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# Analysis of Southern California Seismograms for Earthquake Source Properties

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*Introduction*

This SCEC funded research developed and implemented methods to study earthquake source properties using the vast waveform archives of the Southern California Seismic Network (SCSN). Specifically, we:

- Computed and saved *P*, *S* and noise spectra using a multitaper method for all available southern California seismograms.
- Performed stacking and empirical Green's function (EGF) analysis to isolate earthquake source spectra and study Brune-type stress drops and earthquake scaling relationships.
- Compared earthquake and quarry spectra to develop improved discrimination methods.

These results help address a variety of issues:

• Do earthquake stress drops in southern California vary systematically in space and time? Our results so far indicate that complicated spatially coherent stress drop variations are present in southern California, which have no clear correlation of stress drop with tectonic regime or distance from active faults.

• Can variations in earthquake stress drop be related to changes in the stress field caused by large ruptures? For the Landers and Parkfield earthquakes, we find some evidence that these variations in aftershock stress drops are correlated with the mainshock slip distribution.

• Do earthquake source spectra scale such that apparent stress is constant with respect to event size? This is currently a controversial issue (e.g., Kanamori et al., 1993; Abercrombie, 1995; Mayeda and Walter, 1996; Ide and Beroza, 2001), which can be addressed either by studying earthquake corner frequencies or by computing radiated seismic energy. Our results so far suggest little or no scaling of stress with earthquake size (Shearer et al., 2006), indicating self-similarity is obeyed at least over the $M = 1$ to 3.4 range of our analyses.

This work helps provide a more detailed understanding of earthquake source properties, which will contribute to quantitative assessments of earthquake potential and seismic hazard in southern California.

*Earthquake stress drops for southern California*

In earlier SCEC work, we computed and saved *P*, *S*, and noise spectra from over 2 million seismograms from 1984 to 2003 using a multitaper method applied to a 1.28 s signal window and a pre-arrival noise window. Next, we stacked the *P* spectra to isolate source, receiver, and propagation path contributions to the spectra. The advantage of the method is that it identifies and removes anomalies that are specific to certain sources or receivers. This is an important step because individual spectra tend to be noisy and irregular in shape and difficult to fit robustly with theoretical models.  However, by stacking thousands of spectra it is possible to obtain much more consistent results.

