Final Technical Report

Analysis of Southern California Seismicity Using Improved Locations, Focal Mechanisms and Stress Drops

Award G13AP00041

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ABSTRACT

We are analyzing earthquakes recorded by seismic networks in southern California to build on our recent improvements in earthquake locations and source characterization. In particular we are examining seismicity clustering in space and time to evaluate the extent to which it can be explained as random triggering caused by previous earthquakes versus clustering reflective of some underlying physical process. Large earthquakes followed by thousands of aftershocks are an obvious example of earthquake triggering. Swarms of smaller earthquakes occurring without a clear initiating event are an example of clustering generally believed to be caused by physical changes, such as fluid migration. By using high-resolution catalogs of relocated earthquakes we can examine earthquake clustering at finer spatial scales than has previously been possible and better discriminate between these models. For example, we have identified differences in precursory seismicity that vary with event size, which cannot be explained by standard earthquake triggering models. We have also begun to quantify the relative numbers of foreshocks compared to aftershocks for small earthquakes in southern California, a key step in untangling the properties of the earthquake-to-earthquake triggering that causes aftershock sequences. We have also begun analyzing deformation anomalies observed by the laser strainmeters at Piñon Flat Observatory (PFO) to see if they might be correlated with changes in seismicity rate or explained by models of slow slip on the nearby San Jacinto Fault. In the long run, our results will provide basic knowledge about earthquake statistics that will increase the ability of seismologists to make realistic forecasts regarding strong motion probabilities in different locations, thus contributing to the goal of reducing losses from earthquakes in the United States.

Results

Seismicity patterns and triggering models

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). These two possibilities are illustrated in Figure 1. 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 have been building on these results to study 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.

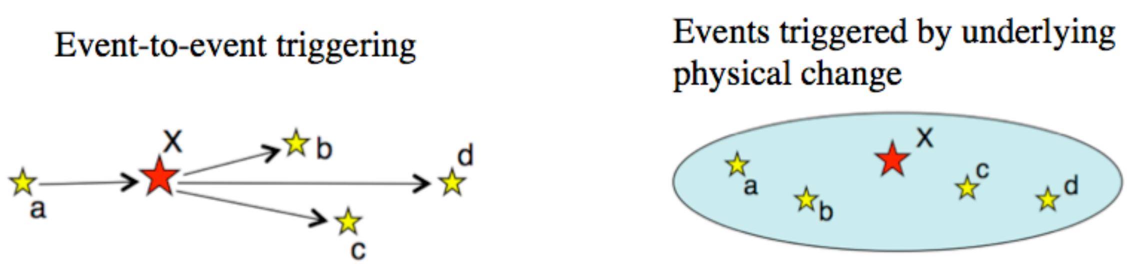

Figure 1. Two possible sources of clustering in short time intervals around target quakes. The target event X is selected to be larger than nearby events within a narrow time window. In the left mechanism, the target earthquake X triggers aftershocks b, c, and d. The target event itself may have been triggered by foreshock a. In the right mechanism, all the earthquakes are triggered by an external event, such as fluid migration or slow slip. From Shearer (2012b)

Our results so far are described in two recent JGR papers (Shearer 2012a,b), which compare observed event behavior in California with computer simulations of triggering. Some conclusions are: (1) Clustering is nearly time-symmetric for small magnitude events, (2) Triggering from *M* 2 to 4 earthquakes is only resolvable to distances of 1 to 3 km, (3) Foreshock-to-aftershock ratios for small earthquakes are too large to be explained entirely with ETAS-like triggering models, and (4) Much of small earthquake clustering is caused by underlying physical drivers, such as fluid flow or slow slip, as illustrated in Figure 1. 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.

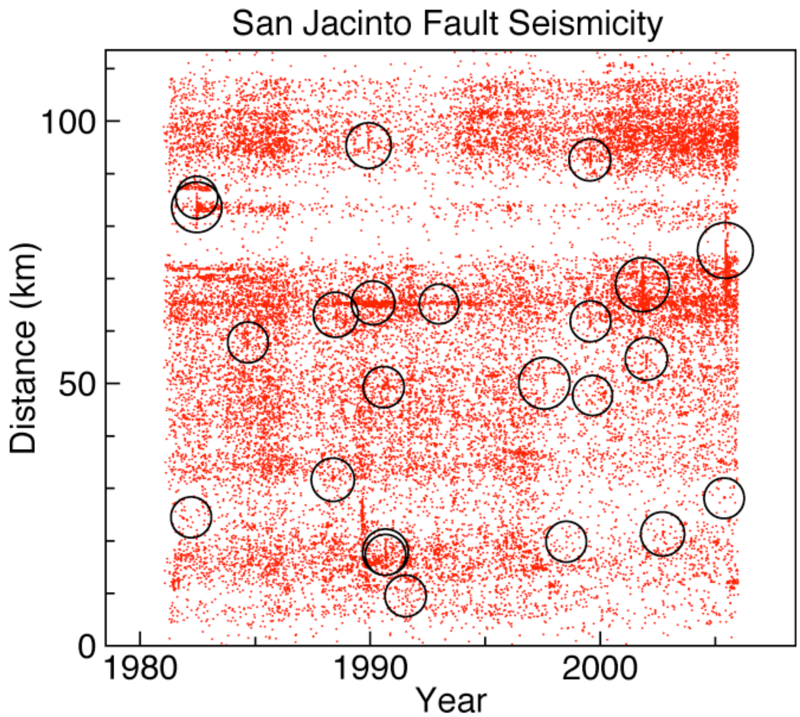

Figure 2. Seismicity along the San Jacinto fault versus time. Distance is from southeast to northwest. Earthquakes of *M* 4 and greater are shown as circles scaled by magnitude. Locations are from the LSH catalog (Lin et al., 2007).

