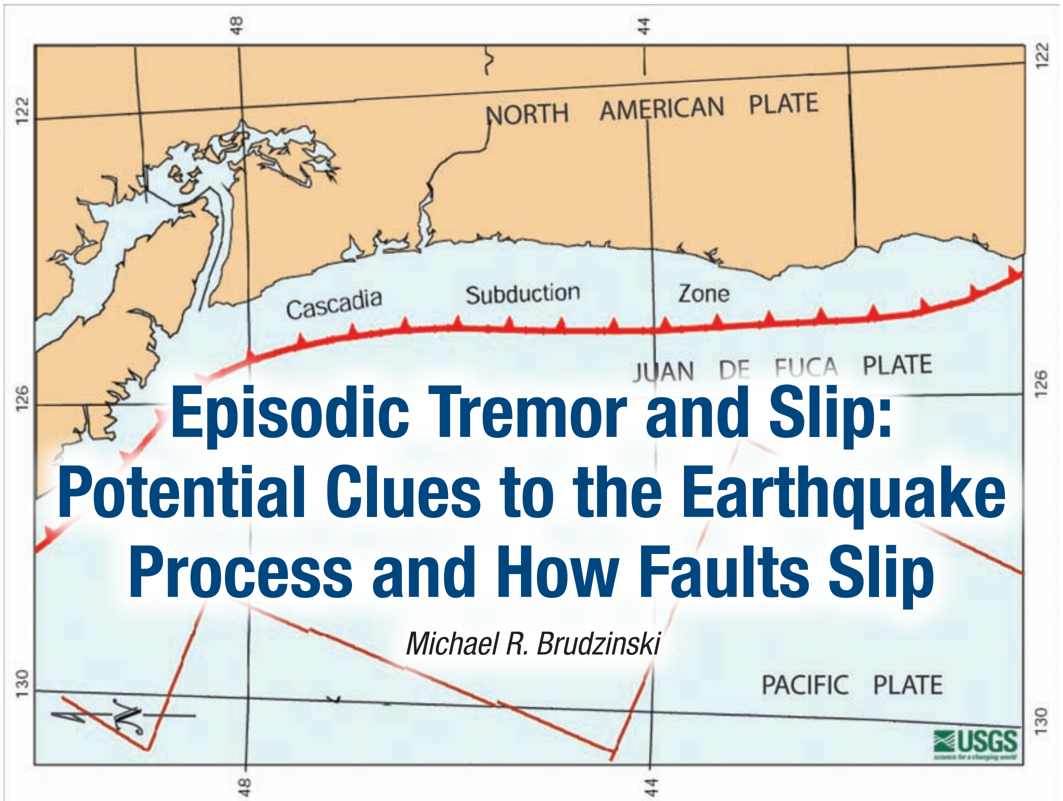

Episodic Tremor and Slip: Potential Clues to the Earthquake Process and How Faults Slip

Michael R. Brudzinski

Abstract

Episodic tremor and slip (ETS) represents a newly discovered mode of fault behavior occurring just below the locked zone that generates great earthquakes. Initially discovered in subduction zones, this new slip mechanism can release energy equivalent to at least a magnitude 7 earthquake! While this is a tremendous energy release, no one ever feels these events because they occur as slow slip episodes lasting weeks or months. As the plates move, high-precision Global Positioning System (GPS) monuments record the magnitude and direction of motion while seismometers record the low amplitude seismic waves released. The importance of this discovery lies in its potential relationship to the part of faults that generate destructive earthquakes. Considering that ETS occurs immediately below to the locked zone of faults, it may be possible for energy released in slow slip episodes to concentrate stresses at the deep edge of the locked zone, incrementally bringing it closer to failure. Thus ETS episodes might be a trigger for great earthquakes or aid in monitoring the stress state of faults as they lead up to the big one.

