In 2001, a paper found a silent slip event on the deeper Cascadia Subduction Interface [*Dragert et al.*, 2001]. This discovery comes from the observation of the GPS stations that reversed their direction of motion (see the following figure). This paper conducted a slip inversion to model the observation. And they found that the sudden displacements are best explained by ~2 centimeters of aseismic slip over a 50-kilo-meter-by-300-kilometer area on the subduction interface downdip from the seismogenic zone, a rupture equivalent to an earthquake of moment magnitude 6.7. This paper provides evidence that slip of the hotter, plastic part of the subduction interface, and hence stress loading of the megathrust earthquake zone, can occur in discrete pulses.



In 2002, anther paper in science found the periodicity of slow earthquakes in Cascadia [*Miller*, 2002]. They found the slow earthquakes occur on average every 14.5±1 months over 10 years. The conclusion from this paper is: the regular and cyclical nature of the transient events indicates that they are a fundamental mode of strain release in subduction zones.

The tremor first found and proposed in non-volcanic setting using seismic network [*Obara*, 2002]. The tremor was found southwest Japan. The predominant frequency of the tremors ranged from 1 to 10 Hz, and was lower than that of ordinary earthquakes of similar size. The tremors are around depth of 30 km. The following figure shows the location of the tremor, but we can see two gaps where there’s no tremors.



The possible cause of the tremor this paper gave is: considering the long duration and mobility of the tremor activity, the generation of tremors may be related to the movement of fluid in the subduction zone. At high temperature and pressure, aqueous fluid mixed with silicate melts exists as a supercritical fluid. The presence of supercritical fluid may reduce the friction and change the fracture criterion of the rock by increasing the pore pressure and/or create new cracks through hydraulic fracturing. Therefore, tremor activity with a long duration time might be caused by a chain reaction of small fractures caused by the supercritical fluid. Periodic

After the Japanese paper about Tremor, [*Rogers and Dragert*, 2003] combine the seismic data and GPS data to prove the tremor on the seismic data is correlate with the slip seen on the GPS at Cascadia. The tremor at Cascadia is different from that in Japan in that: the signals observed in Cascadia correlate temporally and spatially with six deep slip events that have occurred over the past 7 years. Also, in this paper, they first refer to this associated tremor and slip phenomenon as episodic tremor and slip (ETS). They have one paragraph with a definition what is ETS.

[*Nedimović et al.*, 2003] from the reflection profile showed that there is a change in the reflection character on seismic images from a thin sharp reflection where the subduction thrust is inferred to be locked, to a broad reflection band at greater depth where aseismic slip is thought to be occurring. This suggests that these slip events occur where faults deform ductily in zones that are several kilometers thick and that contain substantial fluid-filled porosity. This change in reflection character may provide a new technique to map the landward extent of rupture in great earthquakes and improve the characterization of seismic hazards in subduction zones.

[*Kodaira et al.*, 2004] reported the seismic imaging, which shows a zone of high pore fluid pressure (high Poisson’s ratio) in the subducted oceanic crust located down-dip of a subducted ridge. They propose that these structures effectively extend a region of conditionally stable slips and consequently generate the silent slip.

[*Nadeau and Dolenc*, 2005] found tremor exists at a transform plate boundary zone along the San Andreas Fault (SAF). The SAF tremors are less frequency (fewer than 5 events detected in any 24-hour period), have shorter durations (less than 20 min), have smaller peak amplitudes (< M0.5 earthquake), and release less energy (energy equivalents < M1.5). There’s a correlation between tremor and local earthquake rates at Cholame.

