**Final Technical Report**

Submitted to the
U.S. GEOLOGICAL SURVEY

By the Seismological Laboratory
CALIFORNIA INSTITUTE OF TECHNOLOGY

| | |
|---|---|
| Grant No.: | Award No. G12AP20010 |
| Name of Contractor: | California Institute of Technology |
| Principal Investigator: | Dr. Egill Hauksson<br>Caltech<br>Seismological Laboratory, MC 252-21<br>Pasadena, CA 91125<br>hauksson@gps.caltech.edu |
| Government Technical Officer: | Elizabeth Lemersal<br>External Research Support Manager<br>Earthquake Hazards Program, USGS |
| Title of Work: | Analysis of Earthquake Data<br>From the Greater Los Angeles<br>Basin and Adjacent Offshore Area,<br>Southern California |
| Program Objective: | I & III |
| Effective Date of Contract: | January 1, 2012 |
| Expiration Date: | December 31, 2012 |
| Period Covered by report: | 1 January 2012 – 31 December 2012 |
| Date: | 29 March 2013 |

This work is sponsored by the U.S. Geological Survey under Contract Award No. G12AP20010. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessary representing the official policies, either expressed or implied of the U.S. Government.

# Analysis of Earthquake Data from the Greater Los Angeles Basin and Adjacent Offshore Area, Southern California

U.S. Geological Survey Award No. G12AP20010

Element I & III

**Key words:** Geophysics, seismology, seismotectonics

Egill Hauksson

Seismological Laboratory, California Institute of Technology,
Pasadena, CA 91125
Tel.: 626-395 6954
Email: hauksson@gps.caltech.edu
FAX: 626-564 0715

## ABSTRACT

We synthesize and interpret local earthquake data recorded by the Caltech/USGS Southern California Seismographic Network (SCSN/CISN) in southern California. The goal is to use the existing regional seismic network data to: (1) refine the regional tectonic framework; (2) investigate the nature and configuration of active surficial and concealed faults; (3) determine spatial and temporal characteristics of regional seismicity; (4) determine the 3D seismic properties of the crust; and (5) delineate potential seismic source zones. Because of the large volume of data and tectonic and geologic complexity of the area, this project is a multi-year effort and has been divided into several tasks.

## RESULTS

### State of Stress and Style of Faulting

We invert for the state of stress in the southern California crust using a catalog of high quality earthquake focal mechanisms (1981-2010). The stress field is best resolved where seismicity rates are high but sufficient data are available to constrain the stress field across most of the region. From the stress field, we determine the maximum horizontal compressive stress ($S_{Hmax}$) orientations and the style of faulting across southern California. The style of faulting exhibits similar complexity, ranging from predominantly normal faulting in the high Sierra Nevada, to strike-slip faulting along the San Andreas system, to three consecutive bands of thrust faulting in the Wheeler Ridge area and the Western Transverse Ranges (Figure 1). The local variations in the style of faulting include normal faulting at the north end of the San Jacinto Fault and scattered areas of thrust faulting. The regional variations in the $S_{Hmax}$ trends are very similar to the pattern of the GPS-measured maximum shortening axes of the surface strain rate tensor field although the strain field tends to be smoother and appears to capture some of the upper mantle deformation field. The mean trend of $S_{Hmax}$ departs about approximately 14° to the east from the trend of the maximum shortening directions derived from anisotropy in the upper mantle.

