Seismicity, Swarms, and Strain Changes in Southern California

Report for SCEC Award #15065

Investigator: Peter Shearer (UCSD)

I. Project Overview

A. Abstract

This SCEC funded research involves continued analysis of earthquakes recorded by the Southern California Seismic Network (SCSN). This has led to greatly improved earthquake locations, focal mechanisms, and estimates of stress drop. We are now using these products to perform integrated studies of seismicity and address a number of issues related to seismic hazard. We have recently focused on studying earthquake triggering models and their relationship to swarms and foreshock sequences. We have identified several aspects of the space/time clustering of seismicity that cannot be explained with standard (i.e., ETAS) triggering models, including details of the foreshock and aftershock behavior for small earthquakes. In particular, we have found that a significant fraction of small earthquake clustering is swarm-like and probably caused by underlying physical drivers, such as fluid flow or slow slip. We have now begun a systematic analysis of swarms in southern California, beginning with the development of a new swarm detection algorithm. Our results show that swarms are heterogeneously distributed in time and space and are likely related to foreshock sequences in some regions.

B. SCEC Annual Science Highlights

Seismology
Aseismic Transient Detection
Earthquake Forecasting and Predictability

C. Exemplary Figure

Figure 2. Map view of the detected swarm (solid circle) events in the SJFZ. The circles are color-coded by occurrence time and scaled with the total number of events in each group. Hexagons represent the swarms identified from Vidale and Shearer (2006). Stars mark five $M \geq 5$ earthquakes including two Superstition Hills in 1987 and three occurring south of Anza. Blue line shows the strike of the SJFZ. Grey dots denote the 77,377 catalog events between 1981 and 2014. CCF: Coyote Creek Fault. Note that the events shown on the map are only SJFZ events, and the events in surrounding faults are masked. From Zhang and Shearer (2016).

D. SCEC Science Priorities

2b, 2c, 5d

E. Intellectual Merit

Our research relates to many key SCEC objectives, including characterizing seismicity clustering and its implications for earthquake prediction. Our main contribution has been to systematically and objectively examine large amounts of earthquake data, including swarms and foreshock sequences, to test whether existing models of earthquake clustering are adequate to explain the observations.

F. Broader Impacts

This project helped support postdoc Qiong Zhang. Our research will help quantify earthquake clustering and triggering in southern California, which has broad implications for earthquake forecasting and predictability. Advances in these areas would have clear societal benefits.

G. Project Publications

Entered in publications database

II. Technical Report

Seismicity patterns

Earthquakes cluster strongly in time and space, but it is not yet clear how much of this clustering can be explained as triggering from previous events (such as occurs for aftershock sequences following large earthquakes) and how much the clustering may reflect underlying physical processes (such as apparently drive many earthquake swarms; e.g., Hainzl, 2004; Vidale and Shearer, 2006). Considerable attention has focused on the statistics of earthquake triggering, in which the occurrence of an earthquake increases the probability of a subsequent nearby event, and models have been derived with a single unified triggering law, which can explain the general properties of earthquake catalogs, including many foreshock and aftershock sequences (e.g., Ogata, 1999; Helmstetter and Sornette, 2002). However, these models do not explain some aspects of southern California seismicity, such as swarms (Vidale and Shearer, 2006; Lohman and McGuire, 2007), differences in precursory seismicity behavior between large and small earthquakes (Shearer and Lin, 2009), foreshock/aftershock ratios for small earthquakes (Shearer, 2012a,b), and foreshock migration and low stress drops prior to large earthquakes (Chen and Shearer, 2013). We are now studying the more general problem of determining which features of the space/time clustering observed in seismicity catalogs are well-explained by ETAS-like models and which features more likely reflect underlying physical processes.

Our results so far (Shearer 2012a,b) suggest that most of the small earthquake clustering seen in southern California is caused by underlying physical drivers, such as fluid flow or slow slip. This is most obvious in swarms, and we have developed tools to analyze the spatial migration of seismicity in swarms, specifically to estimate the migration velocity and direction and evaluate its statistical significance. We find that some swarms are best fit with a linear migration velocity, others with the diffusion equation (Chen and Shearer, 2011; Chen et al., 2012). Our estimated fluid diffusion coefficients are similar to those found in previous studies by Hainzl (2004) and El Hariri et al. (2010). However, swarms are likely simply the obvious example of seismicity rate changes driven by physical changes in the crust. Seismicity is often non-stationary and exhibits complex evolution. There are obvious swarms at small scales, but there are also larger scale (> 5 km) changes in seismicity rate. Most of the temporal changes cannot be explained as mainshock/aftershock triggering because often the seismicity rate will change in the absence of a large event. What causes these rate changes? To explore this topic, we have begun a systematic analysis of swarms in southern California.