Introduction

The growing awareness of societal problems caused by natural hazards has piqued the interest of many students who enter our classes. As Earth science educators it should be our goal to convert that interest into problem solving skills. There is possibly no better example than that for earthquakes, where the threat is ever present, but there are many unanswered questions about how and why earthquakes happen. All of these questions will require well-trained and creatively thinking students to help push the research to new discoveries as well as an educated citizenry to apply the science to hazard preparedness and mitigation. A recent discovery that has captured the attention of many geoscientists over the past decade is the observation of a new type of deformation occurring on the large faults between tectonic plates that is different from typical earthquakes. To understand the importance of this new discovery and how it might inspire our students, we must first review the typical earthquake cycle.

As oceanic plates subduct into the mantle, friction on the interface with the overriding plate causes the plates to "lock" together along the megathrust zone (Figure 1, thick solid line). Here the upper plate is pulled down by the lower plate, building up elastic strain in the rocks along the fault, until the strain is relieved when the upper plate pops back up during a potentially devastating earthquake. The rapid fault motion in great (magnitude 8+) earthquakes can result in intense ground shaking and the displacement of ocean water that generates tsunamis, with the 2004 Sumatra great earthquake and tsunami serving as a particularly harrowing example. While much of the energy stored in subduction zones is released in these great megathrust earthquakes, recent GPS observations have revealed that the built-up elastic strain in subduction zones can be released through a process that is much less dramatic than an typical earthquake.

New Fault Behavior Discovered in Subduction Zones

To make these observations, high-precision GPS monuments were monitored continuously for motions over time as small as a millimeter per year. Careful analysis of the relative positions of instruments near the edge of the plate relative to those in the interior found that some instruments occasionally moved back toward the trench, instead of towards North America as would be expected along the convergence boundary in the Pacific Northwest. The magnitude and direction of this motion was similar to what might be expected during the several seconds of a magnitude 7 earthquake. However, this motion occurred much more gradually over the span of several weeks and in some cases over a year (e.g., Rogers & Dragert, 2003). This gradual release of the built-up elastic strain is now referred to as slow slip episodes. Curiously, the largest transient motions were not recorded at the coast above the locked zone (Figure 1, box A) but further inland (Figure 1, box B), suggesting slow slip occurs on the plate interface deeper than the region where great earthquakes are expected (Figure 1, dashed line). Discovering "hidden" slip on the fault equivalent to a magnitude 7 earthquake just below the zone of great earthquakes is cause for both excitement and concern. Further investigation revealed that the slow slip is episodic, sometimes with remarkably consistent frequency, such as the ˜14 month recurrence interval seen between Seattle and Vancouver (Figure 2, box B) (e.g., Rogers & Dragert, 2003). This gives geophysicists the unprecedented luxury of being able to prepare for each event in advance and then watch closely for the start of each episode as the data streams in. This periodicity is not as consistent in other locations (Brudzinski & Allen, 2007), but most cases are more regular than typical earthquakes, suggesting that the frictional conditions on this portion of the fault cause it to be more predictable than where earthquakes occur.