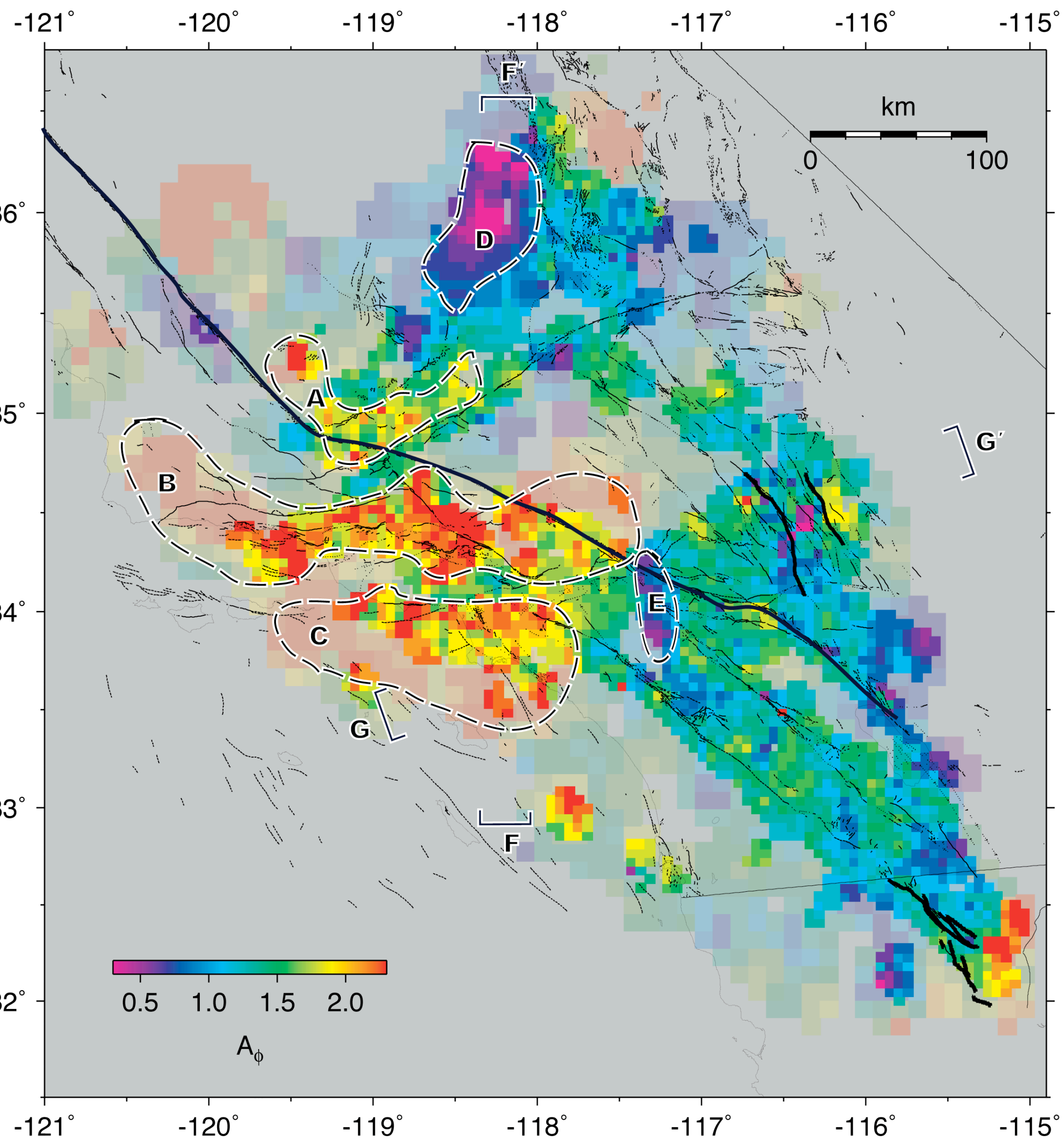


*Figure 1. Composite image for the style of faulting with overlapping models. The San Andreas Fault, Lander, Hector Mine, and El Mayor Cucapah surface ruptures are highlighted in bold black lines. "A", "B" and "C" mark the three identified convergent bends. "D" marks the Normal Faulting Zone to the east of Sierra Nevada Fault. "E" marks the NS Normal Faulting Stripe in San Bernardino Mountains (Yang and Hauksson, 2013).*

The style of faulting exhibits similar complexity and the SHmax orientations, ranging from predominantly normal faulting in the high Sierra Nevada, to strike-slip faulting along the San Andreas system, to three consecutive bands of thrust faulting in the Wheeler Ridge area and the Western Transverse Ranges. The local variations in the style of faulting include normal faulting at the north end of the San Jacinto fault and scattered regions of thrust faulting; this study is in press, Yang and Hauksson (2013).

## The 2012 Brawley Earthquake Sequence

The 2012 Brawley swarm 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).

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). 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).

We summarize the recent data and interpretations for this sequence (Hauksson et al. 2013). 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. These results are published in Hauksson et al. (2013).

