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Lessons learned from the 2022 CONVERSE Monogenetic Volcanism Response Scenario Exercise

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Abstract

When volcanic unrest occurs the scientific community can advance fundamental understanding of volcanic systems, but only with coordination before, during, and after the event across academic and governmental agencies. To develop a coordinated response plan, the Community Network for Volcanic Eruption Response (CONVERSE) orchestrated a scenario exercise centered around a hypothetical volcanic crisis in Arizona's San Francisco Volcanic Field (SFVF) in the United States. The exercise ran virtually from February 4 to March 4, 2022 through asynchronous updates, community forums for online discussion, and synchronous virtual meetings. Over 60 scientists from both academic and governmental spheres participated. The scenario exercise was assessed for its effectiveness in supporting collaborative production of knowledge, catalyzing transdisciplinary collaboration, supporting researcher confidence, and fostering a culture of inclusion within the volcanology community. This identified a need to support early career researchers through community and allyship. Overall, the 2022 CONVERSE exercise demonstrated how a fully remote, extended, USA-based scenario can be authentically implemented and help broaden participation within a volcano science community.

Keywords: Scientific coordination; Early career researchers; Converse; Eruption scenario exercise; Monogenetic volcanic field.

1 Introduction

One of the three Grand Challenges outlined by the 2017 report by the National Academy of Science regarding volcanic eruption was to "develop a coordinated volcano science community to maximize scientific returns from any volcanic event" [Manga et al. 2017]. In response to that challenge, US-based scientists initiated a research coordination network titled Community Network for Volcanic Eruption Response (CONVERSE), with funding from the National Science Foundation. The network set out to maximize the scientific return from response to volcanic unrest and eruption through improving the coordination between volcanologists in various disciplines, in academia and in the United States Geological Survey (USGS). One goal of the current paper is to describe lessons-learned during this and previous CONVERSE activities, which may be useful to the global community of volcano scientists. In 2019, CONVERSE hosted workshops focused on the various disciplines (e.g. seismology, geodesy, modeling). In October 2020, CONVERSE held a scenario exercise that simulated an eruption Mount Hood, located in Oregon, USA, in the Cascade Range [Fischer et al. 2021].

One important outcome of the Mount Hood exercise was the concept of the Scientific Advisory Committee (SAC). The SAC role is to serve as the link between scientists in academia and the USGS in a transparent and equitable way. During crises, communication can be severely hindered, with USGS scientists occupied with response efforts and unable to respond to outside inquiries. Yet, many academic scientists are eager to gain access to the eruption site to ensure specific data are being collected. The SAC model was established to answer these needs. SACs are regional and unrest-specific, comprised of established scientists who are familiar with the area, as well as a representative from the USGS network of volcano observatories. Once an SAC is established (for example, through appointment by the scientist-in-charge at the local observatory, through a public nomination process, or through volunteering), scientists are encouraged to submit requests to the SAC to operate within the restricted areas or in the region of unrest, or to submit requests for samples and sample sharing. The SAC evaluates these requests, communicates with observatory scientists, and provides guidance on how to accommodate research requests and promotes coordination amongst those who wish to take part in the response efforts. An example of this process is depicted in the supplement (Supplementary Material 1) for the K-SAC, which was the scientific advisory committee established in response to the Kīlauea 2020 eruption [Cooper et al. 2023].

The 2022 scenario exercise organized by CONVERSE focused on unrest and an eruption in a monogenetic volcanic field in the southwestern US. Monogenetic volcanic fields are

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areas that contain tens to thousands of small volcanoes, each of which formed during a single eruptive episode [e.g. Connor et al. 2000; Németh and Kereszturi 2015]. This exercise was intentionally designed to take place virtually over a full month, relying on tools such as an online team messaging forum that allows for group and individual messaging, video conferencing, and a cloud-based drive for document storage. Given the new modality of the workshop, and the wide participation of the volcanology community within the workshop, we assessed the workshop for its effectiveness in co-generating knowledge, catalyzing transdisciplinary collaboration, supporting research confidence, and fostering a culture of inclusion within the volcanology community. In this paper, we focus especially on the experiences of early career researchers (ECRs). ECRs both had the most to gain from participating in an exercise like this, and also faced increased challenges compared to their more-senior colleagues. While there are many metrics to define an ECR, we included perspectives from anyone who self-identified as an ECR.

The organization of this paper is as follows: we provide the context for CONVERSE exercises from a scientific and societal point of view (Section 1.1–Section 1.3), describe the Distributed Volcanism scenario from the perspective of the magmatic and volcanic activity (Section 2), detail the activities that comprised the exercises (Section 3), and then present the methodology we use to assess the exercise (Section 4). The outcomes and findings from the scenario exercise are presented in Section 5. We follow with recommendations and lessons learned (Section 6), and end with conclusions in Section 7.

1.1 Geologic setting

The hypothetical unrest and eruption at the center of the 2022 CONVERSE scenario took place at a monogenetic volcanic field in the southwestern US. Monogenetic volcanism refers to volcanic fields that contain tens to thousands of small volcanoes, each of which formed during a single eruptive episode [e.g. Connor et al. 2000; Németh and Kereszturi 2015]. There are monogenetic volcanic fields all around the world, in every tectonic setting. One famous example of such a monogenetic vent is Parícutin, which formed in 1943 and is part of the Michoacán–Guanajuato volcanic field in Mexico.

Monogenetic volcanism often occurs in volcanic fields where volcanism is distributed over an area. The fundamental challenge in forecasting eruptions in such fields is that new volcanoes erupt at new locations within the volcanic field, sometimes tens of kilometers away from the locations of previous eruptions [Condit et al. 1989; Connor et al. 2012; Le Corvec et al. 2013]. This means that scientists must forecast not only when an eruption may occur and how large the eruption might be, but also where the eruption will occur. Furthermore, the relatively low recurrence rates of unrest and volcanic activity in monogenetic fields leads to low awareness of the hazards in nearby communities and to relatively little experience in forecasting of or in responding to unrest in such areas [e.g. Gregg et al. 2004]. Thus, it is paramount that the volcanology community practice scenarios of unrest and eruption in both central vent volcanoes that repeatedly erupt over very long periods of time, and in monogenetic volcanic fields, as captured by the 2020–2022 sequence of CONVERSE exercises.

1.2 Societal setting

In addition to the complexity introduced by the uncertainty in eruption location, monogenetic volcanic fields are often, in contrast with large volcanic centers, not included in an all-encompassing national or regional park. It is not uncommon for monogenetic fields to cover areas that are controlled by many different government agencies and private entities. For instance, the area of the San Francisco volcanic field, which was the site for this exercise (see Figure 1), includes national monuments (controlled by the National Park Service, a bureau of the US Department of the Interior), national forests (controlled by the US Forest Service), tribal lands (Hopi Tribe and Navajo Nation), wilderness areas (controlled by the US Department of Agriculture), private entities (e.g. mines), and the City of Flagstaff itself. This variety of controlling bodies presents a challenge with respect to preparedness for a natural hazard event and for coordinating the response. In the event of a real crisis, an Incident Command System (ICS) would likely be established, following the National Incident Management System (NIMS) doctrine as defined by the Federal Emergency Management Agency [FEMA 2017]. The ICS will coordinate the response efforts by the relevant agencies and land managers. In the context of a scientific response effort, installation of monitoring equipment may require scientists to seek permissions from many different entities. On the other hand, such activity in an area that is not a designated national park may be simpler, due to fewer restrictions. For example, the usage of unoccupied aerial systems (UAS, or 'drones') is not permitted in US national parks, national monuments, or wilderness areas, but is allowed in national forests managed by the the US Forest Service and lands managed by the Bureau of Land Management [The National Park Service 2014; National Forest Service 2023].

A scientific response to eruptions in such areas may be complicated by public unresponsiveness and misinformation. The risk perception of communities near areas that do not look like a classic "volcano" (i.e. a large volcanic cone), and that have not been active recently, may also be that the likelihood of eruption is extremely low [Gregg et al. 2004; Becerril et al. 2021].

1.3 Convergence research

Volcanic unrest provides an opportunity to further the framework of convergence research. Convergence research is defined by two main characteristics: 1) research that focuses on a specific, complex, societally relevant problem, and 2) research that fosters deep integration not only between academic disciplines, but also across multiple knowledge communities both within and outside of academia [NSF 2018]. In conducting convergence research, teams must also transcend organizational boundaries in addition to disciplinary boundaries [Peek et al. 2020].

Scenarios are a useful way to better understand and plan for an uncertain future [Preuss and Godfrey 2006; Amer et al. 2013; Wilkinson et al. 2013]. A fully defined scenario includes the hazard event and its specific impacts to the community, and incorporates the interests of a wide range of stakeholders [Preuss and Godfrey 2006], though methods differ in a variety of ways, from how they are planned, to whom they involve. In the development of a scenario, one goal is that experts across a range of disciplines and sectors have the opportunity to come together to describe a single event from multiple lenses and uncover complexities that would not have been readily apparent through any single perspective. The scenario can also serve to challenge assumptions that are considered typical in any single discipline.

Prior to both 2019 and 2022 CONVERSE exercises, scenario and exercise development within volcanology has been undertaken globally in varying contexts. In 2015, Dohaney et al. developed a training scenario in crisis communication and volcano in eruption forecasting. The premise of the scenario was in line with what was developed by CONVERSE; the focus was on the design and evaluation of an authentic role-play simulation [Dohaney et al. 2015]. Dohaney et al.'s scenario diverged from CONVERSE in Dohaney et al.'s involvement of emergency management and a focus on emergency response, in addition to the focus on the roles of volcanologists. In another example, Deligne et al. explored what can happen to a major city with a volcanic eruption within city boundaries [Deligne et al. 2017]. Their scenario focuses heavily on the development of the hypothetical situation, rather than response.

In monitoring and responding to volcanic unrest, government agencies and academics must work together both to investigate scientific questions and to communicate with the general public about potential risks and recommended protective actions. At the moment of a real-life event, it is often too late to establish such coordination, which relies on trust and information sharing between individuals [Newhall 2017]. Scenario exercises provide the opportunity to practice not only what to do in the event of volcanic activity, but also the opportunity to establish personal connections and build trust between individuals who would be involved in a real-life event [Hicks et al. 2014]. This has been demonstrated in previous scenario studies, which emphasize the role that a scenario can play in providing the opportunity for different sectors and disciplines to communicate and build trust [Hayes et al. 2020]. Beyond the scenario exercise itself, CONVERSE as a network serves to build these connections across organizations and sectors. Therefore, in designing the 2022 CONVERSE scenario as a convergent exercise, one guiding principle was to provide opportunities to develop trust and personal connections between different sectors and individuals participating in the scenario.

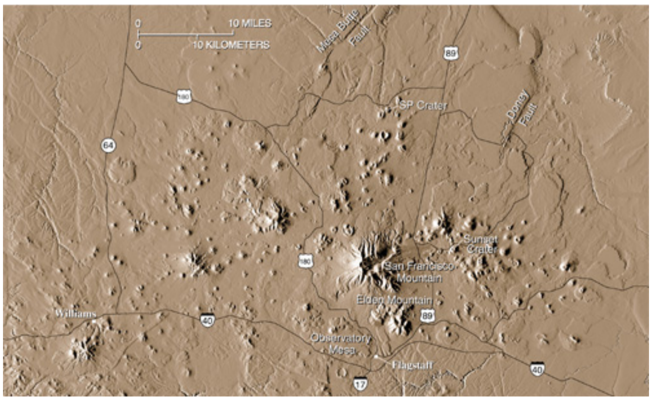

Figure 1: A digital elevation map of San Francisco Volcanic Field, the volcanic field of interest for the 2022 CONVERSE scenario exercise. Credit: U.S. Geological Survey [Priest et al. 2001].