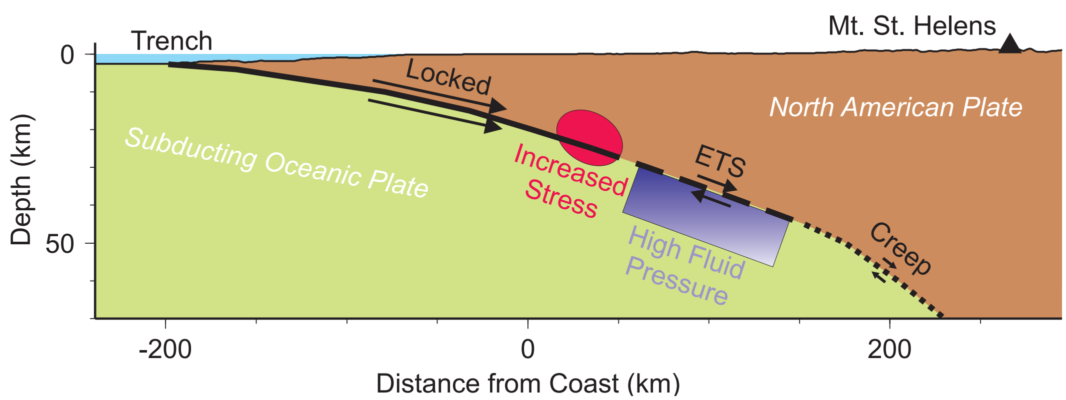

Figure 1. Cross-section slice through a subduction zone illustrating how fault behavior, along the plate interface, changes with depth. At shallow depths, the subducting (green) plate drags the upper (brown) plate down as the fault between them is locked together along the megathrust (thick solid line). The rocks on either side of the fault bend to accommodate this elastic strain until the fault unlocks catastrophically in a great earthquakes. At depths below ~30 km, we find evidence of a more gradual release of elastic strain through episodic tremor and slip (ETS, dashed line). This is a newly discover type of fault behavior which appears to be promoted by high pore fluid pressure from subducting plate dehydration (blue shading). ETS is important as it frequently releases elastic stain energy equivalent to a magnitude 7 earthquake, which is thought to concentrate stresses (red shading) at the deep edge of the locked zone. At greater depths, the increasing pressures and temperatures prevent earthquakes and ETS and result in continuous creep along the plate interface (dotted line). The crust/mantle boundary has limited impact on the fault behavior and has been omitted from this figure to focus attention on the interface between the plates. This figure is vertically exaggerated by a factor of 2.

In addition to being recorded by GPS, slow slip typically corresponds to low-level seismic vibrations referred to as non-volcanic tremor (Figure 2, box B) that can be detected by seismometers. The term non-volcanic tremor was applied to these weak signals as they are emergent, meaning they are not impulsive like a single large earthquake (Figure 2, box A), but gradually appear out of the background noise and often undulate with slowly varying amplitudes (e.g., Obara, 2002) (Figure 1s). Volcanoes generate a similar, but larger and more obvious tremor that has been recognized for many years (Figure 2, box D). Non-volcanic tremor in subduction zones is different because it has a deep source region (Figure 1, dashed line), and it is not harmonic (cf., Figure 2, boxes B and D, bottom panel). The harmonic nature of volcanic tremor is thought to be caused by fluid moving through magma conduits, similar to the way air resonates in an organ pipe.

