2014 Joint UCSD and Caltech SCEC Report

Collaborative proposal from UCSD and Caltech: SCEC Community Data Products of Relocated Seismicity, Improved Focal Mechanisms, and Waveform Spectra for Resolving Fine-Scale Fault Structures and State of Stress in Southern California

Peter M. Shearer
Institute of Geophysics and Planetary Physics
Scripps Institution of Oceanography
U.C. San Diego
La Jolla, CA 92093-0225
pshearer@ucsd.edu

Egill Hauksson
Seismological Laboratory
California Institute of Technology
Pasadena, CA 91125
hauksson@gps.caltech.edu

12 March 2015

Abstract

Our research represents the continuation of an ongoing and very successful collaboration between Caltech and UCSD to perform automatic processing of the SCSN waveform archive. Our SCEC work so far has focused on improving earthquake locations and focal mechanisms using waveform cross-correlation and S/P amplitude ratios, and on computing spectra for use in studies of earthquake source properties and attenuation. These results are described in many papers published in previous years (*Hauksson and Shearer*, 2005, 2006; *Shearer et al*., 2005, 2006; *Lin et al*., 2007a,b, 2008; *Allmann et al*., 2008; *Lin and Shearer*, 2009; *Hauksson*, 2010, 2011; *Hauksson et al*., 2012; *Chen and Shearer*, 2011, 2012; *Yang et al*., 2011, 2012; *Hauksson*, 2014).

The latest version of our relocated catalog (the HYS catalog) contains high-precision locations of over 560,000 events from 1981 through 2014. Our previous catalogs, such as the LHS catalog by *Lin et al*. (2007b) have been widely used by other researchers, leading to new results on a number of topics, including earthquake triggering, swarms, locking depth, and earthquake scaling, which would not have been possible with standard catalogs. We also report on results of a newly created stress drop catalog for earthquakes between M1 and ~M3.5 with occasional events up to M5. The new catalog includes stress drops for more than 24,000 earthquakes between 2000 and 2014.

Technical Report

Introduction

Our SCEC-funded project involves cooperation between Caltech and UCSD in earthquake seismology research in southern California. The ever-expanding SCSN archive of waveforms from more than 500,000 local earthquakes provides an invaluable resource for seismology research that has only begun to be exploited. However, efficient mining of these data requires the development of new analysis methods, an effort that goes beyond the limited resources of individual scientists. We have coordinated our work and developed common tools and data products that can be used by us and other researchers to accomplish many SCEC goals.

Our SCEC research has focused on improving earthquake locations and focal mechanisms using waveform cross-correlation and S/P amplitude ratios, and on computing spectra for use in studies of earthquake source properties and attenuation. These results are described in eleven papers published during the last four years (*Hauksson and Shearer*, 2005, 2006; *Shearer et al*., 2005, 2006; *Lin et al*., 2007a,b, 2008; *Allmann et al*., 2008; *Lin and Shearer*, 2005, 2009; *Hauksson et al*., 2012).

In 2011, we released the HYS relocated catalog containing high-precision locations of over 500,000 events from 1981 to 2011/06. The HYS and our previous catalogs (LSH) have been used by a number of other researchers, leading to new results that would not have been possible with standard catalogs. For example, the debate over the relative importance of static versus dynamic triggering of aftershocks has been informed by our catalogs (*Felzer and Brodsky*, 2006; *Richards-Dinger et al*., 2010), *Vidale and Shearer* (2006) identified many distinctive characteristics of earthquake swarms in southern California, *Davidsen et al*. (2006) found new statistical features of seismicity with unexpected scaling properties, *Shearer and Lin* (2009) identified Mogi-doughnut behavior in seismicity preceding small earthquakes, *Tape et al*. (2009) used the LSH locations in the starting model for their recent adjoint tomography study of the southern California crust, *Smith-Konter et al*. (2011) used the catalog to estimate locking depths for major fault segments, and *Yang and Hauksson* (2013) used the relocated earthquakes and the focal mechanisms to determine the state of stress across southern California.

Our precise earthquake location catalogs are important because they provide direct constraints on physical properties at depth. These constraints help address key questions in earthquake physics and crustal deformation, including the relationship between microseismicity and major faults, the size and scale lengths of variations in absolute stress orientation and in earthquake stress drops, and the driving mechanism for aftershocks and swarm activity.