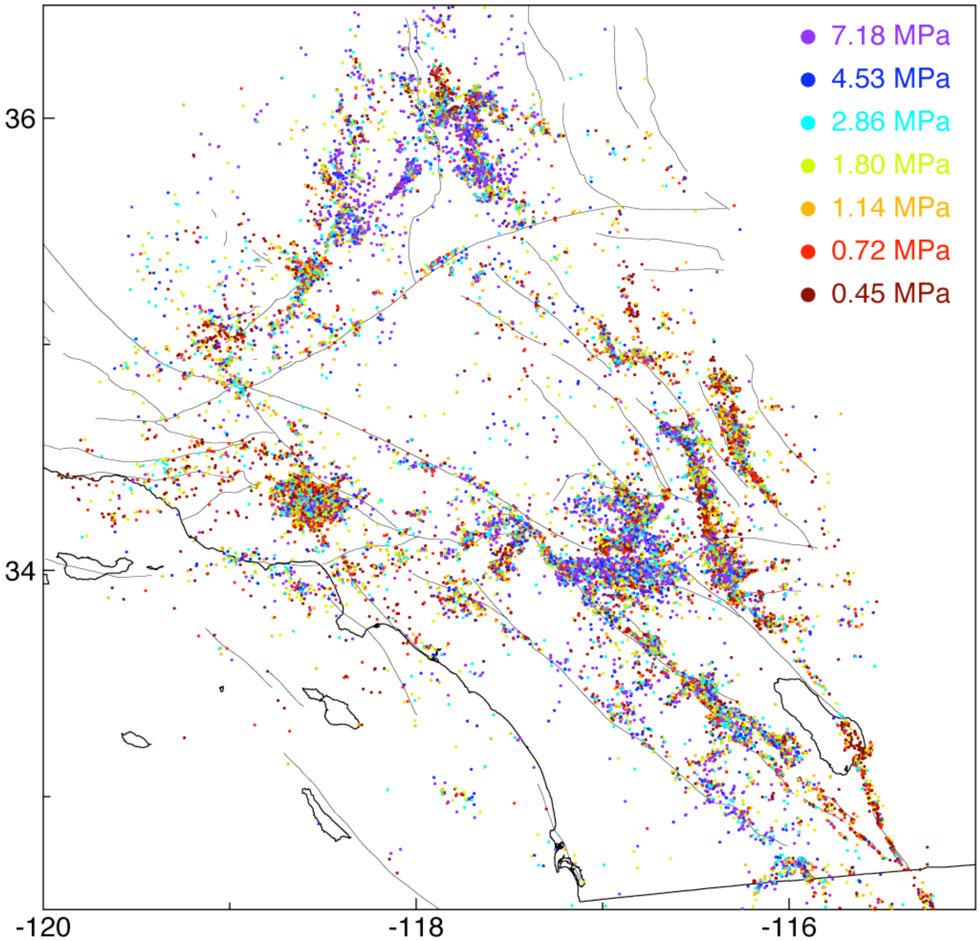


**Figure 1**.  Estimated Brune-type stress drops for over 65,000 southern California earthquakes from 1989 to 2001. Results are colored in equal increments of log $\Delta\sigma$.

Next, we stacked the source spectra within bins of different seismic moment and fit the resulting size-dependent source spectra simultaneously for the theoretical source model of Abercrombie (1995) and a single empirical Green's function (EGF) for the complete dataset.   We obtained a good fit using an $\omega^{-2}$ model and a constant stress drop of $\Delta\sigma$ = 1.6 MPa.  Next, we adapted our EGF method to correct each source spectrum for the response of 500 neighboring earthquakes.  In principle, this will correct for any near-source attenuation differences that could be biasing results between different regions.  Individual event stress drops, as obtained by fitting each EGF-corrected source spectrum using the Aberbrombie (1995) model, are plotted in Figure 1.   These estimated stress drops exhibit spatially coherent patterns.  For example, Northridge aftershocks and events in the Imperial Valley have low average stress drops, whereas apparently high average stress drops are seen in the Big Bear region.

During the last year, we attempted to extend these results to *S* waves and broadband records from larger events.    Specifically, we have:

(1) Processed and analyzed 2000 to 2005 Tri-Net data to obtain results for larger magnitude events.  This is important to better constrain the possible dependence of stress drop on moment.

(2) Examined *S* wave spectra and systematically compared *P* and *S* wave corner frequencies.

Unfortunately, we have found that *S*-wave spectra have much lower signal-to-noise ratios at high frequencies than the *P*-wave spectra that we have previously studied. This is due to contamination from *P*-wave coda and the larger effects of attenuation on *S* waves. The usable frequency band for locally recorded *S* spectra is so limited that it is very difficult to resolve corner frequency. This negative result motivated our most recent SCEC proposal to examine coda waves using techniques similar to those developed by Mayeda and Walter (1996). Using this approach we are optimistic that we will be able to achieve useful results for *S* spectra.

The remainder of this report will describe a related project, mainly funded by DOE, which used many of the same techniques to compare earthquake and quarry spectra in southern California.

