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Analysis of Southern California Seismicity Using Improved Locations and Stress Drops

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Introduction

This SCEC funded research involves continued analysis of the vast waveform archives of the Southern California Seismic Network (SCSN/TriNet) in order to study earthquake source properties. Specifically, we have used recent dramatic improvements in earthquake locations, focal mechanisms and stress drop estimates to address a variety of issues:

• Does the space/time clustering of seismicity largely obey ETAS-like triggering relationships? Can swarms be explained in the context of triggering models or do they require underlying physical driving mechanisms? Are there larger-scale analogs to the small (2-km radius) swarms studied by Vidale and Shearer (2006)?

• Are the dynamic triggering results of Felzer and Brodsky (2006) robust across southern California or do they vary among different regions? Can earthquake clustering caused by triggering be distinguished from clustering that may reflect underlying physical processes that affect seismicity rate?

• Does precursory seismicity vary as a function of event size? That is, are there distinctive seismicity patterns prior to larger earthquakes (e.g., Mogi doughnuts, quiescence, accelerated moment release, growing spatial correlation length) or are event size distributions entirely explained with the Gutenberg-Richter magnitude frequency relation, as many triggering models predict?

• 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.

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). 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 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 1 appear to be real.
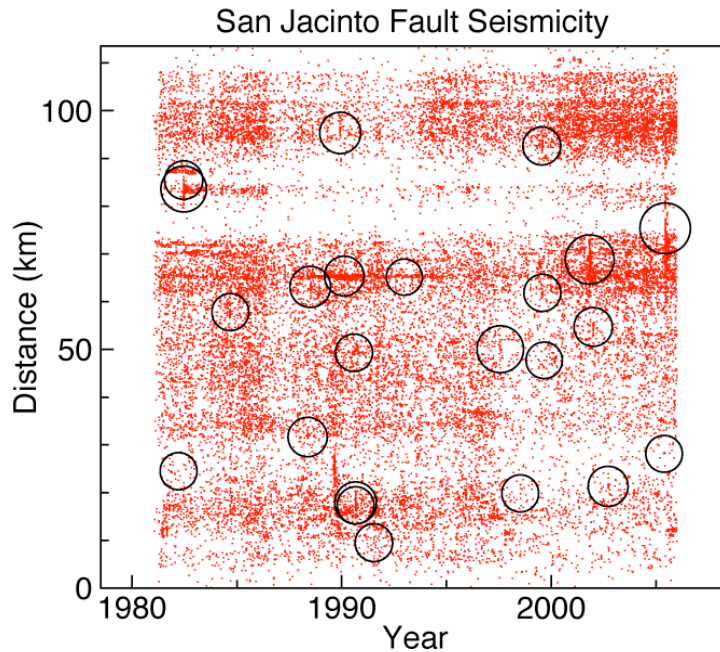

Figure 1. Seismicity along the San Jacinto fault versus time. Distance is from southeast to northwest. Earthquakes of M 4 and greater are shown as circles scaled by magnitude. Locations are from the LSH catalog.

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 foreshock and aftershock sequences (e.g., Ogata, 1999; Helmstetter and Sornette, 2002). In many of these models (Helmstetter and Sornette, 2003; Felzer at al., 2004), prior seismicity increases the probability of a future earthquake in the same region but does not change the size distribution of the triggered events, which is governed by the Gutenberg-Richter magnitude-frequency relation, a power law that produces many more small earthquakes than large earthquakes. These models therefore predict no difference in the average rate or spatial distribution of seismicity prior to any individual earthquakes of any size. However, we recently showed (Shearer and Lin, 2009) that such differences are observed in a high-resolution catalog of southern California earthquakes. In particular, we identified regions of enhanced activity in a 1-day period preceding larger earthquakes at distances comparable to their predicted source radii. The difference in precursory behavior between large and small earthquakes is subtle but statistically significant when averaged over many earthquakes, and it has similarities to the ''Mogi doughnut'' seismicity pattern observed to occur prior to some M 6 and larger earthquakes. These results indicate that many standard earthquake triggering models do not account for all of the processes involved in earthquake occurrence.

Resolving between these competing models is important because of implications regarding the predictability of earthquakes. If observations show that average precursory seismicity is identical between large and small events, then larger earthquakes likely represent the essentially random occurrence of rare events in a power law distribution of event sizes (perhaps representing a runaway cascade of rupture initiated by a smaller earthquake) and will be very difficult to predict. Our results are encouraging because they suggest that there are at least some physical differences in the state existing before larger earthquakes compared to smaller earthquakes. 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 reflect underlying physical processes.

