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.

[*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.

[*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.

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.*, 2007], 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.

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.

**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.

Ide, S., D. R. Shelly, and G. C. Beroza (2007), 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.

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.

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.

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.

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.