Swarms

We have developed a new method to identify seismicity clusters of varying sizes and discriminate them from randomly occurring background seismicity. To fully characterize earthquake swarms, it is desirable to compile as complete a swarm catalog as possible. Our method searches for the closest neighboring earthquakes in space and time and compares the number of neighbors to the background events in larger space/time windows. We describe clusters using the nearest-neighbor approach from Zaliapin and Ben-Zion (2013), which provides a general way to separate clusters from background events. The distance η between two events in space and time is defined as

$$\eta = dt \times dr^d$$

where dt is the time separation between the two events, dr is the 3D space separation, and d is the fractal dimension. We experimented with different values of d and found that the cluster identifications did not change very much, thus we use $d = 1.6$ following the study of Zaliapin and Ben-Zion (2013). Note that we modify the definition of η in Zaliapin and Ben-Zion by dropping the magnitude dependence because we seek to identify all clusters, not just aftershock sequences explained by earthquake-to-earthquake triggering models.

Our algorithm aims to detect event clustering in space and time by comparing local event density with the surrounding distribution of "background" events. We sequentially treat each event in the catalog as a target event and find its n nearest neighbors (for n from 3 to 200) from subsequent events. For each value of n, we save details of the space/time window, i.e., the maximum temporal and spatial distance (t_{max} and r_{max}) from the target event. This defines a reference space/time window, which is shown in green in Figure 1. Similar to the idea of STA/LTA (short-time-average through long-time-average) triggering algorithms, we also define a larger "background" window that scales with t_{max} and r_{max}.

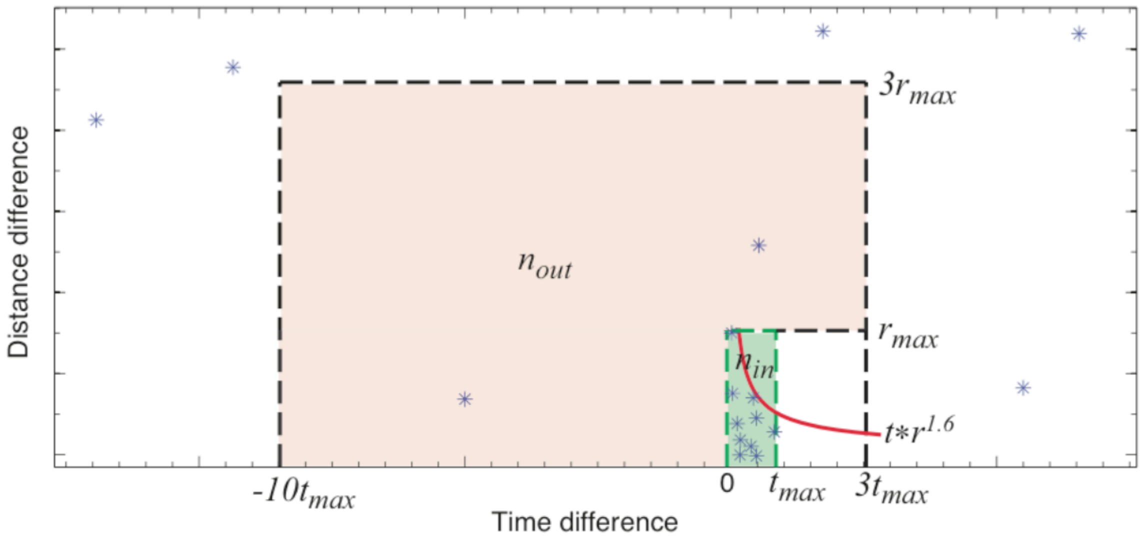


Figure 1. Illustration of our cluster detection method. A cluster is identified when the number of neighbors (n_{in} = 10) within a window of r_{max} km and t_{max} days (green) is significant compared to the number of background events (n_{out} = 2) in a larger window (pink). The maximum neighboring distance from the target event is shown by the red curve.

