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Seismicity Patterns, Swarms and Foreshocks in Southern California

Peter M. Shearer, Principal Investigator

Institute of Geophysics and Planetary Physics
Scripps Institution of Oceanography
U.C. San Diego
La Jolla, CA 92093-0225
pshearer@ucsd.edu

Summary

This SCEC funded research involves continued analysis of earthquakes recorded by the Southern California Seismic Network (SCSN). This has led to greatly improved earthquake locations, focal mechanisms, and estimates of stress drop. We are now using these products to perform integrated studies of seismicity and address a number of issues related to seismic hazard. We have recently focused on studying earthquake triggering models and their relationship to swarms and foreshock sequences. We have identified several aspects of the space/time clustering of seismicity that cannot be explained with standard (i.e., ETAS) triggering models, including differences in precursory seismicity behavior between large and small earthquakes and details of the foreshock and aftershock behavior for small earthquakes. In particular, we have found that earthquake clustering is nearly time-symmetric for small magnitude events, that triggering from M 2 to 4 earthquakes is only resolvable to distances of 1 to 3 km, that foreshock-to-aftershock ratios for small earthquakes are too large to be explained entirely with ETAS-like triggering models, and that much small earthquake clustering is likely caused by underlying physical drivers, such as fluid flow or slow slip.

We have developed a method to quantify seismicity migration in event clusters and find that most swarms exhibit migration whereas most aftershock sequences do not. Swarm migration velocities suggest both slow slip and fluid diffusion mechanisms are involved. We find that extended foreshock sequences more closely resemble swarms than earthquake-to-earthquake triggering cascades, in which there is no fundamental difference between foreshocks, mainshocks, and aftershocks. Our results support previous work that has suggested that major California foreshock sequences are not caused by static stress triggering and may be driven by aseismic processes.

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

Technical Report

Earthquake 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 foreshock/aftershock ratios for small earthquakes (Shearer, 2012a,b). 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.

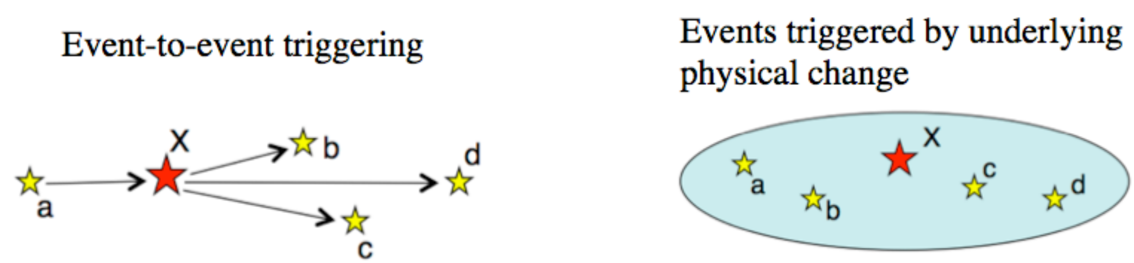

Figure 1. Two possible sources of clustering in short time intervals around target quakes. The target event X is selected to be larger than nearby events within a narrow time window. In the left mechanism, the target earthquake X triggers aftershocks b, c, and d. The target event itself may have been triggered by foreshock a. In the right mechanism, all the earthquakes are triggered by an external event, such as fluid migration or slow slip. From Shearer (2012b)

Our results so far are described in two recently published JGR papers (Shearer 2012a,b), which compare observed event behavior in California with computer simulations of triggering. Some conclusions are: (1) Clustering is nearly time-symmetric for small magnitude events, (2) Triggering from M 2 to 4 earthquakes is only resolvable to distances of 1 to 3 km, (3) Foreshock-to-aftershock ratios for small earthquakes are too large to be explained entirely with ETAS-like triggering models, and (4) Much of small earthquake clustering is caused by underlying physical drivers, such as fluid flow or slow slip, as illustrated in Figure 1. We are continuing this work by examining swarms and foreshock sequences in more detail. It is important to continue 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 the fluid migration or slow slip often believed to drive swarms.

Swarms

We have been developing tools to analyze the spatial migration of seismicity in swarms, specifically to estimate the migration velocity and direction and evaluate its statistical significance. 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. More recently, 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 2, 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).

