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

Peter Shearer[1], Cecily Wolfe[2], & Paul Okubo[3]

[1] U.C. San Diego; [2] University of Hawaii; [3] U.S. Geological Survey, Hawaiian Volcano Observatory

Abstract

Because of ongoing time-dependent variations in volcanism, geodetically observed deformation, and earthquakes, Hawaii's value as a natural laboratory for studying the interactions between magmatic and tectonic processes has long been recognized. We describe initial results of a comprehensive analysis of waveforms from the seismic network operated by the Hawaiian Volcano Observatory (HVO) between 1992 and 2009. This includes records from over 100,000 earthquakes at a variety of depths, including shallow seismicity associated with Kilauea volcano and the east rift zone, intermediate depth events along magma conduits, deeper events along a detachment fault zone near 30 km depth, and long-period earthquakes near 40 km depth beneath Mauna Loa. We have converted all the waveform data to a standard format and are now applying both waveform cross-correlation and spectral analysis to the HVO waveforms, using methods similar to those we have successfully applied in southern California. While prior studies have focused on individual regions, our analyses will provide the first comprehensive catalog of relocated earthquakes across the entire Island of Hawaii. The results should give a sharper view of fault (tectonic) and conduit (magmatic) structures, including improved characterization of detachment faults on the south and west flanks of Hawaii. From a systematic analysis of P-wave spectra, it is possible to separate source, path and receiver contributions, and estimate Brune-type earthquake stress drops. Spatial variations in stress drop provide insight regarding the relationship between stress drop and fault geometry. In addition, there have been several large earthquakes, dike intrusions, and slow slip events that provide targets to investigate possible temporal variations in stress drop that may be associated with changes in absolute stress levels. These large-scale waveform analysis methods can be used in other volcanic areas monitored by local seismic stations, including current and proposed experiments on and around the Galapagos.

Introduction

Previous studies of certain regions have shown that large improvements are possible in resolving fault structures at Hawaii using differential location and cross-correlation methods e.g., Got and Okubo, 2003; Wolfe et al., 2003, 2004). Advances in computer power now permit analyses of entire seismic data sets using methods that have traditionally been applied to much smaller numbers of events. Here we focus on earthquake location and source spectral analysis. In both cases, we can exploit the redundancy in the data set to derive empirical corrections for the effect of structure on travel times (location problem) and spectra (source studies). We first applied these methods to data from the southern California seismic network (SCSN) and are currently using them to study seismicity on Hawaii using data from the Hawaiian Volcano Observatory (HVO). Preliminary results suggest large improvements will be possible in resolving faults and volcanic structures.

Spectral analysis

Once the waveforms are stored in our online database for the cross-correlation project, they are also in a convenient form for spectral analysis for source properties. Analysis consists of several stages:

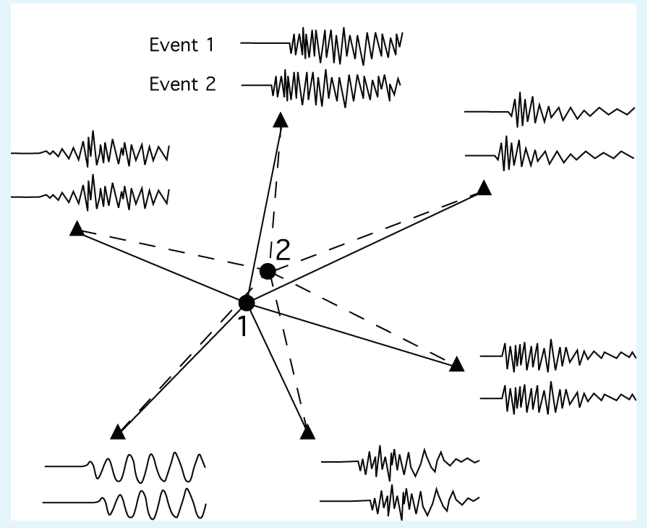
(1) For all seismograms, compute individual P and S spectra in 1.28 s windows around the phase arrivals, as well as a 1.28 s 'noise' window immediately preceding the target phase. Store those spectra meeting a given signal-to-noise cutoff.

