How to respond to (pre-)eruptive volcanic activity for the highest scientific return?

CONVERSE Research Coordination Network & IAVCEI Commission for Volcano Geodesy workshop report

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Introduction

On October 7th and 8th 2019 about 30 members of the volcano geodesy community, representing both the academic community and the USGS Volcano Hazards Program, met in Portland, OR, to discuss the question of the workshop: How can the community prepare for (pre)eruptive volcanic activity at U.S. volcanoes to enable collection of data and observations that will yield the highest possible scientific return from this event? The agenda (see Appendix) addressed four major areas that required discussion:

1) What are the current limits of volcano geodesy and where are the frontiers? What are the big questions in the field that the next eruption can answer?
2) How to respond to precursors and monitor eruptions? What response protocols and engineering problems exist?
3) How to observe and model large and complex deformation?
4) How to handle big data in volcano geodesy, and how can volcano monitoring benefit from real-time (GNSS) applications?

Presentations and discussions around these questions occupied about 1.5 days of the workshop, after which we broke into smaller groups to play through some eruption scenarios at four U.S. volcanoes. The last part of the second day revolved around the question of how to best train and involve early career volcano scientists and establish mentoring networks. A representative from NSF informed on funding mechanisms for rapid eruption response. This report summarizes the key findings from these discussions.

Science Questions

The volcano geodesy community agrees that there remain many major questions that geodesy is well suited to address, and that any volcano in the USA that is well instrumented during an eruption will enable many novel discoveries about not only that particular volcano, but also about volcanic processes in general. This has been demonstrated many times in the past, including, for example, the 2004-2008 Mt. St. Helens eruption (e.g., *Anderson & Segall, 2013)*, the recent eruptions at Eyjafjallajokull (2010, *Sigmundsson et al., 2010*), Grimsvotn (2011, *Hreinsdottir et al., 2014*), and Bardarbunga (2014/15, *Gudmundsson et al., 2016*) in Iceland, and most recently the 2018 Kilauea eruption *(Neal et al., 2018)*, among others.

Key science questions identified during the workshop include:

1) **Can we use geodesy to forecast the beginning and ending of eruptions?**

   Retrospective analysis of several recent eruptions show that the beginnings of the eruptions were obvious from the geodetic data. One example is Grimsvotn volcano in Iceland, where in 2011 high-rate GPS data show a significant pressure drop in the magma reservoir beginning about 1 hour before the subaerial activity due to the formation of a feeder dike (*Hreinsdottir et al., 2014)*. Similar observations on a longer time scale were made before the 2006 eruption of Augustine volcano (*Cervelli et al., 2006)*. Recent work at Okmok shows an increase in failure predictions from geodetic data beginning about two months before the 2008 eruption (*Albright et al., 2019)*. Important questions that remain are: how precise can a forecast be, and how do we determine whether an intrusion will be arrested or reach the surface?

   Forecasting the cessation of an eruption presents additional difficulties, including that we generally do not know how much eruptible material exists in the magma reservoir. It is also difficult to assess how co-eruptive recharge (when it is occuring) may change this volume, and how inelastic processes due to magma evacuation from the reservoir may increase or decrease the volume of eruptible material.

   The final volume of an eruption, however, fundamentally depends on the pressure gradient between magma reservoir and eruptive vent, as well as chamber volume and system compressibility. Recent progress has been made using geodetic data to constrain this, at least for simple scenarios. Yet, this is governed by complex relationships between numerous parameters such as eruptive style, variable flux of material, magma and crustal density distributions, or changes in vent and conduit morphology, all of which can vary with time.

   Progress on this question will require multi-parameter observations at volcanoes. In addition to geodetic observations (gravity, tilt, GNSS, InSAR), seismometers provide obvious signals of rock fracture and magma dynamics. Continuous measurements of eruptive flux are crucial to constrain models and the change in pressure observed by geodesy. Magma compressibility can be constrained by at least basic volatile content inferred from gas-geochemistry observations.

One challenge is particularly large transcrustal magma systems that may enable remobilization of magma mush that is otherwise stagnant in smaller systems. Unknown existing quantities of magma in the crust that can be remobilized due to small intrusions of fresh magma also pose a difficulty in terms of quantifying hazard. Surface deformation observations are sensitive to change, which does not occur until at least a small intrusion takes place, which may be missed in real-time or only be obvious after the fact (e.g., Redoubt, Alaska, prior to its 2009 eruption; *Grapenthin et al., 2013*). Broad gravity and seismic tomography experiments can help to constrain pre-existing magma locations. The hazard from such magma-mixing events is the triggering of large-scale eruptions, which can (e.g., Katmai, 1912), but don't have to come with significant precursors. Lastly, it can be difficult to tie longer-term transient deformation to actual eruptive forecasts. Several volcanoes show time-discontinuous deformation patterns, so the onset of a new inflation period may or may not be related to looming eruptive activity.

A remaining question is the ambiguity related to causes of observed surface deformation. Traditionally, geodetic signal curvature--an exponential trend--has been explained with simple kinematic models of pressure change in an elastic material. With more available time-continuous and densely distributed observations, however, it has been recognized that - at least in certain places - these models may neglect important properties of the system. A long-established magma reservoir, for instance, could be expected to develop a hot aureole due to heat conduction, resulting in visco-elastic behavior even at shallow depths (e.g., *Segall, 2016*). As visco-elasticity is included, questions arise on the kind of rheological model to use (e.g., Maxwell vs. Standard Linear Solid) and whether linear models remain appropriate or non-linear models are required, considerably impacting computational tractability of solutions. Furthermore, the combination of seismicity and deformation in physics-based models of dike propagation (*Heimisson & Segall, 2020*) shows encouraging results unraveling some of the ambiguities inherent in geodetic data that should be built on to understand different aspects of volcanic systems.

2) Where is the magma under a volcano, how precisely do we need to / can we constrain this depth, and what is the magma's composition?