2 Scenario description

The 2022 CONVERSE exercise simulated a scenario of volcanic unrest and eruption at the San Francisco Volcanic Field (SFVF) in northern Arizona (Figure 1). With close to 600 vents, the SFVF is considered to be one of the most frequently active monogenetic volcanic fields in the western continental United States. Volcanism in the SFVF is clustered, and these clusters have been active in different, overlapping periods over time [Conway et al. 1998]. Generally, volcanism is thought to have migrated from west to east. However, sparse radiometric age determinations indicate that this overall pattern of volcanic activity is more nuanced. The eastern part of the volcanic field is more active than the central part of the field, but there is not a monotonic migration of volcanism from west to east [Tanaka et al. 1986].

The most recent eruption in the entire volcanic field is the 1050 CE eruption of Sunset Crater. This eruption occurred near the center of the youngest cluster of volcanoes in the SFVF. Sunset Crater was a complex event, with an early 10-km-long NW-trending fissure system with multiple, briefly active eruptive vents. Hazards associated with this eruption include several lava flows and notable extent (25–35 lateral km) of tephra [Alfano et al. 2019]. This fissure system is within an older, NW-trending alignment of vents, along which dikes have intruded repeatedly [Alfano et al. 2019]. The scenario places the hypothetical activity along this alignment as well.

The scenario was divided into three stages. In the preliminary stage, the volcanic field exhibited unrest. In Phase 1, modelled after the SRVF, included dike intrusions. Stage 2 is when the magma erupts and forms a cinder cone. Stage 3 was the main eruptive stage. The early stages of the scenario included an intrusion that did not immediately lead to eruption. Since such intrusions are not currently exposed at the SFVF, we modeled the activity during these early phases after intrusions exposed at a neighboring volcanic field, the San Rafael Volcanic Field (SRVF) in Utah, which is similar to the SFVF, but more deeply eroded. The SRVF includes more than 6000 dikes and dike segments, as well as numerous sills and conduits. Specifically, the Frying Pan Sill area of the SRVF is used as the basis for this scenario. This dike, sill, and conduit system represents a relatively simple sequence of events compared to others in the San Rafael area, but includes a wide range of processes [Delaney and Gartner 1997; Richardson et al. 2015].

The scenario was divided into three stages: (1) dike injection without eruption; (2) dike injection with sill development, followed by small spatter cone eruptions; (3) renewed dike injection, followed by conduit localization and a sustained eruption, ramping up to explosive—Volcanic Explosivity Index (VEI) 3—activity and then evolving to effusion of a large volume (1 km^3) lava flow. The stages are depicted in Figure 2. The explosive activity is modeled after the violent Strombolian phase of the Sunset Crater eruption [Alfano et al. 2019]. While large volume (e.g. 1 km^3) lava flows are rare in the SFVF, they have occurred (e.g. the eruption of the Sproul and other centers [Moore and Wolfe 1987; Hanson 2007]). Lava flows did occur during the Sunset Crater eruption but were of smaller volumes [Alfano et al. 2019]. Figure 3 displays a map with the main features of the scenario, including dikes, vents, tephra and lava deposits. The City of Flagstaff, Arizona, is visible on the map as well.

Prior to the first stage, a seismic swarm was reported by the organizers to the participants. At that point, scientists couldn't tell if the origin of this swarm is tectonic or volcanic. The Yellowstone Volcano Observatory (YVO), which is responsible within the USGS for the area of the SFVF, issued a map showing the hypocenters of the earthquakes. Measurements of CO_2 did not detect any emissions above background levels, and there was no ground deformation detectable by Interferometric Synthetic Aperture Radar (InSAR). This preliminary phase took place during the first week of the exercise (February 7–13).

Stage 1: The second week of the exercise was when the first stage, a non-eruptive dike intrusion, took place. This stage included an injection of a series of dikes northwest of Sunset Crater. A hypocenter map shared with the participants (Figure 4) showed that the earthquakes migrated from a depth of approximately 9 km to 3 km below the surface. Ground deformation associated with this dike intrusion was reported to the participants through motion of a permanent GNSS station located at Sunset Crater and an interferogram showing a "butterfly wings" lobe pattern (see Figure 7). This pattern is typical of dike events, where the two lobes composing the "wings" of the butterfly are the result of dike-perpendicular opening at depth, with ground moving in opposite directions either side of the dike [Grandin et al. 2010], as is also observed for earthquakes due to the double couple nature of seismic sources [Fialko 2004; Fialko et al. 2005]. The exact locations of the dikes themselves was known only to the organizers.

Stage 2: After a short hiatus, the activity transitioned to Stage 2, which coincided with the beginning of the third week of the exercise. More dikes were injected, a large sill formed, and a small cinder cone erupted. Dimensions of the dikes and the sill were modeled after the components of the Frying Pan Sill complex [Germa et al. 2020]. Up to the point of the cinder cone eruption, the exact position of the dikes was known only to the organizers, and left to be interpreted by the participants based on the observation data that were shared with them. With the magma nearing the surface, more observations became available. Participants requested specific types of data that they were "collecting," and the "Oracle" (the organizers) provided what was deemed realistic to have been collected in a real eruption situation. These included: photos of ground cracks along the trace of the intruding dikes (made by adding cracks to photos of the Sunset Crater area forest roads and using images of cracked roads from the Kīlauea 2018 eruption), InSAR interferograms and GNSS vectors documenting the associated ground motion (generated through forward models of surface displacement resulting from dike intrusions, using analytical solutions for tensile dislocations in an elastic half-space [Okada 1985] available through `dMODELS` [Battaglia et al. 2013] with exponential noise added to simulate atmospheric artifacts present in InSAR data), satellite measurements of heat flux (made by adding a wide Gaussian-shaped anomaly to an ASTER image of the field area, Figure 5A), infrasound recordings (based on infrasound data from the Kīlauea 2018 eruption), soil-gas measurements of elevated CO_2 fluxes (see Figure 6, based on measurements at known discharge areas following a dike emplacement event around Mammoth Mountain, in Long Valley, California, in 1990 [Sorey et al. 1998; Werner et al. 2014]), reports of gas measurements made by UAS-mounted sensors, and seismicity maps.

Stage 3: On February 22, the eruption entered its third, and last, stage. Additional dike injections lead to the opening of new fissures east of the cinder cone. Extrusion quickly localized at a single main vent, located at 111.54°W, 35.412°N. At first, activity at the vent was mildly explosive, which then culminated with a VEI 3 explosion. Data accompanying this activity included gas measurements indicating high SO_2 flux, an ASTER infrared image showing a narrow focused thermal anomaly above the dikes, GNSS ground motion vectors, and InSAR interferograms showing a butterfly pattern of displacement with an area of incoherence due to the deformation rate being too high directly above the sill (Figure 7). Seismicity and infrasound were reported as well. The Oracle provided tephra thickness values in locations where participants placed collection bins (based on calculations by the tephra dispersal model `TEPHRA2`, [Bonadonna et al. 2005]), and images of a cone (utilizing photos collected during the Kīlauea 2018 eruption). As the eruption entered Stage 3, in order to allow for a simulation of an extended eruption, time was artificially accelerated, such that each exercise day accounted for a full week of simulated time.

After a short hiatus, presumably due to blockage of the vent after the explosion, lava effusion began. The lava flowed toward Highway 89 and covered a segment of it, then turned east and flowed in a narrow canyon toward the Little Colorado River. The Oracle provided the remote sensing team of participants with ASTER infrared images (Figure 5B) displaying thermal anomalies that showed the flow footprint as predicted by the `MOLASSES` numerical lava flow model [Gallant et al. 2018]. It also provided a video of flow in the lava channel similar to what would have been collected by a hovering UAS (actual video was from Kīlauea 2018). Lastly, the videography team received from the Oracle a time-lapse video of the lava fountain at the vent (collected during the 2021 eruption of Cumbre Vieja in La Palma) to show what one of their field cameras would have recorded (Figure 8).

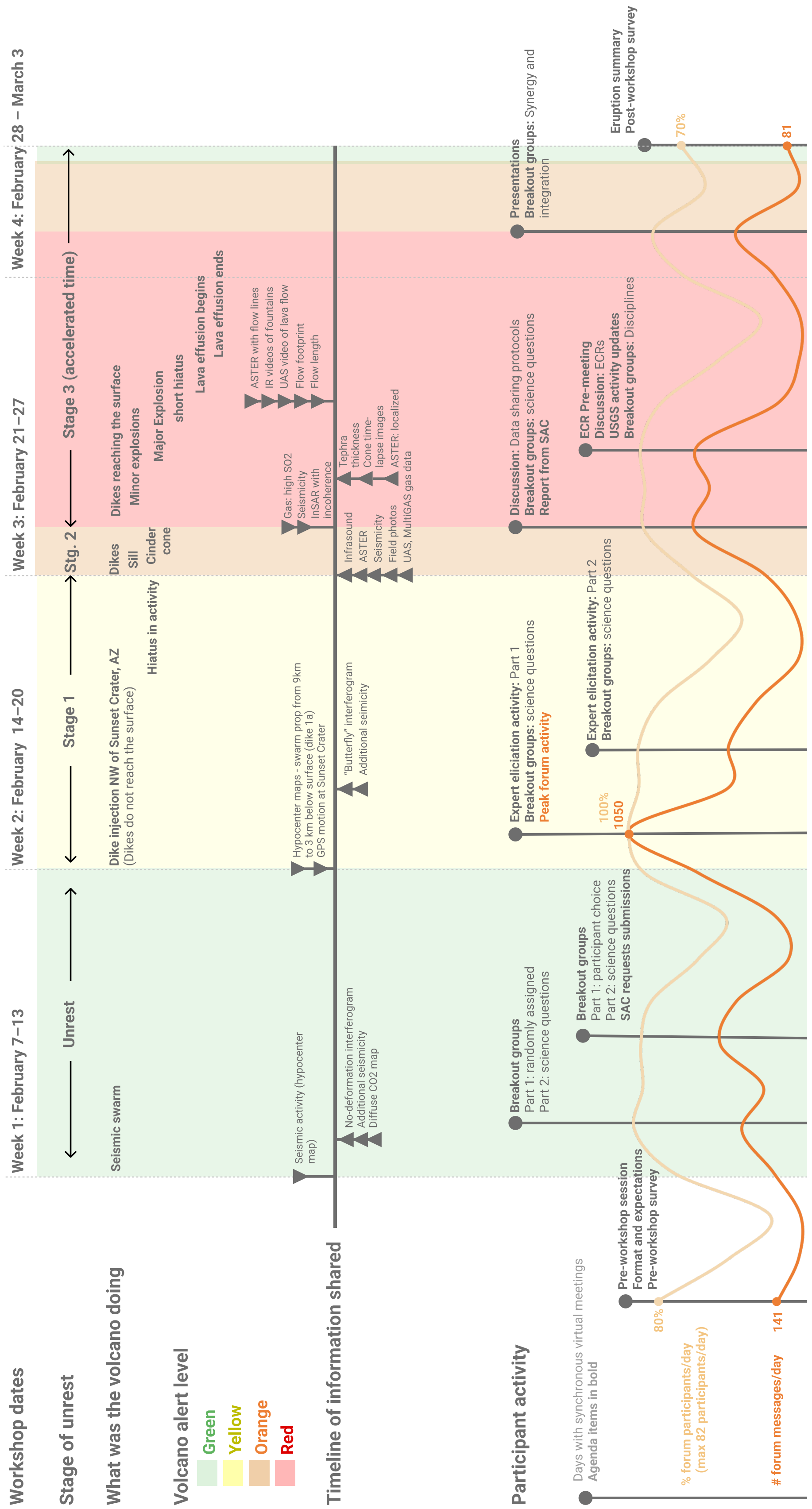

Figure 2: An overview of the scenario exercise that aligns workshop activities with stages of volcanic activity during 2022 CONVERSE exercise.

