Testing and Reconciling Stress Drop and Attenuation Models for Southern California

Technical Report for SCEC Award # 18086

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The aim of our collaborative work is to improve the quality and reliability of stress drop estimates for southern California, and beyond. Our goal is to investigate the reliability of the existing catalogs of stress drop, and also the regional attenuation models. Eventually we plan to develop an improved, multi-scale approach for obtaining more precise, reliable stress drops with known uncertainties, and also simultaneously inverting for attenuation.

Earthquake stress drop is a fundamental source parameter, implicit in many of the science goals of SCEC 5. Stress drops are now commonly estimated from seismic data, but are hard to measure reliably and well. The large uncertainties and scatter in results affect strong ground motion prediction, and also limit our understanding of the physics of the earthquake rupture process, including distinguishing induced seismicity from natural seismicity. We are studying the complementary approaches of the two PIs to investigate sources of consistency and discrepancies, and quantify uncertainties in stress drop estimates. We have made considerable progress on these goals, and request funds to continue this productive collaboration. One of our two original focus areas is the Cajon Pass "Earthquake Gate" region and we will produce reliable measurements, with realistic uncertainties of the spatiotemporal stress drop variation in this SCEC high-priority location. The methods also produce information about attenuation and other path effects that are currently not used. We will study how these measurements compare to existing models of attenuation in southern California. Our longer-term aim is to develop an improved approach to estimate more accurate and reliable stress drops (SCEC5 Q1), together with regional attenuation and site effects (SCEC5 Q4).

Motivation and Relation to the Goals of SCEC5

Small earthquakes dominate earthquake catalogs, but only their locations and magnitudes are routinely determined. To understand the evolving stress state within southern California, a priority of SCEC5, we need to go beyond this. Earthquake stress drop, proportional to the slip divided by the length scale of rupture, is a basic property of earthquakes and is fundamental to the physics of the source and its energy budget. It is often estimated by measuring the corner frequency and assuming a simplified theoretical model of rupture (e.g. Brune, 1970; Madariaga, 1976; Kaneko and Shearer, 2014, 2015). Knowledge of stress drop, and its dependence on magnitude, together with the true variability of stress drop, are essential to strong ground motion modeling and prediction (e.g. Cotton *et al*., 2013; Baltay et al., 2013; Trugman and Shearer, 2018), and are a research priority of the Ground Motion group of SCEC5. Many stress drop studies have been performed, but their widely varying results (~0.1 to 100 MPa), the large uncertainties (when calculated), and the ongoing controversy of whether average stress drop changes with moment, are evidence of how hard it is to calculate stress drop reliably (e.g. Abercrombie *et al*., 2017; Abercrombie and Rice, 2005; Shearer *et al*., 2006; Pacor *et al.,* 2016; Kwiatek *et al.,* 2011; Trugman *et al.,* 2017). The need for measurements of stress drop led Ross and Ben-Zion (2016) to propose an automated approach, similar to that of Abercrombie (2014) and Abercrombie *et al*. (2017), but also subject to the same concerns about reliability as the studies considered here. This uncertainty severely limits the use of stress drop studies in: (a) quantifying the spatial heterogeneity of the stress state over a wide range of scales (e.g. Hauksson, 2014), (b) predicting strong ground motion (e.g. Baltay *et al*., 2013; Trugman and Shearer, 2018), and (c) discriminating induced seismicity (e.g. Huang *et al.,* 2016; Zhang *et al*., 2016; Trugman *et al*., 2017), all priorities of SCEC5.

The main problem in calculating earthquake stress drop is how to separate source and path effects in band-limited signals and so measure corner frequency reliably. The fact that stress drop is proportional to the cube of the corner frequency only exacerbates the problem. Various forms of empirical Green's function (EGF) analysis, in which the seismogram of a nearby small earthquake is used to represent the path effects in a larger earthquake recording, should decrease the trade-offs inherent in extracting the source spectrum (e.g. Kwiatek *et al*., 2014). If multiple earthquakes, recorded at multiple stations, are combined then it is possible to invert for both source parameters (constant for each event) and path effects (constant for individual paths), e.g., Oth *et al*. (2011). Most analyses concentrate on either source (e.g. Shearer *et al*., 2006; Abercrombie *et al*., 2017a) or attenuation (e.g. Hauksson and Shearer, 2006), often with simplifying assumptions, and do not test for the self-consistency of the resulting models. An improved model of attenuation is a priority of the GM group in SCEC5.

