Final Technical Report

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

Award G10AP00066

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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:

(1) How much of the space/time clustering of seismicity can be explained by ETAS-like triggering relationships? Can earthquake clustering caused by triggering be distinguished from clustering that may reflect underlying physical processes that affect seismicity rate?

(2) Given the recent controversy between the results of Felzer and Brodsky (2006), Gomberg and Felzer (2008), Richards-Dinger et al. (2010), and Stein (2011), is there a rigorous way to resolve the range dependence of aftershocks? What can we learn about aftershock triggering from this?

(3) Are there larger-scale analogs to the small (2-km radius) swarms studied by Vidale and Shearer (2006)? Can swarms be explained in the context of triggering models or do they require underlying physical driving mechanisms? Are there robust tests to systematically distinguish swarm-like earthquake clusters from those exhibiting primarily mainshock/aftershock behavior? How can seismicity migration behavior within swarms be quantified? Are there systematic variations in seismicity migration velocities in southern California? Are observed swarm and migration properties more consistent with fluid migration or slow slip events as a physical driving mechanism?

(4) What are the space-time details of small earthquake stress drops? What controls large-scale variations in stress drop across southern California? Do swarms and foreshock sequences have stress drops systematically different from other earthquakes? Can variations in earthquake stress drop be related to changes in the stress field caused by large ruptures? Are there any regions where time dependence in stress drops can be observed? Do these results tell us anything about triggering processes or the absolute level of shear stress in the crust?

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

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). As an example, Figure 1 plots the time variations in seismicity along the San Jacinto fault in southern California. There are clearly temporal and spatial changes in the apparent seismicity rate. Although some of these differences may reflect changes in the station distribution or network operations, many of the rate changes are robust with respect to reasonable variations in network properties and cannot be explained simply as mainshock/aftershock triggering because often the seismicity rate will increase in the absence of a large event.

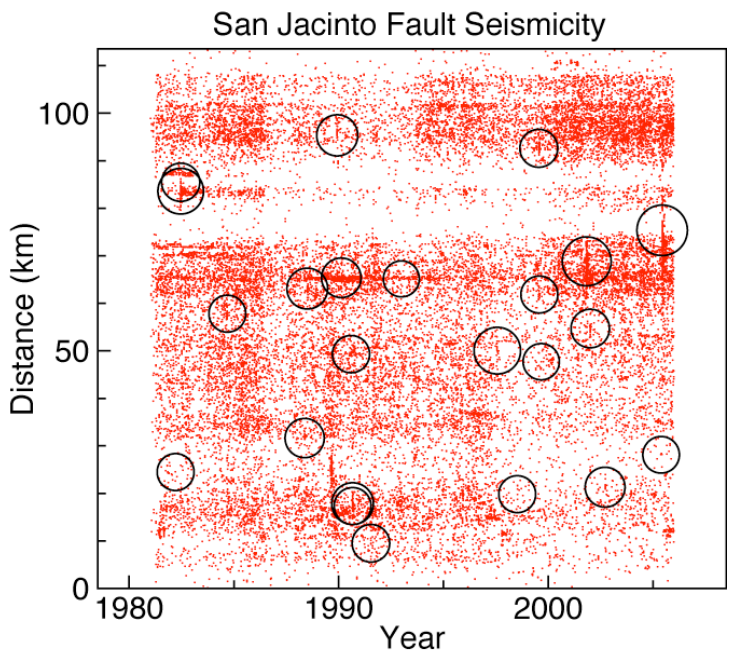

Figure 1. Seismicity along the San Jacinto fault versus time. Distance is from southeast to northwest. Earthquakes of M 4 and greater are shown as circles scaled by magnitude. Locations are from the LSH catalog.

One goal of our research is to analyze the space/time clustering of seismicity to identify consistencies or deviations from ETAS-like triggering models. Because these models are fundamentally statistical in nature, it is important to examine a large number of events in order to obtain reliable results. Our relocated southern California earthquake catalog (the LSH catalog of Lin et al., 2007) is ideal for these studies because its high resolution permits studying the triggering behavior of the numerous small earthquakes (i.e., $M \geq 2$) in the catalog.

Measuring triggering rates

Felzer and Brodsky (2006) demonstrated how the time/space behavior of earthquake clustering could be measured by looking at large numbers of small events. In this way, they were able to estimate aftershock triggering parameters even for earthquakes as small as M 2-3, which do not individually produce noticeable aftershock sequences. However, a shortcoming in their approach is that they did not examine the seismicity rates

immediately prior to each of their target earthquakes. Thus they did not explicitly account for the portion of their observed earthquake clustering that may not be caused by direct triggering from the target event, but instead reflects some other process.

