High-frequency identification of non-volcanic tremor triggered by regional earthquakes

Aurélie Guilhem,[1] Zhigang Peng,[2] and Robert M Nadeau[1]

Received 10 July 2010; accepted 26 July 2010; published XX Month 2010.

[1] Subsequent to the discovery of ambient "non-volcanic" tremor activity along the Parkfield-Cholame section of the San Andreas fault in central California, triggered tremors associated with the surface waves of large teleseismic earthquakes have been recognized. However, no evidence of triggered tremors from regional earthquakes has previously been found either here or in other tremor regions. By systematically filtering seismograms to higher frequencies (i.e., above 20 Hz) associated with 99 regional M5+ earthquakes since 2001, we identify four regional earthquakes that have triggered tremor in central California. Significant high-frequency energy is also observed in previously identified teleseismically triggered and ambient tremors, suggesting a common mechanism. We find that long-period and large-amplitude surface waves from both regional and teleseismic events have a greater potential of triggering tremor in the same region, and that the inferred minimum triggering dynamic stress is ~1 kPa. **Citation:** Guilhem, A., Z. Peng, and R. M. Nadeau (2010), High-frequency identification of non-volcanic tremor triggered by regional earthquakes, *Geophys. Res. Lett.*, *37*, LXXXXX, doi:10.1029/2010GL044660.

1. Introduction

[2] Since their first discovery in Japan in 2002 [*Obara*, 2002], deep "non-volcanic" tremors have been mainly observed along subduction zones such as in the Nankai trough [*Shelly et al.*, 2006], Cascadia [*Rogers and Dragert*, 2003; *Brudzinski and Allen*, 2007] and in Central America [*Brudzinski et al.*, 2010; *Payero et al.*, 2008]. Similar continuous bursts of tremor activity have also been found along the San Andreas Fault (SAF) transform plate boundary in central California near Parkfield-Cholame [*Nadeau and Dolenc*, 2005; *Nadeau and Guilhem*, 2009; *Shelly and Hardebeck*, 2010]. Recent studies of tremor in these environments have shown that they can be dynamically triggered by the passage of the seismic waves from large earthquakes at teleseismic distances (e.g., >1000 km), appearing as a series of a few-seconds-long high-frequency bursts with a periodicity similar to that of the surface waves [*Miyazawa and Mori*, 2005; *Miyazawa et al.*, 2008; *Miyazawa and Brodsky*, 2008; *Rubinstein et al.*, 2007; *Rubinstein et al.*, 2009; *Gomberg et al.*, 2008; *Peng et al.*, 2008; *Peng et al.*, 2008; *Peng et al.*, 2009]. Because both ambient and dynamically triggered tremors occur below the seismogenic zone, they provide important clues for understanding the fundamental processes at the deep roots of major plate-boundary faults [*Rubinstein et al.*, 2010].

[3] *Nadeau and Guilhem* [2009] showed that ambient tremor activity in the Parkfield-Cholame region was strongly modulated for over four years by two earthquakes occurring within 100 km: the 2003 Mw6.5 San Simeon and the 2004 Mw6.0 Parkfield events. However to date, no dynamically triggered tremors have been observed from regional earthquakes at distances between 100 and 1000 km in either subduction or transform environments. *Rubinstein et al.* [2009] explained the absence of regionally triggered tremor in Cascadia by the fact that *P* and *S* coda waves from regional earthquakes and local tremor share similar frequency passband (1–15 Hz) and waveform characteristics (i.e., long durations with no clear phase arrivals). Hence if the amplitude of regional earthquake coda is above that of the local tremor, the tremor signal will be masked, preventing it from being identified during passage of regional event surface waves. In comparison, large earthquakes have been shown to trigger microearthquakes at regional distances [*Hill et al.*, 1993; *Hill and Prejean*, 2007]. In this case the masking effect is not significant because of the impulsive arrivals and relatively high-frequency content of the triggered earthquakes. In particular, *Brodsky and Prejean* [2005] conducted a systematic survey of triggered earthquakes by regional and teleseismic events around the Long Valley Caldera, and found that large-amplitude long-period surface waves have higher triggering potential than the short-period surface waves of similar amplitudes. Whether this is the case for triggered tremor remains an open question.

