# 2017 Caltech Report to SCEC

## SCEC Award: 17044

SCEC Community Data Products of Earthquake Catalogs with improved Focal Depth Estimation, for Resolving Fine-Scale Fault Structures and Crustal Rheology in Southern California


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# Caltech Template Information

## Abstract

For a decade UCSD and Caltech have worked on improving earthquake locations and focal mechanisms, and systematically estimating stress drops from source spectra. Our results have produced a large improvement in earthquake location accuracy for small earthquakes and dramatically sharpened seismicity features in southern California, while providing insight into fault zone processes (see **Figure 1**). We have also produced large catalogs of focal mechanisms and Brune-type stress drop estimates, which have facilitated large-scale analyses of the stress state of the southern California crust. This work has led to a substantial body of published results, both by our group and by others who have used our data products in their own research.

During 2017, we further refined earthquake locations and focal mechanisms. We paid special attention on improving focal depths, as well as hypocentral absolute and relative error estimates. We developed two complementary methods for determining absolute and relative earthquake depth, and applied them to the 2010 El Mayor-Cucapah earthquake sequence. Building on our previous SCEC work, we also maintained and updated our SCEC Community Products of refined earthquake locations and focal mechanisms for southern California.

### Exemplary Figure (see Figure 1 in report)

### SCEC Science Priorities: 1.d, 3.e, 4a

### 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

Hauksson, E. and M.-A. Meirer (2018), Applying Depth Distribution of Seismicity to Determine Thermo-mechanical Properties of the Seismogenic Crust in Southern California: Comparing Lithotectonic Blocks; PAGEOPH, *in review* May 2018

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.

Hauksson, E., J. Andrews, A. Plesch, J. H. Shaw, and D. R. Shelly (2016), The 2015 Earthquake Swarm Near Fillmore, California: Possible Dehydration Event Near the Bottom of the Over-Pressurized Ventura Basin, *Seismological, Res. Letters,*87 ,4 ,p807-815 , doi: 10.1785/0220160020

Hauksson, E., Z. E., Ross, M.-A. Meier, and L. M. Jones (2017), Evolution of seismicity near the southernmost terminus of the San Andreas Fault: Implications of recent earthquake clusters for earthquake risk in southern California, *Geophys. Res. Lett.,* 44, doi:10.1002/2016GL072026

Ross, Z. E., E. Hauksson, Y. Ben-Zion (2017), Abundant off-fault seismicity and orthogonal structures in the San Jacinto fault zone., *Sci. Adv.* 3, doi: e1601946

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.

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### Results: Relocated earthquake (1981-2017)

The relocated (1981 – 2017) HS catalog (*Hauksson et al.* 2012)) of more than 620,000 earthquakes is shown in **Figure 1**. It is produced via the following steps: (1) Initial locations are computed using existing phase picks and the 3D *P* and *S* velocity crustal model of *Hauksson* (2000), (2) Waveform cross-correlation is performed for 500 nearest neighbors or all events on both *P* and *S* arrivals, (3) Similar event clusters are identified based on the waveform correlation coefficients, (4) Events are separately relocated within each similar event cluster using the waveform cross-correlation times and an L1-norm method. The relocated catalog can be downloaded from here:
http://scedc.caltech.edu/research-tools/alt-2011-dd-hauksson-yang-shearer.html

### Results: Focal catalog of mechanisms (1981-2017)

In 2012 *Yang et al*. (2012) published a large refined catalog of focal mechanisms for 1981 to 2010 using the HASH method of *Hardebeck and* Shearer (2002, 2003.). We continue 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.

The focal mechanisms catalog can be downloaded from here:
http://scedc.caltech.edu/research-tools/alt-2011-yang-hauksson-shearer.html

### 1. Absolute focal depth determination by modeling regional depth phases

We determine absolute focal depth by modeling regional depth phases. We mainly focus on *Pn, PmP* and their depth phases. For *Pn* and its depth phases (*pPn* and *sPn*), we use stations with epicentral distance larger than 150 km to avoid contamination from other crustal phases. For

*PmP* and its depth phases (*pPmP* and *sPmP*), the best observing distance range is typically between 100 and 200 km. Theoretically, seismic recording from one single station is enough to constrain the depth once the depth phase is identified. In practice, due to phase interference and 3D structural heterogeneities, depth phase identification can be difficult.