(2) Process the spectra to isolate source, receiver and propagation path terms using a robust, iterative method.

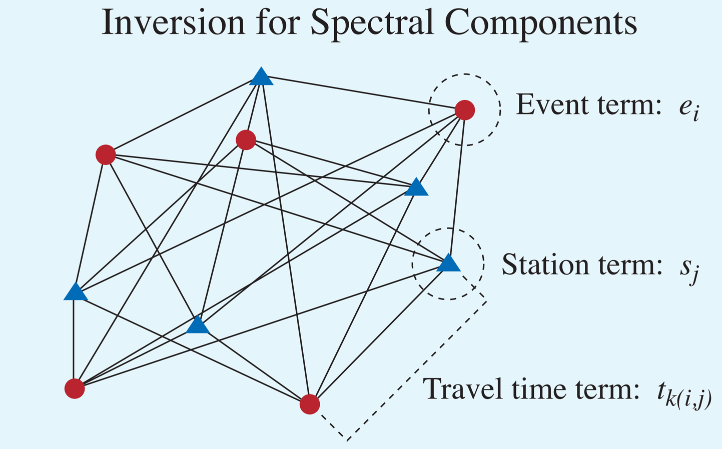
(3) Correct the resulting source spectra using a spatially varying empirical Green's function (EGF) method and estimate individual event stress drops.

Improving earthquake locations using waveform cross-correlation

Dramatic improvements in relative earthquake locations among nearby events can be achieved by exploiting the fact that the biasing effects of 3D structure are similar for closely spaced events. This approach simultaneously locates an entire set of events at once, rather than locating each event separately. The use of waveform cross-correlation to improve the relative timing of phase picks can further improve relative location accuracy (see below). This exploits the fact that nearby earthquakes often generate similar waveforms, which can be cross-correlated to provide better relative timing accuracy than can be obtained from picking the arrival times on each seismogram separately. These methods were originally developed for single clusters of events, but have now been extended to relocate entire seismicity catalogs (e.g., Lin et al, 2007, Waldhauser and Schaff, 2008).



Inversion for Spectral Components

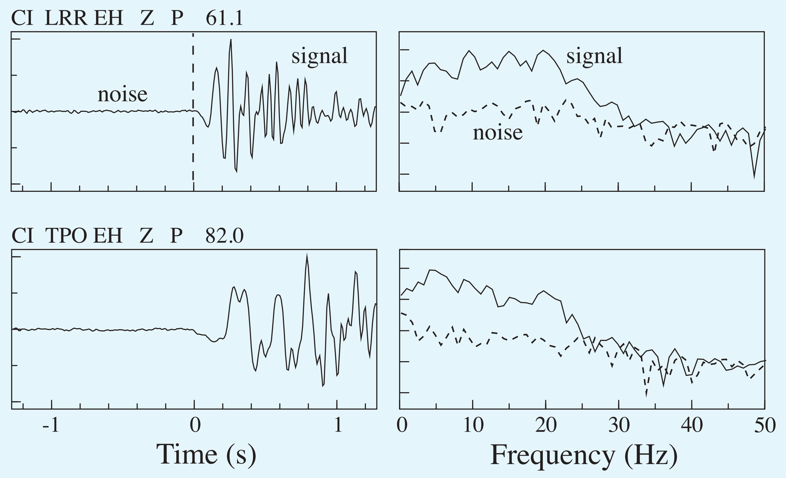


$$d_{ij} \approx e_i + s_j + t_{k(i,j)} + r_{ij} \text{ (residual)}$$

Observed spectrum — Source spectrum — Receiver response — Travel-time dependent term to account for Q