However, swarms may simply be the obvious example of seismicity rate changes driven by physical changes in the crust. As an example, Figure 2 plots the time variations in seismicity along the San Jacinto fault in southern California. There are clearly temporal and spatial changes in the seismicity rate, most of which cannot be explained as mainshock/aftershock triggering because often the seismicity rate will increase in the absence of a large event. Of course, it is important to recognize that properties of seismic networks, including catalog completeness, can change with time, but the small-scale relative variations in seismicity rate seen in Figure 2 appear to be real. What causes these rate changes? Since it is unlikely that fluid flow would affect a very large region, the most likely candidate is stress changes caused by slow slip at depth. The most direct way to test this hypothesis would be to see if such slow slip events can be detected geodetically.

Swarms

An interesting aspect of the swarms is that their seismicity often migrates with time. We have been developing tools to quantify this spatial migration, specifically: (1) to test whether any apparent spatial migration is statistically significant or if it could represent random fluctuations in a spatially uniform distribution of events, and (2) to develop automatic fitting methods to estimate average migration direction and velocity. Our initial work (Chen and Shearer, 2011) focused on the Brawley Seismic Zone (BSZ) in the

Salton Trough, an area prone to energetic swarm sequences. This is a region of extensional as well as strike-slip faulting and has relatively high heat flow and attenuation (e.g., Hauksson and Shearer, 2006). Some of its swarms have been associated with slow-slip events (Lohman and McGuire, 2007). The southernmost section of the San Andreas Fault, thought to be overdue for a large earthquake, terminates in the Salton Trough, making the area of special concern to seismologists. The swarms typically last 1 to 20 days. They differ from mainshock/aftershock sequences in that the largest event typically does not occur near the beginning of the activity period. The most recent of these swarms, the 2009 Bombay Beach swarm, is near the southernmost tip of the San Andreas Fault. Our results generally show linear migration rates of 0.1 to 0.5 km/hour, but with some swarms near active geothermal areas having slower rates more consistent with a fluid diffusion process.

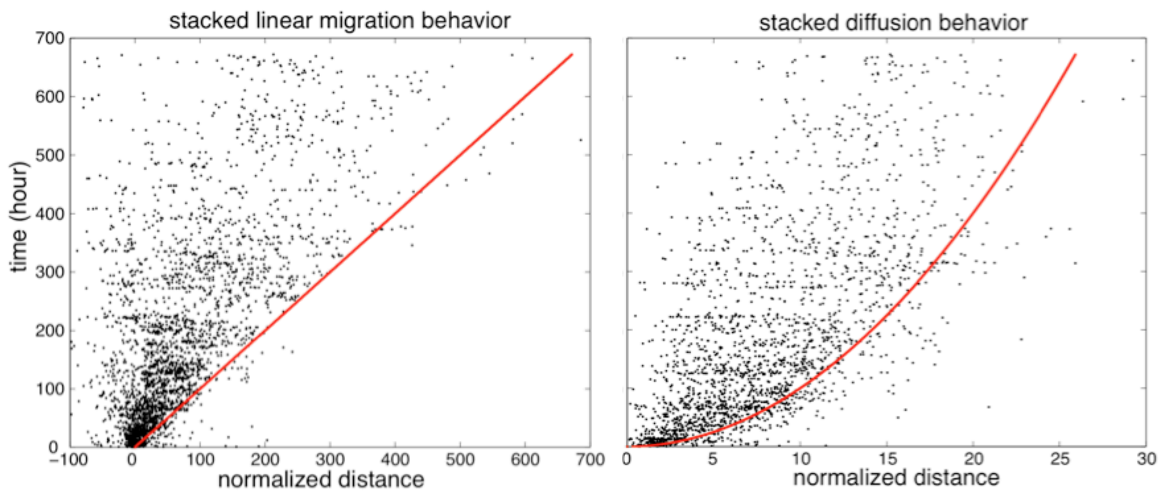

Figure 3. Swarm migration behavior. Event occurrence time versus normalized distance for two categories of southern California swarms: (left) 37 swarms best fit with a linear migration velocity, and (right) 17 swarms best fit with the diffusion equation (right). The red line is the predicted onset time. In the left plot, distance is scaled for each swarm so that the fitted velocity is one. In the right plot, the x-axis is scaled by the square root of 1/4p*D* where *D* is the diffusion coefficient. From Chen et al. (2011).