[4] An effective way to separate the locally triggered tremors from the coda waves of regional earthquakes is to examine higher frequency bands [*Peng et al.*, 2007], in particular frequencies higher than those previously used to identify teleseismically triggered tremors (i.e., 1–15 Hz). Because high-frequency signals recorded by surface stations in the Parkfield-Cholame area are often limited by analog telemetry issues or contaminated by near-surface noise sources, we take advantage of the high sampling rate and low noise data of the borehole High Resolution Seismic Network (HRSN) at Parkfield, CA and apply high-frequency band-pass filters (in the range of 20–50 Hz) to identify tremor triggered by regional earthquakes.

2. Data and Method

[5] We search for tremors dynamically triggered by the passage of seismic waves from regional earthquakes of magnitude 5 or greater (based on the ANSS catalog), occurring between July 2001 and April 2010 (coincident with the updated ambient tremor catalog of *Nadeau and Guilhem*

[1] Berkeley Seismological Laboratory, University of California, Berkeley, California, USA.

[2] School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, Georgia, USA.

0094-8276/10/2010GL044660

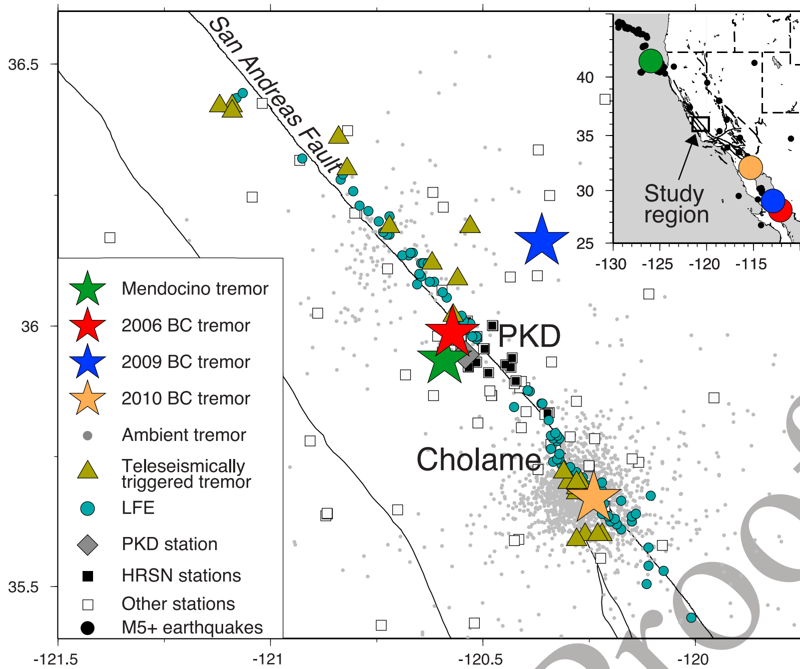

Figure 1. Map showing the study region along the Parkfield-Cholame section of the San Andreas Fault and the M5+ regional earthquakes distributed between 100 and 1200 km from the Berkeley broadband seismic station PKD (circles, inset). Stars show locations of the four triggered tremors and triangles show dynamically triggered tremors from teleseismic events [*Peng et al.*, 2009]. Ambient tremors [*Nadeau and Guilhem*, 2009] are light gray dots and borehole HRSN stations are black squares. Surface stations are the open squares. Low-frequency earthquakes (LFEs) are shown by the circles [*Shelly and Hardebeck*, 2010].

[2009]), and distributed between 100 and 1200 km from the broadband seismic station PKD of the Berkeley Digital Seismic Network (BDSN) located at Parkfield (Figure 1). A minimum distance of 100 km is chosen because dynamic stresses are expected to dominate over static stresses at such distances [*Freed*, 2005]. In addition, it is difficult to separate the seismic signals from the main and triggered events at short distances. We use a maximum distance of 1200 km to allow partial overlap of our events with those of previously studied teleseismically triggered tremor (minimum distance of 1000 km) occurring in the same region [*Peng et al.*, 2009]. A total of 99 regional earthquakes fulfilled these criteria and we systematically downloaded the 250 samples/s HRSN data for these events (Table S1 of the auxiliary material).[1] We searched for triggered tremor within several overlapping frequency bands: 3–15 Hz, 15–30 Hz, and 25–40 Hz (see auxiliary material). In addition, we compared the filtered, HRSN velocity seismograms with unfiltered, instrument-corrected three-component recordings at the broadband station PKD, to examine the full range of low-frequency signals associated with the HRSN data.

