Final Technical Report

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

Award G09AP00052

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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) 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?

(2) 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?

(3) 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?

(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. 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

Seismologists have long studied the seismicity preceding big earthquakes to see if any distinctive precursory patterns could be identified. In some cases, a period of low earthquake activity or quiescence is observed for years in the vicinity of the eventual rupture zone of large earthquakes, surrounded by a region of continuing or increasing activity (e.g., Kanamori, 1981). This seismicity pattern has been given the name Mogi doughnut (Mogi, 1969), with the doughnut hole representing the low seismicity rate around the impending hypocenter. However, analyses of large earthquake catalogs to evaluate the reliability of quiescence in predicting earthquakes have yielded mixed results (Habermann, 1988; Reasenberg and Matthews, 1998). At shorter time scales of days to hours, some earthquakes are preceded by foreshock sequences near their hypocenters (e.g., Dodge et al., 1996), but no distinctive properties in these sequences have yet been identified that would distinguish them from the many observations of earthquake clusters that do not lead to large earthquakes.

Recently, 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 predict no difference in the average seismicity prior to earthquakes of any specified size. There are many more M 4 earthquakes than M 7 earthquakes, but there should be no resolvable differences in the average rate or spatial distribution of seismicity prior to any individual earthquakes of any size. This model therefore contradicts the hypothesis that Mogi doughnuts and quiescence are distinctive precursory phenomena for large earthquakes.

Resolving between these competing models is important because it touches on questions regarding the predictability of earthquakes. If Mogi doughnuts and/or quiescence can be reliably established, this would imply at least some physical differences in crustal properties prior to large earthquakes. However, 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. Testing these models 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 suggest that it may be possible to search for Mogi-like behavior on smaller and more numerous events, thus obtaining more reliable statistics regarding possible precursory behavior. Using our relocated version of the southern California catalog, we have documented regions of enhanced activity in 1-day periods preceding moderate sized earthquakes (M 2 to 5) at distances comparable to their predicted source radii.

We analyze precursory seismicity in southern California using the LSH catalog (Lin et al., 2007), which provides relative location accuracy of 100 m or less among nearby events. This catalog spans 1981 to 2005 and includes 433,166 events over a magnitude range from less than 1 to over 7. To obtain a relatively complete and uniform dataset, we window the catalog to include only events of M ≥ 1.5 that are located inside the network and identified as local earthquakes by the network operators (i.e., excluding quarry blasts), reducing the catalog to 173,058 events.

We sum and average seismic activity prior to target events in three bins at unit magnitude intervals between M 2 and 5. Because catalog completeness often suffers following major earthquakes owing to the high seismicity rate, target events are excluded in 1 to 3 month periods following M ≥ 6 earthquakes in both catalogs (1 month for 1987 Elmore Ranch/Superstition Hills and 1992 Joshua Tree, 2 months for 1994 Northridge, 3 months for 1992 Landers and 1999 Hector Mine). To avoid immediate aftershocks of moderate sized earthquakes, target events are also removed if they follow an event of M ≥ 4 within 3 days and 150 km. Our intention is not to remove all aftershocks or to "decluster" the data, but simply to exclude time periods when it is likely that events are less completely cataloged. For the LSH catalog, this results in 35,560 M 2–3 target events, 2085 M 3–4 events, and 162 M 4–5 events. We do not analyze M ≥ 5 earthquakes because there are too few to provide reliable statistics on their precursory seismicity.

