GeoPRISMS Mini-Workshop: Magmatic Systems in Extensional and Compressional Settings

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Overview

A diverse and enthusiastic community of scientists interested in magmatic systems in a variety of settings attended the pre-AGU GeoPRISMS workshop to discuss and plan future research initiatives in light of new studies in continental and mid-ocean rift zones, and in volcanic arc settings. The over-arching goal of this mini-workshop was to facilitate community-building, and to provide a relaxed setting for early-career scientists in particular to communicate their results, and their ideas on future directions.

Three review talks on the physics of crustal magmatic systems (Joe Dufek), and active deformation (Diana Roman) and time-averaged deformation (Colin Wilson) in rifts and arcs established context. Joe's talk outlined the time and length scales of processes, and critical parameters controlling magma movement and eruptions: crustal state-of-stress, rheology of crust surrounding magma body, thermodynamics and heat transfer of the magma body, and magma composition and volatile content. He highlighted the need for multi-disciplinary observations at key locales, the focus-site hallmark of GeoPRISMS. Diana focused on magmatic systems in compressional settings where fluid and gas pathways tend to be closed. Seismicity may track hydraulic fracture accompanying the upward migration of magma and gasses, enabling some constraint on flux rates, and potentially, rheology of the intruded rocks. Diana's summary demonstrated the need for long-term monitoring at volcanoes. Colin drew on precise dating and field relations to understand the 'chicken and egg' question of tectonic or over-pressure as the trigger for large-volume intrusion and eruption episodes in back-arcs and rift zones. He suggested that critical insights will come from quantification of extrusive to intrusive ratios as the community develops eruption forecast models, and considers the relative importance of buoyancy forces, overpressures, open or closed fault systems, and dynamic triggering from distant earthquakes.

Graduate students and post-docs introduced themselves and their research in 3-minute pop-ups. The future planning aims were achieved through small group discussions focused on specific questions, with questions and questioners changing every 15 minutes. Groups were assembled to achieve breadth and diversity of perspectives. This series of café-style discussions on a specific questions enabled scientists to share perspectives on 1) magma and volatile transfer and their role in strain localization during plate boundary deformation, and 2) the role of tectonic stressing on volcanic eruption cycles and magma emplacement. The café questions facilitated comparison and contrasts between arcs, back-arcs, and continental rift zones, and facilitate discussions with numerical modelers keen to understand the role of magmatism and volatile release in lithospheric deformation processes. As outlined below, participants shared experiences with data and models of from Alaska, East Africa, Cascadia (including Juan de Fuca ridge processes), and Hikurangi, New Zealand focus sites, and looked forward to guide new research initiatives. Summaries of feedback from each group to each of the questions are outlined below.

Question 1: What are the physics of Open Vent Systems, and their responses to external triggers?

Einat Lev, barista

Why study OVs?

- Can reveal details about conduits, which are impossible to see at other volcanoes (e.g., Are conduits cylindrical or elongated? One or several?)
- Can more readily expose response to external triggers: e.g., change in lava lake level after an earthquake locally or far away, change in gas flux or gas composition values or ratios

The bulk of the discussion included defining what OVs are. Options ranged between:

a. only active lava lakes, where the conduit is visible and magma is directly exposed to the surface
b. Continuously degassing volcanoes with or without repeating extrusion of magma as effusive or explosive. But aren't all volcanoes emitting some gat at some level all the time? Are any volcanoes really "closed? Presumably yes: e.g., volcanoes that were considered not active, until a large eruption took place.
c. Volcanoes that emit material (gas or magma) without detectable deformation

The deformation based definition was mostly rejected, as it appears that most volcanoes that were considered to not be deforming, are actually deforming once data is more complete and available. Also, volcanoes that do have lava lakes, and are unquestionably "open" (e.g., Masaya, Kilauea), are deforming

The discussion led to moving from defining volcanoes as "open" versus "closed" to defining a range of "Openness", and volcanoes can fall anywhere on that range, and also change places during their evolution.

- Suggested study: Global ranking of level of openness
- Suggested series of studies: Explore past eruptive history to determine level of volcano openness during volcano's history
- Suggested study: place multi-gas sensors on all volcanoes that are open

It was noted that gas emission from a volcano doesn't have to concentrated at a central conduit, but is often diffuse and occurs more regionally on the flanks and through other cracks. Needs to be factored in when evaluating a volcano's openness level

Follow-on Questions :

Is a volcano like Santiaguito, which has long-term cyclic effusion of high-viscosity lava dome, with frequent gas explosion, considered open?
Is magma flux overall higher at open volcanoes, to keep them open?
Is conduit convection a requirement for an open volcano to stay open?
Is the answer different for Felsic volcanoes (new magma is presumably required) and basaltic (adding heat is presumably sufficient)?
Is the Taupo volcanic zone considered an open volcano?

