patrick et al. 2019, 2020; Namiki et al. 2021) yet, based on this experience, a more robust, transparent system for facilitating scientific collaboration will provide opportunities to learn even more from future events.

The Community Network for Volcanic Eruption Response (CONVERSE) began as a Research Coordination Network funded by the National Science Foundation (NSF) to facilitate collaboration between scientists at the USGS volcano observatories, National Aeronautics and Space Administration (NASA), universities, and other scientific organizations, to advance our ability to monitor volcanoes and volcanic eruptions, to collect critical data and samples, and to develop a new generation of physical and chemical models of volcanoes. Primary responsibility for monitoring, eruption response, and assessment and communication of hazards at US volcanoes falls on the USGS Volcano Science Center and its volcano observatories, part of the US Geological Survey's Volcano Hazards Program. The challenges of coordinating efforts between observatory scientists and non-observatory scientists during an eruption crisis have long been recognized (e.g., Fiske 1984; Newhall 1999; Lowenstern et al. 2022; Saarinen and Sell 1985). The model of a Scientific Advisory Committee (SAC) to help coordinate between observatory and non-observatory scientists grew out of efforts during past eruptions and discussions during workshops organized by CONVERSE during 2019–2020. The SAC concept was tested in a scenario-based workshop in November 2020 that was focused on a simulated eruption at Mount Hood, Oregon (Fischer et al. 2021). A new eruption at Kīlauea that began on 20 December 2020 provided a real-world opportunity to test this model as a framework for a coordinated response of observatory staff and the broader research community. This manuscript summarizes lessons learned from this opportunity, describes policies and procedures developed during the eruption, and assesses what worked well, remaining challenges, and suggestions for future SAC implementation.

Scientific communication and coordination in previous eruptions

The need for, and advantages of, communication and coordination among scientists during eruptions has long been recognized, along with challenges associated with these efforts (e.g., Fiske 1984; Newhall 1999; Lowenstern et al. 2022; Saarinen and Sell 1985). Past committees have been convened around the world to coordinate scientific and field activities as well as to assess hazards to inform eruption response. Different committees have had different goals and mandates. Here, we briefly review a few examples to highlight the challenges posed by the different goals and responsibilities of observatory and non-observatory scientists during previous eruptions.

In 1976, accelerating seismic activity at La Soufrière, Guadaloupe, culminated in explosive activity that triggered a four-month evacuation and bitter disputes among both civil authorities and scientific groups working on eruption response (Fiske 1984). Problems were related to the ambiguous nature of the event itself combined with a lack of baseline data, the inexperience of many scientists involved, and the public nature of disputes between scientific groups. As a result, government authorities in Paris convened a *Comité Scientifique International sur La Soufrière* to assess the scientific data and prepare a final report, the immediate consequence of which was to terminate the evacuation.

The scientific response to the 1980 eruption of Mount St. Helens was handled primarily by the USGS in coordination with the primary land manager, the US Forest Service (USFS), and the emergency management authority, the Washington Emergency Management Division. Academic involvement was initially via the University of Washington, which was responsible for the Pacific Northwest Seismic Network and therefore closely involved with the eruption monitoring and response. A key challenge for the USGS was a shortage of trained personnel and the need to establish a volcano observatory from the ground up during the crisis. Given the rapid acceleration of activity at the volcano, the need to coordinate with federal, state, and local agencies, and the jurisdiction of the state over area closures, the USGS was unable to adequately respond to requests from non-observatory scientists for access to the volcano (Saarinen and Sell 1985). As a result, Professor John Elliot Allen of Portland State University and Ralph Mason, Oregon State Geologist (retired), with representatives from regional universities and the state Geologic Survey, formed the ad hoc Mount St. Helens Research and Education Coordinating Committee (SHCC) to screen academic and other access requests and issue access permits. The stated goals of the committee were to (1) help coordinate requests for field access (for both scientific and education purposes) and (2) to keep records on ongoing projects to reduce duplication. During the 5 months over which it was active, 121 permits were issued, after which the land manager, the USFS, took over the permitting process. Although Allen's commission was appreciated by the USGS and by some academic scientists (Nelson 1980), others were frustrated because of the perceived monopoly by the USGS, a perception that the USGS was turning away local experts, and the experience of some researchers who were refused entry to the restricted zone by the USFS despite having permits from Allen's committee (West 1980). The 1981 USGS Professional Paper on the eruption (Lipman and Mullineaux 1981) presents research conducted during and shortly after the eruption.

There was a concerted attempt by the USGS Cascades Volcano Observatory (CVO) to involve a broader scientific community during the unrest and eruption of Mount St. Helens in 2004. Partly as a consequence of the larger pool of scientists involved in the response, the USGS Professional Paper describing the eruption (Sherrod et al. 2008) reflects the participation of scientists from the USGS, other federal and state agencies, and academic and museum scientists from 16 institutions in the USA, Canada, and the UK. Of course, compared to the 1980 eruption, the 2004 eruption was relatively small, remained relatively non-threatening, and was conducive to sampling large amounts of new lava that could be shared easily, which aided the involvement of non-observatory scientists.

Evolving activity at Soufrière Hills Volcano, Montserrat, following its re-awakening in 1995, prompted an evolving effort at hazard assessment, including the formal appointment of a UK Government Scientific Advisory Committee (SAC) in 2003. The primary charge of this SAC was a twice-yearly meeting with the Montserrat Volcano Observatory (MVO) to perform a quantitative assessment of volcanic hazard and risk (Wadge and Aspinall 2014). Importantly, the risk assessment responsibilities of the SAC were separate from the MVO operations and included handling requests from academic scientists for research access.

After 40-year hiatus in eruptive activity in the Canary Islands and a 200-year hiatus at El Hierro, El Hierro began erupting in October 2011 (Marrero et al. 2015; Solana et al. 2018). Partly in response to unrest in 2004 at Tenerife, a Canarian Volcanic Emergencies Plan (PEVOLCA) had previously been created in 2008 and approved in 2010 (Marrero et al. 2015). This plan established a Scientific Advisory Committee, which would be responsible for scientific decision-making, and communicating information to the civil authorities. Within the legal framework of PEVOLCA, scientific information is linked strictly to response: the Volcanic Activity/Alert Levels (VAL), set by the scientific decision-makers, are directly linked to Emergency Response Levels. As a result, specific color codes for the VAL will trigger particular responses in the Emergency Response Levels, and those responses cannot proceed without the color code having been set by the scientific decision-makers (Marrero et al. 2015). It was recommended in the original plan that representatives of scientific institutions involved in volcanic research in the Canary Islands be included. However, the 2010 plan instead created an advisory committee composed of representatives from the National Geographical Institute (IGN), the Spanish National Research Centre (CSIC), the National

Meteorological Agency (AEMET), and the Canarian Civil Protection (Solana et al. 2018). This approach created several challenges. For example, the exclusion of some members of the scientific community created tensions and led to a difficult legal and financial position for scientists in the broader community who provided advice, and some scientists outside the SC disseminated information that was more speculative and led to unnecessary concern in the public (Solana et al. 2018). In addition, a lack of coordination between the SC and the external scientists led to a lack of data sharing and conflicts over access to monitoring resources and data. As a result, the Canarian Civil Protection has proposed that a new Scientific Committee for the Assessment and Surveillance of Volcanic Phenomena (CSEV) should be created. This committee would be coordinated by Civil Protection and would include representatives from external researchers from universities and research organizations as well as the PEVOLCA advisory committee groups (Solana et al. 2018).

