Testing and Reconciling Stress Drop and Attenuation Models for Southern California

Technical Report for SCEC Award #16020

Investigators: Rachel Abercrombie (BU) and Peter Shearer (UCSD)

The objective of this work is to improve the quality and reliability of stress drop measurements in southern California. The first step of this is to compare different approaches and investigate their consistency. Are the main uncertainties and discrepancies between different measurements of earthquake stress drop the result of the different methods of resolving the source spectra and modeling them, or are they principally a consequence of the limited quality and quantity of the data?

Motivation

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 SCEC4 and SCEC5, as well as earthquake physics and scaling relations, 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 [Kanamori and Brodsky, 2004]. 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 the true variability of stress drop is essential to strong ground motion modeling and prediction [e.g. *Cotton et al*., 2013]. The large number of stress drop studies attest to its importance, but their widely varying results (~0.1 to 100 MPa), the large uncertainties (when calculated), and the ongoing controversy of whether stress drop changes with moment are evidence for how hard it is to calculate reliably (e.g., *Abercrombie* [2013], *Abercrombie and Rice* [2005], *Shearer et al*. [2006], *Pacor et al*. [2016], *Kwiatek et al*. [2011], and references therein). 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], and (c) discriminating induced seismicity [e.g. *Huang et al.,* 2016; *Zhang et al*., 2016], all priorities of SCEC4 and 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 co-located 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, however, concentrate on either source [e.g. *Shearer et al*., 2006; *Abercrombie et al.,* 2016] 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 SCEC4 and SCEC5.

Methods

We worked to compare and improve two different approaches for estimating earthquake stress drops from P-wave spectra: (1) the spectral decomposition method of *Shearer et al*. [2006], a large-scale, automated approach involving stacking and averaging spectra to obtain parameters for large catalogs of events; and (2) the traditional empirical Green's function (EGF) method of

Abercrombie et al. [2017], a smaller-scale approach that attempts to obtain optimal results for a small number of the best-recorded earthquakes. We focused on two test regions with dense seismicity, one near the Landers earthquake epicenter and one around the Cajon Pass borehole, in which previous results predict spatial variability in both earthquake stress drops and attenuation.

Graduate student Daniel Trugman at SIO refined and improved the original *Shearer* [2006] algorithm in a number of ways, including: (a) adding a clip detector to remove clipped data, (b) implementing multitaper spectral estimates, (c) expanding the bandwidth to include higher frequencies, and (d) computing bootstrap error estimates for corner frequency. Perhaps most importantly, he implemented a new EGF approach that drops the constraint of self-similarity. Although the *Shearer et al*. [2006] approach applied a version of the EGF correction, it did so by simultaneously fitting a large number of stacked source spectra to a single self-similar source model. While this has the advantage that small earthquakes can be retained in the analysis (i.e., they are not simply calibration events for study of larger events), it has the disadvantage of potentially biasing the results toward self-similarity (i.e., no scaling of stress drop with moment). To address this we now use a more general version of the spectral decomposition approach that does not require self-similarity, indeed we can use it to test for deviations from self-similarity. Results for five test regions in southern California indicate an increase in median stress drop with moment for the original Brune model. Self-similarity can be preserved if the high-frequency spectral falloff rate is shallower than the f^{-2} of the Brune model, and there is a strong trade-off between the two parameters [*Trugman and Shearer*, 2017].

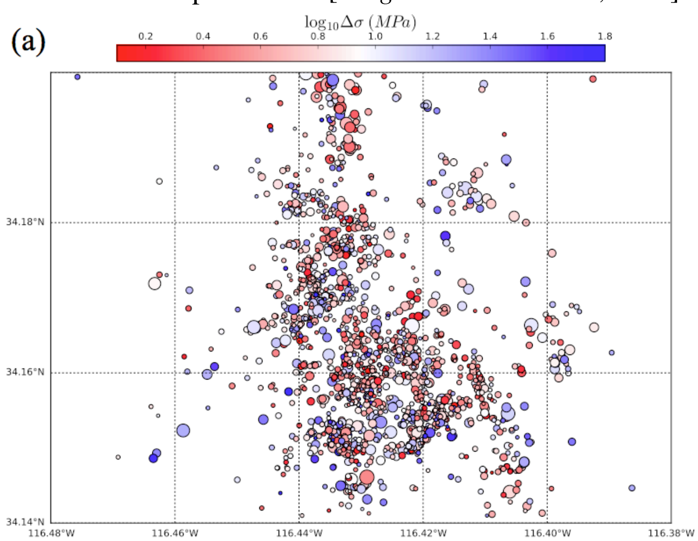

Figure 1. Stress drop estimates for 1709 earthquakes in the Landers epicentral region, computed using P-wave spectral decomposition.

