# 2012 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

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## Summary

This research represents the very successful collaboration between Caltech and UCSD to perform automatic processing of the Southern California Seismic Network (SCSN) waveform archive. Our SCEC work has focused on improving earthquake locations using waveform cross-correlation, and on computing spectra for use in studies of earthquake source properties and attenuation. These results are described in many 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*, 2009; *Hauksson*, 2010, 2011; Chen and Shearer, 2011; *Yang et al*., 2011, 2012; *Hauksson et al*., 2012).

In 2011, we released the latest version of our relocated catalog (the HYS catalog) containing high-precision locations of over 500,000 events from 1981 to June 2011. Our previous catalogs, such as the LHS catalog by *Lin et al*. (2007b) 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, and *Smith-Konter et al*. (2011) used the catalog to estimate locking depths for major fault segments.

The relocated (1981 – 2011/06) HYS catalog contains more than 500,000 earthquakes. 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, and crustal delamination also cause ongoing seismicity. The overall pattern of seismicity reveals fault structures on many scales, as well as 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 (*Hauksson et al*., 2012).

The latest significant earthquake sequence that we have analyzed is the 2012 Brawley swarm. It started near the town of Brawley at 4h30m (GMT) on August 26 with three events of M < 2.0 occurring within 5 minutes. The seismic activity picked up again at 11h43m (GMT), and continued at a steady rate. The three largest earthquakes (M5.3, M4.9, and M5.4) in the sequence occurred over a period of 90 minutes, starting at 19h31m. The largest (M5.4) earthquake was widely felt across southernmost California, northern Baja California and western Arizona. The SCSN ShakeMap showed strong to very strong shaking within 10 km distance of the epicenter (http://www.cisn.org).

## 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, *Felzer and Brodsky* (2006) argued that aftershock behavior from *M* 2–6 mainshocks favors a dynamic triggering model, *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, and *Tape et al*. (2009) used the LSH locations in the starting model for their recent adjoint tomography study of the southern California crust.

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 – 2011/06

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 at 100 sps, and filtered them between 1 and 10 Hz before performing the cross-correlations. We selected P-wave windows of 0.5 sec and S-wave windows of 1.5 sec duration. For the cross-correlation calculation, we included up to 150 nearest neighbors and required the pairs of events be separated by no more than 2.5 km. If less than 150 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 8 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 54 million cross-correlations, of which about 24 million achieved the minimum required values for a similar event pair.

## Preliminary Results: Relocations 1981 – 2011/06

The relocated (1981 – 2011/06) HYS catalog of more than 500,000 earthquakes is shown in Figure 1. 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.

