2015 Joint UCSD and Caltech SCEC Report

SCEC Award: 15017

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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7 March 2016

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 582,000 events from 1981 through 2015. 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.

Results: Relocations 1981 – 2015
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: Focal Mechanism Catalog: 2014
In 2012 we published a large refined catalog of focal mechanisms for 1981 to 2010 using the HASH method of *Hardebeck and Shearer* (2002, 2003.). We have updated this catalog for 2011, 2012, 2013, and 2014 (Figure 4). We plan to keep updating this catalog based on the latest relocated hypocenters.

We have added the following recent improvements to our focal mechanism processing: 1) the capability to use the latest relocations from the refined catalog; 2) modified scripts to use already-downloaded sac waveforms; 3) corrected the code to better include known instrument reversals by referring to station by net code, station, code and location code.

Exemplary Figure (see Figure 3 in report)

SCEC Science Priorities: 2a, 2d, 2f

Intellectual Merit
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 focal mechanism catalogs and 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.

Broader Impacts
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 SCEC workshops.

Project Publications

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

Yang, W., E. Hauksson and P. M. Shearer (2012), 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.

Zhang, Q., and P. M. Shearer (2016), A new method to identify earthquake swarms applied to seismicity near the San Jacinto Fault, California, *Geophys. J. Int.*, doi: 10.1093/gji/ggw073.

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) and *Zhang and Shearer* (2016) 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 – 2015

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.

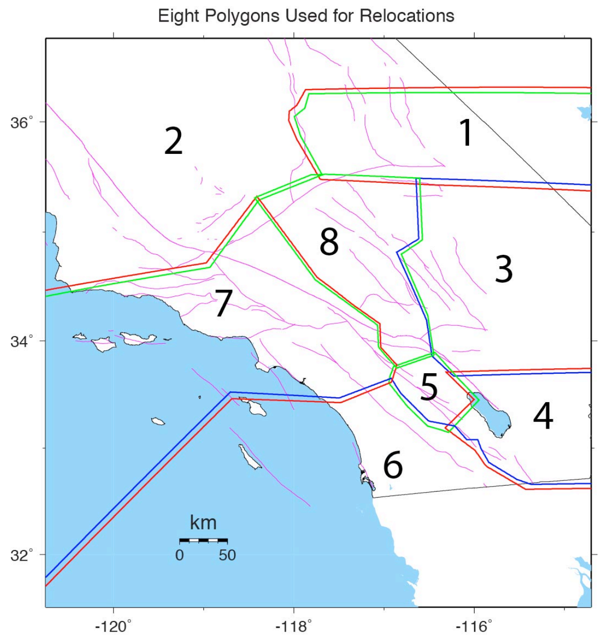

Figure 1. The polygons used to divide the dataset into smaller groups for efficient calculations.

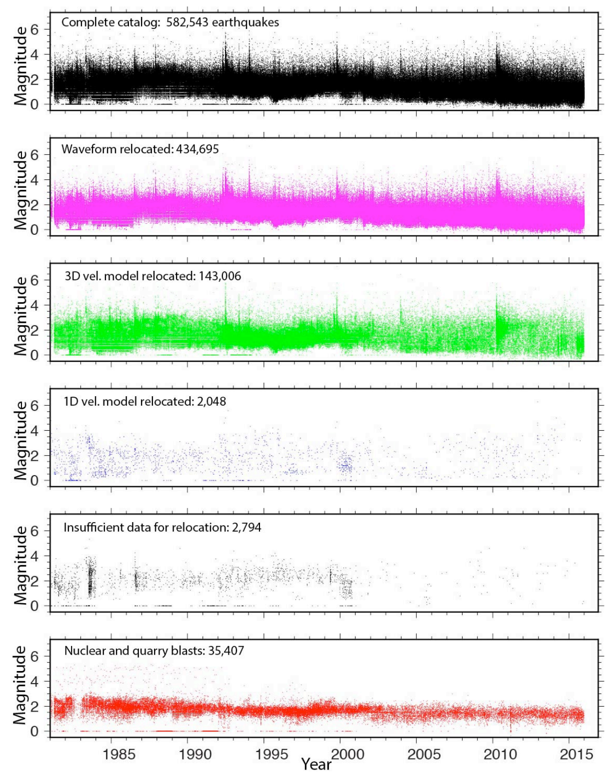

Figure 2. Magnitude versus date of earthquakes and blasts included in the Caltech/USGS catalog.