Working independently, Rachel Abercrombie analyzed the 950 largest earthquakes in the Landers epicentral region. She began with the same stations and earthquakes, used the same phase picks, and implemented the same clipping detector to remove clipped waveforms. Abercrombie tested hundreds of EGFs for each target earthquake, and used only those with a high level of cross-correlation with the target earthquake. In tandem with this Southern California analysis, Abercrombie further developed her approach focusing on earthquakes associated with the Hikurangi subduction zone, New Zealand (Abercrombie *et al*. [2017]). She was then able to compute corner frequency and stress drops for 255 of the Landers region earthquakes that met the quality criteria used by Abercrombie *et al*. [2017], based on the results of Abercrombie [2015]. The method improvements used in Abercrombie *et al*. [2017] were developed with input from this analysis: (a) magnitude-dependent time-window, (b) cross-correlation criteria and (c) stacking criteria.

Results and Significance

Our spectral-decomposition-derived stress drop estimates for 1709 events in the Landers epicentral region are plotted in Figure 1. Spatially coherent patterns of high and low stress drop events are clearly seen, which are correlated with earlier results from *Shearer* [2006], although they differ in some details.

Figure 2 compares the corner frequency estimates from the two methods for common events. Both approaches assume an omega-squared high frequency fall off, and the spectral decomposition fit includes an increase in average stress drop with increasing magnitude. The results are strongly correlated; the spectral decomposition approach has a smaller mean but larger range for the traditional EGF approach. To identify the origins of differences between the methods, we looked at subsets of the earthquakes that met different quality criteria defined by Abercrombie *et al*. [2017]. These focus on the position of the corner frequency within the signal bandwidth, and the amplitude ratio and error range of the spectral fit. The best agreement is for the best-recorded earthquakes, which are best modeled by the simple circular source spectral model (red symbols).