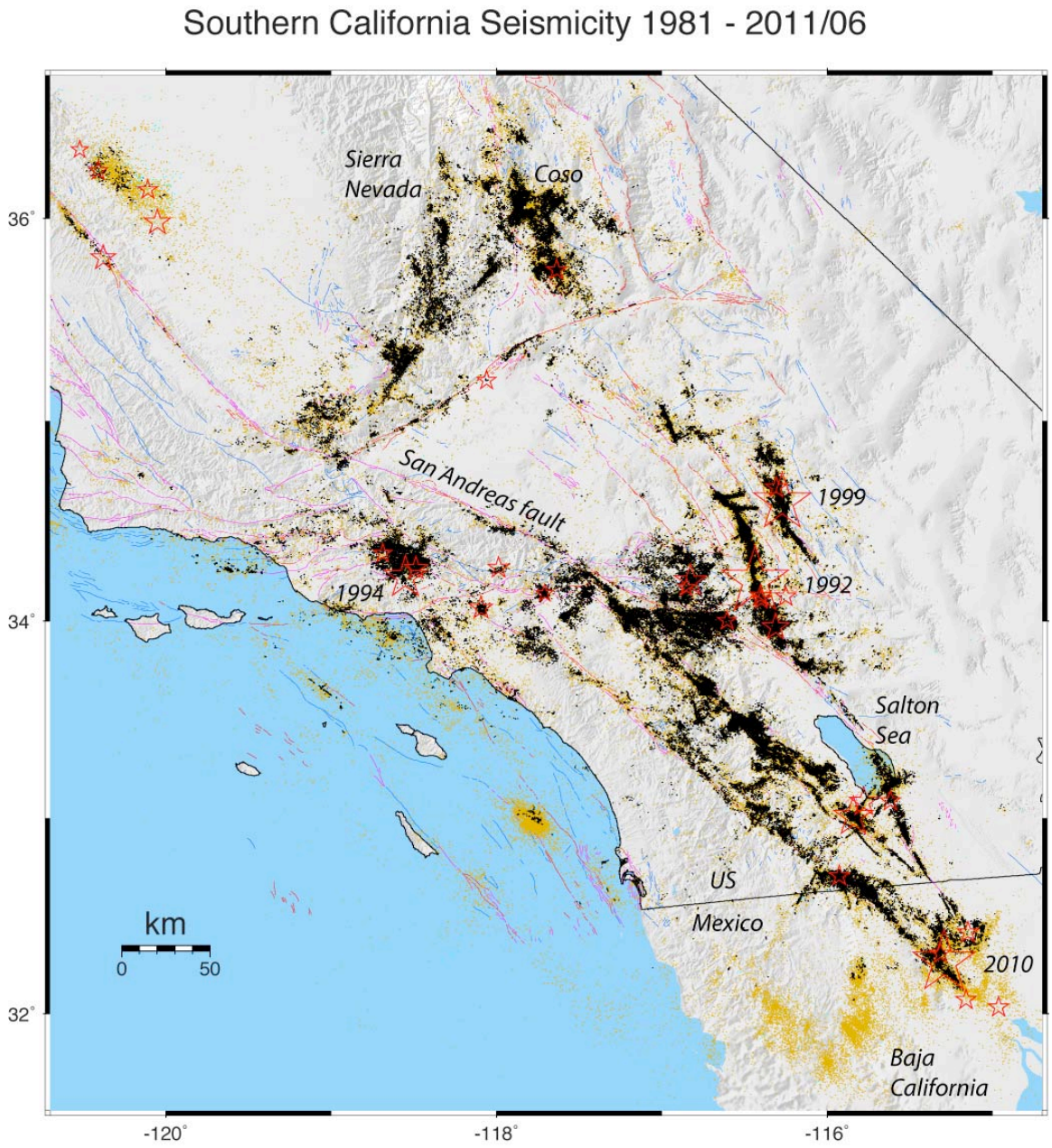


**Figure 1.** Event locations from the HYS catalog (1981 – 2011/06). Similar-event clusters that have been relocated by using waveform cross-correlation are shown in black. Events in the SCSN catalog (and uncorrelated events in the other catalogs) are shown in yellow. Events with M ≥ 5.5 are shown as stars. Faults are from *Jennings* (2010) with late Quaternary faults in shades of red and early Quaternary in blue.

The overall pattern of seismicity shows the 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.

The occurrence of aftershocks is not simply related to the principal slip surfaces of faults that accommodate the bulk of the slip. As an example, the 1992 Landers and 1999 Hector Mine earthquakes exhibit heterogeneous clustered distributions of aftershocks, which may be related to heterogeneous stress release in the region.

