Time-variant behavior of faults and magmatic systems

Summary of Breakout Groups

Monday Afternoon

- Plenary (Thank you to all the speakers!)
  - Webinar and broader Impacts :
    - E&O: David Mogk
    - Fault systems and Volcano Monitoring: Zhigang Peng
  - Speakers
    - Earthquake processes: Jeff McGuire
    - Magmatic processes: Paul Segall
    - EEW: Richard Allen
- Breakouts (Thank you to all the leaders/scribes!)
  - The case for long term observatory style monitoring
  - The case for short-term, targeted experiments
  - The case for new types of observations
  - Enhancing societal use of S&G data

Approach

- Summaries provided by each breakout
  - a lot of redundancy/consistency – a good sign
- Tried to merge "Science opportunities/questions"
- Did not merge "What is needed"
- Please note what is missing / wrong
  - my fault / omission
  - you just had a great idea
- Bring it up during the discussion that follows
- Will probably need a matrix structure

Note: Style of responses different for each group, no attempt to homogenize or to combine recommendations yet

Science Opportunities/Questions 1

Intra-Fault Zones Structure and Source Physics

- What are the roles of fluids in fault?
- What is the fine-scale structure of fault zones and does it relate to fault behavior?
- Spatio-temporal changes of material properties (in)elastic over the EQ cycle
- Observing decadal-scale variations in transient deformation before large EQs (define what is “normal” vs. what is “transient)
- How do earthquakes nucleate, propagate, and stop (small and large events)?
  - Distinguishing between models for foreshocks (aseismic process or cascade triggering)
  - EQ interaction and stress transfer following large EQs
  - Dynamic triggering, how faults react to their environment, hydrology/tides/…
  - Imaging (moderate/large) EQ rupture extent/structure/3D geometry with dense observations
  - Are large/small earthquakes different?
- Controls and changes in fault behavior (stick-slip and aseismic slip) during EQ cycle
- What controls tsunamigenesis? slow earthquakes? Deep earthquakes?
- Predicting strong ground motion with uncertainties
- Non-tectonic earthquakes (glacial EQs, landslides…)

Science Opportunities/Questions 2

Plate boundaries across the seismic cycle

- Space/time variations of locking along Cascadia and Alaska SZs and other convergent margins?
- How does deformation evolve throughout the seismic cycle?
- Need to distinguish between “secular” and “transient” behavior.
- Mandates long-term measurements, particularly geodetic measurements
- Gain resolution with time to discriminate between competing mechanisms that produce similar geodetic signatures
- Dissipation of stress around fault tips: where does it go? over different scales, non-linear yielding
- Visco-elasto-plastic response of crust/upper mantle?
- When does “geology” happen?

Intraplate seismicity, swarms, interaction of faulting and triggering in the absence of resolvable deformation. Why so many? Where?

Why/when/where does deep wastewater injection induce earthquakes?

Science Opportunities/Questions 3

Magmatic Systems

- What is the configuration of magma storage beneath a volcano (Non-cartoon-like magma chambers)?
- Is mantle magma flux constant or intermittent? How fast are ascent rates? What is the role of fluids/composition?
- Improve understanding of phreatic (non-magmatic) events?
- Understanding coupling and interaction among tectonic, volcanic and climatic systems
- How to characterize/understand source (EQ/tremor) mechanisms
- Interactions between passing teleseismic surface waves and induced microseismicity w/in volcanic systems.
- Relationship of crustal magma intrusion to eruptions on short / long timescales?
- Plume monitoring, prediction, atmospheric coupling
- Forecasting (model-based and empirical)
  - Can deformation/seismicity of a volcano reliably inform us as to the likelihood of an eruption?
  - Infer magmatic/host rock properties from to inform forecasts of eruption likelihood, volume, style, duration.
  - Tracking long-term and short-term preparatory phases of eruptions, subtle magma movements and interactions with the hydrothermal system

The case for long-term observatory style monitoring

What is needed?

Foundational

- **Long-Term Dense Arrays** to observe 4D changes in volcanoes and fault zones
- **Maintain existing instrumentation** (e.g., PBO)

Foundationalish

- Quasi-continuous GNSS occupations of intermittent ~3 month observations. Initial investment is modest- monuments (pins) and an initial observation.
- Consistency of reference frame for geomorphic observations, either with LIDAR or other methods, such that comparisons may be made between before/after observations of earthquakes.
- For volcanoes, need surrounding reference sites to isolate volcano signals from others.