[6] We identify triggered tremors by visually searching for consecutive bursts of energy in the higher frequency bands that are phase-correlated with the passing surface waves. Out of the 99 events analyzed, we found four cases of tremor triggered by the following regional earthquakes: the 15 June 2005 M7.2 Mendocino, 04 January M6.6 Baja California (BC), 03 August 2009 M6.9 BC, and 04 April 2010 M7.2 BC. Figure 2 shows an example of tremor triggered by the 2005 Mendocino earthquake. In the higher frequency bands the signal is composed of bursts of energy that are periodic and coincident in time with the surface wave train observed on the unfiltered PKD seismograms, similar to teleseismically triggered tremor in the same region [*Peng et al.*, 2008; *Peng et al.*, 2009] and elsewhere [*Miyazawa and Brodsky*, 2008; *Rubinstein et al.*, 2007; *Rubinstein et al.*, 2009; *Peng and Chao*, 2008].

[7] We located the triggered tremor sources (see auxiliary material) by adapting the envelope based location algorithm for ambient tremors previously applied in the same region [*Nadeau and Guilhem*, 2009]. Figure 1 shows that the triggered tremor sources are located in the general vicinity of the Parkfield section of the SAF, close to the region where ambient and dynamically triggered tremors [*Nadeau and Guilhem*, 2009; *Peng et al.*, 2009] as well as low-frequency earthquakes (LFEs) [*Shelly and Hardebeck*, 2010] have previously been found. The tremors triggered by the 2005 Mendocino, 2006 and 2010 BC earthquakes appear to be on or close to the SAF, while the tremor triggered by the 2009 BC earthquake occurs at a place about 25 km NE of the SAF.

3. Results

[8] As shown in Figure 2, the HRSN data filtered between 3 and 15 Hz mainly show two emergent arrivals that are close to the predicted *P* and *S* arrivals from the 2005 Mendocino mainshock, similar to those reported for regional events in Cascadia [*Rubinstein et al.*, 2009]. For the 04 January 2006 and 04 April 2010 earthquakes, the triggered tremors are best observed in the 15 to 30 Hz band and for the

[1] Auxiliary materials are available in the HTML. doi:10.1029/2010GL044660.