Magma storage depths are important for many volcanic processes. The most important of these is undoubtedly volatile exsolution, which determines the compressibility of the magma and impacts the composition of the magma and how it changes over time. In turn, the quite poorly understood processes right before eruption initiation are governed by the pressure environment, which is determined by storage depth.

While volcano geodesy can, and has, successfully contributed to assessments of where magma is stored under a volcano, most of the techniques currently used are sensitive only to changes in storage as they measure surface deformation. More widespread use of gravity surveys, and where applicable, repeat or time-continuous gravity observations may improve our understanding of magma storage systems. In particular, when gravity is used in tandem with seismic tomography methods questions on storage characteristics, geometry, and magma compositions may be more readily addressed. These observations may also help put surface deformation into context, put better constraints on volume change and material properties, and improve depth constraints below the current kilometer-scale, which would benefit more sophisticated models. This would be an improvement of about an order of magnitude compared to current precision.

Anderson et al. (2019) have shown that untangling of volume and pressure change observations is possible if the pressure change is constrained independently (in that case with Kilauea lava lake levels). This allowed them to put bounds of the total volume of the magma reservoir that fed the 2018 Kilauea eruption, showing that multi-parameter observations are critical in constraining magmatic systems.

3) How do inelastic processes such as magma mush erosion etc. affect eruptive behavior and how can we constrain this with geodetic observations?

Surface deformation and the gravitational field are integrated measures of motion or density distribution in the subsurface. This generally results in model non-uniqueness. Inelastic processes such as magma mush erosion add further complications, and whether we can uniquely identify this geodetically is unclear. Real-time petrologic analyses provide potentially the best approach to identify large crystals eroded from the host rock, or vent/conduit fragments. Geodetically, we may be able to detect such processes if we can establish knowledge of the driving pressure of the eruption - if the pressures are not high enough to maintain an open conduit from reservoir to vent, then some inelastic process must be at work. However, the pressure environment is best constrained through petrologic analyses. Once identified, inelastic processes are likely best modeled with bounded particle methods, etc.

4) What drives the multi-year pulsing behavior that is observed at numerous volcanoes as deformation time series grow? Where is intruding magma coming from in general and what is the signature of its rising from depth? Under what conditions do pulses signify eruption precursors?

Transient pulses, as shown in Figure 1 for station OKNC at Okmok volcano, are usually consistent with volcano inflation and hence suggest episodic recharge through batches of magma that migrate from some deeper region into a shallower reservoir. These often occur on top of a background of long-term inflation, suggesting some time variance in this process. It is unclear whether these pulses reflect some pulsatory behavior at depth, or a path effect (e.g., pooling of limited capacity) as a constant stream of magma migrates to shallow regions. Some hypothesize that this may also be due to fracturing of the stressed rock surrounding the magmatic reservoir. If this is not the mechanism, but the magma is indeed rising in discrete pulses from depth, we should be able to detect some long-wavelength deformation signal in the far field of volcanoes indicating the passing of the magma parcel. Pairing of seismic and geodetic analyses may elucidate the mechanism at work, which may vary by volcano.

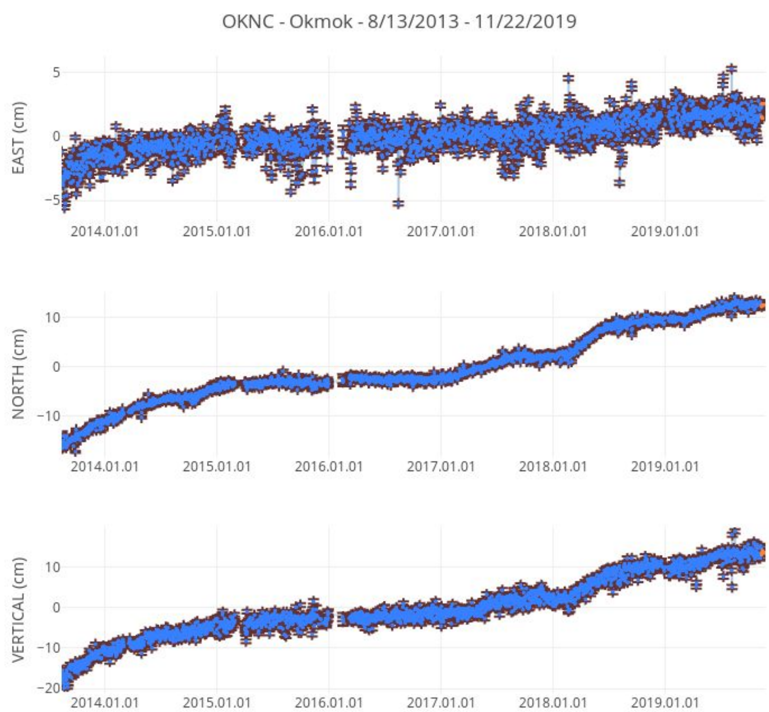

Fig 1: 6 years of GPS data from Okmok site OKNC with respect to nearby site DUTC. North and vertical components, and to a lesser degree the east component, show long-term uplift and outward motion away from a mapped shallow magma reservoir. Superimposed on the long-term motion are 4 transient pulses with much higher rates of motion.

5) **What kinds of magmatic systems (depth range, volume range) can be hidden from a given geodetic network?**

Geodetic observations are constrained by noise in the observations and the geometry of the network or resolution of the imagery. While the network geometry in theory can and should be designed to optimally record signals from suspected sources, in practice station locations are constrained by geography, geology, and landowners. Noise in the data is due to a number of processes that can be modeled and removed, or are inherent to the receiver / observation technique. GNSS observations, for instance, achieve 2-3 mm precision in the horizontal and about twice that in the vertical component under ideal conditions for daily positioning solutions. High-rate and real-time solutions suffer from a higher noise floor, requiring the deformation signal to exceed this level of noise, that has random walk characteristics, sufficiently, to be recognized. Satellite InSAR suffers from atmospheric noise, often caused by the orographic obstacles that volcanoes represent, that can be difficult to characterize and often has a similar magnitude as the deformation signal.

