2013 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

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Abstract

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 *(Allmann et al., 2008; Chen et al. 2012; Chen and Shearer, 2011, 2013; Hauksson, 2010, 2011, 2014; Hauksson et al., 2012, 2013; Hauksson and Shearer, 2005, 2006; Lin et al., 2007a,b, 2008; Lin and Shearer, 2009; Shearer et al., 2005, 2006; Shearer and Lin, 2009; Shearer, 2012; Yang et al., 2012; Yang and Hauksson, 2011, 2013).*

The latest version of our relocated catalog (the HYS catalog) contains high-precision locations of over 550,000 events from 1981 through 2013. 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, *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.

Caption for Exemplary Figure 4.

Event locations from the HYS catalog (1981 – 2013). Similar-event clusters that have been relocated 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 $M \geq 5.5$ are shown as stars. Faults are from Jennings (2010) with late Quaternary faults in shades of red and early Quaternary in blue (Hauksson et al. 2012).

The relocated (1981 – 2013) HYS catalog contains more than 550,000 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 to 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).

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, *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 – 2013

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- and S-wave windows of 0.5 and 1.5 s duration, respectively. For the cross-correlation calculation, we included up to 150 nearest neighbors and required the pairs of events be

Eight Polygons Used for Relocations

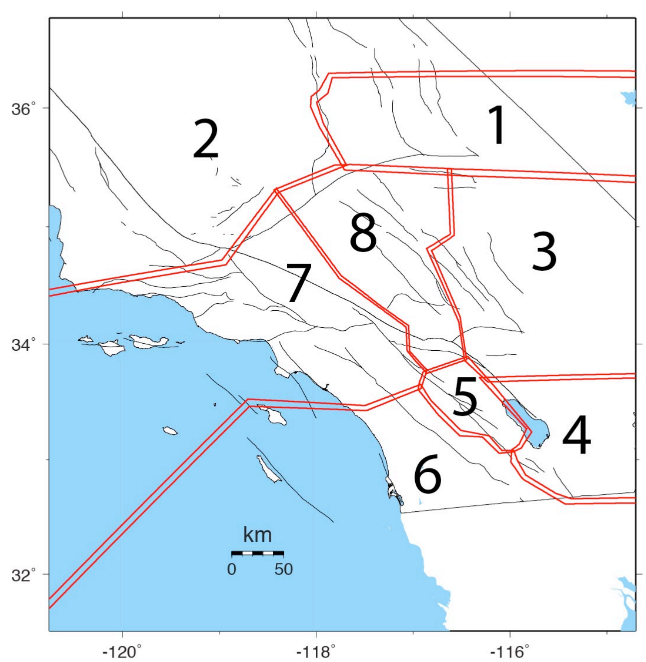

Figure 1. The polygons used to divide the dataset into smaller groups for efficient calculations.

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 more than 54 million cross-correlations, of which about 24 million achieved the minimum required values for a similar event pair.

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 a similar event cluster. Events within each cluster are then relocated using the differential times from the waveform cross-correlation.

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.

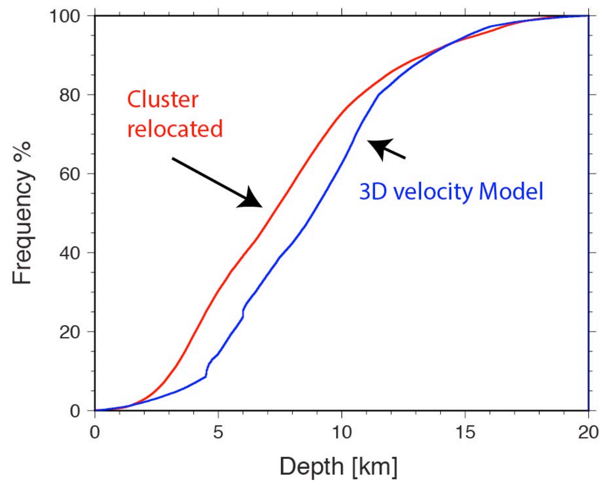

Figure 2. Comparison of the focal depths of the cluster relocated events and the events only relocated with a 3D velocity model.

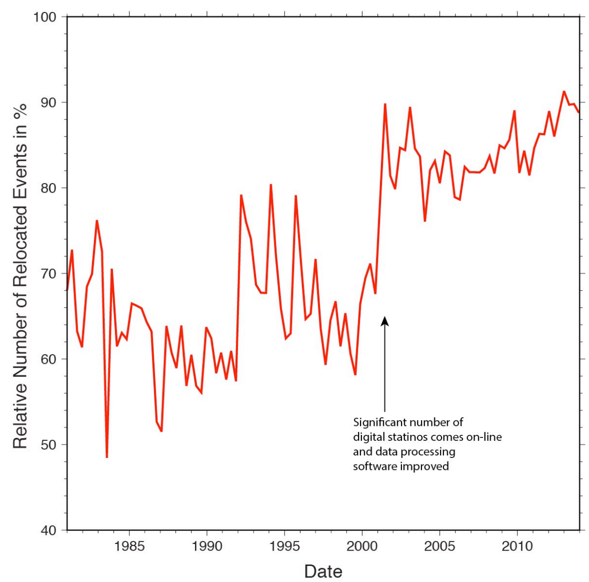

Figure 3. The number of relocated events divided by total number of events in percent versus date.