New Earthquake Catalog for 1981 – 2014

This project consists of both building a new waveform database and developing new tools for the data processing procedures.

We downloaded the digital seismograms for all of the events from the Southern California Earthquake Data Center (SCEDC) (www.data.scec.org). We reformatted the seismograms, resampled the data to 100 sps, and filtered them between 1 and 10 Hz before performing the cross-correlations. We selected P- and S-wave windows of 0.5 and 1.5 s duration, respectively. For the cross-correlation calculation, we included up to 500 nearest neighbors and required the pairs of events be separated by no more than 2.5 km. If less than 500 nearest neighbors existed within 2.5 km distance, we used Delaunay tessellation to add up to 150 more distant events to each cluster (*Richard-Dinger and Shearer*, 2000). To define a similar event pair, we required at least 5 cross-correlation coefficients to be larger than 0.6 and the minimum average of the maximum cross-correlation coefficients to be larger than 0.4. We attempted to calculate more than 189 million cross-correlations, of which about 51 million achieved the minimum required values for a similar event pair.

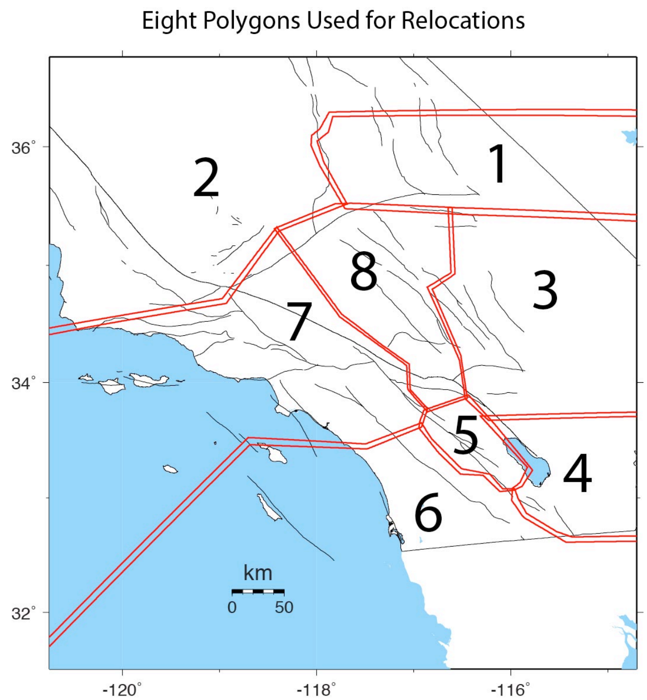

Figure 1. The polygons used to divide the dataset into smaller groups for efficient calculations.

We divided southern California into eight polygons to make the calculations of relocations more efficient (Figure 1). The events within each polygon were relocated separately using methods that were first described by Lin et al. (2007). First, we used the waveform cross-correlation calculations to cluster groups of similar events. Over 400,000 events are part of similar event clusters. Events within each cluster are then relocated using the differential times from the waveform cross-correlation.

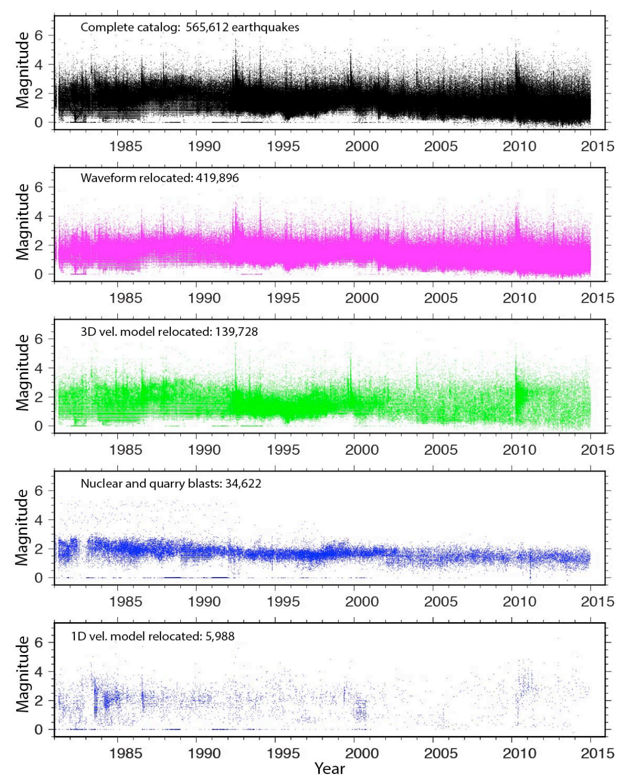

Figure 2. Magnitude versus date of earthquakes and blasts included in the Caltech/USGS catalog.

