Comprehensive Analysis of P and S Spectra
from Southern California Earthquakes

Award 05HQGR0099

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TECHNICAL ABSTRACT

Permanent and portable seismic networks in southern California record a tremendous volume of broadband waveform data from local earthquakes. We propose to continue using a newly created online database of southern California seismograms to systematically compute, store, and analyze *P* and *S* spectra from the over 300,000 events recorded since 1984. Our analyses of the spectra will help address the following issues: (1) Do earthquake source spectra scale such that apparent stress is constant with respect to event size? (2) Do earthquake stress drops in southern California vary systematically in space and time? Can variations in earthquake stress drop be related to changes in the stress field caused by large ruptures? (3) What is the three-dimensional attenuation structure beneath southern California? (4) Can directivity effects be routinely observed in earthquake source spectra? (5) Can *P* and *S* amplitude information help improve earthquake focal mechanism accuracy compared to *P* polarity information alone? Anticipated results of this work include a more detailed understanding of earthquake source properties and new maps of lateral variations in crustal attenuation structure. This knowledge will contribute to quantitative assessments of earthquake potential and seismic hazard in southern California.

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NON-TECHNICAL ABSTRACT

We are developing automated processing techniques to provide a practical way to examine the large seismic data bases collected from permanent and portable networks in southern California. Our recent building of a complete online waveform database for this region makes possible much more comprehensive computation and analysis of earthquake source spectra than has previously been achieved. Analyses of these spectra will directly address a number of issues related to seismic hazard. These include questions concerning:

(1) Earthquake scaling: can the shaking expected from large earthquakes be predicted from that observed much more commonly in small earthquakes?

(2) Crustal stress: Are there variations in stress drops of small earthquakes that can be used to characterize stress field heterogeneity and identify regions of stress concentration?

(3) Subsurface fault orientation: can the geometries of small earthquake faults be resolved through observations of rupture directivity effects?

(4) Attenuation structure: how might ground shaking from future events be affected by differences in the energy loss during wave propagation?

In the long run, our results will provide basic knowledge about source processes and seismic wave propagation that will increase the ability of seismologists to make realistic forecasts regarding strong motion probabilities in different locations, thus contributing to the NEHRP goal of reducing losses from earthquakes in the United States.

Results

Computing P and S spectra

During the last year, we completed the necessary software to compute spectra from the database and have obtained spectra from over 300,000 events. This involves selecting windows around both the *P* and *S* waves, using the operator phase picks, if available, or applying an automatic picking algorithm. Spectra are computed using a multitaper method on all available channels and components, including rotation into transverse and radial components. Spectra are also computed from pre-arrival noise windows in order to estimate signal-to-noise ratios (Figure 1). We store the spectra in a special binary format designed for rapid storage and retrieval of the millions of spectra we obtain. Our spectral database currently requires about 60 Gbytes of storage on a RAID system at Caltech.