Given these constraints, the lack of a signal in the data does not imply that there is no ground deformation. This begs the question: how much new magma could be hidden from the respective geodetic observation? Or rather, what range of the model space can we not resolve? And, looping back to the discussion in question 1, can these “hidden intrusions” be impactful enough to trigger eruptions?

While this question is governed by many constraints, such as source location and geometry, and the rheology of the host rock, simple models in combination with other data can yield powerful results. One example from Bezymianny Volcano is given in Figure 2, showing in light blue background the model space that would induce at least 1 cm motion in the horizontal (Fig. 2a) or the vertical (Fig. 2b) components for a Mogi source (*Yamakawa, 1955; Mogi 1958*) under the dome of the volcano. All blank space shows magma reservoir depth and volume change combinations that could go undetected by the geodetic network that was in place at Bezymianny.

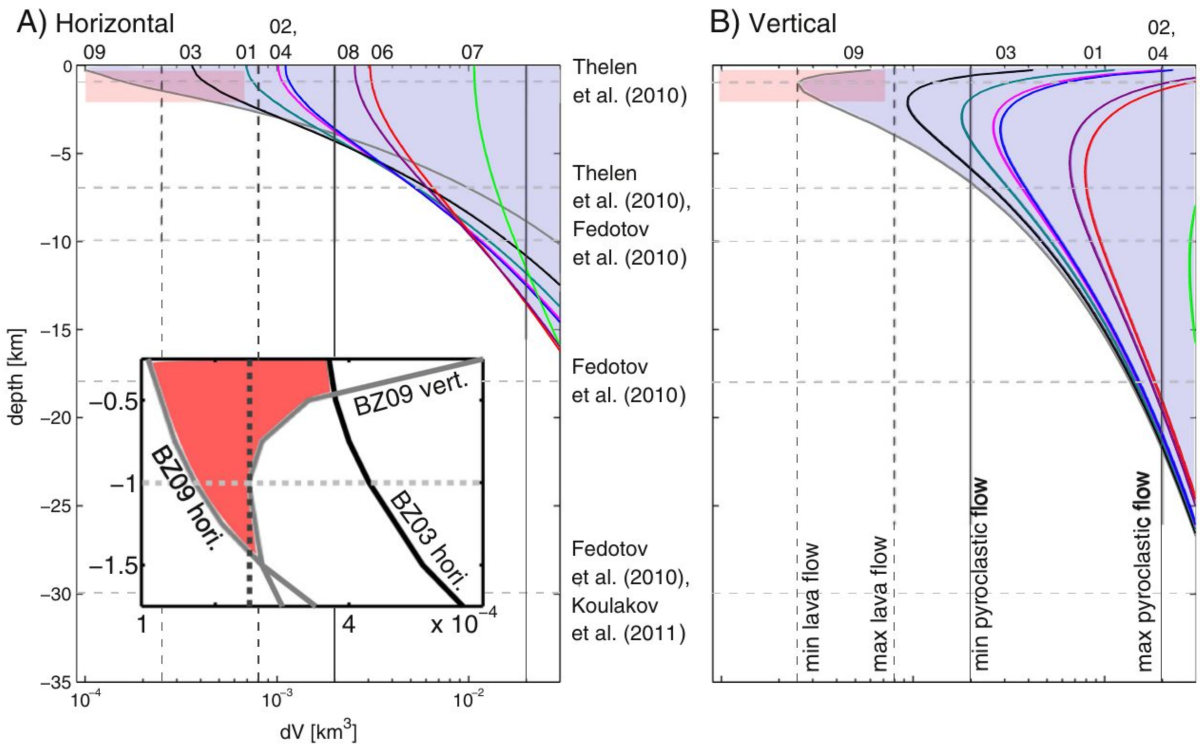

Fig. 2: Model space that is hidden from the geodetic network that was in place at Bezymianny Volcano. A Mogi source is fixed to be underneath the dome of the volcano and depth and volume change are varied. The contours show combinations of volume change and depths that would induce at least 1 cm of motion at the respective GNSS site (indicated by two-digit codes); the blue shaded model space would be picked up by at least one site. The horizontal dashed lines indicate source depths suggested by the studies cited. The vertical dashed and solid lines indicate ranges of recent lava flow and pyroclastic flow volumes. Since the network only showed subtle motion in the horizontal component at station BZ09, the inset shows a zoom of the area highlighted in pink and colors in dark red the model space that could cause this deformation - agreeing with the shallow source mapped by Thelen et al. (2010) using seismic data (from: Grapenthin et al., 2013).

Additional Data Needed

GNSS Considerations

A backbone network of continuous GNSS stations is critical for understanding inter-eruption deformation, detecting the onset of unrest, and directly addressing some of the main scientific questions that remain, including observations of deep magma systems that are primarily detected by small signals in the far field. Observing small deformation signals at far-field GNSS sites requires a long time series of observations to distinguish small deformation signals from other sources of noise.

Multi-GNSS analysis (i.e., inclusion of satellite navigation systems beyond GPS) promises significant noise reduction for both classic static analysis and kinematic or real-time applications *(Geng et al., 2018)*. While effective positioning estimation approaches leveraging the strengths of all available signals are still a very active area of research *(Montenbruck et al., 2014; Liu et al., 2017; Geng et al., 2019; Zheng et al., 2019)*, the improvements are obvious. Standard positioning software packages such as GipsyX *(JPL)* or GAMIT/GLOBK *(Herring et al., 2010)* now have the ability to use multi-GNSS data as orbit information for non-GPS constellations are produced. In many locations, however, hardware in the field may still need to be replaced with multi-GNSS capable antennas and receivers to enable data collection.

To prepare for the next eruption of a U.S. volcano, a network of campaign benchmarks and routine occupation of these with survey equipment will also play a key role in establishing baseline deformation measurements that could then be re-purposed with semi-continuous instruments in the event of unrest. Such semi-continuous GNSS deployments were used, for instance at Redoubt during its 2009 eruption, at Kilauea and Mt. Etna during their respective 2018 eruptions, and are installed at Yellowstone during summer field seasons. Campaign observations can be critical to understand the pre-eruptive magmatic processes as seen, for instance, at Redoubt volcano, 2009. Standardized campaign benchmark pins allowing the placement of an antenna without setting up a tripod simplifies the campaign field work, as well as improves the quality of the measurements.