Our method greatly improves the relative locations of events within each cluster. We iterate to determine the location for each event from the available differential times between the selected event and other events in the respective cluster. We use a robust least squares estimate, which rejects significant differential travel-time outliers. In a final step, we apply a bootstrap method to calculate error estimates. We resample the differential times for each event and repeat the process for 10 subsamples. We assign the standard deviation of the 10 subsamples as the relative standard error for the event.

The 3D velocity model locations are somewhat more scattered than the cluster relocations, especially in depth. In Figure 2 we show the magnitude versus date distribution of: 1) the complete catalog, 2) the waveform relocated events, 3) events that only qualified for relocation using the 3D velocity model, 4) the nuclear explosions and quarry blasts in the catalog; and 5) the events that only qualified for 1D velocity model relocation. These graphs also illustrate the magnitude of completeness, which has decreased as instrumentation has improved.

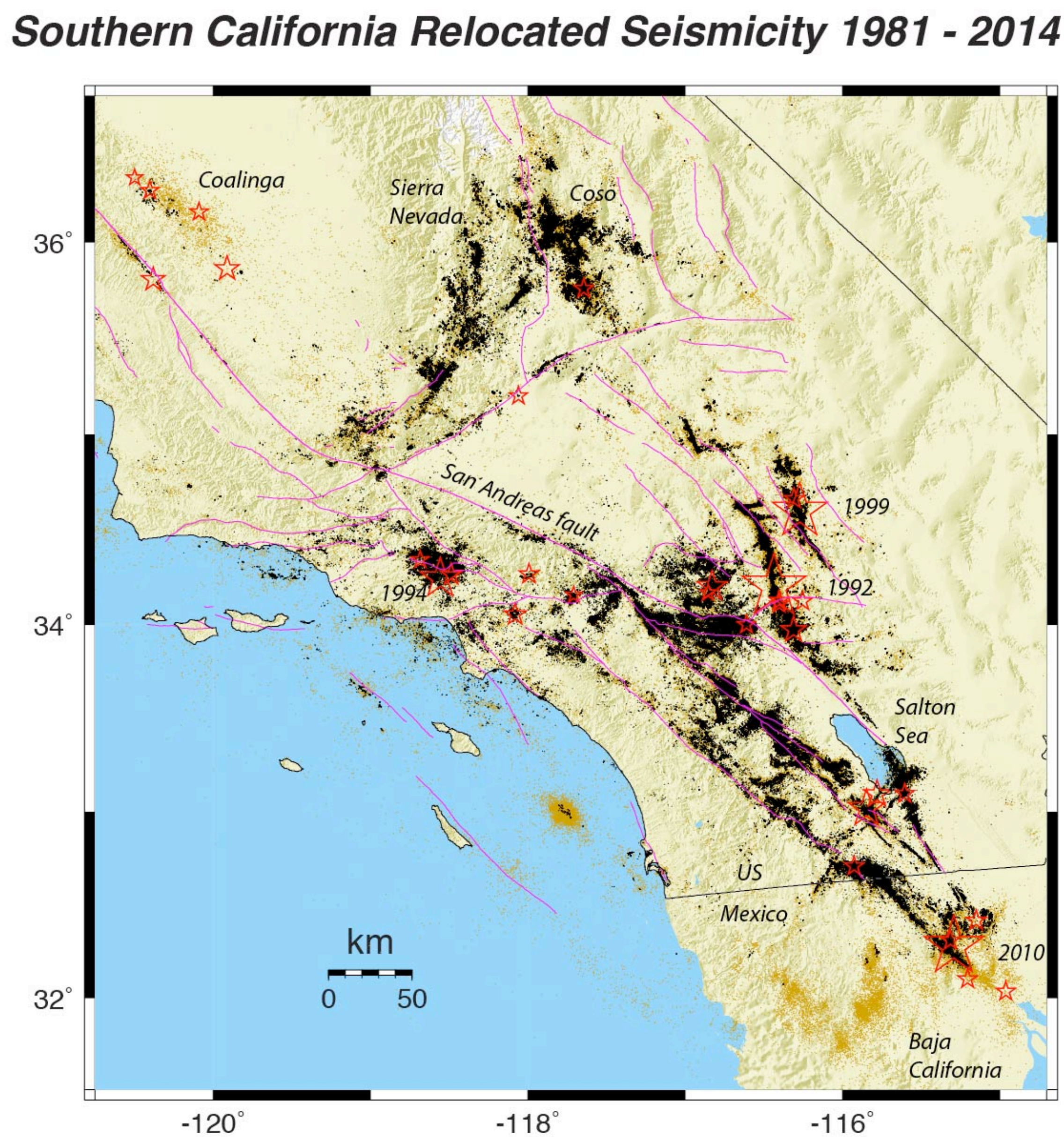

Figure 3. *(**Exemplary Figure**) Event locations from the HYS catalog (1981 – 2014). Similar-event clusters that have been relocated by using waveform cross-correlation are shown in black. Events in the SCSN catalog (and uncorrelated events in the other catalogs) are shown in brown. Events with M ≥ 5.5 are shown as stars. Faults are from Jennings (2010) with late Quaternary faults in shades of red (Hauksson et al. 2012).*

When events do not qualify for cluster relocations, we include their hypocenters determined using the 3D velocity model from Hauksson (2000). We combine the two datasets and add any other unrelocated events to obtain a complete catalog.

The number of events that can be relocated changes with time from 1981 to present (Figure 2). In the 1980s and 1990s the Southern California Seismic Network (SCSN) mostly consisted of single-component short-period stations. Starting in 2000 to 2001 a significant number of three-component stations were brought on-line and the SCSN software system was upgraded. The high-quality digital waveforms are less noisy and thus cross-correlate better. Also, the station spacing has decreased and thus more waveforms are available at short epicentral distances.

