MAGMATIC DRIVERS OF ERUPTION

What controls the location of volcanoes and the occurrence of eruptions?

SCIENTIFIC MOTIVATION

Recent observations and innovations are fueling a new decadal effort in studying Magmatic Drivers of Eruption (MDE). Magma pathways in the crust have been observed "lighting up," with increases in seismic events prior to, between, and during eruptions (e.g., Pesicek et al., 2018) and some magma storage regions inflating and subsiding - "breathing" - over the eruption cycle (e.g., Xue et al., 2020). New petrological and geochemical studies have found that magma assembly, transport, and run-up to eruptions occur over timescales from hours to years (Costa, 2021), similar to timescales of observed volcanic unrest. Changes in gas CO_2/SO_2 measured weeks to months prior to eruption (e.g., Aiuppa et al., 2017) provide a possible signal of deep magma recharge and a new precursory data stream to integrate into physics-based forecast models (Shreve et al., 2019). High-resolution geochronology over the lifecycle of volcanoes (~ 500 ka) shows evidence for changes in eruptive behavior that is in pace with glacial cycles (Watt et al. 2013; Aubry et al., 2022).

The SZ4D MDE implementation plan is motivated by scientific discoveries and societal urgency. Globally, almost 800 million people live in regions that are directly exposed to volcanic hazards (Brown et al., 2015), and the vast majority of these regions are in subduction zone settings. The crustal magmatic systems associated with subduction zone volcanism also produce critical mineral and energy resources, as well as drive the formation and evolution of continental crust. The SZ4D initiative builds on the MARGINS, GeoPRISMS, and EarthScope programs, which were highly successful in tracing magmatic volatiles through the subduction process, imaging melt in the crust and mantle, and modeling the thermal structure of subducting slabs and the growth of the continental crust. The new focus of MDE is on **the initiation of volcanic eruptions at subduction zones**, as we recognize that there are new discoveries to be made that connect the most hazardous volcanoes on the planet today to underlying subduction drivers. Magmas at subduction zones are volatile-rich, and thus inherently different from those in other volcanic settings. Furthermore, subduction zones are responsible for most of the subaerial eruptive activity that occurs each year. Recent work implicates the entire trans-crustal magmatic system (Cashman et al., 2017) and even the mantle in controlling the initiation of eruptions (Grove et al., 2012; Power et al., 2013; Ruprecht and Plank, 2013). Here, we propose to investigate the entire system of controls on volcanic/plutonic behavior in volcanic arcs in four dimensions (**Figure MDE-1**). By focusing on the trans-crustal magmatic system and how it links the mantle melting region above subducting slabs and the magmas and gases emitted at arc volcanoes, SZ4D will provide a fundamentally new perspective on subduction-related volcanic systems, with the goal of identifying subduction drivers and developing long-term forecasts of eruptions.

A central question motivates MDE's envisioned science activities: **How do trans-crustal processes initiate eruptions at arc volcanoes?** The trans-crustal magmatic system is instrumental in controlling eruption initiation and inter-eruptive unrest and quiescence. Processes within the trans-crustal system either prime or initiate volcanic eruptions outright or provide suitable conditions whereby intrusions and/or eruptions can be triggered by external drivers such as earthquakes or edifice collapse.

Additionally, the dynamic processes that govern the evolution of trans-crustal magma systems, including mantle magma production and the partitioning of mass and energy between volcanic and plutonic components along and across volcanic arcs, span wide temporal ranges. While eruptions may occur over short timescales at Earth's surface, their frequency and vigor may be set by processes throughout the crust and that occur over the lifetime of the volcano or longer (**Figure MDE-1**). These trans-crustal processes underpin the internal and external mechanisms that directly initiate eruptions through overpressure, tensile failure, and/or shear failure in the subsurface. These initiation mechanisms also drive eruption style, composition, eruptive volume, unrest behavior, and timescales.

This chapter is structured to follow the process developed by the SZ4D MDE working group, with input from the broader volcanology community to define:

- **Central Hypotheses** that link eruption drivers and responses at subduction zones
- **A Traceability Matrix** that identifies practical activities to support the science questions that arise from the central hypotheses
- **Notional Experiments** that are guided by Traceability Matrix activities and strategies for deployment at arc volcanoes and segments
- **Site Evaluation** that arises from an inventory of arc volcanoes and exhumed systems and the requirements of the hypotheses and notional experiments
- **Activities** that can precede field experiments
- Parallel **Laboratory and Modeling Efforts**
- **Community Coordination**

The Hypothesis Grid

MDE's central question and scientific framework can be articulated most clearly in terms of magmatic system controls and responses (**Table MDE-1**). Our ultimate goals are to identify underlying subduction drivers and develop useful eruption forecasts.

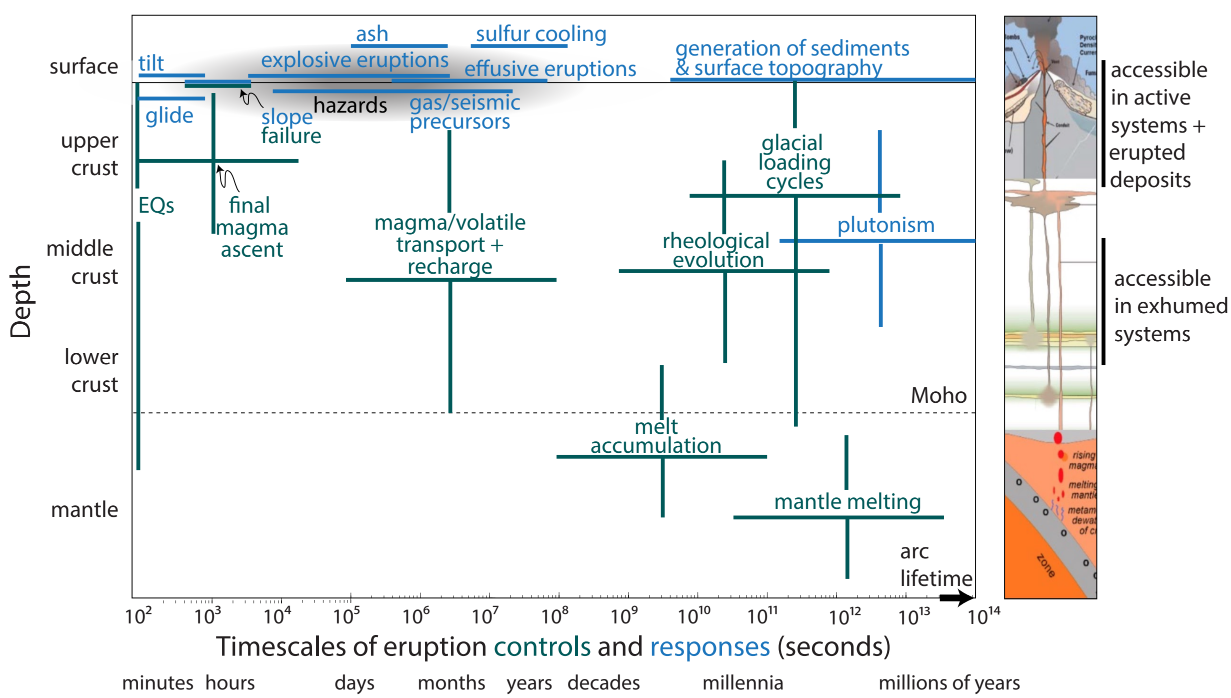
Controls on the magmatic system fall into three broad categories:

1. The supply rates of the magma and volatiles from the mantle to the crust that ultimately fuel all eruptions
2. The volume, depth, and distribution of magma that collectively define a volcano's trans-crustal system
3. The rheology and stress state of magma and surrounding crustal rocks that permit or resist magma movement

System *responses* include consideration of:

1. Eruption precursors and the run-up to eruption
2. Eruption repose, quiescence, and aborted unrest, or intrusion not culminating in eruption, which may lead to plutonism
3. Eruptive style, vigor, and duration - the output of useful forecasts

Figure MDE-1. *Processes across multiple timescales and spanning the trans-crustal magmatic system impact subduction zone hazards near the surface. The goal of MDE research is to connect the volcanic system, the trans-crustal magmatic system, and the subduction system. These systems are typically treated separately, even though they are interrelated. For example, volcanic eruptions may be initiated rapidly by influx of mafic magmas from the mantle wedge. Different trans-crustal magmatic architectures may develop as a response to different mantle magma supply rates. More broadly, arc magmatic systems may respond to and drive FEC and L&S. For example, surface processes such as glacial unloading may lead to greater decompression melting in the mantle and greater eruptive frequency. SZ4D provides the opportunity to test different hypotheses for how subduction processes across a range of timescales - from minutes to millions of years - drive magmatism and volcanism, and the hazards associated with them. The column at right is an amalgamation of three separate cartoons (from the ERUPT report, NASEM, 2017), a reflection of the lack of current integration and the opportunity for SZ4D to make novel connections by drawing on evidence from active volcanoes, erupted deposits, and exhumed arc systems in four dimensions.*



The response of a magmatic system to each control depends on the state of the magmatic system (volume, depth, and magma/pressure distribution) and the mechanical properties of the host crust (rheology and stress state).

The MDE working group considered how recent findings and methodological developments have led to testable hypotheses, and had the MDE Interest Group vote on how to prioritize the resulting Hypothesis Grid. Importantly, additional hypotheses were solicited, and then groups met to discuss the most compelling and testable hypotheses, as well as synergies between them.

