# SCEC project 12150: Spatio-temporal Patterns of Tectonic Tremor Activity (PI: J.-P. Ampuero, Caltech)

## 1 Summary


We studied observational and fundamental aspects of tectonic tremors:

1. **Observational studies**. We conducted a search for spontaneous tremors near the Anza gap of the San Jacinto fault. Initial analysis of three years of waveform data from the Anza and PBO seismic networks was complemented with field experiments based on small-aperture seismic arrays. We detected several periods of transients containing repeating waveforms with spectra peaked around 4 Hz. We determined that these transients are associated with cultural activity, most likely train traffic along the Coachella Valley. Our results place bounds on the capability to detect spontaneous tremors in southern California with current instrumentation.

2. **Theoretical studies**. We conducted theoretical investigations of the spatio-temporal patterns of tectonic tremor activity and their their relation to the mechanics and heterogeneity of faults at the base of the seismogenic zone. We developed a heterogeneous rate-and-state model of the collective behavior of fault asperities mediated by transient creep. We developed efficient software with which we conducted integrated simulations of slow slip and tremor swarms in 2D and 3D. The model provides a unified interpretation of the observed diversity of tremor migration patterns and offers a mechanical connection between speed and orientation of tremor swarms and the distribution of slip velocity within the underlying slow slip pulse. We identified tremor properties that are robust to uncertainties in the characteristics of fault heterogeneities. We developed relations between slow slip rate, friction parameters and the response of tremors to oscillatory loadings, which provide a quantitative framework to interpret the variable sensitivity of tremors to tides and surface waves in California and elsewhere. Our modeling results highlight the potential role of tremors as a monitor for aseismic transients.

# 2 Technical report

Tectonic (aka non-volcanic) tremors, one of the most intriguing discoveries of the last decade in Earth sciences, probe the mechanics of the brittle-ductile transition at the bottom of seismogenic zones, where large earthquakes might be expected to nucleate. Tectonic tremor activity is organized in swarms which spatio-temporal properties might inform about the depth extent and along-strike segmentation of seismogenic zones, two key inputs for earthquake hazard assessment. They might also constitute a natural creepmeter with implications on earthquake predictability, by offering a unique means to monitor deep aseismic slip transients that might precede or affect the occurrence of large earthquakes.
This project was aimed at investigating the relations between spatio-temporal properties of tectonic tremors and fault rheology. The research activities were organized in two separate components: observations and theory.

## Observational component: search for spontaneous tremors in Southern California

While tremors triggered by teleseismic surface waves have been identified in a few areas of southern California (Gomberg et al, 2008; Fabian and Peng, 2009; Brown et al, 2009), detecting spontaneous tremor activity in this region has been more elusive. The analysis of seismic waveform data from borehole stations of the Plate Boundary Observatory (PBO) and surface stations of the Anza seismic network, lead by then Caltech postdoctoral fellow Gregor Hillers, resulted in the identification of tremor-like signals occurring regularly in Southern California near the Anza gap of the central San Jacinto Fault. The analysis employed a two-stage approach: an initial coarse detection of ~10-min-long transients based on similarity of envelope transients across the PBO stations (Obara, 2002) followed by fine resolution detection of repeating waveform patterns by a multi-channel waveform template matching technique (Brown et al, 2008). We analyzed two years of data following the installation of the PBO stations, from January 2008 to December 2009. We found regular occurrence of tremor-like signals with increased activity in May-June and October-December in both years. The amplitude of the presumed tremor signals is very weak, almost ten times weaker than spontaneous tremor recorded near Parkfield. No systematic seasonal changes in background noise were observed in the frequency band. The number of detections is anti-correlated with the daily cultural noise and does not correlate with the number of earthquakes recorded by the stations. The most intriguing aspect of these signals is their narrow spectral content, peaked around 3 to 4 Hz. This nearly monochromatic character is in marked contrast with the broad spectra of the tectonic tremor observed in other regions (Ide et al, 2007).
The location uncertainties obtained with this dataset were large. Leveraging funding from USGS-EHRP, we conducted field experiments to collect higher quality data. The experiments were lead by Caltech graduate student Asaf Inbal. We deployed three small aperture seismic arrays for a few months. Each array consisted of about 15 short-period sensors over apertures of a few hundred meters, with equipment from the IRIS PASSCAL Instrument Center and from the SCEC PBIC. The initial array deployment in the Pinyon Flats Observatory was conducted in collaboration with Jamie Steidl's team (UCSB), with valuable input from Frank Vernon (UCSD). The arrays recorded transients similar to those identified before on PBO and Anza stations. The azimuth and slowness of the transient signals identified in our arrays were found to be inconsistent with a local and deep source (Inbal et al, 2011). For instance, azimuths at Pinyon Flats pointed mainly towards North and East, instead of towards the San Jacinto fault (West). An inspection of waveforms over a broader area revealed that these transients are of cultural origin, mostly likely vibrations induced by the traffic of freight trains along the Coachella Valley. This experience shows that the capability to detect spontaneous tremors in southern California with current instrumentation and analysis techniques is severely challenged by the ubiquity of cultural sources of seismic noise.