Comparing the number of events falling in the windows, we quantify the clustering strength as

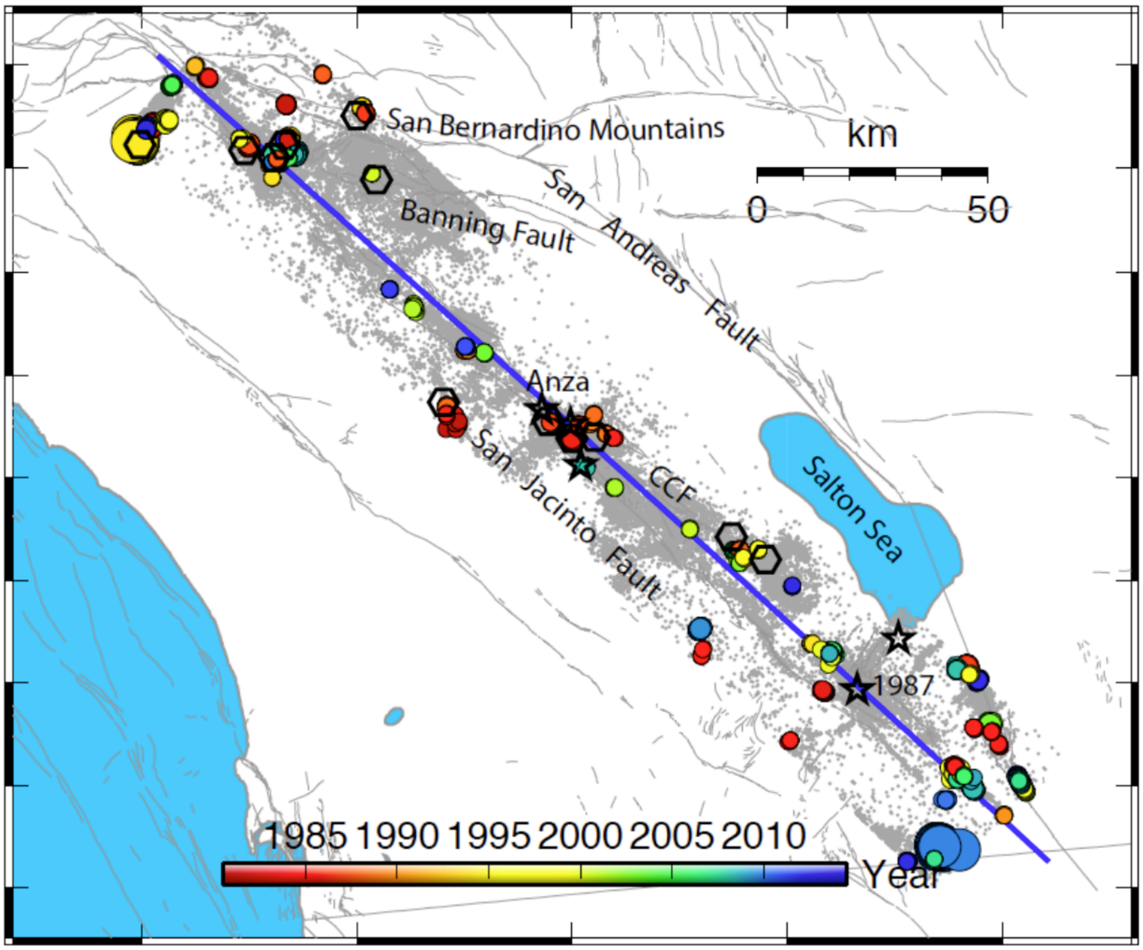
$$Q = \frac{n_{in}}{n_{out} + 1}$$

where n_{in} is the number of neighbors in the reference window and n_{out} is the number of events falling in the background window. For each target event, the largest value of Q (Q_{max}) from the 198 values of n is chosen and the corresponding n_{in} neighbors are saved as daughter events in the cluster group.

From our catalog of 77,377 events near the San Jacinto Fault Zone (SJFZ) this results in a total of 24,689 possible clusters. However, most of these have low Q_{max} values or very small numbers of events. To focus on the most clearly defined clusters, we analyze only groups with $Q_{max} \geq 2$ and containing at least 10 events. Using these criteria, a total of 179 clusters are found in our study area. We then examine the temporal distribution of magnitude within each cluster to separate mainshock/aftershock sequences from swarms and identify 89 groups as clearly swarms.

