Final Technical Report

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

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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), and details of the foreshock and aftershock behavior for small earthquakes (Shearer, 2012a). 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 reflected underlying physical processes.

We have recently focused on the implications of self-similar earthquake triggering models for foreshock and aftershock magnitudes (Shearer, 2012a). Båth's law (Båth, 1965), the observation that the largest aftershock is, on average, 1.2 magnitudes smaller than its mainshock, independent of mainshock size, suggests some degree of self-similarity in earthquake triggering. Observed apparent foreshock and aftershock behavior for events close in space and time to *M* 2.5 to 5.5 mainshocks in southern California appear roughly self-similar, but differ from triggering simulations is several key respects: (1) the aftershock *b*-values are significantly lower than that of the complete catalog (this result was recently questioned by Hainzl, 2013, but please see my reply in Shearer, 2013), (2) the number of aftershocks is too large to be consistent with Båth's law, and (3) the foreshock-to-aftershock ratio is too large to be consistent with Båth's law. These observations indicate for southern California that triggering self-similarity is not obeyed for these small mainshocks or that the space/time clustering is not primarily caused by earthquake-to-earthquake triggering.

This conclusion is further supported by an analysis of the distance dependence of triggering (Shearer, 2012b), which indicates that at least some of the temporal clustering of seismicity at short scales (0.1 to 5 km) does not appear to be caused by local earthquake triggering, but instead reflects an underlying physical process that temporarily increases the seismicity rate, such as is often hypothesized to drive earthquake swarms. Earthquake triggering for $M < 4.5$ earthquakes is only resolvable in average seismicity rates at times less than about one day and to distances of less than about 10 km (see Fig. 1), and its linear density decreases as $r^{-1.5}$ to $r^{-2.5}$, significantly steeper than some previous studies have found (e.g., Felzer and Brodsky, 2006).