In collaboration with Caltech/USGS postdoctoral NSF fellow Justin Brown, we are now working on the development of an automated tremor detector. We are assessing if we can discriminate between tremor and traffic noise based on spectral shapes (Brown et al, 2012a, 2012b).

High frequency train vibrations propagating over distances of several tens of kilometers despite the rough topography might carry information about the wave propagation path and the structure of the valley. The trains follow a path sub-parallel to the San Andreas fault and constitute a somewhat controlled source (train schedules are available with timing at each stop). We are investigating the usefulness of these noise sources to characterize properties of the sedimentary basin relevant for earthquake hazard assessment.

## Theoretical component: integrated modeling of slow slip and tremors

The patterns of tremor migration observed in subduction and strike-slip faults, including the San Andreas fault in central California, are very diverse. In Cascadia, at the largest scale, tremors migrate along-strike at ~10 km/day, in coincidence with the propagating front of slow slip events (SSE). At a finer scale, "rapid tremor reversals" (RTR) are swarms that propagate in the opposite direction at ~100 km/day (Houston et al, 2010). At an even finer scale, fast swarms propagate along-dip on narrow streaks at ~1000 km/day (Ghosh et al, 2010).

Our first objective was to develop a mechanical model that unifies these observations. Our conceptual model (Ampuero, 2010a, 2010b) postulates that tremor migration speed is controlled by the spatial distribution of slip velocity inside the underlying SSE pulse. This is motivated by previous models of pulse-like rupture (e.g. Ampuero and Rubin, 2008; Rubin and Ampuero, 2009) and post-seismic slip migration (Perfettini and Ampuero, 2008). The spatial distribution of sliding velocity inside a slip pulse (e.g. the Yoffe function) is highly asymmetric: it is peaked near the leading front and tapers off gradually towards the pulse tail. Post-seismic creep induced by the rupture of an asperity migrates into the surrounding creeping region with a propagation speed that correlates with the background creep slip velocity (Perfettini and Ampuero, 2008).

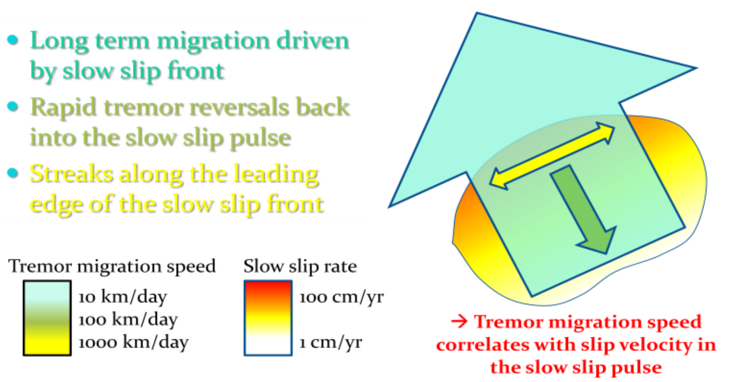


*Figure 1: Conceptual description of a model that unifies three major tremor migration patterns (forward migration, along-dip swarms and rapid tremor reversals) and their relation to the spatial distribution of slip rate within a slow slip pulse.*