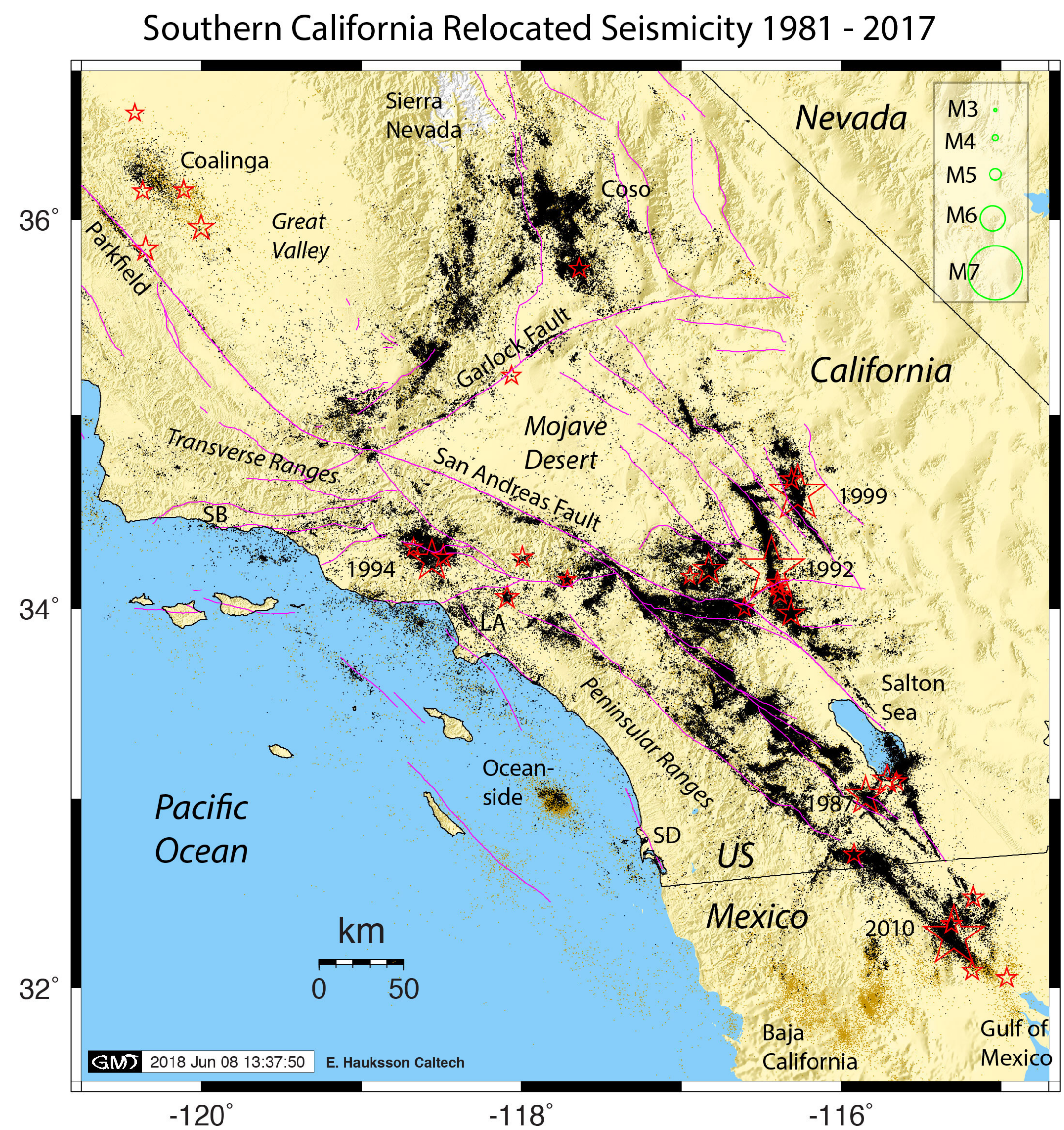


***Figure 1.*** *The HS catalog (1981 – 2017). Similar-event clusters that have been relocated by using waveform cross-correlation are shown in black. Events in the SCSN catalog (and uncorrelated events in the other catalogs) are shown in brown. Events with M ≥ 5.5 are shown as red stars. Faults are from Jennings and Bryant (2010) with late Quaternary faults in shades of red and early Quaternary in blue. Credit: Hauksson et al., (2012).*

We take advantage of the redundancy of seismic waveforms from the Southern California Seismic Network (SCSN) and use array processing (*Rost and Thomas, 2002*) to improve the signal-to-noise ratio of depth phases. The coherency of depth phases at various stations are helpful in phase identification.

