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Analysis of Coda Waves in Southern California for Earthquake Source Properties

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Introduction

This SCEC funded research involves continued analysis of the vast waveform archives of the Southern California Seismic Network (SCSN/TriNet) in order to study earthquake source properties. Specifically, we plan to:

- Extend our southern California waveform database to include longer time windows to fully capture *P*- and *S*-wave coda for all earthquakes of $M > 3.0$.
- Perform comprehensive analysis of coda waves using the methods similar to those of Mayeda and Walter (1996) and Mayeda et al. (2003).
- Apply empirical Green's function (EGF) analysis to isolate earthquake source spectra and study Brune-type stress drops. This will extend our previous results for $M < 3$ events to include earthquakes up to *M* 7.
- Perform numerical modeling of coda using a Monte Carlo method that can separate the effects of scattering and intrinsic attenuation.

Results of this data processing will 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.
- 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 (e.g., Prieto et al., 2004; Shearer et al., 2006), indicating self-similarity is obeyed at least over the $M = 1$ to 3.4 range of our analyses.
- What is the relative importance of scattering and intrinsic attenuation at high frequencies in southern California?

This work will help 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.

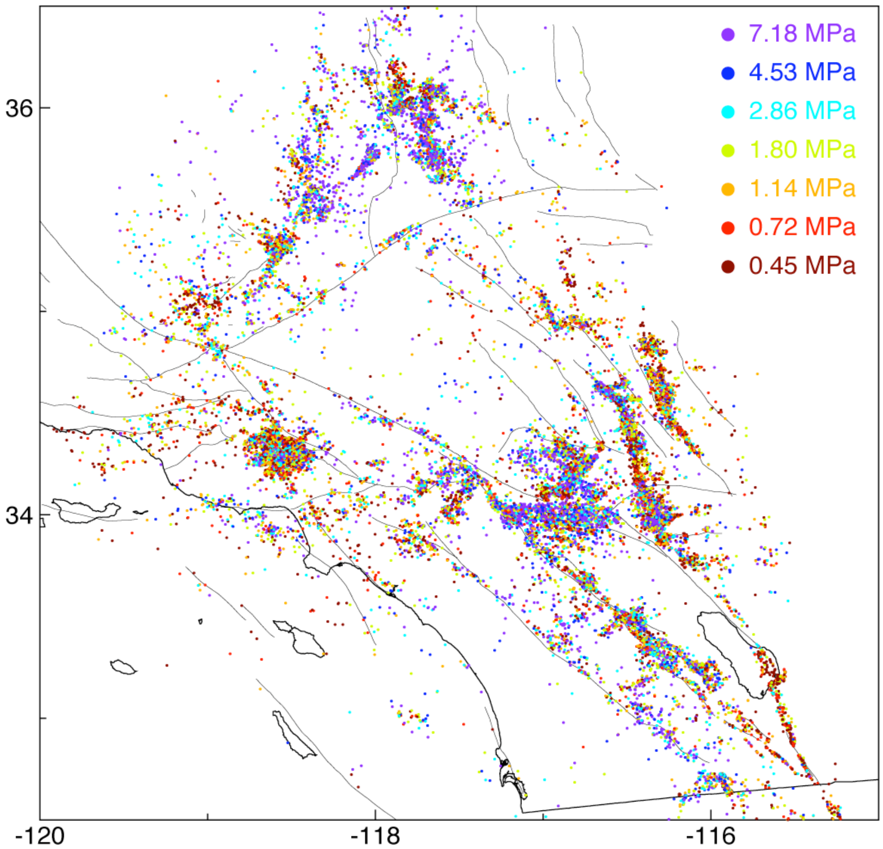

Figure 1. Estimated Brune-type stress drops for over 65,000 southern California earthquakes from 1989 to 2001. Results are colored in equal increments of log $\Delta\sigma$.

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 ω^{-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 Abercrombie (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.

Coda waves

Seismic coda is the wavetrain that follows primary seismic arrivals, and is caused by scattering of energy from small-scale heterogeneities in the crust and mantle. Because this scattering occurs within a considerable volume around the source and receiver, it tends to average out variations in observed wave amplitudes caused by source radiation pattern differences and focusing effects along particular ray paths. For this reason, measurements of coda amplitudes tend to be more stable among different stations than observations of primary phase amplitudes. Several decades ago, this motivated the development of the coda magnitude scale for characterizing event size (e.g., Lee et al., 1972; Herrmann, 1975; Suteau and Whitcomb, 1979; Bakun, 1984a,b; Michaelson, 1990; Mayeda, 1993; Dewberry and Crosson, 1995; Mayeda et al., 2003). These methods initially considered only the coda duration, which was easy to measure on analog records, but a more sophisticated approach considers the relative amplitudes of the code decay curves, which are observed to be of similar shape among different events when plotted on a log scale.

A related approach can be applied to coda waves to compute local site responses, such as the increased seismic wave amplitudes observed for stations located on sediment compared to hard rock (e.g., Phillips and Aki, 1986; Mayeda et al., 1991; Koyanagi et al., 1992; Su et al., 1992). By examining coda amplitudes at varying frequencies, it is also possible to estimate the source spectrum (e.g., Rautian and Khalturin, 1978; Mayeda and Walter, 1996; Mayeda et al., 2003; Eken et al., 2004; Morasca et al., 2005), which can be used to compute corner frequencies and address issues regarding scaling of earthquake properties with moment (e.g., Walter et al., 2006).