Our analysis to date on two selected test regions, one near the Landers earthquake, and one centered on the SCEC5 "Earthquake Gate" focus region of Cajon Pass, has provided significant insight into sources of uncertainty within the methods, and shown that the relative values within a small region are much better constrained than their absolute values. The next stage is to investigate how to expand the analysis to larger regions, applying what we have learnt, and maintaining discrimination between source and path effects. Our work forms part of the essential groundwork for developing an improved approach for inverting for source parameters and attenuation throughout southern California.

Results from Method Comparison

This continuing award has led to a productive collaboration between the PIs and we submitted a paper to *JGR-Solid Earth* in October 2018 focused entirely on our SCEC-funded comparative work. This has now been accepted for publication: Shearer *et al*., (2019), SCEC #8916, and this research has contributed to five further SCEC publications and a number of conference presentations (indicated in the Reference list, most recent Abercrombie & Shearer, 2018). Our work has focused on comparing two distinct EGF-based approaches: (1) the spectral decomposition and global EGF fitting approach, and (2) the more traditional EGF method of modeling spectral ratios with smaller nearby events. The former assumes that a single global EGF is appropriate to a large number of events, stabilizing the analysis compared to the latter approach, but potentially introducing artifacts if there is real variation in the EGF within the analyzed region. To date, the majority of our combined work has focused on a small test region (6x6 km) near the hypocenter of the 1992 Landers earthquake. Using a dense cluster of 3000 events makes the assumption of a single global EGF reasonable and allows analysis of the resolution of the two approaches.

After performing the spectral decomposition to remove effects of a regional, constant attenuation model from the data, we analyzed the resulting event terms for any spatial variation. There was no significant lateral variation, but a clear depth dependence is seen (Figure 1), similar to that observed on a larger scale by Shearer *et al*. (2006). This could result from differing path effects, or from changes in the earthquake source with increasing normal stress. For example, if rupture velocity is proportional to shear-wave velocity we would expect an increase in corner frequency with depth. We therefore restricted our initial comparison to a 6x6x6 km box to remove this effect, and plan to investigate the depth dependence in future work.

Within this small region, we calculated the event terms, and then modeled them to find the best average stress drop. We found that a model with scale-dependence fits best, but it is not significantly better than a self-similar model with a different high-frequency falloff rate. In fact, a range of possible average models are all within the uncertainty limits of the band-limited regional seismic network data (Figure 2).

We compared the spectral ratios from the spectral decomposition with those from the more traditional EGF approach; those averaged over many stations were very similar, but there were significant differences when only a small number of stations recorded both the target and EGF events. The spectral decomposition approach has the advantage of using more of the available data than the spectral ratios, thus often obtaining a better average spectrum over the focal sphere.

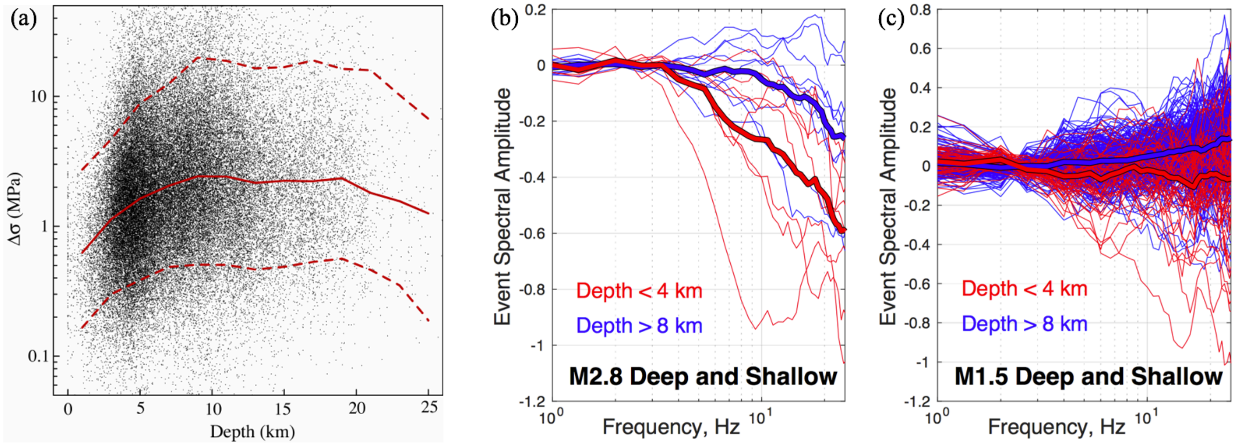

Figure 1: (a) Increase in estimated stress drop with depth from Shearer et al. (2006) study across southern California. Solid red line shows median (50th percentile), with dashed lines at 10% and 90%. (b) and (c) Event terms for deep (blue) and shallow (red) earthquakes from Landers focus region, showing increased high frequency content with depth; the thicker lines are the mean values. Preliminary observations of event ratios suggest that at least part of this depth variation results from depth-dependent attenuation.