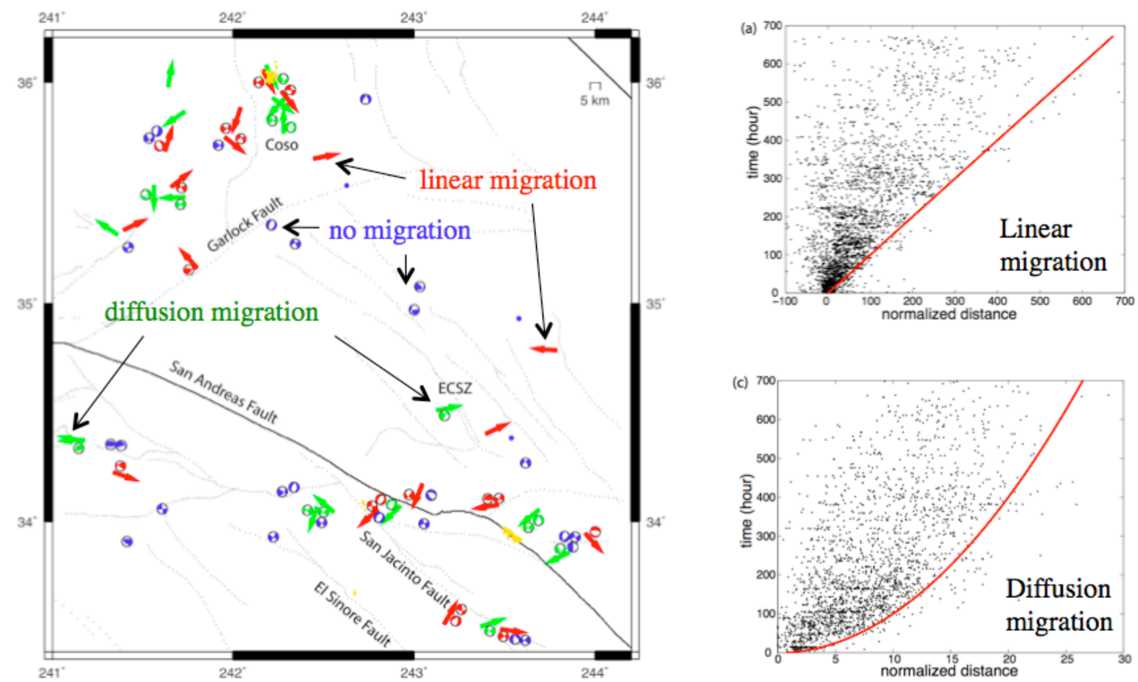

Figure 2. Swarm migration behavior. Southern California swarms (left) may be divided in those that show linear migration behavior (red arrows), those that show diffusion migration behavior (green) and those that have no significant spatial migration (blue). The right-hand panels are stacks of the swarm occurrence times versus normalized distance. From Chen et al. (2012).

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 southern California, that is, when a sequence of seismicity starts in a localized region previously devoid of activity. Defining mainshocks as events of M ≥ 5, these onsets may be divided into five general categories: (1) Main-shock/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.

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 et al., 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. Our results support previous work that has suggested that major California foreshock sequences are not caused by static stress triggering (Dodge et al., 1995, 1996) and may be driven by aseismic creep, and that high foreshock-to-aftershock ratios for East Pacific Rise transform fault earthquakes suggest slow slip transients (McGuire et al., 2005).