InSAR Data Considerations

Continuously operating GNSS stations and InSAR remain complementary, with both providing unique perspectives to fully characterize a deformation field. Routine processing of interferograms over volcanoes seems like it will be a reality in the near future through projects like ARIA, ASF SARVIEWS, and COMET. As a community, the availability of standard processing schemes makes InSAR data accessible to a wider range of researchers, but we can’t lose the ability as a community to perform custom processing. The collapse of Kilauea caldera in 2018 was a prime example of needing to look at low-level data to see features that were obscured by unwrapping and filtering. Other sites, many Cascade volcanoes and Long Valley Caldera for example, illustrate why standard InSAR time series processing methods may not be sufficient for many USA volcanoes due to seasonal coherence problems and low rates of background deformation.

Availability of sufficient GNSS displacements in an area imaged by InSAR (with multiple imaging geometries) allows the estimation of 3D displacements with the resolution of the interferogram; the utility of this type of approach has been demonstrated several times on Etna for imaging and understanding complex ground deformation patterns produced by multiple sources.

InSAR data will be available at a large number of volcanoes, and while some will not ever be viable due to dense vegetation cover, other data at high latitudes in the Arctic could be very valuable. Future plans for NISAR indicate that this data may be culled for “redundant” coverage but the multiple look angles could be very useful for understanding the 3D structure of surface deformation at Alaskan volcanoes that are actively deforming and likely to erupt.

Gravity Data Considerations

Gravity data represent one avenue that can undoubtedly open up a much deeper understanding of volcanic systems. Linking measured deformation to gravity changes is the only way to determine the density of the material causing the deformation. The occupation frequency and spatial resolution of existing ground-based gravity measurements are poor compared to deformation data, specifically GNSS and InSAR, and the orbital constraints for satellite based gravity measurements at a fine enough spatial resolution to study volcanoes are currently intractable. Thus, ground based gravity instrumentation is the only way these data will be collected. The introduction of cheaper MEMS sensors by several groups may make the instrumentation more affordable in the near future, providing a means of increasing the numbers of instruments available and the numbers of volcanoes under study. For any of these observations it is important to consider environmental changes, such as groundwater dynamics - particularly critical at reference stations.

Low-cost Instrumentation

In recent years, several low-cost sensors have been developed with the general purpose to lower the noise level by deploying large numbers of sensors. Dense deployments of so-called nodes in the seismic community have increased our understanding of some fault-related (e.g., *Lin et al., 2015*) and volcanic processes (e.g., *Hansen et al., 2015, 2016*), while low cost positioning instruments have been used in Chile to record earthquake displacements (*Brooks et al., 2016)*. Distributed Acoustic Sensing (DAS) also promises significant advances, such as already shown for offshore fault mapping (*Lindsey et al., 2019)*, through the ability to deploy virtual sensors along a fiber optic cable at meter-scale distances. With any of these instruments, the trade-off is generally between data quality vs. data quantity. Low-cost instruments deliver lower quality data, but their deployment in large numbers can still significantly improve scientific discovery. From a monitoring perspective it is important to keep in mind that much of the cost of an instrument network is not necessarily driven by the individual sensor and its installation, but the logistics required to maintain the instrument in remote areas, and telemetry needs to bring back the data. In regions that are easily accessible by road and foot, with not-too-harsh climate conditions and cell network or local internet access, these may be a very promising option for future high-density observations. It is important to note that the individual volcano dictates the required signal-to-noise ratio. Subtle signals are unlikely to be picked up by a few low quality sensors, but high density instruments can work together to provide useful information.

Offshore Geodesy

The need for seafloor observations was discussed in the context of expanding observations for subaerial volcanoes offshore to increase network aperture and allow capturing of deeper processes at small volcanic islands. Furthermore, the exciting results from the 2015 eruption at Axial volcano demonstrate the potential to unravel volcano dynamics with multi-disciplinary approaches. Ship-assisted seismic imaging can yield a detailed anatomy of the magma domain (*Arnulf et al., 2014*) and is much easier than on land. Continuous observations of ocean bottom pressure, tilt and seismicity, supported through a fiber optic cable that allows real time data retrieval, can capture repose and co-eruptive dynamics of the systems, allowing to predict the eruption from inflation (*Nooner & Chadwick, 2016*), infer structure and dike pathways from seismicity (*Wilcock et al., 2016*) and magma body zonation (*Chadwick et al., 2016)*.

Possible seafloor geodetic observations include ocean bottom pressure sensors, tilt, fiber optic strain, GPS acoustic, and gravity (*Burgmann & Chadwell, 2014*), which can deliver - as in the Axial case - real time data if cabled, or they can be utilized in survey mode for repeat observations. While more costly and logistically challenging, the benefit arising from offshore observations is a more comprehensive view of the magmatic system.

Integrated Multidisciplinary studies

It is clear that to make progress in volcano geodesy, the community must integrate multidisciplinary data. The value of combinations of geodetic data with seismic, petrologic, and gas geochemical observations (both in real-time monitoring, but also in scientific analyses) has been pointed out repeatedly in the Scientific Questions above. The tighter we are able to make constraints on parameters such as material properties, densities, porosity, and gas content, the more feasible it will become to increase model complexity. Such multi-parameter models *(e.g., Anderson & Segall, 2011)* and their (Bayesian) inverse formulations (*Anderson and Segall, 2013*, *Wong et al., 2017*) are at the current cutting edge of volcano modeling practices. However, to extract useful information from the results, significant amounts of multi-parameter data are necessary -- a requirement only few monitored volcanoes currently fulfill. Hence, ultimately, our ability to leverage multi-disciplinary observations remains constrained by the spatial and temporal sampling density.