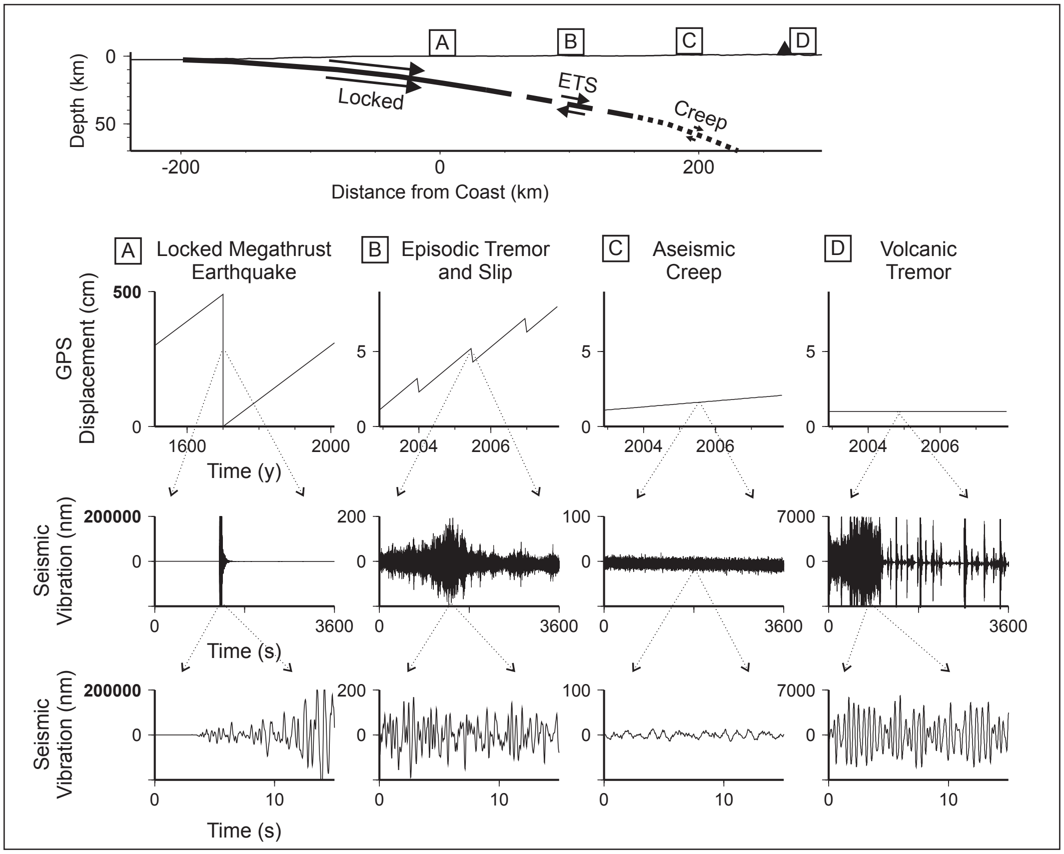

Figure 2. Example GPS data (middle panel) and seismic data (lower panels) recorded at different locations across a subduction zone. (top panel) Cross-section through a subduction zone illustrating 3 types of fault behavior: locked (solid), episodic tremor and slip (ETS, dashed), and creep (dotted). Boxes A through D show locations of seismic and GPS instruments above each of these 3 zones of the plate interface and one near a volcano (triangle) further inland. This cross-section is similar to Figure 1 but with no vertical exaggeration. [A] Instruments above the locked zone record linear trends in GPS data that indicate accumulation of elastic strain energy for hundreds of years. Eventually, a great earthquake occurs, causing several meters of displacement in just a few minutes with very strong seismic shaking. [B] Instruments above the ETS zone record episodes of slow slip with only millimeters of GPS displacement that last a few weeks to months and often recur every year or two. These episodes are typically accompanied by non-volcanic tremor that are small seismic vibrations that gradually emerge out of the background noise. [C] Instruments above the creep zone record very little change in GPS displacement over time with very small and constant seismic vibrations that are likely due to cultural or atmospheric noise. [D] Instruments near a volcano that are far from the plate boundary often see little change in displacement between eruptions, but they record periods of volcanic tremor. The bottom panel shows a short time scale to illustrate how volcanic tremor has repetitive, uniform pulse widths, while non-volcanic tremor has more irregular pulse widths, a key difference that led to the discovery of ETS. This harmonic nature of volcanic tremor is thought to be caused by fluid moving through conduits, similar to how air resonates an organ pipe. Non-volcanic tremor is not harmonic as it is thought to be caused by a swarm of small, low-frequency earthquakes with overlapping P and S waves.

Based on an analysis of non-volcanic tremor, it appears to be composed of swarms of so-called low frequency earthquakes, since typical earthquakes of similar magnitude would have more energy at higher frequencies. The swarm of seismic sources results in many overlapping signals on a seismogram (Figure 2, box B), making it difficult to discern individual P and S waves typically used to estimate key details about the earthquake source. Nevertheless, detailed processing techniques have been able to identify repeating P and S wave signals that indicate the depth and fault motion are consistent with the majority of non-volcanic tremor produced by shear faulting along the plate interface (Ide, Shelly, & Beroza, 2007). These motions are consistent with slow slip motions that regularly relieve the built-up elastic strain along the fault and relax the deep crust. However, the summed magnitude of slip from non-volcanic tremor is still considerably less than that from geodetically recorded slow slip, such that the combination is still mostly an aseismic slip process.