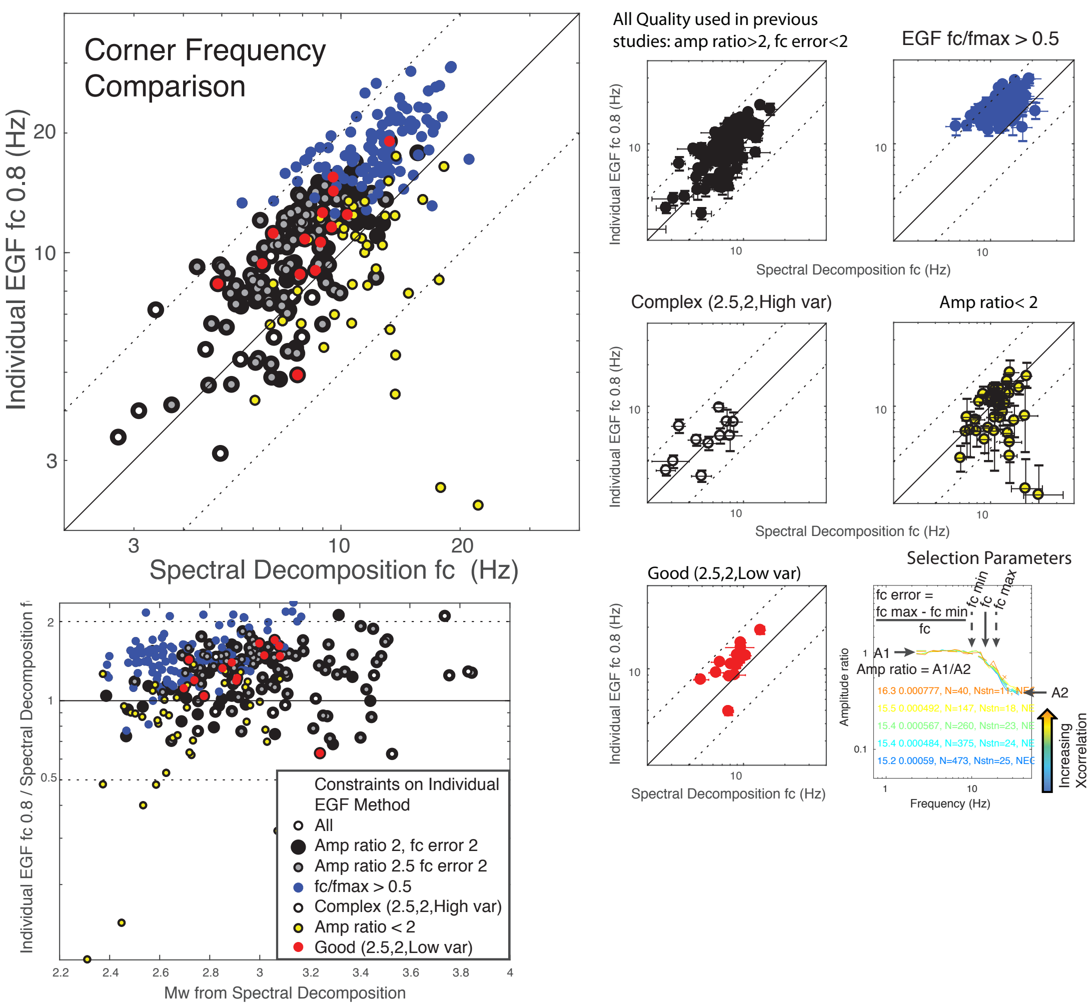

Figure 2: Direct comparison of the individual EGF measurements, cross correlation (xc) ≥ 0.8, with the spectral decomposition results (original Brune model with magnitude-dependent stress drop. The different symbols divide the events by the quality of the individual EGF fits; red should be best, and blue and yellow, poorest quality (see Abercrombie et al. (2017).

We then focused in more detail on individual events that show disagreement beyond the calculated uncertainties. Figure 3 shows some examples; we are encouraged by the similarity of spectral shape between the two methods. We also note that the source spectra from the spectral decomposition look tilted in frequency compared to the ratios from the individual event EGF approach. Varying the tradeoff between self-similarity and spectral fall-off in the spectral decomposition method change this frequency-dependent effect, and also the mean stress drops. Disagreement between the methods appears largely related to station selection and signal-to-noise criteria (particularly for less well recorded events), and inappropriateness of the source model, rather than any fundamental flaw or bias in either method. By implementing bootstrap resampling approaches, and varying the available frequency bandwidth, we have begun computing realistic uncertainties for our corner frequency estimates. Ultimately our goal is to refine the methods (including calculating of uncertainties) such that their estimates agree within their calculated uncertainties. Then we can be sure of the quality of future, independent studies. We are also intrigued by the possibility of using the best-recorded and modeled events from the individual EGF approach to help constrain tradeoffs between parameters in the spectral decomposition analysis.