A hypothesis raised early in the discussion claimed that OVs were occurring at local extensional regime, even at compressional arc settings. This was ruled out with many counter examples of OVs at compressive regions (mostly in the Aleutians). Also, obviously the volcanoes in the African Rift and in Iceland are mostly under extension, and yet only a few are OV.

Question 2. How do hot and cooled intrusions into continental and slow-spreading oceanic crust influence state of stress and rheology (e.g., underplate, foundering, along-axis propagation)?
Cindy Ebinger, barista

As many of the participants worked on extrusion and eruptive processes, some time was devoted to discussion of intrusive-extrusive ratios, and the fate of cumulates in continental crust. Magma intrusions change the density of the crust, and heat transfer to enclosing rock mass decreases strength. Volatile percolation through fractures may lead to fault zone weakening, and overpressurized zones. These combined processes could instigate crustal foundering, or strain localization at plate boundary zones. Mid-ocean ridge specialists offered insights from oceanic Layer 3.

In terms of future studies, the consensus was that quantification of intrusive (I) and extrusive (E) volumes is essential not only for mass balance and geochemical systems, but for improved models of state-of-stress and crustal rheology. Initial data sets suggest that the ratio of E:I may differ between compressional and extensional settings, with more magma stored in the crust in compressional settings. If so, then consequence would be a hotter and weaker lower crust. The E:I ratio is also important to testing models of mantle melt retention and extraction. Studies of enclaves, selvages and xenoliths within eruptive lavas will also provide insights into heating and infiltration of lower crust.

Follow on questions include:
What fraction of the magmatic system assists in crustal destabilization ?
When and where do crustal sill complexes form?
How much of the system is stimulated during eruption ?
What are the time and length scales of magma recharge, and how do they vary between extensional and compressional settings.

All agreed that permanent observatories where an arsenal of geophysical tools can be utilized to monitor subtle changes in properties over time, and coupled to gas and magma flux observations.

Question 3. (a) What are the characteristic forms of the magma transport and storage areas at various depths?
Cliff Thurber, barista

The discussions focused virtually entirely on the magma storage topic. Several common threads emerged from the discussions. Foremost among these was the need for the application of multiple techniques, both geophysical and geochemical, and the integration of the results across a suite of representative systems. Systems that could serve as test cases where significant work has already been accomplished include Santorini, Uturuncu, Taupo, Afar, Soufriere Hills, Laguna del Maule, and of course Mount St. Helens. A hypothesis testing approach can help develop models that account for the observations from all available datasets. New experimental results are needed to guide model interpretations, and new and improved modeling techniques are also required, especially in terms of distinguishing between magma versus other fluids.

A second discussion thread was the need to study exhumed systems. The examination of plutons can provide direct information on the conditions in the crust when and where a large body of magma grew, along with giving information on size and shape as well as the growth history. The degree to which plutons represent the subsurface structure of volcanic systems of different types is a subject of vigorous debate, however. Another potential target is core complexes on slow-spreading ridges.

A third, related thread is, how is the space for magma created in the crust, at different scales? Does the top move up, or the bottom move down? What is the degree of emplacement versus assimilation, and how does that differ across systems and at different depths? The critical role of crustal rheology in controlling how magma bodies form and grow was emphasized.

Regarding magma transport, comments focused mainly on seismic and geodetic techniques: long-period earthquakes and tremor, migrating seismicity, and deformation observations.

(b) What controls the magma residence time at depth and its migration toward the surface?

The discussion on this topic focused on buoyancy, volatiles, stress, rheology, and triggering. These factors must interact in complex ways. What degree of overpressure can exist in a magma reservoir, and how does that depend on size, shape, and depth, as well as the above factors? Geochemical observations can reveal time scales, but not necessarily the factors that control those time scales. The process of feeding new magma into an existing reservoir must play an important role, particularly as one form of triggering. The importance of tectonic triggering is uncertain, although tectonic-magmatic connections are clear in some cases.