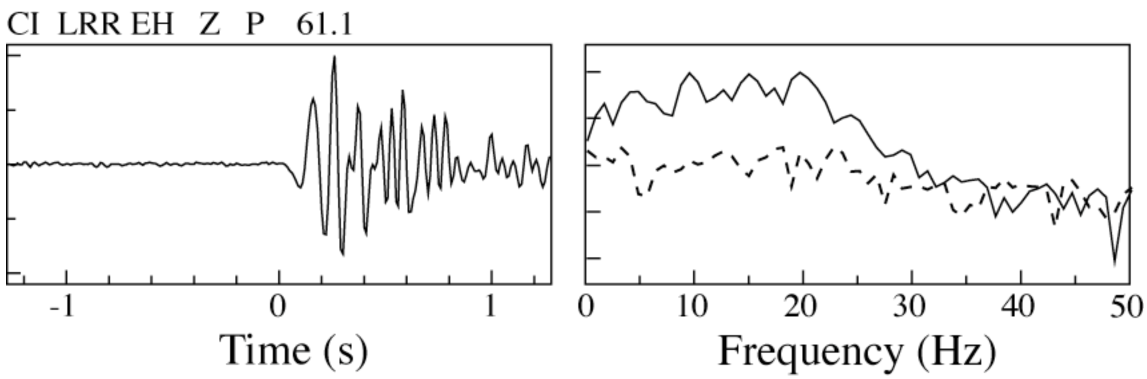

Figure 1. Windowed P-wave time series and displacement spectra for a M = 2.5 earthquake (2 Sept. 1995) recorded by station LLR at 61 km distance, as computed with our automatic algorithm. Noise and signal spectra are computed using 1.28 s windows immediately before and after the phase arrival (the dashed line is the noise spectrum). The *P* wave has good signal-to-noise between about 5 and 25 Hz.

Following application of a signal-to-noise cutoff criteria and corrections for the known gain and instrument response, we process the spectra in ways that isolate source, receiver and propagation path effects. 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. The basic approach is similar to that used by Warren and Shearer (2000, 2002) and Prieto et al. (2004). Each observed displacement spectrum $d_{ij}(f)$ from source i and receiver j is a product of source effects e_i (which include the source spectrum and near-source attenuation), near-receiver effects s_j (which includes any uncorrected part of the instrument response, the site response and the near-receiver attenuation), and a distance dependent term x_k (which includes the effects of geometrical spreading and attenuation along the ray path). Because each station records multiple events and each event is recorded by multiple stations, this is an over-determined problem, which we solve using a robust, iterative, least-squares method. Note that this method resolves only differences in the relative shapes of the spectra. Without additional modeling assumptions, it cannot, for example, resolve how much of the spectral falloff is due to source effects and how much is due to attenuation common to all paths. The advantage of the method, however, is that it identifies and removes anomalies that are specific to certain sources or receivers. Because there may be difficulties in obtaining reliable and accurate instrument response functions for many of the stations in the archive, this is an important processing step that provides a way to correct for some of these problems.

Estimating earthquake stress drops

The low frequency parts of our stacked source spectra are proportional to the relative seismic moment among the events. By using the local magnitude estimates for the earthquakes and assuming that M_L and M_W agree at $M = 3$, we obtain absolute moment estimates. Next, we stack 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 obtain a good fit using an ω^{-2} model and a constant stress drop of $\Delta\sigma = 1.6$ MPa (see Figure 2). The fit is not significantly improved when the stress drop is allowed to vary as a function of moment or when different high-frequency falloffs are applied.

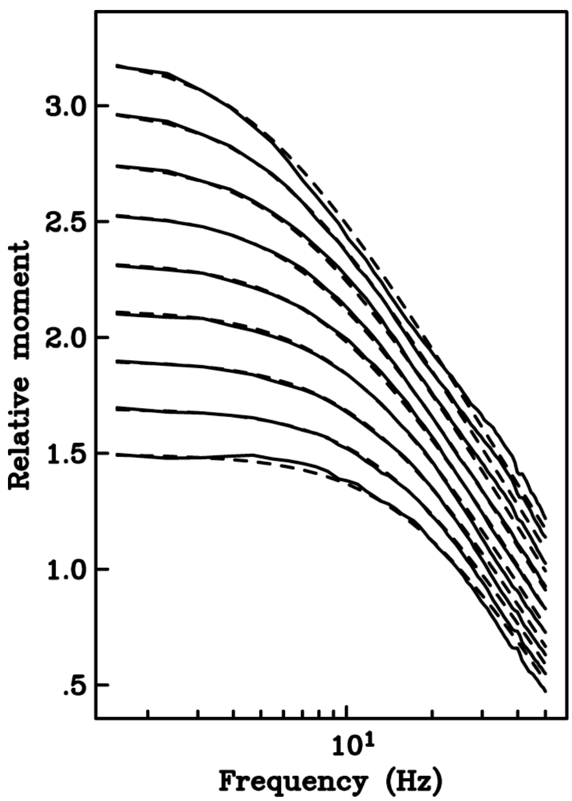

Figure 2. Source displacement spectra stacked within bins of equal log moment (solid lines) compared to the fit obtained using a constant stress drop model of $\Delta\sigma = 1.6$ MPa (dashed lines). Observed spectra are corrected using an EGF method. The fit degrades beyond 20 Hz because of signal-to-noise limitations in the data.

