Final Technical Report

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

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TECHNICAL ABSTRACT

We are analyzing earthquakes recorded by the Southern California Seismic Network (SCSN) to exploit recent dramatic improvements in earthquake locations, focal mechanisms and stress drop estimates to address a variety of issues related to seismic hazard. These include questions concerning:

- Are there aspects of the space/time clustering of seismicity that cannot be explained with ETAS-like triggering models? Can earthquake clustering caused by triggering be distinguished from clustering that may reflect underlying physical processes? Are swarms simply the most obvious examples of general seismicity rate changes caused by fluid migration or slow slip?

- Can high-resolution catalogs resolve aftershocks of small earthquakes and constrain the relative importance of static versus dynamic triggering (see, e.g., Felzer and Brodsky, 2006; Richards-Dinger et al., 2010)? Are aftershock sequences self-similar? For example, on average, do M 5 mainshocks generate the same number of M > 3 aftershocks as M 4 mainshocks generate M > 2 aftershocks? Is their distance decay the same?

- What seismicity migration rates are observed in swarms? Are these more compatible with a fluid diffusion or slow slip process? Is it possible to develop general quantitative measures of seismicity migration that can be applied to entire catalogs to identify migration episodes?

- What fraction of earthquakes in southern California have foreshocks? Are foreshock sequences consistent with triggering models or are they more similar to swarms? Is there anything distinctive about foreshocks compared to event groups that do not lead to larger earthquakes?

Anticipated results of this work include a more detailed understanding of earthquake source properties and seismicity patterns. This knowledge will contribute to quantitative assessments of earthquake potential and seismic hazard in southern California.

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NON-TECHNICAL 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. 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). 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), and details of the foreshock and aftershock behavior for small earthquakes (Shearer, 2012). We are 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 reflected underlying physical processes.

We have recently focused on the implications of self-similar earthquake triggering models for foreshock and aftershock magnitudes (Shearer, 2012). Bath's law (Bath, 1965), the observation that the largest aftershock is, on average, 1.2 magnitudes smaller than its mainshock, independent of mainshock size, suggests some degree of self-similarity in earthquake triggering. This behavior can largely be explained with triggering models in which the increased triggering caused by larger magnitude events is exactly compensated for by their decreased numbers, and these models can account for many features of real seismicity catalogs. A more general test of triggering self-similarity is to plot foreshock and aftershock rates as a function of magnitude m relative to the mainshock magnitude, m_{max}, of the largest event in the sequence. Both computer simulations and theory show that these dN/dm curves should be nearly coincident, regardless of mainshock magnitude. The aftershock dN/dm curves have the same Gutenberg-Richter b-value as the underlying distribution, but the foreshock dN/dm curves have the same b-value only for foreshock magnitudes less than about $m_{max} - 3$. For larger foreshock values, the dN/dm curve flattens and converges with the aftershock dN/dm curve at $m = m_{max}$. This effect can explain observations of anomalously low b-values in some foreshock sequences (e.g., Knopoff et al., 1982) and the decrease in apparent aftershock to foreshock ratios for small magnitude mainshocks. Observed apparent foreshock and aftershock dN/dm curves for events close in space and time to M 2.5 to 5.5 mainshocks in southern California appear roughly self-similar, but differ from triggering simulations is several key respects: (1) the aftershock b-values are significantly lower than that of the complete catalog, (2) the number of aftershocks is too large to be consistent with Bath's law, and (3) the foreshock-to-aftershock ratio is too large to be consistent with Bath's law. These observations indicate for southern California that triggering self-similarity is not obeyed for these small mainshocks or that the space/time

clustering is not primarily caused by earthquake-to-earthquake triggering. The fact that the *b*-value of southern California aftershocks appears to be significantly less than the *b*-value of the complete catalog calls into question some of the assumptions in triggering models, as well as current efforts for operational earthquake forecasting using ETAS models.

Our results so far also support the conclusion of Richards-Dinger et al. (2010) that Felzer and Brodsky (2006) overestimated the far-field triggering rate from small earthquakes by not taking into account the precursory event density immediately prior to their target events. Applying bootstrap resampling tests to the LSH catalog, we estimate that triggering is only resolvable to distances of about 3 km for M 2–4 mainshocks (see Figure 1), far less than the distances cited by Felzer and Brodsky.