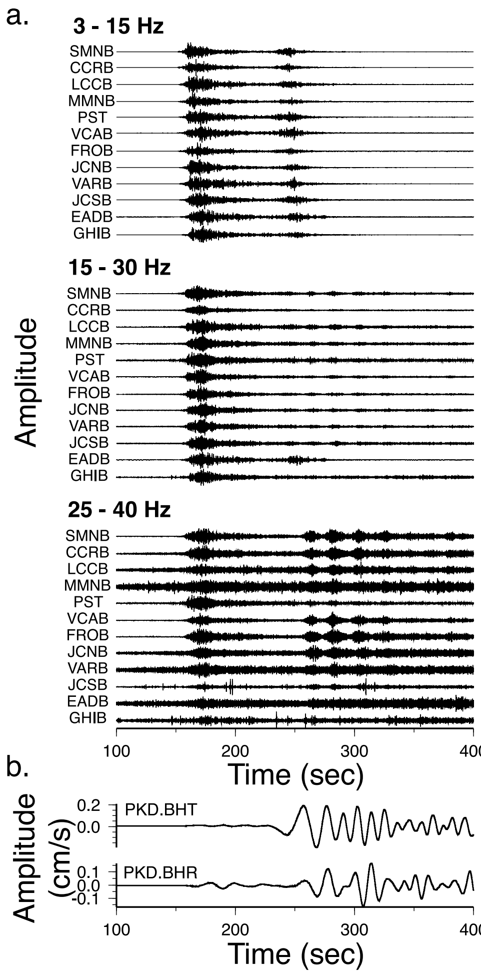

Figure 2. (a) Velocity seismograms (relative scaling) recorded by the vertical (DP1) component of the borehole HRSN and surface NCSN station PST filtered at several frequency bands for the tremor triggered by the 2005 Mendocino earthquake. Seismograms are ordered according to the along-strike (SAF) distance, from (top) northwest to (bottom) southeast. Time scale is given in seconds after 02:50:00 UTC, and the triggered tremor is clearest between 250 and 350 s. (b) Unfiltered, instrument-correlated transverse (BHT) and radial (BHR) components of the broadband surface station PKD showing the surface wave train (time scale same as in Figure 2a).

15 June 2005 and 03 August 2009 events in the 25 to 40 Hz band (Figures 2 and S1–S3). Most tremor signals occur in phase with the large-amplitude, low-frequency surface waves, suggesting a casual relationship between them (Figure S4).

[9] To understand how surface waves trigger tremors, previous studies have examined the wave type (Rayleigh or Love), their amplitude, period, direction of propagation, etc. [*Peng et al.*, 2009; *Miyazawa et al.*, 2008; *Rubinstein et al.*, 2009; *Hill*, 2008, also Surface wave potential for triggering tectonic (non-volcanic) tremor, submitted to *Bulletin of the Seismology Society of America*, 2010]. The propagation directions of the four regional events that triggered tremors are close to the fault strike of the SAF, which is the optimal angle to produce fault-parallel shear stresses from the Love waves [*Peng et al.*, 2008; *Peng et al.*, 2009; *Hill*, 2008, also submitted manuscript, 2010]. However, due to short propagation distances, it is relatively difficult to separate the Love and Rayleigh waves. Hence, in this study we only focus on how the amplitudes and periods of the surface waves affect their triggering potential.

[10] We measured the peak ground velocities (PGVs) of the 99 regional earthquakes at the PKD station using the unfiltered transverse (Figure 3) and vertical components (Figure S5) after correcting for the instrumental response (Table S1). We also included an updated result of *Peng et al.* [2009] for teleseismic earthquakes to evaluate the triggering potential of surface waves in central California. Figure 3a shows that both regional and teleseismic events that triggered tremors have among the largest PGVs recorded at station PKD, supporting the view that large-amplitude surface waves favor tremor generation [*Peng et al.*, 2009].

[11] To further examine the frequency dependence of surface wave triggering potential, we applied a band-pass filter between 0.005 and 0.03 Hz (or 30 and 200 s) to the transverse-component seismograms before measuring the PGVs (Figure 3b). The major changes after applying the long-period band-pass filter are significant reductions of

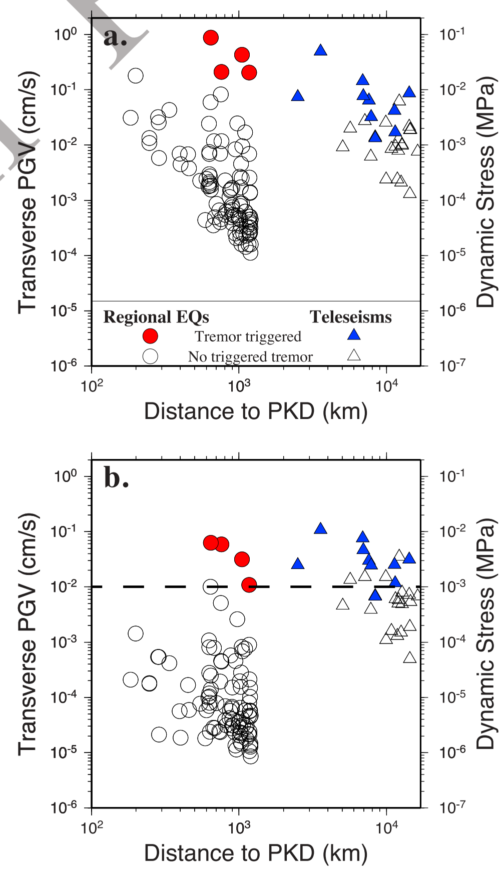

Figure 3. (a) Peak ground velocities (PGV) recorded at broadband station PKD on the unfiltered transverse seismograms for regional and teleseismic (Teleseisms) earthquakes (EQs) (Table S1). Symbols for tremors triggered by regional and teleseismic events are filled. (b) Same as Figure 3a but with transverse components filtered between the period of 30 and 200 s. Dashed line at 0.01 cm/sec marks the PGV threshold for tremor triggering in this pass-band.