We consider a fault with very heterogeneous frictional properties, comprising a collection of unstable asperities (compact fault patches capable of fast slip and seismic radiation) embedded in a more stable fault region (Ampuero, 2012; Ariyoshi et al, 2009, 2012). The asperities fail seismically when loaded by the surrounding transient slip induced by a SSE, and produce the low frequency earthquakes (LFEs) that constitute tremor swarms. Interactions among asperities occur mainly via additional transient creep: each asperity rupture produces a postseismic slip transient that propagates along the fault, carrying a stress perturbation that triggers failure of neighboring asperities. This triggering process mediated by transient creep repeats, resulting in a cascade of brittle asperity failures analogous to a tremor swarm. The migration speed of the tremor swarm is controlled by the propagation speed of the postseismic creep, which in turn is correlated to the background slip rate imposed by the large-scale SSE pulse. The model hence leads to a plausible interpretation of the observed tremor migration patterns (Figure 1): fast along-dip tremors propagate along the rupture front of the ongoing SSE, where background slip velocities are highest, while the slower RTRs propagate towards the tail of the SSE pulse, where background slip velocities are lower.

Our second objective was to develop 2D numerical simulations of a specific realization of this conceptual model within the rate-and-state friction framework, to develop its implications on fault frictional properties (Luo and Ampuero, 2011, 2012). Because our focus was on tremor swarms, we simulated the underlying SSE by a somewhat ad hoc procedure: following Shibazaki and Iio (2003) we assumed a rate-and-state friction with a velocity cut-off that introduces a transition from velocity-weakening to velocity-strengthening at increasing slip rate. We defined asperities as small velocity-weakening patches with shorter characteristic slip distance Dc and higher effective normal stress ($\sigma$) than their surroundings. We adopted the "slip law" for the evolution of the state variable because it allows asperities of a certain size (conditionally stable) to be triggered only by fast enough transient slip. We conducted a series of integrated numerical simulations of slow slip and tremor swarms to investigate the quantitative implications of our model. We studied the effect of model parameters such as the size and spacing of the asperities and the contrast of $a\sigma$ and Dc with respect to the background.

Figure 2 shows an example of modeled tremor swarms triggered by a slow slip front. Our 2D model successfully simulates two observed tremor migration patterns. The slow forward migration is naturally due to tremor triggering near the leading front of the propagating SSE pulse. Less trivially, our model also produces RTRs with similar characteristics as in Cascadia: spatially scattered swarms back-propagating at fast speed of order 100 km/day. These RTRs are rare because they nucleate at the asperities with largest Dc and highest $a\sigma$. Ratios of SSE to RTR migration velocity comparable to observations are obtained for large enough contrasts of $a\sigma$ and small enough distance between asperities.