*Focal Mechanisms.* We used first-motion polarities and S/P amplitude ratios and the HASH method of Hardebeck and Shearer (2002, 2003), as implemented by Yang *et al*. (2012), to determine focal mechanisms for the events in this swarm. There are 13 events of M≥ 3.5 that have A or B quality focal mechanisms (Figure 2). The focal mechanisms of the large earthquakes in the sequence are similar to the corresponding moment tensor mechanisms for the largest event (Table 1). The focal mechanisms of most of the events predominantly exhibit strike-slip motion on northeast- or northwest-striking nodal planes. Overall the focal mechanisms uniformly suggest the presence of a coherent regional stress field.

Along the almost north-south trend of seismicity, normal faulting is more prominent on either north or north-northeast striking nodal planes than along the main northeast-trending aftershock zone. Among the five events of M ≥ 2.0 that have A quality focal mechanisms (Figure 2), three of them exhibit normal faulting in north or north-northeast striking nodal planes. The current plate boundary right-lateral strike-slip motion, in combination with crustal extension and thinning, causes seismicity with left-lateral faulting as well as small-scale normal faulting on north- to north-northeast-striking nodal planes.

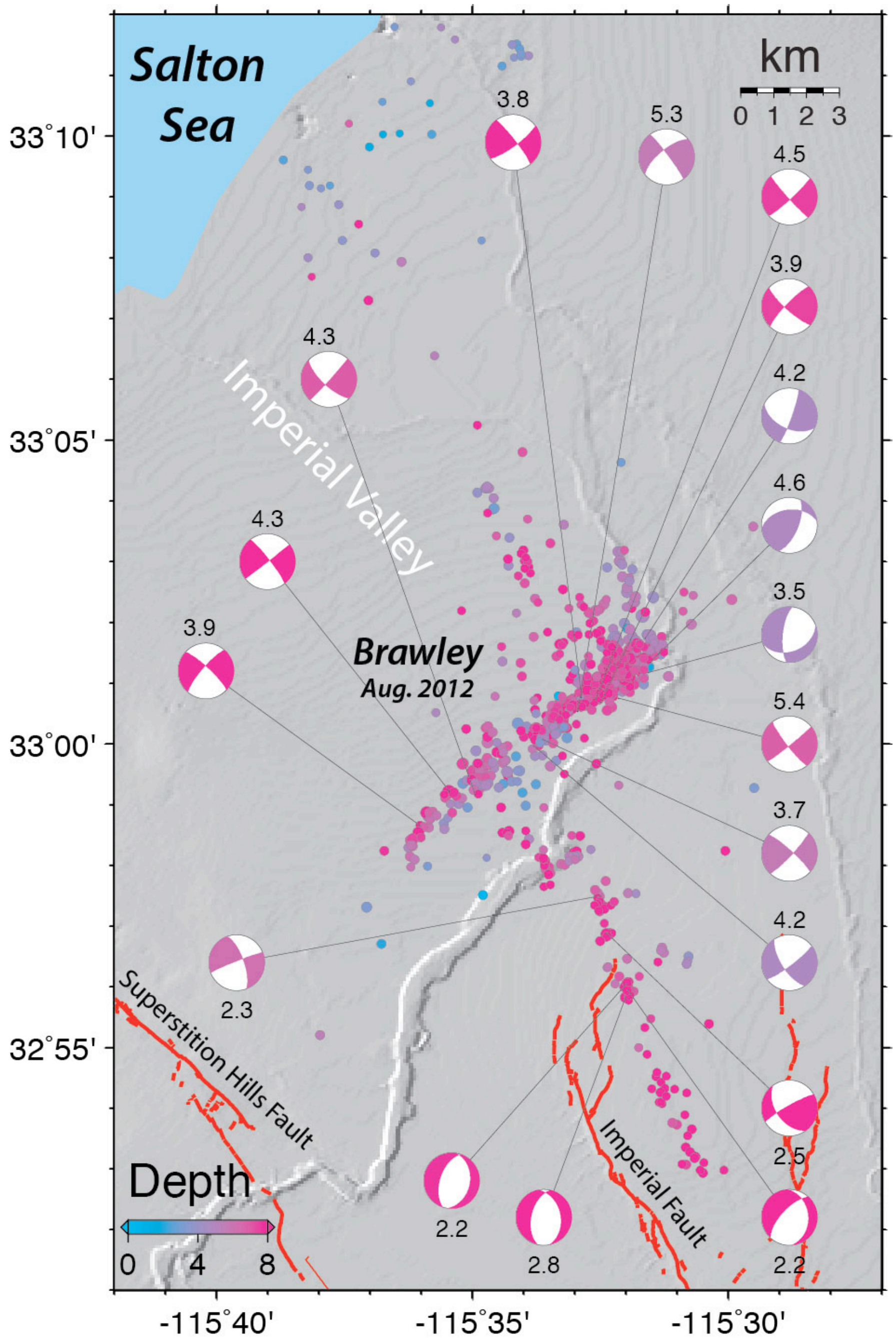


*Figure 2. Selected first motion and S/P ratio lower hemisphere focal mechanisms for the 2012 Brawley sequence. Each event is labeled with its magnitude and the color bar indicates time in days since 26 August 2012 (From Hauksson et al. 2013).*

*Previous Seismicity.* During the past 80 years of SCSN earthquake monitoring, the BSZ has been known for its high rate of both mainshock-aftershock and swarm sequences (Johnson and Hutton 1982; Hutton *et al*., 2010). During the 1970s the whole length of the BSZ was dominated by swarm activity. The largest recent mainshock to occur in the BSZ was the M6.4 1979 Imperial Valley mainshock that had an epicenter just south of the Mexico-US international border, and extended to 33.03° N in the north (Johnson and Hill, 1982). In late 1979, a cluster of aftershocks, with the largest event of M5.8, occurred within the region of the 2012 swarm. The M6.4 mainshock was followed by an average aftershock sequence lasting only for a few years. During the period from 1986 to 1999 seismic quiescence dominated the region. The quiescence was terminated by several swarms in late 1999 and early 2000.