- Observed log spectrum is sum of different components
- Redundancy in system permits isolating source term
- Iterative least squares method with outlier suppression

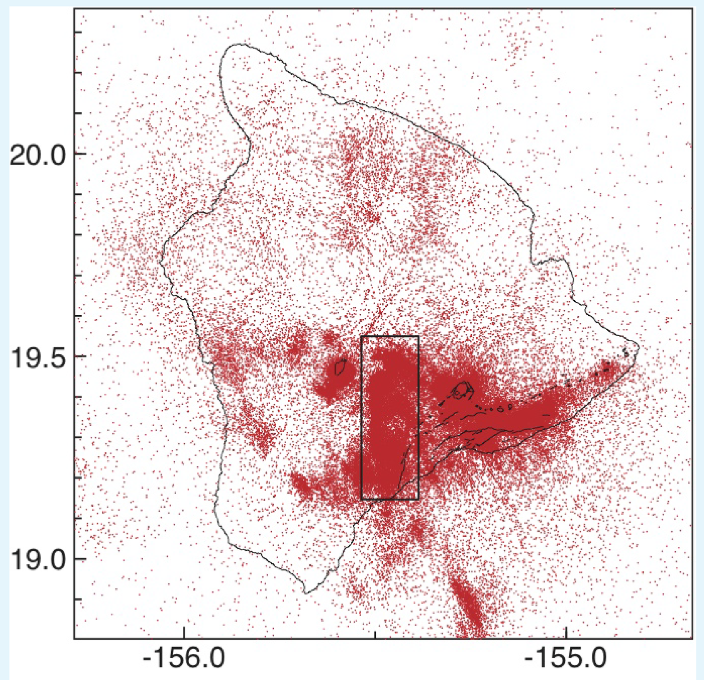
Computing millions of spectra



- Hawaii/UCSD online database of seismograms
- > 130,000 earthquakes, 1992–2009
- Resampled to uniform 100 Hz
- P and S multi-taper spectra computed for all records
- 1.28 s signal and noise windows
- Requires ~5 GB in special binary format