Question 4. What are the feedbacks between local tectonics and magmatic/volcanic processes in triggering volcanic eruptions and unrest (nearby magma bodies, dikes, fault slip, megathrust shaking)?
Christelle Wauthier, barista

There is clear evidence that eruptions can be triggered by large magnitude earthquakes, like recently highlighted in the Southern Andes. However, the timing and exact conditions to be met are still unclear. Many participants suggested that a way to look into this problem could be to investigate magma reservoir dynamics and look for potentially specific signatures and patterns in volatile/diffusion profiles/pressure in magma reservoir. It was proposed that study changes in CO_2 to track magma pressure changes would work for subduction systems but not for all setting and volcanoes.

Many participants also suggested that we need to constrain two characteristics to investigate magma-tectonic interactions in active volcanic areas further: 1/ absolute crustal stresses (local + regional ambient stress field; 2/ amount of fluid/volatiles leading to pressure conditions in magma reservoirs. The first one, absolute crustal stresses, could be estimated using multiple events and also field geology and paleo-seismology (lakes containing turbidites deposits can be a great target to investigate past tectonic and volcanic events). Mapping carefully all existing faults and magma bodies/volcanic features (*i.e.,* cones and fissures) is also required to constrain fully the stress field. We would also need to look at potentially aseismic events/change of stress field orientation that could change the magma pressure and eruption dynamics. The second one, amount of fluid/volatiles in magma reservoirs, can be estimated through geochemistry. It has also been suggested that looking at a given volcano history from a statistical perspective could give us clues on when the magma chamber is “ready to go” if there it is affected by a small perturbation in stress.

Follow on questions:
- How sensitive are volcanoes to external factors (tectonic, climate…)?

- What are the pressure/conditions in the magma chamber?
- That are the pressure changes induced by an earthquake in magma reservoirs?
- Can we use machine learning /cross-correlation statistical algorithms to investigate multiple streams of data to understand a given system better?

All agreed that looking synergistically at datasets obtained through remote-sensing or local geophysical stations (geodetic, seismic, gravity, MT…) on volcanoes can be utilized to monitor subtle changes in properties over time, and coupled to volatiles geochemistry and magma flux observations. However, we also need to look at past event to study magma-tectonic interactions at more significant timescales and not only recent "snapshots".

Question 5: How can we use variations in the flux and chemistry of volatiles and fluids, in combination with deformation data, to constrain different magmatic, volcanic, and tectonic processes?
James Muirhead, barista

Combined volatile/fluid and deformation data was seen as a means for constraining the geometry and interconnectivity of magma pathways, magma volumes and magma depths, as well as timescales of magma generation, recharge, and ascent in plumbing systems.

Participants inquired about the characteristics geometries of the structures that transport gas/fluids at volcanoes. Furthermore, little is known about how these pathways differ for different volcanic-tectonic settings, volcano types, and magma plumbing system geometries. Others were curious about whether gas/fluid data could provide information regarding active behavior of tectonic structures. Is fluid/volatile ascent driving deformation, or are changes in fluid flow reflecting a response to changes in stress and/or strain?

Understanding the geometry, volume, and chemistry of the hydrothermal system of a volcano was seen as critical for interpreting any fluid/gas geochemistry data and the potential for the hydrothermal system to scrub the SO_2 signature. Magnetotellurics was discussed as useful tool when combined with geochemical data. Additionally, continuous monitoring of gas species (e.g., C/S ratios) and fluxes, and isotopes and compositions for magma volumes, depths, and timescales of accent. Automated Multi-GAS measurements of fumaroles and springs was favored, as were diffuse degassing surveys and permanent soil probes. Deformation data discussed included GPS, InSAR, seismicity, and borehole strain data to infer magma/fluid movement and changes in stress. Participants highlighted the need to differentiate between hydrothermal and magmatic gas to understand if deformation is related to magma and/or hydrothermal fluid movement, through measurements of isotopes in spring waters, fumaroles, volcanic lakes and eruptive plumes. It was additionally important to understand the degree of coupling between the magmatic and hydrothermal systems to understand if changes in hydrothermal activity may relate to magma recharge. Finally, the need to understand the geological, magmatic, and eruptive history of the volcano was frequently emphasized. This included diffusion modeling of crystals to look at timescales of magma ascent and recharge events, using uranium series to understand timescales of melt generation and separation, and melt inclusion studies to understand sources of fluids (e.g., mantle vs slab), initial volatile contents, and potential degassing histories.