Eruption Response

Discussions on planning and executing the response to unrest and eruption of a volcano revolved around a set of questions:

1) How to best monitor an eruption to maximize scientific return?
2) Identify shared tools (hardware, software, models) that could be advanced collaboratively for mutual benefit among partners
3) New technologies that will further Volcano Geodesy?

At the end of this section, we provide a list of potential peacetime preparations.

How to best monitor an eruption to maximize scientific return?

A strong consensus of the geodetic community is that any instrumentation must be on the volcano before any eruption. While this may seem obvious, resource constraints make this currently infeasible: of the 90 Holocene active volcanoes in the Aleutians, for example, only 9 have continuous GPS in place, and only 3 of those are also equipped with electronic, shallow-borehole tiltmeters. In the Cascades, Mt. Baker, Mt. Adams, and Glacier Peak currently do not have continuous ground-based geodetic instrumentation despite their record of Holocene eruptions. Other high-threat volcanoes, such as Mt. St. Helens, are well instrumented thanks to their history of eruption.

Having instrumentation in place before the onset of unrest is particularly important for the scientific community to document any pre-eruptive deformation. Eruption initiation, magmatic recharge, and intereruptive evolution of the magmatic system are poorly understood. The threat posed by an active volcano, particularly due to explosive activity, may make it impossible to supplement any instrumentation once the activity has begun. Furthermore, some eruptions may be over before field work mobilization is possible, and an entire cycle of eruptive activity may be missed without instrumentation in place.

The community realizes that not all volcanoes can be permanently instrumented at densities optimal for scientific exploration. Hence, it is important to establish or continue campaign observation networks at as many volcanoes as possible. Routine campaigns have the benefit of resolving baseline activity of a volcano and maintaining updated the coordinate time series, but they are also important to keep a working knowledge in the community for maintaining suitability (e.g., maintain sky view) for rapid temporary continuous GNSS deployments.

The equipment required for either campaigns or temporary continuous deployments may come from UNAVCO, but this resource cannot be guaranteed in the future. However, significant numbers of campaign kits exist dispersed within the community, including observatories and individual academic PIs. Instead of warehousing large amounts of equipment, UNAVCO could fill the role of inventorying equipment locations, working status, and availability, and could facilitate the shipping to where it may be needed during a response. UNAVCO can also provide guidance to the community for standards that pool-acceptable campaign instruments should meet.

To alleviate unnecessary telemetry burdens at remote field sites, cGPS receivers should stream lower rate data (15 seconds) and ring-buffer high rate data (1 or 5 sps) locally on the receiver. In case of interesting activity, the buffered highest-rate data should be downloaded for scientific exploration. While monitoring activities can establish flexible real-time solutions dependent on telemetry possibilities, scientific return is maximized with highest-possible sampling rates. While near-real time or rapid recovery of data from additional response sites may be desired for monitoring, scientific exploration will be possible after the fact.

All data and derived products (time series, velocity fields, model results) should be available to the full scientific community in near-real time or as soon as generated. UNAVCO and the geodetic community have established a culture of open and rapid sharing of data. Digital Object Identifiers (DOIs), as implemented in data centers, allow product attribution. US volcano observatory data are all archived at UNAVCO. USGS, NASA and university collaborators should have data and product pathways planned out before any activity commences. Utilization of community data archives such as UNAVCO and near-instant archival should be the standard for any instrumentation that may not be already automatically contributed.

Routine InSAR analysis of volcanoes and distributed volcanic fields can play an important role to guide ground-based instrumentation and aid in rapid analysis, as the revisit times of current SAR platforms have decreased significantly in recent years (now measured in days instead of weeks). While long-term InSAR time series have the capability to resolve small deformation signals, it is important to note that volcanoes are often a poor environment for InSAR: they are steep-sided, seasonally or perennially snow-covered, affected by significant tropospheric noise, and often host abundant vegetation. These conditions may result in missed detections of even significant deformation. Currently several groups (e.g., ASF-SARVIEWS, JPL-ARIA) already have response systems in place where interferograms are automatically generated upon passing a threshold of activity.

Open engagement of interested communities is very important for maximizing scientific return. This can be established by open, public calls for input of potential scientific targets. This should not become a burden to be handled by the Volcano Observatory scientists; instead, a working group or scientific advisory committee (incl. some observatory scientists, and likely volcano or region specific) should be in place and interface with the community to define the big scientific drivers of the response, solicit and evaluate proposals, and recommend collaborations of community members on, e.g., rapid response proposals to funding agencies, etc. to streamline and expedite the eruption response logistics at all levels. This will also provide flexibility for the community to respond to the evolution of eruptions (e.g., dike propagation, caldera collapse, secondary vents etc.). Such a committee can also be called upon to manage and respond to potential precursory activity to ensure minimal loss of important observational opportunities.

Recent examples in Iceland have shown that even just one near-field high-rate GNSS station can provide tremendous insight into volcanic activity (*Hreinsdottir et al., 2014; Grapenthin et al., 2018)*. Hardened telemetry and power systems are indispensable in such cases. In cases of large and complex deformation, far-field GNSS field stations can also provide important constraints on models of the magmatic system and its evolution, even if the deformation amplitude is significantly smaller at these sites. Here, long time series are very important to decrease the uncertainty in volcanic vs. background deformation or noise.

Identify shared tools (hardware, software, models) that could be advanced collaboratively for mutual benefit among partners

The participants agreed that shared community tools are a valuable asset, particularly in the frenzy of an eruption response. Documented, verified and functional code for data analysis and source model inversions is of particular value. Some of these products exist (e.g., dModels; *Battaglia et al., 2013*), but may not have fully dispersed through the community or may be limited in applicability. Low-cost efforts on the individual researcher side would be the publication of, e.g., JuPyter notebooks or other tutorials that include data and code used in a publication. A community-wide effort would involve the development of shared modeling and analysis tools that are open source, thoroughly benchmarked, and versatile enough to allow expansion to include, e.g., more complex rheologies and enable the user to optimize and adapt inversions to the specific case at hand. Lastly, establishing a community-wide accessible cloud (e.g., vHub) providing shared computing resources and standard, vetted tools to leverage for fast analysis will enable rapid responses without much manual spin up time and search for computational resources.

