The Mechanism of Slow Slip Events and Tremor Beneath the Seismogenic Layer

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Abstract

In the past decade it has been discovered that slow slip events, accompanied by the low level seismic radiation known as non-volcanic tremor, occur quasi-periodically just below the base of the seismogenic region in many subduction zones and the San Andreas fault[1]. Here we show that this activity occurs exclusively in an intermediate region of the lower frictional stability transition. Slow slip events, previously observed in laboratory friction experiments as self-sustained oscillatory sliding, are explained by a rate-state friction law with two state variables in which the oscillatory slip regime occupies an intermediate region of phase space between stick-slip and stable sliding. The tremor is incidental rubbing noise associated with the slow slip events. Previous attempt to model this behavior[2-5] have used a friction law with a single state variable, in which the oscillatory field collapses to a line at the critical point. This requires very special and unrealistic conditions for slow slip events to occur and obscures the underlying physics, which is now explored more fully.

Analysis

Slow slip events (SSEs) were first observed with continuous GPS measurements in the Cascadia subduction zone[6-8] and have been subsequently observed in the Nankai trough subduction zone of southwest Japan[9], in subduction zones elsewhere[1], and beneath the San Andreas fault[10]. SSEs have been shown to be episodes of slow slip on the subduction interface over the depth range 30-40 km[11-13]. In Cascadia the magnitude of their slip is 2-3 cm occurring over several weeks. They propagate at velocities of ~10 km/day, often for several hundred km along strike, and recur at intervals of about 14 months[7, 8]. In Nankai the slip episodes are somewhat smaller and more frequent, reoccurring about every 6 mos[14, 15]. Each slow slip event is accompanied by seismic tremor that consists of a swarm of low frequency events (LFEs)[16-18] that track the position of the SSE and which has been used to monitor the progress of the SSEs[7, 15].

Slow slip events and related phenomena such as LFEs have been shown by Ide et al.[19] to obey a scaling law for their seismic moments $M_o = \mu DWL$ (shear modulus x slip x width x length) in which $M_o \propto T$, their duration. Ide et al. also noted that the tremor and LFEs have spectra that fall off as 1/f. They offered two interpretations of the moment scaling, which imply that rupture velocity V_r scales either as $1/L$ or $1/L^2$. The data, however, show, at least for SSEs and its related tremor, that the along strike V_r is constant over a long distance range[18] with only local fluctuations[20]. Although the transverse (along dip) rupture velocity has been observed to be much higher[21, 22], and has been cited by Ide et al. in support of their interpretations, this may be an apparent velocity due to propagation of the SSE past streaks of unstable patches at high angles to the strike direction[20, 23]. In any case, because the strike velocity is much slower and L>>W, T must be determined by L and the strike velocity V_r. The observations indicate that SSEs are strip-pulses in which a pulse of slow slip propagates in a strip of constant width W=W*. If stress drop $\Delta\sigma=\mu D/W^*$ is scale invariant, then D is also constant and $M_o \propto L$. The scaling law then requires that $T \propto L$, hence V_r and moment release rate are both constant.

Generally when solids rub against one another, some sound is generated. Such sound may be a primary result of the motion when the motion of the bodies is by stick-slip. Such is the case for the seismic waves radiated by earthquakes. When the motion between the bodies is stable sliding, sound is also often generated, but it is incidental to the overall motion. In laboratory rock friction studies, for example, stable sliding is accompanied by acoustic emissions, presumably the result of stick-slip of small regions driven by the overall stable sliding[24]. Obara[25] found that the number of tremors is proportional to the moment of the SSE and their durations are the same. We therefore interpret tremor, and the LFEs that constitute it, as the incidental rubbing noise of the SSE. Because the moment release rate of an SSE is constant, so must be that of the tremor. The tremor is thus similar to persistent fractional Brownian motion with a boxcar function envelope, which, as noted by Ide et al.[19], requires its spectra to fall off as 1/f.