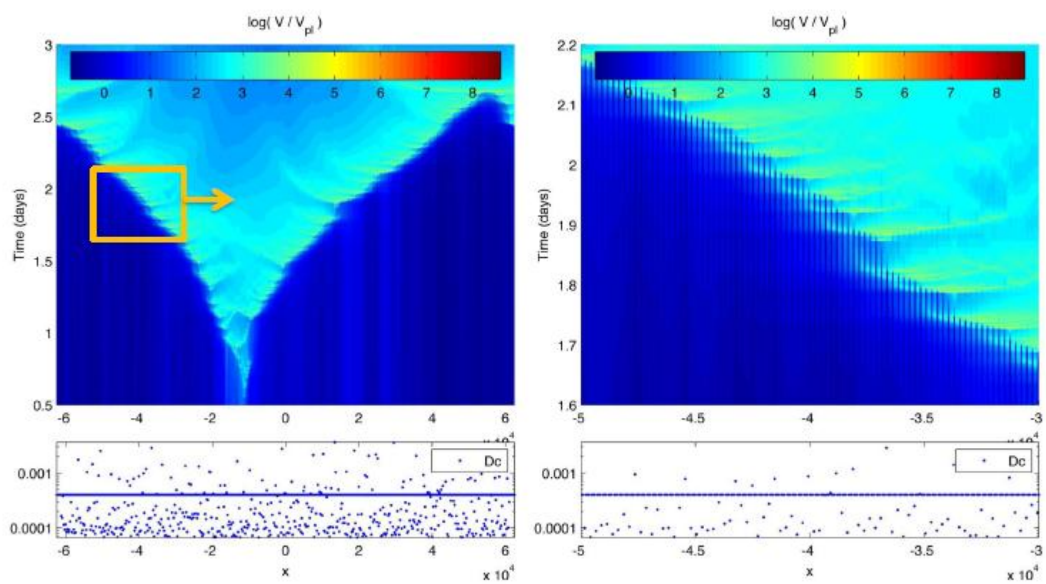


*Figure 2. Top: Spatio-temporal distribution of slip velocity in a simulation of slow slip and tremor. Bottom: assumed spatial distribution of critical slip distance Dc. Right: zoom in on the boxed region of the left plot, showing tremor swarms triggered at the leading front of the slow slip, including rapid tremor reversals.*

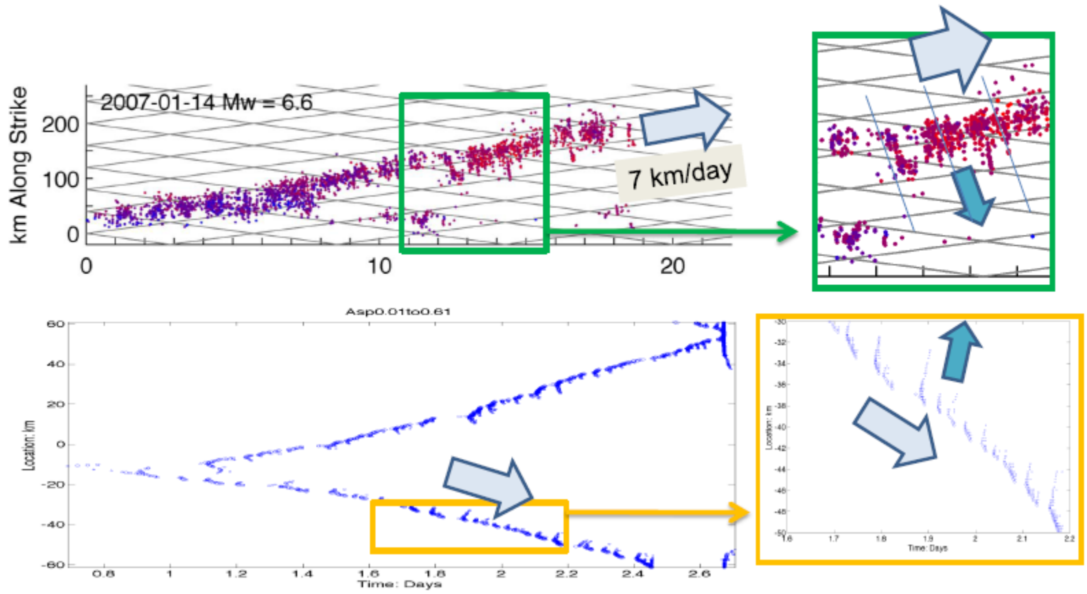


*Figure 3. Top: spatio-temporal distribution of tremor activity during an ETS event in Cascadia (Houston et al, 2011). The light blue arrow shows the large scale slow migration. The zoom (right) shows some rapid tremor reversals (dark blue arrow). Bottom: similar plot derived from the results of the simulation shown in figure 3, showing slow migration and RTRs (Luo and Ampuero, 2011a, 2011b).*

Our third objective was to conduct 3D simulations of slow slip and tremors. For this purpose, we developed an open source 3D quasi-dynamic earthquake simulator based on the boundary element method, QDYN, available at http://code.google.com/p/qdyn/. With this tool we are now in a position to investigate the implications of our model on the along-dip tremor migration patterns and on the earthquake cycle. An example is shown in figure 4, simulation movies are posted in the QDYN website. Our 3D simulation efforts also included collaboration with JAMSTEC colleagues (Ariyoshi et al, 2009, 2012). We were able then to reproduce some key observations of tremors. We also found an interesting precursory pattern of acceleration of tremor migration speed and shortening of tremor recurrence time at the approach of a large earthquake in the overlying seismogenic zone.