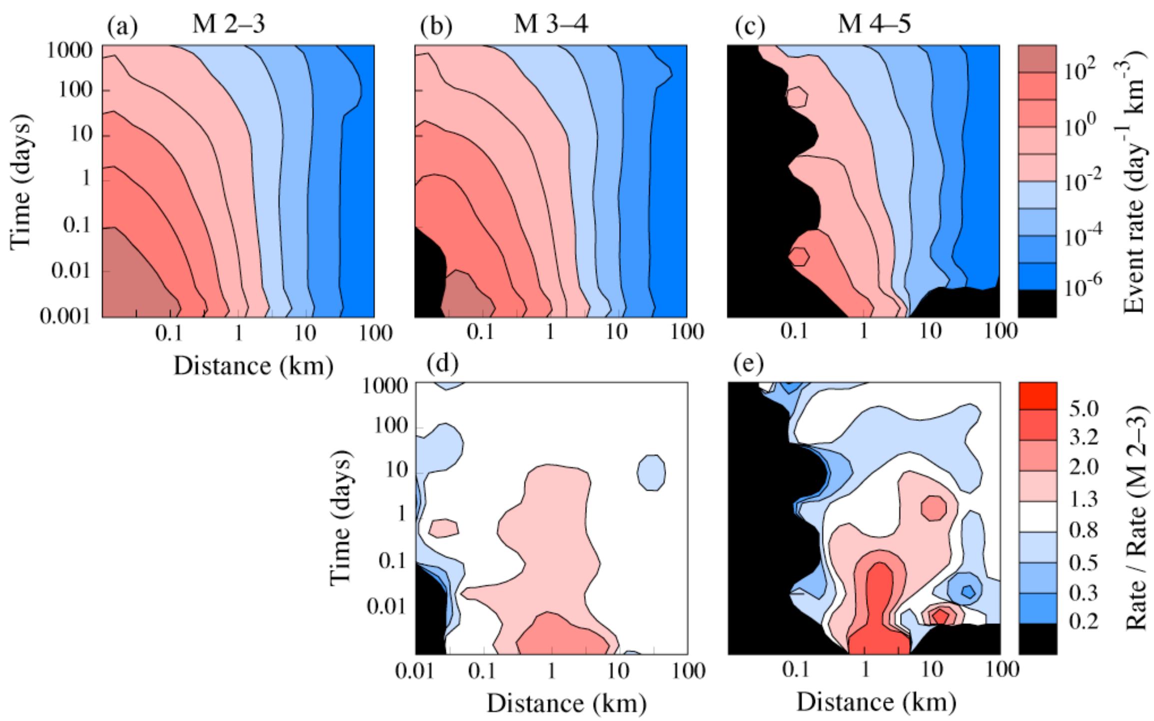

Figure 1. Space/time behavior of precursory seismicity in southern California. The top panels show the average event density prior to target events of (a) M 2–3, (b) M 3–4, and (c) M 4–5, at times from 0.001 day (86 s) to 1000 days prior to the target events at distances from 10 m to 100 km. Contours are uniform in log event density (per day per cubic km). The bottom rows show the difference in precursory seismicity rate for the (d) M 3–4 and (e) M 4–5 target event bins compared to the M 2–3 bin.

Earthquakes prior to the target events are summed in 100 space-time bins, evenly spaced in 10 log distance bins between 0.01 and 100 km and in 10 log time bins from 0.001 to 1000 days. Figure 1a contours the resulting estimates of average precursory event density as a function of time before and distance from the target events in the LSH catalog. The results for the M 2–3 target events are smoothest because of the much larger number of events. The event density is greatest at small times and distances, reflecting the strong space-time clustering of the seismicity.

At short times, the evenly spaced contours in log event density indicate a power-law distribution, which has been previously observed in many earthquake catalogs and often is related to a fractal dimension for the seismicity. However, Figure 1a makes clear that seismicity is clustered in time as well as space and that computed fractal dimensions will vary depending upon the time interval that is considered, as previously noted by Kagan (2007). Part of our proposed new research will be to compare plots of this type showing average seismicity rates before and after the target events in order to address the question of how much the space-time clustering of seismicity is caused by earthquake-to-earthquake triggering, as opposed to an underlying physical process. However, our initial work focused on possible differences in precursory activity among earthquakes of difference sizes, which can be considered independently of the process causing the clustering.