Results: Relocations 1981 – 2014

The relocated (1981 – 2013) HS catalog of more than 550,000 earthquakes is shown in Figure 3. The complex spatial distribution of the events reflects the different processes that contribute to the generation of both background and triggered seismicity. The Pacific North-America plate tectonic deformation is the main process that causes major earthquakes and their aftershock sequences. Secondary processes such as geothermal exploitation, extensional gravitation collapse, or crustal delamination also cause ongoing seismicity.

The overall pattern of seismicity shows familiar features including mainshock-aftershock sequences such as 1992 Landers, 1994 Northridge, 1999 Hector Mine, and 2010 El Mayor-Cucapah. Other regions such as the southern Sierra and Coso regions, the San Jacinto fault, and the Salton Trough also have high ongoing levels of seismicity.

Results: Stress Drop Catalog: 2000 – 2014

Stationarity of stress drop estimates in southern California

We report on results of a newly created stress drop catalog for earthquakes between M1 and ~M3.5 with occasional events up to M5. The new catalog includes stress drops for more than 24,000 earthquakes between 2000 and 2014. Stress drops were computed based on high-quality seismic records (i.e. high signal-to-noise, and at least 5 picks) of broadband stations. Starting in 2000, more broadband stations with higher sampling frequency and wider response spectra became available, allowing for a more reliable estimate of high corner frequencies and stress drops. We estimate stress drops by fitting a Brune-type, ω^2 spectral model [*Brune*, 1968; 1970] to the stacked source spectra. The source spectra are computed by using an iterative least-square method to deconvolve amplitude spectra into source, path and site effects and by correcting high-frequency attenuation by using an empirical Green's function[*Prieto et al*., 2004; *Shearer et al*., 2006; *Allmann and Shearer*, 2007; 2009; *Goebel, T. H. W. et al*., 2015].