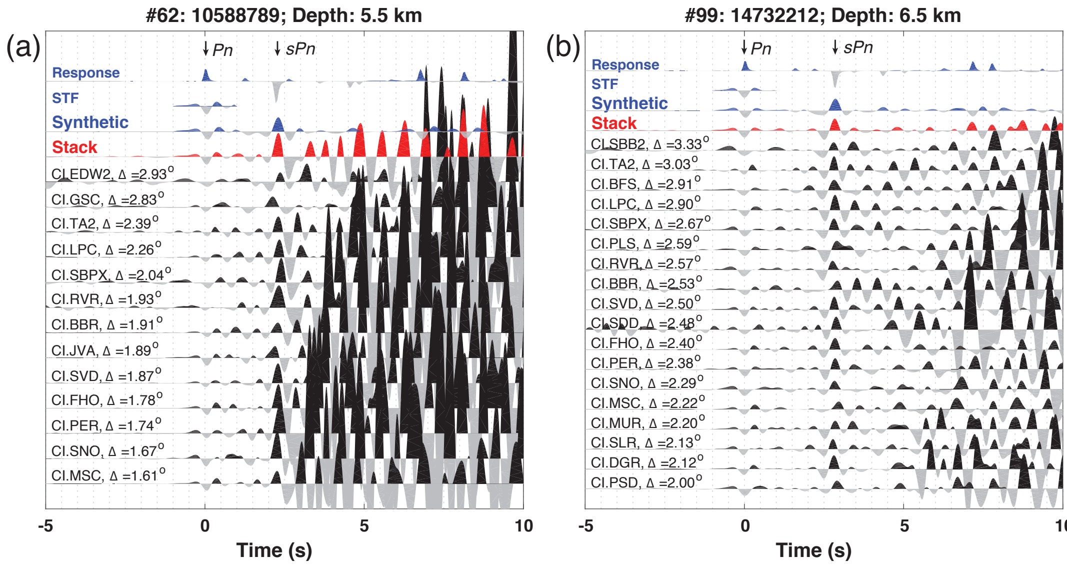


***Figure 2.*** *Examples of absolute depth determination by modeling Pn and its depth phase sPn. Red wiggles are waveforms stacked from individual stations (black). Blue wiggles are synthetic waveforms computed by convolving the structural response (Response) with apparent source time function (STF). Waveforms are aligned by Pn (set to 0 s). The strong phase arriving between 2 s and 3 s, is sPn.*