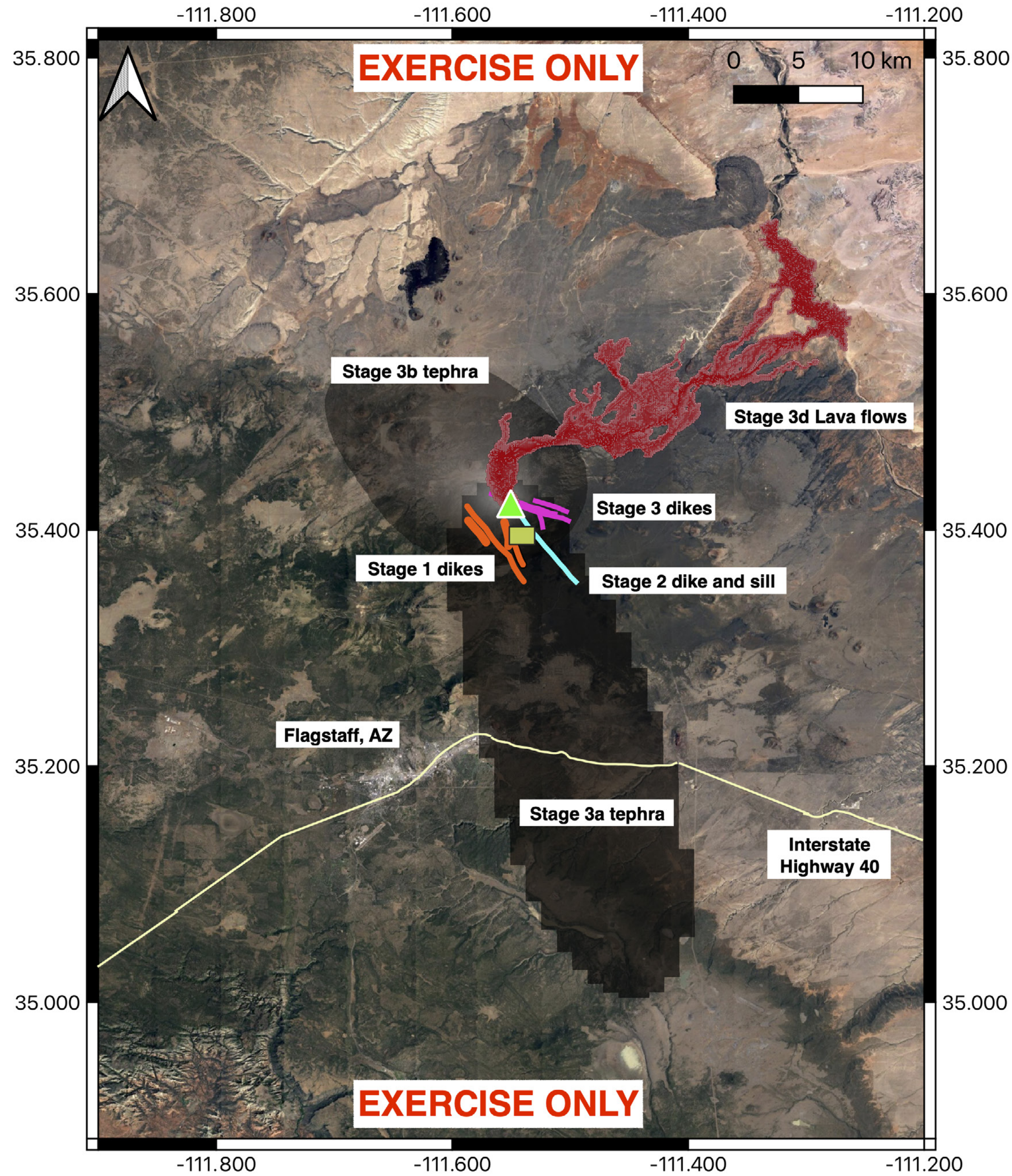

Figure 3: An overview map showing the main features of the magmatic system modeled in the scenario. Lines show dikes (orange: Stage 1; Cyan: Stage 2; Magenta: Stage 3). The olive green ellipse shows the sill that formed in Stage 2. Gray regions show the extent of tephra deposits, and the red region is the footprint of the simulated lava flow. Also visible are the city of Flagstaff, Arizona, Interstate highway 40, and nearby lava flows and vents of the San Francisco Volcanic Field. The background is a satellite image from Landsat / Copernicus, via Google Earth.

3 Exercise activities

3.1 Pre-exercise activities

Prior to the exercise, the prospective workshop community came together in a pre-exercise workshop held virtually in October 2021. The pre-workshop provided a venue to discuss the lessons learned from the Mount Hood exercise and plan for the exercise. Presentations and breakout discussions covered monogenetic volcanism in general as well as the challenges in responding to a distributed volcanism event by the USGS and the academic community.

The exercise itself lasted for four weeks, From February 7 to March 3, 2022. An overview of the exercise, lining up the volcanic scenario alongside the exercise activities, is shown in Figure 2. In preparation for the exercise, a kick-off session was held on February 4th, and the organizers introduced themselves, reviewed the goals of the exercise, provided technical instructions about communications platforms, shared the

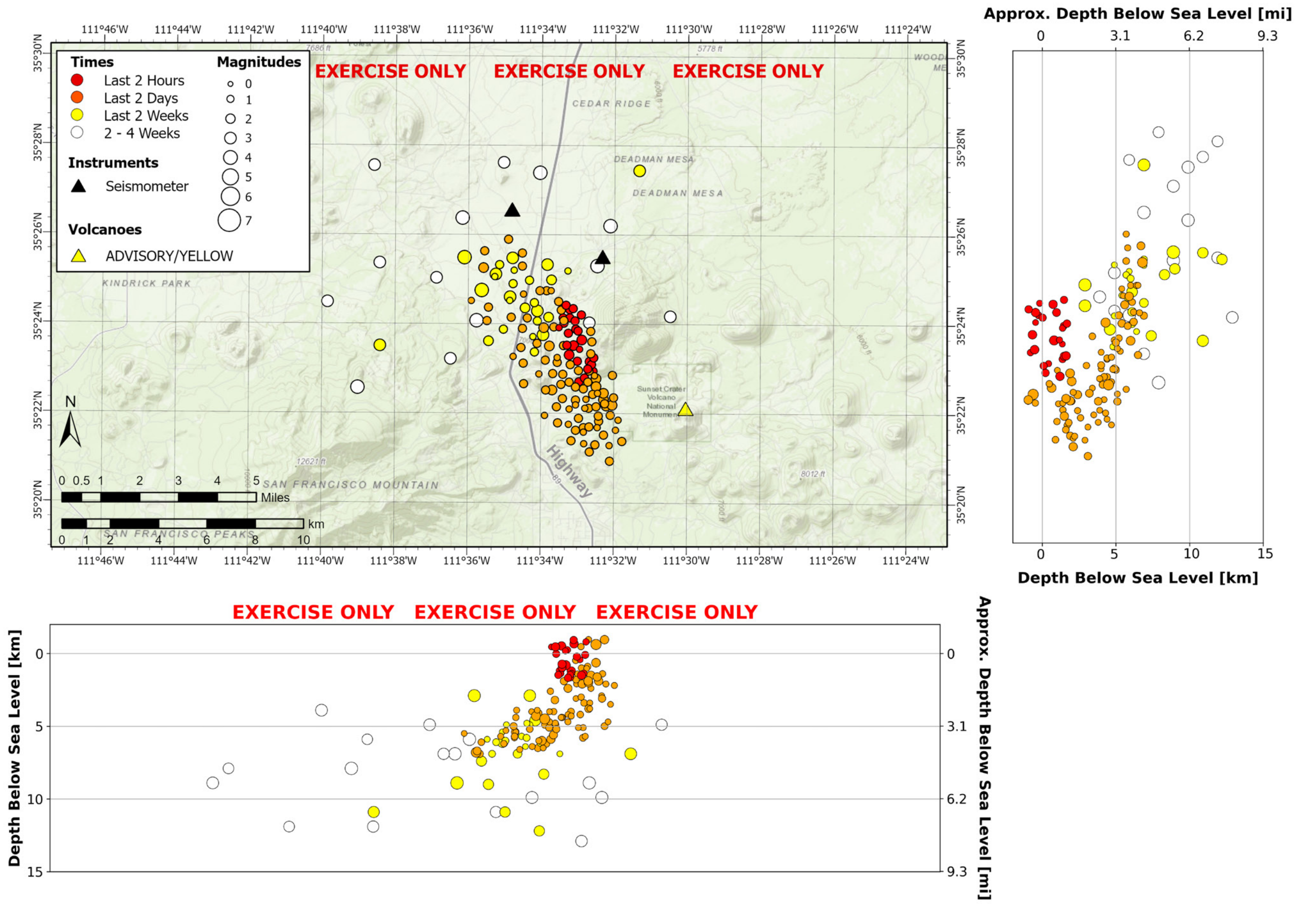

Figure 4: An example of the seismic information shared with the participants on February 15, during Stage 1 of the unrest. This example shows hypocenter locations on a map and in depth cross-sections and suggest a dike intrusion has occurred. Circle color indicates the time of each event, and circle size indicates magnitude.

exercise schedule, and explained the rules of professional conduct. Rules of engagement included (1) keep discussion on the community messaging forum on public channels to promote a community of inclusivity and allow collaboration and (2) use the 3 + me rule; meaning you let 3 other people talk before you add something to the conversation, if you have already spoken. A summary of the Mount Hood exercise and the October pre-workshop was presented by the respective organizers of those events. A representative of the SAC that was established in response to the 2020–2021 Kīlauea eruption (the K-SAC) reviewed the lessons learned during that time, which was the first application of the SAC model (Supplementary Material 1) and the CONVERSE network to a real eruption [Cooper et al. 2023]. The chair of the SAC set up for the exercise introduced their guiding principles—to serve to advise and facilitate research, not as gate-keepers. Lastly, a presentation by a representative from the Integrated Earth Data Alliance (IEDA) introduced and discussed the relevance to CONVERSE of their new Volcano Portal, an online application that connects to different data systems and data repositories (e.g. EarthChem, SESAR, GVP database, EarthScope Consortium, OpenTopography, MaGa) to make their data discoverable and accessible through a single search. After the kick-off, participants were invited to join the community messaging forum space, visit the exercise website, and familiarize themselves with the shared data portal (a shared cloud-based drive).