During the 2018 eruption of Kīlauea, different approaches to coordinating access to the eruption by non-observatory scientists were used in the two eruption locations based on contrasting systems of land management. The US Federal Incident Command System (https://www.ready.gov/incident-management) operated at the active effusive eruption in the lower East Rift Zone (LERZ; see Fig. 1 inset), and as a result, access by scientists to the eruption was largely limited to HVO staff. Access was broadened somewhat later in the eruption as activity stabilized at Fissure 8. Because of this restricted access, science-focused field deployments without immediate value to hazard assessment were essentially impossible in the first month of the eruption, a time when hundreds of homes were destroyed and official evacuations of the residents were taking place. At the summit, access was also restricted by the emergency closure of Hawai'i Volcanoes National Park. The Hawaiian Volcano Observatory received numerous requests for scientific access, including requests directly from researchers and others forwarded by the National Park Service. At the same time, the National Science Foundation (NSF) stated that any funding proposals linked to rapid response to the eruption would require a letter of support from HVO in order to ensure that PIs had coordinated with HVO about any necessary access or HVO involvement. Scientific activities using remote methods (crewed airborne missions, satellite), or based offshore or downwind, were able to be conducted without restrictions by emergency or land managers, both with and without HVO involvement.

To help manage incoming requests for scientific access to both the LERZ and the summit areas, the HVO Scientist-in-Charge (SIC) set up an ad hoc committee of two scientists, one drawn from USGS and one from academia, to oversee a review process for these requests. The committee sought four single-page evaluations of the merits and feasibility of each project (two USGS reviewers and two from academic institutions). Their comments were summarized by a committee member and forwarded to the SIC for endorsement. The rate-limiting step in assessing requests in this way was obtaining the reviews from the people with necessary knowledge and perspective and who also had heavy commitments to the eruption response. A post-eruption analysis of the response recognized this issue and suggested a standing steering committee to evaluate outside research (Williams et al 2020). This experience was a major contributing factor to the formation of the Kīlauea Scientific Advisory Committee (K-SAC, which has now evolved into H-SAC, a broader Hawai'iScientific Advisory Committee).

These examples from previous eruptions provide important context for the concept and implementation of a SAC and show some of the challenges of coordinating efforts in a rapidly evolving and hazardous situation. Our model of a SAC was developed to mitigate some of these challenges through a focus on coordination between observatory and non-observatory scientists, which can lead to their mutual benefit and would advance volcano science, and an effort to minimize conflicts of interest and maintain the trust of both communities. The 2020–2021 eruption of Kīlauea provided an opportunity for developing and testing this framework for SAC operation.

The 2020–2021 eruption of Kīlauea

Following the LERZ eruption and summit collapse in 2018, Kilauea's summit crater began filling with water in July 2019 and a water lake almost 50 m deep was present when the 2020 eruption began. On 20 December 2020 at approximately 9:30 pm HST, fissures opened within Halema`uma`u crater in Kīlauea's summit caldera. Lava effusion continued to fill the crater over the eruption's 5-month duration, creating a 229-m deep lava lake by the end of the eruption on 26 May 2021 (Fig. 1). The onset of this eruption raised or emphasized several important questions: Why did the eruption begin where and when it did? Would there be an explosive eruption from the interaction of magma with the ephemeral water lake? Was this renewed activity a prelude to another long-lived eruption?

Activity remained confined in Halema`uma`u crater within a closed area of Hawai'i Volcanoes National Park throughout this eruption, limiting the potential risks. Its location within the 400 + meter deep 2018 collapse crater (Neal et al. 2019) meant that most of the eruptive material was contained within the crater. Direct access to the lake was not possible due to safety considerations, logistical challenges, and access restrictions established by Hawai'i