The region of tremor and LFEs for the Nankai region is shown in Figure 1a, along with the depth contours of the subduction interface[20]. Despite the convolutions of the plate interface, the activity closely follows the 35 km depth contour. In Figure 1b is shown the seismic coupling coefficient for eastern and central Shikoku inverted from vertical GPS data[26]. The coastline is above the 20km depth contour, so coupling is poorly resolved to the left of that point. Coupling is close to 1 above 30 km depth, indicating a fully locked interface. At 30 km the coupling coefficient drops to a plateau of intermediate coupling between about 30 to 40 km, below which it falls rapidly to zero. This plateau region is well resolved; appearing at the ±95% confidence limits (dashed curves) and corresponding with the region of SSEs and tremor (blue line). The main slip in the 1946 Nankaido earthquake[27] extends to 30 km depth (red line) with about 1 m slip resolved down to 35 km. Some of this may have been postseismic because the inversion for coseismic slip was based on geodetic data collected up to 5 years after the earthquake. LFEs have also been observed on splay thrusts (or possibly the decollement) at about 10 km depth[28] in the accretionary prism. These are shown as green circles and a dashed blue line in Fig. 1a and b, respectively.

It thus appears that the oscillatory slip behavior characterized by periodic SSEs occurs in a transitional regime of the lower frictional stability transition (FST)[29]. The shallow LFEs may likewise be occurring in a similar region of the upper FST. It is noticeable in Fig. 1a that the tremor activity ends abruptly at the Bungo Channel and does not follow the subduction zone south along the coast of Kyushu. This northern part of the Ryukyu subduction zone, except for a small patch that ruptures repeatedly in the M~7 Hyuganada earthquakes, is known to be seismically decoupled, having experienced no great earthquakes in the historic period and accumulating no strain in the upper plate[30]. Therefore there is no FST occupying a great distance along strike there, which explains the absence of tremor and SSEs. The Japan arc is similarly devoid of tremor and deep LFEs, and is also decoupled, except for two patches that produce the frequent (~30 yr recurrence) M 7.6-7.8 Miyagi-oki and Fukushima-oki earthquakes[31]. Therefore this region also has no FST. In California, the main tremor activity occurs beneath the locked section of the San Andreas fault south of Parkfield[32-34]. Tremor there has been observed to propagate as far as 25km along strike[32] in a manner similar to the tremor associated with SSEs in subduction zones. There are also isolated patches of very low amplitude tremor beneath the creeping section of the San Andreas[35]. The division between these isolated low amplitude tremor patches and the regime of high amplitude propagating[32] tremor episodes is at precisely the boundary between the locked and creeping sections just north of Cholame[35]. The latter indicate the presence of an extended FST beneath the locked portion of the fault, whereas the isolated small amplitude activity suggests the absence of a coherent FST beneath the creeping section, as theoretically expected from a model with fault heterogeniety[23]. Tremor has yet to be observed elsewhere in California where seismic networks are less dense than at Parkfield, but tremor triggered by the 2002 M 7.8 Denali earthquake was observed at widespread locations along faults of the San Andreas system and not in regions of hydrothermal activity[36]. We conclude that SSEs and its associated propagating tremor occur exclusively within FSTs.

Oscillatory stable sliding has been observed in laboratory rock friction experiments. Figure 2a shows an experiment[37] in which dry granite is slid in a biaxial apparatus in which the normal stress continuously increases with slip, so as to transit the FST from stable sliding to stick-slip. Small oscillations in the vertical force can be seen in the region labeled 1 between smooth stable sliding and stick-slip. A blow-up of the oscillations on the displacement record is shown in Figure 2b. Spring-slider models using rate/state friction laws show that this behavior is reproduced by a model with two state variables[38]. The stability diagram for the two state variable friction law is shown in Figure 3, which shows velocity jump vs. stiffness normalized to the critical stiffness $k_c = \overline{\sigma}(b-a)/D_c$, where $\overline{\sigma}$ is effective normal stress and the other terms are friction parameters in the rate/state variable friction law. This friction law contains an intermediate regime of oscillatory stable sliding. Moving from right to left within this regime, the oscillations increase in amplitude and period and then enter a region of period doubling in a narrow field just before the transition to unstable slip. The experiment of Fig. 2a,b, in which $\overline{\sigma}$ is gradually being increased, transits this stability diagram from right to left. Similar lab experiments, shown in Fig. 2c, also show the period doubling regime between periodic oscillations and stick-slip[39].