Our stress drop catalog shows the well-known ~three order of magnitude scatter in stress drop estimates, that can approximately be described by a log-normal distribution with a mean value of 3.8 MPa for entire southern California (Figure 4). The overall spatial variations in stress drop estimates are in agreement with Shearer et al., [2006], indicating stationary of regional stress drops between 1989 to 2014. We observe low stress drops in the Imperial Valley and the Brawley Seismic Zone. Stress drops are generally lower on the southern San Andreas fault compared to the Elsinore and San Jacinto faults (Figure 5). Stress drops are generally low within the Los Angeles, Ventura and San Fernando basins. Stress drops are anomalously high in areas with complex fault geometry such as the San Gorgonio pass and for faults that are unfavorably oriented within the remote stress field, for example, between the Elsinore and San Jacinto faults. The eastern California shear zone shows heterogeneous average stress drops between 1 and 10 MPa. Roughly the same systematic variations were also observed by *Shearer et al.,* [2006].

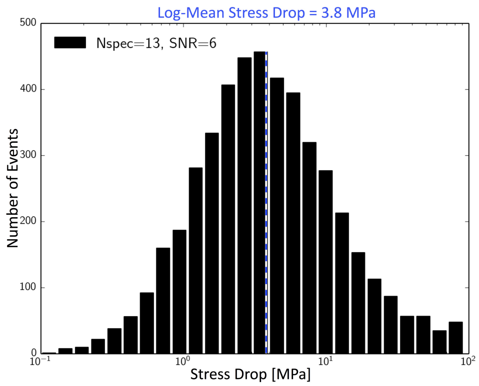

Figure 4: *Histogram of individual earthquake stress drops computed from spectral fits of source spectra that were recorded at more than 13 stations with a signal-to-noise ratio of 6.*

We also observed some local differences to previous work by *Shearer et al*., [2006] most noticeably the lower stress drops close to the Coso geothermal region which is more inline with expectations of low stress drops for geothermally active regions and high heat flow [*Oth*, 2013; *Hauksson*, 2014]. Furthermore, stress drops are higher than average around the ANZA seismic gap. The recent, shallow, 2014, M5.1 La Habra sequence shows lower than average stress drops.

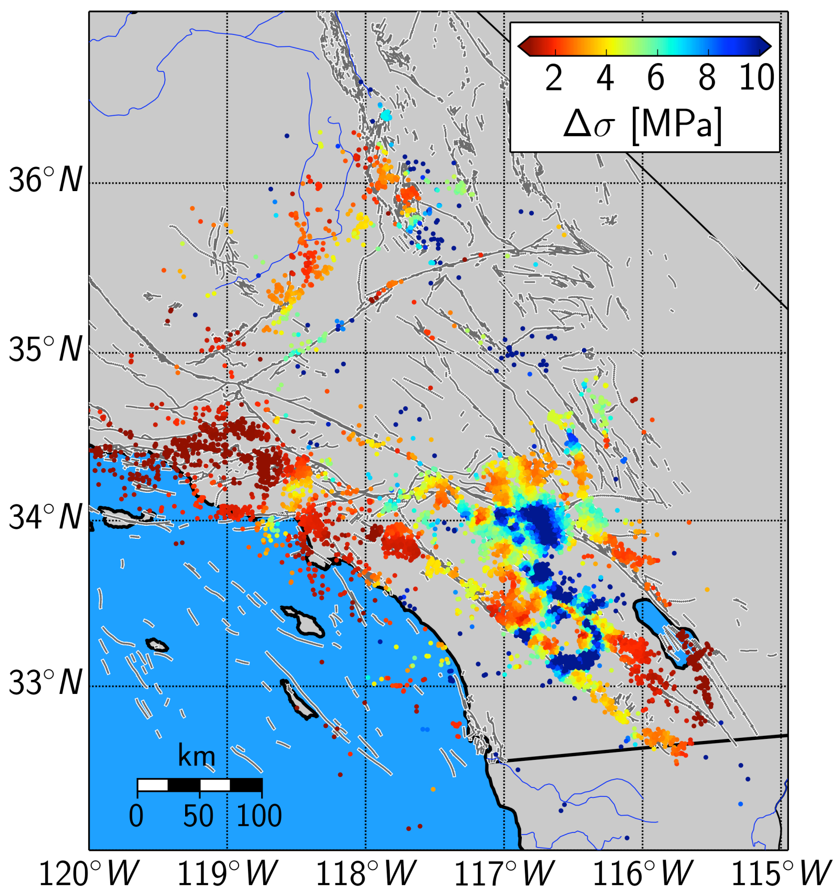

Figure 5: *Spatial variations in log-mean stress drop in Southern California. Log-mean stress drops are computed for 150 closest events and colored according to the colorbar in the upper right.*

Intellectual Merit and Broader Impacts

This project relates to many key SCEC objectives and will improve our understanding of earthquake activity across southern California. In particular, our high-resolution earthquake locations provide better delineation of fault structures and make possible more advanced seismicity studies by us and other SCEC researchers. Our stress drop analyses provide fundamental insights into the earthquake rupture process and the relationships between micro-earthquake activity, the crustal strain field, and major faults.