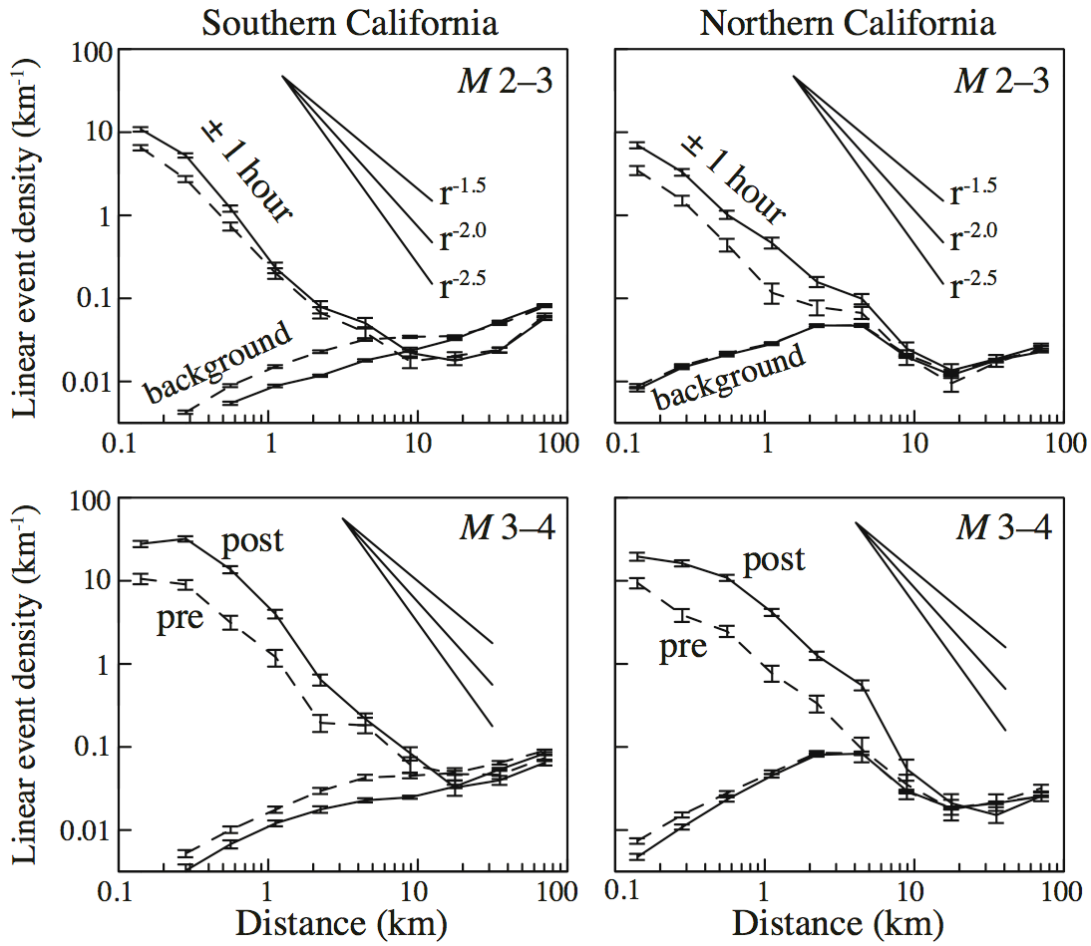

Figure 1. Linear event density versus distance for the windowed southern and northern California catalogs, comparing results for M 2–3 and M 3–4 target earthquakes. Average pre- and post-target event densities are computed in ±1 hour windows from the target event times. For comparison, a 'background' rate estimated for between 900 and 1000 days from the target events is also plotted. The pre-target densities are shown as dashed lines. One standard error bars are estimated from bootstrap resampling of the target events. From Shearer (2012b).

Swarms

An interesting aspect of 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. 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. This is a region of extensional as well as strike-slip faulting and has relatively high heat flow and attenuation (e.g., Hauksson and Shearer, 2006). Some of its swarms have been associated with slow-slip events (Lohman and McGuire, 2007). The southernmost section of the San Andreas Fault, thought to be overdue for a large earthquake, terminates in the Salton Trough, making the area of special concern to seismologists. Major swarms since 1981

are plotted in Figure 2. 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. Our results generally show linear migration rates of 0.1 to 0.5 km/hour, but with some swarms near active geothermal areas having slower rates more consistent with fluid diffusion.

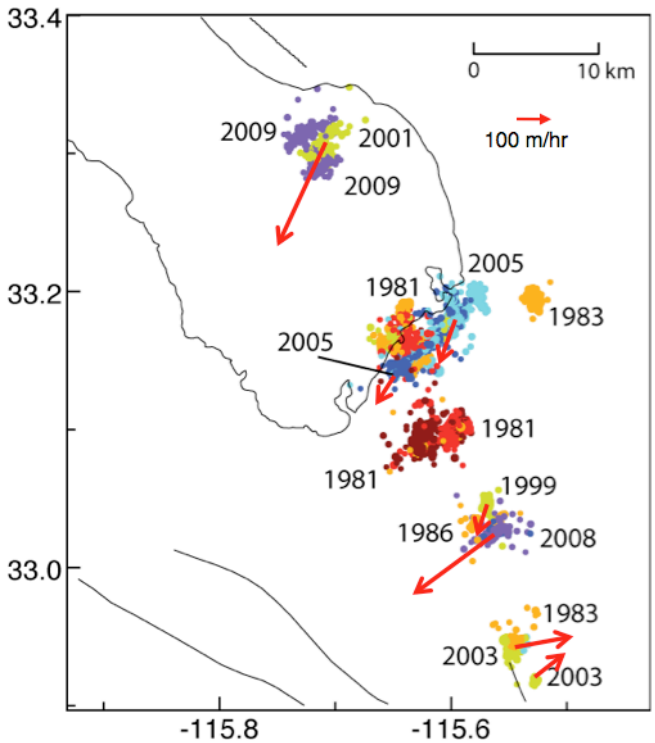

Figure 2. Major earthquake swarms in the Salton Trough since 1981. Examples of estimated seismicity migration vectors are plotted in red. These generally trend SW–NE at velocities of 0.1 to 0.5 km/hr. From Chen and Shearer (2011)