Target volcanoes were therefore identified as ones that ideally have the following characteristics: (1) have been recently active and shown signs of deformation/unrest; (2) have well-constrained hydrothermal systems; (3) have a well constrained geological/eruptive history; (4) have known magma volatile contents from inclusion studies; and (5) have undergone previous geochemical studies investigating timescales of magma generation and ascent. Potential volcanoes identified by participants that may fulfil these categories included Popocatepetl, Colima, St Helens, Soufrier Hills, Katla, Bardabunga, Santorini, and Nyamuragira.

Question 6: What do precursory signals tell us about the physical mechanisms triggering eruptions?
Maya Tolstoy, barista

A variety of precursory signals were discussed, including seismic, geodetic and geochemical signals. Since there are likely different triggers in different settings, precursory signals are undoubtedly variable depending on the setting and the type of eruption.

Earthquakes are one well-known precursory signal, but they are stress indicators as opposed to movement indicators, though magma movement can generate changes in stress making it hard in some situations to separate the two in a volcanic environment. There was a lot of discussion of recent observations that downward propagation of earthquakes has been observed as precursory signals, and it was speculated that this may represent the downward propagation of a pressure wave. Does this imply that something other than magma (and near the surface) is triggering the eruption? Might hydrothermal processes be involved?

There was also discussion about why some volcanoes respond to the passage of surface waves and others do not, without a clear reason. It may be telling us something about the shape or other properties of the magma body and is worth further investigation.

Another point of considerable interest was the utility of precursory signals in predicting eruptions. If we better understood what is causing them, we may be able to better discriminate when a signal is truly precursory, thus reducing false alarms, which are quite common. Conversely research into why some signals appear precursory, but in the end are not, may help us address the question at hand about the physical mechanisms triggering eruptions.

It was noted that there are exciting new time series measurements coming out of CO_2/SO_2 ratios that can inform us about the depth the magma is coming from (the deeper the magma the more the CO_2). Another up and coming area of research is EM/MT and the question was raised whether you could use these techniques to see the magma moving. It's possible there are also other precursory signals that we aren't usually looking for (the example of was given of well depths).

Overall, better global statistics would help address some of these questions, but there is also a need to conduct careful studies of specific volcanoes to understand the details.

Question 7. The rate of crustal production and development of crustal structure is ultimately sensitive to the degree of fractionation versus crustal melting that occurs in thermally mature systems. How can we quantify the heat budget in different levels of the crust subject to variable intrusion histories?
Joe Dufek, barista

The discussion related to this question was wide ranging, and covered topics from the geometry and thermal implications of shallow intrusions to better describing melting relationships from experimental petrology. One common theme of the discussion was developing better descriptions of the melting relations and rheology of partially molten regions of magma reservoirs that can feedback to deformation of the reservoir, and also into the stresses in the system that may influence successive intrusions. This discussion focused on the need for petrologic experiments conducted over composition and pressure ranges that are not well represented in thermodynamic databases, particularly with hydrous mineralogies. The rheological discussion focused both on how these properties could be measured experimentally, and also how they could be incorporated into numerical models that examine both crustal stresses and heat flow.

A second theme explored was the link between hydrothermal systems and magmatic systems, and the resulting heat transfer. The coupling between these systems is gaining greater interest, and has obvious heat transfer implications. However, detailed modeling of each system is usually done in isolation, and these communities have developed different perspectives, terminologies and goals.

Some discussion revolved around the implications of crustal melting versus fractionation for the long-term growth of the crust, and in particular what settings and isotopic systems can best resolve current amounts of melting. There was an emphasis on regional studies aimed at describing the end member lithologies, their melting behavior, and isotopic descriptions of these end members to better quantify relative sources in magma genesis. A major topic of discussion was the use of the crystal-scale chronometers and reconciling the different timescales in mature magmatic systems.

Developing better understanding of the link between tectonics and magmatism was discussed in almost every group. Discussion focused on tectonics role in modifying intrusion histories, and also the dual role of tectonics and magmatism on the thermal state of the crust (the discussions mostly focused on extensional environments). A common theme of these discussions was the integration of different datasets that better define the current and past rates of deformation in regions as well as measurements indicating the current state of magma bodies including pre-eruptive seismic, deformation, gas flux measurements, and geochemical measurements of erupted magmas. Models that make predictions that have implications (and can be tested) by multiple datasets were discussed as a way of integrating measurements.

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