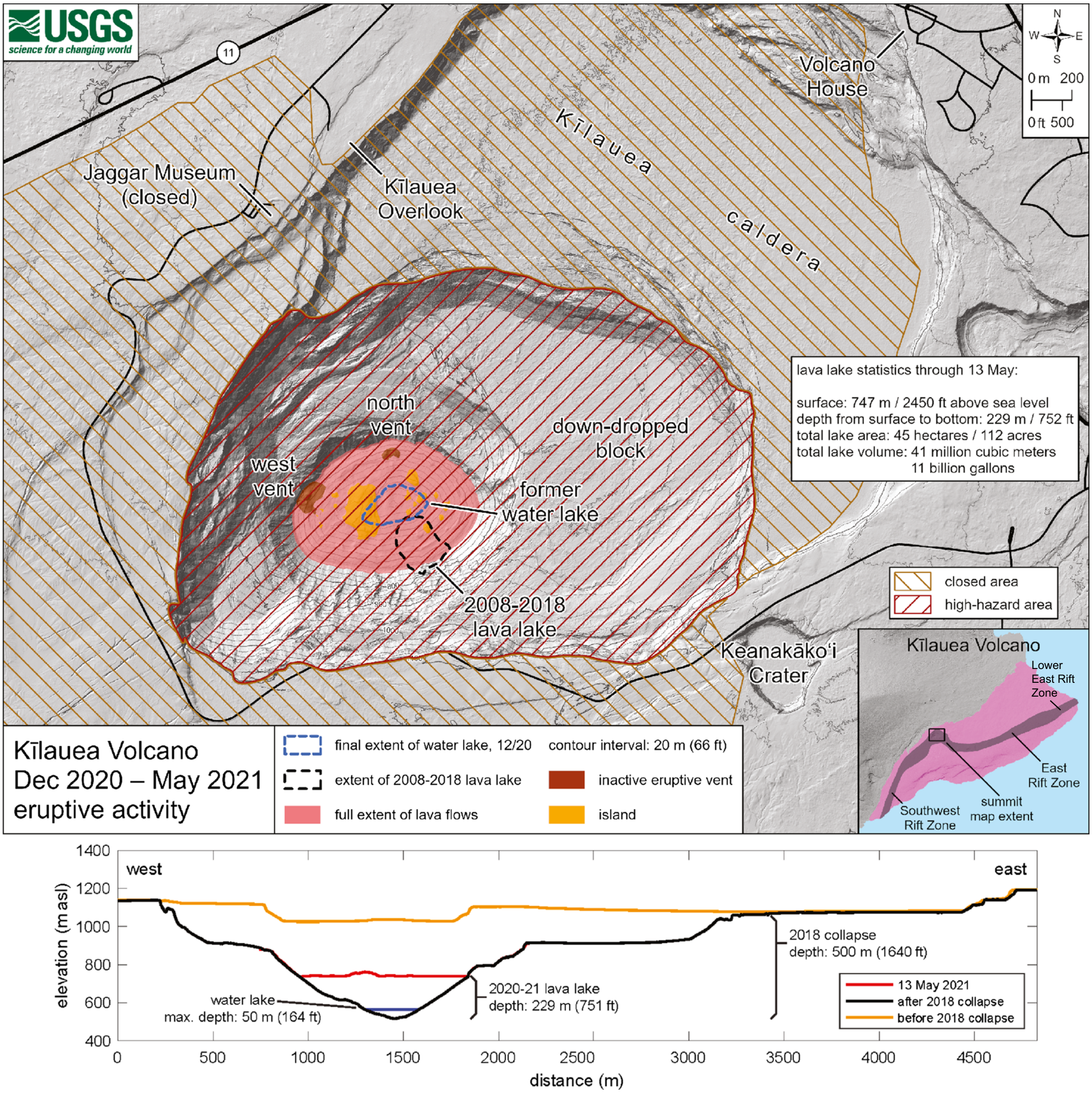

Fig. 1 Eruption site map, with areas of closures/access restrictions marked. This map of Halema`uma`u at the summit of Kīlauea shows 20 m (66 ft) contour lines (dark gray) that mark locations of equal elevation above sea level (asl). The map shows that the lava lake filled 229 m (752 ft) of the crater, to an elevation of 747 m (2450 ft) asl, from the beginning of the eruption on 20 December 2020, through 13 May 2021. The graphic at the bottom shows topographic profiles from west to east across the caldera before 2018, shortly after 2018, and as of May 13, 2021, along with the 2019–2020 Halema`uma`u water lake. The last activity on the lava lake surface was observed on 23 May. Polygons with diagonal ruling indicate the closed area within Hawai‘i Volcanoes National Park and the high-hazard area at the time the eruption began in December 2020. Map modified from the USGS website (https://www.usgs.gov/volcanoes/kilauea/december-2020-may-2021-eruption). Sources/usage: Public Domain

Volcanoes National Park. The lava lake surface remained hundreds of meters below the crater rim (Fig. 1) for the duration of the eruption and the paucity of tephra deposits from minor explosive activity at the onset of the eruption restricted the type of studies that could reasonably and safely be performed.

How the K-SAC was set up and its process

As soon as the Kīlauea 2020 eruption began, USGS and CONVERSE leadership recognized the opportunity to apply the SAC model in a real-world scenario. The goals of CONVERSE in this case were to facilitate communication and coordination of activities between HVO and non-observatory scientists and to broaden the participation of non-observatory scientists in the response. Within days of the start of the eruption, CONVERSE and USGS leaders met to discuss a SAC and criteria for the selection of committee members with diverse expertise, having more than one member from the USGS in order to distribute the workload, and avoiding possible scientific conflicts of interest. Based on these criteria, a SAC was set up consisting of seven members: three from the USGS and four from academia, with an additional USGS communications liaison (Table 1). Meetings of the Kīlauea SAC (K-SAC) began within a week of the start of the eruption. The primary functions of K-SAC were as follows:

1. Evaluate proposals for academic research activities that were time-sensitive and/or required coordination with HVO staff and provide recommendations to the HVO SIC, ideally in less than 48 h.
2. Facilitate communication and collaboration by compiling and sharing information about planned or ongoing research activities within the broader community.

These functions dictated K-SAC priorities during the eruption and provided a framework for the HVO SIC to evaluate research activities proposed by the academic community. K-SAC was envisioned to assist with evaluating projects that required access to closed areas or samples collected by the USGS, that involved HVO researchers, or that required National Park Service permits and/or allocation of HVO staff time, each of which required decisions made by the National Park Service, the land manager, and by the HVO SIC, respectively. A key point is that K-SAC's purpose was to facilitate coordination of scientific work between HVO and non-observatory scientists by providing advice to the HVO SIC as to whether proposed research was (i) time-sensitive (i.e., needed to happen during the course of the eruption), (ii) feasible given the constraints of the nature of the eruption, safety considerations, and access to closed areas, and (iii) likely to improve understanding of volcanic processes and eruptions and/or inform the ongoing eruption response. Research that did not require access to closed areas and that did not require the involvement of HVO scientists (e.g., remote sensing studies), did not need to go through the K-SAC process. Proposals to K-SAC that did not require the collection of time-sensitive data or samples were not prioritized, as they could be pursued after the eruption ended.

Coordinating the broader scientific community response was especially challenging at this time because Covid-19 policies put in place by the State of Hawaii (including a mandatory two-week quarantine period for people arriving in Hawaii) largely prevented outside partners from arriving to conduct their own research whether or not HVO helped to facilitate it. Thus, proposed research activities required a greater commitment of HVO time and resources than might otherwise have been the case. However, the modest number of requests for research activities and samples allowed the SAC to develop policies and procedures for operation while simultaneously facilitating research activities.

In addition to the primary functions listed above, K-SAC identified several activities that could help facilitate communication and coordination of efforts, including the following:

Table 1 Membership of the 2020–2021 Kīlauea Scientific Advisory Committee

Name	Affiliation	Notes
Kyle Anderson	USGS California Volcano Observatory	Rotated onto committee 2/2021
Kari Cooper	University of California Davis	Committee Chair 12/2020–8/2021; co-chair 8/2021–3/2022
Kathy Cashman	University of Oregon	Committee co-chair 8/2021-3/2022; Chair 3/2022 -present
Hannah Dietterich	USGS Alaska Volcano Observatory	
Bruce Houghton	University of Hawai'i Mānoa	
Ingrid Johanson	USGS Hawaiian Volcano Observatory	Rotated off committee 1/2021
Kendra Lynn	USGS Hawaiian Volcano Observatory	
Michael Manga	University of California Berkeley	
Christelle Wauthier	The Pennsylvania State University	

1. If HVO personnel identified a need for expertise or instrumentation beyond their current capabilities, K-SAC communicated that need to the broader community and facilitated collaborations.
2. K-SAC provided information to the broader community on access restrictions related to proposed activities (complexities regarding conducting research on National Park Service lands) and advised on alternative options to achieve scientific goals.
3. K-SAC worked on protocols for sample collection and access with input from the broader USGS and CONVERSE communities, resulting in USGS HVO implementing a "sample sharing agreement" for tracking and enhancing data sharing for distributed USGS samples in concordance with NPS rules for samples from NPS lands.
4. K-SAC made recommendations on how to improve operations for future SACs.