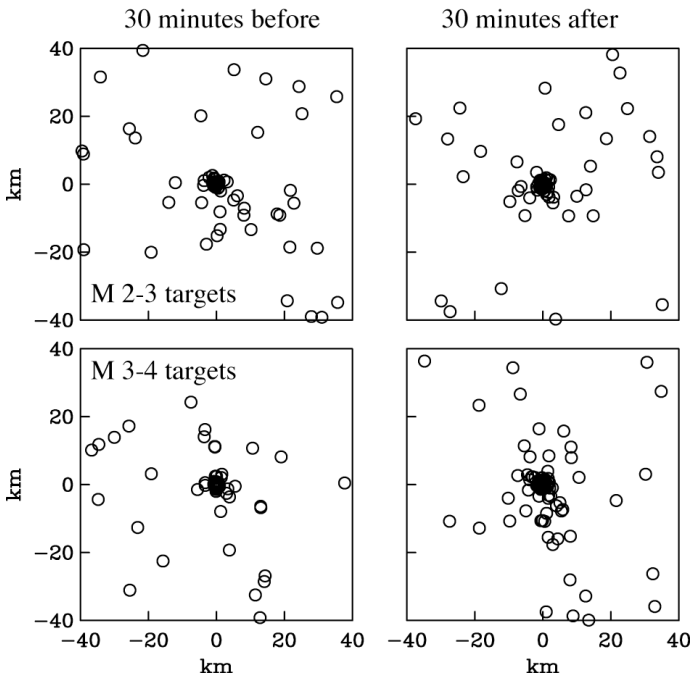

Figure 2. A comparison of events occurring within 30 minutes before and after M 2-3 and M 3-4 earthquakes in southern California. For M 2-3 target events, there were 322 "foreshocks" and 396 "aftershocks"; for M 3-4 target events, there were 243 "foreshocks" and 605 "aftershocks."

Using similar data selection criteria as Felzer and Brodsky on the LSH catalog, we obtained the results shown in Figure 2, which compares events occurring within 30 minutes *before* the target earthquakes to those occurring after the target earthquakes. The precursory seismicity also exhibits strong space-time clustering, which should be taken into account if valid estimates of triggering parameters are to be obtained. Indeed, for the M 2-3 target events, there were almost as many "foreshocks" in the 30 minutes prior to the target event times as there were aftershocks in the following 30 minutes. This foreshock abundance was also recently pointed out by Richards-Dinger et al. (2010). Of course some degree of foreshock activity is expected from the triggering models, and foreshock rates have been observed to obey an inverse Omori's law. Thus, these results are not necessarily inconsistent with a triggering model.

To test this possibility, we created a synthetic earthquake catalog based on an ETAS model with parameters set to match the Felzer and Brodsky (2006) observed decay in event rate with distance. These results are compared to observations for southern California in Figure 3. Note that the data pre- and post-target rates merge at about 3 km and that the difference between the pre- and post-seismicity rates is much greater for the synthetics than for the data. This suggests that some process other than earthquake-to-earthquake triggering is causing at least some of the observed space-time clustering of seismicity. It should be noted that simply increasing the aftershock productivity rate is likely to produce results that violate Bath's law—that on average the largest aftershock is 1.2 magnitude units smaller than the mainshock. In addition, high aftershock productivity rates can lead to physically unrealistic runaway explosions of seismicity.