What is needed?

Frontier

- **Seafloor** seismic, geodetic and MT observatory in subduction zones, spreading ridges, and transforms
- Ultraquiet **borehole** seismic instrumentation with high sampling-rate to capture earthquake nucleation and rupture propagation
- Pre-/Post-event LiDAR coverage for EQ and volcanic process
- Access to high-quality, global **InSAR coverage in usable form** with latest & greatest processing from international constellation of satellites.
- Robust, low-latency **telemetry** for open field sites (globally)
- Lots of **Cheap GPS receivers** around important volcanoes to constrain ash clouds: Need enough sites to be able to constrain the edges, interior densities and particle sizes of ash clouds.

Their Additional Thoughts

- **Optical fibers** as seismometers and strainmeters?
- **Satellite**, airplane and **drone** based sensors should provide increasingly rapid information about surface deformation, gravity, temperature and electro-magnetic field changes
- Include non-PBO geodetic networks in routine scientific analysis.
  - Leverage ongoing construction of NGS/CORS/networks
  - One-time costs with low-cost maintenance
  - Operators need to report hardware changes.
- Fully invest in collaboration with international partners

The case for short-term targeted experiments

Group explicitly separated earthquake and volcano needs

2 breakouts for the price of 1

What is needed (1)?

Foundational (Earthquake)

- **Long-term** (~2yr), **short-term** (~months) temporary seismic/geodetic deployments: targeted networks for both structure/source (e.g., PASSCAL)
- Ground-based or airborne **LIDAR** , SAR, etc. deployments
- GRACE: coseismic changes for large events
- Cascadia **onshore/offshore network** and other OBSIP
- **EM** for imaging pore-pressure variations (*Frontier* for networks)
- HPC (waveform modeling) and communal analysis tools (inversion)
- Small N (seismic/geodetic)
- **InSAR**
- Experimental **drones**

What is needed (2)?

Frontier (Earthquake)

- **Rapid Array Mobilization Program (RAMP)** type facility (aftershocks)
  - on-scale (capturing strong motions), high-sample rate (200-Hz) 3-component, large-N.
  - **Drone-based**, very quick geodetic surveying.
  - **Ground-based (SLR, LIDAR).**
  - Additional support for import/export? Permitting?
  - Efficient partnership with USGS/Federal/State/military and in other countries
  - Instruments ready to go, maintained, fast mobilization (<day? <week?).
  - Storing instruments locally, targeted? Instrument types?
  - Offshore RAMPs? Non-ship deployment offshore?
- **Large-N** for structural longer-term deployments, RAMP, induced EQs.

What is needed (3)?

Frontier (Earthquake)

- **Active source surveys** at appropriate resolution (crustal, imaging faults): vibroseis, other sources, nodes and other recording as a community resource
- **Telemetry** (in real time?)
- **Borehole networks** (Strainmeters, seismometers…)
- Airborne repeat gravity surveys (with drones?)
- **Offshore** / **onshore** dense networks: subduction zone EQs.
- Global airborne **LIDAR**?

What is needed (4)?

Frontier (Volcano)

- **Large N**, long-term (~5-10yr), 3-component, improved resolution, frequencies for targeted networks, to characterize variability.
  - Longer lasting (power, data limits) yet easy to deploy.
  - Mix of broadband, high-frequency sensor (smaller scale than continental) nodes.
  - Fundamental limits to resolution or not?
- **Easy access to InSAR** (e.g. NISAR, Sentinel2,…) low latency response
  - All subaerial volcanoes could be monitored.
  - Automated event detection to guide ground-based studies/response.
  - Want time series not raw data.
- **Volcano RAMP**: Including seismic, geodetic, infrasound, gas, other sensors. Partly overlaps with **earthquake RAMP** with research grade data (beyond hazards mitigation).
  - Overlap with USGS mandate?
  - Protocols? Especially important for rare events such as rhyolitic Plinian eruptions. Telemetry?

What is needed (5)?