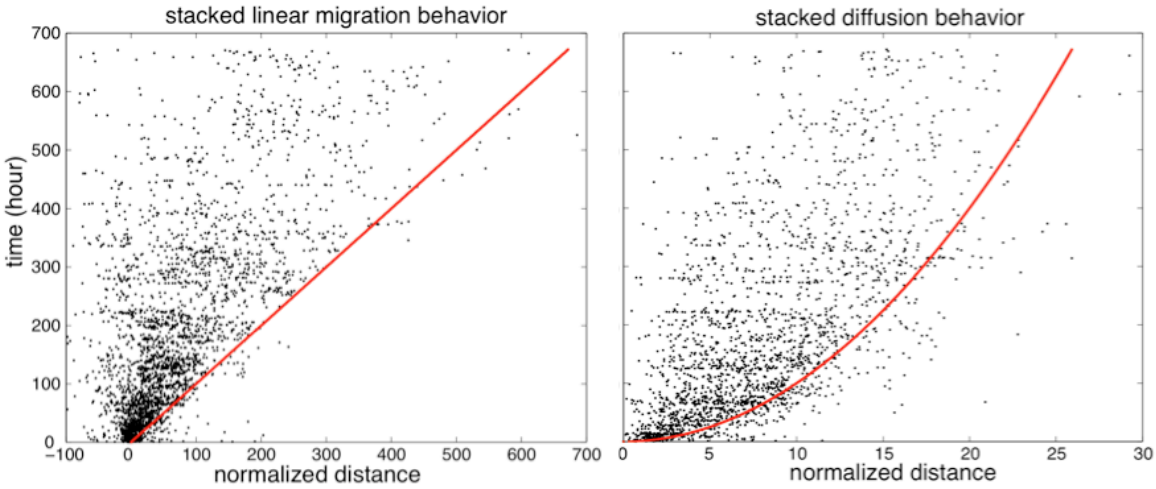

Figure 3. Swarm migration behavior. Event occurrence time versus normalized distance for two categories of southern California swarms: (left) 37 swarms best fit with a linear migration velocity, and (right) 17 swarms best fit with the diffusion equation (right). The red line is the predicted onset time. In the left plot, distance is scaled for each swarm so that the fitted velocity is one. In the right plot, the x-axis is scaled by the square root of 1/4p*D* where *D* is the diffusion coefficient. From Chen et al. (2011).

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. We find that some swarms are best fit with a linear migration velocity, others with the diffusion equation. These properties are shown in Figure 3, 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).

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

For example, the foreshock sequences of the three largest recent southern California earthquakes (Fig. 4), the 1992 Mw 7.3 Landers, 1999 Mw 7.1 Hector Mine, and 2010 Mw 7.2 El Mayor-Cucapah, all exhibit spatial migration (Chen and Shearer, 2013). These extended foreshock sequences, like swarms, do not start with their largest event and are difficult to explain with standard triggering models (e.g., Helmstetter and Sornette, 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.

Another intriguing aspect of many foreshock sequences is that their estimated stress drops are significantly less, on average, than those of aftershocks in the epicentral region. This is shown in Figure 5, which plots stress drop estimates versus time for the 1992 Landers, 1999 Hector Mine, and 2010 El Mayor–Cucapah, earthquakes. In all three cases, the foreshocks feature lower average stress drops and depletion of high-frequency energy compared with the aftershocks of their corresponding mainshocks. Using a longer-term stress drop catalog, we find that the average stress drop of the Landers and Hector Mine foreshock sequences are comparable to nearby swarms.