the PGVs for several moderate-size events (i.e., magnitudes between 5.0 and 6.0) relatively close to the study region. After filtering, the range of PGVs for the 4 regional earthquakes that trigger tremors is more comparable to those of the teleseismic earthquakes. If we use 0.01 cm/s as a threshold PGV to separate the triggering and non-triggering cases at regional distance, the corresponding dynamic stress is 1 kPa (with the nominal surface wave velocity of 3.5 km/s and the elastic modulus of 35 GPa at depth). We note that a few teleseismic events do not satisfy such criteria (see auxiliary material), suggesting that besides frequency and amplitude, other factors, such as the incident angles and the background tremor rate, could also influence the triggering potential [*Rubinstein et al.*, 2009; Hill, submitted manuscript, 2010].

4. Discussion and Conclusion

[12] In this study we identified four cases of regionally triggered tremor along the Parkfield-Cholame section of the SAF by examining signals at frequencies above those typically used for identifying ambient [*Nadeau and Dolenc*, 2005; *Nadeau and Guilhem*, 2009] and triggered tremor [*Peng et al.*, 2009] in the same region (i.e., above 1–15 Hz). The 1–15 Hz range appears sufficient for discriminating locally triggered tremor signals from teleseismic coda and surface waves, mainly due to the attenuation of 1–15 Hz coda energy at long propagation distances from the source region [*Peng et al.*, 2009; *Rubinstein et al.*, 2009]. However, separating locally triggered tremor signals from coda generated by regional earthquakes requires examination at higher frequencies, where the amplitude of triggered tremor signals exceed the amplitude of coda signals from regional events.

[13] To show that the high-frequency content is not unique to the regionally triggered tremor alone, we examined a few teleseismically triggered tremors [*Gomberg et al.*, 2008; *Peng et al.*, 2008; *Peng et al.*, 2009] and ambient tremors [*Nadeau and Guilhem*, 2009] in the Parkfield-Cholame region. We found that the high-frequency signals (25–40 Hz) are clearly visible for the teleseismically triggered tremor associated with the 2002 Mw7.9 Denali Fault and the 2008 Mw7.9 Wenchuan earthquakes (Figures S6 and S7). Similar high-frequency contents are also shown in at least some of the borehole stations during several long-duration ambient tremor events (Figure S8), suggesting that the processes responsible for generating the high-frequency signals in the ambient and triggered tremors could be similar (Figures S9 and S10). The high-frequency triggered and ambient tremor signals are observed on all three components from different types of seismic sensors and data loggers, indicating that they are not instrumentally generated. Furthermore, the fact that the local triggered tremor signals contain greater high frequency content than the *P*-wave energy from regional events (Figure S4) suggests that at the tremor source considerable high-frequency energy is generated and is not fully attenuated at local propagation distances. It remains unclear, however, whether or not the high-frequency content of these SAF tremors is generated by the same shear slip process responsible for the generation of LFEs [e.g., *Shelly et al.*, 2007], or by a related process such as damage zone micro-cracking associated with shear slow-slip events (N. Brantut et al., Damage and rupture dynamics at the brittle/ductile transition: The anomalous case of gypsum, submitted to *Journal of Geophysical Research*, 2010).