We also studied the response to oscillatory loads of a fault region with velocity-strengthening properties close to velocity neutral, i.e. a close to b (Ader et al, 2012a). Combining analytical and numerical investigations of a spring-block model we found that these regions are highly sensitive to cyclic loads: oscillatory stress perturbations in a certain range of periods induce large transient slip velocities. These aseismic transients can in turn trigger tremor activity with enhanced oscillatory modulation. In this sensitive regime, a harmonic Coulomb stress perturbation of amplitude $\Delta S$ causes a slip rate perturbation which amplitude depends exponentially on $\Delta S/((a-b)\sigma)$, where $\sigma$ is the effective normal stress. This result is in agreement with observations of the relationship between tremor rate and amplitude of stress perturbations for tremors triggered by passing seismic waves. Our model of tremor modulation mediated by transient creep does not require extremely high pore fluid pressure and provides a framework to interpret the sensitivity and phase of tidally modulated tremors observed in Parkfield and Shikoku in terms of spatial variations of friction parameters and background slip rate.

The model was recently extended to 1D faults embedded in a 2D elastic continuum (Ader et al, 2012b). We found enhanced sensitivity to periodic loading over all periods with, again, a peak of sensitivity at certain period ranges. A direct interpretation of these results based on our previous spring-block analysis is not straightforward. More work is needed to understand the effect of the periodic loading on the growth and eventual destabilization of the nucleation region.