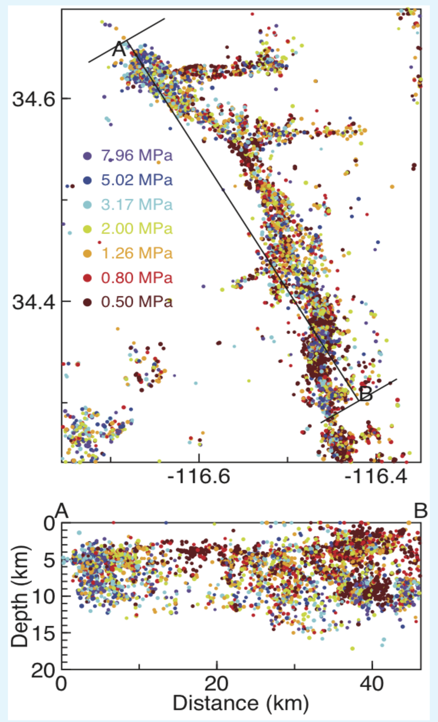
Relocating Hawaiian seismicity

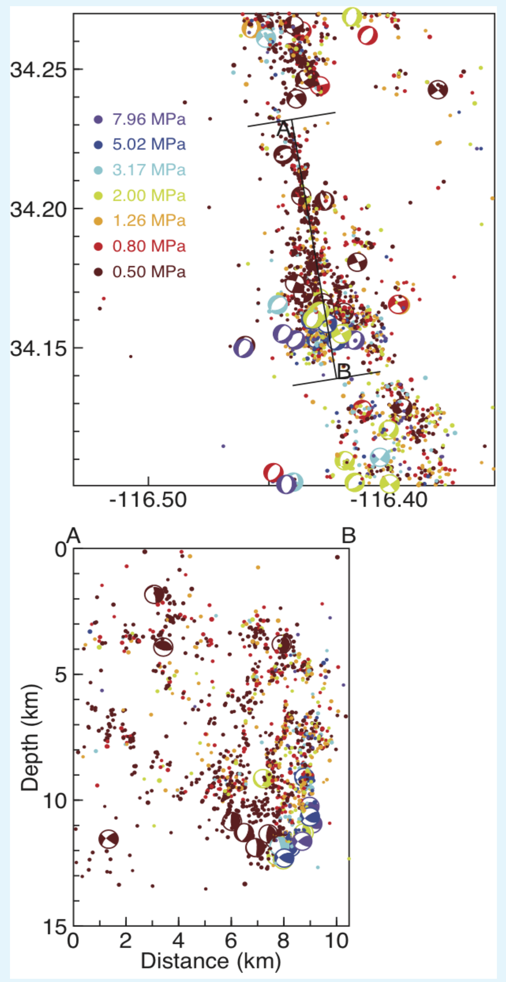
We have recently obtained waveforms for 131,248 Hawaiian events as recorded by the Hawaiian Volcano Observatory (HVO) from 1992 to 2009. We have filtered the data from 1 to 10 Hz and resampled them to a uniform 100 Hz sample rate. We are currently computing waveform cross-correlations between every event and at least 100 surrounding events, including all events within 2 km radius. This calculation did not finish in time for this poster, so here we present some preliminary results for a subset of the data, in this case a N-S profile as shown as the box in the seismicity map below. The accompanying figures show a comparison between the original catalog locations and relocations derived from waveform cross-correlation results. There is a dramatic sharpening of the seismicity features, including details of the likely decollement surface.



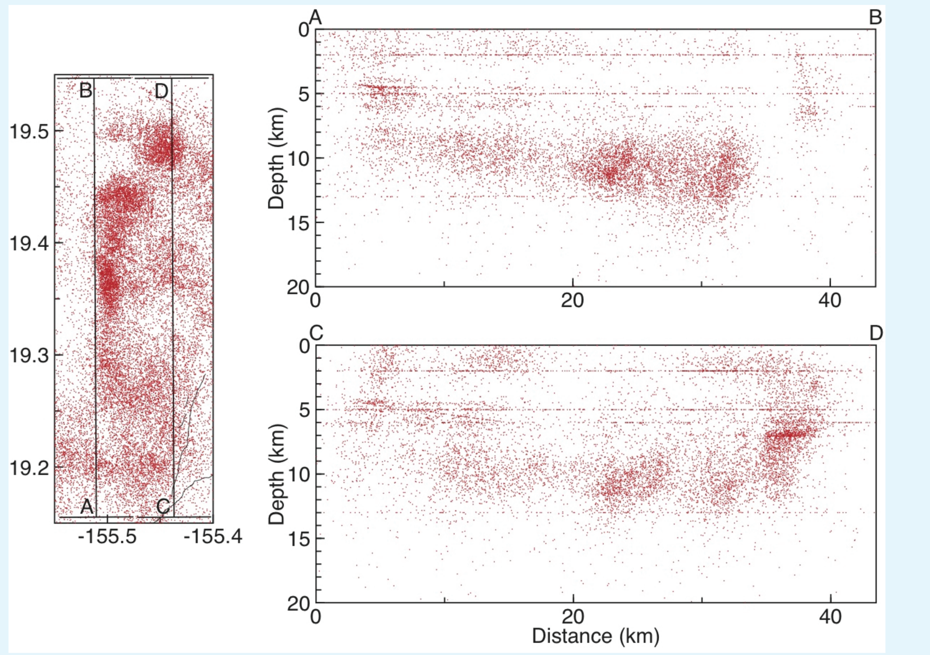
Example for Landers earthquake

We have systematically performed spectral analysis on the southern California catalog between 1989 and 2001 to estimate stress drops for over 60,000 earthquakes (Shearer et al., 2006). Some results for the aftershock sequence of the 1992 M 7.3 Landers earthquake are shown to the right. The left panel is the north end of the rupture, showing higher average stress drop on very north end, and isolated regions of low stress drop. The right panel shows a sharp change in stress drop near the hypocenter. Note that the higher stress drop events tend to be normal faulting.