As a result, three main sets of hypotheses were identified:

HYPOTHESIS A | Gas and magma composition are linked to eruption precursors, run-up times, and eruption intensities

HYPOTHESIS B | Mantle magma production and supply rate are linked to the intrusive/extrusive mass budget, crustal residence time, repose time, and the evolution of crustal magmatic architecture

HYPOTHESIS C | The periods and drivers of different external eruption triggers over timescales of minutes to >100,000 years are linked

Table MDE-1. *The MDE Hypothesis Grid. Magmatic system controls and responses define a grid of inquiry and testable hypotheses.*

Magmatic System Controls	Magmatic System Responses		
	Eruption precursors and run-up time	Plutonism, intrusion, and repose	Eruption style, vigor, and duration
Supply Rates: Magma and Volatiles • What controls production rate in the mantle? • What controls recharge rate? • What controls recharge composition? • What controls volatile accumulation?	High CO_2 / S gases weeks to month prior to eruption signal deep recharge *Werner et al. (2020)* Mafic eruptions have shorter intiation times *Kent et al. (2019)*	Intrusive flux is related to extrusive flux *Till et al. (2019)* Mafic eruptions have shorter repose times *Passarelli & Brodsky (2012)*	Slow subduction is correlated with lava domes *Zellmer (2009)* Fast magma ascent results in higher intensity eruptions *Gonnermann & Manga (2012)*
Depth and Distribution of Magma • How does magma travel through the entire crust? • How deep does the volcanic system extend? • Why and where do magmas stall? • What controls storage depths prior to eruption?	Mantle can recharge during an eruption *Ruprecht & Plank (2013)* Slow vanguard ascent and staging of eruptions *Roman & Cashman (2018)* Magma systems shallow due to thermal priming *Gualda et al. (2018)*	Optimal depth of magma chamber growth *Huber et al. (2019)* Plutons focus due to thermal weakening *Ardill (2018)* Magma supply influences reservoir location *Lerner et al. (2020)*	Basaltic Plinian eruptions are sourced from shallow magma systems *Bamber et al. (2020)*
Rheology and Stress State • What controls magma density, viscosity, and volatiles? • What controls crustal rheology? • What controls the stress state of the crust? • What are the roles of slope failure and earthquakes in eruption triggering?	Rheology, tectonic stress, buoyancy control magma stalling depths *Watanabe et al. (1999)* Static stress from M≥7.5 earthquakes < 200 km away can trigger eruptions *Nishimura (2017)*	Silic magma systems have longer repose *Passarelli & Brodsky (2012)* Longer repose -> weakened crust and reduced failure *DeGruyter & Huber (2014)* Large viscous systems require an external trigger *Gregg et al. (2012)*	Extension favors calderas *Wilson et al. (1995)* Microlites growing rapidly and heterogeneously during ascent from shallow storage can cause basaltic Plinian eruptions *Sable et al. (2006)* *Bamber et al. (2020)*

HYPOTHESIS A | Gas and magma composition are linked to eruption precursors, run-up times, and eruption intensities. For example (**Figure MDE-2A**):

- High observed CO_2/SO_2 in gases (weeks to months) prior to eruption signal deep magma recharge (i.e., magma recharge drives eruption run-up time periods).
- Eruptions driven by mafic rejuvenation involve shorter initiation times than felsic rejuvenation.
- The run-up to eruption (over years or the full inter-eruptive period) involves stealth ascent, second boiling (i.e., crystallization-induced gas exsolution), and magmatic evolution to more silicic compositions.
- Outgassing efficiency during magma ascent controls eruptive intensity.

Critical scientific needs to test these hypotheses include: constraints on and models to predict magma recharge rate, especially for mafic magma; precursory time series in gas chemistry and geophysical signals; and measures of outgassing efficiency. Ideally, sensor arrays would capture events prior to, during, and after eruptions of varying intensity on many volcano targets. A large number of targets would be necessary to capture unrest and eruption at volcanoes that span a range of subduction parameters, including the subduction rate of water, sulfur and carbon, magma production rates, and upper plate stress regimes. The relevant timescales of processes are minutes to decades.

HYPOTHESIS B | Mantle magma production and supply rate are linked to the intrusive/extrusive mass budget, crustal residence time, repose time, and the evolution of crustal magmatic architecture. For example (**Figure MDE-2B**):

- High mantle-derived magmatic flux leads to shallow magma reservoirs and/or long-term progression to shallower storage depths (i.e., the "crustal ladder").
- Short magmatic crustal residence times (from the mantle to the surface in days to months) lead to high intensity, mafic eruptions.
- Mantle magma supply rate is related to subduction drivers (convergence rate, composition, temperature, and angle of the subducting plate) as well as to the state of the mantle in the wedge, ultimately connecting the structure and evolution of the trans-crustal magmatic system to underlying subduction drivers.

In order to test these hypotheses, key actions need to first be taken, including conducting high-resolution geophysical imaging of trans-crustal magmatic systems, detailed mapping and geochemical analyses of past erupted rocks, laboratory experiments, and studies of exhumed plutonic and volcanic systems on a small number of well-chosen systems that are densely instrumented and comprehensively studied for their magmatic histories. Assimilation of these various data streams within coupled thermal and mechanical models of magma intrusion and accumulation in the crust is critical to understanding the processes that control intrusive-extrusive magma partitioning over timescales of years to millions of years.

HYPOTHESIS C | The periods and drivers of different external eruption triggers over timescales of minutes to >100,000 years are linked. For example:

- Glacial unloading is an external trigger

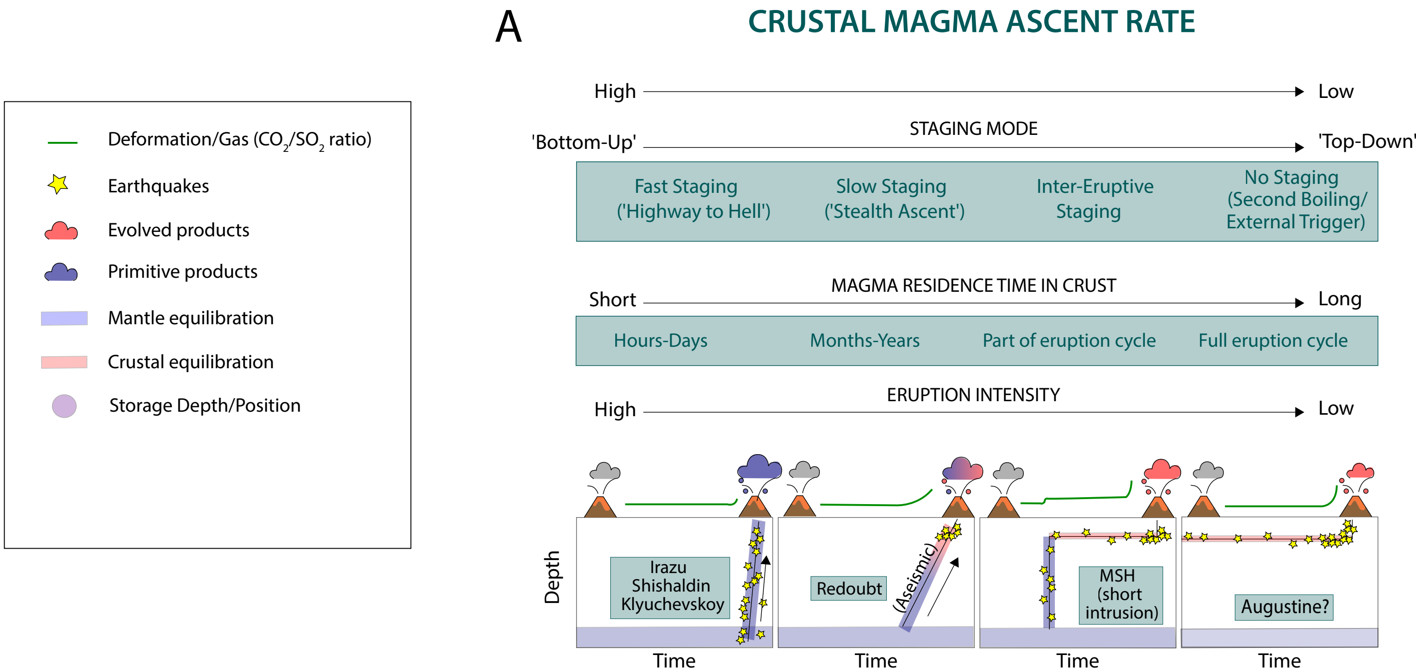
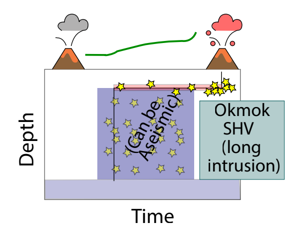
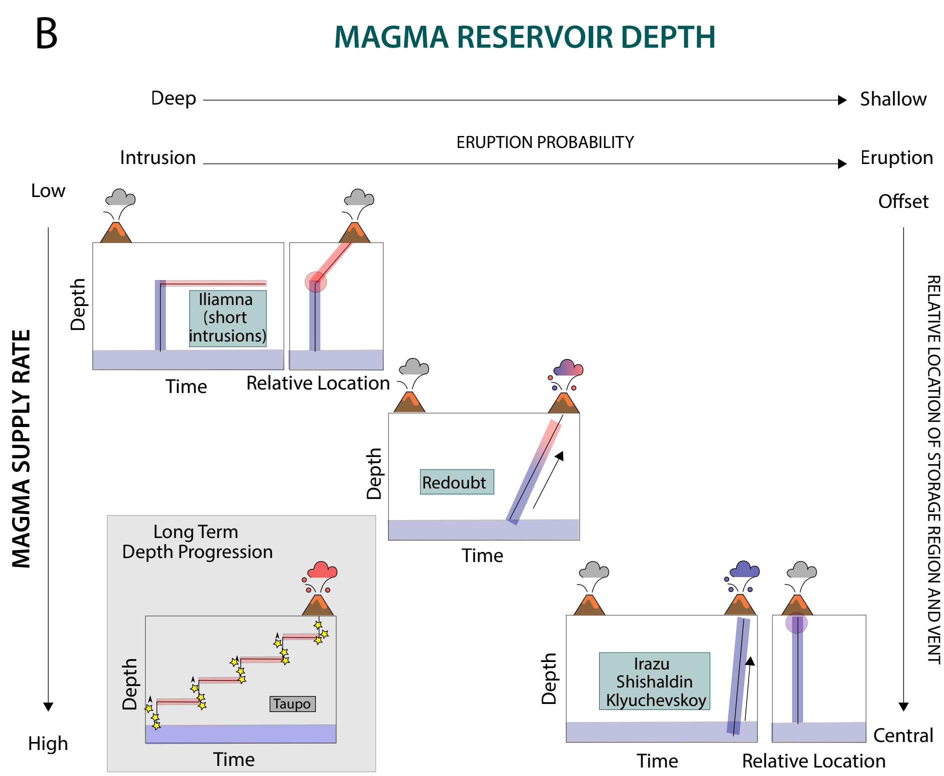


Figure MDE-2. *(A) Graphical summary of Hypothesis Set A, linking crustal ascent rate (left) to crustal staging, residence time and eruption intensity; (B) Graphical summary of Hypothesis Set B, linking mantle magma supply rate (right) to magma reservoir depth and eruption vs intrusion likelihood.*





that occurs over ~10,000–100,000 year timescales.

- Sector collapse can result from hydrothermal alteration of edifice rocks (hundreds of years) or dome growth (months).
- Static and dynamic stress triggering, as from local or teleseismic earthquakes, occurs over hours to seconds, but also requires a magmatic system that has evolved over years toward failure.