In the case of SSEs, we are dealing with the lower stability transition, which lab data[40] indicate is caused by an increase of the friction parameter *a* with temperature, the manifestation of the brittle plastic transition on friction[41], so that we transit the stability diagram from left to right. The strip of the subduction interface that slips by SSEs and shows up as a plateau of intermediate coupling in Fig. 1b is interpreted to be the regime of oscillatory motion in the phase diagram. The spatial location of the FST may also be influenced by high pore pressure (through its reduction of $\overline{\sigma}$), as has been suggested by high V_p/V_s ratios at the appropriate depth in the Nankai region[42, 43].

The period doubling regime has also been observed in nature, in a region of LFEs below the seismogenic region of the San Andreas fault south of Parkfield, California[44]. There, families of LFEs occur with two recurrence intervals of about 3 days and 6 days. The occurrence of the 2004 Parkfield M6.0 earthquake had a pronounced effect on the state of the system at that location. Immediately following that earthquake the period doubling ceased and the period of the primary oscillation was reduced. Over the subsequent 18 months, the period of the primary oscillation gradually increased followed by a sudden resumption of the period doubling. This behavior can be explained by considering the phase diagram of Fig. 3. Suppose, as an illustrative example, that the coseismic effect of the Parkfield earthquake was to increase the pore pressure in the LFE region. This has the effect of reducing k_c, so that a point 1 within the period doubling region would move immediately to point 2, out of the period doubling region and to a position with a reduced period for the primary oscillation. Postseismic recovery of the pore pressure through fluid diffusion would move the system along path 3-4, leading to a gradual increase in period of the primary oscillation followed by a sudden switching to period doubling.

Although lab experiments on rock friction under hydrothermal conditions at elevated temperature require the two state variable friction law[40, 45], for computational simplicity the single state variable friction law has been the one most used in theoretical modeling, and, in particular, in the modeling of SSEs[2-5]. The friction transition for the two state variable law, as described above, follows a typical route for a Hopf bifurcation, from growing oscillations to period doubling (and perhaps, chaos) to instability. The single state variable law, on the other hand, is an exceptional case[38, 39]. In that law the regime of oscillatory motion collapses to a line at the critical point k_c. Oscillatory motion is stable only at that point. In order to model SSEs occurring over a physical space of width W* with a single state variable model it is necessary to require that $\overline{\sigma}$ (and hence k_c) be constant over that width[46]. Without that assumption, the FST for a single state variable law would be abrupt and no intermediate zone of oscillatory motion would exist. We argue that this assumption is so restrictive, as well as unrealistic, that if the single state variable law were correct we would not expect to observe the widespread occurrence of SSEs. The two state variable law requires no such restriction – it naturally predicts a width over which the transitional behavior occurs.

Discussion

The two state variable model that we have explored here in one-dimension needs to be further studied in 2 and 3 dimensional models. However, there are several further implications that deserve mention. We have associated LFEs and tremor with SSEs: therefore the shallow LFEs observed on splay thrusts or decollement in the accretionary prism, shown in Fig. 1, imply that this marks an intermediate region of the upper FST and that SSEs occur there as well, but remain undetected by the land-based instruments. The point that SSEs and tremor occur exclusively in FSTs may prove useful in distinguishing coupled from uncoupled subduction zones in regions where the historic record of great earthquakes is lacking or ambiguous. Those that have it are coupled: those that do not are not.

