Outcomes report from the Workshop on Advancing Integrative Volcanology with Community Experiments

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Executive Summary

Workshop presentations and discussions articulated a timely need for community experiments to accelerate progress in volcanology. In particular, there is a high level of community interest in advancing multi-scale understanding of eruption cycles through integrated observational, laboratory, and modeling projects that demand levels of resources and teams of scientists that are typically impractical for single principal investigator or collaborative proposals to core National Science Foundation programs. Key research target areas for Community Volcano Experiments (COVEs) include:

- Physical and chemical controls on transitions in eruption cycle phase from repose to runup to eruption onset, peak(s), and cessation
- Process-based connections between magmatic processes, dispersal of eruptive products, and hazardous environmental effects
- Geological time-scale controls on magma storage versus transport in the crust and the life-cycle of volcanoes

A common challenge to many aspects of the research target areas above is the need to overcome observational biases through systematic observational components of COVEs. From the beginning of COVE design phases, these observational components must be intertwined with laboratory and modeling research to achieve a process-based multi-scale understanding of the evolution of volcanic systems. Similarly, optimization of COVEs for training of future scientists and engagement of stakeholders beyond the volcanology community must be integral to project design and execution. Recommendations for initiating new COVEs to meet these objectives focused on two complementary observational strategies:

- A synoptic global-style initiative to establish a minimum effective baseline of observations and instrumentation at a large number of active volcanoes globally to overcome observational biases.
- A suite of locally focused experiments chosen to systematically span different eruption regimes. These would densely and diversely, in terms of disciplines, instrument individual or small clusters volcanoes, constrain their geological histories, and push the limits of models rooted in physical processes and observational data assimilation.

Contents

1. Introduction and premise of the workshop

Volcanic processes are understood conceptually and, in some instances, quantitatively. We have a general understanding how magma is generated in subduction zones and how that process relates to plate tectonics, the release of water from the subducting plate, and the movement of magma through the mantle wedge and crust. We have general concepts of crustal magma reservoirs and eruption triggers, such as the influx of new magma or volatiles into an existing chamber, changes in the tectonic stress field, pressurization of a magma chamber due to crystallization and sealing processes, or rapid decompression due to surficial mass movements such as landslides. Once an eruption starts, we occasionally have high spatial and temporal resolution observations that allow us to characterize the eruption and understand causes for differing styles between eruptions and the evolution of the single eruptive events. While we have a general, and sometimes, quantitative understanding of these processes, in most cases we are unable to forecast volcanic activity due to both a lack of detailed multi-parameter observations and insufficient models with which to interpret those observations. This is especially the case for aspects of volcano behavior that relate to the run-up, duration, style, volume, and environmental consequences of eruptions where our understanding remains incomplete and fragmented (*NAS, 2017*). The recent ERUPT consensus report (*NAS, 2017*) provides details on these aspects and highlights three grand challenges:

1. Forecast the onset, size, duration, and hazard of eruptions by integrating observations with quantitative models of magma dynamics.
2. Quantify the life cycles of volcanoes globally and overcome our current biased understanding.
3. Develop a coordinated volcano science community to maximize scientific returns from any volcanic event.

One of the major conclusions of the ERUPT report was that addressing grand challenges in volcanology demands enhanced community coordination (*NAS, 2017*). Following this notion, a large group of 70 volcanologists gathered in November 2018 in Albuquerque, NM, to discuss how community experiments may help address these grand challenges in volcanology. The 2.5-day workshop consisted of a range of formats for discussion and idea sharing: plenary presentations, breakout group discussions, as well as lightning talks and poster presentations (>40 of the 70 participants contributed lightning talks and/or posters). This report summarizes the views of workshop participants regarding the main science questions that should and can be addressed via community experiments (section 3), the observational needs and models that should be built into the design of such experiments (section 4), and key attributes of the community structure that should be built to maximize the return from these experiments. This report closes with recommendations that reflect the workshop participants' input and feedback (section 5). The Appendices include the workshop agenda, participant list, and definitions of acronyms used in the report.

2. What are community (volcano) experiments?

Community experiments are research initiatives where a scientific community comes together by pooling resources to perform observational, analytical, and/or collaborative activities that are beyond the capacity of smaller projects driven by one or few principal investigators (PIs). These projects prioritize advancing the frontiers of open-access for data, physical samples, and analysis methods. Additionally, community experiments immediately provide opportunities for scientists beyond the experiment PIs engage in research benefitting from project resources. Community experiments have become an increasingly popular mechanism for frontier projects spanning continental scale geophysics and geology (*Williams et al., 2010*), seafloor volcanology (*Kelley et al., 2014*), and amphibious investigations of plate margins (*Toomey et al., 2014*). One of the goals of this workshop was to gather input from the community regarding key attributes desired of potential community volcano experiments (COVEs) and the scientific questions that could be best addressed through community experiments.

