Characterizing fault zones and volcanic conduits at Kilauea and Mauna Loa volcanoes by large-scale mapping of earthquake stress drops and high precision relocations

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A big data set...

• >140,000 cataloged earthquakes (1962–2009)
• Standard processing: pick arrival times and locate earthquakes
• Key to more advanced analysis is waveform data (stored for >200,000 events)
• Recently these data have become much easier to access
Our project goals

- Improve location accuracy for entire catalog
- Estimate earthquake stress drops for entire catalog
Why improve locations?

- Better fault locations
- Better delination of features
- Help to refine seismic velocity models
Using waveform cross-correlation to improve locations

Many examples:

Got et al., 1994
Gillard et al., 1996
Rubin et al., 1999
Got & Okubo, 2003
Wolfe et al., 2003, 04, 07
Okubo & Wolfe, 2008

Gillard, Rubin & Okubo (1996)
Absolute vs. relative location error

True locations

Poor absolute locations

Poor relative locations
Sources of location errors

Velocity structure uncertainties

Strategies:

- Custom 1-D models
- Master event relocation
- Joint hypocenter-velocity inversion

Phase picking uncertainties

Strategies:

- Careful repicking (not effective)
- Waveform cross-correlation (often very effective)
Relative event location using waveform cross-correlation
HVO/UCSD/U Hawaii Relocation Project

- 1992 to 2009 waveforms now online at UCSD
- Time-domain cross-correlation method, previously used for southern California
- Cross-correlation completed for millions of event pairs
- Relocated catalog version 1.0 nearly ready
Poster yesterday had many plots and examples:

TH-14 Robin S. Matoza | Systematic Re-Analysis of Seismicity on Hawai'i Island from 1992 to 2009
decollement surface, see Got & Okubo, 2003
our relocations

Got & Okubo (2003)
our relocations

Gillard, Rubin & Okubo (1996),
see also Thelen poster (Tuesday)
New catalog *almost* finished...

- Still in QC stage, comparing to older results to validate approach.

- Many parameter choices. Is it better to separately relocate many smaller clusters versus a few larger clusters? How far apart can events be and still have useful cross-correlations?

- How to best characterize absolute and relative location error bars?
Our project goals

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What can we learn about small earthquakes?

Lots of data for big earthquakes (rupture dimensions, slip history, etc.)

Small earthquakes are only observed from seismograms; no direct measurements of physical properties
What can we learn from seismograms of small earthquakes?

- Location from timing of P and S arrivals
- Magnitude from wave amplitudes
- Focal mechanism from wave polarities (and amplitude)
- Stress drop from frequency content of waves
Two key parameters

\[ \text{displacement} = D \]
\[ \text{area} = A \]

Moment \( M_0 = \mu AD \)

\[ \text{Stress drop} \Delta \sigma = \sigma_{\text{final}} - \sigma_{\text{initial}} \]

fault area
average displacement
shear modulus
average shear stress on fault
Two quakes with same moment:

**Fault model**

- **High stress drop**: large slip on small fault
- **Low stress drop**: small slip slip on large fault

**Seismic pulse**

- Tall narrow pulse
- Short wide pulse

**Spectrum**

- High $f_c$, more high freq.
- Low $f_c$, less high freq.
But small earthquake stress drops are hard to measure from real data

Problems:

- Individual spectra are very irregular, do not resemble theoretical models
- Attenuation and scattering deplete high frequencies
- Path and site effects also influence spectra
- Large range of observed stress drops
- Hard to compare different studies due to different modeling approaches
Our strategy:

• Examine *lots* of data. Stack and average to try to see coherent patterns

• Use consistent modeling approach, to facilitate comparisons among different regions

• Successfully applied to southern California seismicity
HVO spectral analysis

- Online database of seismograms, 1992–2009
- > 120,000 earthquakes
- $P$ and $S$ spectra computed for all records
- $\sim$10 GB in special binary format
Isolating Spectral Contributions

\[ d_{ij} \approx e_i + s_j + x_{k(i,j)} + r_{ij} \text{ (residual)} \]
$d_{ij} \approx e_i + s_j + x_{k(i,j)}$

- > 60,000 earthquakes, >350 stations
- 1.38 million $P$-wave spectra (STN > 5, 5-20 Hz)
- Iterative least squares approach with outlier suppression
HVO source spectra binned by relative moment

Shallow (≤15 km) events only.

Constant stress drop model gives good fit.

Theoretical model prediction (dashed lines) is for $\Delta \sigma = 0.8$ MPa (compared to 1.6 MPa for southern California)
Problem: Bias from lateral attenuation differences

Reality

Model

inferred low stress drops

recording station

Identical stress drop quakes

inferred high stress drops
Empirical Green’s Function (EGF)

Subtract small event from big event to get estimate of true source spectrum for big event
Source-specific EGF method

For each event, find 500 neighboring events:

Fit moment binned spectra to $\Delta \sigma$ and EGF

Then subtract EGF from target event spectrum and compute $\Delta \sigma$ for this event
Observed source $\Delta\sigma$ using spatially varying EGF method

depth $\leq 15$ km
low stress drops

high stress drops
Relation to long-period (LP) events

HVO classifies many events as long-period (LP), many of which are related to activity at Kiluea activity (Koyanagi et al., 1987).

Our analysis does not treat these events any differently than 'regular' quakes.

However, their average stress drop is much lower.
The future

Short term for our project:

• Complete and release relocated catalog and stress drop estimates
• Integrate with other data sets to better characterize fault zones and volcanic conduits

Longer term:

• Continue long-term monitoring of Hawaii using seismology and other methods
• Improve access to large data sets and develop tools for community use