3.2 Basic weekly schedule

The four weeks of the exercise followed a common structure: On Mondays, the YVO members of the organizing team released an official "Information Statement" describing the status of the volcano (all the Information Statements are provided in Supplementary Material 2). These were disseminated to the community via the "Official Statements" and the "General" channels in the community messaging forum. All participants met virtually on two-hour video calls every Tuesday and Thursday. The SAC met on Fridays to review requests and proposals. During the rest of the week, communication amongst participants as well as between participants and organizers (the "Oracle") was conducted through the community message forum.

The twice-weekly video meetings were usually structured to begin with a volcano activity report from YVO, followed by presentations about relevant topics such as the volcanic

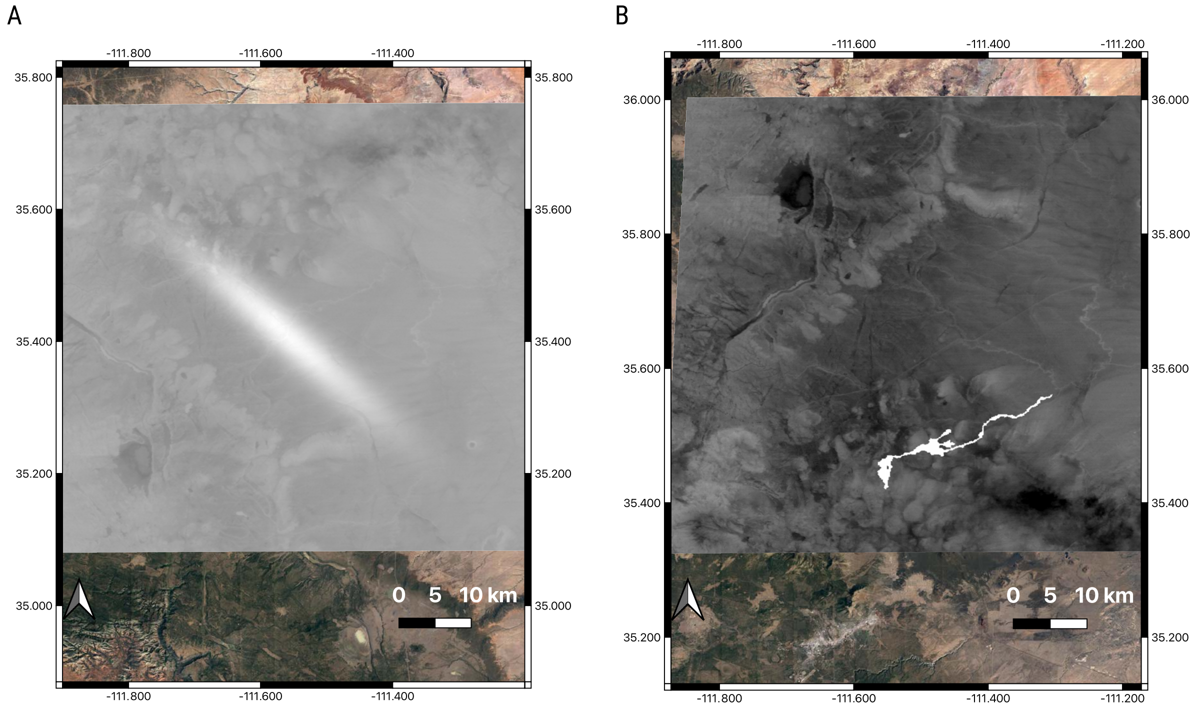

Figure 5: Examples of synthetic thermal satellite data (ASTER scenes) provided to the participants. Left: A diffuse thermal anomaly localized over the intruding dike of Stage 2 (given on February 22nd); Right: A bright thermal anomaly reflecting the lava flow after 40 days of effusion. The anomalies were superimposed on an actual ASTER background of the simulation region. Participants extracted flow lengths and advance rate from the sequence of "ASTER" images of the flow region.

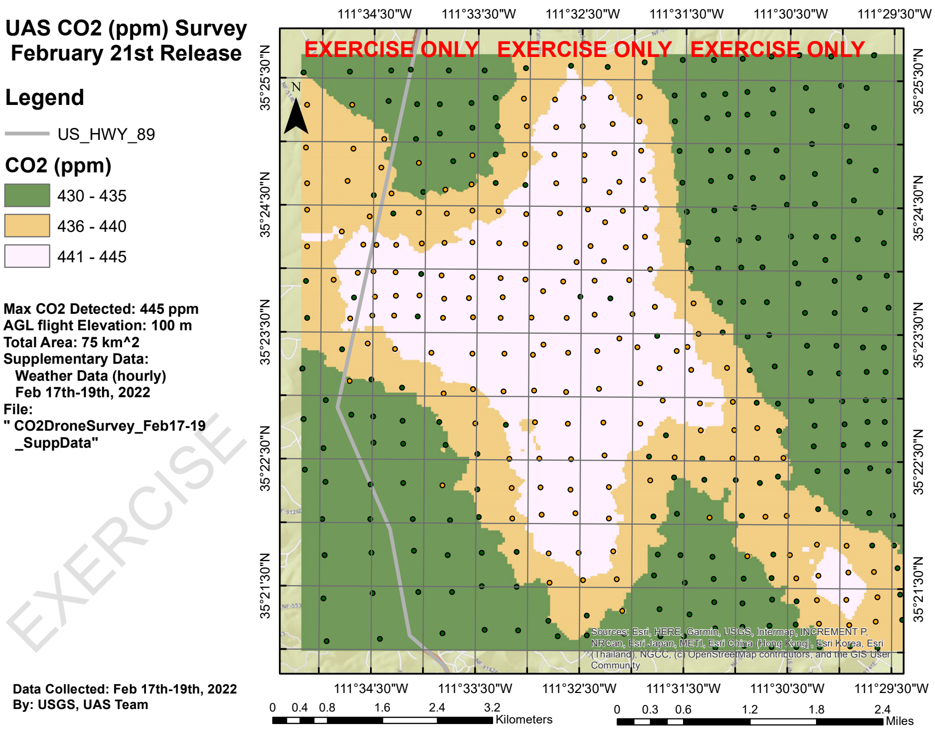

Figure 6: A map showing the simulated CO_2 flux measurements shared with the participants on February 21st, during Stage 2 of the eruption. Data were based on measurements taken at Mammoth Mountain in 1990 [Sorey et al. 1998; Werner et al. 2014].

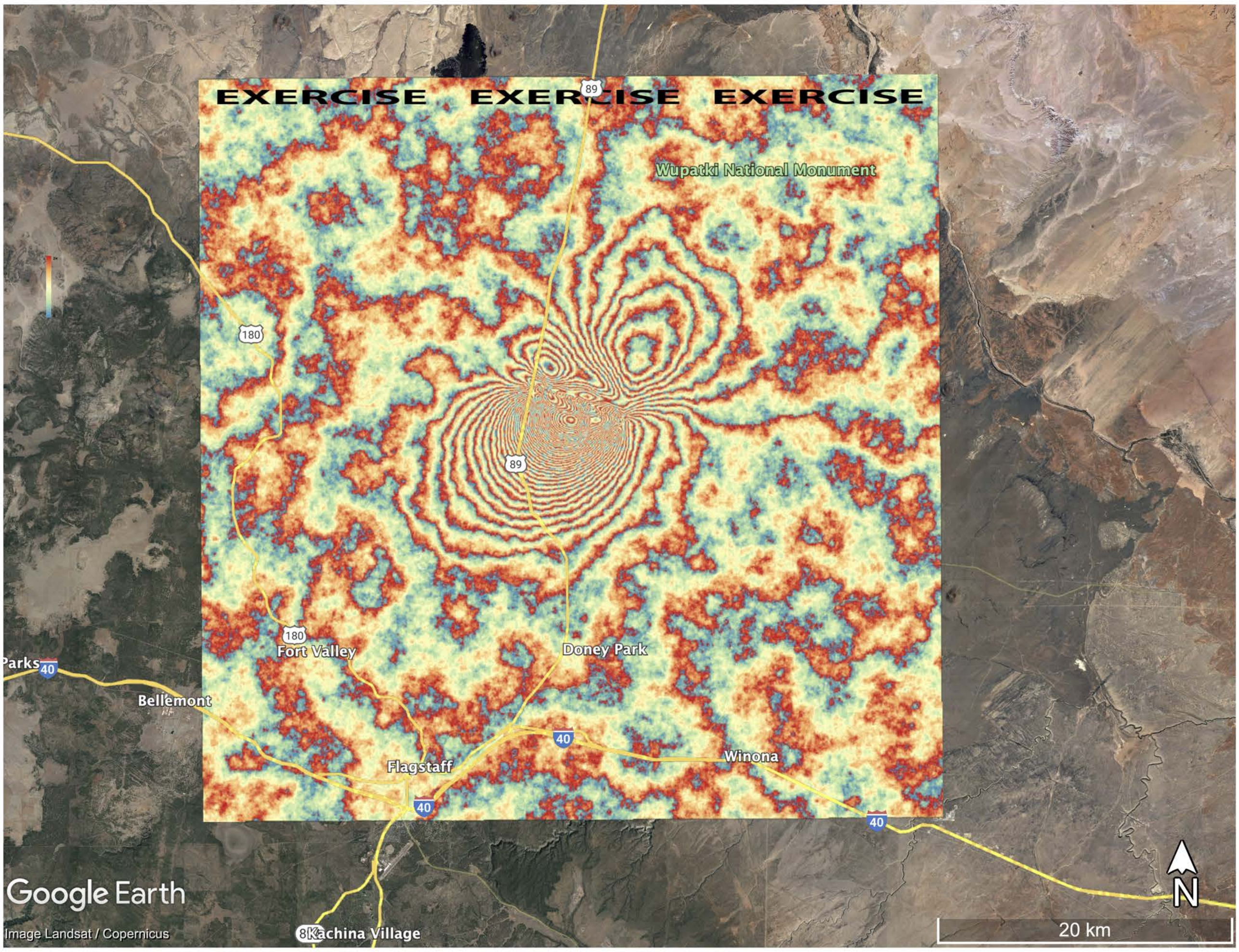

Figure 7: An example of synthetic interferogram data shared with the participants. This interferogram simulates an ascending orbit X-band (3.1 cm wavelength) interferogram. This example was shared on February 23rd, during Stage 3 of the eruption, and indicates a major dike injection. Participants inverted the geodetic data to provide estimates of intrusion depth and volumes.

Figure 8: Thermal infrared images of the main vent at the 2021 Cumbre Vieja eruption, which were provided to the exercise participants as simulated footage from the scenario vent during Stage 3 of the activity. Participants were able to extract time series of plume height from the provided footage. Source: LDEO / AVERT camera system. Full image catalog can be found in http://vulcan1.ldeo.columbia.edu/vulcand/ldeo/raw/data/siteCv/.

history of the general field area, community facilities such as the EarthScope Consortium (previously IRIS and UNAVCO), which support instrumentation and data services for the geophysical scientific community, the SAC process, inclusion of early-career scientists, expert elicitation (described in more detail in Section 3.4), and time for questions and answers. The bulk of the time was spent in breakout rooms. During the first breakout session, participants were assigned randomly to one of seven rooms, and were asked to discuss the scientific questions they would like to address given the initial unrest and the potential for a volcanic eruption in the general field area. In most of the following breakout sessions, rooms were organized either by theme, science question, or monitoring technique, and participants were able to join the rooms of their choice and switch between rooms. One of the rooms was often dedicated as a "USGS room," to allow the representatives from the USGS to confer on what the agency's response would be. This separate room also simulated to the other participants a realistic situation where USGS scientists are difficult to contact during an emergency event. To facilitate coordination of field activities, all participants had access to a shared map (Figure 9), where they were able to mark locations and types of new instruments, location of permanent gear, and pre-existing samples.