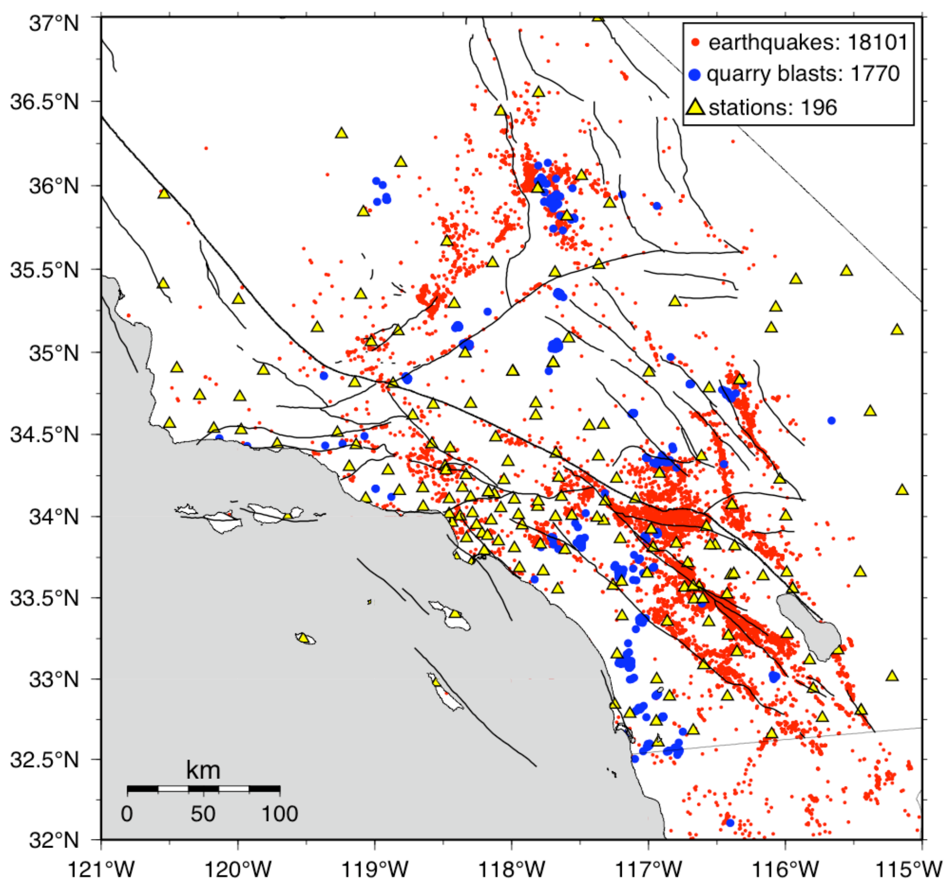


**Figure 2**. Locations of 18,101 earthquakes (red) and 1770 explosions (blue) in southern California from 2000 to 2005 as recorded by broadband stations (yellow) of the Southern California Seismic Network (SCSN).

*Quarry versus earthquake spectra*

The goal of this project is to systematically analyze and compare source spectra from locally recorded earthquakes and explosions in southern California (Figure 2) in order to develop new insights into discrimination methods. The project builds upon a recently completed large-scale analysis of southern California earthquake spectra (Shearer et al., 2006), to include a set of 1770 mining and other explosions between 2000 and 2005. The Shearer et al. earthquake study has already provided the largest set of earthquake spectra and stress drops computed to date, showing that individual event stress drops range between 0.2 and 20 MPa. The large number of stations and events available in southern California make possible empirical calibration methods to remove receiver response and path propagation effects. Our efforts focus on southern California because of the unmatched size and quality of the available data, but we expect the results and insights will be applicable to other regions of more direct interest to nuclear monitoring programs. While the Shearer et al. (2006) study analyzed 1989–2001 data from short-period vertical-component stations, we examine 2000–2005 data from three-component, broadband stations. The newer data have the advantage of the horizontal components and a larger dynamic range (i.e., the older data clip on earthquakes above ~M3.5).

To study the average shape of the spectra, we stack our results within equally spaced bins in estimated seismic moment (obtained from the low-frequency part of the spectrum) using the empirical Green's function approach described in Shearer et al. (2006). Figure 3 shows these stacked spectra for both earthquakes and quarry blasts. The dashed lines show the best-fitting predictions of the $\omega^{-2}$ source model of Madariaga (1976), assuming a constant stress drop.