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.

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 events that only qualified for 1D velocity model relocation, 5) un-relocated events due to lack of data, and 6) the nuclear explosions and quarry blasts in the catalog. These graphs also illustrate the improved data quality with time and the magnitude of completeness, which has decreased as instrumentation has improved.

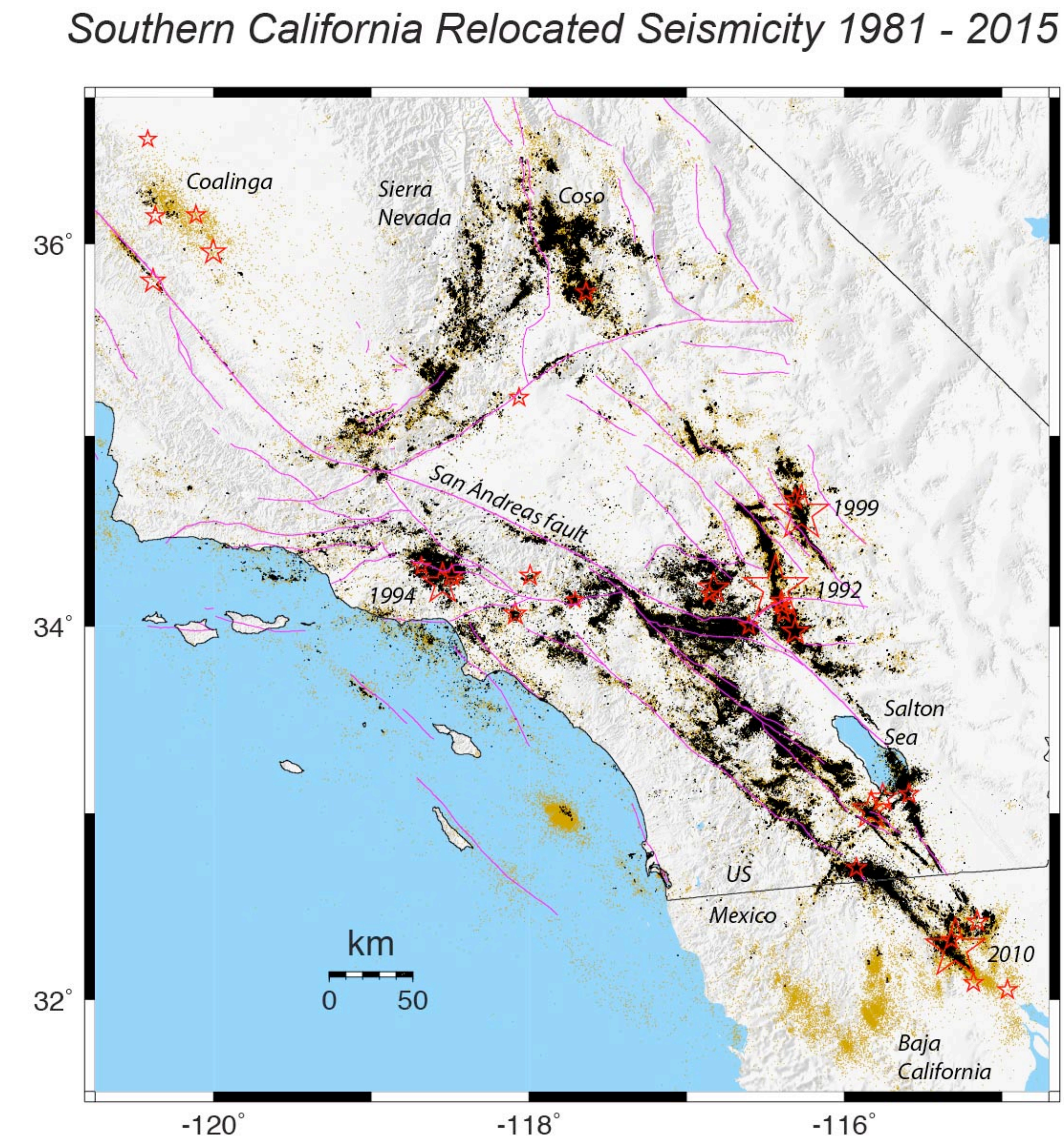

Figure 3. (Exemplary Figure) Event locations from the HYS catalog (1981 – 2015). Similar-event clusters that have been relocated by using waveform cross-correlation are shown in black. Events in the SCSN catalog (and uncorrelated events in the other catalogs) are shown in brown. Events with M ≥ 5.5 are 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 a 3D or 1D 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.