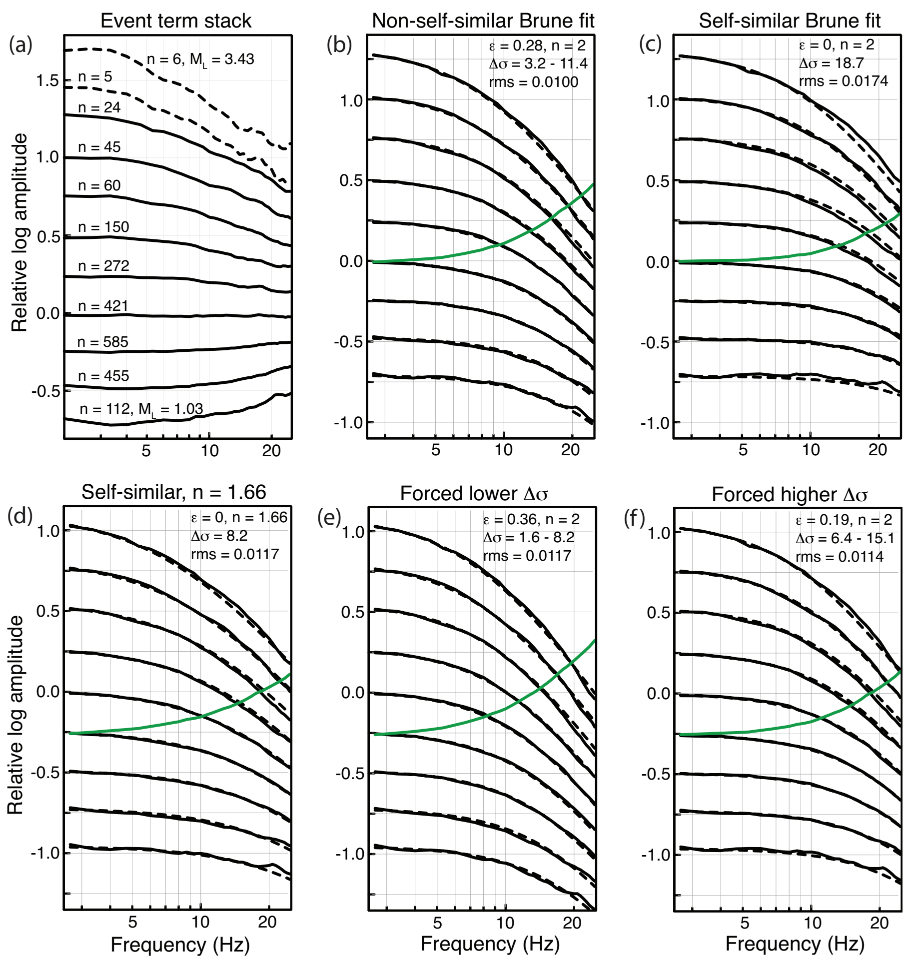

Figure 2: Stacked event term spectra and fits to a global EGF function for the Landers seismicity cluster. (a) Event-term stacks from spectral decomposition. Terms are averaged within bins of 0.25 in relative log amplitude (proportional to log M_0); n is the number of contributing earthquakes. The dashed lines indicate stacks with n<10, not included in the EGF fitting. (b) The best-fitting non-self-similar Brune model, the global EGF function in green, EGF stacks (solid) and model fit (dashed). (c) The best-fitting self-similar Brune model. (d) (e) & (f) alternative lower and higher Δσ models with statistically indistinguishable fits to the data.

We calculated the spectral ratios of each of the larger events to the same stack of 285 smaller events, and then fit the spectral ratios, as in the more traditional EGF approach. The ratio fits, with free corner frequencies for both large event (fc1) and stacked EGFs (fc2), fit better than the ratio of the results from using a global EGF, but this is largely because of the extra free parameter (fc2), Figure 3. In our test case, we know that the stacked EGFs are the same for all target events, hence fc2 should be the same for all ratios. This is true of the global EGF inversion shown in the top row of Figure 3, but not for the individual ratio fits shown in the bottom row of Figure 3. This comparison shows that fitting spectral ratios requires some constraints on fc2 because of the limited frequency bandwidth and the variation of the individual earthquakes from the simple source model.