3.3 The Scientific Advisory Committee (SAC)

Following the experience from the Mount Hood exercise and the Kīlauea 2020–2021 eruption, an SAC was set up for this exercise as well. The SAC was comprised of established members of the community, and was designed to provide local and community expertise. The five-member SAC included a chair who is a senior expert in volcano science, a representative of the USGS, and local experts closely familiar with the field area and with varying disciplinary expertise. We note that for this exercise, the members of the SAC were selected by the organizers, while in reality, the CONVERSE community is still considering the procedures for nominating SAC members [Fischer et al. 2021; Cooper et al. 2023]. The participants were encouraged to submit requests to the SAC through a form on the website. The SAC request form, available as an online survey, asked for information about the team's goals, methods, data management plan, and coordination with the USGS (Supplementary Material 3).

The SAC was introduced to the participants through a presentation by the SAC chair during the kick-off meeting. Its role as an advising and coordinating team, rather than as a gate-keeper, was emphasized. The SAC updated the participants on the status of submissions, reviews, and potential gaps in data collection during the bi-weekly video meetings. Since the SAC was also convening virtually (as will most likely be the case during a real eruption scenario), they used an online form (Supplementary Material 4) to register and coordinate their evaluations. The form listed the six review criteria that grew out of the K-SAC and Mount Hood exercise experiences, including: (1) the potential to address critical needs in data collection or scientific response that significantly advance the science of volcanology, (2) the time-sensitivity of data/sample collection/instrument deployment, (3) contribution of results to mitigating volcanic and related hazards to life and property, (4) the likelihood of success, (5) the ability to be performed safely, and (6) the potential for cross-disciplinary advances [Fischer et al. 2021; Cooper et al. 2023].

The SAC in this scenario excercise was set up at the start of the activity and requested proposals from the community about half-way into stage 1 of the activity. This is in contrast to the 2020 eruption of Kīlauea where it was recognized only at the beginning of the eruption that the SAC concept, which was developed during the Mount Hood exercise [Fischer et al. 2021], should be implemented. Within days of the start of that Kīlauea 2020, an SAC was discussed amongst USGS and CONVERSE leadership and criteria for selection of members were developed. Meetings of the SAC (K-SAC) began within a week of the start of the eruption [Cooper et al. 2023]. Since the Kīlauea 2020 eruption, the K-SAC has broadened to the H-SAC to encompass all eruptions occurring in Hawai'i and has remained in place and active with HVO and non-HVO representation. As Kīlauea erupted again in September 2021, the H-SAC approved sample-based requests within two days of a request. Likewise, when Mauna Loa started erupting in November 2022, CONVERSE responded within 24 hours by announcing the proposal process through the already established H-SAC and an invitation to participate in correspondence through a dedicated channel on the community messaging forum. Up to the date of this writing the H-SAC remains active and is helping with the coordination of the intermittent activity at Kīlauea's summit. CONVERSE also remains active during this current period and is maintaining the community messaging forum, a spreadsheet with information on who is performing measurements and collecting data as well as an interactive map that shows the scientific activities occurring on the volcano. These interactive aspects of CONVERSE with the community have been developed and tested in the SFVF scenario exercise and are being continuously implemented.

3.4 Expert Elicitation activity

Previous scenario development studies featured heavily on uncertainty, with focus on communicating to decision-makers in times of volcanic crisis [Doyle et al. 2014; Hicks et al. 2014]. The main uncertainties of interest are often the uncertainty of evacuation and the necessity to better understand the relationship between the probability value and the time window stated in a forecast—in other words, knowing how much time there is between an event and the necessity to evacuate [Doyle et al. 2014]. One way to address these uncertainties is through expert elicitation, a formal structured method for obtaining information from expert judgement, originally formulated by Cooke [1991] and since applied in volcanic contexts in number studies [e.g. Aspinall and Cooke 1998; Runge et al. 2014].

Building upon these studies, an anonymous online expert opinion elicitation and subsequent discussion were facilitated during the second week of the CONVERSE exercise to discuss combined observatory/academic goals of increasing scientific understanding and improving eruption forecasts during a crisis. The CONVERSE expert elicitation activity aimed to identify possible precursors to unrest, eruptive scenarios, eruptive progressions and outcomes, and to seed future research ques-

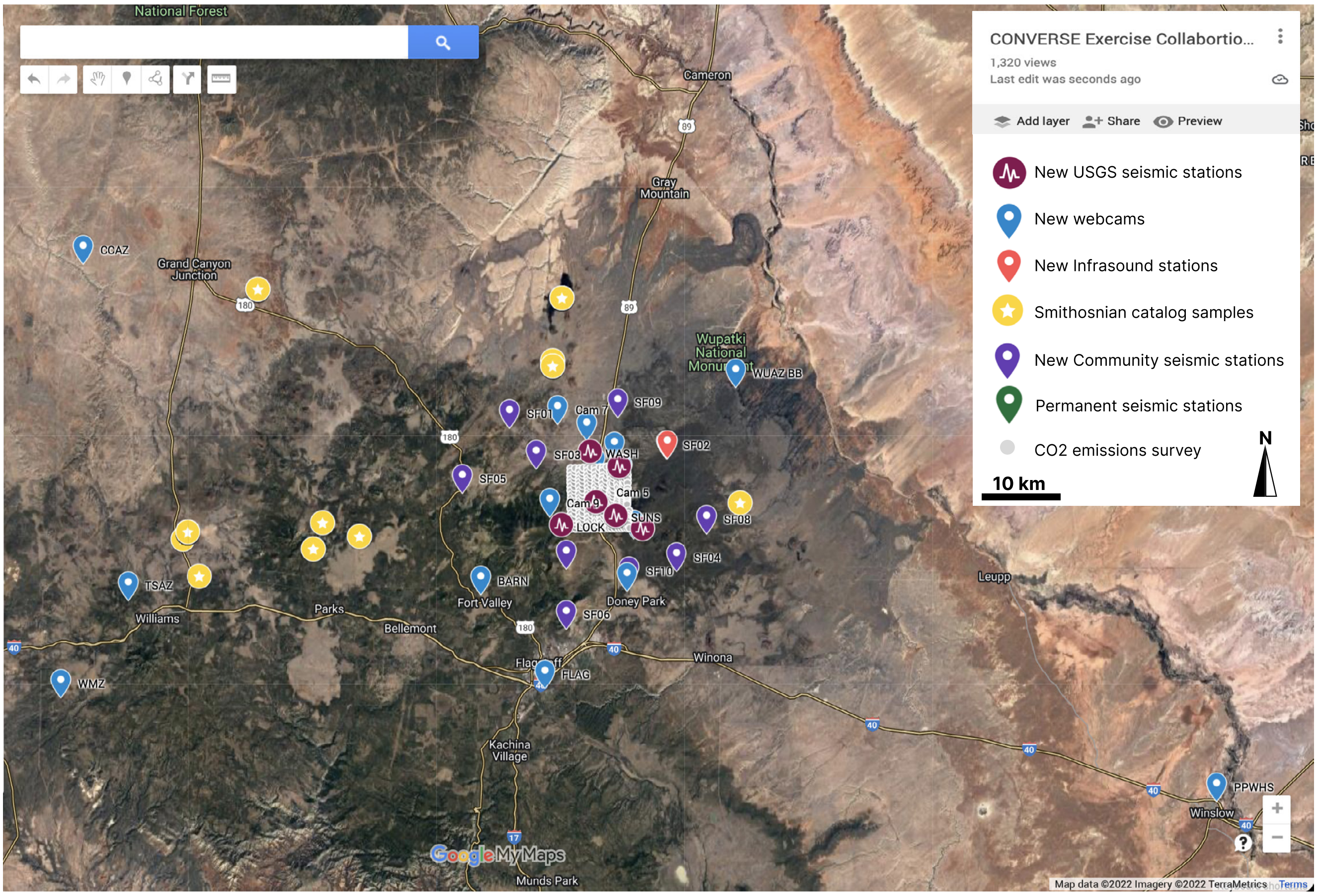

Figure 9: A screen capture of the collaborative map used by the participants to share the locations of their instruments, or, mostly, to let others know what data are being collected and from what locations.

tions. After an introductory presentation about forecasting methods, practical implementation of forecasts, and an explanation of the ways in which human bias affect forecast interpretations, participants were asked a series of questions, including likelihood that there would be an eruption; likely time until eruption onset; likely eruption style at onset; possible lateral distance between seismic unrest and vent location; and potential duration of an eruptive episode. Participants were asked to document the basis for their answers, conceptual models that shaped their interpretations, sources of uncertainty, and a list of outstanding questions for future research or for targeting monitoring efforts.

Thirty-one participants completed the elicitation survey. Subsequent broader discussions about the results were successful in seeding discussion about data sources, interpretations, and mechanisms of forecasting and monitoring during unrest. As in many other fields, results demonstrated the effects of human bias, despite training about its potential effects. Participants were asked to use a random number generator (from 0–100) and enter the value, referred to as their "participant ID," into the top of the survey. Random number values loosely correlated with subsequent participant estimates of eruption likelihood, showing the effect of "anchoring bias" [Furnham and Boo 2011]. Moreover, variation in opinion between experts decreased with career stage, but self-assigned uncertainty range increased with career stage, again following expectations [e.g. Kruger and Dunning 1999]. Variation in opinion documented in the surveys prompted creation of an online document collating base rate information (likelihood that unrest leads to eruption; durations of pre-eruptive unrest and/or delay times between recharge and eruption at analog systems; eruption style and chronology at analog systems; eruption durations at analog systems), SFVF eruptive history data, discussion of appropriate analog systems and tectonic environments, potential mechanisms for eruption initiation, and a list of monitoring signals that may help forecast eruption duration. Finally, elicitation surveys established a mechanism for collection of interpretations that did not require live discussion or self-identification, adding to the wide variety of engagement opportunities provided by the CONVERSE exercise over its duration.

3.5 Media activities

The media, both traditional and social, play an important role during volcanic unrest and eruption events [Rattien 1990; Calabrò et al. 2020; McBride and Ball 2022]. To represent this component in the scenario exercise, we collaborated with a journalist who contacted participants for comments on the events. The journalist was not made privy to the details of the eruption scenario, just as would be the case during a real eruption, and was charged with gathering information, insights and impressions from the participants. Participants were guided to keep in mind the importance of consistent messaging during a time of crisis [e.g. Fearnley et al. 2017; Lowenstern et al. 2022]. One way to achieve this goal was the wide distribution of the informational statement by the YVO representative to all the workshop participants, emphasizing what was known and not known and that this was the official state of the unrest or eruption at that time. Discussions of the concept of consistent messaging amongst the participants led to one of the participants, an experienced communicator of volcano science, volunteering to produce a Talking Points document. This document was shared through the "General" channel on the community messaging forum and the shared cloud-based drive, with the goal of helping the group achieve consistent messaging in their interactions with the media representative.