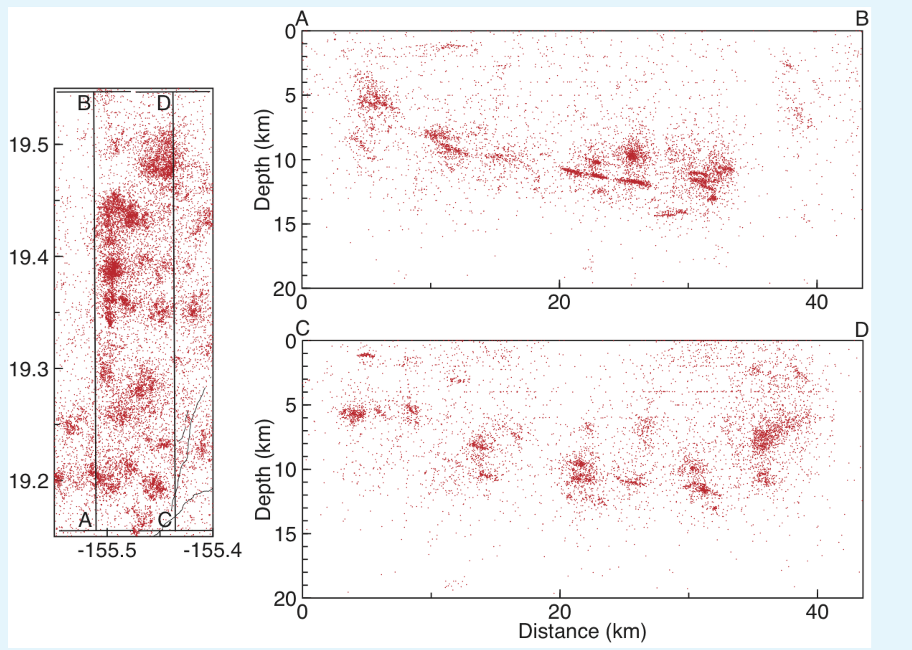




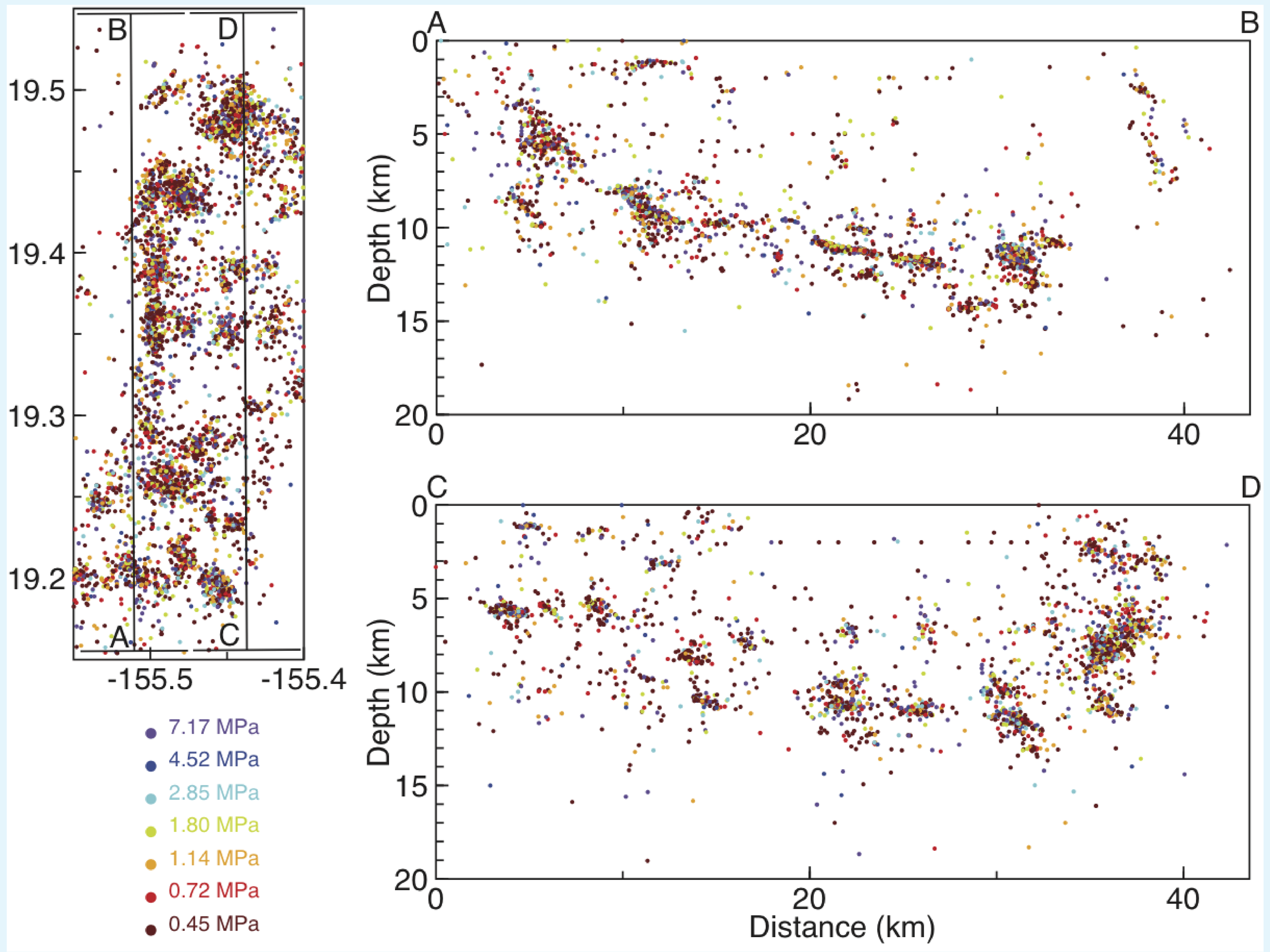
Catalog Locations



Relocations from cross-correlation



Preliminary result for Hawaiian seismic profile



References

Got, J.-L., and P. Okubo, New insights into Kilauea's volcano dynamics brought by large-scale relative location of microearthquakes, *J. Geophys. Res.*, 108, doi: 10.1029/2002JB002060, 2003.

Lin, G., P. M. Shearer and E. Hauksson, Applying a three-dimensional velocity model, waveform cross correlation, and cluster analysis to locate southern California seismicity from 1981 to 2005, *J. Geophys. Res.*, 112, doi: 10.1029/2007JB004986, 2007.

Shearer, P. M., G. A. Prieto, and E. Hauksson, Comprehensive analysis of earthquake source spectra in southern California, *J. Geophys. Res.*, 111, doi:10.1029/2005JB003979, 2006.

Waldhauser, F., and D. P. Schaff, Large-scale relocation of two decades of Northern California seismicity using cross-correlation and double-difference methods, *J. Geophys. Res.*, 113, doi: 10.1029/2007JB005479, 2008.

Wolfe, C.J., P.G. Okubo, G. Ekstrom, M. Nettles and P.M. Shearer, Characteristics of deep (>= 13 km) Hawaiian earthquakes and Hawaiian earthquakes west of 155.55W, *Geochem. Geophys. Geosyst.*, 5, doi:10.1029/2003GC000618, 2004.

Wolfe, C.J., P.G. Okubo and P.M. Shearer, Mantle fault zone beneath Kilauea volcano, *Science*, 300, 478-480, 2003.