Part of the reason non-volcanic tremor remained undiscovered through seismic analysis until the last decade was that its signal is close to wind or cultural noise (Figure 2, box C), and when combined with its weak and undulating nature, it typically looks like slightly more than normal background noise on an individual seismogram. The key indicator that it is indeed generated by a tectonic source is that the signals correlate at several stations over distances of up to 100 km, whereas cultural noise is different at every station. The situation is analogous to other discoveries in geology, where key features in rocks remain unnoticed for a many years until someone goes looking for a specific feature. What helped draw the attention of many geophysicists is the remarkable correlation in space and time between the geodetic signatures of slow slip and the seismic signals of non-volcanic tremor (e.g., Rogers & Dragert, 2003) (Figure 2, box B).

Physical Causes for Slow Slip Behavior

Episodic tremor and slip (ETS) is exciting to scientists because it occurs at the deep edge of great earthquakes where rupture often begins, indicating that ETS could help explain why great earthquakes are restricted to certain parts of the plate interface. As mentioned earlier, these great earthquakes are thought to result from frictional behavior on the fault between the plates. In order to understand why slow slip occurs we need to examine the physics of faulting in detail. Under the right conditions, which are typically met at shallow depths in the Earth's crust (Figure 1, thick solid line), the friction on the fault while stationary is larger than the friction on the fault once the fault is moving. As a result, an instability is formed once a fault begins to rupture, and the rupture is able to continue quickly causing an earthquake until something stops it, such as a bend in the fault. As pressures increase with depth in the Earth, a region is reached where there is no longer a decrease in friction after the fault starts to slip (Figure 1, dotted line). At these depths, this lack of decreased friction when the fault is in motion prevents fault slip from becoming an earthquake. As a result, the fault creeps along at a stable rate.

In between the locked and creeping regions (Figure 1, dashed line), theory predicts the possibility that slow slip rupture can be initiated due to the presence of high fluid pressures that "lighten the load" of the overriding plate thereby reducing the friction (e.g., Liu & Rice, 2007). We believe this is occurring as the subducting oceanic plate loses its water on its descent into the Earth, and a seal above the plate interface could cause fluids to build up along the fault (Figure 1, blue shading). Seismic waves traveling through the source region of ETS show unusually slow speeds and elastic properties consistent with fluid overpressuring (e.g., Audet, Bostock, Christensen, & Peacock, 2009). Further evidence for this comes from another set of observations showing that ETS can be dynamically triggered by tidal forces (e.g., Rubinstein, La Rocca, Vidale, Creager, & Wech, 2008) or passing surface waves from a large earthquake (e.g., Rubinstein et al., 2007). Since normal earthquakes on strong faults are rarely triggered by tides and surface waves, such response to smaller stresses indicates the fault is weaker. Fluid overpressuring is a worthy candidate for weakening or drastically reducing friction on the fault (e.g., Thomas, Nadeau, & Burgmann, 2009).

Why is ETS an Important Discovery?

The importance of ETS to the general public lies in its potential relationship to great earthquakes. Considering that ETS occurs near the deepest extent of where earthquakes rupture (Figure 1, dashed vs. solid line), one can simply use the location of ETS to estimate how far inland future great earthquake ruptures will extend (Chapman & Melbourne, 2009). In the Pacific Northwest (Figure 3), the spatial extent of the last great earthquake in 1700 is not well determined, making hazard estimates more difficult. Here, ETS occurs further inland than previous estimates of the extent of the great earthquake rupture. This suggests strong ground shaking could extend further inland towards cities like Seattle, Portland and Vancouver, and there are active discussions about how to incorporate this information into seismic hazard assessment.