Shared hardware, discussed above (and apart from computer resources that are best shared in the cloud) is mainly composed of geodetic instrumentation such as campaign GNSS equipment, tiltmeters, or gravimeters. Ideally, such instrumentation would be available via UNAVCO's instrument pool, but as mentioned above, that resource has been declining. Above, we lay out a proposal on how the equipment distributed across the community could be inventoried and made available through UNAVCO during responses. Some resources (drill & operators for tilt installations, for instance) may be difficult to mobilize rapidly. Any installations should be approved by the scientific advisory committee for the respective volcano.

New technologies that will further volcano geodesy?

While not an entirely new technology, multi-constellation GNSS, ideally operated at the highest possible sampling rates, was mentioned repeatedly by the community to lower the noise floor and allow for more plume piercing points (to detect and characterize ash plumes; *Grapenthin et al., 2013; Larson, 2013*). Receiver onboard positioning capabilities would decrease the telemetry costs, but would prohibit any non-positioning applications (plume analysis, reflection studies, *Larson, 2019*). Retrieval of phase and range observations seems crucial to fully leverage the observations for scientific knowledge gain. Real-time analysis and publication of these data during eruption response was seen as a critical component for transparent community engagement.

Campaign gravity observations are also not a new technology, but have been woefully underutilized around volcanoes - mostly because of the instrument expense and the need for extended field campaigns. However, such surveys have the potential to illuminate the density distribution below the volcano and hence give a detailed picture of the magmatic plumbing systems before and after eruptions. In special cases where the magmatic system is very shallow, or directly and persistently connected to the surface (via lava lakes, for example), continuous gravity observations can reveal exciting views of the magma properties and dynamics. MEMS gravimeters hold the promise of very dense and continuous observations at a low cost, with higher noise levels compensated for by numerous observation points. In regions with easy access to high-bandwidth telemetry, large-N deployments of such sensors may result in unprecedented views of pre-eruption signals and dynamics.

Drones were seen as a crucial new technology that could be leveraged in various ways. One application was repeat photogrammetry and structure-from-motion analysis at high resolution in both optical and thermal bands. This would provide insight into very shallow and likely inelastic or non-linear source processes near eruptive vents, which are difficult to resolve in any other way. Along those lines, the rapidly evolving drone technology will likely open currently inaccessible or dangerous-to-access places to ground-based instrument deployments.

Airborne or satellite missions include SAR and optical observations. Cubesat constellations with hourly revisit times, for instance, may enable pixel offset tracking and 50 cm or higher resolution. NASA’s GLISTIN, an aircraft mounted interferometer for ice sheet topography measurements, was successfully deployed to monitor the 2019 Kilauea eruption. Other aircraft mounted SAR, such as NASA’s UAVSAR, can provide multiple view angles, rapid repeat times and higher spatial resolution than satellite-based methods.

Offshore geodesy has the potential to increase the network aperture for volcanic islands and submarine volcanoes. The results at Axial Volcano demonstrate that significant progress in understanding magma domain architecture and magma transfer can be made when solving the logistical challenges around establishing and retrieving such observations.

Peacetime Preparations

The general consensus - and the main driver behind the CONVERSE RCN - is that the time between eruptions, or “peacetime,” should be used as effectively as possible to prepare for eruption responses such that the best possible data for scientific analyses are collected once unrest and eruption begin. This includes, but is not limited to the following activities:

- Generate a table of ground-based / satellite based collaborators that are willing to generate and make available to the community higher-order products during eruptions.
- Develop checklists for processing flow, communication flow, and instrumentation deployments
- Routinely run tests of analyses, instruments, standards, and data collection checklists

- Offer training in equipment deployments and data analysis to keep the community updated on the latest standards and to educate a pool of competent field & lab assistants
- For GNSS, identify existing benchmarks or install new ones and establish campaign sites
- Perform routine (GNSS) campaign measurements to establish deformation baseline and enable temporary continuous deployments to immediately generate useful data during a crisis
- Preplan instrumentation networks through modeling and field constraints
- Prepare permitting and funding, including designation of potential leaders to organize the efforts.

Modeling

One of the traditional limitations in modelling of deformation signals is, ironically, that the Mogi model (Yamakawa, 1953; Mogi, 1958) produces generally a very good fit for source geometries for which we don't necessarily think that they are spherical. However, pressure change and volume change are inseparable in such models, which results in generally broad assumptions about magma incompressibility such that changes in source strength are inferred to be new intrusions of incompressible magma. Multi-parameter observations are required to resolve this issue, for instance, gravity or continuous gas observations, as deformation observations alone cannot constrain all the parameters of interest.

Other simplistic analytical models representing different geometries remain useful in the short term and in regions with sparse data, but increases in temporal and spatial sampling density of multi-parameter observations assimilated in physics-driven modeling frameworks will afford us deeper insight into more subtle changes within magmatic systems. Frontiers in data collection include openly available high-quality SAR acquisitions every few days, which - with good coherence and few atmospheric artifacts - can provide exceptional high-resolution deformation maps, albeit in line-of-sight space. Multi-GNSS provides substantially lower data noise to study rapid changes in the sub-InSAR sampling rates (seconds to tens of min to days).

Advances in time-dependent data assimilation and model estimation based on such improved data sets can fundamentally change our ability to forecast volcanic activity over short timescales. This is possible with, for instance, sequential estimation filters (Kalman filter), which allow time-dependent estimation of model parameters - useful in volcanology as magma dynamics are generally not constant in time (e.g., *Albright et al., 2019*). Methods to increase efficiency of complex models (i.e., emulations of simulators via statistical models, e.g., *Gu & Berger, 2016*) will also help improve modeling results.

In general, the availability of ready-to-use, well-tested and validated tools, particularly for more sophisticated analyses, will be instrumental in the future to drive volcano geodesy forward and enable deep insight into processes captured by multi-parameter data. Increasing the availability of real-time data streams and feeding these into real-time models has tremendous potential to improve short term forecasts of volcanic activity.

