Magmatic Processes
Paul Segall (Stanford)

Volcano Seismicity and Tremor

Seismic Imaging

Geodetic + Seismic

Model based joint inversion

Geodetic Monitoring
Key Scientific Questions

• How is magma stored in the crust? geometry, volume and physical state of crustal melts.

• Can we move from empirical to physics-based eruption forecasting?

• How to predict not only that an eruption is likely, but also eruptive style?

• Can we predict the duration and size of an eruption once its underway?

• Link different data types: deformation, seismic, gravity, gas, petrology, tomography, …
Imaging a Magmatic Sill Complex Beneath Toba

K. Jaxybulatov et al. 2014, A large magmatic sill complex beneath the Toba caldera, Science
Imaging temporal changes in mechanical properties

Also work extracting body waves from ambient noise
Nori Nakata

Obermann et al, JGR 2013
Augustine
Pre-eruptive deformation

velocities from 9/1 through 11/19, 2005.

Cervelli et al., GRL 2006

velocities from 9/1 through 11/19, 2005.
Extension continued following first explosion, forecasting that eruption would continue.
40 km Long Dike Intrusion in Iceland

Dike Deformation and Seismicity


Segall et al, JGR (2013)
Seismicity Patterns
June 2007 “Fathers Day” Kilauea Intrusion

Segall et al, JGR (2013)
Intrusion into Rift Zone
Long Valley 2014 swarm

- Max magnitude: 2.8

468 catalog earthquakes

-> 2468 precisely located events after processing

Dave Shelly, AGU 2014
Repeating Quakes and Gliding Tremor

- repeating earthquakes $M \sim 1$

Gliding Harmonic Tremor eruption

![Graph showing time before eruption vs. shear loading rate](image1)

- Seismic silence $\sim 30$ sec

![Graph showing inter-earthquake time vs. minutes before eruption](image2)

Model: Dmitrieva et al., 2013 NatGeo
Galapagos Uplift, Trapdoor Faulting, & Eruption

(Ameling et al. 2000; Chadwick et al. 2006; Geist et al. 2008).

Global monitoring feasible
Mount St. Helens: 2004-2008

The “whaleback” 2/22/2005
Mount St Helens Dome Forming Eruption 2004-2008

Net Displacements

JRO1 Radial Time Series

Lisowski et al. [2008]
Key model parameters

- Chamber volume, initial overpressure, aspect ratio, volatile content, conduit length, chamber influx, and frictional plug parameters

Key assumptions

- Radial symmetry, 1D conduit
- Newtonian rheology
- No gas loss from fluid conduit
- Fixed crystallization depth

Anderson and Segall, Physics–based models of ground deformation and extrusion rate at effusively erupting volcanoes: Model development and analysis JGR 2011
Model Fits both GPS and Extrusion Data

Radial GPS Deformation

Extruded volume, DRE

KELS, P702, P687, JRO1, P698, TWIW, TGAU

[mm]

Volume extruded [million m^3]

Model
Mount St. Helens

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Kinematic vs. Physics-Based Inversion

Anderson and Segall, JGR 2013
Grimsvötn GPS and Erupted Flux from Plume Height

Hreinsdóttir et al, Volcanic plume height correlated with magma-pressure change at Grímsvötn Volcano, Iceland; 2014 Nature
Grimsvøtn GPS and Inferred Flux

Hreinsdóttir et al, 2014
Assessing Physical Properties in Magma Chamber

\[ \frac{q_{\text{out}}}{\dot{u}(r)} = f(r/d, a/b, \ldots) \frac{d^2 \mu}{c_{\text{hember geometry}}} = \bar{\beta} \]

Segall 2013

Calculations: Kyle Anderson
• Physics-based Monte Carlo Forecasting

• Forecast based on knowledge of the system and all existing data.
Axial Volcano

2.4 meter subsidence
April 2015

Bill Chadwick
Recommendations

• Long term monitoring of volcanic systems required to record intrusive and eruptive processes.

• Advances in methodology (e.g. ambient noise imaging, precise event location, 4D inversion) require spatially and temporally dense data sets.

• Joint inversion of seismicity and deformation is feasible and potentially powerful in forecasting eruptions.

• Physics based models provide key links between different data types and *may* allow for dynamical forecasts.
Taisne et al, Imaging the dynamics of magma propagation using radiated seismic intensity, GRL, 2011
Dike Seismicity

Cross section
Dike Seismicity

Cross section
Monte Carlo inversion

Initial model $m_0$

Solve fluid equations

Eruption over?

yes

Calculate observables for all time steps

Pre-computed influence functions $G$

no

Timestep using DAE solver

(Inverse problem)

Calculate residuals & probability

Data (GPS, extrusion, gas)

Choose new model $m$ using Metropolis step

yes

Iterate?

done

Final posterior PDF

(Forward problem)

$$P(d_1, d_2, \ldots, d_K|m) = \prod_{k=1}^{K} \left\{ (2\pi \gamma_k^2)^{-N_k/2} |\Sigma_k|^{-1/2} \exp \left( -\frac{1}{2\gamma_k^2} r_k^T \Sigma_k^{-1} r_k \right) \right\}$$