Final Technical Report

Comprehensive Analysis of P and S Spectra from Southern California Earthquakes

Award 08HQGR0083

Peter M. Shearer
Institute of Geophysics and Planetary Physics
Scripps Institution of Oceanography
University of California, San Diego
La Jolla, CA 92093
858-534-2260 (phone), 858-534-5332 (fax)
pshearer@ucsd.edu

Program Element: III

Research supported by the U.S. Geological Survey (USGS), Department of the Interior, under USGS award number 08HQGR0083. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

Award 08HQGR0083

Peter M. Shearer
Institute of Geophysics and Planetary Physics
Scripps Institution of Oceanography
University of California, San Diego
La Jolla, CA 92093
858-534-2260 (phone), 858-534-5332 (fax)
pshearer@ucsd.edu

TECHNICAL ABSTRACT

The automated processing techniques we are developing provide a practical way to examine the large seismic databases collected from permanent and portable networks in southern California. Our maintenance of a complete online waveform database for this region makes possible much more comprehensive computation and analysis of earthquake source spectra than have previously been achieved. Analyses of these spectra will directly address a number of issues related to seismic hazard. These include questions concerning: (1) 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? (2) Earthquake scaling: Can the shaking expected from large earthquakes be predicted from that observed much more commonly in small earthquakes? (3) Earthquake physics: Which dynamic source models are most consistent with seismic observations? (4) Subsurface fault orientation: Can the geometries of small earthquake faults be resolved through observations of rupture directivity effects? Anticipated results of this work include 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. One issue of particular interest is whether large, damaging earthquakes are simply "scaled up" versions of smaller earthquakes, in which case strong ground motions could be predicted for future large quakes by studying records of the much more numerous smaller earthquakes that are detected instrumentally. In addition, the frequency content of earthquakes—a direct focus of our work—has important implications for the design of earthquake-resistant structures. Finally, our research should help unravel the complicated tectonics and fault geometries in southern California, the most vulnerable part of the United States to earthquakes, given the large population and recognized seismic hazard from many major faults.

Award 08HQGR0083

Peter M. Shearer
Institute of Geophysics and Planetary Physics
Scripps Institution of Oceanography
University of California, San Diego
La Jolla, CA 92093
858-534-2260 (phone), 858-534-5332 (fax)
pshearer@ucsd.edu

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 goal of reducing losses from earthquakes in the United States.

Results

Figure 1 shows estimated Brune-type stress drops for over 65,000 southern California earthquakes between 1989 and 2001, computed using the Madariaga (1976) model from *P*-wave spectra using a stacking method that separates source, receiver and propagation path terms (Shearer et al., 2006). Individual event stress drops exhibit large scatter, with values ranging from 0.2 to 20 MPa. 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. We observe a significant dependence in observed stress drop with event depth. Median stress drop increases from 0.6 MPa near the surface to 2.0 MPa at 8 km depth and then remains nearly constant at depths between 8 and 18 km depth. However, it should be noted that this trend of lower corner frequencies at shallower depth could also be explained with reduced rupture velocities, as might be expected because of the lower shear velocities close to the surface. The fundamental observation is that on average shallow earthquakes in southern California radiate less high frequency energy than deeper earthquakes of the same moment. This is not an effect of increased attenuation at shallow depth because we apply an Empirical Green's Function (EGF) method that corrects for attenuation differences.