Personnel and Early Career Involvement and Resources

Volcano geodesy requires a unique combination of field-to-model knowledge that is difficult to find in a student. Looking forward, the volcano-geodesy community needs periodic training opportunities for students to build their quantitative analysis skills and to integrate field observations to instill an appreciation for error sources and uncertainties, and to develop an intuition for real -particularly small scale- signal vs. noise in the data. Related to this, it will remain important for students to understand that GNSS time series are derived products, and not a primary measurement.

While much of the focus of volcano geodesy is often on continuous GNSS instrumentation, one key necessity of deformation studies is having dense historical deformation data to which new co-eruptive deformation measurements can be compared. Participating in GNSS campaigns at volcanoes would be a fantastic opportunity for students to learn about geodesy and gain both field and quantitative experience necessary to pursue research in this area.

Since GNSS or InSAR may not capture deformation signals at systems with very shallow magmatic systems (e.g., in the edifice) or at open-system-type volcanoes, students should also become familiar with other instrumentation and their advantages and drawbacks, such as tiltmeters, strainmeters, gravimeters, or structure-from-motion data sets.

The group identified several avenues for students and early career scientists to get involved in volcano geodesy work:

Undergraduate Students:

- Volunteer at Volcano Observatories
- UNAVCO internship programs (USIP)
- Undergraduates should be encouraged to sign up for various listservs as many opportunities are only advertised there
- NSF REU sites with focus on volcano geodesy, or involve students in existing projects with focus on volcano geodesy via REU supplements
- Promote UNAVCO data in classes

Graduate Students / Postdocs

- IAVCEI early career network (not just US focused) https://www.iavceivolcano.org/about-iavcei/iavcei-s-early-career-researchers-network.html
- Listservs! Many opportunities advertised there
- Summer schools / Field schools: UAF (Katmai, Kamchatka), CIDER - allow connections
- Alaska Volcano Observatory at UAF-GI often has graduate student funding

Involvement in (high profile) eruption response:
- Build network of collaborators early
- Work on open and freely available data, share results
- Offer a **unique** contribution to the response team

Future Needs:
- GNSS processing short courses (e.g., via UNAVCO)
- Courses introducing students to a range of modeling methods
- 2-week short course that includes a multi-instrument geodetic campaign on a volcano, data processing and modeling
- Continued offerings of Strainmeter / tiltmeter workshops (e.g., UNAVCO)
- Mentor-Mentee networks

Hypothetical Case Studies

Mauna Loa

An eruption of Mauna Loa could potentially allow observation of magma ascending from depth. A plausible scenario for such an eruption would include increased motion on the decollement, possibly due to a strong earthquake, that results in unclamping of the rift zone, promoting dike formation and eruption. Likely these processes would be intimately linked. Dense multi-parameter instrumentation may answer several important questions: How do sheeted dike intrusion systems evolve in space and time? Why does magma accumulate in the shallow part of the edifice, in dike-like fashion? This may result in a deeper understanding of the stress profile within the edifice. Also, a wide-aperture instrument network may illuminate the deep magmatic system (this may require having to go off-shore).

The volcano is well instrumented (at small aperture), but most of the GNSS stations are on the southeastern flanks of the volcano. Additional data collection to be initiated during unrest includes supplementing the seismic network, likely with a nodal deployment. UAVSAR or similar aerial acquisitions for high-spatial-resolution InSAR and lava flow mapping could be initiated (and may be useful to routinely perform before an eruption). A broadening of network aperture (seismic, geodetic) at sufficient density will increase our ability to discern deep from shallow sources. Continuous gravity at the summit could potentially provide insights on magma density at shallow depths and system evolution over time. Pre- and post-eruptive bathymetry is likely the only mechanism to determine total eruptive volume, as lava may flow into the sea.

Sunset Crater

An eruption of a small monogenetic cinder cone in one of the volcanic fields of the southwestern USA would test the capabilities of the current geodetic monitoring infrastructure. It is unknown whether eruptions from this type of volcano would be accompanied by substantial precursory deformation, seismicity, or gas emissions. Observations from analog eruptions (e.g., Sierra Negro, Paracutin) would be heavily relied upon for interpreting precursors. This type of eruption would be an opportunity to investigate alignments with background stress fields and magma ascent. However, current instrument networks of GNSS and seismometers are sparse, and thus would need to be densified to learn new information from this type of eruption. Campaign networks would be good to have established in some of these remote volcanic fields.

This type of eruption would be good for academic involvement due to remote occurrence, yet easy road access. Funding for pre-eruption work might be difficult to procure on volcanoes of this type due to little knowledge of the location where the next eruption might occur.

Akutan

Akutan, about 1200 km west of Anchorage in the central Aleutian arc on Akutan Island, has had episodes of inflation in the past, as well as a lava flow in 1978 and eruptions as recently as 1992. Currently, it has been inflating at small (0.5 cm/year) and subtly time-varying rates since at least 2006, much less than during the 1996 seismic swarm with InSAR measured uplift of about 60 cm and modeled as a complex system of 3 deflating and 1 inflating sill/dike sources at varying depths (*Lu & Dzurisin, 2014)*. *Ji et al. (2017)* explain the current inflation episodes with Mogi sources at about 4 km depth.

The geodetic network in place consists of a mix of AVO and NOTA stations. The latter are about to be adopted into the AVO network, making for a total of 12 continuous GPS and 4 shallow borehole tiltmeters. The island is about 20-25 km in diameter and about 13 km the east of the caldera is the small town of Akutan village, home to about 1000 citizens. About 50 km to the West liest the small town of Dutch Harbor, an important fishing industry and location of the nearest regional airport. In addition, an ash-producing eruption poses significant hazard to air traffic, both local and intercontinental between North America and Asia.

The complexity of the previously imaged sources and the episodic inflationary activity over the course of more than a decade hints to a mature plumbing system undergoing recharge. Therefore, continued unrest and potentially eruptive activity could yield significant insight into several of the scientific questions posed above, including causes of pulsatory behavior, or questions related to arrests of dike intrusions versus eruptive activity.