References

1. Schwartz, S. Y. & Rokosky, J. M. Slow slip events and seismic tremor at circum-pacific subduction zones. Reviews of Geophysics 45 (2007).
2. Matsuzawa, T., Hirose, H., Shibazaki, B. & Obara, K. Modeling short- and long-term slow slip events in the seismic cycles of large subduction earthquakes. J. Geophys. Res. in press (2010).
3. Shibazaki, B. & Iio, Y. On the physical mechanism of silent slip events along the deeper part of the seismogenic zone. Geophysical Research Letters 30 (2003).
4. Liu, Y. J. & Rice, J. R. Spontaneous and triggered aseismic deformation transients in a subduction fault model. Journal of Geophysical Research-Solid Earth 112 (2007).
5. Liu, Y. J. & Rice, J. R. Aseismic slip transients emerge spontaneously in three-dimensional rate and state modeling of subduction earthquake sequences. Journal of Geophysical Research-Solid Earth 110 (2005).
6. Dragert, H., Wang, K. L. & James, T. S. A silent slip event on the deeper Cascadia subduction interface. Science 292, 1525-1528 (2001).
7. Kao, H., Shan, S. J., Dragert, H. & Rogers, G. Northern Cascadia episodic tremor and slip: A decade of tremor observations from 1997 to 2007. Journal of Geophysical Research-Solid Earth 114 (2009).
8. Rogers, G. & Dragert, H. Episodic tremor and slip on the Cascadia subduction zone: The chatter of silent slip. Science 300, 1942-1943 (2003).
9. Obara, K. Nonvolcanic deep tremor associated with subduction in southwest Japan. Science 296, 1679-1681 (2002).
10. Nadeau, R. M. & Dolenc, D. Nonvolcanic tremors deep beneath the San Andreas Fault. Science 307, 389-389 (2005).
11. Melbourne, T. I., Szeliga, W. M., Miller, M. M. & Santillan, V. M. Extent and duration of the 2003 Cascadia slow earthquake. Geophysical Research Letters 32 (2005).
12. McGuire, J. J. & Segall, P. Imaging of aseismic fault slip transients recorded by dense geodetic networks. Geophysical Journal International 155, 778-788 (2003).
13. Brown, J. R. et al. Deep low-frequency earthquakes in tremor localize to the plate interface in multiple subduction zones. Geophysical Research Letters 36 (2009).
14. Hirose, H. & Obara, K. Recurrence behavior of short-term slow slip and correlated nonvolcanic tremor episodes in western Shikoku, southwest Japan. Journal of Geophysical Research-Solid Earth 115 (2010).
15. Obara, K. Phenomenology of deep slow earthquake family in southwest Japan: Spatiotemporal characteristics and segmentation. Journal of Geophysical Research-Solid Earth 115 (2009).
16. Shelly, D. R., Beroza, G. C. & Ide, S. Non-volcanic tremor and low-frequency earthquake swarms. Nature 446, 305-307 (2007).
17. Shelly, D. R., Beroza, G. C., Ide, S. & Nakamula, S. Low-frequency earthquakes in Shikoku, Japan, and their relationship to episodic tremor and slip. Nature 442, 188-191 (2006).