3. Scientific Motivations

The participants at the COVE workshop were asked to define the knowledge gaps and scientific motivations that should guide future COVEs. This section summarizes the themes and views expressed at the workshop in a list of questions. These questions all fall within Challenges 1 and 2 from the ERUPT report (*NAS, 2017*), but present a more detailed view aimed toward helping guide the design of effective community experiments.

3.1 *Can we forecast eruptions?*

There are many aspects to addressing this question because observational geophysics, geochemistry, and geological constraints must be continually integrated to develop, improve, and apply models for eruption forecasting. Following the hypothesis that eruptions can be forecast (at least in many circumstances), there are subsidiary questions about how the observable triggers and essential aspects of models vary across volcanic systems (e.g., open or closed vent, shorter/longer repose time). It is possible, and perhaps likely, that different model components and geophysical, geochemical, and geological input data will be diagnostic for different types of volcanoes. We should seek to understand commonalities and ways to transfer forecasting expertise across different and diverse volcanic systems. By focusing on process-based rather than statistical forecasting, we should be able to address other fundamental questions about the ascending phase of the eruption cycle. For instance, what physical and chemical parameters primarily control eruption repose time and run-up time?

3.2 *Once an eruption starts, what controls its evolution?*

Beyond forecasting the likelihood of eruptions within a given time interval, we should seek to forecast eruption size, duration, and associated primary and secondary hazards. While there is great diversity in how volcanic eruptions evolve, it is important to investigate the degree to which there are more physically probable sequences that eruptions follow from run-up to one or more maxima and eventual cessation. The need to better identify controls on eruption evolution reinforces the importance of process-based models that can efficiently assimilate emerging observational constraints. Such models coupled with multiparameter observations could elucidate the processes underlying temporal variations in eruption rate and style.

3.3 *How do the life-cycle stage of volcanoes and evolving state of the surrounding crust affect the eruption cycle?*

Presumably, magmatic processes within the observational record are a key driver of volcanic activity, but there are also roles for the geological history of magmatism and the evolving state of the surrounding crust. We should strive for an understanding of the eruption cycle in the context of the life-cycle of the volcano itself as well as feedbacks with stress, strain, and rheology in the host crust. Such an approach is motivated by the outstanding need to systematically understand the leading factors controlling volcanic diversity (e.g., position of specific volcanoes, compositional variability) and why many volcanoes change the way they erupt through their lifetimes. Volcanic products document this evolution in the geological record, but it remains a challenge to unravel the intertwined roles of the history of the magmatic system (e.g., integrated flux and its temporal variations) and the tectonic or geomorphic settings (e.g., stress/strain redistribution due to rheological and/or volumetric changes). Addressing this challenge is at the root of understanding how best to transfer modeling approaches between systems with different volcano life-cycle stages and crustal settings.

3.4 *What controls magma storage and transport?*

Most volcanism is ultimately driven by the flux of primitive magma into the crust, but accurate accounting for system inputs and outputs through time is lacking (i.e., mass balance from mantle to crust and atmosphere). We should seek to use the geologic record in conjunction with modern observations to constrain mass transport and rate changes through the entire system, including the factors that control stalling versus ascent of magmas. A key question in this context is why do some magmas reach the surface while others stall to form crustal intrusions? Addressing this question will be informative over geological time scales but it is also inherently linked to the ability to forecast eruption cycles because useful observationally-driven models should be able to forecast when unrest is unlikely to result in eruption.

3.5 *How do we successfully overcome observational biases that distort modern perspectives on the eruption cycle?*

There is a great need to initiate systematic observational programs including instrumental monitoring of active volcanoes and detailed constraints on their geologic history. Given that many volcanic systems have long repose times relative to scientific goals, it appears essential to attempt spatial sampling of many volcanoes to compensate for the brevity of the instrumental record at any given system. In conjunction with dense ground-based measurements, we should fully take advantage of remote-sensing approaches (e.g., InSAR) which provide a much better sampling over *in situ* approaches. An outstanding question is if we can trade space for time in this manner and still emerge with the correct understanding of the processes that govern eruption cycles? The alternative of observing over geologic time scales is obviously infeasible so we should try to push limits of trading space for time while being cognizant that the history of specific systems and their unique geological settings may add unconstrained complexity to the resulting observations. Taking this strategy further we should also seek to address the degree to which we can extrapolate inferences from extinct and exhumed volcanic systems to active ones.

3.6 *Can eruptive processes including the evolution of lava flows, volcanic jets, plumes, and ashfall be forecast with physical models coupled to magmatic processes?*

Once eruptions begin, their eventual hazards and expressions in the geological record are controlled by the dynamics of mass transport in lava flows, volcanic jets, plumes, and ashfall. We should strive to advance physics-based frameworks for modeling these processes and coupling such models of eruptive mass transport to models of magmatic processes used to forecast the eruption onset, duration, and mass flux. An integrative approach is important to identification of potential feedbacks between subsurface, surface, and atmospheric components of eruptions. Advancement of models of eruptive mass transport will require enhanced understanding of microphysical properties of rapidly evolving jets and plumes as well as lava flow rheology. We should carefully investigate the strengths and limitations of how well controlled lab experiment phenomena can be scaled up to make inferences about volcanic eruptions.