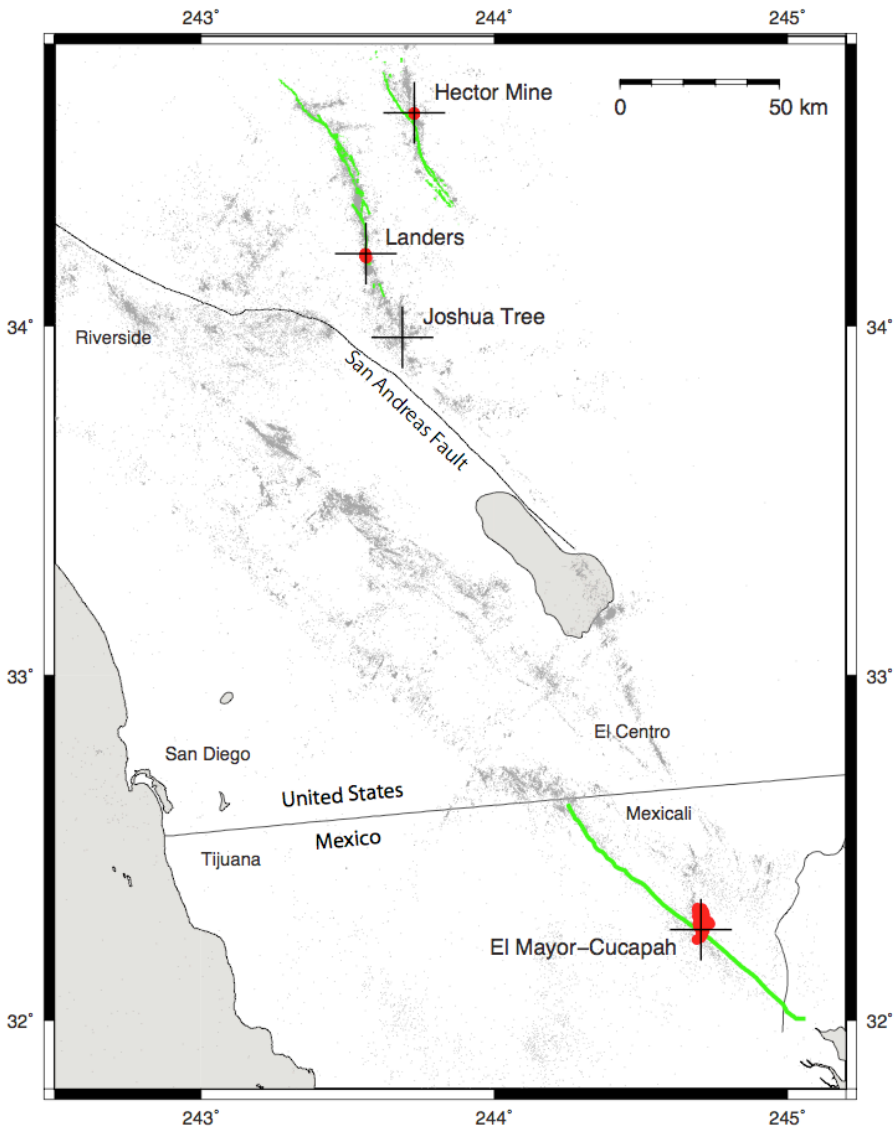

Figure 4. A map of southern California, showing the epicenters of three M > 7 mainshocks (black "+"), their foreshocks (red dots) and a random 2% of total seismicity in the region (small grey dots). Green lines are surface fault traces. From Chen and Shearer (2013).

Quasi-static slip signals prior to rapid dynamic rupture have been observed from numerical modeling and laboratory observations (Ohnaka and Shen, 1999; Lapusta and Rice, 2003). Emergent onsets in seismic waveforms and immediate foreshock sequences have been interpreted to represent a slow nucleation process (Dodge et al., 1995, 1996; Ellsworth and Beroza, 1995). However, the observed spatial-temporal evolution patterns for the foreshocks studied here differ from a nucleation-related pre-slip model. There is no temporal acceleration of foreshock occurrence, and the three similar sized mainshocks have very different foreshock areas and durations, suggesting no simple scaling relationship with mainshock magnitude (Abercrombie and Mori, 1996). Rather, the spatial pattern resembles features of earthquake swarms, where an external aseismic transient is likely involved.