Same year in 2005, a paper published in Nature show the tremors in northern Cascadia are distributed over a depth range exceeding 40 km within a limited horizontal band [*Kao et al.*, 2005]. They are using a newly developed method ‘source scanning algorithm’ (SSA) to identify the tremors. They found the tremors are distributed over a wide depth range than thought before only at the slab interface. They gave the difference of tremors and earthquakes in this paper: (1) difference in the distribution, tremors tend to occur in places where local earthquakes are sparse; (2) tremors are more in the 1 – 5 Hz frequency band. The possible explanations of tremor are: (1) fluid released from the dehydration of subducted materials facilitating the occurrence of ETS tremors. (2) Alternatively, if the tremors are interpreted as the de facto seismic part of the episodic slip, then the slip may have occurred in a zone much more diffuse than previous studies have suggested.

The two following papers from Greg Beroza’s group provided many evidences to argue that LFEs (Low Frequency Earthquakes) and the tremors are from the same processes. These papers are really great to show you how you use difference evidences to support your hypothesis.

[*Segall et al.*, 2006] report on swarms of high-frequency earthquakes that accompany silent slips at Hawaii. The temporal evolution of earthquakes is well explained by increased stressing caused by slow slip, implying that the earthquakes are triggered. However, there have been many well documented episodes of slow slip in Cascadia, Japan, Mexico, Alaska, and Costa Rica, none of which have been accompanied by a large earthquake.

[*Lowry*, 2006] argues that the periodic slow fault slip may be a resonant response to climate-driven stress perturbations. Fault slip resonance helps to explain why slip events are periodic, why periods differ from place to place, and why slip focuses near the base of the seismogenic zone. These events must initiate in velocity weakening conditions – that is, within the zone of nucleation of a future great earthquake – further suggesting that slow slip events can illuminate the frictional properties that control earthquake slip.

[*Shelly et al.*, 2006] published a nature paper about low-frequency earthquakes in Japan. But they showed strong evidence that these earthquakes occur on the plate interface, coincident with the inferred zone of slow slip. This paper brings in many different type of new information to support the idea. The first thing they did is to align these LFEs based on cross-correlation, and relocate the events. The relocation of the events showing them occurred on the slab interface. And the correlations with regular seismicity along with observed larger S-wave amplitudes suggest that the LFEs themselves represent shear failure. They also plot the LFEs with P and S wave speed from the tomography, and the Vp/Vs ratio. And they find the high Vp/Vs ratio which indicate that these LFEs are enabled by the release of fluids in the subduction zone. Last, they propose that the coupled phenomena of tremor, LFEs and episodic slow slip events represent a mode of failure ofr a transition zone between a locked and continuously creeping fault. Put everything together: Precise locations indicate that the LFEs analysed in this study occur on the plate interface. The correlation between LFEs and regular seismicity, the fact that LFEs are primarily composed of shear waves, and the remarkable correspondence with slow slip events5–7 argue that LFEs represent shear slip on this interface. They propose that LFEs may be generated by local slip accelerations at geometric or frictional heterogeneities that accompany large slow slip events on the plate interface. Long-duration tremor may result simply from a superposition of many concurrent LFEs. Alternatively, long-duration tremor might represent a combined signal of shear slip and fluid flow. We hypothesize that increasing fluid pressure may reduce the effective normal stress and enable slip on the plate interface; this slip could increase permeability and allow pressurized fluid to escape, possibly contributing to the tremor signal in the process. In either case, evidence discussed above suggests that fluids play a key role in the failure process. Remote triggering of tremor and LFEs , reminiscent of earthquake triggering seen in hydrothermal regions, provides additional evidence for fluid enablement.

At the beginning of 2007, a paper published in science from a Japanese group found Very-Low-Frequency (VLF) Earthquakes that accompanies and migrates with the activity of deep low-frequency tremors and slow slip events [*Ito et al.*, 2007]. The VLF earthquakes are in the frequency band 0.02 – 0.05 Hz, and seem located at the plate interface as well, though the depth constrain is not good. The moment tensor and the waveform P and S phase apart suggest that the VLF earthquakes are caused by shear. Also the migration of the VLF earthquakes coincidence with the deep low-frequency tremors. The excitations of wave trains caused by VLF earthquakes appear to always overlap with the peak amplitude of wave trains caused by deep low-frequency tremors, but not the other way around, make them suggest that the VLF event and the deep low-frequency tremors are two distinct phenomena. Based on these, they gave the possible scenario of the stress-relaxation process in the transition zone based on the asperity model.