4. Needs for Observations, Models, and Community Structure

4.1 Addressing observational bias

A central concern expressed by the recent community reports (*NAS, 2017; The SZ4D Initiative, 2017; Gomberg, et al. 2017)* and the workshop participants was the observational bias that currently exists in volcano science. Our understanding of volcanic processes and the life cycle of a volcano is informed predominantly by the small number of volcanoes that have been studied in the past few decades with modern multidisciplinary instrumentation and detailed investigations of their geologic record (*NAS, 2017)*. These well-studied volcanoes are often located in relatively accessible regions and in countries with greater economic resources. Generally, highly instrumentally studied systems have produced only relatively small and frequent eruptions while large eruptions are still rare in the modern instrumental era. Conversely, large eruptions are best represented in the long-term geological record. Consensus emerged from the workshop that this observational bias needs to be addressed -- and could be addressed through community experiments -- in order to significantly advance our understanding of the broad spectrum of volcanic activity.

4.2 Observing the full eruption cycle

All volcanoes studied to date are characterized by periods of eruptions or prolonged restlessness, separated by, generally, longer periods of quiescence. The lengths of the quiet periods, the run-up time to eruptions, and the eruptive periods vary widely between volcanoes. Eruptions may last from a few days to decades while the quiet periods may last from days to many centuries (*Gomberg et al., 2017*). This variability of activity, run-up periods, and repose periods makes the study of volcanoes inherently challenging, given the short observational time scales of human lives and agency funding cycles. The ERUPT report and the discussions at the COVE workshop stressed the importance of simultaneous multidisciplinary observations of the full eruption cycle in order to overcome previous limitations in understanding based on the investigation of a few volcanoes that are in or close to an eruptive episode. Many volcanoes have clear eruptive precursory signals (*NAS, 2017; The SZ4D Initiative, 2017; Gomberg et al., 2017).* In order to understand the underlying processes causing these precursory signals and move eruption forecasting beyond the more commonly used statistical approaches, we need to integrate high-fidelity, multidisciplinary observations with adequate process-based volcano models that incorporate the relevant physics and chemistry (*NAS, 2017*).

Currently active or short-repose period volcanoes are better suited for COVEs, simply for the reason that we are likely to observe run-up to an eruption or to a 'failed' eruption within a realistic observational project and funding cycle. The community stressed that observations of 'failed' eruptions, where unrest is detected through seismic, deformation or gas measurements but an eruption does not occur, are important. These events may even be similarly valuable to the understanding of volcanic systems as 'catching' an eruption (see, for instance, decadal run-up to the 2010 Eyjafjallajokull eruption, *Sigmundsson et al., 2010*). If an eruption occurs, well-planned observational strategies would enable the community to investigate the processes that directly affect the evolution of the eruption, including the transport of erupting materials and the termination of the eruption. While observations of volcanic systems that are currently in long repose are useful scientifically and for understanding volcanic hazards and the eruption cycle, they do not warrant a broad-scale community experiment that aims to provide the best possible data streams to volcano scientists. Selection of the most adequate and productive COVE targets needs to be grounded in geochronological and physical volcanology studies to determine prior eruptive behavior and recurrence rates. Physical volcanology, characterization of the deposits and petrological studies, in addition to geophysical observations and models, will be instrumental once the eruption starts. This information will provide key details on processes of magma depth, ascent rates, and volatile contents that are salient ingredients for volcano models as well as guiding observational strategies during the eruption.

Ultimately, the selection of the COVE targets that provide insights into the full eruption cycle and how volcanic systems move through the cycle will provide the most complete understanding of volcanic eruptions, their repose, and timing. This information in turn will lead to better model-based forecasting approaches that will further guide instrumentation and monitoring adjustments and improvements.

4.3 Eruption response and COVEs

The COVE workshop highlighted the need to establish well planned experiments to capture the full eruption cycle, entirely consistent with the suggestions of the recent community reports (*NAS, 2017; The SZ4D Initiative, 2017; Gomberg, et al. 2017).* COVEs are not envisioned to focus on rapid response to eruptions at volcanoes that are not already incorporated in pre-planned and ongoing community projects. While rapid response is directly related to Grand Challenge #3 (*NAS, 2017),* this aspect of volcano science is being addressed by another initiative, the Community Network of Volcanic Eruption Response (CONVERSE). CONVERSE is currently organizing multidisciplinary groups to prepare for obtaining the best possible data and samples from eruptions in the U.S. in the near future (*volcanoresponse.org*).