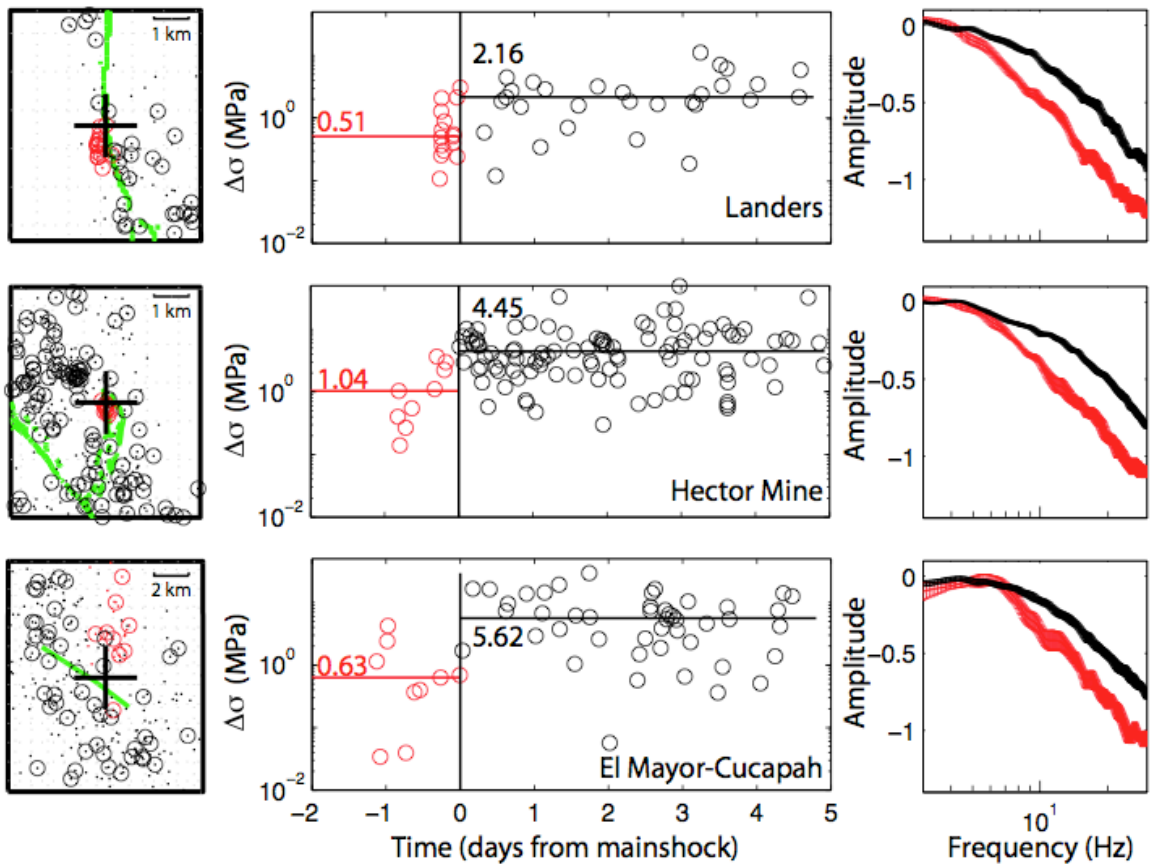

Figure 5. Foreshock vs. aftershock comparison. Left column: map view of seismicity, mainshock (shown in black "+") and fault trace (green lines) within the mainshock source region. Middle column: temporal variation of estimated earthquake stress drops (open circles), median values (horizontal lines). Vertical black lines are mainshock occurrence times. Right column: averaged source spectra for foreshocks and aftershocks. In all figures, foreshocks are shown in red, and aftershocks are shown in black. From Chen and Shearer (2013).