These results show that the average stress drop of small earthquakes in southern California has no significant dependence on seismic moment, confirming the earlier results of Prieto et al. (2004) on a more restricted dataset. This suggests that the earthquakes obey self-similarity, at least over the $M = 1 - 3.4$ range of our observations. Another check on our method is obtained by fitting the distance dependent spectral terms with a constant *P*-wave *Q* model. Here we find a good fit is achieved using $Q = 560$, in reasonable agreement with results of Schlotterbeck and Abers (2001).

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 (i.e., Q variations that deviate from the average value for all of southern California obtained with our stacking approach). Individual event stress drops as obtained by fitting each EGF corrected source spectrum using the Aberbrombie (1995) model are plotted in Figure 3. Lower than average $\Delta\sigma$ values (reduced high frequencies) are plotted in red and higher than average $\Delta\sigma$ values (increased high frequencies) are plotted in blue. These source terms exhibit spatially coherent patterns. For example, Northridge aftershocks and events in the Imperial Valley are relatively depleted in high frequencies, indicating either lower than average stress drops or slow rupture velocities (we assume constant rupture velocity for comparison purposes). In contrast, apparently high average stress drops are seen in the Big Bear region.

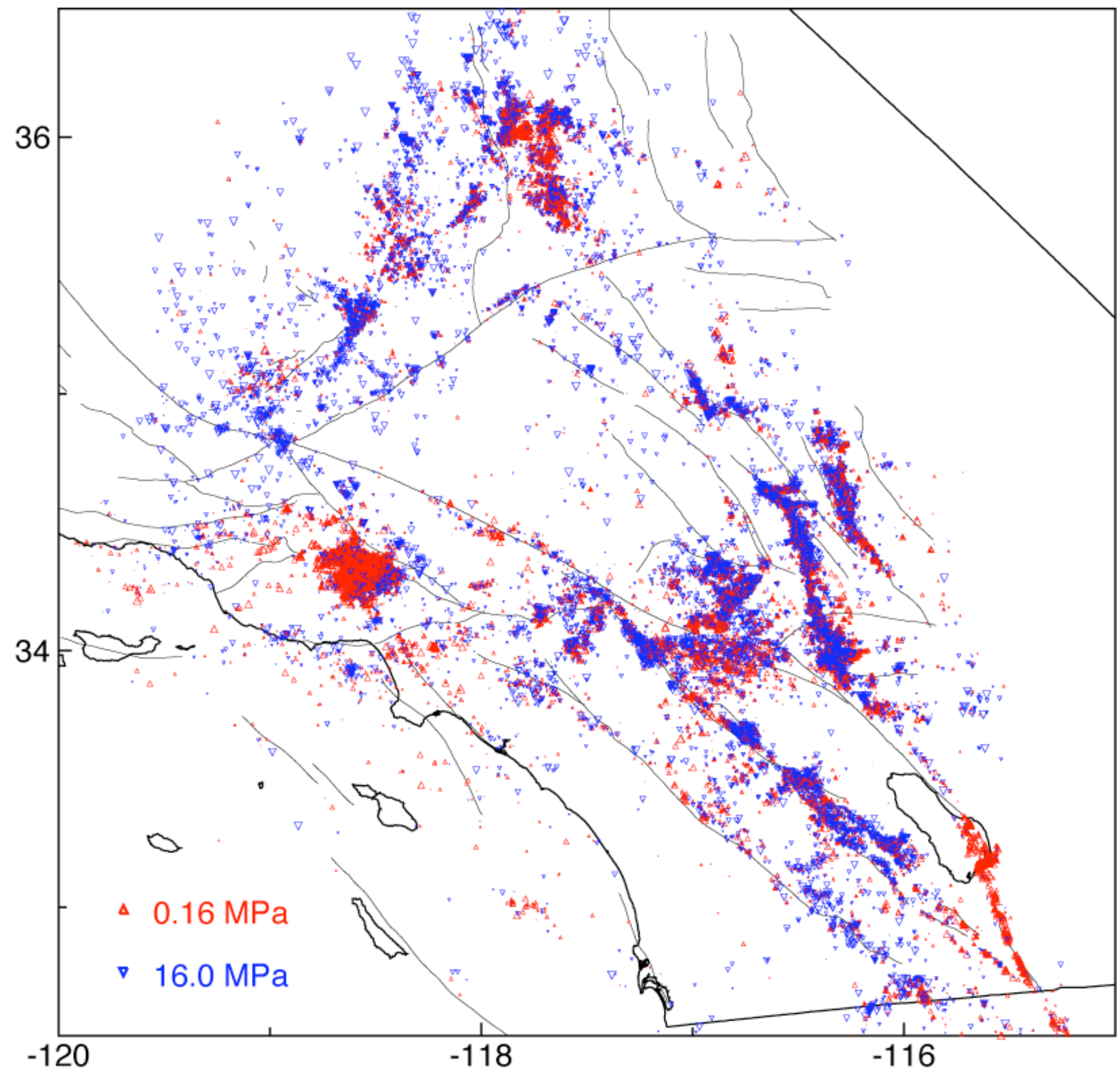

Figure 3. Estimated stress drops for over 65,000 southern California earthquakes from 1989 to 2001. Red indicates stress drops less than the median value of 1.6 MPa, blue indicates higher than average stress drops. Symbol size is proportional to the log deviation from 1.6 MPa.