K-SAC was envisioned as the formal link between the academic scientific community and the USGS for the eruption ongoing at that time, but it continued to operate for Kīlauea's 2021–2022 eruption as well and it has now evolved into a broader Hawai‘i Scientific Advisory Committee (H-SAC) that is independent of a specific eruption.

K-SAC process

K-SAC advertised the process for submitting and evaluating proposals by posting information to the CONVERSE website, to the Volcano listserv (Volcano@lists.asu.edu), and by communication through individual professional networks. Information about proposal guidelines and evaluation criteria was posted on the CONVERSE website (Online Resource 1; Online Resource 3). A key point is that K-SAC's purpose was to facilitate the coordination of scientific work between USGS and non-observatory scientists. However, all decisions involving the use of USGS resources (including staff person-hours) were made by the HVO SIC, and the SAC had no authority or ability to fund projects. Thus, the K-SAC acted as a facilitator, gathering information to inform the SIC who was prioritizing limited HVO resources. Also, as noted above, scientific projects that did not require access to HVO resources or personnel did not need to go through the K-SAC proposal process, although K-SAC encouraged all scientists working on the eruption to provide information to the community about their projects in order to facilitate collaborations (see below).

Submission and evaluation of proposals to K-SAC followed a multi-step process (illustrated schematically in Fig. 2).

1) Interested scientists wrote a one-page proposal following the K-SAC guidelines and submitted it via email to the K-SAC Chair.
2) The Chair assigned at least three K-SAC members (including one USGS scientist and one non-USGS scientist) to review the proposal based on the following criteria (not listed in order of importance):

A. Potential to identify critical gaps in data collection or scientific response to advance volcano science.
B. Time-sensitivity of data/sample collection: does this project require data, samples, or analyses that must be completed on a time scale of weeks to months?
C. Direct contribution of the results to mitigating volcanic and related hazards to life and property, augmenting HVO work.
D. The likelihood of success (is the project feasible with the resources in hand? Is it likely to enhance hazard mitigation and/or volcano science?).
E. Familiarity of the PIs with logistics of and constraints on working on the island of Hawai‘i.
F. Ability to be performed without interfering with ongoing emergency response.
G. Safety of personnel in performing the work.
H. Identification of an HVO or other USGS collaborator, if applicable.

3) The K-SAC Chair compiled and summarized the feedback from reviewers, gathering additional information from proponents if needed.
4) The K-SAC Chair sent a packet consisting of the proposal, K-SAC summary, and reviews to the K-SAC USGS committee member who had reviewed it. This person then determined the feasibility of the work and whether there was an HVO staff member who was interested in collaborating and whether they had sufficient time available to do so.
5) If an HVO scientist agreed to support the project, the complete packet was sent to the HVO SIC, who determined whether the needed USGS resources could be allocated.
6) The SIC notified the K-SAC chair of the decision, and the K-SAC chair notified the proponents. Between December 2020 and February 2021, eight proposals were submitted to K-SAC, of which seven were ultimately approved by the HVO SIC (one proposal was not recommended to proceed due to lack of physical samples needed to conduct the research and significant overlap of the proposed project with work already in progress at HVO).

Another function of K-SAC—to facilitate longer-term collaboration by compiling and communicating information about research interests and activities—was addressed through several approaches. First, information was solicited from both HVO and external scientists about research activities and interests related to the eruption