For the Landers and El Mayor-Cucapah earthquakes, observations of smaller sub-events (Wei et al., 2012; Abercrombie and Mori, 1994) indicate that the direct mainshock nucleation may start after the last observed foreshocks. It is interesting to note the association between fault zone complexity (Jones, 1985) and the foreshock migration pattern. Both numerical modeling and laboratory experiments have found that fault zone complexity is critical in the generation of smaller events (Ohnaka and Shen, 1999; Lapusta and Rice, 2003; Rice and Ben-Zion, 1996). For constant shear loading on a rough fault, the shear stress accumulates non-uniformly along the fault zone with concentration at stronger positions. The failure starts at weaker positions and grows at 0.3 to 4 km/hr (Ohnaka and Shen, 1999), consistent with our observed foreshock migration rate. In this scenario, stress loading from the external transient event accumulates within the localized area, in which abrupt failure events are promoted. Due to strong heterogeneity, the critical pore creation slip distance is small (Yamashita, 1999), and swarm-like behavior is generated. The transient event then causes stress loading at the mainshock hypocenter, which may trigger the eventual mainshocks. The origin and nature of the hypothesized transient event is unknown, but either slow slip or fluid flow

could lead to reduced fault strength and lowered differential stress (Chen and Shearer, 2011; Allmann et al., 2011), which could account for the smaller stress drops seen for the foreshocks. Not all large earthquakes are preceded by observable foreshock sequences and not all swarms lead to large earthquakes. But our results suggest that many foreshock sequences, like swarms, may reflect an underlying aseismic triggering process. For the Eastern California Shear Zone, small seismicity bursts are less frequent than in other parts of southern California (Chen et al., 2012); therefore, at least in this region, burst occurrence may be a useful contributor to short-term earthquake probability estimates.

References

Abercrombie, R. E., and J. Mori, Local observations of the onset of a large earthquake: 28 June 1992 Landers, California, *Bull. Seismol. Soc. Am.*, **84**, 725–734, 1994.

Abercrombie, R. E., and J. Mori, Occurrence patterns of foreshocks to large earthquakes in the Western United States, *Nature*, **381**, 303–307, 1996.

Allmann, B. P., A. Goertz, and S. Wiemer, Stress drop variations of induced earthquakes at the Basel geothermal site, *Geophys. Res. Lett.*, **38**, doi: 10.1029/2011GL047498, 2011.

Båth, M., Lateral inhomogeneities of the upper mantle, *Tectonophysics*, **2**, 483–514, 1965.

Chen, X. and P. M. Shearer, Comprehensive analysis of earthquake source spectra and swarms in the Salton Trough, California, *J. Geophys. Res.*, **116**, doi: 10.1029/2011JB008263, 2011.

Chen, X., and P. M. Shearer, California foreshock sequences suggest aseismic triggering process, *Geophys. Res. Lett.*, **40**, doi:10.1002/grl.50444, 2013.

Chen, X., P. M. Shearer, and R. E. Abercrombie, Spatial migration of earthquakes within seismic clusters in Southern California: Evidence for fluid diffusion, *J. Geophys. Res.*, **117**, B04301, doi:10.1029/2011JB008973, 2012.

Dodge, D. D., G. C. Beroza and W. L. Ellsworth, Foreshock sequence of the 1992 Landers, California, earthquake and its implications for earthquake nucleation, *J. Geophys. Res.*, **100**, 9865–9880, 1995.

Dodge, D. D., G. C. Beroza and W. L. Ellsworth, Detailed observations of California foreshock sequences: Implications for the earthquake nucleation process, *J. Geophys. Res.*, **101**, 22,371–22,392, 1996.

El Hariri, M., R. E. Abercrombie, C. A. Rowe and A. F. do Nascimento, The role of fluids in triggering earthquakesL observations from reservoir induced seismicity in Brazil, *Geophys. J. Int.*, **181**, 1566–1574, doi: 10.1111/j.1365-246X.2010.04554.x, 2010.

Ellsworth, W. L., and G. C. Beroza, Seismic evidence for an earthquake nucleation phase, *Science,* **268**, 851–855, 1995.