The completeness of the SCSN catalog in the region improved with time as seismic stations were added to improve coverage (Hutton *et al*., 2010). A major improvement took place in 2008 when the SCSN began recording data from a dense network of stations around the south end of the Salton Sea.

The two seismicity clusters that begin forming in the late 1980s, at the south shore of the Salton Sea, are related to the geothermal areas. The production of geothermal energy started at that time and has resulted in steady seismicity in the region. The seismicity is expressed as two geographically separate distributions.

The April 1981 Westmoreland swarm occurred 15 km to the north-northwest of Brawley. It was characterized by a strike-slip faulting mainshock of M5.8 followed by numerous aftershocks, forming a left-lateral northeast trend. The 2005 Obsidian Butte sequence ruptured across the geothermal fields near the southern end of the Salton Sea. The sequence exhibited swarm like behavior and Lohman and McGuire, (2007) attributed its migration pattern to a slow aseismic slip event at depth.

## References

Hardebeck, J. L., and P. M. Shearer (2002). A new method for determining first-motion focal mechanisms, *Bull. Seism. Soc. Am.* **92,** 2264.

Hardebeck, J. L., P. M. Shearer (2003). Using S/P amplitude ratios to constrain the focal mechanisms of small earthquakes, *Bull. Seism. Soc. Am.* **93**, 2434–2444.

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., 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 (2013) 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*

Hudnut, K. W., L. Seeber, and J. Pacheco (1989). Cross-fault triggering in the November 1987 Superstition Hills earthquake sequence, southern California, *Geophys. Res. Lett.* **16**, 2, 199-202.

Hutton, L. K., J. Woessner, and E. Hauksson (2010). Seventy-Seven Years (1932 – 2009) of Earthquake Monitoring in Southern California, *Bull. Seismol. Soc. Am*, **100**, 2, 423-446, doi: 10.1785/0120090130.

Johnson, C. E., and D. P. Hill (1982). Aftershocks and pre-earthquake seismicity: *U. S. Geological Survey Professional Paper* 1254, 15-24.

Johnson, C. E., and L. K. Hutton (1982). Seismicity of the Imperial Valley, in The Imperial Valley, California, earthquake of October 15, 1979, *U. S. Geological Survey Professional Paper 1254*, 59-76.