In 2007, [*Shelly et al.*, 2007] bring in more evidences to show that tremor and slow slip are different manifestations of a single process. They first show the support from the mechanism of LFEs they calculated in [*Ide et al.*, 2007b], and argue it is similar to the recent megathrust earthquake in the same area. Besides, they also show the similarity of the waveform between the LFEs and regular earthquakes. This can be shown in the similarity of the frequency content of LFEs and tremor. All these lines of evidence indicate that LFEs are generated by shear slip on the plate interface. Then they argue if the same shear-faulting source generates both LFEs and tremor, we might expect to see additional weaker events within tremor with waveforms similar to the previously identified LFEs. So they conducted a matched-filter technique (not sure if this is the first paper propose this method) using the LFEs as the template, and reveals a nearly continuous sequence of LFEs during periods of active tremor. The detections are highly clustered, but heterogeneous distributed on the plate, which reflects the properties of the plate boundary. Clusters of relatively strong LFEs may occur in places of geometric or compositional variations where the fault sticks and slips as part of much larger scale slow slip transients – a process analogous to that proposed for some foreshock sequences or earthquake swarms in other environments. In this case, high fluid pressure on the plate boundary could allow slip to occur under low shear stress, resulting in relatively slow rupture and slip velocities (compared with ordinary earthquakes) and a corresponding deficit in high frequency energy.

[*Ide et al.*, 2007a] show the deep episodic tremor, low-frequency earthquakes, very-low-frequency earthquakes, slow slip events, and silent earthquakes all follow a simple, unified scaling relationship that clearly differentiates their behavior from that of regular earthquakes. This scaling and spectral behavior demonstrates that they can be thought of as different manifestations of the same phenomena. They also proposed two different models, i.e. constant low-stress drop mode and diffusional constant-slip model to explain the observed scale dependence of rupture velocity for these events.

Tremors can be triggered by large distant earthquakes have already been explored by many groups. [*Rubinstein et al.*, 2007] identifies bursts of tremor at Cascadia subduction zone caused by the Love wave displacement from the Denali, Alaska earthquake. They show the displacements correspond to shear stresses of approximately 40 kPa on the plate interface, which suggests that the effective stress on the plate interface is very low. They conclude that tremor and possibly slow slip can be instantaneously induced by shear stress increases on the subduction interface – effectively a frictional failure response to the driving stress. The interesting part of this paper is how they relate the stress from the Love wave to the triggered tremor, which support their hypothesis that shear stress on the plate interface from love waves of the Denali earthquake triggered the tremor. They also show the similarity in the frequency domain of the triggered and regular tremor, which they argue these driven by the same mechanism but slightly different conditions.

In 2008, [Gomberg et al., 2008] shows the triggered tremor at 7 different sites in California, i.e. 5 strike-slip faults, and 2 minor faults. The distribution of the tremors have no clear correlation between where the faults are creeping, locked, or transitional, and also, the lack of triggered tremor n these geothermal regions implies that high fluid pressure and/or temperatures, although they may be necessary, are not alone sufficient to produce tremor.

[*Rubinstein et al.*, 2008] shows clear pulsing of tremor activity with periods of 12.4 and 24 to 25 hours, after rule out other possibilities, they conclude that these periods corresponding to lunar and lunisolar tides. They show the correlation both in the time domain, and the dominant period of the tremor and the tides. Since stress associated with tides are small, they argue that tremors occurs on very weak faults.

[*La Rocca et al.*, 2009] proposed a new method to estimate the location of the tremor by using cross-correlation of the vertical and horizontal seismograms with array process techniques. This method can resolve the depth of tremor sources within ±2 km. With the better estimate of the location, they argue that the sources of Cascadia tremor are located near or on the subducting slab interface. Strong correlations and steady S-P time differences imply that tremor consists of radiation from repeating sources. But this method has two limitations that can be only used in specific settings and difficult to generalize to other cases.