Critical scientific needs to test these hypotheses include:

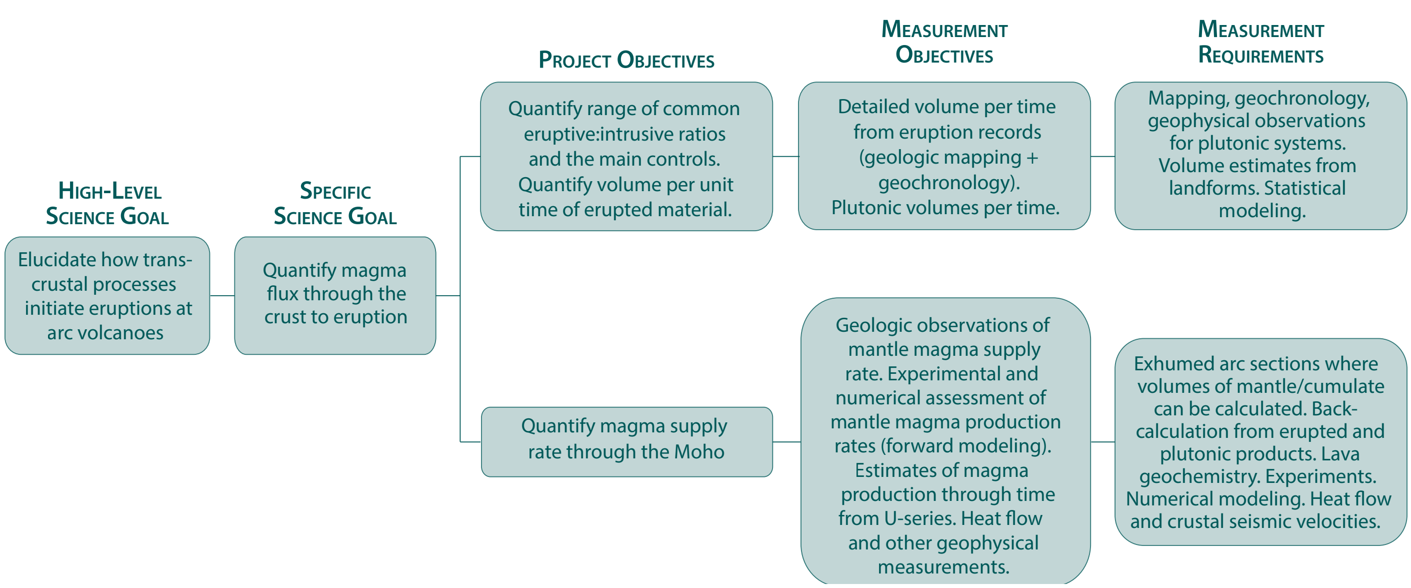
- seismic time series over the shortest timescales;
- geodetic and gas chemistry time series over medium timescales;
- and landscape, geological, petrological, and geochronological studies over the longest timescales.

Furthermore, modeling studies and analog experiments representing a wide range of timescales would constrain the effects of different crustal and magma rheologies and the dynamics of mechanical and thermal evolution. We note that this is an opportunistic hypothesis set, dependent on the nature of activity in the target region(s) during the deployment period in the case of medium- to short-range external triggers. However, as it draws on the same observations required to address Hypothesis Sets A and B, it requires minimal additional observational effort while providing key potential linkages to crosscutting themes and FEC and L&S science goals.

TRACEABILITY OF THE SCIENTIFIC QUESTIONS THROUGH PRACTICAL ACTIVITIES TO ADDRESS HYPOTHESES

The SZ4D MDE working group utilized a *Traceability Matrix* to outline how the three sets of hypotheses will be tested. The traceability matrix provides a logical framework for relating science goals, project objectives,

Figure MDE-3. *Example from the traceability matrix showing how science goals can be related to specific measurements from a variety of disciplines.*



specific measurements, and data products. This approach is useful for identifying linkages between the primary MDE hypotheses. The traceability matrix also provides an efficient way of identifying where datasets from different disciplines should be integrated. **Figure MDE-3** provides an example from the *Traceability Matrix* of how it can be utilized to connect science goals to data collection.

NOTIONAL EXPERIMENTS: INSTRUMENTAL, REMOTE SENSING, AND GEOLOGICAL EFFORTS

The science goals and measurements defined by the *Traceability Matrix* allow us to develop a set of Notional Experiments involving instrument arrays and remote-sensing observations aimed at addressing the key MDE hypotheses. Observations required to address Hypothesis Set A, such as CO_2/SO_2 in volcanic gas emissions and the number and rate of seismic events and locations, can be collected with smaller arrays of instruments (**Volcano Sensor Arrays**, **Figure MDE-4A**) and are thus feasible at a larger number of systems. Thus, for example, a hypothesized relationship between outgassing efficiency and eruption intensity can be targeted with sparse instrument deployments (e.g., seismometers, acoustic sensors, MultiGas sensors, differential optical absorption spectrometers [DOAS], Global Navigation Satellite System [GNSS] receivers), and geochemical and geological studies of recent eruptive products, coupled with a program of **Volcano Remote Sensing**, at a large number of systems that are likely to erupt within the coming decade. In conjunction with these activities, **Volcano Rapid Response Arrays** will enable the flexibility to deploy instrumentation and conduct geologic sampling on volcanoes that erupt or exhibit unrest and have the potential to address science questions.

In contrast, observations required to address Hypothesis Set B include high-resolution geophysical images of trans-crustal magmatic systems, detailed mapping/sampling and geochemical analysis of past erupted rocks, and a detailed understanding of the state of the stress regime, thickness, and thermal maturity of the crust for systems that form in response to a range of mantle magma supply rates (Katz et al., 2022). Thus, tests of Hypothesis Set B will come from detailed observations on the volume and distribution of magma accumulation, along with a complete record of eruption frequencies and volumes from the geological record (see **Exhumed Systems and Their Past Eruptive Records**).

This challenging set of observations requires dense instrumentation arrays that will only be feasible to deploy on a few carefully chosen systems (**Volcano Imaging Arrays**, **Figure MDE-4B**). Volcano remote sensing observations and modeling of, for example, deformation may also help to constrain the distribution and volume of magma accumulation.

Taken together, the Volcano Sensor Arrays, Volcano Imaging Arrays, Rapid Response Arrays, and Remote Sensing observations comprise the complete **VolcArray** needed to address the three main sets of hypotheses (**Figure MDE-4**) in combination with geological, experimental, and modeling work.

Volcano Sensor Arrays

Targeted hypotheses: A and C

Proposed experiments

To investigate some hypotheses requires relatively sparse instrumentation for characterization

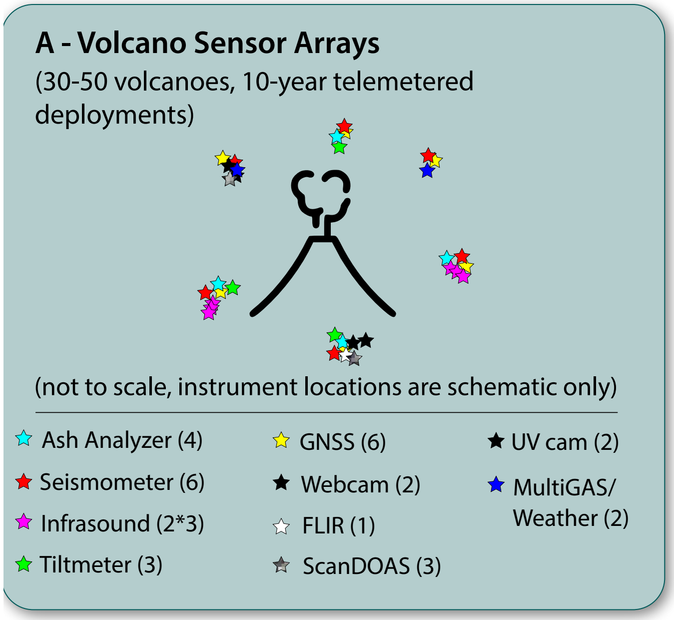
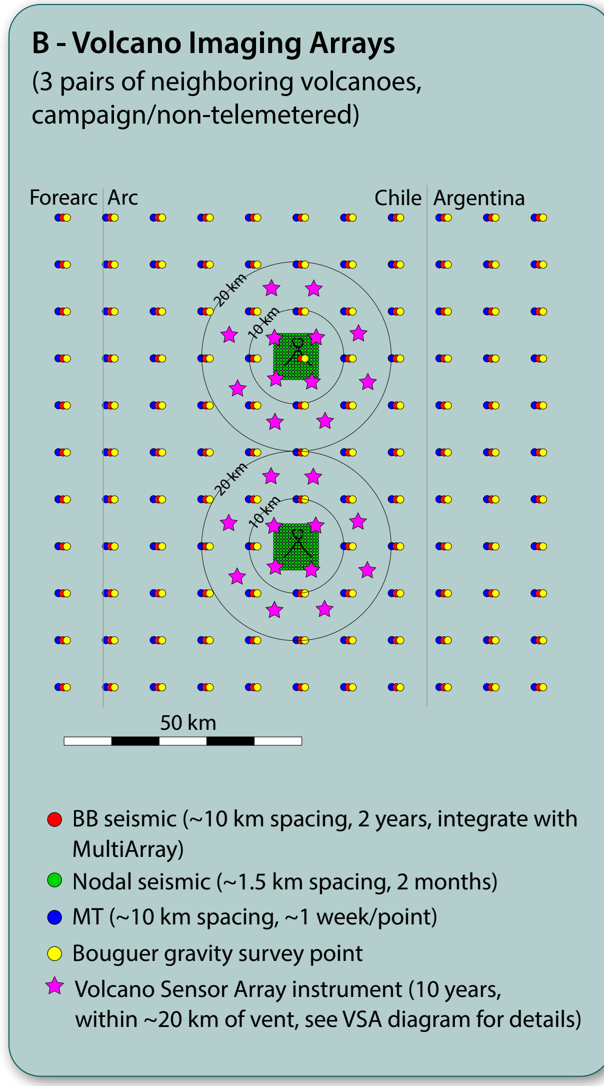


Figure MDE-4. *Schematic of VolcArray. Left panel: Schematic of the Volcano Sensor Array (VSA). Data collected by the array will be complemented with remote sensing observations, rapid response deployments, and a petrologic study of eruptive products produced during the deployment period. Right panel: Schematic of the Volcano Imaging Array (VIA). Data collected by the array will be complemented with remote sensing observations, an in-depth study of past eruption products, and quantification of mantle magma supply. Note VIAs will be co-deployed on a small number of the systems hosting VSAs.*



of unrest during various phases of the eruption cycle (**Volcano Sensor Arrays**), combined with geochemical and geological studies of eruptive products from the observation period. Such deployments are feasible at a relatively large number of systems, likely to erupt within the coming decade. The overarching goals of these experiments are to understand how gas and magma composition are linked to eruption precursors, run-up times, and eruption intensities.