We map the spatial distribution of the 2035 swarm-like events between 1981 and 2014 in Figure 2, in which large and small clusters are defined based on the number of events in each group. These swarms span our study region but do not appear to be distributed uniformly within the seismicity. The northern and southern ends of the SJFZ have more frequent and larger swarms, such as the area in the San Bernardino Mountains near the intersection of the San Andreas Fault and the SJFZ, and the area close to the Salton Sea. Regions of the SJFZ with a high background seismicity rate do not always produce swarms, such as the areas close to the Banning Fault and the Coyote Creek Fault (CCF) and the region near south of the 1987 M 6.6 Superstition Hills.

In the same study area, Vidale and Shearer (2006) identified 12 swarms, each of which contains at least 40 events occurring within 4 weeks and a 2 km radius. The swarms identified from our method range from 0.14 to 7.23 km in radius and last from 15 minutes to 22 days. Because swarm sequences can contain gaps in space or time, the parent and daughter events for a certain sequence identified using two different methods might be different. In general, our results included the Vidale and Shearer clusters but added additional swarms and span a winder range of sizes.



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SCEC Related Publications (from 2010)

Chen, X., and P. M. Shearer, Comprehensive analysis of earthquake source spectra and swarms in the Salton Trough, California, *J. Geophys. Res.*, **116**, B09309, doi:10.1029/2011JB008263, 2011.

Chen, X., and P. M. Shearer, California foreshock sequences suggest aseismic triggering process, *Geophys. Res. Lett.*, **40**, doi:10.1002/grl.50444, 2013.

Chen, X., and P. M. Shearer, Analysis of foreshock sequences in California and implications for earthquake triggering, *Pure Appl. Geophys.*, doi: 10.1007/s00024-015-1103-0, 2015.

Chen, X., P. M. Shearer, and R. E. Abercrombie, Spatial migration of earthquakes within seismic clusters in Southern California: Evidence for fluid diffusion, *J. Geophys. Res.*, **117**, B04301, doi: 10.1029/2011JB008973, 2012.

Goebel, T. H. W., E. Hauksson, P. M. Shearer, and J. P. Ampuero, Stress drop heterogeneity within tectonically complex regions: A case study of San Gorgonio Pass, southern California, *Geophys. J. Int.*, **202**, 514–528, 2015.

Hauksson, E., J Stock, R. Bilham, M. Boese, X. Chen, E. H. Fielding, J. Galetzka, K. W. Hudnut, K. Hutton, L. C. Jones, H. Kanamori, P. M. Shearer, J. Steidl, J. Treiman, S. Wei, and Wenzheng Yang, Report on the August 2012 Brawley earthquake swarm in Imperial Valley, Southern California, *Seismol. Res. Lett.*, **84**, 177-189, doi: 10.1785/0220120169, 2013.

Kane, D. L., G. A. Prieto, F. L. Vernon, and P. M. Shearer, Quantifying seismic source parameter uncertainties, *Bull. Seismol. Soc. Am.*, **101**, 535–543, doi: 10.1785/0120100166, 2011.

Kane, D. L., P. M. Shearer, B. P. Goertz-Allmann, and F. L. Vernon, Rupture directivity of small earthquakes at Parkfield, *J. Geophys. Res.*, **118**, doi: 10.1029/2012JB009675, 2013.

Kaneko, Y., and P. M. Shearer, Seismic source spectra and estimated stress drop from cohesive-zone models of circular subshear rupture, *Geophys. J. Int.*, doi: 10.1093/gji/ggu030, 2014.

Kaneko, Y., and P. M. Shearer, Variability of seismic source spectra, estimated stress drop and radiated energy, derived from cohesive-zone models of symmetrical and asymmetrical circular and elliptical ruptures, *J. Geophys. Res.*, **120**, doi: 10.1002/2014JB011642, 2015.

Lin, G., C. H. Thurber, H. Zhang, E. Hauksson, P. M. Shearer, F. Waldhauser, T. M. Brocher and J. Hardebeck, A California statewide three-dimensional seismic velocity model from both absolute and differential times, *Bull. Seismol. Soc. Am.*, **100**, 225-240, doi: 10.1785/0120090028, 2010.

Shearer, P. M., Self-similar earthquake triggering, Båth's law, and foreshock/aftershock magnitudes: Simulations, theory, and results for southern California, *J. Geophys. Res.*, **117**, B06310, doi: 10.1029/2011JB008957, 2012a.

Shearer, P. M., Space-time clustering of seismicity in California and the distance dependence of earthquake triggering, *J. Geophys. Res.*, **117**, B10306, doi: 10.1029/2012JB009471, 2012b.