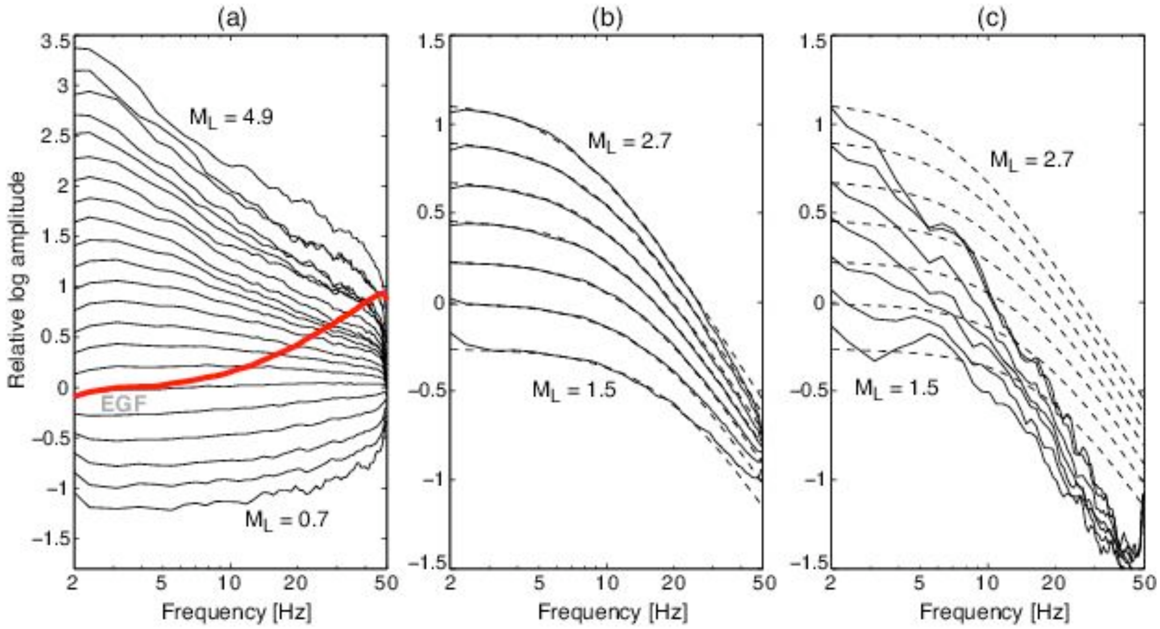


**Figure 3**. Stacked P-wave source displacement spectra from 2000 to 2005 within bins of estimated seismic moment for 17810 earthquakes and 1744 quarry blasts. (A) Stacked earthquake source terms obtained from the iterative inversion. Red line shows the empirical Green's function (EGF) used to correct these spectra for attenuation and other path effects assuming a constant stress drop model. (B) EGF corrected earthquake source terms compared to predictions of the Madariaga (1976) source model (dashed lines). (C) Stacked source terms for quarries.

Figure 3 shows that averaged earthquake spectra in southern California are well fit by a standard source model. However, the averaged quarry spectra appear anomalous in at least two respects: (1) They exhibit large misfit compared to the source model predictions, and (2) They have generally steeper falloffs at high frequencies than $\omega^{-2}$, which will lead to lower corner frequencies and stress drop estimates. The lack of high frequency radiation from the quarries is somewhat surprising and may reflect ripple firing and/or strong near-surface attenuation.

We have used these differences between the average *P* spectra between earthquakes and explosions to develop discrimination strategies (Allmann et al., 2008). We find that the observed earthquake spectra fit reasonably well with a constant stress drop model over a wide range of moment, whereas the RMS misfit for quarry blasts is significantly larger and may therefore serve as a discriminant for man-made seismicity. Explosion spectra show significant differences from the earthquake spectra and have generally steeper falloff at high frequencies. We also compare *P* and *S*-wave amplitudes and find modestly smaller average *S* amplitudes for the explosions compared to the earthquakes. For Southern California, the RMS misfit to an $\omega^{-2}$ source model is a more reliable explosion discriminant than the *P*/*S* amplitude ratio. The discrimination in this manner is fully automatic and works for about 90% of the events.

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