ACTIVITY 1 | Instrument and remotely sense a set of restless (i.e., currently exhibiting seismicity, deformation, or degassing) or potentially active arc volcanoes with visual, thermal, gas, seismic/acoustic, and geodetic monitoring equipment to observe the evolution of the data collected in near-real time, from background state through run-up to and syn-eruption.

ACTIVITY 2 | At the same volcanoes, conduct a petrological examination of erupted rocks in order to determine the cause (e.g., mafic rejuvenation) and - using diffusion chronometry - timing of the eruption initiation event.

ACTIVITY 3 | Compare the results of both sets of studies (Parts 1 & 2), in addition to any regional seismic studies from the FEC working group, to determine whether the hypothesized correlation exists between the recorded gas and geophysical signals and the petrological timing of the eruption-initiation events.

ACTIVITY 4 | Systematically compare petrological/textural and geophysical determinations of magma storage depth and ascent rate for each event with extrusion rate and eruptive styles monitored at the vent.

ACTIVITY 5 | Develop physical models that can assimilate these different datasets (from Activities 1–4) to investigate magma transport processes to forecast eruptions. The observations from Parts 1–4 will also provide the opportunity to investigate the effects of external triggers (Hypothesis Set C) on processes at multiple timescales in magmatic and hydrothermal systems.

SCOPE | We propose to deploy a large number (30–50) of **Volcano Sensor Arrays** to observe volcanoes at different stages of their eruption cycle. The chosen volcanoes should also have different recharge magma chemistries (including mafic) and different eruptive styles. The proposed number of target volcanoes is based on the following analyses. First, if we had deployed **Volcano Sensor Arrays** at all 99 volcanoes worldwide that were degassing (Carn et al., 2017) or deforming (Furtney et al., 2018; Reath et al., 2020) over a 10-year period between 2000 and 2020, we would have observed ~30 full eruption cycles and characterized multiple eruptions that followed repose periods of one to eight years and had a Volcanic Explosivity Index (VEI; Newhall and Self, 1982) of 0–4 (**Figures MDE-5 and MDE-6A, B**). While the probability of capturing a VEI 4+ eruption during a 10-year deployment is low, should such an eruption occur, **Rapid Response Arrays** would enable rapid deployment as the eruption evolves. With 30 to 50 **Sensor Arrays** focused regionally in the Americas, we estimate a probability of ≥0.8 in "capturing and characterizing" approximately ten eruptions in a 10-year period (**Figure MDE-6**). Given the large number of proposed targets, **Volcano Sensor Arrays** could potentially be deployed incrementally, focusing first on a few volcanoes in geographic proximity to the systems chosen for **Volcano Imaging Arrays** and expanding progressively to cover all 30 to 50 target volcanoes.

Expected outcomes

1. We expect to directly characterize the relationship between magmatic processes (e.g., mafic rejuvenation) and associated gas emissions and/or geophysical signals (e.g., deformation). This would enable real-time interpretation of volcanic gas signals during future volcanic unrest, critically improving forecasting abilities.
2. We expect to establish a correlation between mafic rejuvenation as a driver of eruptions and the characteristic timescales over which it initiates eruptions.
3. We expect to identify the critical thresholds in outgassing efficiency and magma ascent rate that correspond to different eruptive behaviors.
4. We expect that any correlation between local and regional seismicity, deformation, and changes in degassing and volcanic seismicity will permit differentiation between external (stress changes on magmatic systems) and internal triggering mechanisms (mafic rejuvenation, or changes in magmatic pressure).

Volcano Imaging Arrays

Targeted hypotheses: B and C

Proposed experiments

To investigate some hypotheses requires dense instrumentation for high-resolution geophysical imaging (Volcano Imaging Arrays), combined with detailed mapping and sampling studies. Deployments are only feasible at a handful of selected volcanoes that represent a potential range of mantle magma supply rates. The overarching goals of these experiments are to quantify magma supply rates from the mantle, the geometry of the trans-crustal magmatic system, and eruptive histories. Therefore, these systems do not need to erupt during the duration of the Volcano Imaging Array deployment, although Volcano Sensor Arrays will also be in place on volcanoes targeted for imaging for opportunistic study in case of eruption or unrest.

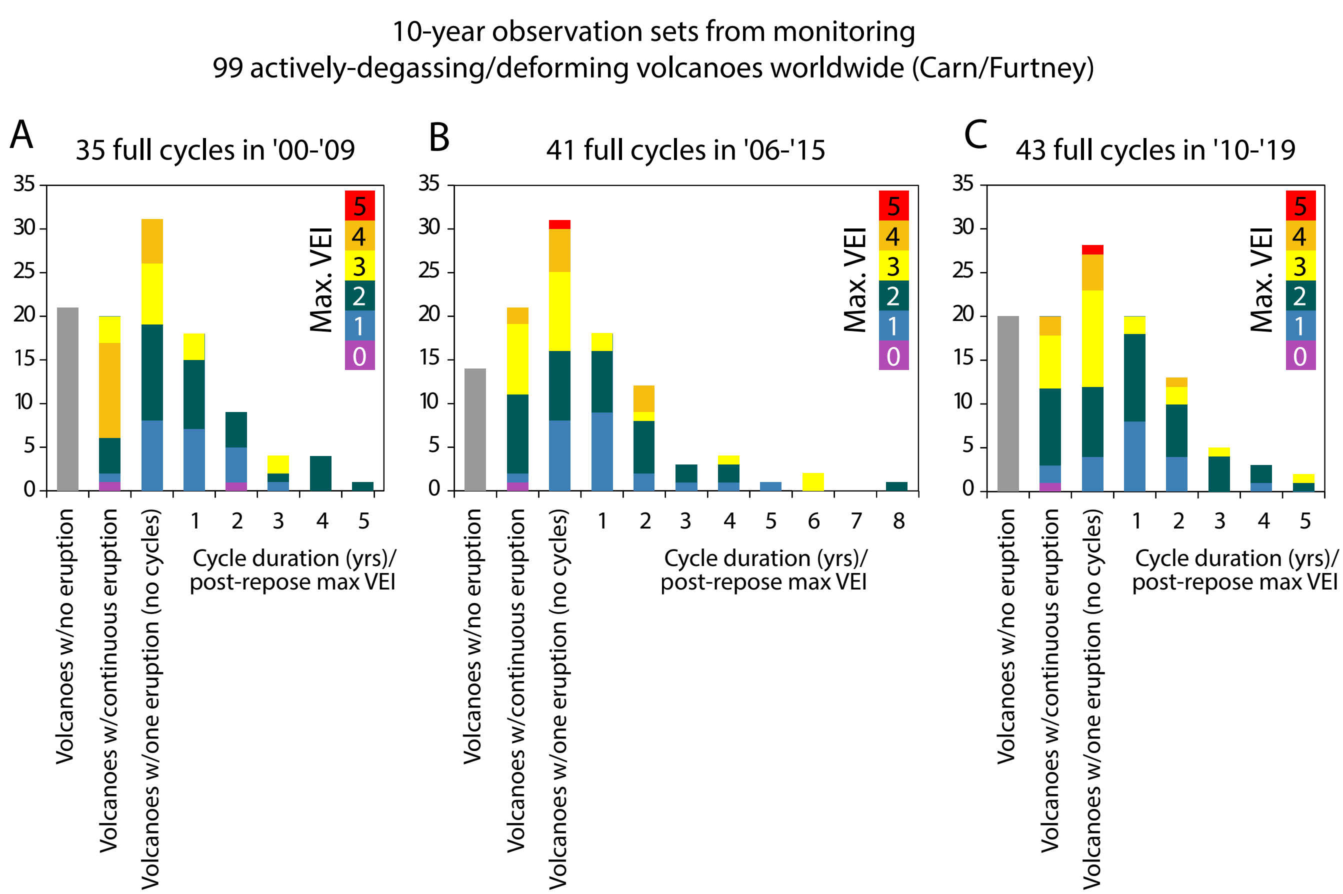
ACTIVITY 1 | Collect data that will provide constraints on mantle magma supply rate from ^{3}He and CO_2 flux campaigns and heat flow.

ACTIVITY 2 | Conduct extended mapping surveys and sampling of eruptive products to estimate volumes, eruption history and explosivity, and to identify parental melt compositions through geochronological, geochemical, and petrological studies.

ACTIVITY 3 | Conduct geothermobarometry and textural studies of eruptive products to constrain magma pressure, temperature, and physical properties, including timing of magma recharge.

ACTIVITY 4 | Collect images of the magma system and crustal properties along with dense observations for seismic tomography, magnetotellurics (MT), and gravimetry.

Figure MDE-5. *"Best-case scenario" for observations of eruption with Volcano Sensor Arrays. Each plot characterizes eruptive activity at these 99 volcanoes within a 10-year period (A) 2000–2009; (B) 2006–2015; (C) 2010-2019), coded by maximum VEI and repose period (cycle duration).*