Individual event stress drops exhibit considerable scatter, with values ranging from 0.2 to 20 MPa. This scatter is not significantly reduced when more records are required for each event stack, indicating that this variation is a real feature and not simply a measure of noise in our estimation methods. Spatial variations in average stress drop are less, but nonetheless range from 0.5 MPa for earthquakes at the southern end of the Salton Sea to 4 MPa at the northern end of the San Jacinto fault.

There is also a significant dependence in observed stress drop with event depth, as illustrated in Figure 4. Median stress drop increases from 0.6 MPa near the surface to 2.0 MPa at 8 km depth. Median stress drop is nearly constant at depths between 8 and 18 km depth and then appears to decrease for deeper earthquakes (although the results may be biased by the small number of regions that include earthquakes this deep).

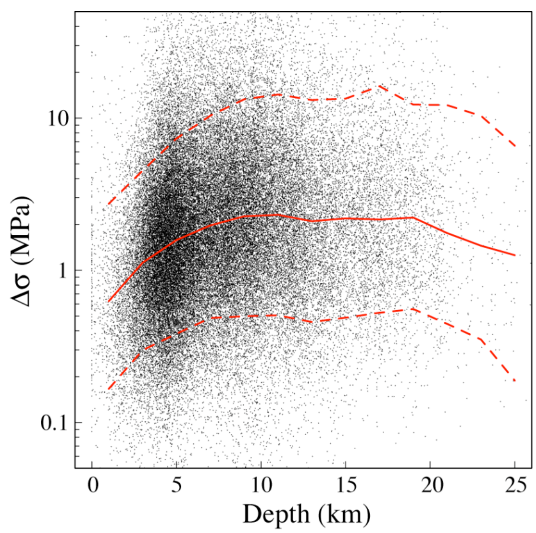

Figure 4. Estimated individual earthquake stress drops versus depth. Median, 10% and 90% levels within 2 km depth bins are plotted as the solid and dashed red lines.

Aftershocks of the 1992 Landers earthquake exhibit significant along-strike variations in frequency content and inferred stress drop. These are among the best-resolved features in our analysis and indicate rapid spatial variations in earthquake source properties. An important question is whether these stress drop variations can be related to the mainshock slip distribution. To test this, Figure 5 compares our estimated aftershock stress drops with the Wald and Heaton (1994) Landers slip model.