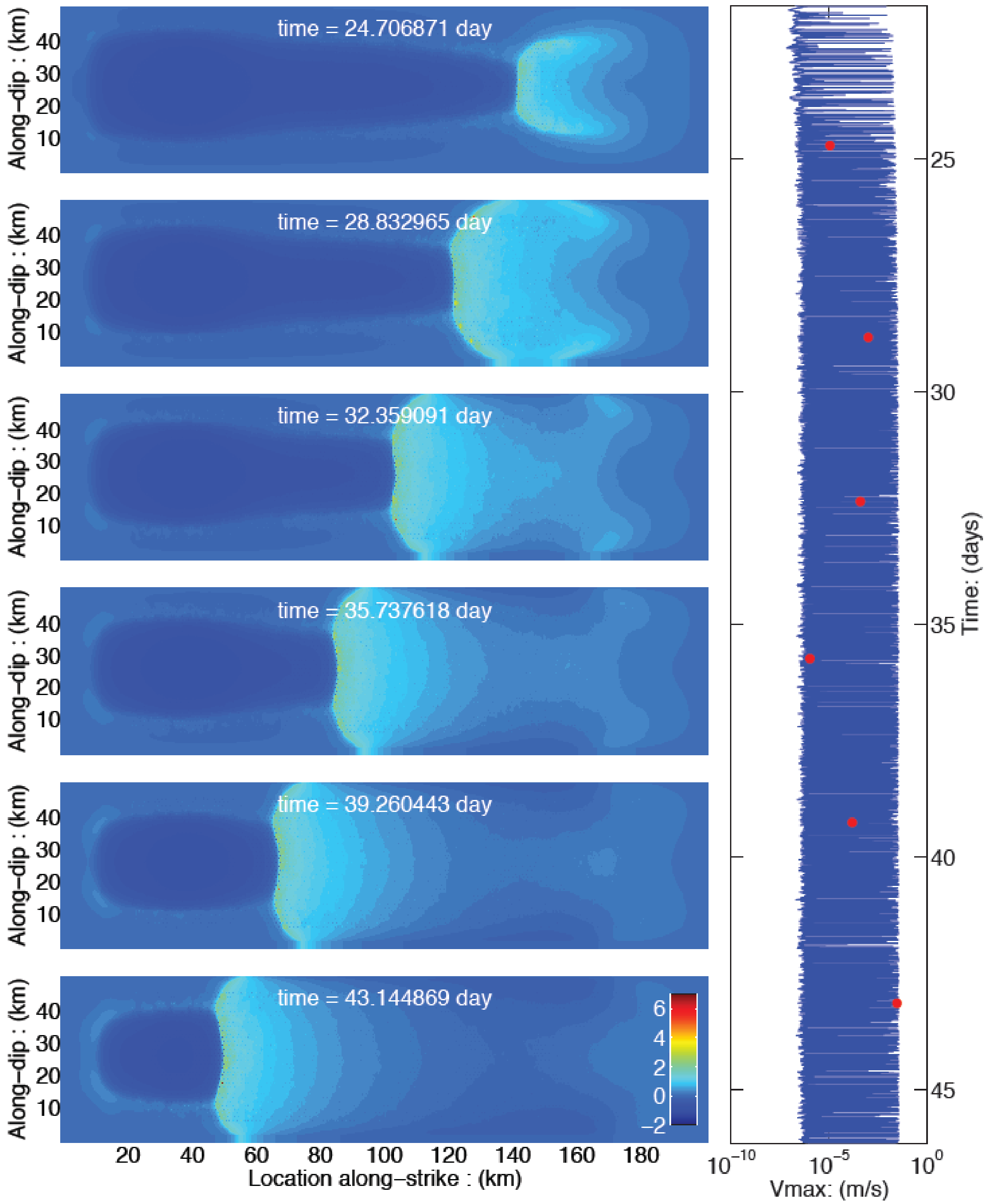


*Figure 4. A 3D integrated simulation of slow slip and tremor with the software QDYN. Left: spatial distribution of the logarithm of slip velocity, normalized by the plate rate, at 5 different times during a slow slip event. The simulation includes tremors triggered on small velocity-weakening asperities by slow slip , and interacting with each other via local creep transients. Right: tremor activity indicated by peaks of the maximum slip velocity as a function of time (Luo and Ampuero, 2012c).*

## 3. Intellectual merit

This research addresses a priority objective of FARM to understand the implications of slow slip events and non-volcanic tremors on the constitutive properties of faults and overall seismic behavior, and that of CDM to investigate possible causes and effects of transient slip. Slow slip and tremors, one of the most intriguing discoveries of the last decade in Earth sciences, has been the target of many observational studies but modeling studies are still needed. Spontaneous tremor has not been documented yet in southern California. The data analysis developed here will guide future efforts to detect tremor activity in southern California. The model developed here provides a framework to unify a diversity of tremor observations and to relate them to the mechanical properties of faults and their heterogeneity near brittle-ductile transition zones. Our models contribute to the physical basis of using tremors as a monitor for aseismic transients. They also contribute to the design and interpretation of laboratory observations (Lengline et al, 2011a, 2011b, 2012; Yamaguchi et al, 2012).
Our research directly addressed the following SCEC4 research priorities and requirements.

- 1b: We conducted a "focused numerical study of the character of the lower crust, its rheology, stress state". Our overarching goal is to extract information about the rheology and heterogeneity of the brittle-ductile transition region of active faults from the study of tremor activity patterns.
- 5d: Our research includes a "development of physics-based models of slow slip and tectonic tremor" constrained by observed features of tremor occurrence.
- 5c: Our work includes "collaboration with rock mechanics laboratories on laboratory experiments to understand the mechanisms of slow slip and tremor". Our focus is currently on acoustic emission data from analog experiments (not rocks) that capture the main ingredients of our proposed models (Lengline et al, 2011a, 2011b, 2012).

## 4. Broader impacts

The project provided training and research opportunities for three graduate students in Caltech. The observational activities involved other SCEC researchers (Jamie Steidl, UCSB) and SCEC PBIC instrumentation. Open source software for quasi-dynamic earthquake simulation was produced and was made available online (http://code.google.com/p/qdyn/). A workshop on its usage was provided to Caltech graduate students and to researchers in a European university (Utrecht). This research has implications on earthquake nucleation and predictability.

## 5. Cited references

See also section "Publications and presentations related to this project".

Ampuero, J.-P., and A. M. Rubin (2008), *Earthquake nucleation on rate-and-state faults: aging and slip laws*, J. Geophys. Res., 113, B01302, doi:10.1029/2007JB005082K.