Outreach activities consist of providing the relocated catalog to SCEC scientists and others doing research on seismicity in southern California. The relocated catalog is available at the Southern California Earthquake Data Center (SCEDC). We have also presented results at the SCEC workshop and E. Hauksson gave an oral presentation at the Northridge Symposium, UCLA, in January 2014.

References

Allmann, B. P., and P. M. Shearer (2007), Spatial and temporal stress drop variations in small earthquakes near Parkfield, California, *J. Geophs. Res.,* 112(B4), B04305.

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.

Allmann, B. P., and P. M. Shearer (2009), Global variations of stress drop for moderate to large earthquakes, *J. Geophys. Res.*, 114(B1), B01310.

Brune, J. N. (1968), Seismic moment, seismicity, and rate of slipalong major fault zones, J. Geophys. Res., 69, 2605–2620.

Brune, J. N. (1970), Tectonic stress and the spectra of seismic shear waves from earthquakes, J. Geophys. Res., 75(26), 4997–5009.

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., 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.

Chen, X., and P. M. Shearer, California foreshock sequences suggest aseismic triggering process, *Geophys. Res. Lett.*, **40**, doi:10.1002/grl.50444, 2013.

Davidsen, J., P. Grassberger, and M. Paczuski, Earthquake recurrence as a record breaking process, *Geophys. Res. Lett.*, **33**, L11304, doi: 10.1029/2006GL026122, 2006.

Felzer, K.R. and E.E. Brodsky, Decay of aftershock density with distance indicates triggering by dynamic stress, *Nature*, **441**, 735-738, doi: 10.1038/nature04799, 2006.

Goebel, T. H. W., E. Hauksson, J.-P. Ampuero, and P. M. Shearer (2015), Stress drop heterogeneity within tectonically complex regions: A case study of San Gorgonio pass, Southern California, Geophys. J. Int., doi:GJI-S-14-0861.

Hauksson, E., Crustal structure and seismicity distributions adjacent to the Pacific and north America plate boundary in southern California, *J. Geophys. Res.*, *105*, 13,875-13,903, 2000.

Hauksson, E., Spatial Separation of Large Earthquakes, Aftershocks, and Background Seismicity: Analysis of Interseismic and Coseismic Seismicity Patterns in Southern California, *Special Frank Evison Issue of PAGEOPH,* DOI 10.1007/s00024-010-0083-3, 2010.

Hauksson, E., Crustal geophysics and seismicity in southern California. *Geophysical Journal International,* 186: 82–98. doi: 10.1111/j.1365-246X.2011.05042.x, 2011.

Hauksson, E. and P. Shearer, Southern California Hypocenter Relocation with Waveform Cross-Correlation: Part 1. Results Using the Double-Difference Method, *Bull. Seismol. Soc. Am.,* **95**, 896-903, 2005.

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.

Hauksson, E., J. Stock, R. Bilham, M. Boese, X. Chen, E. J. Fielding, J. Galetzka, K. W. Hudnut, K. Hutton, L. M. 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 *Seismological Research Letters,* March/April 2013, v. 84, p. 177-189, doi:10.1785/0220120169, 2013.

Hauksson, E. and W. Yang, and P. M. Shearer, Waveform Relocated Earthquake Catalog for Southern California (1981 to June 2011); *Bull. Seismol. Soc. Am.,* Vol. 102, No. 5, pp. 2239–2244, October 2012, doi: 10.1785/0120120010

Hauksson, E. (2014), 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.

Jennings, C.W., Bryant, W.A., 2010 Fault Activity Map of California. Geologic Data Map No. 6, California Geological Survey, Sacramento CA, 2010.

Lin, G. and P. Shearer, Tests of relative earthquake location techniques using synthetic data, *J. Geophys. Res*., **110**, B4, B04304, doi: 10.1029/2004JB003380, 2005.