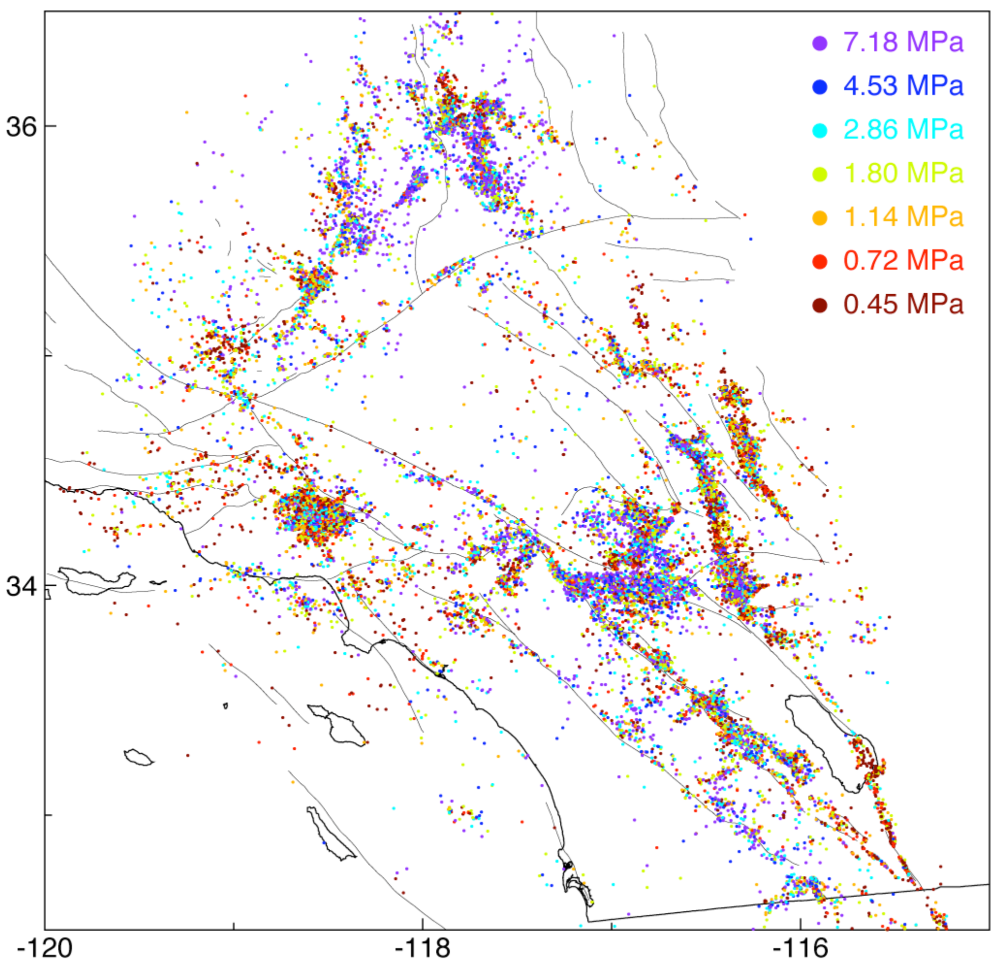

Figure 1. Estimated stress drops for over 65,000 southern California earthquakes from 1989 to 2001.

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).

These results for southern California are described in Shearer et al. (2006) and application of a similar method to data from the Parkfield region of the San Andreas fault are described in Allmann and Shearer (2007). At Parkfield we obtain stress-drop estimates that vary from 0.1 to over 100 MPa with a median value of 6.75 MPa, significantly higher than we observed across most of southern California. The estimated median stress drops show significant lateral variations; we found lower stress drops near the Middle Mountain asperity and along the creeping fault section, and higher stress drops in the hypocentroidal region of the 2004 M6.0 Parkfield earthquake. Comparing stress drops before and after the mainshock, we found that the pattern of high- and low-stress-drop regions is largely unaltered by the earthquake. However, we were able to identify some statistically significant increases in stress drop, most clearly in the vicinity of the 1966 mainshock and along the creeping fault section. In addition, we observed generally increased t^* values following the 2004 mainshock, indicating increased attenuation, particularly in the area between the 1966 and 2004 hypocenters.

A puzzling aspect of these results is that there is no obvious relationship between the stress drops and the location of faults and tectonic features. We do not yet understand what may be controlling the large observed variations in average stress drop and this will be a focus of our future work. Preliminary analyses do not show a significant correlation between stress drop and focal mechanism type. The stress drop patterns in some regions appear to correlate to changes in seismic b-value, which has been proposed to be a proxy for fault stress levels (e.g., Wiemer and Wyss, 1997), but in other areas there is no correlation or an anti-correlation. 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. Comparisons to slip models for the Landers mainshock suggest that there may be some correlations between slip and aftershock stress drop, but these correlations are highly dependent upon which of the many published slip models is considered.