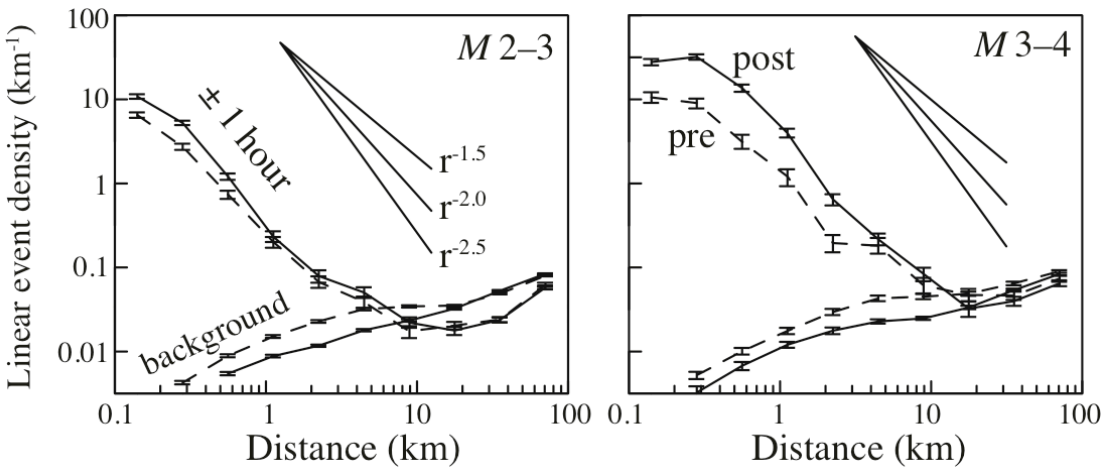

Figure 1. Linear event density versus distance for the windowed LSH catalog, comparing results for *M* 2–3 and *M* 3–4 target earthquakes. Average pre- and post-target densities are computed in ±1 hour windows from the target event times. For comparison, a "background" rate estimated for between 900 and 1000 days from the target events is also plotted. The pre-target densities are shown as dashed lines. One standard error bars are estimated from bootstrap resampling of the target events. Reference slopes of distance $r^{-1.5}$ to $r^{-2.5}$ are also plotted.

Swarms

An interesting aspect of 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. Major swarms since 1981 are plotted in Figure 2. 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.

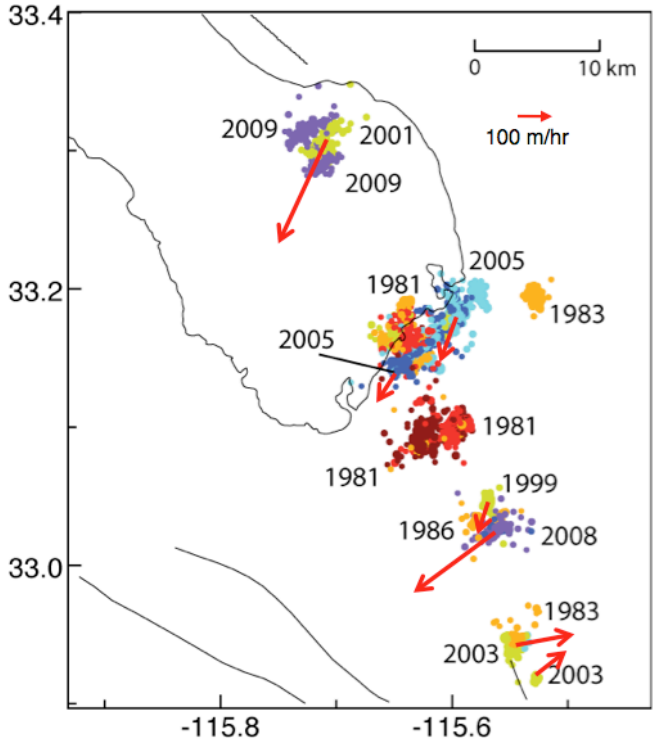

Figure 2. Major earthquake swarms in the Salton Trough since 1981. Examples of estimated seismicity migration vectors are plotted in red. These generally trend SW–NE at velocities of 0.1 to 0.5 km/hr. From Chen and Shearer (2011)

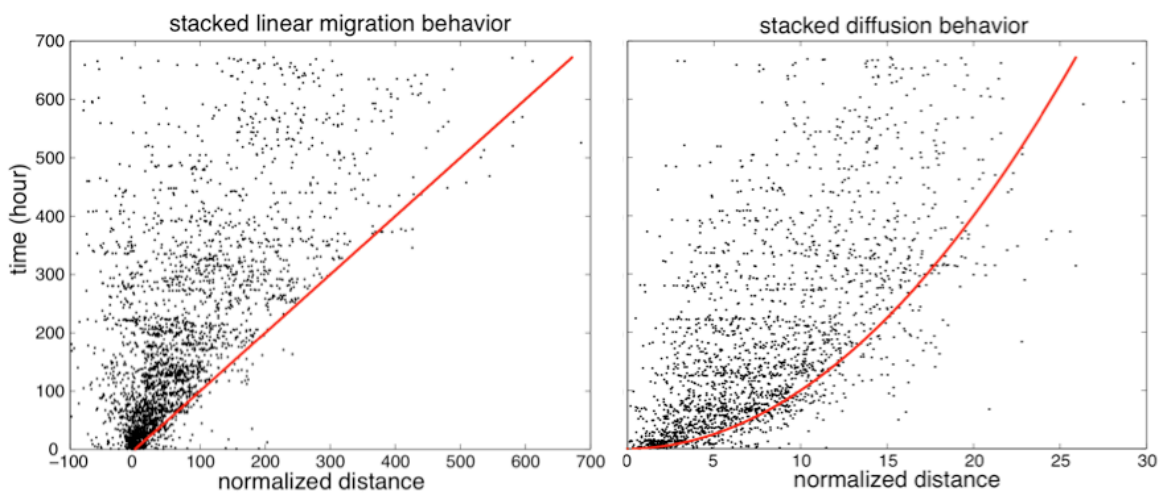

Figure 3. Swarm migration behavior. Event occurrence time versus normalized distance for two categories of southern California swarms: (left) 37 swarms best fit with a linear migration velocity, and (right) 17 swarms best fit with the diffusion equation (right). The red line is the predicted onset time. 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).