To simulate what would potentially be the public's engagement and response to the events on social media, the organizers produced sequences of social media posts that included speculations, rumors, and witness accounts (Figure 10).

Figure 10: Examples of manufactured social media messages shared with the participants, to emphasize the aspect of interaction with the public and the media during a response.

4 Survey design and methods

Although large-scale scenario exercises have been conducted before, this exercise uniquely captured a workshop specifically designed for the emerging virtual format for scenario exercises, necessitated in part by the COVID-19 pandemic [Ahn et al. 2021]. Not only did this exercise take place entirely remotely and virtually, the duration of the exercise spanning a full month is also unique. Given the design of the workshop from in-person to virtual, and duration change from a few days to a full month, experiences from this scenario workshop, and understanding the effectiveness of the workshop, are especially timely and relevant to capture.

In addition, bringing together a group of researchers from disparate disciplinary, professional, and/or personal backgrounds to address challenges does not automatically lead to knowledge integration. Done without care, knowledge co-production can lead to undesired results where some voices may be over-amplified, with other voices excluded, and the original goal for transdisciplinary collaboration is effectively lost [Klenk and Meehan 2015].

As such, we evaluated the design and contribution of specific workshop elements in (1) co-generating knowledge, (2) catalyzing transdisciplinary collaboration, (3) supporting researcher confidence, and (4) fostering a culture of inclusion within the volcanology community in the context of a virtual, long-format scenario exercise. With approval from the University of New Mexico Institutional Review Board (IRB approval #19121), evaluation was conducted through a pre- and post-survey that included both likert-scale questions and free-response questions and participant observation. We include observations from both the synchronous virtual video-call meetings and virtual asynchronous activities and interactions, such as through the community messaging forum.

In the pre-scenario meeting, exercise participants were invited to complete the pre-workshop survey (February 4, 2022, $N = 32$). The pre-workshop survey was introduced both during the virtual meeting and shared via the community messaging forum, and was open to participants until the first virtual meeting of the workshop (February 8, 2022). On the last day of the workshop, exercise participants were invited once more to complete the post-workshop survey (March 3, 2022, $N = 39$). Again, the option to participate in this post-workshop survey was introduced both during the virtual meeting and shared via the community messaging forum, and the survey was open to participants for a week after the workshop. Participation in the first survey was not required for participation in the second survey. The demographics for post-workshop survey respondents are included in Table 1. We provide demographics for the post-workshop survey because the majority of the following analysis focuses on the post-workshop survey, which is also more representative of the workshop participants since it had higher rates of completion relative to the pre-workshop survey. Counting exact participation in the scenario is nuanced, as few individuals participated in every aspect of the month-long exercise. For reference, we have provided the number of active users per day on the community messaging forum in Figure 2, and synchronous virtual meetings typically had 45–60 attendees at any given time, and people were free to join and leave as needed so this number fluctuated within a single virtual meeting session.

Both surveys were designed to be anonymous. The pre-workshop survey provided a baseline for attitudes toward workshops like this. The post-workshop survey investigated specific workshop elements, such as the weekly virtual meetings, community message forum, and SAC interactions. Because the survey consisted of a mix of Likert-scale and free response questions, respondents had multiple ways to share their feedback on the effectiveness of the workshop in achieving the aforementioned goals.

Responses were analyzed by grouping the question types together and then coding responses into different categories. Examples of codes used were "early career researcher," "in-

Table 1: Demographics for post-workshop survey (*N*=39).

Career stage and sector	# of respondents
Government Personnel	13
Graduate Student	10
Academic Faculty	10
Postdoctoral Researcher	5
Research Scientist	1
Gender	**# of respondents**
Man	17
Woman	21
Non-Binary	1
Early Career Researcher	**# of respondents**
Yes	19
No	20
Race and Ethnicity	**# of respondents**
White	36
Asian	3
Native American	1
Hispanic	1

cluded," "effectiveness," "useful," "workshop," and "connections." In determining the contributions of the workshop in co-generating knowledge, catalyzing transdisciplinary collaboration, supporting researcher confidence and fostering a culture of inclusion in volcanology, we were interested in the opinions respondents held toward the workshop as a whole. The questions were organized topically, with Likert-scale questions presented first and followed by a free-response question to invite respondents to elaborate further following each topic.

5 Scenario outcomes

The qualitative results from this study, including free-response survey questions and participant observation, are organized in five themes in the following sections: 5.1 Advancing volcanology, 5.2 Fostering a culture of intra- and cross-sector collaboration, 5.3 Co-generation of knowledge and coordinating in a digital space, 5.4 Assessing researcher confidence, and 5.5 [building a culture of] Inclusion within volcanology. Quantitative results from the pre- and post-workshop surveys are summarized in Table 2 and Table 3.

5.1 Advancing volcanology

The scenario exercise contributed to advancing volcanology in multiple ways. First, it focused the attention of a large group of volcanologists on volcanic field activity, which receives less attention than volcanoes with established edifices such as the stratovolcanoes of the Pacific Northwest and Alaska or the shield volcanoes of Hawai'i. Specifically, the exercise drove participants to take a closer look at the SFVF; for example, one team produced a comprehensive list of volcanic vents at the SFVF by combining data from multiple sources. The discussions highlighted open questions that are key in any unrest situation, such as "What are the warning signs that precede an eruption and can help scientists forecast if unrest will lead to eruption, and how long until eruption ensues?" or "What is the influence of the tectonic setting and the composition of the magma on magma storage, ascent rates, and the outcome of unrest?" The discussion also explored relevant analog systems that have data: Mexico (Parícutin), Aotearoa New Zealand (Auckland), Tanzania (Nabor Soito distributed field), and Saudi Arabia were mentioned. These open questions guided the breakout room discussions during the bi-weekly virtual calls and the formation of collaborative teams that submitted proposals to the SAC. Overall, a total of 15 proposals were submitted to the SAC. There were an average of 4.7 collaborators on each proposal (min: 1, max: 15).

5.2 Fostering a culture of intra- and cross-sector collaboration

Collaboration is a key tenet to the success of work in volcanology [Donovan and Oppenheimer 2015]. Volcanology is structured in such a way that there are several essential parties involved, both when it comes to research and in eruption response. The essential parties and actors include: academics, private partners, government personnel, and local communities. In the setting of the CONVERSE workshop, we had participants from both the academic sphere and government agencies, including USGS and the National Aeronautics and Space Administration (NASA). This included volcanologists whose specialties within the field vary broadly as well—geodesists, geochemists, geologists, statisticians, seismologists, and more were all present to work together. Scientists were put into groups that encouraged collaboration during virtual meetings. The initial goal of this structure was to allow those who had different academic backgrounds or trainings, but similar application possibilities, to work together. Once a week, virtual breakout room topics were decided by the organizers. The other day of the week, topics were suggested by participants. Those participants who were USGS employees had their own room to discuss government specific response issues.

The virtual breakout rooms were the most popular part of the exercise and the part that most participants stated was the most useful in the post-workshop survey. Participants enjoyed having the time to discuss the weekly updates and reports with one another and largely felt that the rooms did a good job of bringing like-minded individuals together. Of the few complaints, the largest was that some early career researchers found it difficult to participate and cut in at times. In addition, there were comments that pointed out that despite the best efforts to *not* silo separate disciplines, sometimes the rooms ended up becoming very rigid in their topical structure, with some people wishing that they could attend several breakout room sessions. Overall, the breakout rooms provided the most fruitful space for participants to collaborate, as shown in the post-workshop survey.

The overall impact of the SAC model was largely positive, yet there were several mixed reviews to the model, especially concerning how confident researchers felt submitting propos-

Table 2: Select pre-workshop survey results (*N*=32).

Question	Positive	Neutral	Negative
Based on your experience, how do you rate the effectiveness of transdisciplinary workshops in terms of co-production of knowledge?	90.6 %	6.3 %	3.1 %
Based on your experience, how do you rate the effectiveness of transdisciplinary workshops in terms of cultivating transdisciplinary connections?	87.5 %	9.4 %	3.1 %
Based on your experience, how do you rate the effectiveness of transdisciplinary workshops in terms of boosting your confidence in engaging in transdisciplinary research?	68.7 %	31.3 %	0 %
To what extent do you agree or disagree with the following statement regarding your academic/ professional field?	Positive	Neutral	Negative
I feel like a part of my academic/professional field.	93.8 %	3.1 %	3.1 %
I feel my perspectives were valued by my academic/ professional field.	81.3 %	15.6 %	3.1 %
I feel I am included in my academic/ professional field.	81.2 %	9.4 %	9.4 %
I feel I am treated with respect in my academic/ professional field.	87.5 %	9.4 %	3.1 %
I'm glad I am in my academic/ professional field.	90.7 %	9.4 %	0 %

als, with one participant stating, "It was sometimes unclear what the role of the SAC was and...how flexible proposals could be and when they would be approved." Another participant praised the usefulness of the SAC in its conception, but noted that some of the logistical aspects became messy as the workshop went on, "The idea of the SAC was useful in suggesting how different groups could engage. However, I think it got overwhelmed when the time speed up, lots of proposals got submitted, and everyone got busy. At that point, there was not much suggestion from the SAC about other groups to engage with." Participants were clearly on board with the concept of the SAC but there was sometimes a disconnect in how the SAC's role actually played out.

One hundred percent of respondents of the post-workshop survey had either positive or neutral views on their general interactions with the SAC influencing their transdisciplinary connections. Some portions of the SAC model may need to be amended (discussed further in Section 6); however, the overall outlook was, "The SAC helped put folks in touch with each other for stronger projects. They helped remind us to seek out certain types of data that were perhaps missing from our investigations." The proposal process had similar results with ninety-two percent of respondents saying that they felt the proposal process helped to foster interdisciplinary connections.

5.3 Co-generation of knowledge and coordinating in a digital space

A growing method in knowledge co-production is the need to coordinate digitally [e.g. Lowenstern et al. 2022]. The CONVERSE workshop predominantly included participants from across the entirety of the United States, from Hawai'i and Alaska to the East Coast, as well as some international participation. Coordinating workshop activities across six different time zones meant that much of the collaborations occurring were taking shape digitally. To help keep data organized and communications efficient, three different methods were used for communication throughout the workshop: the creation of a community messaging forum, a cloud-based drive folder for data sharing, and bi-weekly virtual meetings with the whole group of participants.

The closest to in-person communications was the use of the bi-weekly virtual meeting. Each meeting consisted of some grouping of over 60 participants, though this was often a different set of participants at each meeting due to schedule conflicts and availability. Participants were generally pleased with the outcomes of these meetings, with seventy-two percent of respondents indicating that the virtual meetings had a positive impact on the creation of transdisciplinary connections and eighty-seven percent saying that it had a positive impact on the co-production of knowledge. Notably, of the six people who responded that the virtual meetings had a negative impact, all but one were early career researchers (ECRs). Scholars early in their career traditionally face particular problems due to the lack of long-term experience in their fields and their fragile position within academia [Jaeger-Erben et al. 2018]. During the CONVERSE exercise, some ECRs found the virtual meetings intimidating at times, stating, "I feel this was hard as an early career scientist to get involved. Ideas brought up by myself or others, at least in my area, seemed to get picked up by more experienced scientists in the group and they ran with it and we got left behind. I didn't feel confident participating anymore." On the other hand, several people stated that the breakout rooms "were the best space to communicate with a smaller group and really get [their] ideas across" and that the virtual meetings as a whole "were a great way to talk through what was said on [the community messaging forum]."