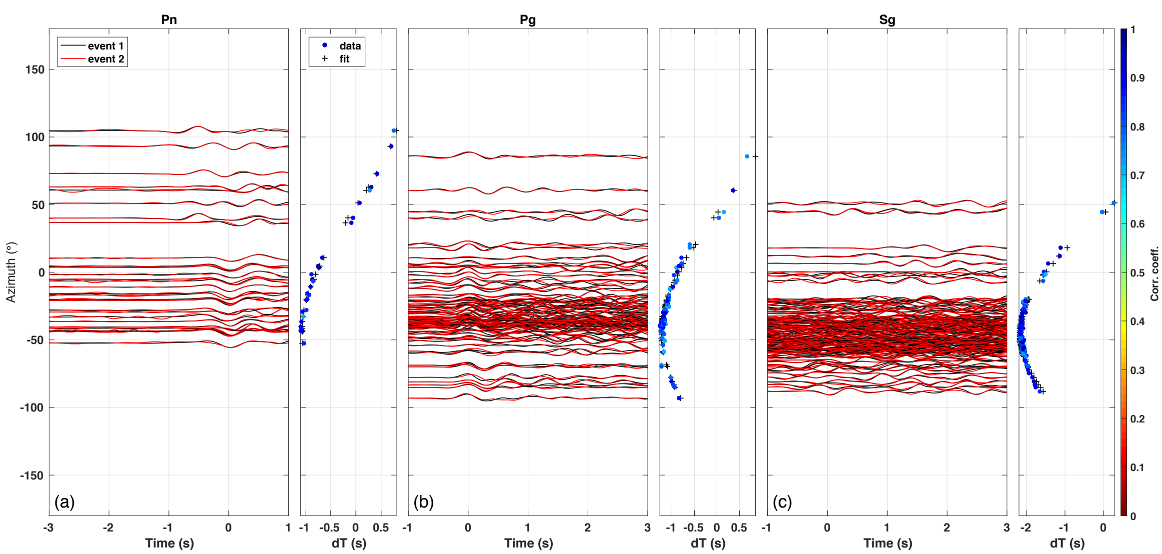


***Figure 3.*** *Differential travel time measurements via waveform cross correlation for an event pair in the Yuha desert. (a), (b), (c) are for Pn, Pg, and Sg, respectively. Black and red traces are for event 1 and event 2, respectively. Solid circles are measured differential travel time. Dark pluses are predicted differential travel times using the best-fit relative location in **Figure 4**.*

The amplitude and polarity of depth phases are modulated by the earthquake focal mechanism. To this end, a complete catalog of earthquake focal mechanism in southern California is desirable (*Yang et al., 2012*). Here, we first determined earthquake focal mechanisms using the Cut-and-

Paste method of *Zhu and Helmberger* (1996). We then applied a grid search of focal depths and determine the optimal value by matching synthetic waveforms (Green's function convolved with source wavelet) with the stacked waveform. An example of waveform fitting for *Pn* and its depth phases are shown in **Figure 2**. Both events are taken from the 2010 El Mayor-Cucapah earthquake sequence. The strong coherent phase at 2~3 s following the *Pn* phase is the identified *sPn* phase. By fitting the *sPn* depth phase, we determined precise focal depths of 5.5 and 6.5 km for these two events, respectively.

## 2. Relative depth determination by incorporating *Pn* into conventional double-difference algorithm

Depth phases sometimes are difficult to identify due to either phase interference or strong 3D structural heterogeneities. Conventionally, relative earthquake locations are more precisely determined using the double-difference algorithm. However, the conventional double-difference algorithm fails to constrain relative focal depth if stations are far away from the hypocenter.

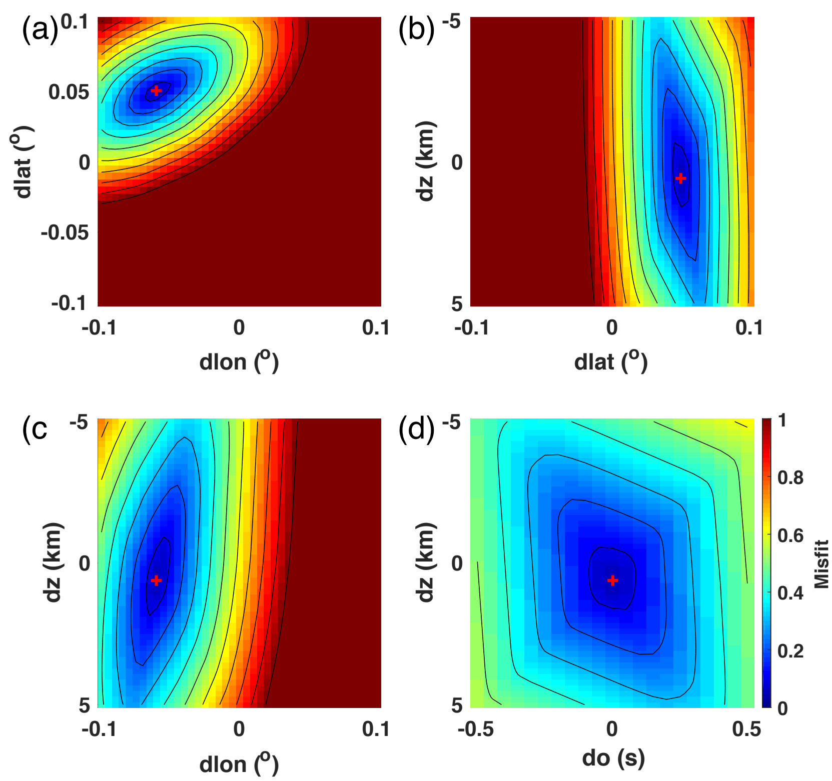


***Figure 4.*** *Misfits between observed and predicted travel times via grid search. (a)-(d) show misfits in different cross sections. The best-fit solution suggests that event 1 is slightly deeper than event 2, by ~0.5 km.*