COVEs are intended to focus on capturing the time between eruptions and ideally the longer run-up to an eruption than would be impossible to capture with a rapid response approach. However, once an eruption begins at a pre-planned COVE site, there should be a degree of flexibility in the COVE resources to capture unprecedented details of processes occurring during the eruption and its eventual cessation. A clear pre-planned approach specific to the organizational and logistical characteristics of any COVE site is considered an important requirement. Open and frequent communication between COVEs and CONVERSE will generate unparalleled synergies between longer-term pre-planned experiments and rapid response approaches. Coordination between these different observational modes will maximize the scientific return from exceptional events at sites that provide an outstanding level of pre-eruptive constraints and integrative models with which to test and improve our process-based understanding of eruption cycles.

4.4 Observational approaches

The expertise of the workshop participants represented the wide variety of observational approaches that exist in volcanology. Participants were encouraged to think about and discuss observations that should be made as part of a COVE to best address the scientific motivations identified on the previous day of the workshop. A list of of the most-discussed observational approaches is provided below:

- Rock, ash, and gas samples (comprehensive survey and responsive field campaigns, and where possible auto-collection via pre-installed collectors)
- Continuous gas measurements (composition and flux)
- Ground-based geodetic sensors: GNSS, tiltmeters, gravimeters
- UAS-based observations of surface and low altitude atmosphere (visual, thermal, gas, ash)
- Seismic sensors (sparser longer-term broadband networks, denser shorter-term short-period networks)
- Controlled seismic sources
- Radar remote sensing for deposit mapping, pyroclastic density currents (PDC), plumes
- Satellite geodesy (InSAR)

- Optical remote sensing (e.g., thermal, ash, CO_2, SO_2)
- High-resolution and repeated topography surveys
- Infrasound (arrays and single sensor, co-located with seismic)
- Plume observations (optical, IR, scanning DOAS)
- Volcanic stratigraphy (pits, shallow wells or lake cores)
- Magnetotelluric imaging in 3-D (and maybe time-dependent conductivity structure)
- Thermal infrared and visual cameras (potentially enabling high-frequency repeat photogrammetry)
- Lightning detectors
- Potential frontier observations such as muon transmission should be kept in mind if practical

Workshop participants attempted to define the baseline of analyses that will be needed on the raw data and samples collected and the baseline products that should be provided back to the community by COVEs. These are meant to be foundational resources to aid more in-depth and innovative analyses by any interested investigators. Mentioned baseline activities and products include but are not limited to:

- Baseline geologic maps
- Volcanic deposit stratigraphy, textural analyses, and geochronology
- Topography and mapping products from UAS surveys and other airborne or spaceborne remote sensing measurements
- Preliminary geocoded radar amplitude, coherence and deformation maps from satellite geodesy
- Corrected time-series from GNSS (daily positions as standard product, sub-daily high-rate positions for eruptions / short-term rapid deformation)
- Preliminary seismic and infrasound event catalogs in addition to access to continuous waveforms
- Multi-gas and scanning DOAS and UV cameras time series
- Corrected gravimetry time series
- Basic rapid-response petrology to enable sample requests for specialized analyses
- Rapid-response physical analyses of grain and vesicle size distributions and shapes
- Deposit thickness data following an eruption
- Measurements of fragmentation level if possible
- Accurate, detailed geophysical metadata, including problem identification
- Atmospheric winds and temperature structure

4.5 Integrative models

One of the motivations of COVEs is to bring together observational and theoretical approaches and scientists to enable a new level of process-based models needed to address the questions in section 3. There is a need for a wide range of observational constraints at the same systems as described in the preceding sections. These observational resources must be coupled with development and optimization of models rooted in physical and chemical processes. Model parameters should be optimized based on assimilation of observational data including uncertainties. Requirements for facilitating model development include easily accessible observational constraints on magmatic system structure and temporal variations in activity such as surface deformation, degassing, and seismicity. Some of these products are often available at volcanic systems, but not necessarily all in the same place and there is a need to improve metadata and uncertainty constraints to ensure that observational results are appropriately incorporated in modeling efforts. Translating observational constraints such as seismic velocity or conductivity into magmatic properties like melt, fluid, or gas fraction and composition remains a challenge in linking models to observations. Continued advances in laboratory and theoretical investigations of material properties will be needed to increase the robustness of models guided by data assimilation. In the domain of computational implementation of process-based models, open-access codes and convenient environments for collaborative code development and testing are needed to facilitate progress and broaden the user base. Code and code documentation should be treated the same as observational data in terms of sharing, maintenance, credit, citation, and version control. While increased model complexity will likely be needed to enable process-based prediction of diverse observational constraints, the overarching goal is to use process-based models and data assimilation to identify the key controlling factors of the eruption cycle.

4.6 Considerations for COVE data sharing and distribution

Timely and effective sharing and distribution of data are critical aspects of COVE. The workshop participants raised several related considerations:

1. While national data archives exist for some types of relevant data, for instance IRIS for seismic and UNAVCO for geodetic data, other kinds of data do not currently have an established 'home'. For example, no database exists for real-time gas chemistry.
2. Standards for reporting data quality, data uncertainties, and metadata must be defined at the start of an experiment.
3. Data archiving and distribution is a large undertaking, and the appropriate staff resources must be dedicated and included in COVE budgets.
4. Data sets must be citable and allowed to evolve; a suggested mechanism is a version-specific DOI.
5. As for data, resources are required for archiving, re-distributing, and analyzing physical samples. In some cases, suitable repositories already exist (e.g., seismic data at IRIS DMC or rock samples at the Smithsonian).