Foreshocks

Foreshocks are one of the few recognized precursors to earthquakes, but they do not precede every earthquake nor are foreshock sequences readily discernable as foreshocks until after the mainshock occurs. To put foreshock sequences into a more general context, we have begun a systematic study of seismicity "onsets" in California, that is when a sequence of seismicity starts in a localized region previously devoid of activity. Defining mainshocks as events of $M \geq 5$, these onsets may be divided into five general categories: (1) Mainshock/aftershock clusters that begin with their largest event, (2) Foreshock/mainshock/aftershock clusters in which a small number (typically one to three) of precursory events occur immediately prior to the mainshock, (3) Foreshock sequence/mainshock/aftershock clusters, in which an extended foreshock sequence occurs prior to the mainshock, (4) Swarms, in which seismicity initiates and continues without a clearly identifiable mainshock, and (5) Isolated small groups of events. Figure 4 plots the locations of these seismicity onsets.

Our results so far suggest that groups 3 and 4 are similar in properties until the time of the mainshock, i.e., extended foreshock sequences resemble swarms up to the point that a large earthquake occurs. These extended foreshock sequences, like swarms, are difficult to explain with standard triggering models (e.g., Helmstetter and Sornette, 2003; Felzer et al., 2004) in which there is no fundamental difference between foreshocks, mainshocks, and aftershocks. Rather they appear to reflect some underlying physical process, such as fluid diffusion or slow slip. This is supported by the fact that many foreshock sequences, such as those proceeding Landers and Hector Mine, exhibit spatial migration.

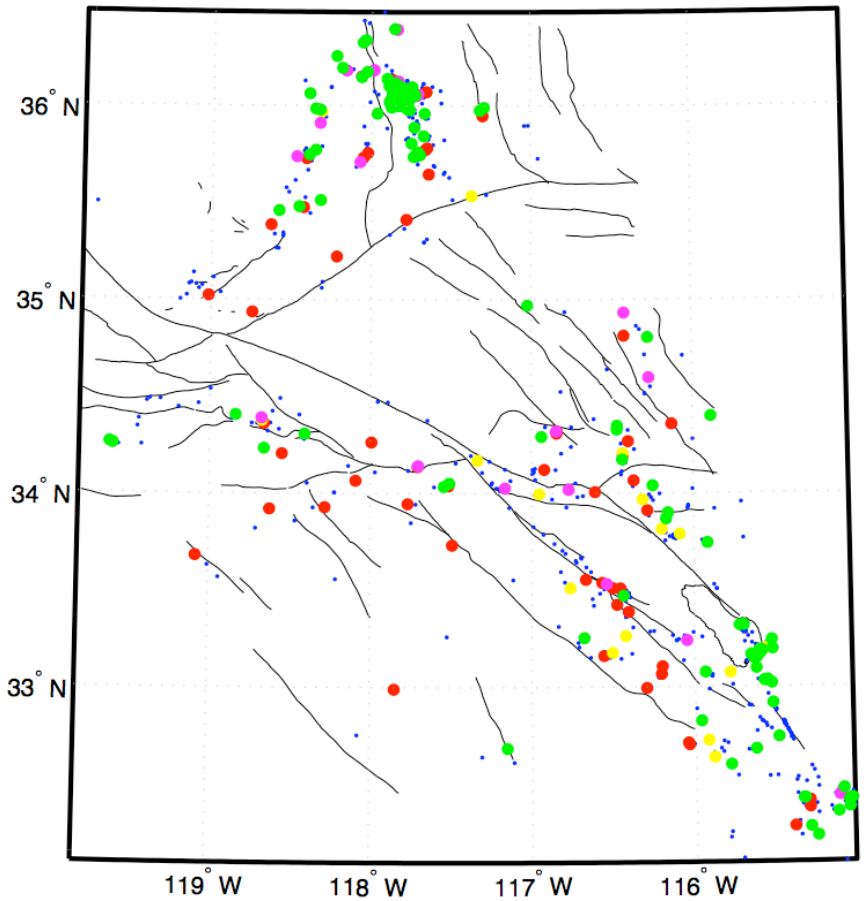

Figure 4. Seismicity onsets in southern California, showing: 58 mainshocks that begin with their largest event (red), 20 mainshocks with immediate foreshocks (yellow), 25 mainshocks with extended foreshock sequences (magenta), 111 swarms (green), and 530 isolated small groups of events (tiny blue dots).

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