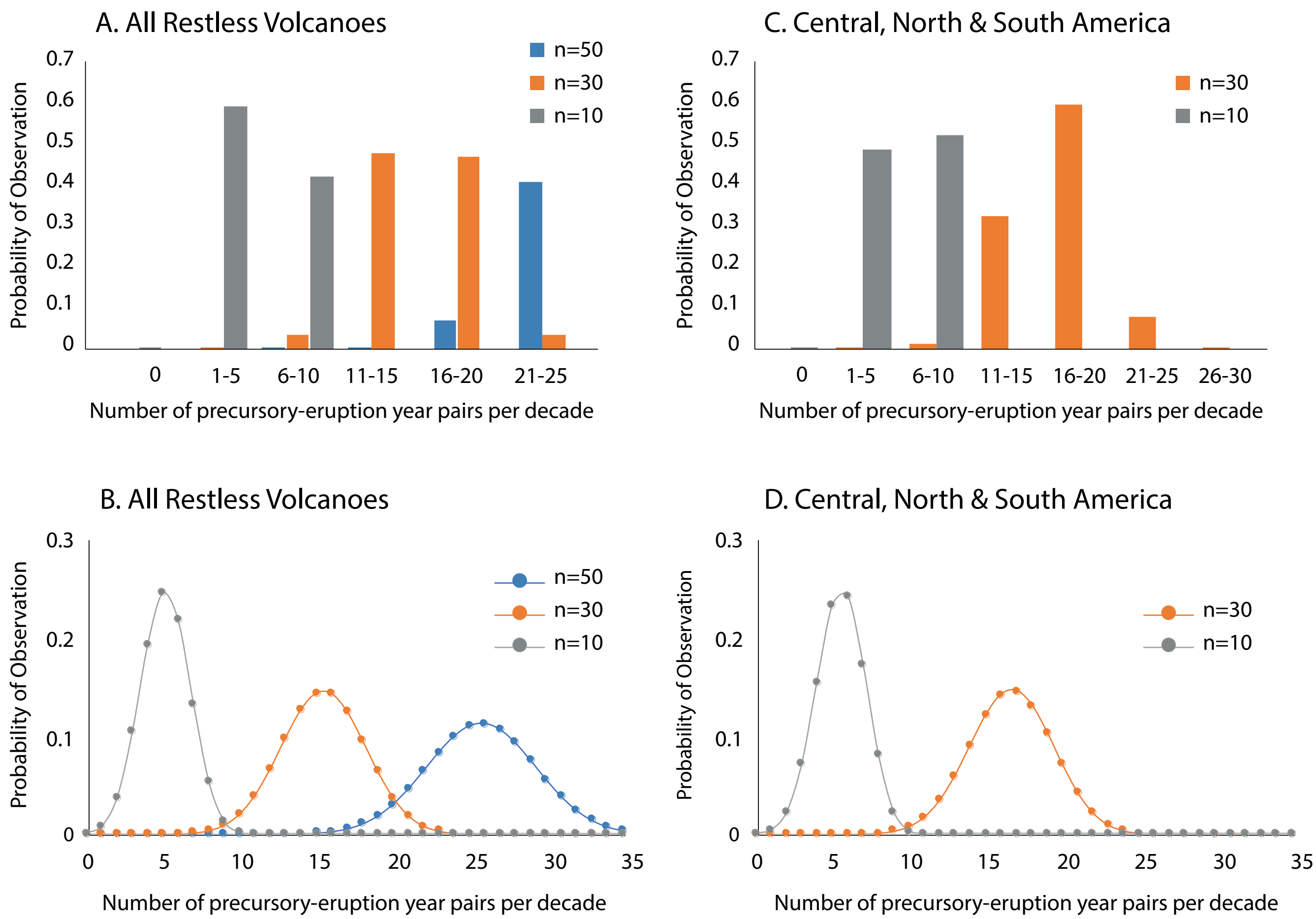


Figure MDE-6. *Calculated probabilities for n = 10, 30, and 50 Volcano Sensor Arrays observing eruption cycles for the 99 identified restless volcanoes, and n = 10 and 30 for a subset of these from North, South, and Central America (36 volcanoes). Probabilities were determined using observed eruption behavior for the 99 restless volcanoes in Carn et al. (2017) and Furtney et al. (2018) based on the decade 2000–2009. A precursory-eruption year pair is defined as a year without an eruption followed by a year with at least one eruption during this decade (such that both precursors and the eruption would be observed with the Volcano Sensor Arrays). Some volcanoes show more than one eruption cycle in this decade. Calculations use the binomial theorem for observational arrays of n = 10, 30, and 50 volcanoes. Probabilities for all restless volcanoes determined as P = (number of observed volcanoes that had ≥1 precursory-eruption year pair in the 2000–2009 decade)/(total number of volcanoes) for all volcanoes, or for the subset of volcanoes in North, South, and Central America. This is 51/99 volcanoes for the entire set of restless volcanoes and 25/36 volcanoes for North, South, and Central America. Results are shown individually for each number of eruption cycles in (B) and (D) and binned into groups of five (A) and (C).*

ACTIVITY 5 | Collect terrestrial and satellite geodetic measurements (e.g., NISAR) of deformation induced by the magma system as well as temporal changes in gravity. Activity 6. Investigate changes in seismic rate and event location. The geophysical imaging methods should be designed for observing eruptible magma and exsolved volatiles. This will require investments in instrumentation on nearby volcanic edifices that connect with strategies proposed by the FEC and L&S working groups. The observations from Parts 2–3 will also provide the opportunity to investigate the effects of external eruption triggers (e.g., glacial unloading in Hypothesis Set C) on processes at long timescales.

SCOPE | It will be important to develop experiments in at least three different island arcs: those related to slow, medium, and fast mantle magma supply rates. Furthermore, targeting proximal pairs of stratovolcanoes and nearby monogenetic centers will allow examination of variations in crustal architecture, stress, or composition at constant subduction parameters. Such a strategy could lead to targeting a pair of neighboring volcanoes at three different arcs.

Expected outcomes

1. We expect to quantitatively constrain and contrast the time-averaged and current supply rate of magma into the trans-crustal volcanic system - one of the "holy grails" of volcanology - through multidisciplinary measurements.
2. Detailed geophysical imaging of the subsurface beneath volcanoes should reveal the architecture of the magmatic system, the melt fractions in different regions, and how centralized it is relative to the edifice.
3. We will test hypotheses regarding the relationship between magma supply rate and depth-evolution of magma reservoirs.
4. We will test the relationship between magma crustal residence time and eruption intensity.

Volcano Rapid Response Arrays

Targeted hypotheses: A, B, and C

Given the goal of capturing eruption-related and external triggering phenomena inherent in Hypothesis Sets A and C, a component of the MDE implementation plan will involve rapid response to eruptions or episodes of volcanic unrest in cases when there is potential to make observations of precursory and syn-eruptive behavior, particularly for VEI 4+ eruptions or in response to major potential external triggers (large earthquakes and/or sector slides or collapses). Thus, we envision maintaining strategic caches of **Rapid Response Arrays**, ideally housed in target regions. We also plan to implement a program of routine remote sensing (see section **Remote Sensing Program** below) to detect anomalous gas, thermal emissions, and/or deformation for identifying candidate targets, and to organize protocols for rapid-response ash/lava sampling and analysis. The approaches to the development of the **Rapid Response Arrays** will be informed by the results of the CONVERSE initiative (Fischer et al., 2021).

Remote Sensing Program

Targeted hypotheses: A, B, and C

Hypothesis Sets A, B, and C all require a coordinated program of continuous and opportunistic remote sensing in addition to ground-based observations. Routine satellite observations, such as those from the upcoming NASA-ISRO Synthetic Aperture Radar (NISAR) mission (NISAR, 2018), the TROPOspheric Monitoring Instrument (TROPOMI) on board the Copernicus Sentinel-5 satellite (Theys et al., 2019), and the planned *Surface Biology and Geology (SBG) imaging spectrometer mission*, as well as observations of thermal anomalies from satellite-borne sensors such as the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Terra and Aqua satellites (e.g., Girona et al. 2021), will provide critical information on the state of deformation and degassing at all volcanoes in target regions and will aid in early identification of rapid response targets and potential external triggers such as flank instabilities (e.g., Schaefer et al., 2017). Additional spaceborne instruments, such as the EMIT instrument on the International Space Station that measures mineral composition of wind-blown dust in arid regions, and the Nanosatellite Atmospheric Chemistry Hyperspectral Observation System (NACHOS) Cubesat-hosted prototypes, may also provide useful observations towards MDE goals. Depending on the selected target regions, MDE may develop partnerships with one or more *Geohazard Permanent Supersites* to ensure regular acquisition and processing of critical satellite data. Additionally, campaign or opportunistic airborne (e.g., lidar, aeromagnetics, aerogravity surveys) and drone-based observations can be used to complement ground-based observations in cases where safe summit access is limited.

NOTIONAL EXPERIMENTS: EXHUMED MAGMATIC SYSTEMS

In parallel with instrument deployments and field efforts related to eruptive products (**Section III**), and building on immediate scientific activities (see **section VII**), a spectrum of work on exhumed magmatic systems will be critical to testing MDE hypotheses.

Exhumed Systems and Their Past Eruptive Records

Targeted hypothesis: B

Proposed experiments

Plutonic rocks and the products of past eruptions at **Exhumed Systems** can be used to constrain magma supply rates from the mantle to the crust, magma storage conditions (e.g., depths, temperatures, volatile contents), the spatial distribution and volumes of magma, and the timescales of magmatic processes in the crust. Plutonic localities enable testing of hypotheses for how these variables influence the evolution of subsurface magmatic systems that in turn drive surface hazards.

ACTIVITY 1 | Combine geochronology, geospeedometry, laboratory experiments, and models to explore processes over a wide range of timescales of pluton assembly (millions of years to minutes, e.g., Glazner et al. 2004) and rates (e.g., mantle supply and ascent rates within the crust, longevity and periodicity of eruptible and uneruptible magmatic states).

ACTIVITY 2 | Use geobarometry to establish the structure and distribution of phases within magmatic systems, and magma within the crust through time.

ACTIVITY 3 | Conduct (hyper)-dense geochemistry analyses throughout the stratigraphy of plutons and past eruptive sequences, as well as conduct experiments on natural compositions, to assess the evolution of critical magmatic properties (e.g., volatile contents) and relationships between magmatic events and eruptions (e.g., recharge).

ACTIVITY 4 | Assess micro (crystal/pore) to macro (field) scale structural information preserved in intrusive systems to estimate processes related to magma movement (e.g., emplacement, stalling, percolation, extraction from mushes, and replenishment).

ACTIVITY 5 | Synthesize these results to place constraints on the thermal structure of the crust in time and space, and on the rate and efficiency of internal processes (phase segregation and magma transport to shallower portions of the crust). These measurements will be applied in models that address the eruptibility of magmas and incubation time for reservoir growth, which will also incorporate geophysical measurements from active systems (see Section III). They will also be important for identifying volcanic and plutonic systems that are genetically related, helping to identify the magmatic processes that result in eruptions versus those that are decoupled from them.

SCOPE | Different exposed plutons provide access to distinct levels within the crust (from 0–60 km), architectures (oceanic versus continental arcs), and inferred tectonic regimes (compressional versus extensional). Different sites have been studied to greater or lesser detail and with different methods. Given the variability in characteristics of exhumed systems, a common approach may not be appropriate for every site (as for active volcanoes). Rather, each site may have independent research needs with the goal of understanding magmatic compositional variation with depth, storage times, and magma supply rates. The scale will range from the individual plutons to a trans-crustal cross section of an exhumed arcs. The number and diversity of sites should be selected based on their utility in testing hypotheses, and proposed initiatives should build off existing datasets.

Expected outcomes

We expect to characterize the magmatic history (e.g., composition, storage depths, transit times) and state of the crust through time and their relationship to magma eruptibility, eruption periodicity, and drivers of magmatic eruptions. Comparison of this arc-scale magmatic history with long-term histories of erosion and landscape evolution will be critical to evaluating cross-disciplinary questions regarding how arc structure links to surface topography and sediment generation.