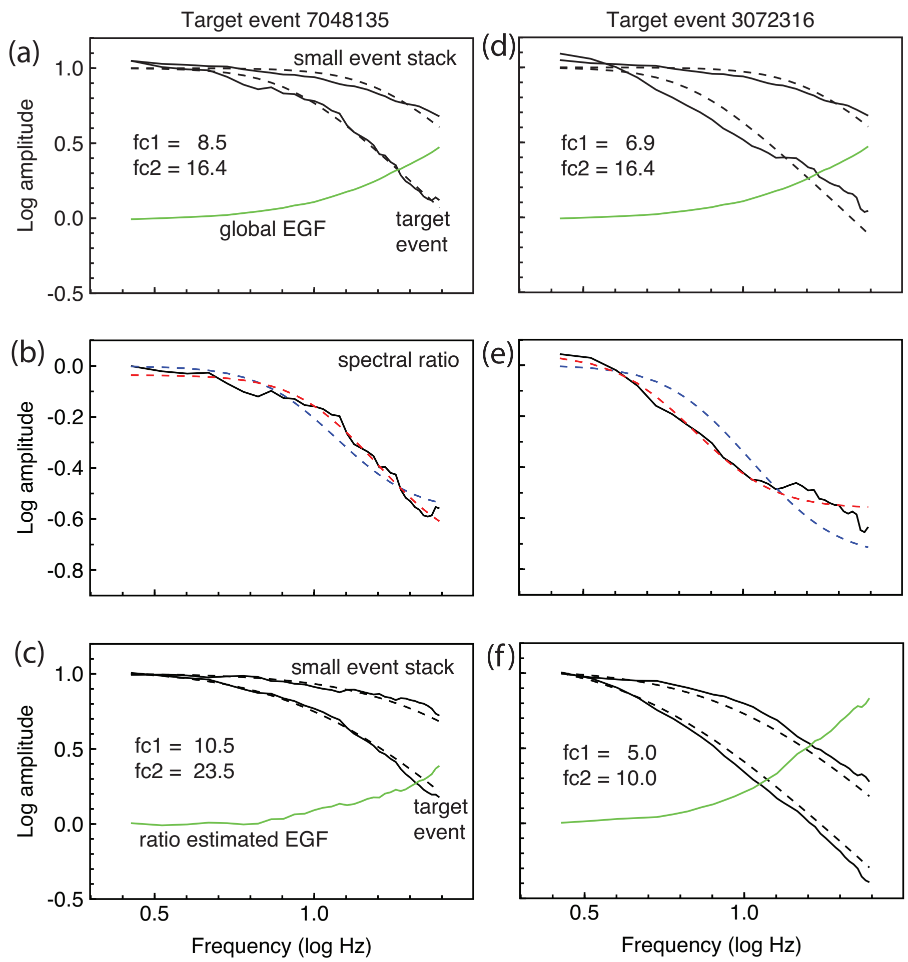

Figure 3: Comparison of the Boatwright-model fits from the global EGF approach to the spectral ratio method for two different target events. Top row: event spectra for the target events and the stack of 258 smaller EGF events, each corrected for the (same) global EGF function (green). Dashed blue lines are the model fits, fc1 and fc2 labeled. Middle row: spectral ratios of the target event spectra to the EGF stacks, the best fitting model (red-dashed line) and the blue-dashed line from the global EGF fits. Bottom row: Target and EGF stacks corrected for the ratio-estimated EGF (green lines), with models (red dashed lines), fc1 and fc2 labeled. (Using the Brune-model results in a similar effect).

Our initial testing and comparison therefore imply that much of the disagreement between different published analyses results from tradeoffs inherent in band-limited data, and suggests a path toward ways to improve resolution and quantification of uncertainties (Shearer *et al*., 2018).

We have begun synthetic tests to investigate the tradeoffs uncovered in the spectral decomposition approach. Initial results suggest that the magnitude and frequency range of the Southern California seismic network data are too limited to be able to resolve any magnitude-dependent non-self-similar scaling, as there are too many tradeoffs with the EGF and other parameters, such as the high-frequency falloff rate. These synthetic tests have the potential to determine the ranges needed to resolve scaling, and hence interpret past and future work using different earthquake data sets and recording networks.

Our initial results have focused on understanding existing methods, rather than developing new techniques or exploring new datasets. This has been an important step because we now understand where the differences between our methods are coming from and the tradeoffs among parameters that are inherent in corner-frequency fitting. In this respect, our work can be considered similar to the recent earthquake source inversion validation project (Mai *et al.*, 2016).

The results of our comparison are already being implemented as improvements to a number of ongoing analyses, because both PIs are collaborating with multiple groups and analyzing earthquakes in many parts of the world. Our work therefore meets the both the specific and broader goals of SCEC, to use Southern California as a natural laboratory to improve our understanding of earthquake processes in Southern California and beyond.

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