Ariyoshi, K., T. Hori, J.-P. Ampuero, Y. Kaneda, T. Matsuzawa, R. Hino and A. Hasegawa (2009), *Influence of interaction between small asperities on various types of slow earthquakes in a 3-D simulation for a subduction plate boundary*, Gondwana Res., 16, 3-4, 534-544, doi:10.1016j/j.gr.2009.03.006

Brown, J. R., G. C. Beroza, and D. R. Shelly (2008), An autocorrelation method to detect low frequency earthquakes within tremor, Geophys. Res. Lett., 35, L16305, doi:10.1029/2008GL034560.

Brown, J. R., D. R. Shelly, A. Aguiar, and G. C. Beroza (2009), Triggered tremor on the San Jacinto fault from the 3 August 2009 Mw 6.9 Gulf of California earthquake, Annual SCEC meeting poster 1-095, Palm Springs

Fabian, A., and Z. Peng (2009), Systematic Search of Triggered Non-Volcanic Tremor in Southern California, Annual SCEC meeting poster 1-094, Palm Springs.

Ghosh, A., J. E. Vidale, J. R. Sweet, K. C. Creager, A. G. Wech, and H. Houston (2010),Tremor bands sweep Cascadia, *Geophys. Res. Lett.*, 37, L08301, doi:10.1029/2009GL042301.

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

Houston H., B. G. Delbridge, A. G. Wech and K. C. Creager (2011), Rapid tremor reversals in Cascadia generated by a weakened plate interface, Nature Geoscience 4, 404–409, doi:10.1038/ngeo1157

Ide, S., G. C. Beroza, D. R. Shelly, and T. Uchide (2007), A scaling law for slow earthquakes, Nature, 447, 76–79, doi:10.1038/nature05780.

Lengline, O., J. Schmittbuhl, J. E. Elkhoury, J.-P. Ampuero, R. Toussaint and K. J. Maloy (2011a), *Downscaling of fracture energy during brittle creep experiments*, J. Geophys. Res., 116, B08215, doi:10.1029/2010JB008059

Lengline, O., R. Toussaint, J. Schmittbuhl, J. Elkhoury, J.-P. Ampuero , K. T. Tallakstad, S. Santucci and K. J. Maloy (2011b), *Average crack-front velocity during subcritical fracture propagation in a heterogeneous medium*, Phys. Rev. E, 84, 036104 , doi:10.1103/PhysRevE.84.036104

Lengline, O., J. E. Elkhoury, G. Daniel, J. Schmittbuhl, R. Toussaint, J.-P. Ampuero and M. Bouchon (2012), *Interplay of seismic and aseismic deformations during earthquake swarms: an experimental approach*, Earth Plan. Sci. Lett., 331-332, 215-223, doi:10.1016/j.epsl.2012.03.022

Obara, K. (2002), Nonvolcanic Deep Tremor Associated with Subduction in Southwest Japan, Science, 296, 1679–1681.

Perfettini, H., and J.-P. Ampuero (2008), Dynamics of a velocity strengthening fault region: Implications for slow earthquakes and postseismic slip, J. Geophys. Res., 113, B09411, doi:10.1029/2007JB005398

Rubin A. and J.-P. Ampuero (2009), Self-similar slip pulses during rate-and-state earthquake nucleation, J. Geophys. Res., 114, B11305, doi:10.1029/2009JB006529

Shibazaki, B. and Y. Iio (2003), On the physical mechanism of silent slip events along the deeper part of the seismogenic zone, Geophys. Res. Let., 30 (9), 1489, doi:10.1029/2003GL017047

Yamaguchi, T., M. Morishita, M. Doi, T. Hori, H. Sakaguchi and J.-P. Ampuero (2011), *Gutenberg-Richter's law in sliding friction of gels*, J. Geophys. Res., 116, B12306, doi:10.1029/2011JB008415

## 6. Publications and presentations related to this project


T. J. Ader, J.-P. Ampuero and J.-P. Avouac (2012a), The role of transient slow slip on the modulation of tectonic tremor activity by periodic loading, Geophys. Res. Lett., 39, L16310, doi:10.1029/2012GL052326.

T. J. Ader, J.-P. Ampuero, J.-P. Avouac and N. Lapusta (2012b), Response of rate-and-state faults to periodic stress variations (poster), Abstract S21B-2486, AGU Fall Meeting, San Francisco, CA, Dec. 2012.