Felzer, K., R. Abercrombie, and G. Ekstrom, A common origin for aftershocks, foreshocks, and multiplets, *Bull. Seismol. Soc. Am.*, **94**, 88 – 98, doi:10.1785/0120030069, 2004.

Felzer, K. R., and E. E. Brodsky, Decay of aftershock density with distance indicates triggering by dynamic stress, *Nature*, **441**, doi: 10.1038/nature04799, 2006.

Hainzl, S., Seismicity patterns of earthquake swarms due to fluid intrusion and stress triggering, *Geophys. J. Int.* **159**, 1090–1096, 2004.

Hanizl, S., Comment on "Self-similar earthquake triggering, Båth's law, and foreshock/aftershock magnitudes: Simulations, theory, and results for southern California" by P. M. Shearer, *J. Geophys. Res.*, **118**, doi:10.1002/ jgrb.50132, 2013.

Hauksson, E., and P. M. Shearer, Attenuation models (Qp and Qs) in three dimensions of the southern California crust: Inferred fluid saturation at seismogenic depths, *J. Geophys. Res.*, **111**, B05302, doi:10.1029/2005JB003947, 2006.

Helmstetter, A. and D. Sornette, Diffusion of epicenters of earthquake aftershocks, Omori's law, and generalized continuous-time random walk models, *Phys. Rev. E.*, **66**, 061104, 1–24, 2002.

Helmstetter, A. and D. Sornette, Foreshocks explained by cascades of triggered seismicity, *J. Geophys. Res.*, **108**, 2457, doi: 10.1029/2003JB002409, 2003.

Jones, L. M., Foreshocks and time-dependent earthquake hazard assessment in Southern California, *Bull. Seismol. Soc. Am.*, **75**, 1669–1679, 1985.

Lapusta, N., and J. R. Rice, Nucleation and early seismic propagation of small and large events in a crustal earthquake model, *J. Geophys. Res.*, **108**, 2205, 2003.

Lohman, R. B., and J. J. McGuire, Earthquake swarms driven by aseismic creep in the Salton Trough, California, *J. Geophys. Res.*, **112**, doi: 10.1029/2006JB004596, 2007.

Ogata, Y., Seismicity analysis through point-process modeling: a review, *Pure Appl. Geophys.*, **155**, 471–507, 1999.

Ohnaka, M., and L. Shen, Scaling of the shear rupture process from nucleation to dynamic propagation: Implications of geometric irregularity of the rupturing surfaces, *J. Geophys. Res.*, **104**, 817–844, 1999.

Rice, J. R., and Y. Ben-Zion, Slip complexity in earthquake fault models, *Proc. Natl. Acad. Sci*, **93**, 3811–3818, 1996.

Shearer, P. M., Self-similar earthquake triggering, Båth's law, and foreshock/aftershock magnitudes: Simulations, theory, and results for southern California, *J. Geophys. Res.*, **117**, B06310, doi: 10.1029/2011JB008957, 2012a.

Shearer, P. M., Space-time clustering of seismicity in California and the distance dependence of earthquake triggering, *J. Geophys. Res.*, **117**, B10306, doi: 10.1029/2012JB009471, 2012b.

Shearer, P. M., Reply to comment by S. Hainzl on "Self-similar earthquake triggering, Båth's Law, and foreshock/aftershock magnitudes: Simulations, theory and results for southern California," *J. Geophys. Res.*, **118**, doi: 10.1002/jgrb.50133, 2013.

Shearer, P. M., and G. Lin, Evidence for Mogi doughnut behavior in seismicity preceding small earthquakes in southern California, *J. Geophys. Res.*, **114**, doi: 10.1029/2009JB005982, 2009.

Vidale, J. E., and P. M. Shearer, A survey of 71 earthquake bursts across southern California: Exploring the role of pore fluid pressure fluctuations and aseismic slip as drivers, *J. Geophys. Res.*, **111**, B05312, doi:10.1029/2005JB004034, 2006.