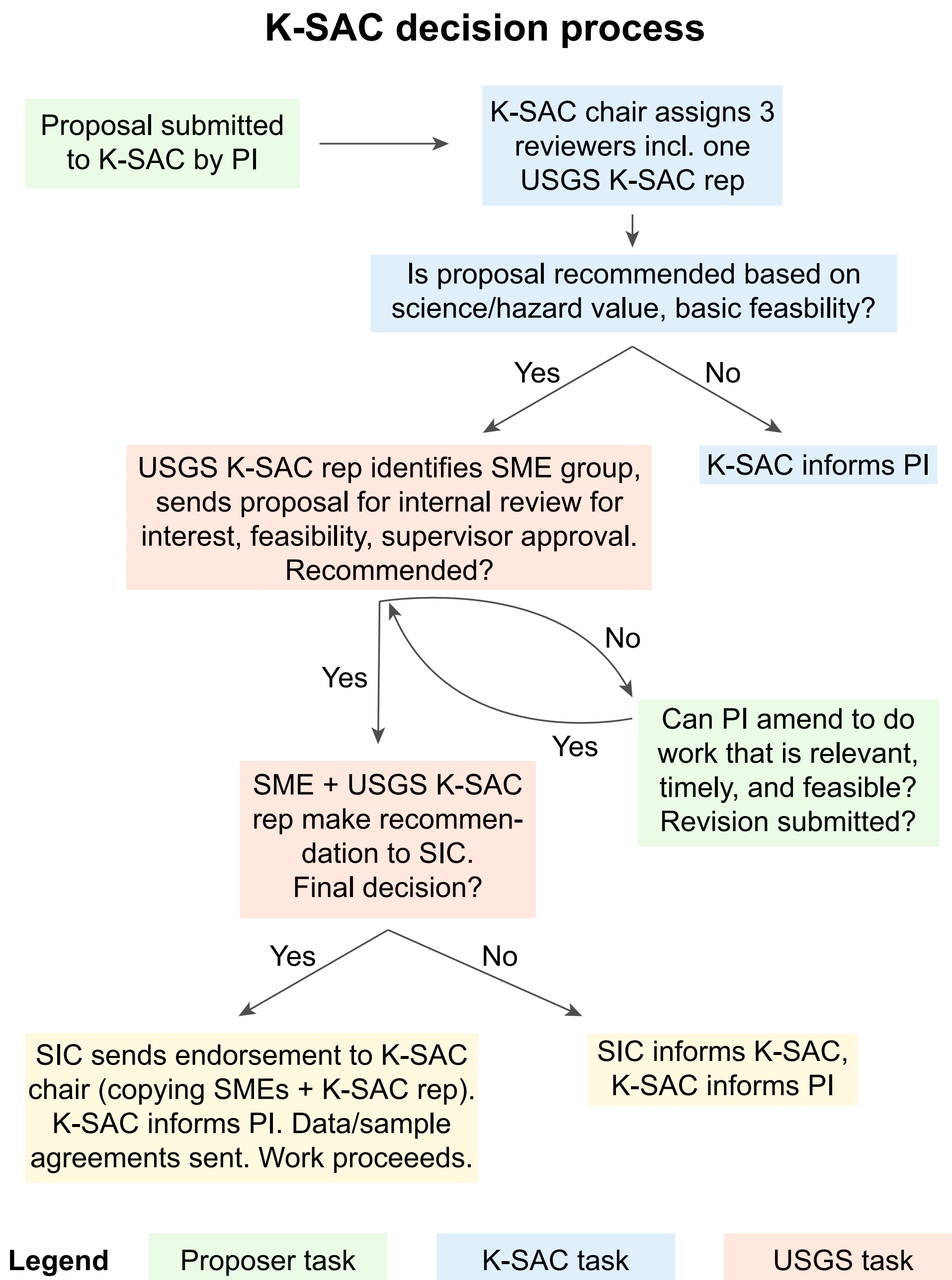

Fig. 2 Flow chart of the 2020 K-SAC proposal process, with boxes color-coded by role. This decision process evolved from the initial workflow for K-SAC committee approval of a proposal submitted by a primary investigator (PI) to incorporate the necessary USGS subject matter expert (SME) whose collaboration was needed for proposal success and approval by the USGS HVO Scientist-in-Charge (SIC). As proposals were reviewed, this workflow was also amended to reflect the need for revision of the initial proposal to incorporate any changes necessary for final approval. Online resources: documents outlining procedures and policies for K-SAC. OR_1, proposal guidelines and evaluation criteria; OR_2, proposal evaluation procedure; OR_3, proposal evaluation form used by K-SAC reviewers

and was compiled in a spreadsheet that was available on the CONVERSE website, which was updated as new information was received. Second, K-SAC members participated in several CONVERSE-run open-house events online, providing information to the broader science community about updates on the nature of the eruption and the status of access to closed areas and availability of samples and data. Third, an instant messaging workspace (Slack) was set up, and all interested scientists were invited to participate. Information about eruptive activity, datasets that were being collected and by whom, and activities such as open-house events were posted to the site, and it also provided a forum for scientists to communicate with each other about research and share plans and results.

The 2021–2022 Kīlauea eruption

In September 2021, Kīlauea provided a second opportunity to put K-SAC into practice. At approximately 3:30 pm HST on 29 September 2021, another summit eruption began in Halema` uma`u Crater with similar characteristics and limitations as the 2020–2021 eruption. The only physical samples that were available for study were of an initial basaltic pumice deposit on 29 September, as the eruption remained confined deep within Halema`uma`u Crater. Through the end of the eruption in December 2022, activity was confined to a lava lake on the floor of Halema`uma`u Crater. Nonetheless, K-SAC (reformulated as Hawaiʻi Scientific Advisory Committee, H-SAC) approved within 2 days of the request a sample-based proposal that was an extension of one that had been previously authorized by the SIC for the 2020–2021 eruption, using the same submission and evaluation process described above.

What worked well?

One of the goals of CONVERSE broadly, and K-SAC in particular, was to broaden the group of academic scientists involved in science during a volcanic eruption response. We feel that this goal was met during the 2020–2021 eruption response for two reasons: outreach to the broader community prior to the eruption and a proposal submission process that did not require previous contact with HVO scientists. For example, a relatively high proportion of proposals submitted (approximately half) were from early-career researchers, one of which became part of a successful NSF RAPID proposal. Through the online open house meetings and Slack channel, K-SAC's USGS representatives provided several timely updates and presentations of eruption progress and response. The resulting new connections between HVO and non-observatory scientists resulted in more collaborative work being done than would otherwise have been the case (see Rader et al. 2021). In addition, having designated USGS K-SAC members made it easier for HVO staff to communicate about K-SAC matters and largely avoided overwhelming observatory staff involved in eruption response activities with large numbers of outside inquiries.

The K-SAC developed a number of documents and materials for handling science requests and proposals, including those outlining procedures for proposal submission and review (Online Resources 1–3), and information about protocols for sample sharing and the process of requesting research permits from the National Park Service. The size of the committee and the diversity of expertise among committee members helped in evaluating and coordinating activities.

What were the limitations and challenges and how could these be addressed in the future?

Despite many successes, a number of challenges were encountered in the process of implementing the K-SAC model during the Kīlauea 2020–21 eruption. Four broad and interrelated areas of challenges remain and are described below:

1) The process of proposal submission, review, and decision-making was slow and would not have been effective during a faster-moving or larger-scale, more hazardous eruption such as, for example, the Kīlauea 2018 eruption or Mauna Loa 2022 eruption.
2) The goals of maximizing basic science during an eruption and of further broadening participation likely require activities and planning with USGS and non-observatory scientists that starts well before an eruption begins.
3) More could be done to help scientists identify priority scientific questions and propose activities that are practical, safe, and feasible given access restrictions and that respond to the changing nature of an eruption.
4) There is a sometimes difficult balance that must be maintained between providing information and advice to the SIC to help manage requests for science activities during an eruptive crisis on the one hand and the potential (or perceived potential) for this process to limit the science that can be accomplished during an eruption on the other hand.

In the following, we examine each of these challenges in more detail and provide some initial suggestions for changes that may improve the operation and utility of SACs. One of the main goals of CONVERSE and the SAC concept is to facilitate and promote science activities *during* an eruption response when conditions are often dynamic, hazards are present, and there are often demands on observatory staff to prioritize work that directly supports public safety. The rapidly evolving nature of many eruptions means that activities must move quickly to gather ephemeral data or deploy instrumentation to capture the entire event. The K-SAC goal was to finish the committee evaluation of proposals and to send information to the HVO SIC within 1 week of receipt, and the average turnaround time for the initial K-SAC review (from step 1 to step 5 above) was 6 days. However, once proposals were passed on to HVO, it was often difficult to move quickly through the rest of the approval process. One factor that impeded a quick resolution was that the K-SAC proposal process was designed to be open to those who did not have pre-existing collaborations with HVO staff. As a result, a significant amount of time and effort on the part of the USGS K-SAC member responsible for handling the proposal was needed in order to identify potential collaborators and for those collaborators subsequently to assess whether they had the time and interest to participate in the research. A second factor was that many proposals were not entirely feasible as written, requiring an additional amendment step in consultation with HVO staff and the USGS K-SAC member to adequately take into account the eruption conditions and available resources.