4.7 Community building aspects of COVE

COVEs would require building upon and improving connections among existing community resources for storage and distribution of data, data products, and software for data interpretation and visualization. Examples of resources to leverage include: WOVOdat (*wovodat.org*), EarthChem (*earthchem.org*), IRIS DMC and EMC (*ds.iris.edu/ds/nodes/dmc/*; *ds.iris.edu/ds/products/emc/*), UNAVCO (*unavco.org/data/data.html*), CIG (*geodynamics.org*), SZ4D Modeling Collaboratory (*sz4dmcs.org*), VHub (*vhub.org*), Smithsonian Global Volcanism Program (*volcano.si.edu*), Geohazards Supersites and Natural Laboratories GEO initiatives (https://geo-gsnl.org/), SARVIEWS Hazard Portal (*sarviews-hazards.alaska.edu*), and others. In many cases it may be practical to simply incorporate COVE products in existing frameworks. In other cases there may not be an ideal venue and COVEs must establish ways to adhere to FAIR data principles (Findable, Accessible, Interoperable, Re-usable). Some form of meta-platform dedicated to individual COVEs should be created or adopted and then provide convenient links to all data stored at the appropriate repositories. Recent efforts within NSF's EarthCube or Interdisciplinary Earth Data Alliance (IEDA) should be leveraged as much as possible to efficiently realize such a framework.

Any COVE will need to develop mutually beneficial working relationships with long-term volcano observatories and hazard mitigation agencies. These connections will likely be required in multiple countries. There is a need to seek out expertise gained through prior community volcanology efforts that required collaboration between academia and domestic and international hazard mitigation agencies such as VUELCO (*vuelco.net*), DECADE, CEOS (*ceos.org*), and STREVA (*streva.ac.uk*).

The community dynamics and behavior are an important aspect of a successful COVE. Workshop participants discussed the potential of technology, e.g., social media and online communication channels to maintain activity among thematic working groups during and following COVE. At the same time, the importance of a framework for in-person meetings was stressed. Standards for in-person meetings would help improve the ability to attract new participants and stimulate well documented progress in collaborative research. Basic examples include clear prior statements of meeting goals that are distributed to potential participants and openly accessible meeting minutes and outcomes reports. The potential value of involving social scientists and management experts was put forth as way to utilize best-practices in large project management and organizational dynamics.

A reward structure and incentive system was mentioned as critical to sustaining community efforts for the long-term. Positive rewards ('carrots') for data sharing are likely to succeed and supplement or surpass enforcement mechanisms ('sticks'). Examples of positive rewards include the ability to contribute data, data products, and software to data repositories as a means of satisfying data policy requirements for journals and grants. Additional benefits may come from enhanced use of research products due their open accessibility and reducing the PI burden for ensuring long-term archival. Participants emphasized the need for mechanisms for proper data citation and appreciation for leadership and community-benefiting efforts in professional review processes.

5. Recommendations for Community Projects

5.1 Overview

The consensus was that while there may be multiple formats that effective COVEs could take, there are several principles that should guide all of them. These include:

- Address important volcanological questions as defined by the community
- Allow quick, open access to the data collected, following disciplinary best-practices and guidelines for FAIR data (Findable, Accessible, Interoperable, Reusable) as defined to suit the specific needs of the volcanology community
- Include components of training, education, and local capacity building to support instrument maintenance and data interpretation

Among the wide range of possibilities for COVE designs, two primary strategies for understanding the eruptive cycle emerged from the workshop discussions:

- A synoptic global-style experiment, that would establish a minimum effective baseline of observations and instrumentation at a large number of active volcanoes globally to overcome observational biases
- A locally focused approach would aim to densely and diversely, in terms of disciplines, instrument one or a small cluster of volcanoes, obtain detailed constraints on their geological history, and push the limits of integrative models rooted in physical processes and assimilation of observational data. A suite of focused experiments should be chosen to systematically span different eruption regimes.

Ideally, both strategies would be implemented in tandem as they represent complementary components, each with the potential to address different problems mentioned in section 3.

5.2 Standardized global survey of diverse active volcanic systems

The synoptic component would provide relatively large-scale low-resolution coverage by deploying a basic set of instrumentation (e.g., seismic, gas, geodetic) on a large number of volcanoes globally. A synoptic approach aims to capture observations that span volcanoes in different stages of their life cycles. This approach is consistent with some of the recommendations that emerged from the recent SZ4D workshop report which provided a suggestion of observing 80 of the most actively degassing and deforming volcanoes globally (*The SZ4D Initiative, 2017).* The workshop participants pointed out that it will be critical for this approach to establish and standardize data distribution and system maintenance protocols through clear agreements with the wide network of international collaborators that will be involved in such a global project. The facilitators of this component should put an emphasis on local capacity building, training and recognition and being cognizant to enhance and not disturb ongoing operational monitoring. Examples of synoptic experiments are the global seismic network (GSN), the international GNSS Service (IGS), EarthScope, and the Network for Observation of Volcanic and Atmospheric Change (NOVAC).