[14] We also showed that large-amplitude (>0.01 cm/s) and long-period surface waves (>30 s) have a greater potential for triggering tremor at regional and teleseismic distances (Figures 3 and S5). These results are consistent with those found for triggered earthquakes in the Long Valley caldera [*Brodsky and Prejean*, 2005], although the amplitude threshold in that study is slightly larger (>0.05 cm/s). Because triggered and ambient tremor occur at sub-seismogenic depths (~20–30 km), such frequency dependent effects may be explained by increased attenuation of short-period surface waves with depth [*Brodsky and Prejean*, 2005] and by differences in the mechanism of earthquakes that occur in the shallow, brittle crust and tremors occurring in the deeper, ductile crust. Our calculated dynamic stress change (1 kPa) is in the same range as the 1–3 kPa inferred from teleseismically triggered tremor [*Peng et al.*, 2009], tidal modulation of tremor [*Thomas et al.*, 2009], and static triggering of tremor by nearby moderate earthquakes [*Nadeau and Guilhem*, 2009] in the same region. These results, together with other recent studies, suggest that tremor is very sensitive to small stress changes at depth, most likely due to near-lithostatic fluid pressures [*Thomas et al.*, 2009]. Given such stress sensitivities, it is important to continue monitoring the tremor activity in this region and elsewhere for a better understanding of fault mechanics in the deep crust and its relationship to large earthquake cycles.

[15] **Acknowledgments.** Supported by the U.S. Geological Survey through awards 07HQAG0014 and 08HQGR0100 and by the National Science Foundation through award EAR-0537641. Z.P. was supported by the National Science Foundation through awards EAR-0809834 and EAR-0956051. Seismic data are archived at the Northern California Earthquake Data Center. Data processing was done at the University of California's Berkeley Seismological Laboratory. We thank David Hill, an anonymous reviewer, Uhrhammer and Doug Dreger for their constructive advises and review comments. Berkeley Seismological Laboratory contribution 10–07.

References

Brodsky, E. E., and S. G. Prejean (2005), New constraints on mechanisms of remotely triggered seismicity at long Valley Caldera, *J. Geophys. Res.*, *110*, B04302, doi:10.1029/2004JB003211.

Brudzinski, M. R., and R. Allen (2007), Segmentation in episodic tremor and slip all along Cascadia, *Geology*, *35*(10), 907–910, doi:10.1130/G23740A.1.

Brudzinski, M. R., H. R. Hinojosa-Prieto, K. M. Schlanser, E. Cabral-Cano, A. Arciniega-Ceballos, O. Diaz-Molina, and C. DeMets (2010), Nonvolcanic tremor along the Oaxaca segment of the Middle America subduction zone, *J. Geophys. Res.*, doi:10.1029/2008JB006061, in press.

Freed, A. M. (2005), Earthquake triggering by static, dynamic, and postseismic stress transfer, *Annu. Rev. Earth Planet. Sci.*, *33*, 335–367, doi:10.1146/annurev.earth.33.092203.122505.

Gomberg, J., J. L. Rubinstein, Z. Peng, K. C. Creager, J. E. Vidale, and P. Bodin (2008), Widespread triggering of nonvolcanic tremor in California, *Science*, *319*, 173, doi:10.1126/science.1149164.

Hill, D. P. (2008), Dynamic stresses, coulomb failure, and remote triggering, *Bull. Seismol. Soc. Am.*, *98*(1), 66–92, doi:10.1785/0120070049.

Hill, D. P., and S. G. Prejean (2007), Dynamic triggering, in *Treatise on Geophysics*, vol. 4, *Earthquake Seismology*, edited by G. Schuber and H. Kanamori, pp. 257–292, Elsevier, Amsterdam.

Hill, D. P., et al. (1993), Seismicity remotely triggered by the magnitude 7.3 Landers, California, earthquake, *Science*, *260*, 1617–1623, doi:10.1126/science.260.5114.1617.

Miyazawa, M., and E. E. Brodsky (2008), Deep low-frequency tremor that correlates with passing surface waves, *J. Geophys. Res.*, *113*, B01307, doi:10.1029/2006JB004890.

Miyazawa, M., and J. Mori (2005), Detection of triggered deep low-frequency events from the 2003 Tokachi-oki earthquake, *Geophys. Res. Lett.*, *32*, L10307, doi:10.1029/2005GL022539.

Miyazawa, M., E. E. Brodsky, and J. Mori (2008), Learning from dynamic triggering of low-frequency tremor in subduction zones, *Earth Planets Space*, *60*, e17–e20.

Nadeau, R., and D. Dolenc (2005), Nonvolcanic tremors deep beneath the San Andreas fault, *Science*, *307*, 389, doi:10.1126/science.1107142.