At best, this led to some new collaborative relationships, but at worst, it made HVO scientists feel pressured into collaborations that may not have been their priority given limited time available during a response. This was particularly challenging because public health measures in place during the Covid-19 pandemic meant that there was no opportunity for additional personnel to travel to the eruption site to assist, and all outside collaborations required HVO staff to conduct any necessary fieldwork. In addition, this proposal process required a final review and decision by the HVO SIC, which presented a bottleneck due to the many other demands on the SIC's time during the response. For the 2020–2021 eruption, this bottleneck was exacerbated by a change of SIC during the course of the eruption. As a result, some proposals were not approved rapidly enough to be implemented.

Based on our experience, it is clear that the two K-SAC goals of maximizing scientific return during an eruption response and of broadening participation in eruption response may be at odds during an eruptive crisis. In practice, pre-existing collaborative relationships tended to lead to more rapid science proposals and implementation. One solution that could help mitigate both of these challenges would be to conduct community-building efforts aimed both at broadening participation and seeding scientific collaborations during the time periods between eruptions. For example, CONVERSE and/or SACs could run community workshops aimed at building networks and facilitating scientific planning during non-eruptive periods. In order to make the scientific response more equitable and diverse, such workshops would need to be open to all researchers interested in conducting science during a volcanic eruption response and would likely require proactive efforts and financial resources to reach out to early-career scientists and scientists from underrepresented groups. Part of the goal of these workshops would be to make connections between USGS observatory scientists and those from other institutions around specific science goals and plans to be implemented during different styles and locations of eruptions. For example, developing lists of high-priority data and samples to be collected during eruptions (e.g., Wilson and Head 1981), preparing research plans in advance that outline specific research questions that could be addressed (contingent on the availability of necessary samples and/or data types for a particular eruption), and/or written agreements outlining some plans for instrument deployment and data gathering, could all be done between eruptions. Of course, observatory staff time is finite and not all potential collaborations can be supported, but a workshop model would offer the potential to make connections beyond what can be accomplished by individuals acting alone.

These community-building efforts would need to be tailored to account for the differing eruptive frequency and eruptive style characteristic of different regions, along with discussion of location-specific constraints such as remoteness or permitting processes. For example, developing specific research plans is likely to be effective in regions with frequent eruptions, such as Hawaii or Alaska, but in areas such as the Cascade Range, where eruptions may happen only once or twice per century, such plans are likely to become obsolete before they are ever implemented. More discussion among the US volcano observatory scientists and the broader scientific community is necessary in order to address these regional differences and to maximize scientific opportunities during an eruption. One possible approach in areas with less-frequent eruptions is to have SACs facilitate collaborative studies of past eruptions, evaluating knowledge gaps that could lead to more effective hazard assessment, volcano monitoring, and eruption forecasting. In the absence of eruptions, these data gaps could be the targets of collaborative research, building the community of interested and knowledgeable scientists in advance of eruptions.

An additional challenge both to effective scientific response and to rapid proposal evaluation in 2020–2021 was that not all proposed work was relevant (or even possible) given the way in which the eruption proceeded. During the 2020–2021 eruption, activity was confined to Halema`uma`u Crater and time-series sampling of lava from the lava lake and eruptive vents was impossible, ruling out a number of potential lines of scientific inquiry. Although frequent eruption updates and real-time monitoring data were presented on the HVO website and social media during the course of the eruption, in some cases, the level of detail was insufficient to assess the feasibility of scientific projects, and in other cases, PIs were not aware of how to access the necessary information.

In addition, the logistics of field access, permitting, and deployment combined with COVID-19 safety protocols precluded many projects or limited them to activities that HVO staff could do on an external researcher's behalf. A number of activities could mitigate this in future eruptions. For example, increasing the information shared with non-observatory researchers through additional activity updates or presentations/Q&A sessions like those run by K-SAC in 2020–2021 could provide more detailed and up-to-date information on which to base proposals. In addition, although it is unclear whose responsibility it should be to gather this information, outlining constraints on feasibility could encourage more realistic proposals from non-observatory researchers. Information on access/permit limitations (especially for eruptions located in national parks or monuments), field access, and HVO staff scientific expertise could be provided through these activity updates and/or through Slack or a similar platform. More broadly, creating some regional frequently asked questions (FAQ) documents for each area served by a SAC could be a way to convey information about permitting requirements and procedures, general information about access to different areas around the volcano, etc. and could be prepared in advance of an eruption. In addition, requiring specific information in the proposals (such as field sites, HVO staff needs, permitting status), and using an online form with required fields, would make the proposal review process more streamlined. Finally, the SAC could take a more active role in working with PIs during the early stages of the proposal review process to address some of the feasibility concerns before the proposals are evaluated by the observatories, which would also streamline the process.

A broader challenge concerns the role of the SAC in decision-making about what scientific projects may be conducted during an eruption response. From the observatory perspective, one of the primary advantages of a SAC (in addition to the overall goal of advancing volcano science) is to have a single point of contact for non-observatory scientists who would like to be involved in the science response. In addition, although it was less of a concern in the Kīlauea 2020–2021 eruption than in more significant volcanic crises in the recent past (e.g., Kīlauea 2018 eruption), another potential function of the SAC could be to reduce the workload for the SIC in reviewing requests for collaboration during a very demanding time. The SIC has the ultimate decision-making responsibility for science that will be supported by the observatory, but SACs can streamline this process by providing information and expert opinions to the SIC about proposal feasibility and potential scientific gains. Balanced against the needs of the SIC to have assistance managing proposals by non-observatory scientists are the goals of CONVERSE and the SAC to facilitate as much science as possible. In addition, SAC members do not make decisions beyond the committee's authority—during an eruption response the SIC authorizes decisions about the deployment of USGS resources, but the incident command structure (if in place) or land manager makes decisions about access to the eruption site. How best to handle this challenge of structuring a SAC that can facilitate science activities within the bounds of the decision-making structure requires more discussion between USGS and CONVERSE leadership. Some options to consider would be for the SIC to empower the SAC to make some types of decisions regarding prioritizing science goals and activities, and/or for the SIC to designate an alternate individual within the observatory to make decisions about SAC proposals. For instance, a senior USGS researcher could have this authority, because they would be likely to have the expertise both in the scientific and operational realms to make these decisions.