18. Ito, Y., Obara, K., Shiomi, K., Sekine, S. & Hirose, H. Slow earthquakes coincident with episodic tremors and slow slip events. Science 315, 503-506 (2007).
19. Ide, S., Beroza, G. C., Shelly, D. R. & Uchide, T. A scaling law for slow earthquakes. Nature 447, 76-79 (2007).
20. Ide, S. Striations, duration, migration and tidal response in deep tremor. Nature 466, 356-U105 (2010).
21. Shelly, D. R., Beroza, G. C. & Ide, S. Complex evolution of transient slip derived from precise tremor locations in western Shikoku, Japan. Geochemistry Geophysics Geosystems 8 (2007).
22. Ghosh, A., Vidale, J. E., Sweet, J. R., Creager, K. C. & Wech, A. G. Tremor patches in Cascadia revealed by seismic array analysis. Geophysical Research Letters 36 (2009).
23. Ando, R., Nakata, R. & Hori, T. A slip pulse model with fault heterogeneity for low-frequency earthquakes and tremor along plate interfaces. Geophysical Research Letters 37 (2010).
24. Scholz, C. H. Microfracturing and the inelastic deformation of rock in compression. J. *Geophys. Res.* 73, 1417-1432 (1968).
25. Obara, K. Phenomenology of deep slow earthquake family in southwest Japan: Spatiotemporal characteristics and segmentation. Journal of Geophysical Research-Solid Earth 115, B00A25 (2010).
26. Aoki, Y. & Scholz, C. H. Interseismic deformation at the Nankai subduction zone and the Median Tectonic Line, southwest Japan. Journal of Geophysical Research-Solid Earth 108 (2003).
27. Sagiya, T. & Thatcher, W. Coseismic slip resolution along a plate boundary megathrust: The Nankai Trough, southwest Japan. Journal of Geophysical Research-Solid Earth 104, 1111-1129 (1999).
28. Ito, Y. & Obara, K. Very low frequency earthquakes within accretionary prisms are very low stress-drop earthquakes. Geophysical Research Letters 33 (2006).
29. Scholz, C. H. Earthquakes and friction laws. Nature 391, 37-42 (1998).
30. Ito, T., Yoshioka, S. & Miyazaki, S. Interplate coupling in southwest Japan deduced from inversion analysis of GPS data. Physics of the Earth and Planetary Interiors 115, 17-34 (1999).
31. Hashimoto, C., Noda, A., Sagiya, T. & Matsu'ura, M. Interplate seismogenic zones along the Kuril-Japan trench inferred from GPS data inversion. Nature Geoscience 2, 141-144 (2009).
32. Shelly, D. R. Migrating tremors illuminate complex deformation beneath the seismogenic San Andreas fault. Nature 463, 648-U75 (2010).
33. Shelly, D. R. Possible deep fault slip preceding the 2004 Parkfield earthquake, inferred from detailed observations of tectonic tremor. Geophysical Research Letters 36 (2009).
34. Zhang, H. J., Nadeau, R. M. & Toksoz, M. N. Locating nonvolcanic tremors beneath the San Andreas Fault using a station-pair double-difference location method. Geophysical Research Letters 37 (2010).

35. Shelly, D. R. & Hardebeck, J. L. Precise tremor source locations and amplitude variations along the lower-crustal central San Andreas Fault. Geophysical Research Letters 37 (2010).
36. Gomberg, J. et al. Widespread Triggering of Nonvolcanic Tremor in California. Science 319, 173 (2008).
37. Scholz, C., Molnar, P., and Johnson, T. Detailed studies of frictional sliding of granite and implications for the earthquake mechanism. *J. Geophys. Res.* 77, 6392-6406 (1972).
38. Gu, J. C., Rice, J. R., Ruina, A. L., and Tse, S. T. Slip motion and stability of a single degree of freedom elastic system with rate and state dependent friction. J. *Mech. Phys. Sol.* 32, 167-196 (1984).
39. Gu, Y. & Wong, T.-F. in Nonlinear Dynamics and Predictability of Geophysical Phenomena 15-35 (Geophysical Monograph 18, American Geophysical Union, Washington, D.C., 1994).
40. Blanpied, M. L., Lockner, D. A. & Byerlee, J. D. Frictional Slip of Granite At Hydrothermal Conditions. J. Geophys. Res.-Solid Earth 100, 13045-13064 (1995).
41. Scholz, C. H. The Mechanics of Earthquakes and Faulting (Cambridge University Press, Cambridge, 2002).
42. Kodaira, S. et al. High pore fluid pressure may cause silent slip in the Nankai Trough. Science 304, 1295-1298 (2004).
43. Kato, A. et al. Variations in fluid pressure within the subducting oceanic crust and slow earthquakes. Geophys. Res. Lett. 37, L14310 (2010).
44. Shelly, D. R. Periodic, Chaotic, and Doubled Earthquake Recurrence Intervals on the Deep San Andreas Fault. Science 328, 1385-1388 (2010).
45. Nakatani, M. & Scholz, C. H. Intrinsic and apparent short-time limits for fault healing: Theory, observations, and implications for velocity-dependent friction. Journal of Geophysical Research-Solid Earth 111 (2006).
46. Liu, Y. J. & Rice, J. R. Spontaneous and triggered aseismic deformation transients in a subduction fault model. Journal of Geophysical Research-Solid Earth 112 (2007).