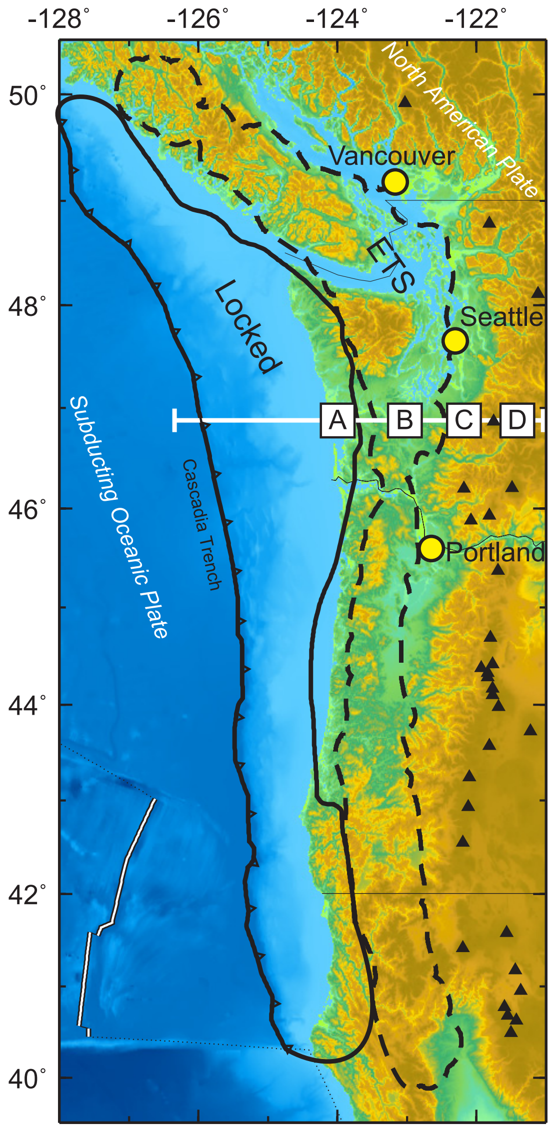

Figure 3. Map of the Pacific Northwest showing regions affected by the fault interface between the subducting oceanic plate and the overriding North American plate. Since the last great earthquake occurred in 1700, scientists have tried to estimates of where the fault is locked (solid curve) to predict where the next great earthquake will occur. The region of the fault producing episodic tremor and slip (ETS, dashed curve) occurs slightly inland of these estimates of where the earthquake will occur. If the locked zone actually extends all the way up to the edge of the ETS zone, the next great earthquake will bring seismic shaking further inland and closer to Seattle, Portland, and Vancouver (yellow circles). Cascades volcanoes are shown as triangles. The white line indicates the location of the cross section shown in Figures 1 and 2. Boxes A-D indicate locations of seismic and GPS instruments for which data is shown in Figure 2.

The proximity of ETS to the zone of great earthquakes indicates that stress release in slow slip episodes could concentrate stresses at the deep edge of the locked zone (Figure 1, red ellipse), incrementally bringing it closer to failure (Dragert, Wang, & Rogers, 2004). If true, ETS could be thought of as "tickling the dragon's belly" such that great earthquakes would be more likely during or just after an ETS event. Regardless of whether ETS has a causative relationship with great earthquakes, ETS may still be useful in monitoring the stress state of faults as they lead up to the big one. Changes in the location, recurrence, or migration of ETS phenomena could all serve as indicators of the increasing likelihood of earthquake rupture. Unfortunately, the closely spaced instrumentation necessary to fully test hypotheses regarding ETS and the earthquake cycle has not yet existed in areas where the handful of great earthquakes have occurred over the past decade. While no one hopes for a great earthquake, scientists continue to prepare to catch the next big one with a better distribution of higher quality instrumentation.

ETS on Other Fault Types

Although the majority of this article has focused on ETS behavior in subduction zones (e.g., Cascadia, Japan, Mexico, Alaska, Costa Rica), there are indications that ETS, or aspects of it, occur on other faults as well. A series of slow slip episodes have been recorded on the south flank of Kilauea (e.g., Montgomery-Brown, Segall, & Miklius, 2009), where the weight of erupted rock is causing it to slough away along nearly horizontal faults. In this case, slow slip episodes are not accompanied by non-volcanic tremor but they are accompanied by a swarm of regular earthquakes.

About the Author

Michael Brudzinski (brudzimr@muohio.edu) is an Associate Professor of Geophysics in the Department of Geology at Miami University, Oxford, OH 45056.