Testing these ideas for large earthquakes is challenging because of the limited number of these earthquakes in the available catalogs. However, recent advances in the location accuracy of small earthquakes make it possible to study triggering statistics on smaller and more numerous events. For example, Felzer and Brodsky (2006) used our SHLK catalog to examine the aftershock properties of small earthquakes. However, their analysis was limited because they assumed that all the temporal clustering they observed was caused by earthquake-to-earthquake triggering, that is, they did not fully consider the possibility that some of the clustering was caused by other processes. This is illustrated in Figure 2, which plots the seismicity within 30-minute windows both before and after M 2–3 mainshocks in the LSH catalog of Lin et al. (2007). Felzer and Brodsky considered only the post-target event clustering, but the precursory event density is almost as large. Indeed, for target events of this size, the temporal clustering is nearly time symmetric. By not taking into account the precursory event density immediately before the target events, Felzer and Brodsky overestimated the triggering rate. 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, far less than the distances cited by Felzer and Brodsky.
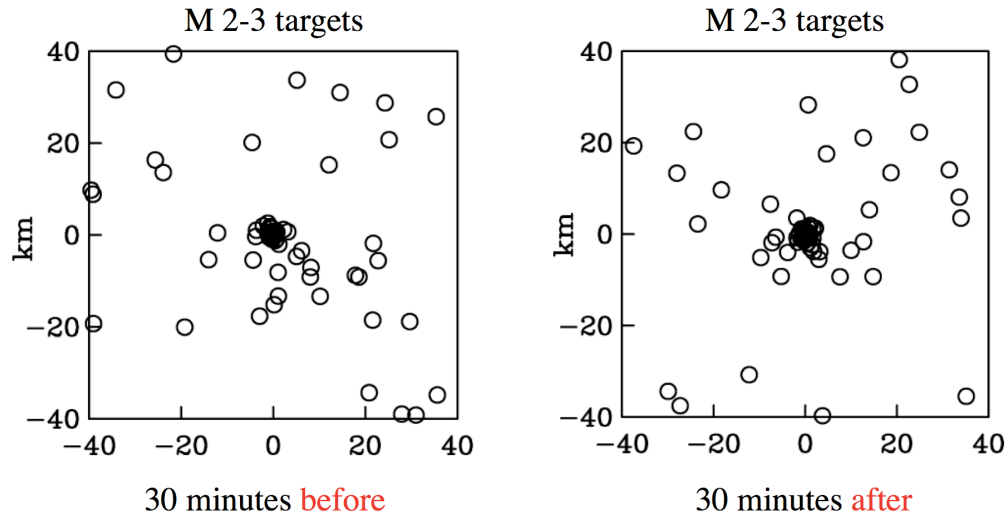

Figure 2. Seismicity in 30 minute windows before and after M 2-3 target earthquakes in the LSH catalog. There are 322 "foreshocks" and 396 "aftershocks." Following Felzer and Brodsky (2006), target events are selected only if there is no larger magnitude event within 3 days before or 0.5 days following the target event, thus all events plotted are smaller than the target events.

Of course some degree of foreshock activity is expected in ETAS-like models, but the amount that we observe is greater than that expected for reasonable triggering rates (i.e., which generate aftershock sequences consistent with Bath's law—that on average the largest aftershock is 1.2 magnitude units smaller than the mainshock). This is illustrated in Fig. 3, which compares our observations for the LSH catalog with those predicted by an ETAS model (the AftSimulator.m code of Karen Felzer, personal communication, 2008, with parameters set to values roughly compatible with Bath's law and the observed distance dependence of aftershocks in southern California). Note that the data pre and post 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.

We are building on these results by systematically examining the space/time clustering and magnitude distributions in our relocated catalogs and comparing these results with those predicted by ETAS-like triggering models. Important issues include: (1) Is the triggering process self-

similar as Bath's law suggests? That is, do earthquakes of varying magnitude M always trigger the same average number of aftershocks with magnitudes larger than M – dM, where dM is some fixed magnitude interval. (2) Is the spatial clustering of first-generation aftershocks statistically independent from the temporal clustering? Alternatively, does the distance dependence of aftershock probabilities change with time? (3) What can explain the time-symmetric clustering behavior observed for small earthquakes in southern California?