NOTIONAL EXPERIMENTS: LABORATORY AND NUMERICAL MODELING STUDIES

Laboratory Experimental Studies

Targeted hypotheses: A, B, and C

Proposed laboratory experiments

ACTIVITY 1 - volatiles | Perform new sets of volatile solubility and diffusivity experiments at magmatic conditions. While solubility laws for H_2O are well characterized, CO_2 solubility is poorly known under lower crustal conditions. The behavior of S is as yet highly underconstrained given the complex partitioning relationships that exist across multiple melt and gas species as a function of P, T, and oxidation state. Diffusive loss/gain of volatiles from melt inclusions in various mineral phases is important for understanding the fidelity of melt inclusions for pressure estimates and their use as geospeedometers (e.g., ascent rates). More work is also needed to fully understand the behavior of halogens and noble gases and the effect of gas fluxing (e.g., CO_2 fluxing) on melt inclusion records and gas emissions.

ACTIVITY 2 - diffusion | Precisely determine the timescales of magmatic processes such as ascent rate, residence time, and mixing timing through new experiments to develop accurate diffusion laws as a function of P-T-X (and importantly H_2O).

ACTIVITY 3 - Geobarometers | Perform new sets of phase equilibria experiments targeted to specific arc melt compositions and trans-crustal P-T space to increase the utility of geobarometers. To understand the rate, path, and distribution of magma through the crust, it is essential to reliably determine the pressure growth history of crystals. Geobarometers for magmatic systems have been improving over the fifty years, yet they remain inaccurate when applied to crustal magmatic systems. We will complement these experiments with new fluid inclusion barometers that will significantly increase the precision of pressure constraints.

ACTIVITY 4 - Rock physics experiments on realistic and analog materials | Explore the effects of solid and multi-phase liquid rheology on magma movement, rock alteration, and changes in mechanical strength, pluton growth, and outgassing efficiency.

ACTIVITY 5 - Seismic velocity and attenuation and electrical conductivity measurements | Conduct experiments necessary to interpret geophysical images as a function of melt and bubble contents for different compositions, fractions, and geometries. Correlate the physical properties of magma with evolving mush structure in four dimensions at various temporal and spatial scales to allow extrapolation of laboratory-calibrated rheological models to geological scales that are many orders of magnitude larger than in the laboratory. Synchrotron and neutron radiation has emerged as powerful tools for characterizing the time-resolved three-dimensional distribution of mineral phases, stress states, and grain orientation in materials (e.g., Zhu et al., 2011; 2016). These technological advances provide a tremendous opportunity to develop new experimental methodologies so that evolving properties and microstructures can be quantified in operando.

Expected outcomes

1. We expect to improve current degassing models by incorporating better solubility and partitioning laws into multi-component systems. This is critical to interpreting measured volcanic gas compositions in terms of magmatic processes.
2. We expect to improve our capacity to characterize magmatic events (e.g., mixing or recharge events) and quantify the duration of residence in reservoirs and rate of ascent.
3. We expect to significantly improve our understanding of the depths at which magmas reside and better reconstruct their pressure-time histories.
4. Rock physics experiments would both improve understanding of the mechanical coupling between magmas and their host during transport and accumulation and provide more accurate models to relate

elastic and electrical properties of multi-phase magmas for geophysical inversions.

Modeling Studies (MCS)

Targeted hypotheses: A, B, and C

Numerical models integrate observations into a framework that enables testing of hypotheses. Models represent a powerful tool for exploring the physics underlying magmatic processes, making eruption forecasts, and connecting processes in active magmatic systems to the geologic record. Modeling will play an important role in testing hypotheses (see **Section III**), in developing the VolcArray design, in interpreting observational data and forecasting eruptions (**Section IV**), and in executing immediate science activities preceding array deployment (**Section V**).

The Modeling Collaboratory for Subduction Volcanic Systems Workshop took place online from September 2020 to May 2021, producing a report (Gonnermann and Anderson, 2021) that encompasses:

1. Challenges and opportunities for subduction zone volcano modeling and collaboration, and
2. A vision for how a modeling collaboratory would best advance the science objectives.

This section summarizes key outcomes of the workshop report in the context of the MDE objectives within three main pathways.

Physical/numerical model development involves both the study of novel physical processes as well as model implementation and verification/validation. Examples of poorly understood processes that could be addressed include non-equilibrium phase separation and reactive transport in magma reservoirs, the dynamics of dike ascent, controls on magma reservoir formation and eruptive vent locations/geometry, magma-groundwater interactions, and the mechanics of deep melt transport into the crust. For problems in which there is broad agreement on modeling needs and relevant physical processes, an MCS facility could support focused (open source) new code development and updating of old codes. Examples of problems that could benefit from accessible community codes and open-source model development include multiphase, unsteady conduit flow; ground deformation associated with magma reservoirs and heterogeneous, elastic, and viscoelastic rock rheology; multi-component thermal conduction; and equilibrium thermodynamics of multi-phase magmas. A volcano MCS can also organize model verification and validation to establish reproducibility standards and promote collaborative modeling practices. Model development could be supported through thematic community working groups (CWGs) to bring researchers – modelers, experimentalists, and observationalists, as well as those from other fields such as computer science or applied mathematics –- together to work on common problems, producing models and results through workshops and collaborative proposals.

Inversion and data assimilation. Inverse methods provide the critical link between data and models. Techniques vary widely, from simple optimization approaches to sophisticated Bayesian inference frameworks. An MCS could play an important role in organizing different research communities to develop frameworks for synthesizing diverse data, joint inversions, and uncertainty quantification. Data types with complementary sensitivity to structure and processes include deformation, seismicity, seismic wave tomography, electromagnetics, gravity, geochemistry and petrology, and gas and thermal emissions.

Inverse methods and data assimilation are fast-evolving fields following the explosion of new statistical methods in data sciences. Anomaly detection and pattern recognition have been revolutionized using machine learning techniques and have benefited greatly from the quantity of freely available data. An MCS could also provide a bridge between volcano researchers, applied mathematicians, and data scientists. These collaborations could improve sensor network design, reduce non-uniqueness inherited from inversions, and provide more accurate, physics-based, forecasting frameworks.

Training and human capacity building. To advance hypothesis-driven science objectives through integrative modeling of magmatic-volcanic systems requires a critical mass of geoscientists who are skilled in model development and in the application of models. An MCS could serve as a programmatic conduit in this regard, assuring through workshops and networking (in particular, through the CWG structure) that a growing pool of modelers will be optimally positioned to collaborate with experimental and observational scientists through model development and hypothesis-driven model use. MCS can also provide training for researchers interested in learning more about specific models, including code utilization, implementation of existing codes in modern open-source formats,and the underlying physics and assumptions behind the models. These efforts are clearly aligned with the capacity building, education, and Belongining, Accessibility, Justice, Equity, Diversity, and Inclusivity (BAJEDI) goals of the SZ4D BECG Group.

SITE EVALUATION

The Notional Experiments in **Section III** will involve all aspects of the complete **VolcArray**. **Imaging Arrays** will be required at a small number (~4–6) of systems that are driven by a range of mantle magma supply rates and that have imageable trans-crustal magmatic systems and accessible volcanic histories. It is also necessary to deploy **Volcano Sensor Arrays** at a large number (~30–50) of arc volcanoes that exhibit magmatic unrest and have a history of frequent eruption or potential for near-term eruption, with the potential for augmentation by **Rapid Response Arrays** during emerging episodes of unrest. All sites should be logistically feasible (accessibility and open data are key) and involve close partnership with local observatories and academic institutions. The selected regions/sites should also be a good fit with FEC and L&S priorities to maximize logistical support and allow for crosscutting science activities.

Ideal Location Characteristics and the MDE Arc Volcano Inventory

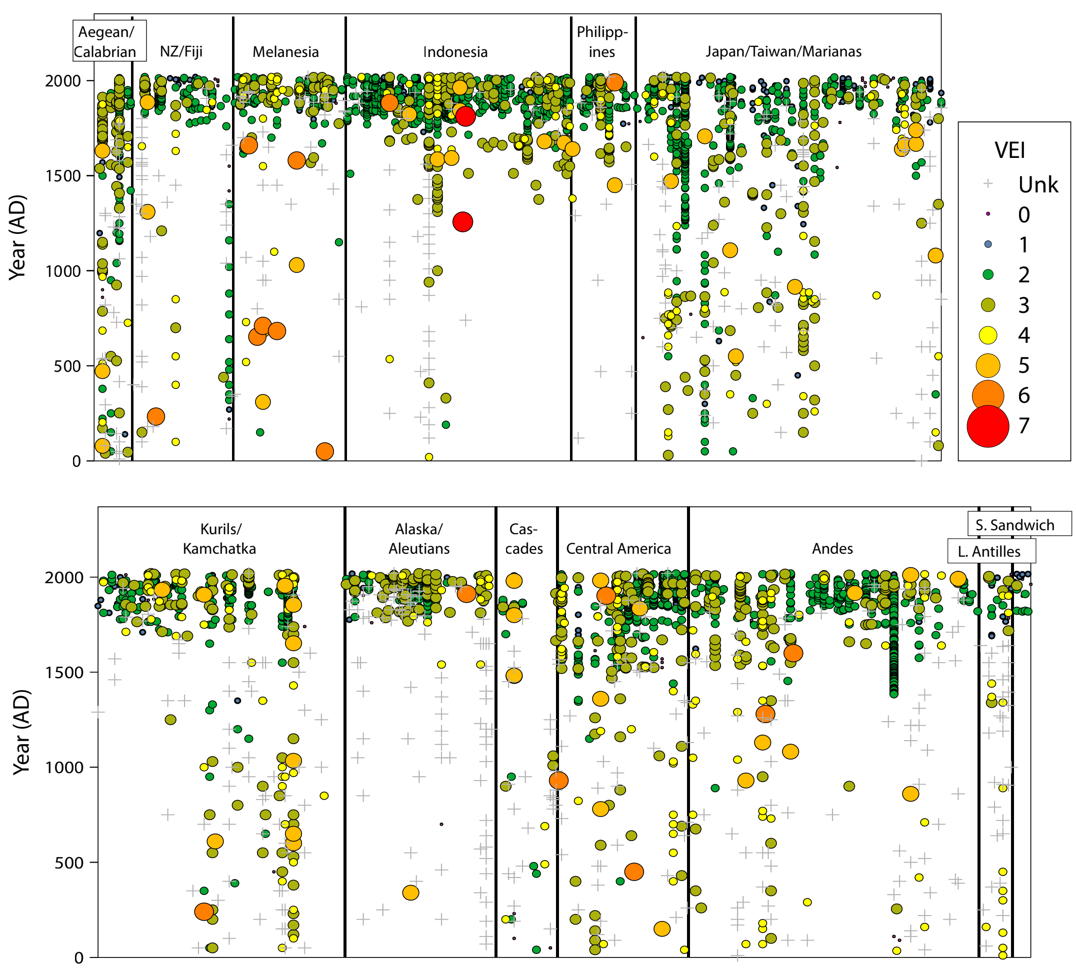
Volcano Sensor Arrays are largely aimed at Hypothesis sets A and C, with many diverse targets (~30–50). Ideal location characteristics include:

- Systems "potentially active," in that they show unrest and/or probability for eruption within the next decades. Indications of potential activity may include whether a system is actively emitting gas (Carn et al., 2017) or deforming (Furtney et al., 2018).
- Good summit access to deploy MulitGas and other gas measurement (DOAS) units year-round or with unmanned aircraft system (UAS) campaigns, for time-series characterization of gas chemistry.