J.-P. Ampuero (2010a), Tremor Migration Patterns and Scaling Laws Resulting From the Interaction of Fault Asperities Mediated by Transient Creep (invited talk), The EarthScope Institute on the Spectrum of Fault Slip Behaviors, Portland, OR, Oct. 2010.

J.-P. Ampuero (2010b), Migration Patterns and Scaling Laws of Slow Slip and Tremor Resulting From the Collective Behavior of Fault Asperities Mediated by Transient Creep (Invited), Abstract S13D-03, AGU Fall Meeting, San Francisco, CA, Dec. 2010.

J.-P. Ampuero (2012), Slow slip, tremor and the multi-scale mechanics of heterogeneous fault (Invited), Abstract S44B-01, AGU Fall Meeting, San Francisco, CA, Dec. 2012.

K. Ariyoshi, T. Matsuzawa, J.-P. Ampuero, R. Nakata, T. Hori, Y. Kaneda, R. Hino and A. Hasegawa (2012), Migration process of very low-frequency events based on a chain-reaction model and its application to the detection of preseismic slip for megathrust earthquakes, Earth, Planets and Space, 64 (8), 693-702, doi:10.5047/eps.2010.09.003

J. Brown, S. E. Hough and J.-P. Ampuero (2012a), Detecting Ambient Tectonic Tremors in Southern California, Poster 165, SCEC Annual Meeting, Palm Springs, CA, Sep. 2012.

J. Brown, S. E. Hough and J.-P. Ampuero (2012b), Detecting Ambient Tectonic Tremor in Southern California (poster), Abstract S33B-2534, AGU Fall Meeting, San Francisco, CA, Dec. 2012.

J. E. Elkhoury, O. Lengliné, J.-P. Ampuero, and J. Schmittbuhl (2010), Intermittent Fault Slip Embedded in Creep Generates Seismic Events: Insight from Acoustic and Optical Monitoring of Crack Propagation (poster), SCEC Annual Meeting, Palm Springs, CA, Sep. 2010.

A. Inbal, J.-P. Ampuero, and J.H. Steidl (2011), Monitoring Tectonic Tremors in the San-Jacinto Fault Zone Using Multiple Small-Aperture Seismic Arrays (poster), SCEC Annual Meeting, Palm Springs, CA, Sep. 2011.

Y. Kaneko and J.-P. Ampuero (2011a), A mechanism for preseismic steady rupture fronts observed in laboratory experiments, Geophys. Res. Lett., 38, L21307, doi:10.1029/2011GL049953

Y. Kaneko and J.-P. Ampuero (2011b), A mechanism for preseismic steady rupture fronts observed in laboratory experiments (poster), Abstract T13A-2362, AGU Fall Meeting, San Francisco, CA, Dec. 2011.

Y. Luo and J.-P. Ampuero (2011a), Numerical Simulation of Slow Slip Triggered Tremor Migration and Rapid Tremor Reversals (poster), SCEC Annual Meeting, Palm Springs, CA, Sep. 2011.

Y. Luo and J.-P. Ampuero (2011b), Numerical Simulation of Tremor Migration Triggered by Slow Slip and Rapid Tremor Reversals, Abstract S33C-02, AGU Fall Meeting, San Francisco, CA, Dec. 2011.

Y. Luo and J.-P. Ampuero (2012a), A heterogeneous view of the deep seismic/aseismic transition of subduction zones: modeling of complex tremor migration patterns (poster), workshop on "Materials' Deformation : Fluctuations, Scaling, Predictability ", Les Houches, France, Jan. 2012.

Y. Luo and J.-P. Ampuero (2012b), Modeling of 3D complex tremor migration patterns, Seism. Res. Lett., 83:2, 408, SSA Annual Meeting, San Diego, CA, Apr. 2012.

Y. Luo and J.-P. Ampuero (2012c), A Quasi-DYNamic Earthquake Simulator (QDYN) for earthquake cycle, slow slip and tremor modeling, Poster 278, SCEC Annual Meeting, Palm Springs, CA, Sep. 2012.

Y. Luo and J.-P. Ampuero (2012d), Simulation of complex tremor migration patterns, Abstract S44B-02, AGU Fall Meeting, San Francisco, CA, Dec. 2012.