We believe 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. In addition, our results on spatial and temporal clustering will apply to some of the goals of the SCEC Working Group on California Earthquake Probabilities (WGCEP).
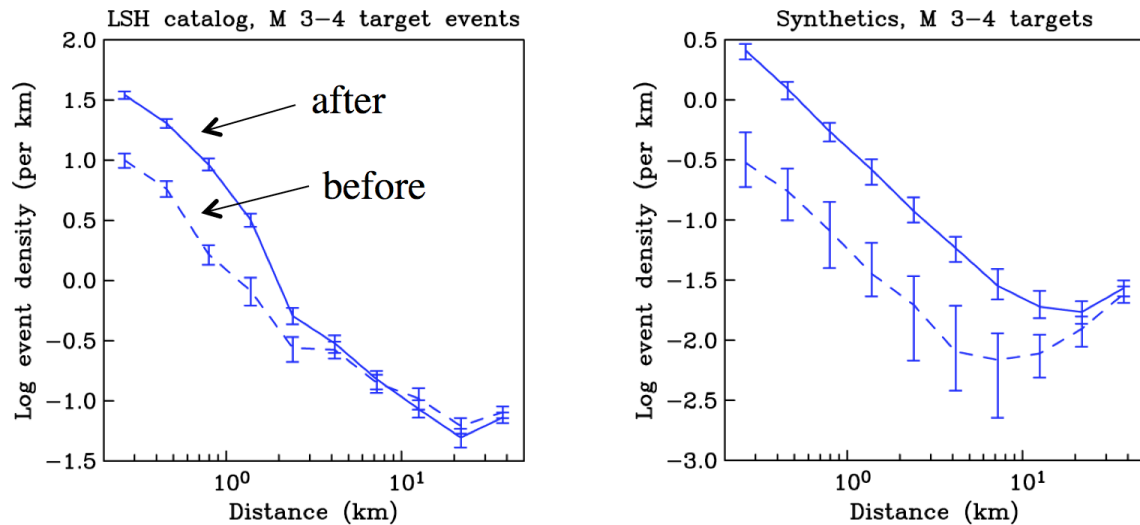
Figure 3. Event density as a function of distance in one-hour windows before and after M 3–4 target earthquakes, comparing the LSH catalog of southern California seismicity (left) with predictions of an ETAS-like triggering model (right). One-standard error bars are computed using a bootstrap resampling method.

Earthquake stress drops

We have estimated Brune-type stress drops for over 65,000 southern California earthquakes between 1989 and 2001, computed from *P*-wave spectra using a stacking method that separates source, receiver and propagation path terms (Shearer et al., 2006). A puzzling aspect of these results is that there is no obvious relationship between the stress drops and the location of faults and tectonic features. We do not yet understand what may be controlling the large observed variations in average stress drop and this will be a focus of our future work. Preliminary analyses do not show a significant correlation between stress drop and focal mechanism type. The stress drop patterns in some regions appear to correlate to changes in seismic b-value, which has been proposed to be a proxy for fault stress levels (e.g., Wiemer and Wyss, 1997), but in other areas there is no correlation or an anti-correlation. Aftershocks of the 1992 Landers earthquake exhibit significant along-strike variations in frequency content and inferred stress drop. These are among the best-resolved features in our analysis and indicate rapid spatial variations in earthquake source properties. Comparisons to slip models for the Landers mainshock suggest that there may be some correlations between slip and aftershock stress drop, but these correlations are highly dependent upon which of the many published slip models is considered.

Our 2006 study showed that average stress drops in the Salton Trough are anomalously low. This region is of particular interest because of its frequent swarm activity and the occurrence of slow slip events (Lohman and McGuire, 2007). Graduate student Xiaowei Chen has begun examining stress drops in this region, using an expanded data set of events between 1981 and 2008. Her preliminary results confirm that the average stress drop of the Salton Sea events is about 0.5 MPa, substantially below the southern California average of 1.8 MPa. Some individual events have estimated stress drops as low as 0.01 MPa. We are continuing this work to see if spatial and/or temporal variations in stress drop can be observed. In particular we are examining the relationship, if any, between our observed Brune-type stress drops and swarm activity and slow slip events. In addition, we are building on our recent results suggesting that anomalously low Vp/Vs ratios characterize the source regions of similar event clusters in southern California (Lin and Shearer, 2009) to see if there is any relationship between earthquake stress drops and in situ Vp/Vs. Our results are likely to provide further insight into the physical driving mechanisms for earthquake activity in this region.

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