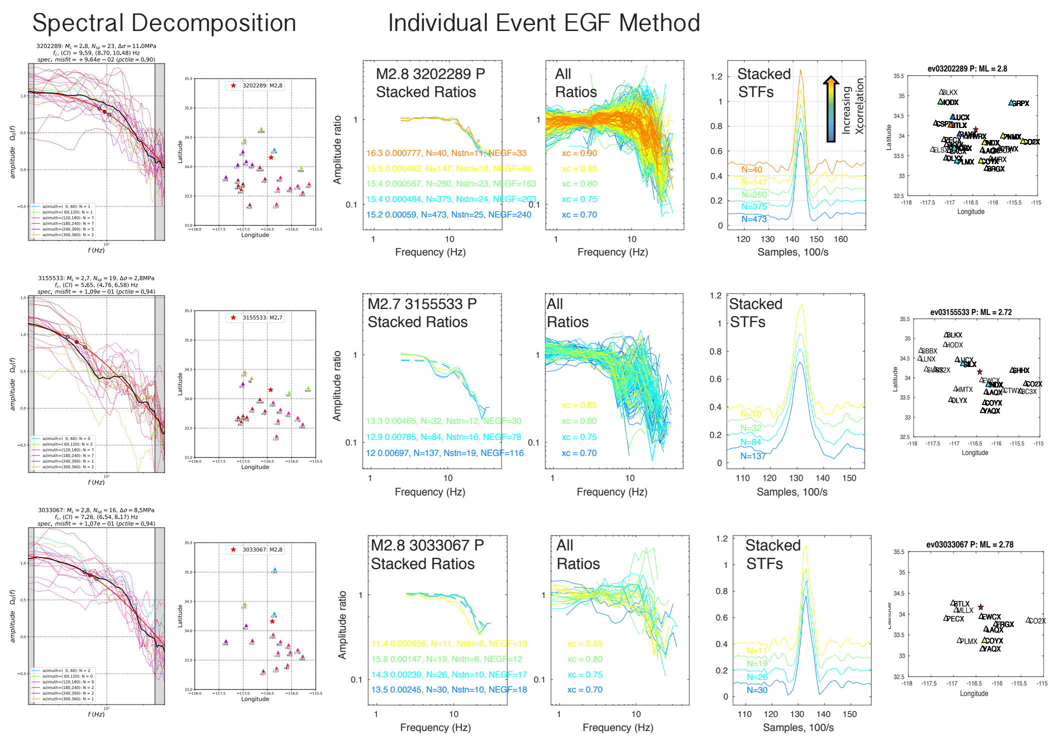

Figure 3. Comparison of individual events from the two approaches. For the spectral decomposition approach the different colored source spectra correspond to the stations on the adjacent maps. The black line is the mean. For the individual EGF approach, the colors represent the minimum cross-correlation for EGF included. All the spectral ratios are shown, as well as the stack over all stations and EGFs, and the map of stations used**.**

SCEC Related Publications (from 2010) by Abercrombie and Shearer

Abercrombie, R. E., Comparison of direct and coda wave stress drop measurements for the Wells, Nevada, earthquake sequence, *J. Geophys. Res.*, *118*, 1458–1470, doi: 10.1029/2012JB009638, 2013.

Abercrombie, R. E., Stress drops of repeating earthquakes on the San Andreas Fault at Parkfield, *Geophys. Res. Lett., 41*, 8784–8791, doi:10.1002/2014GL062079, 2014.

Abercrombie, R. E., Investigating uncertainties in empirical Green's function analysis earthquake source parameters, *J. Geophys. Res.*, doi: 10.1002/2015JB011984, 2015.
Abercrombie, R. E., S. Bannister, J. Ristau and D. Doser, Variability of earthquake stress drop in a subduction setting, the Hikurangi Margin, New Zealand, *Geophys. J. Int.*, doi:10.1093/gji/ggw393, 2017.
Chen, X., and P. M. Shearer, Comprehensive analysis of earthquake source spectra and swarms in the Salton Trough, California, *J. Geophys. Res.*, **116**, B09309, doi:10.1029/2011JB008263, 2011.
Chen, X., and P. M. Shearer, California foreshock sequences suggest aseismic triggering process, *Geophys. Res. Lett.*, **40**, doi:10.1002/grl.50444, 2013.
Chen, X., and P. M. Shearer, Analysis of foreshock sequences in California and implications for earthquake triggering, *Pure Appl. Geophys.*, doi: 10.1007/s00024-015-1103-0, 2015.
Chen, X., P. M. Shearer, and R. E. Abercrombie, Spatial migration of earthquakes within seismic clusters in Southern California: Evidence for fluid diffusion, *J. Geophys. Res.*, **117**, B04301, doi: 10.1029/2011JB008973, 2012.
El Hariri, M., R. E. Abercrombie, C. A. Rowe, and A. F. do Nascimento, The role of fluids in triggering earthquakes: Observations from reservoir induced earthquakes in Brazil, *Geophys. J. Int., 181,* 1566-1574, 2010.
Goebel, T. H. W., E. Hauksson, P. M. Shearer, and J. P. Ampuero, Stress drop heterogeneity within tectonically complex regions: A case study of San Gorgonio Pass, southern California, *Geophys. J. Int.*, **202**, 514–528, 2015.
Hauksson, E., J Stock, R. Bilham, M. Boese, X. Chen, E. H. Fielding, J. Galetzka, K. W. Hudnut, K. Hutton, L. C. Jones, H. Kanamori, P. M. Shearer, J. Steidl, J. Treiman, S. Wei, and Wenzheng Yang, Report on the August 2012 Brawley earthquake swarm in Imperial Valley, Southern California, *Seismol. Res. Lett.*, **84**, 177-189, doi: 10.1785/0220120169, 2013.
Kane, D. L., G. A. Prieto, F. L. Vernon, and P. M. Shearer, Quantifying seismic source parameter uncertainties, *Bull. Seismol. Soc. Am.*, **101**, 535–543, doi: 10.1785/0120100166, 2011.
Kane, D. L., P. M. Shearer, B. P. Goertz-Allmann, and F. L. Vernon, Rupture directivity of small earthquakes at Parkfield, *J. Geophys. Res.*, **118**, doi: 10.1029/2012JB009675, 2013.
Kaneko, Y., and P. M. Shearer, Seismic source spectra and estimated stress drop from cohesive-zone models of circular subshear rupture, *Geophys. J. Int.*, doi: 10.1093/gji/ggu030, 2014.
Kaneko, Y., and P. M. Shearer, Variability of seismic source spectra, estimated stress drop and radiated energy, derived from cohesive-zone models of symmetrical and asymmetrical circular and elliptical ruptures, *J. Geophys. Res.*, **120**, doi: 10.1002/2014JB011642, 2015.
Lin, G., C. H. Thurber, H. Zhang, E. Hauksson, P. M. Shearer, F. Waldhauser, T. M. Brocher and J. Hardebeck, A California statewide three-dimensional seismic velocity model from both absolute and differential times, *Bull. Seismol. Soc. Am.*, **100**, 225-240, doi: 10.1785/0120090028, 2010.
Ruhl, C. J., R. E. Abercrombie, K. D. Smith, and I. Zaliapin, Complex Spatiotemporal Evolution of the 2008 M_w 4.9 Mogul Earthquake Swarm (Reno, Nevada): Interplay of Fluid and Faulting, *J. Geophys. Res.*, **121**, doi:10.1002/2016JB013399, 2016.
Shearer, P. M., Self-similar earthquake triggering, Båth's law, and foreshock/aftershock magnitudes: Simulations, theory, and results for southern California, *J. Geophys. Res.*, **117**, B06310, doi: 10.1029/2011JB008957, 2012a.
Shearer, P. M., Space-time clustering of seismicity in California and the distance dependence of earthquake triggering, *J. Geophys. Res.*, **117**, B10306, doi: 10.1029/2012JB009471, 2012b.
Shearer, P. M., Reply to comment by S. Hainzl on "Self-similar earthquake triggering, Båth's Law, and foreshock/aftershock magnitudes: Simulations, theory and results for southern California," *J. Geophys. Res.*, **118**, doi: 10.1002/jgrb.50133, 2013.