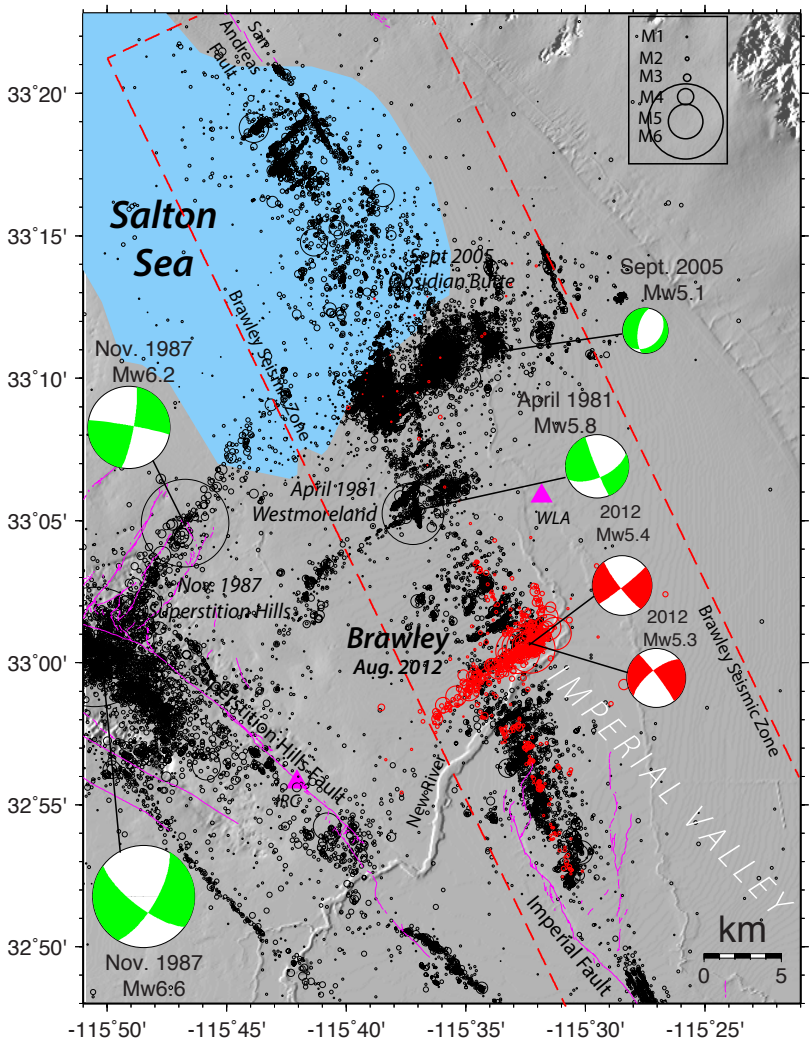


Figure 2. The seismicity from 1981 to 2012 August is shown as black open circles, and the events of the 2012 August Brawley swarm are shown as red circles. Lower hemisphere focal mechanisms of the M > 5 events are shown. IRC - Imler Road creepmeter; WLA – Wildlife Liquefaction Array. The east and west boundaries of the Brawley seismic zone as defined by *Johnson and Hill* (1982) are shown with red dash-lines. Late Quaternary fault traces (magenta) from *Jennings and Bryant* (2010).

**The 2012 Brawley Earthquake Swarm**

The 2012 Brawley earthquake swarm occurred in the Brawley Seismic Zone (BSZ) within the Imperial Valley of southern California (Figure 2). The BSZ is the northernmost extensional segment of the Pacific-North America plate boundary system. *Johnson and Hill* (1982) used the distribution of seismicity since the 1930s to outline the geographical extent of the BSZ, defining boundaries of the BSZ as shown in Figure 2. Its north-south extent ranges from the northern section of the Imperial Fault, starting about 10 km north of the US Mexico international border and connecting to the southern end of the San Andreas Fault, where it terminates in the Salton Sea. *Larsen and Reilinger* (1991) who defined a similar geographical extent of the BSZ, argued that the BSZ was migrating to the northwest, which they associated with the propagation of the Gulf of California rift system into the North American continent (*Hauksson et al*., 2013).

The causative fault of the 2012 swarm had not been previously mapped. Nonetheless, surface fractures that are related to the swarm were identified both from InSAR images and field

observations. Prior occurrences of surface faulting in association with swarm activity within the Brawley Seismic Zone activity include the 2005 swarm (*Lohman and McGuire*, 2007; *Rymer et al*., 2011). The largest event of the 2005 swarm was M 5.1, yet surface rupture was up to 20 cm in that case. Similarly, the 2006 Cerro Prieto swarm with largest event of M 5.4 had surface rupture along the Morelia Fault of 20-30 cm (*Suarez-Vidal,* 2007). Also, just to the west of the BSZ, the Elmore Ranch event $M_S$ 6.2 of the 1987 Superstition Hills sequence involved extensive surface rupture on a zone of cross-faults (e.g., *Hudnut et al*., 1989; *Sharp et al*., 1989).

Our report (*Hauksson et al*., 2013) summarizes the recent data and interpretations for this sequence. In particular we highlight efforts to 1) find the surface rupture; 2) develop a finite source modeling using both seismic and GPS waveforms, together with 3) data from creepmeters and 4) a liquefaction array. The temporal and spatial evolution and focal depths of the events are very important for understanding the crustal deformation processes that cause such swarms.

*Relocations of Hypocenters*. We relocated the swarm using a 3-D velocity model (*Hauksson*, 2000) and HypoDD (*Waldhauser and Ellsworth,* 2000). Prior to inversion, we adjusted the starting P-wave velocity model in the Imperial Valley basin to be approximately 2.5 km/s at 1 km depth, to account for the low Vp velocities in basin sediments (*Han et al*., 2012). This 3D-model can be used to determine accurate hypocenters because the azimuthal distribution of stations is fairly complete, but the model needs to be further refined before it can be used for tectonic interpretation. The relocations reveal a narrow 10-km-long, linear southwest seismicity trend, concentrated in the depth range of 4 to 9 km. This trend is aligned along the southwest-striking nodal plane of the mainshock moment tensors and extends mostly to the southwest away from the mainshock.

The distribution of focal depths for the swarm earthquakes is consistent with the finite source model. The events surround the two high-slip asperities, with more seismicity near the bottom of the large-slip asperity and on the northeast side, and less seismicity near the base of the smaller low-slip asperity located 3 km to the southwest. Furthermore, the three largest events, of Mw5.5, Mw5.3, and Mw4.9 are located within about 1 km of each other with focal depths of 6.9, 5.7 and 5.2 km. These focal depths are fairly shallow but they are typical for this area (Hauksson *et al*., 2012). The uncertainties in the depth determinations are small, (~0.7 km), because of the dense distribution of seismic stations in the region.