- A diversity of magma chemistries, from mafic to felsic. A significant proportion of the target volcanoes should be of basaltic composition to test hypotheses as to magma initiation time, mafic recharge, and gas chemistry.
- Accessible targets, in order to deploy and maintain near-field instrumentation and to provide telemetry options for near-real-time, open data transmission.
- A subset of volcanoes with a good probability of eruption multiple times with different intensities over the observation period.
- Systems that exhibit a diversity of eruptive styles and intensity. Ideally **Volcano Sensor Arrays** would capture eruptions from VEI 1 to 4. This may require **Rapid Response Arrays** as well (see **Section IIIc**).
- Proximity to large magnitude earthquakes to test for triggering of volcanic unrest and eruption.

Volcano Imaging Arrays are largely aimed at Hypothesis sets B and C, with a small number (~4–6) of targets for intensive and integrated geological, geochemical, and geophysical studies.

Figure MDE 7. *Number of eruptions through time (past ~2000 years) per subduction zone, coded by VEI. Each vertical column represents one volcano that erupted in the Holocene; the width of data in each segment thus roughly indicates the number of different volcanoes that have been active in the Holocene (data from Smithsonian Global Volcanism Program, grouped by CAVW number; Global Volcanism Program, 2013).*



Ideal location characteristics include:

- Access to significant land area for certain key observations, such as wide-aperture seismic and geodetic deployments and InSAR. This would likely preclude island arc volcanoes, though active source imaging could also be possible offshore for submarine volcanoes. Island arc volcanoes could be included among the Volcano Sensor Arrays.
- Excellent exposures or records of past eruptive deposits should be accessible for study of volume, eruptive intensity, composition, thermobarometry, geochronometry, and geospeedometry over timescales ranging from 10^{-2} to 10^{4} years.
- Targets that span a range of mantle magma supply rates. Ideally, **Volcano Imaging Arrays** would be deployed at systems formed from high, medium and low mantle magma supply rates.
- Target volcanoes that enable tests of mantle magma supply rate as a driving parameter for the location, depth, distribution, and chemistry of the trans-crustal magma system. For this reason, magmas should not be substantially contaminated by crustal interactions (e.g., thick crust). Alternatively, variations in crustal thickness could be viewed as a critical control parameter that varies along strike in Chile.
- Co-location of some of the **Volcano Imaging Arrays** with FEC and L&S targets. This will offer the greatest opportunity for intensive study across the arc system.

To identify candidate sites that meet the above criteria, we assembled an *MDE Arc Volcano Inventory* that tabulates relevant characteristics for all of Earth's currently active volcanic arcs. The *Arc Volcano Inventory* includes both scientific and logistical considerations. Ultimately, host country priorities and expert input across the community will be critical for identifying specific target systems for both **Volcano Sensor Arrays** and **Volcano Imaging Arrays**.

Ideal Arc Segments for Volcano Sensor Arrays

Ideal arc segments for **Volcano Sensor Arrays** are those that host multiple restless volcanoes that span the full range of eruption intensity (VEI), magma type, degassing and deformation mode, unrest and eruptive style, and subduction and upper plate parameters. The primary requirement for **Volcano Sensor Array** targets is restlessness, such that multiple time series (e.g., gas chemistry, volatile flux, seismicity, and/or deformation) can be measured. A secondary target is volcanoes with the potential for eruption in the coming decades. As **Figure MDE-7** shows, regions with the largest number and VEI range of frequently erupting volcanoes (indicated by vertical/horizontal extent and size/color of dots in each region box) include Indonesia, Kurils/Kamchaka, Alaska/Aleutians (though many eruptions are of unknown VEI), Central America, and the Andes. The *MDE Arc Volcano Inventory* further indicates that these regions host a relatively large number of restless volcanoes spanning a range of magma types. Thus, for hypotheses that require capturing eruptions with a range of VI, these regions are most fertile for the deployment of **Volcano Sensor Arrays**.

Locating **Volcano Sensor Arrays** in a small number of regions or countries would enable the most efficient logistics, focused capacity building efforts, and the caching of instruments for **Rapid Response Arrays**. It would also have the potential to link to FEC and L&S observational campaigns. A small number of regions or countries would also limit the range of subduction and upper plate variables that could be explored. Taking into account access and logistical considerations, the ideal regions for **Volcano Sensor Arrays** are Alaska/Aleutians and the Andes, with a proposed primary focus of Volcano Sensor Array deployments in Chile as the single country with the largest number and most diverse suite of potentially active volcanoes, and a secondary focus area of study in the Aleutians using data from the permanent networks maintained by the Alaska Volcano Observatory. To provide adequate coverage to address the science questions underlying Hypothesis Sets A and C, **Volcano Sensor Arrays** may extend beyond the focus subduction segments.

Ideal Arc Segments for Volcano Imaging Arrays

Volcano Imaging Arrays should be located in arcs with a range in mantle magma supply rates. However, due to the difficulty in constraining these rates, we rely on known "subduction parameters" (i.e., volatile flux, convergence rate, plate age, composition of the slab, stress state of the upper plate) such that a "representative" picture of typical arc volcanism (e.g., not in back-arc, relatively simple crustal tectonics/structure) can be formed. Below we list and evaluate candidate arcs representing a range of magma supply rates (see the *MDE Arc Volcano Inventory* for a full list). Given the necessary aperture of geophysical arrays required to image deep roots of trans-crustal magmatic systems, we note that island and submarine arcs are problematic for some types of imaging; however, others (e.g., active-source seismology) may be better suited for offshore deployment. Therefore, integrated seafloor observations may be desirable in any SZ4D target locations within island arcs.

Other considerations include imageability, logistical access, viability of international collaborations, and magma composition. The pairwise comparison between mafic (distributed volcanism) and felsic systems at any arc segment provides important perspectives. Feeble or low-volume systems are less likely to host large, easily imageable mid-to-lower crustal magma systems that would inform models of the trans-crustal system. Logistical considerations have greatly limited volcano studies in many regions and include concerns about physical accessibility, permitting, and weather. These considerations vary depending on the type of imaging involved; long-term observatories require different access than quick, low-impact studies. Operating outside the United States requires extensive coordination from international collaborators. All of these considerations vary globally and regionally.

An overarching imaging objective is to compare systems with different magma supply rates at both trans-crustal and shallow-magmatic levels. However, there are no direct measures of magma supply or production rates in the mantle. We instead rely upon proxies and secondary "subduction parameters" that may ultimately drive magma supply to guide prioritization of specific arcs. Volatile flux models depend on a variety of kinematic and thermal parameters and are important to the extent that flux melting controls input (e.g., Cagnioncle et al., 2007; Wilson et al., 2014; Zellmer et al., 2015; Cerpa et al., 2018). These parameters depend largely on thermal paths followed by the descending plate (van Keken et al., 2011).

The second major source of magma, decompression melting, is more likely controlled by the speed of corner flow, and hence convergence rate modified by wedge geometry and upper-plate thermal structure (Grove et al., 2012; England & Wilkins, 2004). Other parameters such as the stress state of the upper plate also have been hypothesized to have strong control on mantle magma production (Karlstrom et al., 2009).

Given all of these potential proxies for magma supply rate, a variety of prioritizations could be made. One "endmember" in nearly all of these proxies is Cascadia, with its very young incoming plate, slow convergence, and the likelihood that sediments and upper oceanic crust dewater before reaching subvolcanic depths. Thus, magma supply should be relatively low in Cascadia compared with other arcs. Many other subduction zones (e.g., Peninsular Alaska, Central Chile, North Japan) likely deliver substantial volumes of volatiles to sub-arc depths and drive flow at many tens of km/My rates and would be useful to contrast with Cascadia. However, proxies vary between them, with higher subduction rates in Central America or Chile than off Alaska, but younger incoming plate ages. Comparisons between Cascadia and at least two other, colder subduction zones should provide new perspectives on magma supply rate. Taking into account the above considerations as well as proposed locales for Volcano Sensor Array deployments in Alaska and Chile, we propose locating **Volcano Imaging Arrays** in Central Chile, Cascadia, and Peninsular Alaska.

Ideal Locations for Study of Exhumed Systems

Exhumed systems afford a potentially complementary record to active volcanic systems as they represent accessible deeper crustal records of the transit of magmas from the mantle to the surface. Ancient arc systems, representing both accreted oceanic and continental arc crust, are widely present in the geologic record and range in age, exposure depths, and lithologies. A handful of localities represent nearly complete arc crustal sections, preserving depths from the crust-mantle interface to surface volcanic and sedimentary rocks, and have been extensively studied (e.g., Talkeetna arc, Kohistan arc). Other localities may only preserve a record of magmatic activity within a restricted depth range (e.g., Southern Alisitos Arc). To aid in assessment of candidate sites that meet the above criteria, we assembled an inventory of *Global Exhumed Arc Plutonic Sections* that tabulates relevant characteristics (age, range of depth exposed, lithologies, and whether a complementary, coeval volcanic section is present) for all known localities.

Desired Attributes

The choice of localities that can be used to address the three sets of hypotheses defined in Section I will depend on considerations such as their lithologies, age ranges, availability of prior information, and geologic contexts. Multiple localities will be used to test the hypotheses. The chosen sites could serve as comparisons between active systems, or could potentially be used to relate active processes observed by the VolcArray to those taking place at depth using exhumed, ancient analogs of these systems. For example, many arcs display variability in terms of magma supply rate (e.g., Sierran Arc). Comparing crustal residence times, magmatic compositions, and storage depths during "high"- and "low"-magma supply time periods is an example of a specific study that could be undertaken. In addition, localities preserving both contemporaneous plutonic and volcanic records could be particularly useful for connecting observations of plutons to samples of volcanic products. The *Global Exhumed Arc Plutonic Sections* highlights potential study localities (e.g., Talkeetna, ancient Cascades, Southern Alisitos, Fiordland, Famatina, Sierran) that are well characterized and are useful archives of the deep crust, but potential study sites are not meant to be limited to those listed. Prior characterization (in terms of chemistry, geochronology, modeling, etc.), while useful, is not required. Sites could also be selected to coordinate field experiences and logistics with **Volcano Sensor** and **Imaging Arrays** on active systems (e.g., in South America or Cascadia)

IMMEDIATE SCIENCE ACTIVITIES THAT CAN PRECEDE SZ4D DEPLOYMENTS

Results from work on existing data and samples, along with key experimental and modeling efforts, will be essential for guiding details of future SZ4D deployments and ultimately achieving the main goals of MDE. These efforts include using petrologic studies, laboratory experiments, geophysical studies, and physical models to:

1. Constrain the architecture, composition, and thermodynamic state of both active and extinct magmatic systems;
2. Establish new observational tools for use in future experiments;
3. Tie together geophysical and petrological data to create broadly self-consistent constraints on magmatic systems; and
4. Develop robust numerical modeling frameworks that can assimilate diverse data, make predictions about observations, and explore the phenomenology of magma transport processes. Each of these activities is directly linked to the MDE hypotheses.