Frontier (Volcano)

- **Borehole stations** for smaller events, reducing uncertainties with structure
- **Drones**
  - Gas sensing, digital cameras (UV/IR/visible?)
  - Deformation
  - Stability and power
  - Consumer electronics becoming available and adoptable
- Infrasound (interactions with other interested groups)
- **EM**
  - Training in theory, tools and instrument use
  - Representative datasets for a range of volcanoes for comparative studies
  - Repeated imaging to detect conductivity changes from rapid magma ascent?
  - EM data from any volcanoes?
  - Self-potential methods?
- **Analysis Tools**: Waveform modeling / forward models in complex structure / HPC access & ease / Improved inversion methods

The case for new types of observations

Licensed to dream

What is needed (1)?

Frontier - only thing relevant for this group

(Some not really new types of observations, just improved deployment)

Megathrust locking

- Seafloor geodesy (GPS, pressure gauges) - dense observations
- High-resolution bathymetry
- Large N Ocean Bottom Seismometers (OBS)
- MT - evaluate time-dependent capabilities

What is needed (2)?

Frontier - only thing relevant for this group

(Some not really new types of observations, just improved deployment)

Fault mechanics and earthquake response

- Post-earthquake rapid-response drilling
- Pre-/Post-earthquake high-resolution topography/**LiDAR** (repeat; **drones**)
- Core recovery from a brittle failure patch (SAFOD)
- Near-field seismic observations (SAFOD)
- Deploy **strainmeters** to fill time-scale gap
- Need to instrument wells to assess poroelastic effects
- **Large N** - nodal instruments
- Induce an earthquake (*get a lawyer*)
- Instrument entire SAF with fiber **optic distributed acoustic sensing** and webcams

What is needed (3)?

Frontier - only thing relevant for this group

(Some not really new types of observations, just improved deployment)

Taking the pulse of active volcanoes

- Ground-based InSAR, nextgen photogrammetry, etc. (**drones**)
- Large N - nodal instruments
- Very Large N - fiber optic distributed acoustic sensing
- Gravity and GPS to infer subsurface change
- Strainmeters
- MT - evaluate time-dependent capabilities

Understanding induced seismicity

- Political action to release essential data
- Hydrogeophysics

Enhancing Societal Use of S&G Data

Early warning
Hazard, Risk and Resilience
Post-event Response
Climate Impacts
Resources and Infrastructure
Monitoring

Early warning

- Many potential phenomena that can be considered
  - Earthquake
  - Tsunami
  - Volcano
  - Extreme weather
  - Surface processes (catastrophic landslides, sink holes)
- Need dense S&G networks around hazardous faults, volcanoes, etc.
- Must ensure data reaches the right/responsible agencies
- Big data meets Big needs

Hazard, Risk and Resilience

- Long-term monitoring of seismicity and deformation
- Strong-motion characterization
  - temporary deployments to characterize amplifications
- Geodetic (GPS/InSAR) monitoring of activity and to inform physical models (volcanic, earthquake,…)
- Develop higher-level data products to help characterize hazard

Post-event Response

- Damage assessment and data collection
  - InSAR
  - Optical imagery
  - Other?
- GPS & Lidar
- Seismic
  - dense
  - wide dynamic range on-scale
  - 200 sps
- Need instrument packages that are easier to deploy rapidly
- Rapid mobilization
- Need authority to respond

Climate impacts (list of targets)

- Hydrological cycle
  - Soil moisture
  - Snow pack
  - Water resources
  - Aquifer geometry/behavior/evolution
- Sea level
- Cryosphere change
- Water vapor (storms, extreme events)
- 4D monitoring of carbon sequestration

Resources and infrastructure monitoring (list of targets)

- Mineral, hydrocarbon and water exploration
- Induced seismicity
- 4D monitoring of carbon sequestration
- Nuclear monitoring
- Power grid and other lifelines
- Buildings / dams …
- Aquifers

Facility

- Consider multi-use in hardware design (**science grade**), acquisition and siting
- Access to raw data and products
- Need capability to rapidly deploy seismometers and GPS and task InSAR and other remote sensing data (lidar, optical, etc.) acquisitions to respond to events
- Establish personnel, protocol and framework to allow for rapid response
- Training Field Crew: emphasize multi-use of data when siting (optimize)
- Discoverable archive, metadata, description of how it can be used, appropriate use, etc.
- The community of data users must make decisions about scope, e.g. of data archive
- High-rate, real-time seismic and GPS data products and analysis