The San Andreas Fault has also shown evidence for slow slip (Linde, Gladwin, Johnston, Gwyther, & Bilham, 1996) and non-volcanic tremor (Nadeau & Dolenc, 2005), but they have not yet been recorded in the same part of the fault. The tremor observations, though, are particularly intriguing since a magnitude 6 earthquake occurred in the region where tremor was discovered, and there have been clear indications of changes in tremor patterns leading up to and following the earthquake (e.g., Nadeau & Guilhem, 2009).

Episodic slow slip and non-volcanic tremor appear to occur in a range of environments and understanding this newly discovered phenomena is helping us decipher the physics of earthquakes. While we are in no position to use ETS to predict earthquakes, such observations give hope to the prospects of using ETS to better understand when and where earthquakes will occur. And considering the sobering history of failed prospects in earthquake prediction (e.g., Hough, 2009), any hope is good news.

References

Audet, P., Bostock, M. G., Christensen, N. I., & Peacock, S. M. (2009). Seismic evidence for overpressured subducted oceanic crust and megathrust fault sealing. *Nature, 457*(7225), 76-78.

Brudzinski, M. R., & Allen, R. M. (2007). Segmentation in episodic tremor and slip all along cascadia. *Geology, 35*(10), 907-910.

Chapman, J. S., & Melbourne, T. I. (2009). Future cascadia megathrust rupture delineated by episodic tremor and slip. *Geophysical Research Letters, 36* doi:10.1029/2009GL040465 ER

Dragert, H., Wang, K., & Rogers, G. (2004). Geodetic and seismic signatures of episodic tremor and slip in the northern cascadia subduction zone. *Earth Planets and Space, 56*(12), 1143-1150.

Hough, S. E. (2009). *Predicting the unpredictable: The tumultuous science of earthquake prediction* Princeton University Press.

Ide, S., Shelly, D. R., & Beroza, G. C. (2007). Mechanism of deep low frequency earthquakes: Further evidence that deep non-volcanic tremor is generated by shear slip on the plate interface. *Geophysical Research Letters, 34*(3), 5. doi:L03308 10.1029/2006gl028890

Linde, A. T., Gladwin, M. T., Johnston, M. J. S., Gwyther, R. L., & Bilham, R. G. (1996). A slow earthquake sequence on the san andreas fault. *Nature, 383*, 65-68.

Liu, Y. J., & Rice, J. R. (2007). Spontaneous and triggered aseismic deformation transients in a subduction fault model. *Journal of Geophysical Research-Solid Earth, 112*(B9), 23. doi:B09404 10.1029/2007jb004930

Montgomery-Brown, E. K., Segall, P., & Miklius, A. (2009). Kilauea slow slip events: Identification, source inversions, and relation to seismicity. *Journal of Geophysical Research-Solid Earth, 114* doi:10.1029/2008JB006074 ER

Nadeau, R. M., & Dolenc, D. (2005). Nonvolcanic tremors deep beneath the san andreas fault. *Science, 307*, 389.

Nadeau, R. M., & Guilhem, A. (2009). Nonvolcanic tremor evolution and the san simeon and parkfield, california, earthquakes. *Science, 325*(5937), 191-193. doi:10.1126/science.1174155

Obara, K. (2002). Nonvolcanic deep tremor associated with subduction in southwest japan. *Science, 296*(5573), 1679-1681.

Rogers, G., & Dragert, H. (2003). Episodic tremor and slip on the cascadia subduction zone: The chatter of silent slip. *Science, 300*(5627), 1942-1943.

Rubinstein, J. L., La Rocca, M., Vidale, J. E., Creager, K. C., & Wech, A. G. (2008). Tidal modulation of nonvolcanic tremor. *Science, 319*(5860), 186-189.

Rubinstein, J. L., Vidale, J. E., Gomberg, J., Bodin, P., Creager, K. C., & Malone, S. D. (2007). Non-volcanic tremor driven by large transient shear stresses. *Nature, 448*(7153), 579-582. doi:10.1038/nature06017

Thomas, A. M., Nadeau, R. M., & Burgmann, R. (2009). Tremor-tide correlations and near-lithostatic pore pressure on the deep san andreas fault. *Nature, 462*(7276), 1048-U105. doi:10.1038/nature08654 ER