Preliminary work is needed to lay the foundation for a standardized global survey. Science-based recommendations for the minimum necessary level of multi-parameter observation should be developed based on the capabilities of existing volcano monitoring networks, emerging capabilities due to new instrumentation and telemetry options, and results to emerge from CONVERSE efforts. A global network would require initiating or expanding academic partnerships with domestic, international and local observatories, government and hazard mitigation agencies. The maintenance of such a global network will be a major challenge and would have to be addressed and resolved in the planning stages with local observatories and agencies. Equally important for the success of such a network and buy-in from local agencies are arrangements that would allow instruments to remain on the volcanoes past the duration of the project. Global satellite data and other studies, including but not limited to historical and geological records of volcanism, should be used to develop a prioritized list of potential sites for the standardized global network.

5.3 A set of focused scale pre-planned experiments

In a focused approach, one, two or a small cluster of volcanoes would be densely instrumented with multi-disciplinary observational equipment that provides (at least partially or near real-time) high rate, high-resolution data over several years. This approach requires careful selection of the volcano site(s) to capture different stages of the volcano life cycle. Strong consensus emerged from the discussions that it is critical to focus on volcanoes with shorter repose times and those that provide the opportunity for multi-disciplinary and detailed observations of the signals during run-up to eruption. An example of a targeted experiment that follows the COVE principles are the current observatory at the Axial submarine volcano (*Kelley et al., 2014*) and the proposed facility at Erebus volcano, Antarctica. It was also noted by the participants that a more focused approach should also incorporate local capacity building, training, and existing monitoring efforts.

There is not a single volcanic system that would optimally address all the driving questions so multiple focused COVEs are recommended to build up to a set of focused experiments at a range of volcanic systems (acknowledging limits to relatively short repose times of decades or less). If a few or several COVEs are possible they should prioritize spanning diverse systems rather than conducting multiple COVEs at similar systems in different locations (e.g., variable magmatic flux, composition, prior eruption styles).

5.4 Framework for participation, integration, and synthesis

The specific framework for participation, integration, and synthesis will need to be molded to serve specific project goals, but the workshop discussions identified key attributes generally applicable to COVEs. Opportunities for participation in fieldwork, opportunities to leverage COVE resources to bolster individual PI proposals, and opportunities to engage in meeting and research working groups should be openly advertised through a central COVE website, on listservs and other commonly used and emerging community engagement mechanisms. Effective integration will require regular goal-oriented interactions among multidisciplinary scientists. Regular in-person meetings with clear goals should be a high priority and modern tools for remote communication should be used with greater frequency to sustain and document progress between in-person meetings. A potentially useful analog for collaborative research working groups focused on specific products and questions comes from the Southern California Earth Center (SCEC; *scec.org*), which supports an evolving set of goal-oriented working groups that often lead to open-access community products such as fault zone models or structural seismology models. A lesson learned from recent large-scale community projects including new major observational capabilities is that synthesis efforts and resources should be planned at the outset of the project. Otherwise the results of observational approaches may not be optimally transferred to fueling advances in integrative models that can eventually enhance the societal impact of research on hazardous volcanic processes.

5.5 Broader impacts

COVEs should be beneficial to local populations and hazard mitigation agencies wherever they take place and regardless of the specific design such as focused projects or a standardized global network. Positive impacts should include outreach, formal and informal education, training opportunities, and capacity building for increased resilience to volcanic hazards. To achieve these goals, COVE site selection should give consideration to threat levels and societal impact related to the specific system(s) that are targeted or close analogs to those systems that would also benefit from enhanced understanding of fundamental volcanic processes. Outreach efforts may take many forms, but COVEs should strive to use formal media (e.g., local journalism) as well as social media to increase local awareness of the occurrence, goals, and ways to learn about or be involved in projects. Interested COVE scientists should be trained in effective public and stakeholder communication. Consideration of citizen science opportunities such as visual monitoring reports and rapid collection or documentation of ashfall could be especially effective in volcanological studies provide mutual benefits for community members and researchers. In addition to imperative connections to local volcanology observatories from the onset of the project design, COVEs should strive to establish connections with experts in a variety of non-volcanology fields. Local engineers, land managers, computer scientists, and public policy or health officials are among the wide range of people who may have interest and expertise relevant to broadening the impact of COVEs.