*Spatial and Temporal Evolution*. A weighted-least-squares method is applied to model the spatial-temporal migration behavior of this swarm based on the relocated earthquake hypocenters in the depth range from 4 to 8 km. This weighting approach accounts for the upper-triangular nature of the time versus distance behavior by applying the L1-norm only within a 0.5 hour window, and penalizing earlier events more than late events outside of this window (further details of the method are provided by, *Chen and Shearer* 2011, appendix A).

The seismicity before the first M > 5 earthquake migrated bilaterally along an azimuth of about 55 degrees (approximately NE-SW) at a velocity of about 0.5 km/hour (Figure 3). The first three events (which occurred at 4h30m) that were significantly separated in time from the main sequence (about 8 hours later), did not show migration and were not included in the velocity calculation. The SW migration stopped after the first M > 5 earthquake, but the NE migration continued until the second M > 5 earthquake.

Four smaller swarms before 2009 (1983, 1986, 1999, and 2008) occurred in the same region (*Chen and Shearer*, 2011). The most recent one in 2008 had a roughly similar migration velocity of 0.3 km/hour. Each of these swarms exhibited either bilateral or unilateral migration directions, with three swarms having unilateral southwestward migration.

Estimated stress drops for the 2012 swarm earthquakes show a fair amount of scatter, ranging from 0.05 MPa to 1.4 MPa following a log-normal distribution. The stress drops are computed using the method described in *Shearer et al*. (2006), where an EGF (empirical Green's function) is obtained by fitting a Brune-type source model to binned source spectra at 0.2 magnitude intervals. When EGFs are computed for subsets of the data using temporal or spatial binning, the stress drop estimates exhibit some degree of instability in their median values and also with different magnitude bin ranges. The origin of these instabilities warrants further study. However, when all events from 1981 to 2012 are included, the results are consistent and stable, with a median value of 0.25 MPa, agreeing with the values obtained in *Chen and Shearer* (2011).