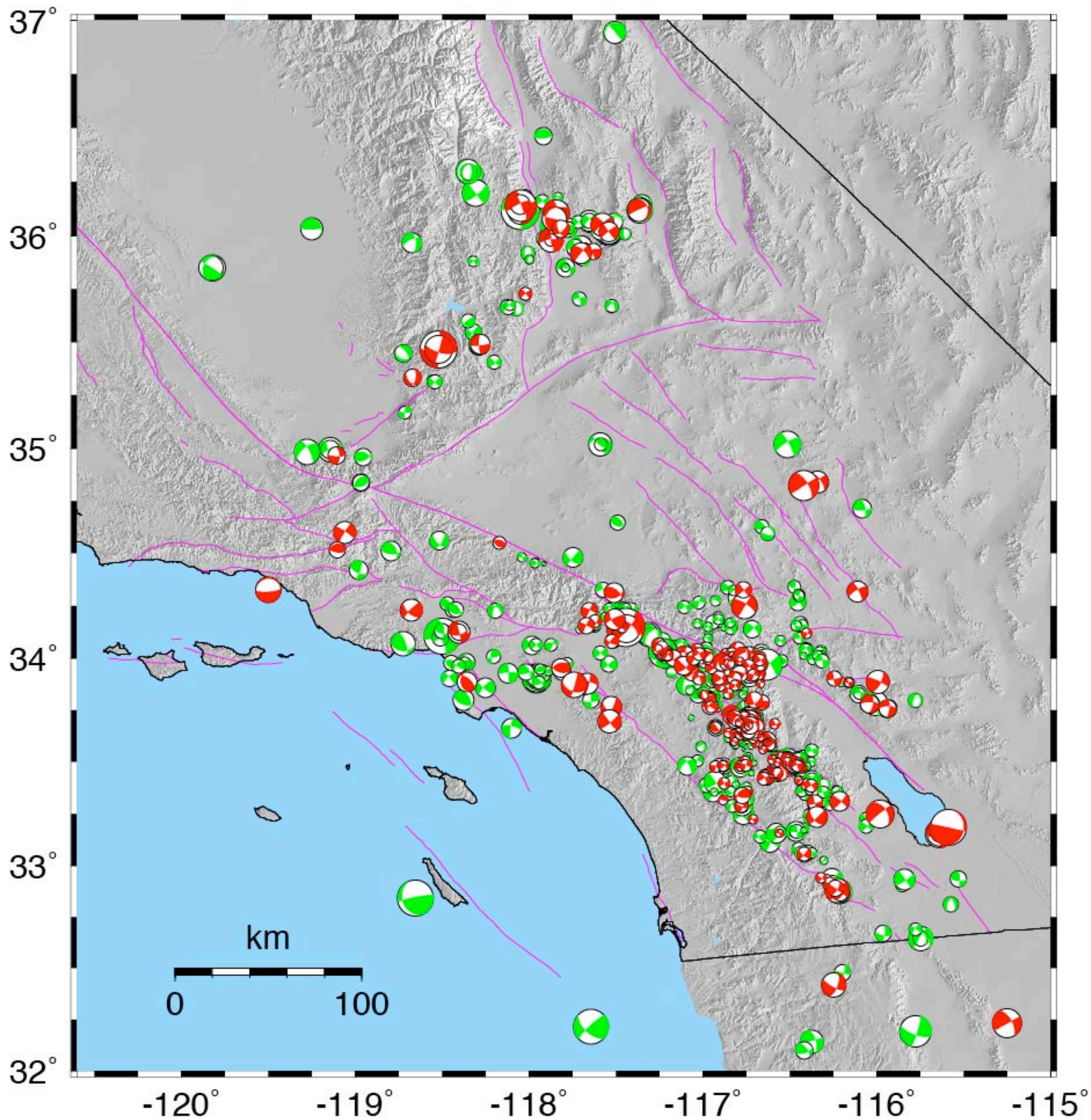

Figure 4: The 2014 A (red) and B (green) quality focal mechanisms for southern California.

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