Recent developments in regional simulations of fault and earthquake processes: Applications to volcanic systems

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With thanks to:
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“We visited the crater intending to stay all night, but the bottle containing our provisions got broke, and we were obliged to return.”

Mark Twain, 7 June 1866
Some observations about internal dynamics of volcanic systems

• Research is inherently multidisciplinary
• Dynamical system – tightly coupled interactions among
  • Magma transport, intrusion and eruption
  • Faulting (stable slip, earthquakes, fault creep)
  • Thermal structure
  • Geochemical evolution (magma and volatiles)
  • Ground water
• Phenomena we observe emerge from dynamical interactions of the system
• Monitoring observations are not well-integrated
• Analyses tend to focus on quantifying observations

Question: How can we make progress on system-level modeling of volcanic systems?
Southern California Earthquake Center (SCEC)

- Began in 1991 with 7 core institutions
- Now 17 core institutions, >60 participating organizations, ~600 scientists and students
- Originally organized around the concept of the Master Model of Earthquakes
- Quickly realized need for community models that describe the system

Core Institutions
- University of Southern California
- California Institute of Technology
- Columbia University
- Harvard University
- Massachusetts Institute of Technology
- San Diego State University
- Stanford University
- University of California, Los Angeles
- University of California, Riverside
- University of California, San Diego
- University of California, Santa Barbara
- University of California, Santa Cruz
- University of Nevada, Reno
- U.S. Geological Survey, Golden
- U.S. Geological Survey, Menlo Park
- U.S. Geological Survey, Pasadena
- U.S. Geological Survey,
SCEC Community Models

Stress model (planning stage)
Hawaiian Volcano Community Models?

- Fault model
- Seismic velocity model
- Deformation model $f(t)$
- Magma Reservoir/conduit model
- Thermal model
Rate-State Quake Simulation (RSQSim)

- Boundary elements – 50,000 fault elements
  - Detailed representation of complex fault network geometry
- 3D stress interactions
- Strike-slip, dip-slip, and mixed mode fault slip
- Basic elements of rate-state friction
  - Time-dependent nucleation
  - Earthquake clustering (foreshocks and aftershocks)
- Represent earthquake slip, fault creep, slow slip events (SSEs)
- Very efficient computations (10^6 year simulation of >6x10^6 earthquake events)
Normal Stress on Fault
(Background Stress = 120 MPa)

DYNA3D – Fully dynamic finite element simulation

RSQsim – Fast quasi-dynamic simulation
SCEC community Fault Model

Data sources
- Geologic mapping
- Historic earthquakes
- Microseismicity
- Drilling
- Reflection surveys
California Model

- ~3 km squares
- ~15,000 elements (no creep)
- ~35,000 elements (deep fault creep)
Entire California fault system – Cumulative magnitude-frequency

Cumulative number

Magnitude

All California observed seismicity, excluding Cascadia, with 95% confidence bounds (UCERF2)

$b = 1$
Magnitude-area Scaling
Showing only 200 years of simulated events

Wells and Coppersmith

RSQSim

- Wells and Coppersmith (1994)
- WGCEP 02 Appendix D
- Hanks and Bakun (2007)
Example – 1906 type earthquake on San Andreas Fault
Inter-event Waiting Time Distributions

**California Catalog: M5 to M6**

- Probability Density (s)
- Interevent Time (s)
- Slope = -0.884

**California Catalog: M6 to M7**

- Probability Density (s)
- Interevent Time (s)

**California Catalog: M7+**

- Probability Density (s)
- Interevent Time (s)

**RSQSim Catalog: M5–M6**

- Probability Density (s)
- Interevent Time (s)
- Slope = -0.882

**RSQSim Catalog: M6–M7**

- Probability Density (s)
- Interevent Time (s)
- Slope = -0.998

**RSQSim Catalog: M7+**

- Probability Density (s)
- Interevent Time (s)
- Slope = -1
Space – Time Distributions
Repeating Earthquakes

Omori's law $R \propto t^{-1}$

Schaff, Beroza, Shaw (1998)
There were 72 aftershocks (M>4) in the 2 days following the M7.8 earthquake.

183 aftershocks in the 100 days following the M7.5 earthquake.

220 events > M 7

137 isolated by at least 4 years,
34 pairs, 5 triples
Aftershocks of Non-Clustered and Clustered M≥7 Events

Clustered: Red
Non-Clustered: Blue

Seismicity relative to background

Time after mainshock (yr)

Slope=-0.93
Slope=-0.96
Linking short-term and long-term forecasts
Cumulative probability of earthquakes
(on San Jacinto fault segment of the San Jacinto fault)

- From random time
- From time of $M\geq 6.5$ on adjacent Anza segment

Cumulative Probability

Waiting time (years)

$P \sim 0.06$
In 1st hour

$P \sim 0.60$
In 1st hour
Kilauea and Mauna Loa

• Dynamical system – made up of interacting dynamical systems
  • Faulting (stable slip, earthquakes, fault creep)
  • Magma transport, intrusion and eruption
  • Thermal structure
  • Geochemical evolution (magma and volatiles)
  • Ground water
Rift expansion

\[ \mu_{eff} = \mu - \frac{p_f}{\sigma} \]

\[ \rho_m = 2.7 \]

\[ \rho_1 = 2.3 \]

Change of Stress Along Rift Axis Caused By Slip on a Patch at Base of Wedge

A schematic model of Kilauea south flank
Earthquake rate formulation

• Earthquake occurrence is controlled by earthquake nucleation processes

• Earthquake nucleation required by rate- and state-dependent friction is time dependent and highly non-linear in stress and gives the following

\[ R = \frac{r}{\gamma S_r} \]

\[ d\gamma = \frac{1}{A \sigma} \left[ dt - \gamma dS \right] \]

Dieterich (2007) *Treatise on Geophysics*
M~5 Earthquakes following Sept. 13 1977 eruption

From Dieterich, Cayol, Okubo (2003) USGS Prof Paper 1676
M~5 Earthquakes following Jan. 1, 1983 eruption

From Dieterich, Cayol, Okubo (2003) USGS Prof Paper 1676
Coulomb stress 1 MPa/division

Deformation $\dot{S}$
- 1976-1983: 0.5 MPa/yr
- >1983: 0.1 MPa/yr

Seismicity $\dot{S}$
- 1976-1983: 0.3–0.6 MPa/yr
- >1983: ≤0.1 MPa/yr

Rift intrusion rate
- 1976-1983: 0.18 km$^3$/yr
- >1983: 0.06 km$^3$/yr

NS extension (Summit region)
- 1976-1983: 25 cm/yr
- >1983: 4 cm/yr

From Dieterich, Cayol, Okubo (2003) USGS Prof Paper 1676
Montgomery-Brown, and others, 2009, JGR
Kalapana Earthquake M7.3 1975

Horizontal displacement  Vertical displacement

-12 bars

5 m

-1 m

-3 m

-2 m

12 bars

5 km scale
Kalapana Earthquake M7.7 1975
Schematic of Kilauea south flank
Cascadia – type SSEs

Modified from McCrory et al. (2006)
Cascadia megathrust model

Depth to megathrust contour interval = 5km
Colella and others (GRL, 2011)
Colella and others (GRL, submitted)
Colella and others (GRL, submitted)
Slip
Space-time of slipping elements
Example of space-time of tectonic tremor
Colella and others (GRL, submitted)