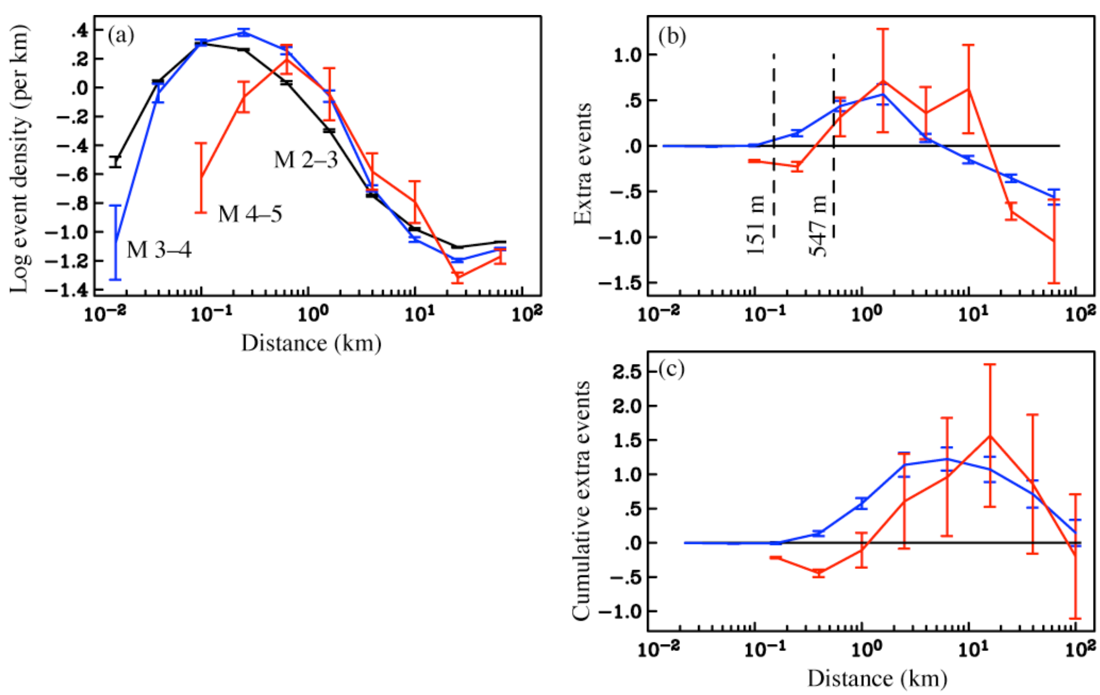

Figure 2. Average seismicity during the day prior to earthquakes of different sizes, plotted versus distance. Results for target events of M 2–3, 3–4 and 4–5 are shown as black, blue and red, respectively, with one-standard error bars. (a) Linear event density, (b) extra events in each distance bin compared to the M 2–3 results, (c) distance-integrated extra events, i.e., the number of extra events within each distance limit.

Average precursory event densities for the M 3–4 and M 4–5 bins (Figs. 1b and 1c) are grossly similar to the M 2–3 bin but are more irregular and less complete owing to the smaller number of target events available for averaging. Figure 1d and 1e show the difference in precursory seismicity rates for the larger magnitude bins compared to the M 2–3 bin. These results exhibit considerable variation but the clearest anomaly is a 30% to 100% increase in the precursory seismicity rate for the larger events (compared to the M 2–3 events) at distances between 0.3 and 5 km from their eventual hypocenters. The seismicity increase is most pronounced in the 1-day period preceding the earthquakes. To see this anomaly more clearly, Figure 2 plots results for this 1-day period for (a) linear event density (events per day per km from source, rather than normalized by volume as in Fig. 1), (b) the increase or decrease in the average number of precursory events for larger magnitude earthquakes compared to the M 2–3 events, and (c) the cumulative number of extra or missing events (i.e., integrating (b) over distance). A bootstrap resampling approach is used to estimate standard error bars. A statistically significant increase in seismicity rate for the larger earthquakes is apparent between about 0.2 and 5 km.

The seismicity increase is more pronounced and peaks at a larger distance for the M 4–5 earthquakes than the M 3–4 earthquakes. There is also a deficit of precursory events for the largest target earthquakes at short distances, which is most apparent for the M 4–5 results at distances less than 300 m. No results are shown for M 4–5 precursory event densities at distances less than 100 m only because there were no events to count. The increase in precursory seismicity occurs at distances that roughly correspond to the expected source radius of the target earthquakes, which is 151 m for Mw 3 earthquakes and 547 m for Mw 4 earthquakes, assuming a circular crack model and a 2 MPa stress drop (the median stress drop observed by Shearer et al. (2006) for small earthquakes in southern California).

Because the reliability of our results depend upon the accuracy of the underlying earthquake catalog and the validity of our processing steps, we have performed a number of tests to show that our results are robust (Shearer and Lin, 2009). It should be emphasized that these magnitude-dependent differences in the precursory behavior of California earthquakes are apparent only after averaging over hundreds to thousands of earthquakes. The average increase in the number of precursory events for M 4–5 quakes compared to M 2–3 quakes is less than one. Thus, these results are not useful for devising prediction schemes for individual M 4 earthquakes. Rather, their importance is that they imply a failure of the hypothesis of many earthquake triggering models that large earthquakes have average precursory seismicity identical to small earthquakes. The fact that the distance to the region of enhanced seismicity seems to roughly scale with the radii of the ensuing earthquake supports the idea that stress release may concentrate at the edges of the eventual rupture zone. But these effects are subtle and occur clearly only within a ~1 day interval before the target earthquakes. It is possible that larger and longer-lasting precursory differences also exist for bigger earthquakes (i.e., M > 5), but there are too few of these earthquakes in the LSH catalog to yield statistically reliable results.

There have been many efforts to identify precursory patterns in seismicity, both in real and simulated earthquake catalogs. In addition to the Mogi doughnut hypothesis, other ideas have included accelerated moment release (e.g., Jaume and Sykes, 1999; Bowman et al., 1998; Mignan et al., 2006) and growing correlation lengths (e.g., Zoller et al., 2001). However, the validity of these possible precursors is often in question because of limited numbers of events and the possibility that data windowing methods may be biasing the results (e.g., Hardebeck et al., 2008). An advantage of examining smaller earthquakes is that more reliable statistics can be obtained.

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Non-technical Summary

We have identified differences in precursory seismicity in southern California that vary with event size. In particular, we have learned that earthquake activity is enhanced in a one-day period prior to magnitude 3 to 5 earthquakes at a distance of about 1 km, compared to the activity seen prior to smaller earthquakes. This behavior is not predicted by standard earthquake triggering models and suggests physical differences in crustal properties that are related to the size of fault breaks. These results have implications for seismic hazard assessments.

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