Wei, S. J., E. Fielding, S. Leprince, A. Sladen, J. P. Avouac, D. Helmberger, E. Hauksson, R. S. Chu, M. Simons, K. Hudnut, T. Herring, and R. Briggs, Superficial simplicity of the 2010 El Mayor-Cucapah earthquake of Baja California in Mexico, *Nature Geoscience*, **4**, 615–618, 2012.

Yamashita, T., Pore creation due to fault slip in a fluid-permeated fault zone and its effect on seismicity: Generation mechanism of earthquake swarm, *Pure and Applied Geophysics*, **155,** 625–647, 1999.

Reports Published

Chen, X., and P. M. Shearer, Comprehensive analysis of earthquake source spectra and swarms in the Salton Trough, California, *J. Geophys. Res.*, **116**, B09309, doi:10.1029/2011JB008263, 2011.

Chen, X., and P. M. Shearer, California foreshock sequences suggest aseismic triggering process, *Geophys. Res. Lett.*, **40**, doi:10.1002/grl.50444, 2013.

Chen, X., P. M. Shearer, and R. E. Abercrombie, Spatial migration of earthquakes within seismic clusters in Southern California: Evidence for fluid diffusion, *J. Geophys. Res.*, **117**, B04301, doi:10.1029/2011JB008973, 2012.

Hauksson, E., J Stock, R. Bilham, M. Boese, X. Chen, E. H. Fielding, J. Galetzka, K. W. Hudnut, K. Hutton, L. C. Jones, H. Kanamori, P. M. Shearer, J. Steidl, J. Treiman, S. Wei, and Wenzheng Yang, Report on the August 2012 Brawley earthquake swarm in Imperial Valley, Southern California, *Seismol. Res. Lett.*, **84**, 177-189, doi: 10.1785/0220120169, 2013.

Kane, D. L., G. A. Prieto, F. L. Vernon, and P. M. Shearer, Quantifying seismic source parameter uncertainties, *Bull. Seismol. Soc. Am.*, **101**, 535–543, doi: 10.1785/0120100166, 2011.

Kane, D. L., P. M. Shearer, B. P. Goertz-Allmann, and F. L. Vernon, Rupture directivity of small earthquakes at Parkfield, *J. Geophys. Res.*, **118**, doi: 10.1029/2012JB009675, 2013.

Yang, Z., A. Sheehan, and P. Shearer, Stress-induced upper crustal anisotropy in southern California, *J. Geophys. Res.*, **116**, doi: 10.1029/2010JB007655, 2011.

Shearer, P. M., Self-similar earthquake triggering, Båth's law, and foreshock/aftershock magnitudes: Simulations, theory, and results for southern California, *J. Geophys. Res.*, **117**, B06310, doi: 10.1029/2011JB008957, 2012.

Shearer, P. M., Space-time clustering of seismicity in California and the distance dependence of earthquake triggering, *J. Geophys. Res.*, **117**, B10306, doi: 10.1029/2012JB009471, 2012.

Shearer, P. M., Reply to comment by S. Hainzl on "Self-similar earthquake triggering, Båth's Law, and foreshock/aftershock magnitudes: Simulations, theory and results for southern California," *J. Geophys. Res.*, **118**, doi: 10.1002/jgrb.50133, 2013.

Smith-Konter, B. R., D. T. Sandwell, and P. Shearer, Locking depths estimated from geodesy and seismology along the San Andreas Fault System: Implications for seismic moment release, *J. Geophys. Res.*, **116**, doi: 10.1029/2010JB008117, 2011.

Sumiejski, P. E., and P. M. Shearer, Temporal stability of coda Q^{-1} in southern California, *Bull. Seismol. Soc. Am.*, **102**, 873–877, doi: 10.1785/0120110181, 2012.

Uchide, T., H. Yao, and P. M. Shearer, Spatio-temporal distribution of fault slip and high-frequency radiation of the 2010 El Mayor-Cucapah, Mexico earthquake, *J. Geophys. Res.*, **118**, doi: 10.1002/jgrb.50144, 2013.