Final Technical Report

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

Award G14AP00070

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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. 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), 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.

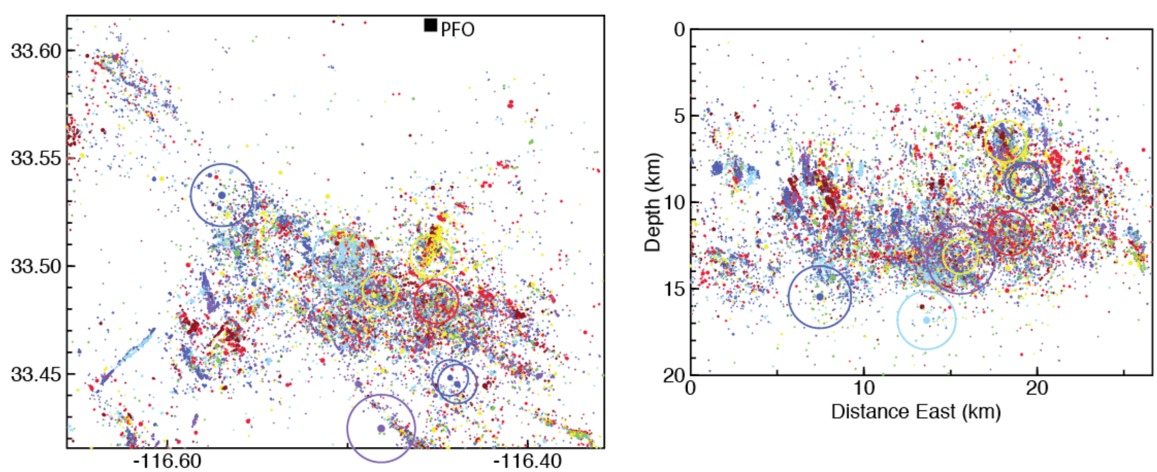

Figure 1. Seismicity on a portion of the San Jacinto fault, colored by year of occurrence (brown: 1980–1984, red: 1985–1989, yellow: 1990–1994, green: 1995–1999, cyan: 2000–2004; blue: 2005–2009, purple: 2010–2013. Earthquakes of M 4 and greater are shown as circles, with size proportional to magnitude. Locations are from the HYS catalog (Hauksson et al., 2012).

Our results so far (Shearer 2012a,b) suggest that most of the small earthquake clustering seen in southern California is caused by underlying physical drivers, such as fluid flow or slow slip. 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. We find that some swarms are best fit with a linear migration velocity, others with the diffusion equation (Chen and Shearer, 2011; Chen et al., 2012). Our estimated fluid diffusion coefficients are similar to those found in previous studies by Hainzl (2004) and El Hariri et al. (2010). However, swarms are likely simply the most obvious example of seismicity rate changes driven by physical changes in the crust. As an example, Figure 1 plots seismicity along a portion of the San Jacinto fault in southern California, colored by year of occurrence. The seismicity is non-stationary and exhibits complex evolution. There are obvious swarms at small scales, but there are also larger scale (> 5 km) changes in seismicity rate. Most of the temporal changes cannot be explained as mainshock/aftershock triggering because often the seismicity rate will change 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 local relative variations in seismicity rate seen in Figure 1 appear to be real. What causes these rate changes? Since it is unlikely that fluid flow would affect more than a very localized 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.

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. There are some additional strain anomalies that appear to be associated with local $M > 3$ earthquakes. However, sometimes earthquakes of similar size occur without associated strain episodes, and some apparent strain anomalies occur in the absence of significant earthquakes. 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, 2014). We are currently working with the PFO strain meter group to classify the observed strain episodes by their relative behavior on the different strain meter components, as well as nearby borehole strain meters, and distinguish deep geophysical signals from local effects, such as rainfall or rapid atmospheric pressure changes. We are also testing whether there are models of deep slow slip on the San Jacinto or nearby faults that might plausible explain the strain anomalies and whether there are any localized seismicity rate changes that might support these models.

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).

Swarm detection and characterization

Vidale and Shearer (2006) identified 57 swarms in southern California by applying a simple search criteria that required 40 or more earthquakes within a 2-km radius volume and a 4-week interval, and then removing obvious aftershock sequences. However, this approach neglects swarms that don't meet these specific requirements or that have smaller numbers of events. A more general approach to identifying earthquake clustering was recently proposed by Zaliapin and Ben-Zion (2013a, b) who used a nearest-neighbor approach to separate random background events from event groups clustered in time and space. A variation on this method was used by Reverso et al. (2015) to find six swarms in Aleutian seismicity.