Beyond these broad challenges, some other insights were gained during the K-SAC process. For example, although we did not develop a formal conflict of interest (COI) policy for the committee in 2020–2021, this will be important for future success because those scientists with the most relevant knowledge for serving on a SAC are often the same scientists involved in science activities related to the eruption. Having members drawn from the broader community of people with research interests in the erupting volcanic system (in this case, Kīlauea) but whose research does not require data collection during the actual eruption and/or access to the eruption while in progress would be beneficial, though other models are possible. During the 2020–2021 response, the informal COI policy was that K-SAC members from outside the USGS were expected not to engage directly in research activities on that eruption during the response. In addition, for the USGS K-SAC members, it was useful to have several members to distribute the workload of SAC-related tasks that required USGS personnel and to have those members not all be from HVO so that not all of them were involved in the day-to-day response efforts. Other conflicts of interest are possible (and even likely, given the small size of the volcano science community); therefore, it is important to develop explicit COI policies for SACs in the future. For example, if a conflict of interest were to arise during a new crisis—such as a SAC committee member becoming involved in a related National Science Foundation RAPID proposal—an alternate member could be called upon to temporarily join the committee to replace the conflicted member. A list of such alternate members would need to be identified during the staffing of the SAC.

Finally, implementing the SAC structure for volcanoes across the USA will likely require multiple committees because no single SAC can be expected to have the regional expertise necessary and because different USGS volcano observatories are responsible for different areas. Furthermore, as discussed above, the differing eruptive frequency and style together with differing access and logistical restrictions between regions means that SACs would need to tailor their approach and operations to each region. Rather than forming a SAC for each eruption, these regional SACs could be in operation continuously, coordinating scientific efforts during eruptions and coordinating planning and community-building during non-eruptive times. In addition, the focus of each SAC might vary from region to region: areas with more frequent eruptions (Hawaii, Alaska) could have SACs that spend relatively more time coordinating scientific efforts during eruption responses, whereas areas with infrequent eruptions (e.g. Cascade Range, Yellowstone Caldera) might have SACs that are focused more on community-building and seeding research collaborations that would contribute information to future eruption response.

Some observatories in the USA (e.g., the Alaska and Yellowstone Volcano Observatories) already have annual review and planning meetings that SAC representatives could join on behalf of the larger science community. In some ways, this planning between eruptions is even more important in areas with infrequent eruptions, because fewer people are familiar with the important science questions and the logistics and challenges associated with response to eruptions in these areas. Assuming that eventually multiple SACs are in operation across the country, they will be most effective if there is a structure that fosters information exchange among them and if general policies are developed that are consistent across all SACs but which can be tailored in detail to local conditions. Such information transfer and consistency of approach could be aided by having regular meetings and workshops involving multiple SACs and encouraging members of SACs to rotate through different SACs over time.

Although this article has focused on insights about the SAC concept as applied in the USA based on our experience in Hawaii, many of the observations could be relevant to maximizing scientific gains from volcano response efforts at volcanoes worldwide. For example, the overarching goal of maximizing science during eruptions is broadly relevant, and the need to collect diverse data and samples to facilitate scientific studies applies to any volcanic eruption. Volcano science is a global field, and scientific advances from studies in one location will inevitably lead to a greater understanding of volcanic systems in general. Furthermore, we suggest that diverse groups of people who have pre-existing trusting relationships are most effective at coordinating science during a crisis and that this concept applies globally, although cultural differences will certainly affect the ways in which each community develops and how it is structured. Common elements necessary for the most effective scientific response include having a decision-making structure for eruption science that is viewed as objective and open, and in which the decision-makers take into account the local conditions, threats to life and property, investigator safety, access restrictions, and regulations or laws governing response in different countries. Most importantly, we argue that building community and connections between scientists prior to an eruption will be key regardless of where the eruption occurs. Whether the SAC concept will be useful elsewhere depends on the nature (or existence) of a region's volcano observatory and emergency response structure. It may be useful to have discussions or workshops where information and approaches can be compared across countries, perhaps facilitated by international scientific organizations such as IAVCEI, EGU, or AGU. The more the global volcano science community can learn from each eruption, the more rapidly the science will advance, leading to a greater understanding of volcanic phenomena, to more effective eruption response efforts, and to reduced societal risk in the face of volcano hazards.

Summary

As demonstrated by the Kīlauea 2020–2021 eruption, the facilitation of science between observatories and non-observatory scientists by a Scientific Advisory Committee (SAC) has the potential to maximize science and critical data collection during an eruption response. The 2020–2021 Kīlauea SAC applied lessons from the 2018 Kīlauea response and provides a foundation for future efforts. In order to be most effective, planning and community-building must occur well before an eruption begins. Informative and timely communication from observatory responders to the interested scientific community regarding the situation on the ground is needed in order for non-observatory scientists to effectively contribute to any given eruption response. In addition, more inter-eruption discussion between the broader scientific community and volcano observatories is needed to refine the goals and mandates of SACs so that these committees will meet the shared and disparate needs of both. Fortunately, all of these objectives are eminently possible, as long as there is sufficient support, resources, and long-term commitment to do so. Such efforts would also benefit from sharing information and approaches among the broader global volcano science community. Continuing to improve the volcano science community's effectiveness in maximizing the scientific gains from future eruptions will have long-term benefits to both science and society.

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Declarations

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References

Anderson KR, Johanson IA, Patrick MR, Gu M, Segall P, Poland MP, Montgomery-Brown EK, Miklius A (2019) Magma reservoir failure and the onset of caldera collapse at Kīlauea Volcano in 2018. Science 366(6470):eaaz1822. https://doi.org/10.1126/science.aaz1822

Fischer TP SC, Moran KM, Cooper DC, Roman, LaFemina PC (2021) Making the most of volcanic eruption responses, Eos, 102, https://doi.org/10.1029/2021EO162790

Fiske RS (1984) Volcanologists, journalists, and the concerned local public: a tale of two crises in the Eastern Caribbean. Explosive volcanism: inception, evolution and hazards. National Academies Press, Studies in Geophysics, pp 170–176

Gansecki C, Lee RL, Shea T, Lundblad SP, Hon K, Parcheta C (2019) The tangled tale of Kīlauea's 2018 eruption as told by geochemical monitoring. Science 366(6470). https://doi.org/10.1126/science.aaz0147

Lipman PW and Mullineaux DR (1981) The 1980 eruptions of Mount St. Helens, Washington. USGS Prof Pap 1250, US Government Printing Office, Washington DC, pp 844. https://doi.org/10.3133/pp1250

Lowenstern JB, Ewert JW, Lockhart AB (2022) Strengthening local volcano observatories through global collaborations. Bull Volcanol 84:10. https://doi.org/10.1007/s00445-021-01512-w

Major JJ, Janda RJ, Daag AS (1996) Watershed disturbance and lahars on the east side of Mount Pinatubo during the mid-June 1991 eruptions. In: Newhall CG, Punongbayan RS (eds) Fire and Mud: Eruptions and Lahars of Mount Pinatubo. University of Washington Press, pp 895–919

Marrero JM, García A, Llinares Á, Berrocoso M, Ortiz R (2015) Legal framework and scientific responsibilities during volcanic crises: the case of the El Hierro eruption (2011–2014). J Appl Volcanol 4(1):13. https://doi.org/10.1186/s13617-015-0028-8