The CONVERSE community messaging forum was highly active throughout the entirety of the workshop. Participants posted throughout the day and all the groups had rapid-fire discussions in individual channels. Several people commented on the messiness that comes with an online community mes-

Table 3: Select post-workshop survey results (N=39).

What was the effectiveness of the breakout rooms during the Tu/Th virtual meetings in the following ways?	Positive	Neutral	Negative
Co-production of knowledge	87.2 %	5.2 %	7.7 %
Cultivating transdisciplinary connections	64.1 %	7.7 %	28.2 %
Boosting confidence in engaging in transdisciplinary research	61.6 %	20.6 %	17.9 %
Developing and fostering your interpersonal connections	84.6 %	7.7 %	7.7 %
What was the effectiveness of the SAC proposal process in the following ways?	**Positive**	**Neutral**	**Negative**
Co-production of knowledge	46.6 %	51.3 %	2.6 %
Cultivating transdisciplinary connections	48.7 %	43.6 %	7.7 %
Boosting confidence in engaging in transdisciplinary research	38.5 %	51.3 %	10.3 %
Developing and fostering your interpersonal connections	38.5 %	56.4 %	5.1 %
What was the effectiveness of the community messaging forum in the following ways?	**Positive**	**Neutral**	**Negative**
Co-production of knowledge	87.1 %	2.6 %	10.3 %
Cultivating transdisciplinary connections	82.1 %	7.7 %	10.3 %
Boosting confidence in engaging in transdisciplinary research	69.3 %	20.5 %	10.3 %
Developing and fostering your interpersonal connections	79.5 %	10.3 %	10.3 %
To what extent do you agree or disagree with the following statement regarding your academic/ professional field?	**Positive**	**Neutral**	**Negative**
I feel like a part of my academic/ professional field.	92.3 %	2.6 %	5.2 %
I feel my perspectives were valued by my academic/ professional field.	89.7 %	5.1 %	5.2 %
I feel I am included in my academic/ professional field.	87.2 %	2.6 %	10.3 %
I feel I am treated with respect in my academic/ professional field.	89.7 %	5.1 %	5.1 %
I'm glad I am in my academic/ professional field.	92.3 %	5.1 %	2.6 %
To what extent do you agree or disagree with the following statement?	**Positive**	**Neutral**	**Negative**
I felt like a part of the workshop.	94.8 %	0 %	5.2 %
I felt my perspectives were valued.	94.9 %	0 %	5.2 %
I felt I was included in the workshop activities.	94.9 %	0 %	5.1 %
I felt I was treated with respect.	94.9 %	2.6 %	2.6 %
I'm glad I attended the workshop.	92.3 %	5.1 %	2.6 %

saging forum but ultimately agreed it was a great option with one participant saying, "Keeping track of everything was difficult at times, but it was a great space to accomplish and discuss many different things," and another stating that, "While there were some things that were difficult about it, it was the first platform that allowed me to feel included in discussions." The online messaging space also served as an option for asynchronous participation in the workshop. As mentioned earlier, the virtual meetings usually had about over 60 participants a day, while asynchronous activity through the community messaging forum reached a maximum of 82 active participants per day (see Figure 2).

The cloud-based drive space was perhaps underutilized. It was envisioned to be used as a space to keep the data that were being shared. However, most participants and respondents to the survey remarked that they felt neutral about the space as, "there was no way to discuss things, it was just an unsearchable repository that was underutilized." On one end of the spectrum, over half the respondents stated that the cloud-based drive space was effective in co-producing knowledge, but on the other, almost seventy-four percent marked either "N/A" or "ineffective" on the cloud-based drive's effectiveness at fostering interpersonal connections. This suggests that the cloud-based drive was an adequate repository to store data, but lacked any critical engagement. Upon examination of the shared cloud-based drive space we noticed that several groups had created a well-designed folder-tree structure, with subfolders designated to specific types of data (e.g. Gas→Raw data→Ground-based data→DOAS). Such examples serve to educate the exercise participants of common practices among USGS observatory staff and can help ease collaboration in the future.

The shared cloud-based drive was used by the participants not only for data storage and distribution, but also for keeping documents and forms that needed to be accessed by the participants. For example, a draft document describing the CONVERSE policy for data and sample sharing was being developed within the cloud-based drive space. Participants from both the USGS and universities developed a checklist for field area access (Supplementary Material 5) and an emergency contact form for field teams (Supplementary Material 6). The geology group merged two previous spreadsheets to create a one-stop list of essential sample-related field tasks and analytical facilities and capabilities. These forms and documents, produced collaboratively by the community, can serve as templates for procedures during response to future events.

5.4 Assessing researcher confidence

From the perspective of forecasting and risk, researchers need to feel confident enough to voice their opinion, but they should not be so confident that they no longer consider others' opinions [Newhall 2017]. The latter attitude illustrates the importance of inclusion alongside confidence, which we discuss in the following section. A major goal of the CONVERSE scenario was to be more inclusive to ECRs. Bringing together researchers from varied institutions and career stages is not easy, and there were a variety of differences in perceived confidence in ECRs versus more established researchers. While the organizers worked hard to keep ECR inclusion at the forefront throughout the workshop, there were still some bumps in the process. For instance, one ECR noted that "As an ECR, I am not sure that it helped 'calling out' ECRs all the time. I know it was meant well but not sure if this was effective (i.e. almost no ECRs ever responded). In the breakout rooms, some questioning was exam-like and I felt the pressure to perform and impress. On a different note there were 1-3 other people of my field in this workshop, which meant that basically all the work landed on our table. With it being a scenario and having to simultaneously finish my PhD, it was difficult to balance the pressure of performing as an ECR and also as one of the only people in this field."

In Section 6, we discuss potential remedies for some of this sentiment, especially how to better include ECRs without putting them on the spot. In a large, online setting, it is hard for certain voices to be heard, with one ECR commenting, "Imposter syndrome combined with actually being early career/inexperienced combined with more senior scientists often dominating the scene at conferences/workshops has not historically been the best combo for me." This is something that was expressed several times, and a main reason that the breakout rooms were so appreciated, so long as the breakout room 'exam' setting was avoided. Several respondents stated that the breakout rooms were the main place that they felt they could be heard, due to the smaller group size, or that they preferred to communicate on the messaging forum because they could comment without the pressure of later-career researchers being in the room. In that vein, one ECR stated that "I really enjoyed participating in the CONVERSE exercise as an ECR. I was able to meet people whose papers I have read and...[throughout the workshop] was able to gain confidence to speak up in the breakout rooms while feeling...supported." Overall, while mid- and later-career scientists felt confident in their abilities to participate, ECRs had mixed opinions on how confident they felt in their role in the workshop.

5.5 Inclusion within volcanology

It is important to foster a culture of inclusion in all academic fields. For the CONVERSE workshop, it was a major goal of the organizers to ensure that both ECRs and mid/late career scientists felt included, no matter the type of institution that they were housed within. In the US, volcanology is a relatively small field, with practitioners spread over a wide geographical area, i.e. from the East Coast to Alaska to Hawai'i and many places in between. This poses challenges for collaborative work across disciplines, especially in an eruption response situation where time is often of the essence. While the overall state of inclusion within volcanology appears positive, as indicated by over 90 % of post-workshop survey researchers who indicated that they are happy to be in the field and 87 % who feel at least somewhat included in their field, there is still room for improvement. Understanding identity and collecting demographic data is a necessary step towards inclusion [Ali et al. 2021]. Notably, the participants of this workshop were overwhelmingly White. This reflects a larger diversity issue within the geosciences as a whole, where only 3.8 % of tenured/tenure-track faculty in the top 100 geoscience departments are faculty of color, and little to no improvement on the ethnic and racial diversity of PhD-earning researchers in the United States in the last 40 years [Bernard and Cooperdock 2018]. Additionally, non-ECR scientists are still majority male across the major volcanological professional groups [Kavanagh et al. 2022].

Similar to the ideas concerning researcher confidence, it was often ECRs who were faced with the most scrutiny and potential to feel alienated from the conversation. In addition, demographics played a role, with white males feeling most included and women and researchers of color commenting on sometimes feeling separated from the community as a whole. "I probably am deluding myself, but I've always felt very accepted and respected. Of course, I'm a cisgender White male. I don't expect my experience to be particularly representative of others." This was a statement made by a young, White, ECR, and while his sense of inclusion is not out of the ordinary, his acknowledgement of the plight of others in his community is valuable.

To be able to ensure that inclusion exists within the volcanology community, there has to be an acknowledgement that some people may not be feeling included. When asked about feeling included in their fields, almost eighty percent of pre-workshop survey respondents, and nearly 90 % of post-workshop survey respondents, said "yes" or "somewhat." However, upon further investigation, only ten percent of the outright "yes" respondents in the post-workshop survey were ECRs, with most answering "somewhat" and then filling in comments such as the following, "It's...hard to know if someone isn't including you because of social awkwardness or because they would rather work in their own network and not include new people...". Without a sufficient level of inclusion, whether due to career stage, ethnicity, language, or other factors, crucial opinions may not be shared (e.g. in sharing perspectives on eruption forecast). Additionally, within the context of a scenario exercise, the level of inclusion at this stage can signal to ECRs the professional culture that is acceptable within volcanology. If that level of inclusion is low, the motivation to persist in such a field can be adversely affected.

Overall, it is those who identify as ECRs who have a harder time feeling included. The key lesson taken in inclusivity comes in the form of support. One respondent said that they "felt it was [their] duty as a mid-stage researcher to stand up for the ECRs. But I also wasn't 100% confident." How can individual volcanologists and the community as a whole come together to create that space for inclusiveness so that volcanologists from all institutions and all career stages can feel welcome?

6 Recommendations and lessons learned

Drawing upon the survey results, participant observation, and the organizing committee's experiences, we identify seven key recommendations and lessons learned from this inaugural four-week long, intentionally digitally- and remotely-run scenario exercise.

6.1 The SAC model

The SAC model evolved somewhat since its inception at the Mount Hood exercise and its practice during the Kīlauea 2020-2021 eruption. The role of the SAC as a facilitator of collaboration and connection should be maintained going forward. For future scenario exercises, an ECR contact person and/or an ECR could play an important role on the SAC. One lesson is that during an extended unrest and eruption event there may be a need to rotate the SAC membership, or provide a more clear definition of the roles within the SAC itself, so that the work load is distributed better. In addition, one USGS liaison on the SAC may not be enough during an extended crisis.