We have begun implementing our own version of a nearest-neighbor algorithm to detect swarms and other seismicity clusters. We define the time-space separation between two events as:

$$h = dt\ dr^d$$

where dt is the time separation, dr is the distance separation, and d is related to the fractal dimension. We experimented with different values of d in applying our method and found that the results did not change very much. Thus we use $d = 1.6$, the value preferred by Zaliapin and Ben-Zion. Note that we do not include magnitude in this equation because we are interested in all groups of nearby events, not just aftershock sequences or other examples of clusters due to earthquake-to-earthquake triggering.

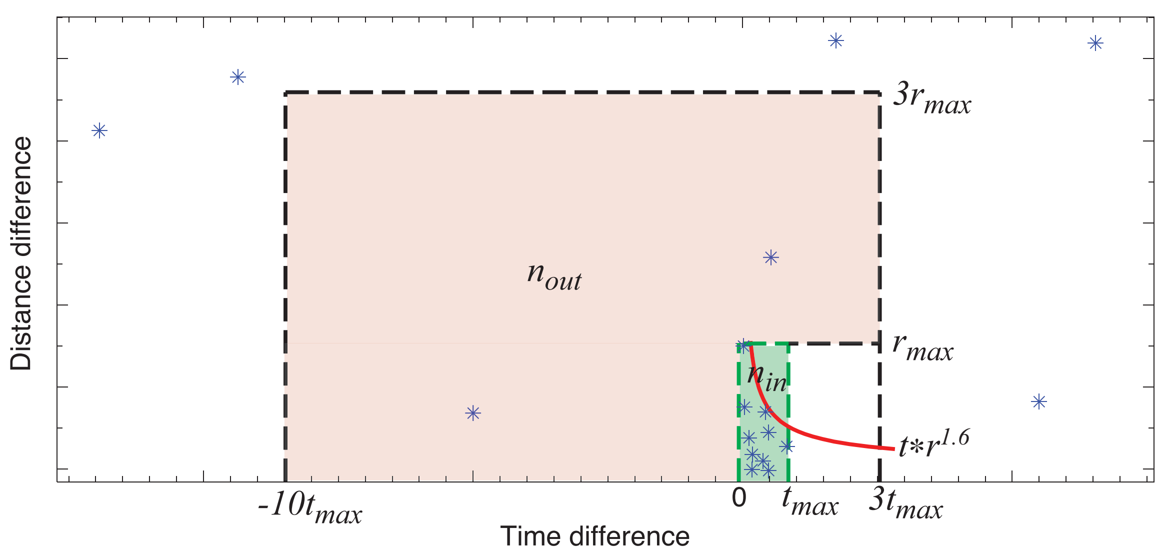

Figure 2. A cartoon illustrating a swarm detection method based on a time-space nearest-neighbor approach. The number of events, n_{in}, within r_{max} km and t_{max} days from a target event is compared to the number of events, n_{out}, in a larger window proceeding and surrounding the region of the cluster. See text for more details.

Our algorithm works as follows: (1) for each target event in the catalog, find the n "closest" events (i.e., with the smallest values of h); (2) set r_{max} as the distance to the furthest of these events (if r_{max} < 1 km, set r_{max} to 1 km); (3) set t_{max} to the maximum time from the target (i.e., last event time minus target event time); (4) set n_{in} to the number of events in a sphere of radius r_{max} occurring within t_{max}; (5) set n_{out} to the number of events in a sphere of radius $3r_{max}$ occurring within $10t_{max}$ before the target event, as well as events at radii between r_{max} and $3r_{max}$ occurring up to $3t_{max}$ after the target event (see Figure 2); (6) define $Q = n_{in} / (n_{out} + 1)$, a parameter that has larger values for clusters that are spatially and temporally isolated from other seismicity; (7) for each target event, search over n values from 5 to 200, and find the largest value of Q; (8) remove target events that are included within other event clusters with larger Q values; (9) flag and examine clusters with values above a threshold Q value.

Figure 2 illustrates how the method works, for an example in which set $n_{in} = 10$, $n_{out} = 2$, and $Q = 3.3$. We have found that this approach is quite effective in identifying obvious seismicity clusters and have written a graphical user interface (GUI) that plots a figure similar to Figure 2, as well as a magnitude versus time plot, and allows the user to flag whether the clusters appear to be aftershock sequences or swarms. Figure 3 shows the locations of 89 identified swarms on the San Jacinto Fault between 1981 and 2014. For comparison, Vidale and Shearer (2006) identified only 11 swarms in the same region.

The distribution of swarms is clearly non-random along the fault, with proportionally more swarms at its northern and southern ends. The temporal distribution of swarms also appears non-random, as illustrated in Figure 4, where there are time periods of greater or lesser swarm activity. We are currently testing the statistical significance of these results and whether swarm activity can be linked to large local or regional earthquakes, as well as observable strain transients.