Matoza RS, Fee D, Assink JD, Iezzi AM, Green DN, Kim K, Toney L, Lecocq T, Krishnamoorthy S, Lalande J-M, Nishida K, Gee KL, Haney MM, Ortiz HD, Brissaud Q, Martire L, Rolland L, Vergados P, Nippress A, Park J, Shani-Kadmiel S, Witsil A, Arrowsmith S, Caudron C, Watada S, Perttu AB, Taisne B, Mialle P, Pichon AL, Vergoz J, Hupe P, Blom PS, Waxler R, Angelis SD, Snively JB, Ringler AT, Anthony RE, Jolly AD, Kilgour G, Averbuch G, Ripepe M, Ichihara M, Arciniega-Ceballos A, Astafyeva E, Ceranna L, Cevuard S, Che I-Y, Negri RD, Ebeling CW, Evers LG, Franco-Marin LE, Gabrielson TB, Hafner K, Harrison RG, Komjathy A, Lacanna G, Lyons J, Macpherson KA, Marchetti E, McKee KF, Mellors RJ, Mendo-Pérez G, Mikesell TD, Munaibari E, Oyola-Merced M, Park I, Pilger C, Ramos C, Ruiz MC, Sabatini R, Schwaiger HF, Tailpied D, Talmadge C, Vidot J, Webster J, Wilson DC (2022) Atmospheric waves and global seismoacoustic observations of the January 2022 Hunga eruption. Tonga Science 377(6601):95–100. https://doi.org/10.1126/science.abo7063

Miller CD, Mullineaux DR, Crandell DR (1981) Hazards assessments at Mount St. Helens. In: Lipman PW, Mullineaux DR (eds) The 1980 Eruptions of Mount St Helens, Washington, USGS Prof Pap 1250, U.S. Government Printing Office, Washington, DC, pp 789–802

Minnis P, Harrison EF, Stowe LL, Gibson GG, Denn FM, Doelling DR, Smith WL Jr (1993) Radiative climate forcing by the Mount Pinatubo eruption. Science 259(5100):1411–1415

Namiki A, Patrick MR, Manga M, Houghton BF (2021) Brittle fragmentation by rapid gas separation in a Hawaiian fountain. Nat Geosci 14(4):242–247

National Academies of Sciences Engineering and Medicine, (2017) Volcanic eruptions and their repose, unrest, precursors, and timing. The National Academies Press, Washington, DC, p 170

Neal CA, Brantley SR, Antolik L, Babb JL, Burgess M, Calles K, Cappos M, Chang JC, Conway S, Desmither L, Dotray P, Elias T, Fukunaga P, Fuke S, Johanson IA, Kamibayashi K, Kauahikaua J, Lee RL, Pekalib S, Miklius A, Million W, Moniz CJ, Nadeau PA, Okubo P, Parcheta C, Patrick MR, Shiro B, Swanson DA, Tollett W, Trusdell F, Younger EF, Zoeller MH, Montgomery-Brown EK, Anderson KR, Poland MP, Ball JL, Bard J, Coombs M, Dietterich HR, Kern C, Thelen WA, Cervelli PF, Orr T, Houghton BF, Gansecki C, Hazlett R, Lundgren P, Diefenbach AK, Lerner AH, Waite G, Kelly P, Clor L, Werner C, Mulliken K, Fisher G, Damby D (2019) The 2018 rift eruption and summit collapse of Kīlauea Volcano. Science 363(6425):367–374. https://doi.org/10.1126/science.aav7046

Nelson D (1980) Monitoring nature's big blow-up. Dartmouth alumni magazine 74:48–49. https://archive.dartmouthalumnimagazine.com/article/1980/9/monitoring-natures-big-blow-up

Newhall C (1999) Professional conduct of scientists during volcanic crises. Bull Volcanol 60:323–334. https://doi.org/10.1007/PL00008908

Patrick MR, Dietterich HR, Lyons JJ, Diefenbach AK, Parcheta C, Anderson KR, Namiki A, Sumita I, Shiro B, Kauahikaua JP (2019) Cyclic lava effusion during the 2018 eruption of Kīlauea Volcano. Science 366(6470). https://doi.org/10.1126/science.aay9070

Patrick M, Johanson I, Shea T et al (2020) The historic events at Kīlauea Volcano in 2018: summit collapse, rift zone eruption, and Mw 6.9 earthquake: preface to the special issue. Bull Volcanol 82(6):46. https://doi.org/10.1007/s00445-020-01377-5

Rader E, Forsberg E, Baker L (2021) Beyond thermal: VNIR imaging of molten basalt at the Halema'uma'u lava lake, HI. In AGU Fall Meeting, New Orleans, LA, pp 13–17

Saarinen TF, Sell JL (1985) Warning and response to the Mount St. Albany, State University of New York Press, Helens eruption, p 240

Sherrod DR, Scott WE, Stauffer PH (eds) (2008) A volcano rekindled: the renewed eruption of Mount St. Helens, 2004–2006. USGS Prof Pap 1750, p 856

Solana MC, Calvari S, Kilburn CRJ, Gutierrez H, Chester D, Duncan A (2018) Supporting the development of procedures for communications during volcanic emergencies: lessons learnt from the Canary Islands (Spain) and Etna and Stromboli (Italy). In: Fearnley CJ, Bird DK, Haynes K, McGuire WJ, Jolly G (eds) Observing the Volcano World: Volcano Crisis Communication. Springer International Publishing, Cham, pp 289–305

Wadge G, Aspinall W (2014) A review of volcanic hazard and risk assessments at the Soufrière Hills Volcano, Montserrat from 1997 to 2011. In: Wadge G, Robertson REA, Voight B (eds) The Eruption of Soufriere Hills VolcanoMontserrat from 1997 to 2011. Geological Society, London, Memoirs 39(1):439–456. https://doi.org/10.1144/M39.24

West S (1980) The right to research. Science News 118:61–62. https://www.sciencenews.org/archive/right-research

Williams DM, Avery VF, Coombs ML, Cox DA, Horwitz LR, McBride SK, McClymont RJ, Moran SC (2020) U.S. Geological Survey 2018 Kīlauea Volcano eruption response in Hawai'i—After-action review: US Geological Survey Open-File Report 2020-1041, 56 p. https://pubs.er.usgs.gov/publication/ofr20201041

Wilson L, Head JW (1981) Morphology and rheology of pyroclastic flows and their deposits, and guidelines for future observations. In: Lipman PW, Mullineaux DR (eds) The 1980 Eruptions of Mount St. Helens, Washington, USGS Prof Pap 1250. US Government Printing Office, Washington, DC, pp 513–524