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

The 3D velocity model locations are somewhat more scattered than the cluster relocations, especially in depth. In Figure 2 we show the cumulative distribution of the focal depths for the cluster and 3D velocity model relocated datasets. The focal depths determined with the 3D velocity model dataset are on average 2 km deeper than the cluster relocations but the overall shape of the depth distribution is similar.

The number of events that can be relocated changes with time from 1981 to present (Figure 3). 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 had been brought on-line and the SCSN software system had been upgraded. Clearly 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.

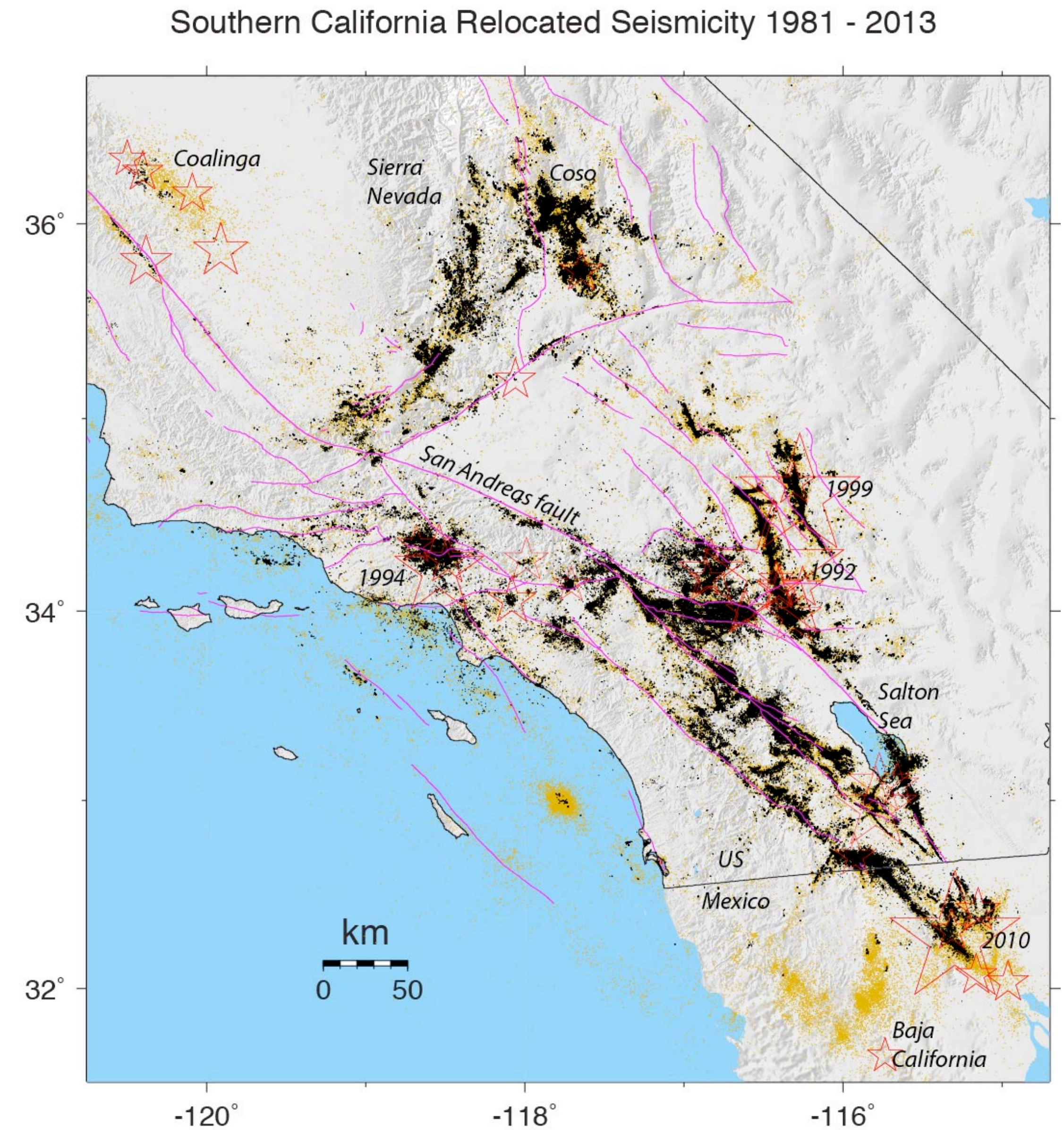

***Figure 4.** **(Exemplary Figure)**. Event locations from the HYS catalog (1981 – 2013). Similar-event clusters that have been relocated by using waveform cross-correlation are shown in black. Events in the SCSN catalog (and uncorrelated events in the other catalogs) are shown in yellow. Events with $M \geq 5.5$ are shown as stars. Faults are from Jennings (2010) with late Quaternary faults in shades of red and early Quaternary in blue (Hauksson et al. 2012).*

Results: Relocations 1981 – 2013

The relocated (1981 – 2013) HS catalog of more than 550,000 earthquakes is shown in Figure 4… 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 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.