Legacy Instrumental Data and Mapping Studies

Depending on the selected region(s), years to decades of campaign or continuous data may be available for systematic reanalysis in light of MDE science questions and observational objectives. Assessment of existing data (e.g., from campaign or continuous seismic, GNSS, and gas monitoring instruments, and from remote-sensing observations), and previous studies (e.g., geologic, heat flow, $^3He/^4He$, CO_2 flux surveys/maps) are thus critical immediate science activities to guide detailed site selection and experiment planning, to provide baselines for MDE deployments, and to provide initial constraints on mantle magma supply rates.

Samples from Prior Eruptions

Existing samples that are currently housed in repositories and individual research collections can be studied to constrain the architecture, composition, and thermodynamic state of arc magmatic systems at present and through time. Similarly, studies to examine intrusive-extrusive relationships in magmatic systems are necessary and can be conducted using existing samples. Specifically, applying well-established petrologic tools (e.g., geothermobarometers, hygrometers, phase relations, geochemistry, geochronology) to these samples will constrain pressures, temperatures, compositions, depth, average repose times, melt extraction efficiency, and eruption initiation mechanisms of magmas and magma storage regions of prior eruptions

(Hypothesis Sets A and B). Few such studies have been systematically undertaken for a whole arc, or even an arc segment, especially for active systems. However, such information is critical for understanding the evolution and current state of the crust and magma storage at both active and inactive systems. For example, only 27 of the 99 "restless" volcanoes that are emitting SO2 and/or actively deforming (Carn et al., 2017; Furtney et al., 2018) have had enough petrological data collected to provide estimates of magma storage pressures and temperatures. These efforts to collect new, and synthesize existing, data for target volcanoes will be critical in contextualizing field measurements made with the **Volcano Sensor** and **Imaging Arrays**.

Laboratory Experiments

Laboratory experiments are an essential tool for furthering our understanding of magmatic processes in arcs, can be used as a starting point to address MDE hypotheses, and can inform the design and deployment of field experiments. Experiments will be critical in constraining the P-T-X-H_2O-CO_2 conditions of magma storage. For example, laboratory exploration of phase equilibria in P-T-X space can provide more context and more precise estimates than geothermobarometers for a targeted system. Only six of the 99 "restless" volcanoes mentioned above have been subjected to detailed phase equilibria experiments, highlighting the need for this work. Such experiments will be particularly useful for the active magmatic systems chosen for comprehensive 4D study using **Volcano Imaging Arrays**. Similarly, experiments that constrain the pressure-composition controls on volcanic gas CO_2/SO_2 ratios are critical for interpreting gas time series that will be measured using **Volcano Sensor Arrays** and relating them to processes at depth and accompanying geophysical time series. Additionally, the development of improved geothermobarometers and calibrations of crystallinity-temperature relationships will be needed to extract information about the state of the magma from erupted samples and can precede instrumental deployments.

Currently, there is a dearth of experimental data on petrophysical properties and rheological behaviors of volcanic mushes and country rocks. The mechanisms (e.g., over-pressure, chemical instability) by which magma and volatiles coalesce and erupt are unclear. Can over-pressured magma rupture volcanic mushes? If so, what are the key parameters that control the transition from ductile flow to brittle fracture? Rock physics experiments are needed to provide realistic magma and host rock rheologies that can be incorporated into models of magma movement and eruption forecasting, as well as to develop constitutive models relating geophysical parameters (e.g., elastic moduli, electrical resistivity) to the thermodynamic state of the imaged magma body.

Numerical Modeling

Modeling is essential to tie together field observations (petrology, geodetic, and geophysical inversions) and to build a framework for investigating the evolution of magmatic systems over a range of time and length scales. Pre-deployment modeling efforts can also be leveraged to design and guide the instrumentation and data integration strategies. Mechanical modeling allows assessment of the response of the magmatic system, defined by petrological, laboratory experiment, and geophysical datasets and subject to assumed governing equations as well as numerical implementation approaches, to different rates of magma supply and magma composition. Past and present signals of unrest can be combined to hindcast and forecast the conditions that may initiate an eruption and link active volcanic processes with the geologic record. The Modeling Collaboratory for Subduction will provide a framework for addressing common modeling challenges between working groups of SZ4D, community code development, and training support.

COMMUNITY COORDINATION PLAN

Clear plans for community-wide science and outreach coordination are critical to the success of SZ4D. In an SZ4D survey of the volcanology community, 85% of respondents identified a multidisciplinary, community-driven effort like SZ4D as important for understanding subduction zones. However, in the same survey, about half of the respondents identified the US academic volcanology community as 6/10 or less in terms of organization. Evidently, there are both broad agreement on the need for an initiative like SZ4D to understand integrative questions like subduction zone hazards and significant challenges in building organizational capacity within the MDE-aligned community. Indeed, the *National Academy of Sciences ERUPT report* (NASEM, 2017) highlighted improved organization and coordination as major goal. Fortunately, in the wake of the ERUPT report, several linked efforts such as the Community Network for Volcanic Eruption Response (CONVERSE) RCN and MCS have forged a clear path toward enhanced community coordination. We will build on the successful coordination plans from these efforts to develop MDE- and SZ4D-wide science coordination plans.

Key lessons from CONVERSE regarding rapid response (see **Section IIIc**) include a transparent organizational structure with science advisory committees to ensure an open application process for sample and data collection, sample distribution, and other fieldwork. For example, one-page proposals were solicited from the community for proposed field campaigns and access to samples from the Kilauea 2020 eruption. These proposals were evaluated by a scientific advisory committee that worked closely with the observatory (Fischer et al., 2021). Also important are clear and consistent protocols for data and sample handling, and the accessibility and equitable representation in decision-making across communities, career stages, and nationalities. The interest and high participation rates in CONVERSE and MCS activities suggest they represent the starting point for a successful blueprint for coordination across SZ4D, with the overall goal of more interdisciplinary and stronger scientific results.

SUMMARY OF KEY SCIENTIFIC AND BROADER OUTCOMES

A major metric for the success of the SZ4D initiative is the extent to which it will enable the subduction zone science community to address questions and hypotheses that would not be accessible absent the scale and integration of the SZ4D effort. The motivating hypotheses for the MDE community relate the mantle supply of magma to the trans-crustal magmatic system and ultimately to volcanic hazards at the ground surface. Testing these hypotheses will build an improved understanding of how volcanoes work, with implications for hazards and forecasts along subduction zones. More broadly, the SZ4D effort will build organizational, infrastructure, and training capacity across the volcano science community.

Links to MDE Tracability Matrix and Databases

- *Traceability Matrix*
- *MDE Arc Volcano Inventory*
- *Global Exhumed Arc Plutonic Sections*

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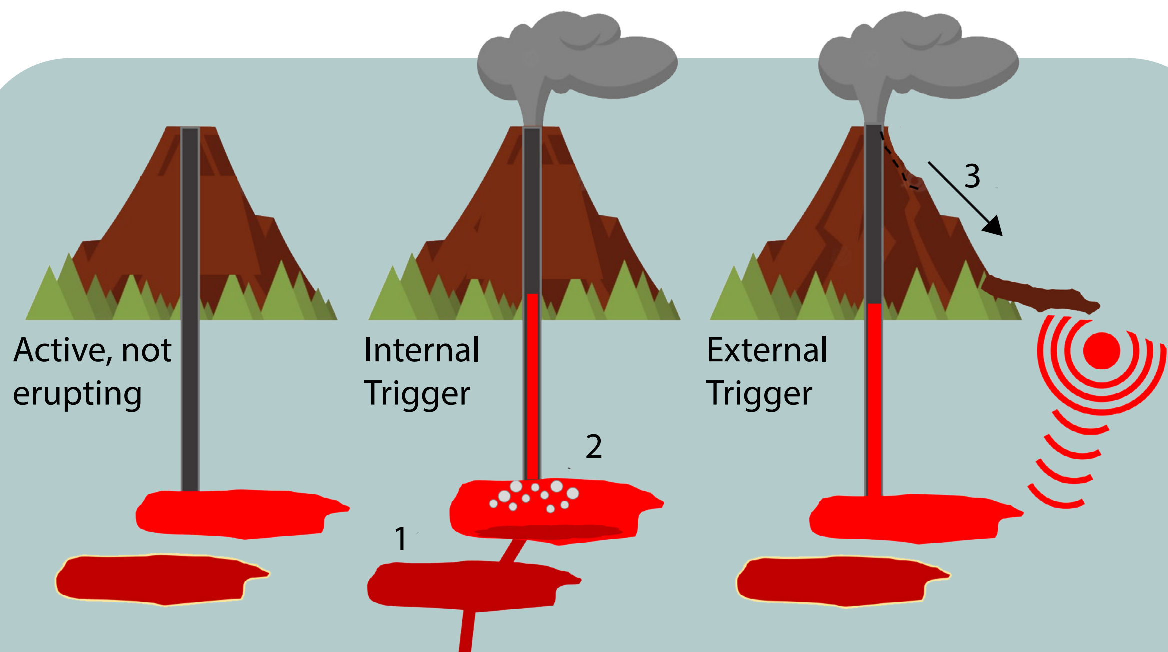
SIDEBAR 3

What drives a volcanic eruption?



1. Magma injection
2. Gas pressurization (bubbles)
3. External trigger (landslide)

Volcanic eruptions are triggered by both internal processes (from within the magma or magmatic system) and external process (e.g., landslides, earthquake). The most common mechanism for triggering eruptions in arc settings is deeper, hotter magma entering a shallower magma storage region, but eruptions can also be initiated by buildup of gas pressure related to crystallization. One open question volcanologists are trying to constrain is how much time will elapse between the triggering event, and the physical eruption.