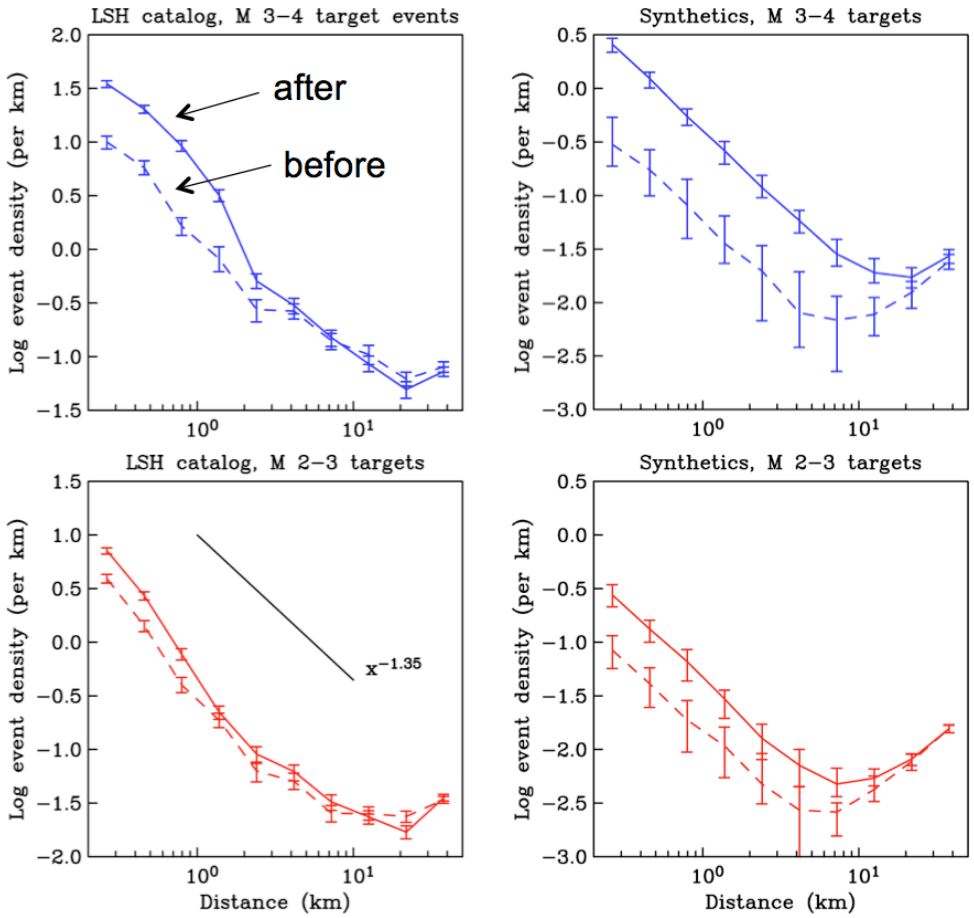

Figure 3. Event density as a function of distance in one-hour windows before and after M 3–4 target earthquakes (top) and M 2–3 target earthquakes (bottom), comparing the LSH catalog of southern California seismicity (left) with predictions of an ETAS-like triggering model (right). One-standard error bars are computed using a bootstrap resampling method.

It is important to explore the limitations of the current generation of ETAS-like models both to improve the models and to identify those seismicity features that most likely reflect physical changes in the crust, such as fluid migration or slow slip. Our research should produce more accurate estimates of triggering as a function of earthquake magnitude and distance, as well as quantifying the fraction of earthquakes that are "background" versus "triggered." Ultimately these results should lead to more reliable statistical approaches for evaluating earthquake probabilities.

Swarms

Seismic swarms are an example of clustered earthquakes that do not obey standard triggering models. The Brawley Seismic Zone (BSZ) in the Salton Trough is prone to energetic swarm sequences. Major swarms since 1981 are plotted in Figure 4. 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. Although these swarms occur in a region of generally low stress drops, it does not appear that the swarm events themselves have anomalously low stress drops compared to other earthquakes in the BSZ. However, 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.

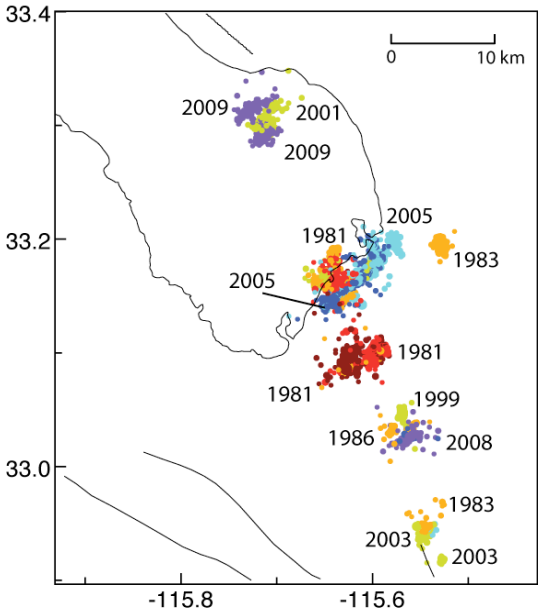

Figure 4. Major earthquake swarms in the Salton Trough since 1981.

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