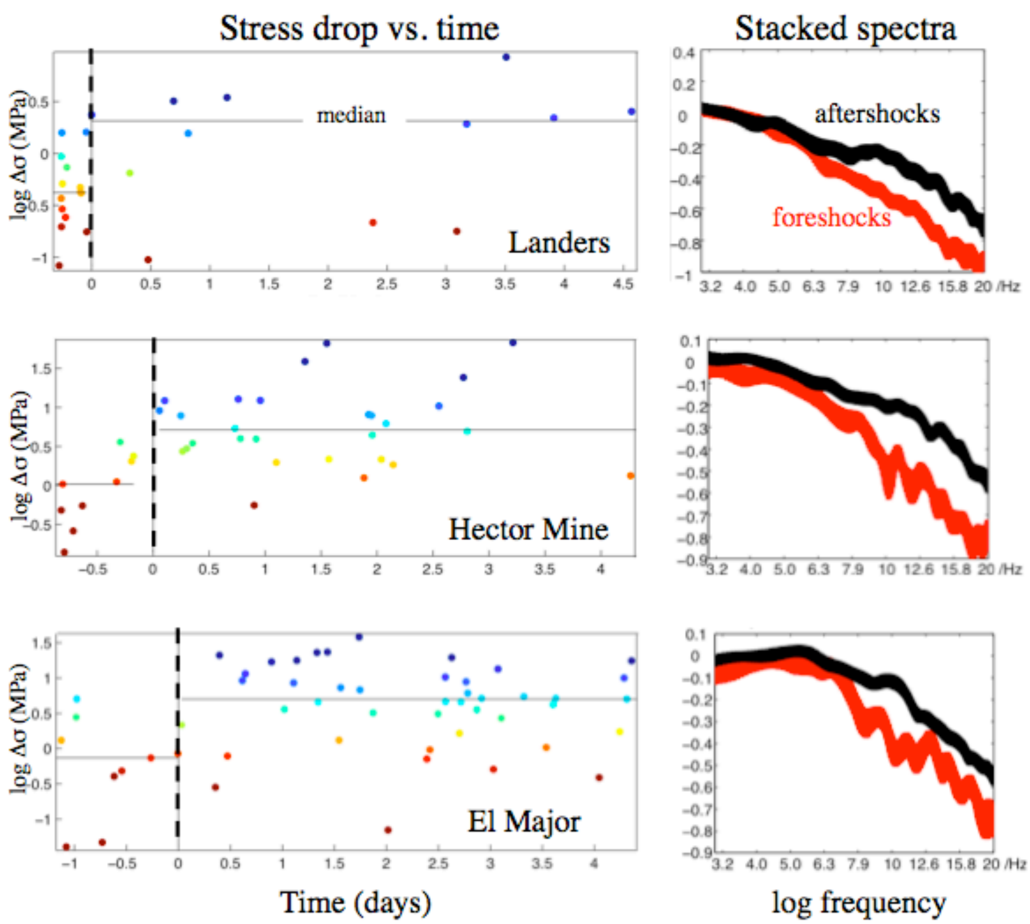

Figure 3. (left) Estimated event stress drops versus time for foreshocks and aftershocks of the Landers, Hector Mine, and El Major earthquakes. Note the lower median stress drops for the foreshock sequences. (right) Stacked source spectra for the foreshocks (red) versus aftershocks (black), normalized for moment differences, confirming the lower frequency content of the foreshocks.

Recently we have also discovered that the foreshock sequences before the Landers, Hector Mine, and El Major earthquakes have systematically lower stress drops than aftershocks in the same region (see Fig. 3). This lends further support to the idea that the foreshocks are not primarily caused by earthquakes-to-earthquake triggering, but are driven by underlying physical changes.

It is interesting that recent results for the 1999 Izmit earthquake (Bouchon et al., 2011) and the 2011 Tohoku earthquake (Ando and Imanishi, 2011; Kato et al., 2012) are also suggesting slow slip or a nucleation phase immediately preceding the mainshock.

These results have important implications for short-term earthquake forecasts, in which triggering models are often invoked to justify predictions that there is about a 5% chance that moderate sized earthquakes will be followed within a few days by a larger event (e.g., Jones, 1985; Christophersen and Smith, 2008). If many California foreshock sequences behave like swarms, then understanding the underlying physical changes that drive swarms, and that may ultimately lead to a large event, is crucial for improving earthquake forecasts.

Intellectual Merit

Our research relates to many key SCEC objectives, including characterizing seismicity clustering and its implications for earthquake prediction. Our main contribution has been to systematically and objectively examine large amounts of earthquake data, to test whether existing models are adequate to explain the observations.

Broader Impacts and Outreach

This project helped support female graduate student Xiaowei Chen. Our research will help quantify earthquake clustering and triggering, which has broad implications for earthquake forecasting and predictability. Advances in these areas would have clear societal benefits.

SCEC Related Publications (from 2008)

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