Engagement of local schools should occur at multiple levels. At K-12 levels this could take the form of information and class materials for teachers as well as in-person class visits. For local or regional university and community college students fieldwork opportunities and internships that provide deeper interactions with COVE scientists would be beneficial. COVE sites should also be included in already existing local field courses and exercises to broaden participation of local students and experts. COVE budgets should include some resource for paid internships to make these opportunities more accessible. Students from host regions involved in COVE research activities (field or analysis) should gain transferable skills and exposure relevant future opportunities. Focused multi-year COVEs should seek to develop a cohort of students who are positively impacted and able to benefit from interactions with each other as well as COVE scientists. The current Cooperative Institute for Dynamic Earth Research (CIDER) could serve as a well-established and highly successful and effective approach to train students in multi-disciplinary and in-depth training and education.

The breadth and depth of recommended activities to promote broader impacts would require substantial resources and those should be considered in the design of COVEs. Depending on the scale of COVEs (e.g., focused versus global network) a centralized office may be the best approach. Potentially, multiple COVEs could share common resources as education and outreach approaches may be useful for multiple sites. Regardless of the scale of COVEs, a clear plan and budgeted resources for coordinating broader impact efforts are considered important components.

Appendix

A1. Workshop Agenda

Start	End	28-Nov	Invited Penary Speakers
8:00 AM	8:45 AM	Introduction, NSF, USGS, SZ4D	
8:45 AM	9:45 AM	Plenary 1 - Grand Challenges, Role of Community Projects	Bruce Houghton
9:45 AM	10:00 AM	break	
10:00 AM	12:00 PM	Plenary 2 - Observational Limits/Challenges	Kari Cooper, Diana Roman, Angie Diefenbach
12:00 PM	1:30 PM	Lunch on-site, posters	
1:30 PM	1:45 PM	Goals for Breakout 1	
1:45 PM	3:30 PM	Breakout 1 - Grand Challenges, Role of Community Projects	
3:30 PM	4:15 PM	Posters	
4:15 PM	5:00 PM	Lightning talks 1	
5:00 PM	7:00 PM	Dinner off-site	
7:00 PM	7:45 PM	Lightning talks 2	
7:45 PM	8:30 PM	Plenary 3A - Integrative Models	Kyle Anderson
Start	End	29-Nov	
8:00 AM	8:30 AM	Day 2 intro/goals	
8:30 AM	9:15 AM	Plenary 3B - Integrative Models	Amanda Clarke
9:15 AM	10:00 AM	Lightning talks 3	
10:00 AM	10:15 AM	break	
10:15 AM	11:00 AM	Plenary 4 - Potential Community Project Designs	Terry Plank
11:00 AM	12:00 PM	Breakout 1 reports	
12:00 PM	1:30 PM	Lunch on-site, posters	
1:30 PM	2:15 PM	Plenary 4 - Potential Community Project Designs	Mike Poland
2:15 PM	2:30 PM	Goals for Breakout 2	
2:30 PM	4:15 PM	Breakout 2 - Potential Community Project Designs	
4:15 PM	5:00 PM	Posters	
5:00 PM	7:00 PM	Dinner off-site	
7:00 PM	7:45 PM	Breakout 2 reports	
7:45 PM	8:30 PM	Plenary Discussion, Lightning talks (as needed)	
Start	End	30-Nov	
8:00 AM	9:00 AM	Plenary 5 - Framework for Community Participation	Kerstin Lehnert
9:00 AM	10:30 AM	Breakout 3 - Framework for Community Participation	
10:30 AM	10:45 AM	break	
10:45 AM	11:15 AM	Breakout 3 reports	
11:15 AM	11:45 AM	post-workshop outcomes/resources	

A2. Workshop Participants

Adam Kent	Oregon State University
Adam Schultz	Oregon State University
Alberto Roman	Jet Propulsion Lab, Caltech
Amanda Clarke	Arizona State University
Angie Diefenbach	U.S. Geological Survey
Ashton Flinders	U.S. Geological Survey
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Beth Bartel	UNAVCO
Brandon Schmandt	University of New Mexico
Brett Carr	Columbia University, LDEO
Bruce Houghton	University of Hawaii
Charlie Mandeville	U.S. Geological Survey
Christelle Wauthier	Penn State University
Christy Till	Arizona State University
David Fee	University of Alaska Fairbanks
Dennis Geist	National Science Foundation
Diana Roman	Carnegie Institution for Science
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Emily Brodsky	UC Santa Cruz
Erika Rader	University of Idaho
Esteban Gazel	Cornell University
Eva Zanzerkia	National Science Foundation
Federica Lanza	University of Wisconsin-Madison
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Geoffrey Abers	Cornell University
Glen Mattioli	UNAVCO
Greg Waite	Michigan Tech. University
Helen Janiszewski	Carnegie Institution for Science
Holli Frey	Union College
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Josef Dufek	University of Oregon
Julia Gestrich	University of Alaska Fairbanks
Julie Oppenheimer	Columbia University, LDEO
Kari Cooper	University of California Davis
Kathleen McKee	Carnegie Institution for Science
Kent Anderson	IRIS, PASSCAL
Kerstin Lehnert	Columbia University, LDEO
Kevin Ward	South Dakota School of Mines & Technology