We are planning to study coda using methods similar to those developed by Kevin Mayeda and co-workers (e.g., Mayeda and Walter, 1996; Mayeda et al., 2003) for simultaneously fitting a set of events recorded by multiple stations. This involves the computation of coda envelopes in a series of narrowband filtered records and then fitting these traces using an empirical model of coda decay that includes station terms and a distance-dependent term. These results provide relative source spectra estimates, which are then calibrated to agree at low frequencies with independent observations of moment and to have overall shapes comparable to those predicted using an empirical Green's function (EGF) method. An advantage of the Mayeda approach is that it has the flexibility to handle variations in usable coda window length, which arise from differences in the size of the source, the source-receiver distance, the frequency band, and the noise levels. It is therefore well suited to the automated analysis and calibration of large data sets.

We also plan to model our coda observations using the Monte Carlo synthetic scattering algorithm of Shearer and Earle (2004), a fully elastic code based on radiative transfer theory that can handle multiple scattering from random heterogeneity structures. Our goal is to develop a first-order 1-D model that can explain the main features in the coda observations, including depth-dependent scattering and intrinsic attenuation, which could be used as a basis for resolving 3-D variability.

However, progress during the last year has been slow on the coda project for several reasons, including delays in setting up a suitable waveform database and getting a graduate student up to speed on the project. For this reason, I will briefly describe a different SCEC-related project for the remainder of this report, in which more progress has been made.

Mogi doughnut behavior preceding small earthquakes in southern California

Earthquakes cluster strongly in time and space, but it is not yet clear how much of this clustering can be explained as triggering from previous events (such as occurs for aftershock sequences following large earthquakes) and how much the clustering may reflect underlying physical processes (such as apparently drive many earthquake swarms, e.g., Hainzl, 2004, Vidale and Shearer, 2006). Seismologists have long studied the seismicity preceding big earthquakes to see if any distinctive precursory patterns could be identified. In some cases, a period of low earthquake activity or quiescence is observed for years in the vicinity of the eventual rupture zone of large earthquakes, surrounded by a region of continuing or increasing activity (Kanamori, 1981). This seismicity pattern has been given the name “Mogi doughnut” (e.g., Mogi, 1969), with the doughnut hole representing the low seismicity rate around the impending hypocenter. However, analyses of large earthquake catalogs to evaluate the reliability of quiescence in predicting earthquakes have yielded mixed results (Habermann, 1988; Reasenberg and Matthews, 1988). At shorter time scales of days to hours, some earthquakes are preceded by foreshock sequences near their hypocenters, but no distinctive properties in these sequences have yet been identified that would distinguish them from the many observations of earthquake clusters that do not lead to large earthquakes.

Recently, considerable attention has focused on the statistics of earthquake triggering, in which the occurrence of an earthquake increases the probability of a subsequent nearby event, and models have been derived with a single unified triggering law, which can explain the general properties of earthquake catalogs, including foreshock and aftershock sequences (e.g., Ogata, 1999; Helmstetter and Sornette, 2002). In many of these models (e.g., Helmstetter and Sornette, 2003; Felzer et al., 2004), prior seismicity increases the probability of a future earthquake in the same region but does not change the size distribution of the triggered events, which is governed by the Gutenberg-Richter magnitude-frequency relation, a power law that produces many more small earthquakes than large earthquakes. These models predict no difference in the average seismicity prior to earthquakes of any specified size. There are many more M 4 earthquakes than M 7 earthquakes, but there should be no resolvable differences in the average rate or spatial distribution of seismicity prior to any individual earthquakes of any size. These models therefore contradict the hypothesis that Mogi doughnuts and quiescence are distinctive precursory phenomena for large earthquakes.

Resolving between these competing models is important because it touches on questions regarding the predictability of earthquakes. If Mogi doughnuts and/or quiescence can be reliably established, this would imply at least some differences in the stress distribution or crustal properties prior to large earthquakes. However, if observations show that average precursory seismicity is identical between large and small events, then larger earthquakes likely represent the essentially random occurrence of rare events in a power law distribution of event sizes (perhaps representing a runaway cascade of rupture initiated by a smaller earthquake) and will be very difficult to predict. Testing these models for large earthquakes is challenging because of the limited number of these earthquakes in the available catalogs. However, recent advances in the location accuracy of small earthquakes suggest that it may be possible to search for Mogi-like behavior on smaller and more numerous events, thus obtaining more reliable statistics regarding possible precursory behavior.

We have examined the average space-time behavior of seismicity preceding M 2–5 earthquakes in southern California from 1981 to 2005 using a high-resolution catalog and identified regions of enhanced activity in a 1-day period preceding larger earthquakes at distances comparable to their predicted source radii (Shearer and Lin, 2009). The difference in precursory behavior between large and small earthquakes is subtle but statistically significant when averaged over many earthquakes, and has similarities to the “Mogi doughnut” seismicity pattern observed to occur prior to some M 6 and larger earthquakes. These results indicate that many standard earthquake triggering models do not account for all of the processes involved in earthquake occurrence.

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