One of the sharpest spatial changes in stress drop for the Landers aftershocks is plotted in Figure 2. Near 34.16˚N, there is an abrupt change from low stress drop events to the north to a cluster of high-stress drop events to the south. The low stress-drop events appear to have mainly strike-slip mechanisms whereas the high stress-drop events are mostly normal faulting earthquakes. This local observation is consistent with the general result for southern California that normal faulting earthquakes have higher median stress drops than strike-slip earthquakes (Shearer et al., 2006). This is opposite to the prediction of Andersonian faulting theory for absolute stress levels, but the relationship between stress drop and absolute stress is unclear as there is a continuing controversy over absolute crustal stress levels (e.g., Scholz, 2000, 2006; Brune and Thatcher, 2002, Townend, 2006). Resolving temporal changes in stress drops in response to mainshock induced stress changes might help to resolve this issue. Results for the 2004 Parkfield earthquake suggest that such temporal changes are relatively small (Allmann and Shearer, 2007). We plan to continue searching for temporal changes in stress drop, but note the difficulty of reliably resolving such changes, given the large scatter in individual stress drops and the sparseness of pre-mainshock seismicity in most aftershock regions (the recent Parkfield earthquake was a notable exception).

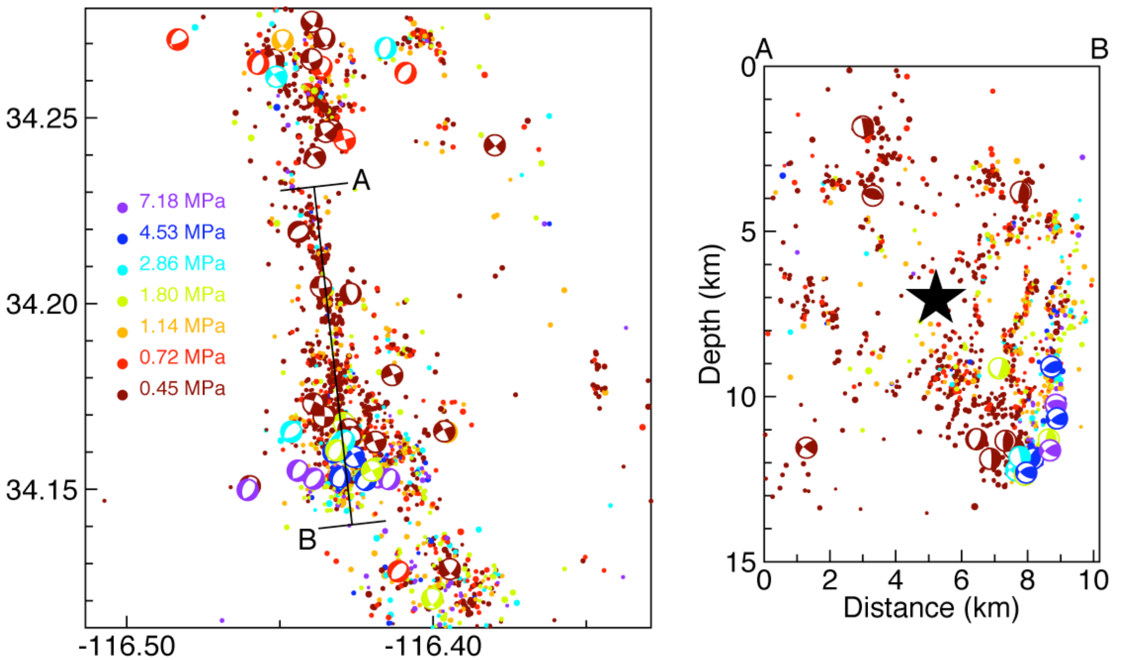

Figure 2. Map view and vertical cross-section of part of the Landers aftershock sequence, showing stress drop estimates (see color scale) and focal mechanisms (J. Hardebeck, personal communication). The mainshock hypocenter is shown as the star. Beach balls in the cross-section are shown in side view.