[*Song et al.*, 2009] using Receiver Function method to model the converted SP arrivals and teleseismic underside reflections in southern Mexico, and found a ultra-slow velocity layer (USL) near the top of the subducting plate. This USL coincide with the slo slip, tremors. They give the hypothesis that this layer is probably the blueschist-eclogite dehydration reaction, the fluid released from this reaction could percolate into the overriding plate, produce the observed high electric conductivity, and probably trigger the Non-Volcanic tremors. Fluid appear to be trapped up-dip in a high pore-fluid pressure layer and it is probably controlled by material-dependent permeability and fluid generation processes near the interface.

In [*Nadeau and Guilhem*, 2009], the author found a couple of differences of tremors at San Andreas Fault (SAF) and that at the subduction zone. It also suggests that the SAF may broaden into several distinct subparallel zones as it extends into the ductile lower crust. With stress modeling, this paper also suggests that tremors are a more sensitive indicator of stress change than are earthquakes, but it more sensitive to shear stress than normal stress. Possible cause of tremor in this setting was give due to fluid, but two hypothesis are (1) serpentinite bodies are present at depth to be a potential fluid sources, and (2) deep mantle-derived fluids might be another source.

[*Thomas et al.*, 2009] identify a robust correlation between tidally induced shear stress parallel to San Andreas Fault (SAF) and non-volcanic tremor activity near Parkfield. They conduct a chi-square statistic to test the null hypothesis that event times are randomly distributed with respect to tidal influence, and found that they can reject the null hypothesis for tremor. They also explore the apparent correlation between tremor and tidally induced stress by comparing tremor times with the loading conditions under which they occur. Induced right-lateral shear stresses seems have the most compelling correlation. Assuming a frictional Coulomb failure process, they found the optimal friction coefficient is 0.02, which demonstrates that tidally induced shear stress parallel to the SAF, although of much smaller magnitude than normal stress changes, has the most robust correlation with non-volcanic tremor near Parkfield.

[*Shelly*, 2010] using matched filter method to identify tremor and decomposing them into different families from continuous seismic data from mid-2001 to 2008. He finds that tremor exhibits nearly continuous migration, which suggest that San Andreas Fault remains a localized through-going structure, at least to the base of the crust. He also finds that the tremor rates and recurrence behavior changed markedly in the 2004 M6.0 Parkfield earthquake, but these changes were far from uniform within the tremor zone, probably reflecting heterogeneous fault properties and static and dynamic stresses decaying away from the rupture. In this paper, he also explains the difference of the tremors in SAF and in japan and Cascadia, which is quite clear. Besides, he talks about the advantage of using matched filter over other method in this paper as well.

**References:**

Dragert, G., K. Wang, and T. S. James (2001), A silent slip event on the deeper Cascadia subduction interface., *Science*, *292*(5521), 1525–8, doi:10.1126/science.1060152.

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.

Ide, S., G. C. Beroza, D. R. Shelly, and T. Uchide (2007a), A scaling law for slow earthquakes, *Nature*, *447*(7140), 76–79, doi:10.1038/nature05780.

Ide, S., D. R. Shelly, and G. C. Beroza (2007b), Mechanism of deep low frequency earthquakes: Further evidence that deep non-volcanic tremor is generated by shear slip on the plate interface, *Geophys. Res. Lett.*, *34*(3), doi:10.1029/2006GL028890.

Ito, Y., K. Obara, K. Shiomi, S. Sekine, and H. Hirose (2007), Slow Earthquakes Coincident with Episodic Tremors and Slow Slip Events, edited by Intergovernmental Panel on Climate Change, *Science (80-. ).*, *315*(5811), 503–506, doi:10.1126/science.1134454.