In collaboration with Rachel Abercrombie, we extended our analyses of swarm migration to all of southern California by examining the 71 bursts studied by Vidale and Shearer (2006). One characteristic of the migration is that once activity starts in a particular area, it can persist for some time, thus the onset times rather than the entire catalog show the clearest migration pattern. We have developed a simple empirical model for these properties, in which we assume the onset time for activity at a given point migrates at a constant velocity and direction, and that the resulting activity is a Poisson process in which the events occur at varying time delays after the assumed onset time. We find that some swarms are best fit with a linear migration velocity, others with the diffusion equation. These properties are shown in Figure 3, which plots time versus normalized distance for the two different categories of swarms. Our estimated fluid diffusion coefficients are similar to those found in previous studies by Hainzl (2004) and El Hariri et al. (2010).

Seismicity and Geodetic Transients

In some cases, swarms can be clearly linked to slow slip events, such as the 2005 swarm in the Salton Trough associated with aseismic slip recorded by InSar and GPS (Lohman and McGuire, 2007). However, most swarms are deeper than this example and slow-slip events below 5 to 10 km depth are difficult to detect with GPS. The laser strainmeters at Piñon Flat Observatory (PFO) have greater sensitivity to strain changes than GPS and, because they have operated for many years, they provide an interesting data set to search for correlations between seismicity and strain. Aseismic strain changes at PFO are observed to follow both large distant earthquakes and more moderate sized earthquakes closer to PFO. For example clear anomalies are seen following the El Mayor Cucupah M 7.2 earthquake in Baja, as well as $M \sim 5$ earthquakes near PFO in 2005 and 2013.

Not all the strain changes observed at PFO are fully understood, and many likely reflect local site effects. A number of strain anomalies can be correlated with large rainfall events. However, there are also at least ten examples where strain anomalies are associated with peaks in the local seismicity rate. Most of these occurred at the time of large distant or local $M > 3$ earthquakes. However, sometimes earthquakes of similar size occur without associated strain episodes. This suggests the anomalies are not due to a localized site effect in response to strong shaking, but are indicative of large-scale strain changes, perhaps caused by slow slip events at depth on the San Jacinto Fault (Duncan Agnew, personal communication, 2013). This idea is supported by the apparent correlation of strain changes with three different seismicity rate peaks in 2005, 2007 and 2009 that do not contain any $M > 3$ events. These seismicity rate increases occur within the region of ongoing seismicity on the San Jacinto Fault south of PFO and just north of the 2005 M 5.2 Anza earthquake.

These results are preliminary and more work is needed to resolve the exact timing of the strain changes compared to the seismic activity, the locations of the earthquakes involved, and to test whether there are models of deep slow slip on the San Jacinto Fault that might explain both the strain anomalies and the seismicity rate changes. This will be a focus of our research in the next year. It will be particularly important to examine cases where strain anomalies are not associated with seismicity changes and vice versa, before concluding that the apparent correlation of strain changes with small earthquake activity is real.

It should be noted that deep creep has been proposed to explain the high seismicity rate observed on the San Jacinto Fault (Wdowinski, 2009) and that high-frequency tremor, often associated with slow-slip events, was observed to be triggered near Anza by surface waves of the 2002 Denali earthquake (Gomberg et al., 2008). The tremor is difficult to locate precisely, but appears to be located within a compact source region on or near the San Jacinto Fault northwest of PFO (Wang et al., 2013).

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 earthquakesL observations from reservoir induced seismicity in Brazil, *Geophys. J. Int.*, **181**, 1566–1574, doi: 10.1111/j.1365-246X.2010.04554.x, 2010.

Gomberg, J., J. L. Rubinstein, Z. Peng, K. C. Creager, J. E. Vidale, and P. Bodin, Widespread triggering of nonvolcanic tremor in California, *Science,* **319**, 173, 2008.

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

Hauksson, E., and P. M. Shearer, Attenuation models (Qp and Qs) in three dimensions of the southern California crust: Inferred fluid saturation at seismogenic depths, *J. Geophys. Res.*, **111**, B05302, doi:10.1029/2005JB003947, 2006.

Helmstetter, A. and D. Sornette, Diffusion of epicenters of earthquake aftershocks, Omori's law, and generalized continuous-time random walk models, *Phys. Rev. E.*, **66**, 061104, 1–24, 2002.

Lohman, R. B., and J. J. McGuire, Earthquake swarms driven by aseismic creep in the Salton Trough, California, *J. Geophys. Res.*, **112**, 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.

Wang, T.-H., E. S. Cochran, D. Agnew, and D. D. Ogelsby, Infrequent triggering of tremor along the San Jacinto Fault near Anza, California, *Bull. Seismol. Soc. Am.*, **203**, 2482–2497, 2013.

Wdowinski, S., Deep creep as a cause of the excess seismicity along the San Jacinto Fault, *Nature Geoscience*, **2**, 882–885, doi: 10.1038/ngeo684, 2009.

Bibliography (Reports Published)

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., 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.

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.

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

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, 2012.

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, 2012.

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.

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.