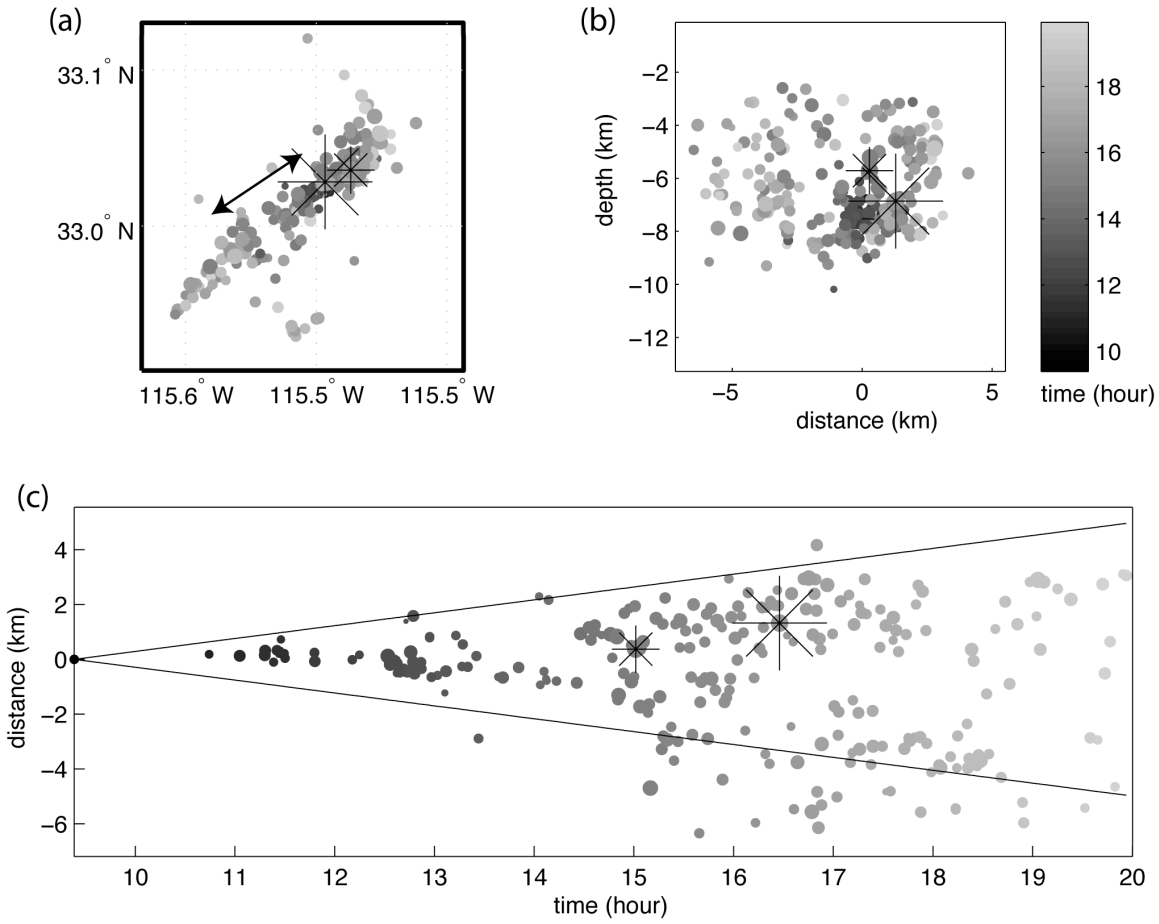


Figure 3. (a) Map of epicenters shaded in gray by time of occurrence. Arrow indicates the bi-lateral migration direction, away from the first hypocenter in the sequence. (b) Depth versus distance along the bi-lateral migration direction from the first hypocenter. (c) The spatial and temporal migration of the hypocenters. Smaller black star is the first M > 5 event (M5.3), larger star is the second M > 5 event (M5.4). In all three figures, events are shaded in gray by time as indicated in the gray-scale bar.

## Outreach Activities

The outreach activities consisted 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).

E. Hauksson, The Goldilocks Seismicity of Southern California, (**talk** presented at AEG Southern California Section, Steven's Steak House in City of Commerce, CA, 12 June 2012)

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**Publications Supported by SCEC**

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.

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Yang, W. and E. Hauksson, The 3-D Tectonic Crustal Stress Field and Style of Faulting Along the Pacific North America Plate Boundary in Southern California, *Geophys. J. Int.*, in review, March 2013.

## Abstracts for Recent Oral, Reports, OR Poster Presentations

E. Hauksson, W. Yang, and P. Shearer, Elucidating Regional Tectonic and Secondary Causes of Seismicity in Southern California: Application of Waveform Relocated Seismicity and High Precision Focal Mechanisms and Other Geophysical Data Sets; Abstract; *Seismo Soc. Res. Lett.*, 83, 364, presented at the 2012 SSA Meeting, San Diego, CA, 17-19 April 2012

X. Chen, P. M. Shearer, and E. Hauksson, Systematic analysis of foreshock sequences in southern California, Abstract; *Seismo Soc. Res. Lett.*, 83, 366, presented at the 2012 SSA Meeting, San Diego, CA, 17-19 April 2012

E. Hauksson and W. Yang, Effects of heat flow, shear strain rate, and other geophysical variables on the southern California seismicity and state of stress, (**talk** presented at USGS, Menlo Park 2012

E. Hauksson and W. Yang, Stress at San Gorgonio, (**talk** presented at 2012 SCEC Workshop on San Gorgonio Pass).

X. Chen, P. M. Shearer, and E. Hauksson, California foreshock sequences suggest underlying aseismic process, (2012 SCEC Annual Meeting poster).

E. Hauksson, Understanding Seismicity in the Context of Complex Fault Systems and Crustal Geophysics, (2012 SCEC Annual Meeting poster).

E. Hauksson. August 2012 Brawley Earthquake Swarm in Imperial Valley, (2012 SCEC Annual Meeting invited talk).

W. Yang and E. Hauksson, Seismotectonic Crustal Stress Field and Style of Faulting Along the Pacific North America Plate Boundary in Southern California, (2012 SCEC Annual Meeting poster).

D. A. Weiser, L. M. Jones, and E. Hauksson, Aftershock Decay with Distance from a Fault, (2012 SCEC Annual Meeting poster).

E. Hauksson, and L. Jones, Understanding Earthquake Scaling in the Context of Complex Fault Systems and Crustal Geophysics; abstract for **talk** presented at ECGS workshop in

Luxembourg, Oct. 2012

W. Yang and E. Hauksson, Southern California tectonic stress, (talk presented at SCEC Community Stress Model Workshop Agenda, October 15-16, 2012

E. Hauksson; Wenzheng Yang; Peter M. Shearer, Observational Constraints from Waveform Relocated Southern California Seismicity and Refined Focal Mechanisms for Synthesizing Heterogeneities in Fault Zone Properties and Signatures of Seismic Rupture, *Abstract Talk S14A-03, presented at 2012 Fall Meeting, AGU, San Francisco, Calif., 3-8 Dec*..

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