Shearer, P. M., Reply to comment by S. Hainzl on "Self-similar earthquake triggering, Båth's Law, and foreshock/aftershock magnitudes: Simulations, theory and results for southern California," *J. Geophys. Res.*, **118**, doi: 10.1002/jgrb.50133, 2013.

Smith-Konter, B. R., D. T. Sandwell, and P. Shearer, Locking depths estimated from geodesy and seismology along the San Andreas Fault System: Implications for seismic moment release, *J. Geophys. Res.*, **116**, doi: 10.1029/2010JB008117, 2011.

Sumiejski, P. E., and P. M. Shearer, Temporal stability of coda Q^{-1} in southern California, *Bull. Seismol. Soc. Am.*, **102**, 873–877, doi: 10.1785/0120110181, 2012.

Trugman, D.T., P. M. Shearer, A. A. Borsa, and Y. Fialko, A comparison of long-term changes in seismicity at the Geysers, Salton Sea, and Coso geothermal fields, *J. Geophys. Res.*, doi: 10.1002/2015JB012510, 2016.

Uchide, T., H. Yao, and P. M. Shearer, Spatio-temporal distribution of fault slip and high-frequency radiation of the 2010 El Mayor-Cucapah, Mexico earthquake, *J. Geophys. Res.*, **118**, doi: 10.1002/jgrb.50144, 2013.

Yang, Z., A. Sheehan, and P. Shearer, Stress-induced upper crustal anisotropy in southern California, *J. Geophys. Res.*, **116**, doi: 10.1029/2010JB007655, 2011.

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

References

Chen, X. and P. M. Shearer, Comprehensive analysis of earthquake source spectra and swarms in the Salton Trough, California, *J. Geophys. Res.*, **116**, doi: 10.1029/2011JB008263, 2011.

Chen, X., and P. M. Shearer, California foreshock sequences suggest aseismic triggering process, *Geophys. Res. Lett.*, **40**, doi:10.1002/grl.50444, 2013.

Chen, X., P. M. Shearer, and R. E. Abercrombie, Spatial migration of earthquakes within seismic clusters in Southern California: Evidence for fluid diffusion, *J. Geophys. Res.*, **117**, B04301, doi: 10.1029/2011JB008973, 2012.

El Hariri, M., R. E. Abercrombie, C. A. Rowe, and A. F. do Nascimento, The role of fluids in triggering earthquakes: observations from reservoir induced seismicity in Brazil, *Geophys. J. Int.*, **181**, 1566-1574, 2010.

Hainzl, S., Seismicity patterns of earthquake swarms due to fluid intrusion and stress triggering, *Geophys. J. Int.* **159**, 1090–1096, 2004.

Helmstetter, A., and D. Sornette, Diffusion of epicenters of earthquake aftershocks, Omori's law, and generalized continuous random walk models, *Phys. Rev. E.*, **66**, 061104, 2002.

Lohman, R. B., and J. J. McGuire, Earthquake swarms driven by aseismic creep in the Salton Trough, California, *J. Geophys. Res.*, **112**, B04405, doi: 10.1029/2006JB004596, 2007.

Ogata, Y., Seismicity analysis through point-process modeling: a review, *Pure Appl. Geophys.*, **155**, 471–507, 1999.

Shearer, P. M., Self-similar earthquake triggering, Båth's law, and foreshock/aftershock magnitudes: Simulations, theory, and results for southern California, *J. Geophys. Res.*, **117**, B06310, doi: 10.1029/2011JB008957, 2012a.

Shearer, P. M., Space-time clustering of seismicity in California and the distance dependence of earthquake triggering, *J. Geophys. Res.*, **117**, B10306, doi: 10.1029/2012JB009471, 2012b.

Shearer, P. M., and G. Lin, Evidence for Mogi doughnut behavior in seismicity preceding small earthquakes in southern California, *J. Geophys. Res.*, **114**, doi: 10.1029/2009JB005982, 2009.

Vidale, J. E., and P. M. Shearer, A survey of 71 earthquake bursts across southern California: Exploring the role of pore fluid pressure fluctuations and aseismic slip as drivers, *J. Geophys. Res.*, **111**, B05312, doi:10.1029/2005JB004034, 2006.

Zaliapin, I. and Y. Ben-Zion, Earthquake clusters in southern California I: Identification and stability, *J. Geophys. Res.,* **118,** 2847-2864, 2013.