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Megan Newcombe	Carnegie Institution for Science
Mel Rodgers	University of South Florida
Michael Ort	Northern Arizona University
Michael Poland	U.S. Geological Survey
Michelle Coombs	U.S. Geological Survey
Paul Lundgren	Jet Propulsion Lab, Caltech
Paul Wallace	University of Oregon
Peter Kelly	U.S. Geological Survey
Philipp Ruprecht	University of Nevada, Reno
Richard Aster	Colorado State University
Ronni Grapenthin	New Mexico Tech
Seth Moran	U.S. Geological Survey
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Taryn Lopez	University of Alaska Fairbanks
Terry Plank	Columbia University, LDEO
Thomas Giachetti	University of Oregon
Thomas Shea	University of Hawaii at Manoa
Tobias Fischer	University of New Mexico
Tom Murray	U.S. Geological Survey
William Wilcock	University of Washington
Yan Zhan	University of Illinois at Urbana-Champaign

A3. Acronyms

CEOS - Committee on Earth Observation Satellites
CIDER - Cooperative Institute for Dynamic Earth Research
CIG - Computational Infrastructure for Geodynamics
CONVERSE - Community Network for Volcanic Eruption Response
COVE - Community Volcano Experiment
DECADE - volcanoes highlighted by the International Decade for Natural Disaster Reduction
DOAS - Differential Optical Absorption Spectrometer
DOI - Digital Object Identifier
ERUPT - Volcanic Eruptions and their Repose, Unrest, Precursors, and Timing
FAIR - Findable, Accessible, Interoperable, Re-usable
GNSS - Global Satellite Navigation System
GSN - Global Seismic Network
IEDA - Interdisciplinary Earth Data Alliance
IGS - International GNSS Service
InSAR - Interferometric Synthetic Aperture Radar
IR - Infrared
IRIS - Incorporated Research Institutions for Seismology
IRIS DMC - IRIS Data Management Center
IRIS EMC - IRIS Earth Model Collaboration
NAS - National Academies of Science
NASA - National Aeronautics and Space Administration
NOVAC - Network for Observation of Volcanic and Atmospheric Change
NSF - National Science Foundation
PDC - Pyroclastic Density Current
PI - Principal Investigator
SCEC - Southern California Earthquake Center
STREVA - Strengthening Resilience in Volcanic Areas
SZ4D - Subduction Zones in 4 Dimensions
SZ4D MCS - SZ4D Modeling Collaboratory for Subduction
UAS - Unmanned Aerial Systems
USGS - United States Geological Survey
VUELCO - Volcanic Unrest in Europe and Latin American Countries
WOVOdat - World Organization of Volcano Observatories Database

References

Gomberg, J.S., Ludwig, K.A., Bekins, B.A., Brocher, T.M., Brock, J.C., Brothers, Daniel, Chaytor, J.D., Frankel, A.D., Geist, E.L., Haney, Matthew, Hickman, S.H., Leith, W.S., Roeloffs, E.A., Schulz, W.H., Sisson, T.W., Wallace, Kristi, Watt, J.T., Wein, Anne (2017). Reducing risk where tectonic plates collide—U.S. Geological Survey subduction zone science plan: U.S. Geological Survey Circular 1428, 45 p., https://doi.org/10.3133/cir1428.

Kelley, D. S., Delaney, J. R., & Juniper, S. K. (2014). Establishing a new era of submarine volcanic observatories: Cabling Axial Seamount and the Endeavour Segment of the Juan de Fuca Ridge. *Marine Geology*, *352*, 426-450.

McGuire, J.J., T. Plank, et al. (2017). The SZ4D Initiative: Understanding the Processes that Underlie Subduction Zone Hazards in 4D. Vision Document Submitted to the National Science Foundation. The IRIS Consortium, 63 pp.

National Academies of Sciences, Engineering, and Medicine. (2017). *Volcanic Eruptions and Their Repose, Unrest, Precursors, and Timing*. Washington, DC: The National Academies Press. https://doi.org/10.17226/24650.

Sigmundsson, F., S. Hreinsdóttir, A. Hooper, T. Árnadóttir, R. Pedersen, M. J. Roberts, N. Oskarsson, A. Auriac, J. Decriem, P. Einarsson, H. Geirsson, M. Hensch, B. G. Ofeigsson, E. Sturkell, H. Sveinbjörnsson, and K. L. Feigl, (2010). Intrusion triggering of the 2010 Eyjafjallajökull explosive eruption. *Nature*, vol. 468, no. 7322, pp. 426–430.

Toomey, Douglas R., Richard M. Allen, Andrew H. Barclay, Samuel W. Bell, Peter D. Bromirski, Richard L. Carlson, Xiaowei Chen, et al. (2014). The Cascadia Initiative: A sea change in seismological studies of subduction zones. *Oceanography* 27, no. 2: 138-150.

Williams, M. L., Fischer, K. M., Freymueller, J. T., Tikoff, B., & Tréhu, A. M. (2010). Unlocking the secrets of the North American continent: An EarthScope science plan for, 2010-2020*,* 78.