Smith-Konter, B. R., D. T. Sandwell, and P. Shearer, Locking depths estimated from geodesy and seismology along the San Andreas Fault System: Implications for seismic moment release, *J. Geophys. Res.*, **116**, doi: 10.1029/2010JB008117, 2011.
Sumiejski, P. E., and P. M. Shearer, Temporal stability of coda Q^{-1} in southern California, *Bull. Seismol. Soc. Am.*, **102**, 873–877, doi: 10.1785/0120110181, 2012.
Trugman, D.T., P. M. Shearer, A. A. Borsa, and Y. Fialko, A comparison of long-term changes in seismicity at the Geysers, Salton Sea, and Coso geothermal fields, *J. Geophys. Res.*, doi: 10.1002/2015JB012510, 2016.
Trugman, D. T., and P. M. Shearer, GrowClust: A hierarchical clustering algorithm for relative earthquake relocation, with application to the Spanish Springs and Sheldon, Nevada, earthquake sequences, *Seismol. Res. Lett.*, **88**, 1-13, doi: 10.1785/0220160188, 2017.
Trugman, D. T., and P. M. Shearer, Application of an improved spectral decomposition method to examine earthquake source scaling in southern California, *J. Geophys. Res.*, doi: 10.1002/2017JB013971, 2017.
Uchide, T., H. Yao, and P. M. Shearer, Spatio-temporal distribution of fault slip and high-frequency radiation of the 2010 El Mayor-Cucapah, Mexico earthquake, *J. Geophys. Res.*, **118**, doi: 10.1002/jgrb.50144, 2013.
Viegas, G. M., R. E. Abercrombie, and W.-Y. Kim, The 2002 M5 Au Sable Forks, NY, earthquake sequence: source scaling relationships and energy budget, *J. Geophys. Res., 115,* B07310, doi:10.1029/2009JB006799, 2010.
Yang, Z., A. Sheehan, and P. Shearer, Stress-induced upper crustal anisotropy in southern California, *J. Geophys. Res.*, **116**, doi: 10.1029/2010JB007655, 2011.
Zhang, Q., and P. M. Shearer, A new method to identify earthquake swarms applied to seismicity near the San Jacinto Fault, California, *Geophys. J. Int.*, doi: 10.1093/gji/ggw073, 2016.