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

Sharp, R. V., K. E. Budding, J. Boatwright, M. J. Ader, M. G. Bonilla, M. M. Clark, T. E. Fumal, K. K. Harms, J. J. Lienkaemper, D. M. Morton, B. J. O'Neill, C. L. Ostergren, D. J. Ponti, M. J. Rymer, J. L. Saxton, and J. D. Sims (1989). Surface faulting along the Superstition Hills fault zone and nearby faults associated with the earthquakes of 24 November 1987, *Bull. Seism. Soc. Am.*, **79**, 252-282.

Shearer, P. M., G. A. Prieto, and E. Hauksson (2006), Comprehensive analysis of earthquake source spectra in southern California, J. Geophys. Res., 111, B06303, doi:10.1029/2005JB003979.

Suárez-Vidal, F., L. Munguía-Orozco, M. González-Escobar, J. González-García, and E. Glowacka (2007). Surface Rupture of the Morelia Fault Near the Cerro Prieto Geothermal Field, Mexicali, Baja California, Mexico, during the Mw 5.4 Earthquake of 24 May 2006, *Seism. Res. Letters* **78**, 394-403.

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.*, in press, March 2013.

## RECENT REFEREED PUBLICATIONS

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., 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 (2013) 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*

Shao, G., C. Ji, and E. Hauksson (2012), Rupture process and energy budget of the 29 July 2008 *Mw* 5.4 Chino Hills, California, earthquake, *J. Geophys. Res.*, 117, B07307, doi:10.1029/2011JB008856.

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. 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.*, in press, 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

J. Crummey, and 7 others, Caltech/USGS Southern California Seismic Network: Recent upgrades of instrumentation and Operational Capabilities, Poster Abstract; *Seismo Soc. Res. Lett.*, 83, 381, 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, The Goldilocks Seismicity of Southern California, (**talk** presented at AEG Southern California Section, Steven's Steak House in Commerce, 12 June 2012)

C. Nicholson, E. Hauksson and A. Plesch, Active fault geometry and crustal deformation along the San Andreas fault system through San Gorgonio Pass, California: The view at depth in 3D from seismicity, (**talk** presented at 2012 SCEC Workshop on San Gorgonio Pass).

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).

C. Nicholson, A. Plesch, J. Shaw, and E. Hauksson, Upgrades and Improvements to the SCEC Community Fault Model: Increasing 3D fault complexity and compliance with surface and subsurface data, (2012 SCEC Annual Meeting poster).

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. Yu, A. Bhaskaran, S.-L. Chen, F. Chowdhury, D. Given, K. Hutton, E. Hauksson, and R. Clayton, Products and Services Available from the Southern California Earthquake Data Center (SCEDC) and the Southern California Seismic Network (SCSN), (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 W. Yang and P. 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..*

C. Nicholson, E. Hauksson, and A. Plesch, Active Fault Geometry and Crustal Deformation Along the San Andreas Fault System Through San Gorgonio Pass, California: The View in 3D From Seismicity, *Abstract Talk T22C-03, presented at 2012 Fall Meeting, AGU, San Francisco, Calif., 3-8 Dec.*

P. M. Shearer, R. S. Matoza, E. Hauksson, C. J. Wolfe, P. Okubo, and G. Lin, High-resolution earthquake catalogs for southern California and Hawaii from waveform cross-correlation *(Invited)*, *Abstract Talk* S42C-06*, presented at 2012 Fall Meeting, AGU, San Francisco, Calif., 3-8 Dec.*.

W. Yang and E. Hauksson, The 3-D Tectonic Crustal Stress Field and Style of Faulting Along the Pacific North America Plate Boundary in Southern California, *Abstract Talk* T44A-02*, presented at 2012 Fall Meeting, AGU, San Francisco, Calif., 3-8 Dec.*.

X. Chen, P. M. Shearer, and E. Hauksson, California foreshock sequences suggest underlying aseismic process *Abstract Talk* S51F-02*, presented at 2012 Fall Meeting, AGU, San Francisco, Calif., 3-8 Dec.*.

D. A. Weiser, L. M. Jones, and E. Hauksson, Aftershock Decay with Distance from a Fault, *Abstract Poster* S53A-2486*, presented at 2012 Fall Meeting, AGU, San Francisco, Calif., 3-8 Dec*.