The geodetic network in place covers the island well, but it is limited in its depth resolution by the geographic constraints the small island places on network aperture. Offshore seafloor geodetic measurements (repeat bathymetry, pressure sensors, GPS-Acoustic) could be a useful addition to the on-shore observations. InSAR analysis can be challenging due to decorrelation issues, but has been successful for C-band and L-band radar during the 1996 seismic swarm where portions of the island maintained coherence. UAV's could be useful for repeat DEM flights.

The relatively remote location, often with difficult weather, results in challenging logistics requiring significant pre-planning for both field operations and academic involvement in eruption response.

Funding Mechanisms and Permitting

NSF's RAPID program must be initiated by an NSF PI, preferably one per event. NASA's Rapid Response program provides an additional avenue that can be invoked. Collaboration of PI's on such proposals is beneficial. Both organizations request contact of a program manager by the prospective PI before proposal submission. The IAVCEI-Geodesy email list could be used to solicit and organize collaborators when an event begins.

The permitting process for sites, especially in wilderness areas, can be time consuming and expensive. Establishing networks in advance of eruptions would minimize the permitting process. It is also noted, however, that the demonstration of unrest may help facilitate some permitting processes, but waiting until after the onset of unrest means that the early precursors of the eruption may be missed.

Resources Required for Data Accessibility

USGS data releases require data review, etc., and the process is longer. Direct deposit of any GNSS data into the UNAVCO data repository would enable rapid redistribution. Funding should be requested in any RAPID proposals to fund the deposit and retention of data.

Agenda

CONVERSE & IAVCEI Workshop:
"How to respond to (pre)eruptive volcanic activity for highest scientific return?"

Location: Hilton Portland Downtown, 921 SW Sixth Avenue, Portland, Oregon
Room: Galleria North
Dates: 10/7/19-10/8/19

MONDAY 10/7/19 - DAY 1

Introduction 8:00-8:10 Welcome & Purpose of the Workshop
Ronni Grapenthin, UAF
Emily Montgomery-Brown, USGS

Session 1 Science Questions - What are the limits of Volcano Geodesy? Where are the Frontiers?

8:10-9:05 Paul Segall, Stanford
9:05-10:00 Jeff Freymueller, MSU

10:00 - 10:15 Coffee Break

Discussion 1 10:15-noon Discussion of Research Problems
Leaders: Ingrid Johanson, Paul Lundgren

charge:

What are the big questions in volcanology / volcano geodesy that the next eruption can answer?
What benefits brings interfacing with other disciplines? How to do that?

noon-1:00 pm Lunch on own.

Session 2 Eruption Monitoring / Precursor Responses

1:00-2:00 Peter LaFemina, Penn State
2:00-3:00 Alessandro Bonforte, INGV

3:00-3:15 Coffee Break

Discussion 2 3:15-5:00 Response Protocols and Engineering Problems
Leaders: Emily Montgomery-Brown, Ronni Grapenthin

charge:

How to best monitor an eruption to maximize scientific return?
How to deal with lack of precursory deformation / signals?
Protocols to manage precursory activity
Identify shared tools (hardware, software, models) that could be advanced collaboratively for mutual benefit among partners

Which new technologies will further Volcano Geodesy?

6:00 PM Dinner on own.

TUESDAY 10/8/19 - DAY 2

Session 3 Strategies for observing and modeling large and complex deformation

8:00-8:45	Patricia Gregg, U Illinois	
8:45-9:30	Sigrun Hreinsdottir, GNS Science, (remote)	

Session 4 Big Data Volcano Geodesy (Sentinel and upcoming Nisar

9:30-10:30 David Bekaert, JPL

10:30-10:45 Coffee Break

Session 5 Real-time / high-rate applications of GNSS to volcano monitoring w/ discussion

10:30-11:30 Ingrid Johansen, HVO
11:30-noon Ronni Grapenthin, UAF

noon-1:00 pm Lunch on own

Discussion 3	1:00-2:00	Breakouts: How to respond to eruptions at volcano … ?		
		V1	Sunset Crater, AZ	
		V2	Mt. Baker, WA	
		V3	Mauna Loa, HI	Ronni Grapenthin
		V4	Akutan, AK	
Discussion 4	2:00-3:00	How best to train / involve early career volcano scientists and establish mentoring networks Leaders: Patricia Gregg, Sarah Conway		
	3:00-3:15	Coffee Break		
Discussion 5	3:15-5:00	How to get the best scientific value out of any (US) eruption? Leaders: Dennis Geist, Ken Austin, Peter LaFemina		
	3:15- ~3:30	Dennis Geist, NSF	NSF perspective on funding mechanisms	

Charge:
Consider permitting,
resources for data accessibility / distribution

5:00 wrap-up, next steps for CONVERSE
Ronni Grapenthin
Emily Montgomery-Brown

Workshop Participants

Alberto Roman	Jet Propulsion Laboratory
Alessandro Bonforte	INGV - Osservatorio Etneo
Bill Chadwick	Oregon State University
David Bekaert	Jet Propulsion Laboratory
Dennis Geist	NSF
Emily Montgomery-Brown	USGS
Estelle Chaussard	University of Oregon
Falk Amelung	University of Miami
Ingrid Johanson	USGS, Hawaiian Volcano Observatory
Jeff Freymueller	Michigan State University
Jeffrey Johnson	Boise State University
Ken Austin	UNAVCO, Inc.
Mary Grace Bato	NASA-Jet Propulsion Laboratory
Michael Poland	U.S. Geological Survey
Patricia Gregg	University of Illinois
Paul Lundgren	JPL, Caltech
Paul Segall	Stanford University
Peter LaFemina	Penn State
Rebecca Kramer	USGS - CVO
Ronni Grapenthin	University of Alaska Fairbanks
Sage Kemmerlin	University of Oregon
Sarah Conway	US Geological Survey - Hawaiian Volcano Observatory
Sigrun Hreinsdottir	GNS Science (remote)
Yan Zhan	University of Illinois at Urbana Champaign

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