6.2 Tools for conducting a remote scenario

The bi-weekly virtual meetings were appreciated and are a good way to share information pertaining to the entire group. As a virtual scenario, the use of a digital conferencing software also promotes inclusion by reducing the need for funding to conduct these exercises since travel is not required, and built-in features such as automated closed captioning can help to make the space more accessible. These sessions should also be used to share updates from the different groups and proposal teams, so that the whole group is up to date on activities. The community messaging forum was a useful coordination platform but it was difficult for participants to follow everything that was going on, especially in parallel groups they were not members of; brief updates during the all-hands sessions will amend that. Guidance for the structure and use of a shared cloud-based drive space could help increase its utility within an exercise. These tools are potentially also useful in the case of an actual crisis, and utilizing the same platforms between an exercise and actual event supports the authenticity of the scenario, while also preparing participants to be trained in the digital tools that are used in times of volcanic unrest. Within the USGS, internal communication tools, analogous to the community messaging forum described for this exercise, have been crucial in helping teams to communicate during eruption crises [Lowenstern et al. 2022]. Having a community messaging forum could be equally as useful for a broader community to enable timely communication. Potential challenges can include the security of these platforms and accessibility to reliable wireless networks [Lowenstern et al. 2022].

6.3 Maintaining authenticity of a scenario exercise

Keeping a scenario exercise authentic requires that all its components are reliable and entice participation. The authentic format of the information statements was applauded and should be used in future scenario exercises. Designing the exercise as an extended virtual workshop was more authentic and reflective of the reality during a real eruption compared with a tabletop activity where everyone is in the same room, or compared with a shorter format virtual workshop (as was the case for the Mount Hood scenario exercise, which was designed as an in-person workshop and moved online in response to COVID-19). Time management during an exercise is difficult to perfect because it is unrealistic to follow exact eruption timelines, yet accelerated timelines such as the one used for this exercise quickly overwhelm the participants. One suggested solution is to limit the activities during the accelerated timeline to only represent a subset of the activities that would be taking place during a real event, to avoid a sudden surge of information and action. Future exercises may also choose to be shorter, i.e. two weeks instead of four, to avoid participant exhaustion. There are times, however, when *authenticity* of a scenario to represent an actual crisis and other purposes of the scenario—mentorship, training, and relationship building—are at odds. A scenario exercise is an appropriate context to take the extra time that is required to *develop* those necessary relationships and skills, while an actual crisis relies on the *existence* of those relationships to succeed. To maintain the authenticity in this aspect of a scenario would be a disservice to the broader purposes of the scenario.

6.4 Extending utility of scenario exercise materials

Producing a reliable and engaging scenario exercise is a deeply involved activity that requires significant effort from the organizers. This burden can be mitigated by turning the production of scenario materials into an educational activity, for example, in the form of a graduate level seminar class. In addition, the materials from each exercise should be open, easy to find, and well-documented, so that it can be re-used and improved upon by multiple communities and groups, as we have attempted to provide in this paper.

6.5 Toward a more inclusive community in volcano science

Understanding the state of inclusion requires both understanding who is in the room, and who is not in the room, what voices are being heard, and what voices are missing. Based on the best available demographic data (from the post-workshop survey, $N = 39$), participants came from varied backgrounds academically, with a relatively even split between graduate students, faculty, and government personnel. Research scientists and postdoctoral researchers were fewer. Early career researchers made up almost exactly half of the survey respondents. The exercise overall lacked diversity with 36 out of 39 respondents stating their demographic information as White. This may indicate a need for increased diversity in the field of volcanology as a whole, since participants ranged from across states, countries, and disciplines. Gender was also fairly equally divided. We note that demographic data were not collected for all participants at the time of registration for the 2022 exercise, and this has been implemented as an intentional change for future CONVERSE events and activities to better understand who is, and is not, included in CONVERSE-related activities. Collecting fully representative demographic data would strengthen our understanding of the state of inclusion; we recognize this as a limitation of the current paper and we suggest collecting this information at the registration phase for future scenarios.

To promote an inclusive environment, strategies such as "3 before me," where people in the room are encouraged to let others speak and to be mindful of dominating the conversation, can work well, but only with those already in the room. The DVF scenario was advertised through an announcement on the Volcano listserv*, which is the largest electronic mailing list for volcano scientists with currently about 3600 members that has been active since 1984 [Koenig and Fink 2002]. It was also advertised on the CONVERSE email list, which included everyone who has expressed interest in CONVERSE or has participated in a previous scenario or actual eruption response. We held a two-day webinar in October 2021 that had about 80 participants and included presentations from United States. and international speakers to brief potential participants on what to expect from joining the exercise.

To truly create a more inclusive community moving forward, additional recruiting effort is first needed to reach potential participants from a broader range of institutions, for example: Minority-Serving Institutions, Hispanic-Serving Institutions, Historically Black Colleges and Universities, non-R1 universities, and Primarily Undergraduate Institutions. The shift from an in-person workshop to an extended digital workshop both increased the authenticity of the workshop response, and also reduced financial barriers to bringing additional participants into the scenario workshop. In addition, this shift to a remote workshop can also help support those who may have difficulty traveling due to other professional or personal reasons. For these reasons, we have determined this remote format would be highly effective for future scenario exercises.

6.6 Breaking down silos between academic and governmental sectors

Creating more time and varied spaces for free-flowing collaboration can help break down sector silo-ing. In the event of real-life volcanic unrest, pre-existing collaborative relationships between individuals in different sectors (e.g. academic and governmental) are key to successful response coordination, as well as to rapid development of new science proposals [Newhall 2021; Cooper et al. 2023]. The time to build those collaborative relationships, therefore, must be prior to an actual crisis situation. Exercises such as the 2022 CONVERSE scenario are one way to provide this opportunity. Survey results showed that participants would have enjoyed the option to be able to work in different virtual breakout rooms throughout the exercises. Participants indicated that more time dedicated to breakout rooms in the large bi-weekly virtual calls would have provided the opportunity to switch into different rooms and meet more people. Another solution would be to have rotating breakout rooms. For example, the first half of the meeting time could be dedicated to one set of topics. After the first half, participants could rotate rooms but the topics would remain the same, allowing participants to engage in different sub-disciplines where they might also be able to contribute valuable information. Another issue that was raised was the fact that the USGS participants had their own room, which made them somewhat unapproachable. Some of the perceived inaccessibility of the USGS participants was addressed through having one individual serve as the liaison between the SAC and the rest of the participants, but several participants commented that it would have been useful to have the USGS participants in the breakout rooms with them, rather than isolated into their own room. This limitation could be remedied similarly to above, by using half the breakout room time to discuss USGS-specific issues and then separate out into their individual disciplines, making the USGS much more accessible to the rest of the scientists. However, the level of accessibility for the purpose of collaboration and relationship building within the scenario must be balanced by the reality that, in an actual crisis, USGS scientists would be relatively inaccessible. Future scenario exercises could more explicitly be used to educate the participating community on expectations and pathways for working with the USGS during an active crisis by highlighting differences between what can happen in the scenario for purposes of relationship-building versus the realities of what to expect in an active crisis.

6.7 Supporting ECRs through community and allyship

Building community amongst ECRs as early as possible in the workshop, identifying champions for ECRs amongst more-senior faculty, and including ECRs in key leadership positions can all help to elevate ECRs. While most participants shared the intention and desire to support ECRs, some of these efforts had the opposite effect. The issues mentioned above in Section 5, including discomfort is speaking up in the virtual call, noticing that their ideas were "taken over" by a senior scientist with the ECR left behind, or of ECRs being "called out" in an "exam-like" way to participate, all indicate room for improvement in supporting ECRs in similar virtual workshop settings.

A potential remedy could be to provide some level of training of best practices of including early-career scientists, or designating certain later-career researchers as champions for ECRs to bring up any related issues or behavior issues to the organizing committee. Having designated people available to talk about these kinds of issues could do a great deal to encourage ECRs to speak up when they are feeling overwhelmed or excluded. Positive outcomes could also be achieved by reminding later-career scientists to explain their thought processes during breakouts; ECRs learn a great deal by listening and absorbing from others in the field, so not brushing over any step in a process that may be new to ECRs is extremely useful. Notably, the CONVERSE exercise organizing committee did include ECRs, which helped alert the rest of the com-

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mittee to these concerns and strategize for ways to address these issues. To continue this involvement, it may be useful to include an ECR on the SAC as well.

Toward the end of the workshop, at the request of some of the ECRs and organized by ECRs on the organizing committee, the CONVERSE exercise dedicated time and space for ECRs to connect so they could identify one another and work to form a community. ECRs indicated that this meeting was helpful, and it was evident that hosting this meeting at the start of the workshop would have been even more useful. An early meeting of ECRs could also be used as a time to identify strategies that they would specifically like to see utilized to support them, and provide feedback on the already-identified strategies for elevating ECRs in the upcoming workshop.

In addition, ECRs stand to gain much in their careers by participating an exercise like this both through networking and through publications. Setting up a way for ECRs to truly grow through mentorship would benefit both later-career scientists and ECRs in the long run, but the experiences of authorship and inclusion in publications can be varied based on gender and career stage [Kavanagh et al. 2022]. Effective mentorship and collaboration requires a genuine relationship built on trust, communication, and mutual understanding [Stelter et al. 2021]. In addition to training later-career researchers on best-practices for including ECRs in workshop activities, training for cultivating effective mentor-mentee relationships [Nearing et al. 2020] could help support ECR professional development and success in future scenario exercises.

7 Conclusions

The CONVERSE Distributed Volcanism Scenario Workshop that ran from February 4 to March 4, 2022, sought to prepare the volcanology community in order to maximize scientific return from future volcanic unrest events, and promote cooperation, collaboration, and coordination within the volcano science community. We assessed the scenario workshop for its effectiveness in co-generating knowledge, catalyzing transdisciplinary collaboration, supporting research confidence, and fostering a culture of inclusion within the volcano science community. Through survey responses and discussions within the workshop meetings, supporting and elevating early career researchers emerged as a clear priority for the volcano science community. Future scenario workshops have been identified as an opportunity to deliberately support, mentor, and elevate early career researchers. This is important for broadening participation within actual unrest events, where time and resources may be limited or variable and the same level of mentorship and support may not always be feasible.

In contrast to previous similar workshops, this workshop was the first of its kind, known to the coauthors, to intentionally design an extended, month-long remote exercise via current software platforms. The extended duration of the scenario contributed to the authenticity of the exercise. As a remote event, this modality also allowed for broader participation of more individuals by removing financial constraints and alleviating other barriers to participation.

Given the importance of preparing for volcanic unrest events, scenario exercises play an important role within the volcano science community. Both organizers and participants found the month-long exercise to be engaging and productive, while also acknowledging the significant effort required both to prepare and to execute the exercise. With additional attention to opportunities to support ECRs and more deliberate participant recruitment strategies for the workshop, future exercises can better support the goals of broadening participation and inclusion within the volcano science community.

Author Contributions

YCL contributed to conceptualization, methodology, writing (original draft and review); EL contributed to conceptualization, methodology, writing (original draft and review); RM contributed to investigation, analysis, and writing (original draft); TPF contributed to conceptualization, methodology, funding acquisition, project administration, and writing (review); CC contributed to conceptualization, analysis, and writing (review); WS contributed to conceptualization, analysis, writing (original draft and review); MPP contributed to conceptualization, analysis, writing (review); AMI contributed to conceptualization, analysis, and writing (review); CW contributed to conceptualization, analysis, and writing (review); JGS contributed to analysis, and writing (review); HW contributed to writing (original draft), SW contributed to analysis and project administration; TK contributed to analysis.

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Data Availability

Data set related to this paper available at: https://doi.org/10.5281/zenodo.7041968.

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