Nadeau, R. M., and A. Guilhem (2009), Nonvolcanic tremor and the 2003 San Simeon and 2004 Parkfield, California earthquakes, *Science*, *325*, 191–193, doi:10.1126/science.1174155.

Obara, K. (2002), Nonvolcanic deep tremor associated with subduction in southwest Japan, *Science*, *296*, 1679, doi:10.1126/science.1070378.

Payero, J. S., V. Kostoglodov, N. Shapiro, T. Mikumo, A. Iglesias, X. Pérez-Campos, and R. W. Clayton (2008), Nonvolcanic tremor observed in the Mexican subduction zone, *Geophys. Res. Lett.*, *35*, L07305, doi:10.1029/2007GL032877.

Peng, Z., and K. Chao (2008), Non-volcanic tremors underneath the Central Range in Taiwan triggered by the 2001 Mw7.8 Kunlun earthquake, *Geophys. J. Int.*, *175*, 825–829, doi:10.1111/j.1365-246X.2008.03886.x.

Peng, Z., J. E. Vidale, M. Ishii, and A. Helmstetter (2007), Seismicity rate immediately before and after main shock rupture from high-frequency waveforms in Japan, *J. Geophys. Res.*, *112*, B03306, doi:10.1029/2006JB004386.

Peng, Z., J. E. Vidale, K. C. Creager, J. L. Rubinstein, J. Gomberg, and P. Bodin (2008), Strong tremor near Parkfield, CA, excited by the 2002 Denali Fault earthquake, *Geophys. Res. Lett.*, *35*, L23305, doi:10.1029/2008GL036080.

Peng, Z., J. E. Vidale, A. G. Wech, R. M. Nadeau, and K. C. Creager (2009), Remote triggering of tremor along the San Andreas Fault in central California, *J. Geophys. Res.*, *114*, B00A06, doi:10.1029/2008JB006049.

Rogers, G., and H. Dragert (2003), Episodic tremor and slip on the Cascadia subduction zone: The chatter of silent Slip, *Science*, *300*, 1942, doi:10.1126/science.1084783.

Rubinstein, J. L., J. E. Vidale, J. Gomberg, P. Bodin, K. C. Creager, and S. D. Malone (2007), Non-volcanic tremor driven by large transient shear stresses, *Nature*, *448*, 579–582, doi:10.1038/nature06017.

Rubinstein, J. L., J. Gomberg, J. E. Vidale, A. G. Wech, H. Kao, K. C. Creager, and G. Rogers (2009), Seismic wave triggering of nonvolcanic tremor, episodic tremor and slip, and earthquakes on Vancouver Island, *J. Geophys. Res.*, *114*, B00A01, doi:10.1029/2008JB005875.

Rubinstein, J. L., D. R. Shelly, and W. L. Ellsworth (2010), Non-volcanic tremor: A window into the roots of fault zones, in *New Frontiers in Integrated Solid Earth Sciences*, edited by S. Cloetingh and J. Negendank, pp. 287–314, Springer, Dordrecht, Netherlands.

Shelly, D. R., and J. L. Hardebeck (2010), Precise tremor source locations and amplitude variations along the lower-crustal central San Andreas Fault, *Geophys. Res. Lett.*, *37*, L14301, doi:10.1029/2010GL043672.

Shelly, D. R., G. C. Beroza, S. Ide, and S. Nakamula (2006), Low-frequency earthquakes in Shikoku, Japan, and their relationship to episodic tremor and slip, *Nature*, *442*, 188–191, doi:10.1038/nature04931.

Thomas, A., R. M. Nadeau, and R. Bürgmann (2009), Tremor-tide correlations and near-lithostatic pore pressure on the deep San Andreas Fault, *Nature*, *462*, 1048–1051, doi:10.1038/nature08654.

A. Guilhem and R. M. Nadeau, Berkeley Seismological Laboratory, University of California, 225 McCone Hall, Berkeley, CA 94720-4670, USA. (aurelie@seismo.berkeley.edu)

Z. Peng, School of Earth and Atmospheric Sciences, Georgia Institute of Technology, 311 Ferst Dr., ES&T Building, Room 2256, Atlanta, GA 30332-0340, USA.