This is mainly because of nearly horizontal ray paths of *P* and *S* waves. We solved this problem by incorporating *Pn* differential times into the conventional double-difference algorithm. *Pn* leaves the source downward at a constant slowness, and thus the *Pn* differential travel times are more sensitive to the focal depth. **Figure 3** shows the relative travel time measurements of *Pn*, *Pg* and *Sg* between an event pair in the Yuha desert. The relative depth for this event pair can be determined by minimizing the misfit function through either linear inversion algorithm or grid search (**Figure 4**).

## Results

To demonstrate the effectiveness of our methods, we relocate the depth of the 2010 El Mayor Cucapah earthquake sequence (M≥4). The routine travel-time relocation method doesn't provide good constraints on the focal depth, especially for events occurring near the southern part of the rupture zone. This is largely due to limited station coverage near earthquake hypocenters (*Hauksson et al., 2011*).

We relocated 93 out of 122 events with M>=4 in this earthquake sequence. The rest of events mostly occurred directly after the main shock and thus have low signal-to-noise ratio. In our new result, aftershock focal depths are mostly located between 5 and 10 km., which is very different from the original SCSN catalog (which show widely distributed earthquake depths in the central and southern part of the main rupture zone), but is consistent with the relocated catalog using a temporary network deployed near the source region but after the main shock (Castro et al., 2011). Our results show that most aftershocks are located underneath or near the lower terminus of the coseismic slip (*Wei et al., 2011*). There is a general anti-correlation between the distribution of aftershocks and coseismic slip. The result is consistent with the interpretation that aftershocks release residual strains near high slip patches (*Wei et al., 2011*).

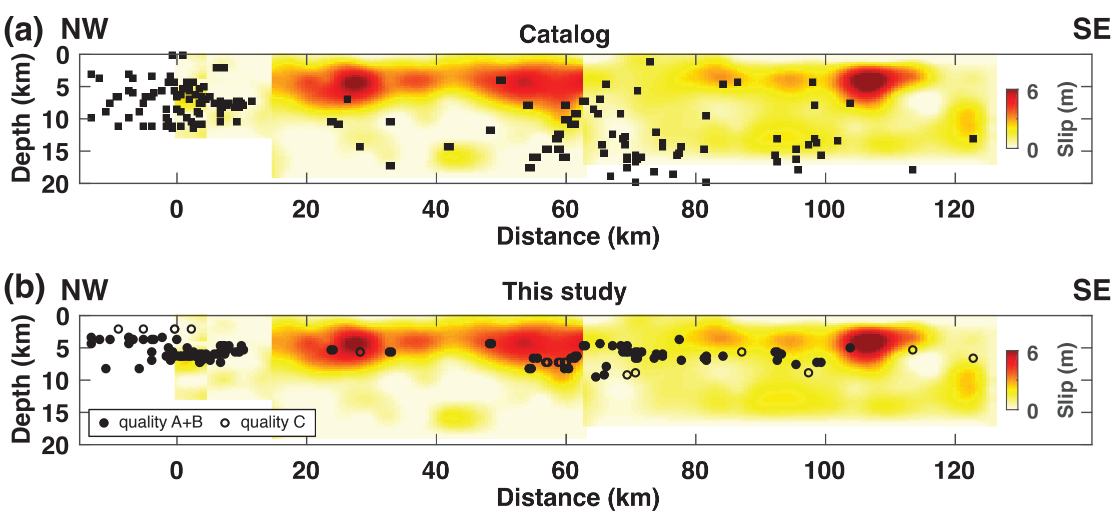


***Figure 5.*** *Depth distribution of the 2010 El Mayor-Cucapah earthquake sequence (M>=4). (a) Depth from the SCSN catalog (Hauksson et al., 2012). (b) Depth from this study. Solid circles mark focal depth determined from Pn depth phase modeling. Open circles are results from relative depth determination. The background image shows the coseismic slip (Wei et al., 2011).*

### Presentation and publication

Postdoc Chunquan Yu presented the work at 2017 SCEC annual meeting. The manuscript on the depth determination of the 2010 El Mayor-Cucapah earthquake sequence is in preparation.

## References

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