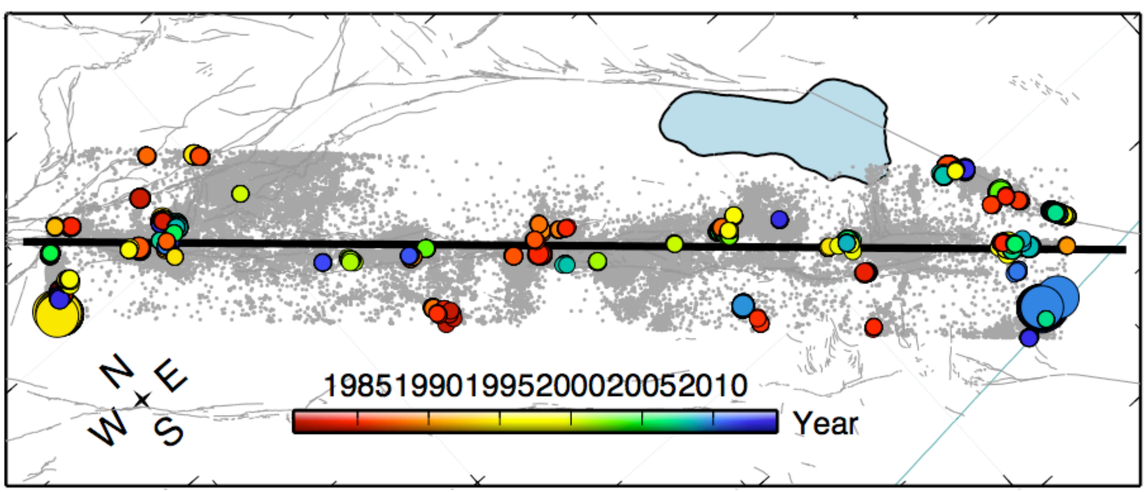

Figure 3. Swarms near the San Jacinto Fault, colored by year of occurrence. Symbol size scales with the number of events in the swarm. Background seismicity is shown in gray.

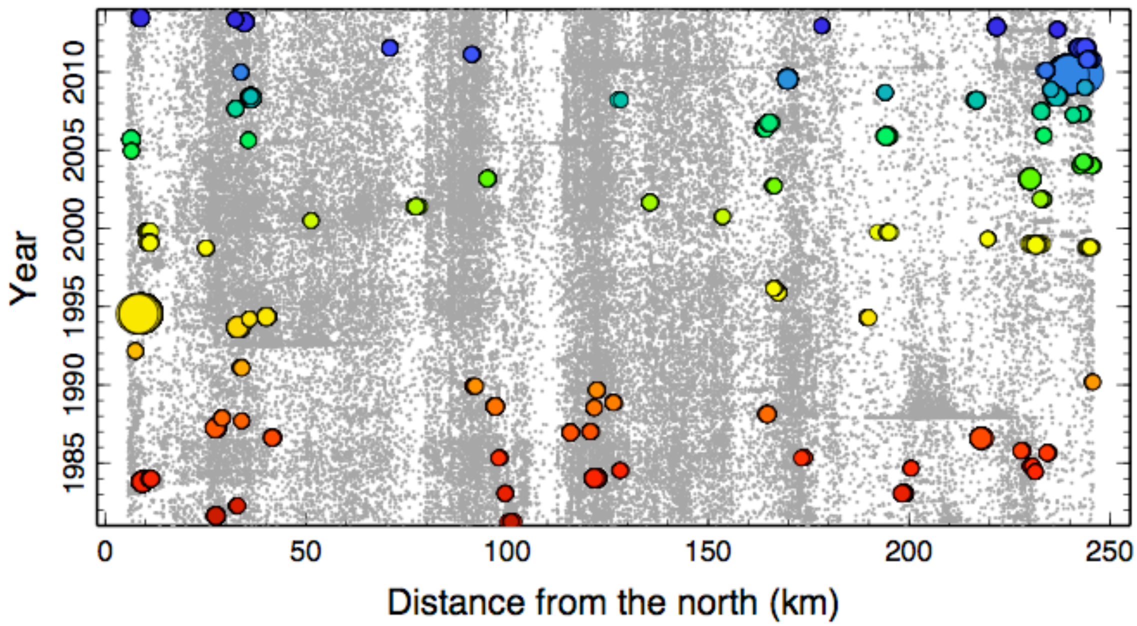

Figure 4. Time versus along-fault distance for observed swarms near the San Jacinto Fault, as projected onto the line shown in Fig. 3. Background seismicity is shown in gray.

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