Kao, H., S.-J. Shan, H. Dragert, G. Rogers, J. F. Cassidy, and K. Ramachandran (2005), A wide depth distribution of seismic tremors along the northern Cascadia margin, *Nature*, *436*(7052), 841–844, doi:10.1038/nature03903.

Kodaira, S., A. Kato, and J. Park (2004), High Pore Fluid Pressure May Cause Silent Slip in the Nankai Trough, *Science (80-. ).*, *304*(May), 1295–1299, doi:10.1126/science.1096535.

Lowry, A. R. (2006), Resonant slow fault slip in subduction zones forced by climatic load stress., *Nature*, *442*(7104), 802–805, doi:10.1038/nature05055.

Miller, M. M. (2002), Periodic Slow Earthquakes from the Cascadia Subduction Zone, *Science (80-. ).*, *295*(5564), 2423–2423, doi:10.1126/science.1071193.

Nadeau, R. M., and D. Dolenc (2005), Nonvolcanic tremors deep beneath the San Andreas fault, *Science (80-. ).*, *307*(January), 389, doi:10.1126/science.1107142.

Nadeau, R. M., and A. Guilhem (2009), Nonvolcanic tremor evolution and the San Simeon and Parkfield, California, earthquakes, *Science (80-. ).*, *325*(5937), 191–193, doi:10.1126/science.1174155.

Nedimović, M. R., R. D. Hyndman, K. Ramachandran, and G. D. Spence (2003), Reflection signature of seismic and aseismic slip on the northern Cascadia subduction interface, *Nature*, *424*(6947), 416–420, doi:10.1038/nature01840.

Obara, K. (2002), Nonvolcanic Deep Tremor Associated with Subduction in Southwest Japan, *Science (80-. ).*, *296*(5573), 1679–1681, doi:10.1126/science.1070378.

La Rocca, M., K. C. Creager, D. Galluzzo, S. Malone, J. E. Vidale, J. R. Sweet, and A. G. Wech (2009), Cascadia Tremor Located Near Plate Interface Constrained by S Minus P Wave Times, *Science (80-. ).*, *323*(5914), 620–623, doi:10.1126/science.1167112.

Rogers, G., and H. Dragert (2003), Episodic tremor and slip on the Cascadia subduction zone: the chatter of silent slip., *Science*, *300*(5627), 1942–1943, 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*(7153), 579–582, doi:10.1038/nature06017.

Rubinstein, J. L., M. La Rocca, J. E. Vidale, K. C. Creager, and A. G. Wech (2008), Tidal Modulation of Nonvolcanic Tremor, *Science (80-. ).*, *319*(5860), 186–189, doi:10.1126/science.1150558.

Segall, P., E. K. Desmarais, D. Shelly, A. Miklius, and P. Cervelli (2006), Earthquakes triggered by silent slip events on Kīlauea volcano, Hawaii., *Nature*, *442*(7098), 71–74, doi:10.1038/nature05297.

Shelly, D. R. (2010), Migrating tremors illuminate complex deformation beneath the seismogenic San Andreas fault, *Nature*, *463*(7281), 648–652, doi:10.1038/nature08755.

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*(7099), 188–191, doi:10.1038/nature04931.

Shelly, D. R., G. C. Beroza, and S. Ide (2007), Non-volcanic tremor and low-frequency earthquake swarms., *Nature*, *446*(7133), 305–307, doi:10.1038/nature05666.

Song, T.-R. A., D. V Helmberger, M. R. Brudzinski, R. W. Clayton, P. Davis, X. Pérez-Campos, and S. K. Singh (2009), Subducting Slab Ultra-Slow Velocity Layer Coincident with Silent Earthquakes in Southern Mexico, *Science (80-. ).*, *324*(5926), 502–506, doi:10.1126/science.1167595.

Thomas, A. M., R. M. Nadeau, and R. Bürgmann (2009), Tremor-tide correlations and near-lithostatic pore pressure on the deep San Andreas fault., *Nature*, *462*(7276), 1048–1051, doi:10.1038/nature08654.