For the north segment of the slip model, the zone of highest slip correlates with low-stress-drop aftershocks, with higher stress drop events found on the edges of the rupture, where one might expect increased shear stress. There is a weaker correlation for the south segment, where the maximum slip region near the mainshock hypocenter in the Wald and Heaton model does not extend to deep enough depth to explain a cluster of low-stress-drop events. It is possible, however, that the sharp change to higher stress drop aftershocks south of the hypocenter marks the southern edge of the rupture. The correlation breaks down for the middle fault segment, where a high slip region corresponds to high stress drop aftershocks. It should be recognized, however, that published Landers fault slip models do not always agree very well. Several, including the Zeng and Anderson (2000) model, do not include strong slip in the middle fault segment in the same place as the Wald and Heaton model. Thus, overly detailed comparisons to the existing slip models are probably not warranted. Nonetheless, there is at least a suggestion of some correlation to the Wald and Heaton model.

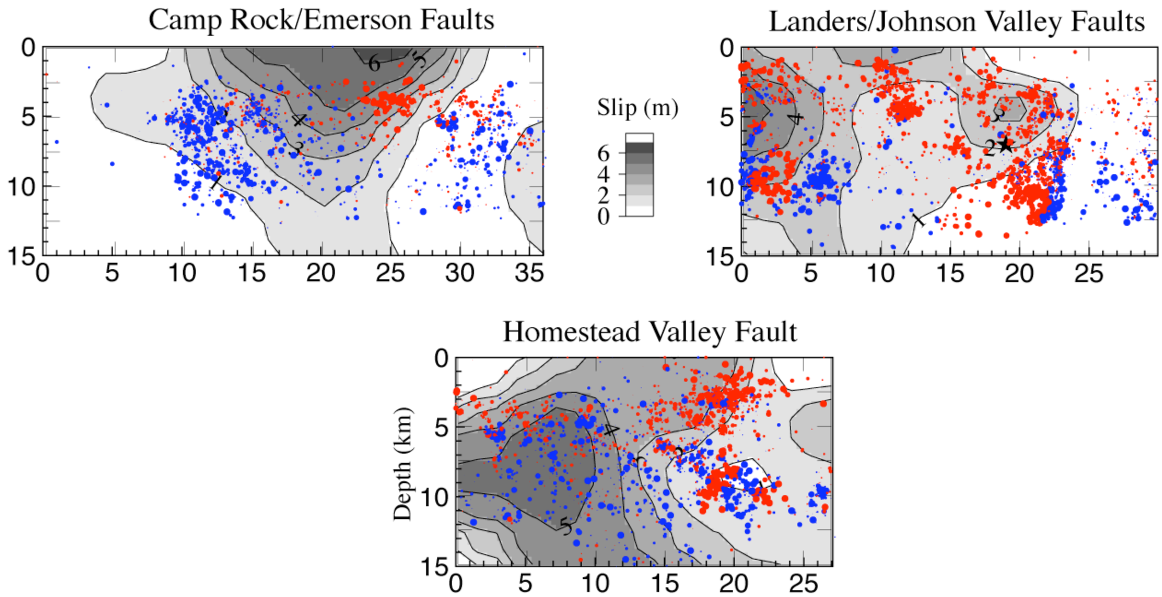

Figure 5. Landers aftershock stress drops compared to the Wald and Heaton (1994) mainshock slip model. Red indicates stress drops less than the median value of 1.6 MPa, blue indicates higher than average stress drops. Symbol size is proportional to the log deviation from 1.6 MPa.

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<u>Non-technical Summary</u>

Seismic wave spectra provide valuable information about earthquake source properties and the attenuation structure of the southern California crust. We systematically compute compressional and shear-wave spectra from over 300,000 southern Californian earthquakes and analyze them to separate source and propagation path effects.

Reports Published

Shearer, P. M., G. A. Prieto, and E. Hauksson, Comprehensive analysis of earthquake source spectra in southern California, *J. Geophys. Res.*, 111, B06303, doi:10.1029/2005JB003979, 2006.