A related project involved comparing the spectra of earthquakes and quarry blasts in southern California. A constant stress drop model gives a good fit to the observed average earthquake spectra over a wide range of moment, but provides a mediocre fit to the average quarry blast spectra, which have a generally steeper falloff at high frequencies than the earthquakes. We also compared *P* and *S*-wave amplitudes and found modestly smaller average *S* amplitudes for the explosions compared to the earthquakes. For southern California, the RMS misfit of *P*-wave spectra to the source model is a more reliable explosion discriminant than the *S*-to-*P* amplitude ratio and works for about 90% of the events. Results of this study are described in Allmann et al. (2008).

References

Allmann, B.P., and P.M. Shearer, Spatial and temporal stress drop variations in small earthquakes near Parkfield, California, *J. Geophys. Res.*, **112**, B4, B04305, doi:10.1029/2006JB004395, 2007.

Allmann, B.P., P. M. Shearer, and E. Hauksson, Spectral discrimination between quarry blasts and earthquakes in southern California, *Bull. Seismol. Soc. Am.*, **98**, 2073–2079, doi: 10.1785/0120070215, 2008.

Brune, J.N. and W. Thatcher, Strength and energetics of active fault zones, in *International Handbook of Earthquake and Engineering Seismology*, IASPEI Committee on Education, 2002.

Madariaga, R., Dynamics of an expanding circular fault, *Bull. Seismol. Soc. Am.*, **66**, 639-666, 1976.

Prieto, G., P.M. Shearer, F.L. Vernon and D. Kilb, Earthquake source scaling and self-similarity estimation from stacking P and S spectra, *J. Geophys. Res.*, 109, B08310, doi:10.1029/2004JB003084, 2004.

Schlotterbeck, B.A. and G.A. Abers, Three-dimensional attenuation variations in southern California, *J. Geophys Res.*, **106**, 30,719-30,735, 2001.

Scholz, C.H., Evidence for a strong San Andreas fault, *Geology*, **28**, 163–166, 2000.

Scholz, C.H., The strength of the San Andreas Fault: a critical analysis, in *Earthquakes: Radiated Energy and the Physics of Faulting, AGU Geophysical Monograph Series 170*, 301–311, 2006.

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.

Townend, J., What do faults feel? Observational constraints on the stresses acting on seismogenic faults, in *Earthquakes: Radiated Energy and the Physics of Faulting, AGU Geophysical Monograph Series 170*, 313–327, 2006.

Wiemer, S. and M. Wyss, Mapping the frequency-magnitude distribution in asperities: am improved technique to calculate recurrence times?, *J. Geophys Res.*, **102**, 15,115–15,128, 1997.

Non-technical Summary

Seismic wave spectra provide valuable information about earthquake source properties and the attenuation structure of the southern California crust. We systematically analyzed spectra from over 300,000 southern Californian earthquakes and analyzed them to compute earthquake stress drops. Our results show considerable variability in stress drops among different events, but we observe spatial variations in average stress drop and no clear dependence of stress drop with earthquake size. These results relate to earthquake scaling issues (are large earthquakes simply scaled up versions of smaller earthquakes) and ultimately to predictions of strong ground motions from future earthquakes.

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.

Allmann, B.P., and P.M. Shearer, Spatial and temporal stress drop variations in small earthquakes near Parkfield, California, *J. Geophys. Res.*, **112**, B4, B04305, doi:10.1029/2006JB004395, 2007.

Allmann, B.P., P. M. Shearer, and E. Hauksson, Spectral discrimination between quarry blasts and earthquakes in southern California, *Bull. Seismol. Soc. Am.*, **98**, 2073–2079, doi: 10.1785/0120070215, 2008.