References

Abercrombie, R. E., Comparison of direct and coda wave stress drop measurements for the Wells, Nevada, earthquake sequence, *J. Geophys. Res.*, *118*, 1458–1470, doi: 10.1029/2012JB009638, 2013.
Abercrombie, R. E., Investigating Uncertainties in Empirical Green's Function Analysis Earthquake Source Parameters, *J. Geophys. Res.*, doi: 10.1002/2015JB011984, 2015.
Abercrombie, R. E., S. Bannister, J. Ristau and D. Doser, Variability of earthquake stress drop in a subduction setting, the Hikurangi Margin, New Zealand, *Geophys. J. Int.*, doi:10.1093/gji/ggw393, 2017.
Baltay, A. S., T. C. Hanks and G. C. Beroza, Stable stress drop measurements and their variability: implications for ground-motion prediction. *Bull. Seism. Soc. Am., 103*, doi: 10.1785/0120120161, 2013.
Brune, J., Tectonic stress and the spectra of seismic shear waves from earthquakes, *J. Geophys. Res.*, *75*, 4997-5009, 1970.
Cotton, F., R. Archuleta and M. Causse, What is the sigma of the stress drop? *Seismol. Res. Letts., 84*, 42-48, doi: 10.1785/0220120087, 2013.
Hauksson, E., Average Stress Drops of Southern California Earthquakes in the Context of Crustal Geophysics: Implications for Fault Zone Healing, *Pure Appl. Geophys.*, 1–12, doi:10.1007/s00024-014-0934-4, 2014.
Hauksson, E., and P. M. Shearer, Attenuation models (Qp and Qs) in three dimensions of the southern California crust: Inferred fluid saturation at seismogenic depths, *J. Geophys. Res.*, **111**, B05302, doi:10.1029/2005JB003947, 2006.
Huang, Y., G. C. Beroza, and W. L. Ellsworth, Stress drop estimates of potentially induced earthquakes in the Guy-Greenbrier sequence*, J. Geophys. Res. Solid Earth, 121*, 6597–6607, doi:10.1002/2016JB013067, 2016.

Kanamori, H. and E.E. Brodsky, The physics of earthquakes, *Reports on Progress in Physics*, **67**, 1429 - 1496, DOI:10.1088/0034-4885/67/8/R03, 2004.

Kaneko, Y., and P. M. Shearer, Seismic source spectra and estimated stress drop from cohesive-zone models of circular subshear rupture, *Geophys. J. Int.,* doi: 10.1093/gji/ggu030, 2014.

Kwiatek, G., Bulut, F., Bohnhoff, M., Dresen, G., High-resolution analysis of seismicity induced at Berlín geothermal field, El Salvador. - *Geothermics*, *52*, 98-111, doi: org/10.1016/j.geothermics.2013.09.008, 2014.

Kwiatek, G., K. Plenkers and G. Dresen, Source parameters of picoseismicity recorded at Mponeng deep gold mine, South Africa: implications for scaling relations. *Bull. Seism. Soc. Am., 101*, 2592-2608, doi: 18101/10.1785/0120110094, 2011.

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

Oth, A., D. Bindi, S. Parolai and D. Di Giacomo, Spectral analysis of K-NET and KiK-net data in Japan, Part II: On attenuation characteristics, source spectra, and site response of borehole and surface stations. *Bull. Seismol. Soc. Am., 101*, 667-687, doi: 10.1785/0120100135, 2011.

Pacor, F., D. Spallarossa, A. Oth, L. Luzi, R. Puglia, L. Cantore, A. Mercuri, M. D'Amico and D. Bindi, Spectral models for ground motion prediction in the L'Aquila region (central Italy): evidence for stress drop dependence on magnitude and depth, *Geophys. J. Int. 204*, 697-718, doi:10.1093/gji/ggv448, 2016.

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.

Trugman, D. T., and P. M. Shearer, Application of an improved spectral decomposition method to examine earthquake source scaling in southern California, *J. Geophys. Res*., doi: 10.1002/2017JB013971, 2017.

Uchide, T., and K. Imanishi, Small Earthquakes Deviate from the Omega-Square Model as Revealed by Multiple Spectral Ratio Analysis, *Bull. Seism. Soc. Am., 106*, 1357–1363, doi: 10.1785/0120150322, 2016

Zhang, H., D. W. Eaton, G. Li, Y. Liu, and R. M. Harrington, Discriminating induced seismicity from natural earthquakes using moment tensors and source spectra, *J. Geophys. Res. Solid Earth, 121,* 972–993, doi:10.1002/2015JB012603, 2016,