Lin, G., P. M. Shearer, E. Hauksson and C. H. Thurber, A 3-D crustal seismic velocity model for southern California from a composite event method, *J. Geophys. Res*., **112**, doi: 10.1029/2007JB004977, 2007a.

Lin, G., P. M. Shearer and E. Hauksson, Applying a 3D velocity model, waveform cross-correlation, and cluster analysis to locate southern California seismicity from 1981 to 2005, *J. Geophys. Res*., **112**, B12309, doi: 10.1029/2007JB004986, 2007b.

Lin, G., P. M. Shearer and E. Hauksson, A search for temporal variations in station terms in southern California from 1984 to 2002, *Bull. Seismol. Soc. Am*., **98**, 2118–2132, doi: 10.1785/0120070243, 2008.

Lin, G., and P. M. Shearer, Evidence for water-filled cracks in earthquake source regions, *Geophys. Res. Lett*., **36**, L17315, doi: 10.1029/2009GL039098, 2009.

Lohman, R., McGuire, J., Earthquake swarms driven by aseismic creep in the Salton Trough, California. Journal of Geophysical Research 112, 2007.

Oth, A. (2013), On the characteristics of earthquake stress release variations in Japan, Earth and Planetary Science Letters, 377, 132–141.

Prieto, G. A., P. M. Shearer, F. L. Vernon, and D. Kilb (2004), Earthquake source scaling and self-similarity estimation from stacking P and S spectra, J. Geophys. Res., 109(B8).

Richards-Dinger, K., R. S. Stein, and S. Toda, Decay of aftershock density with distance does not indicate triggering by dynamic stress, *Nature*, **467**, 583–586, doi: 10.1038/nature09402, 2010.

Shearer, P., E. Hauksson, and G. Lin, Southern California hypocenter relocation with waveform cross-correlation: Part 2. Results using source-specific station terms and cluster analysis, *Bull. Seismol. Soc. Am*., **95**, 904-915, doi: 10.1785/0120040168, 2005.

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.

Shearer, P. M., and G. Lin, Evidence for Mogi doughnut behavior in seismicity preceding small earthquakes in southern California, *J. Geophys. Res*., **114**, doi: 10.1029/2009JB005982, 2009.

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, 2012.

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.

Tape, C., Q. Liu, A. Maggi and J. Tromp, Adjoint tomography of the southern California crust, *Science*, **325**, 988–992, doi: 10.1126/science.1175928, 2009.

Vidale, J.E. and P.M. Shearer, A survey of 71 earthquake bursts across southern California: Exploring the role of pore fluid pressure fluctuations and aseismic slip as drivers, *J. Geophys. Res.*, **111**, B05312, doi: 1029/2005JB004034, 2006.

Waldhauser, F and W.L. Ellsworth, A Double-Difference Earthquake Location Algorithm: Method and Application to the Northern Hayward Fault, California, *Bull. Seismol. Soc. Am., 90,* 1353-1368, 2000.

Yang, W. and E. Hauksson, Evidence for Vertical Partitioning of Strike-Slip and Compressional Tectonics From Seismicity, Focal Mechanisms, and Stress Drops in the East Los Angeles Basin Area, California, *Bull. Seismol. Soc. Am.*, v. 10, no. 3, p. 964-974; DOI: 10.1785/0120100216, 2011.

Yang, W., E. Hauksson, and P. Shearer, Computing a large refined catalog of focal mechanisms for southern California (1981 – 2010): Temporal Stability of the Style of Faulting, *Bull. Seismol. Soc. Am.,* June 2012, v. 102, p. 1179-1194, doi:10.1785/0120110311, 2012.

Yang, W., E. Hauksson and P. M. Shearer, Computing a large refined catalog of focal mechanisms for southern California (1981–2010): Temporal stability of the style of faulting, *Bull. Seismol. Soc. Am.*, **102**, 1179–1194, doi: 10.1785/0120110311, 2012.

Yang, W. and E. Hauksson, The tectonic crustal stress field and style of faulting along the Pacific North America Plate boundary in Southern California,Geophys. J. Int. (July, 2013) 194 (1): 100-117 first published online April 22, 2013 doi:10.1093/gji/ggt113