Results: San Gorgonio Stress Drop Study

In general, seismic slip along faults reduces the average shear-stress within earthquake source regions, but individual stress drops during earthquakes are observed to vary widely in size. The details of how crustal and fault properties influence variations in stress drop are poorly understood.

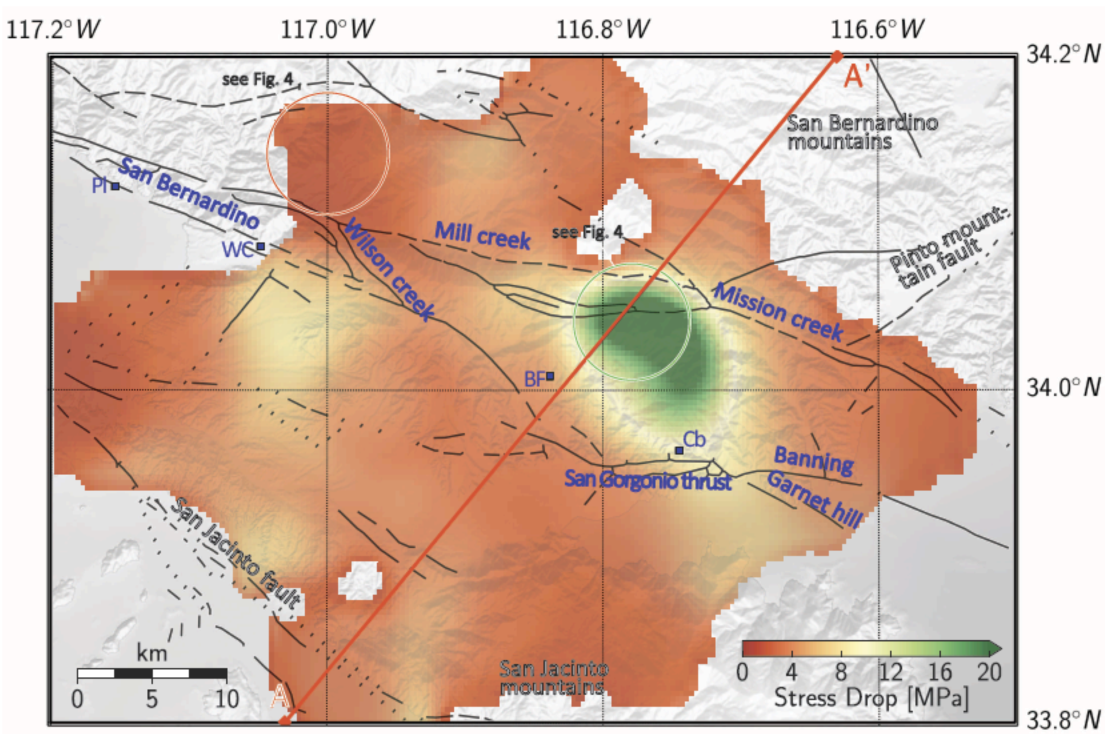

Figure 5. *Map view of smoothed stress drop variations within the study region. Fault segments of the San Andreas fault system are labeled in blue. The red line from A to A' marks the location of the depth cross sections in Figures 2b and 8. The blue squares show the sites of geologic slip rate estimates (see Figure 10 and description for details). Stress drops vary substantially from about 1 MPa to more than 20 MPa (see color-bar).*

To advance our understanding of variations in stress drop, we analyze source parameters of small and intermediate magnitude events within the greater San Gorgonio Pass region, southern California. The tectonics within the region are controlled by a restraining bend of the San Andreas fault system, which results in distributed deformation, and heterogeneous slip along numerous strike-slip and thrust faults. Stress drops are computed by fitting a Brune-type spectral model to individual event spectra obtained through separating the observed spectra into site, path and source contributions. The latter are obtained by iteratively removing stacked site and path terms and correcting high-frequency contributions using a regional empirical Green's function.

The stress drops show strong lateral variations from _1 to _25 MPa with a median of 4.8 MPa (Figure 5). We observe anomalously high stress drops (>20 MPa) in a small region between the traces of the San Gorgonio and Mission Creek segments of the San Andreas fault. Detailed analyses of focal mechanisms reveal that stress drops are slightly higher for thrust faulting events

(6 MPa) than for normal events (3.5 MPa). Stress drops also increase below depths of 10 km and along the San Andreas fault segments, both from north and south, towards San Gorgonio Pass, showing a negative correlation with geologic slip rates.

To test the stability of our results, we conducted a sensitivity analysis of input parameters and event selection criteria, confirming the robustness of the observations. We identified both crustal conditions and fault properties that are connected to local increases in stress drops including the style of faulting, changes in average tectonic slip rates, mineralogical composition of the host rocks, as well as the hypocentral depths of seismic events. A detailed spatial mapping of stress drop variations can thus advance the assessment of expected earthquake ground motions (*Goebel at al*. 2014).

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.

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