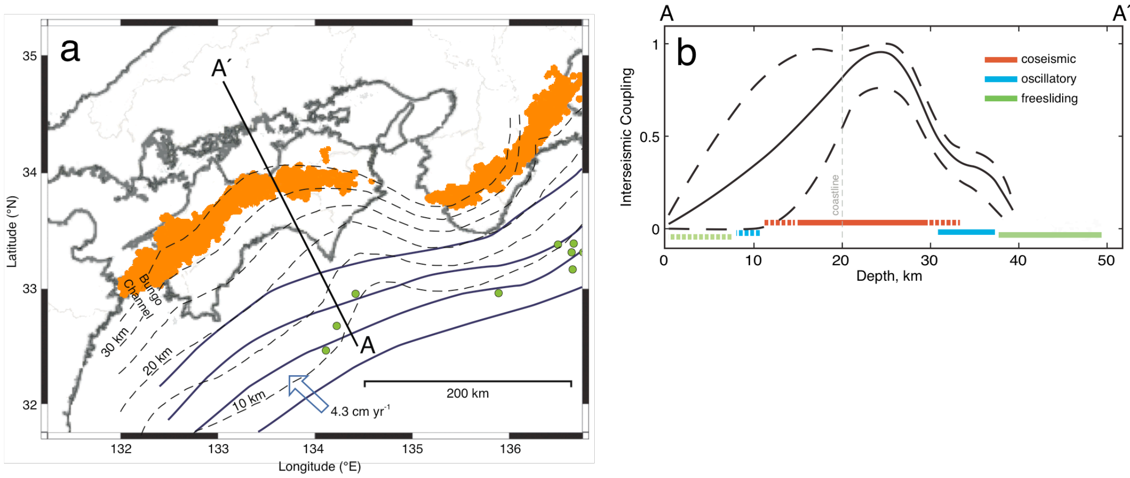

Figure 1. a) Map of southwest Japan, based on refs. 20, 25, and 28, showing the region of deep SSEs and tremor (orange shaded region) and shallow LFEs (green circles) and the contours of the subducting plate interface. b) Seismic coupling coefficient in the interseismic period vs. depth in profile A-A' of map, based on vertical GPS data (ref. 26), with regions of SSEs and tremor (blue line), coseismic slip in the 1946 Nankaido earthquake, red line (ref. 27) and shallow LFEs, dashed blue line (ref. 28).

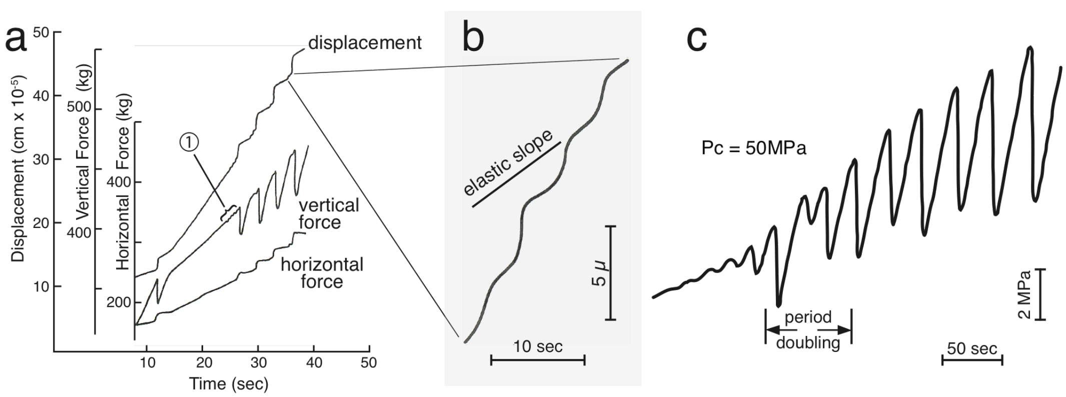

Figure 2. Laboratory observations of oscillatory stable sliding. a) frictional sliding of granite at room temperature and pressure in a biaxial experiment where normal stress is continuously increasing. Label 1 shows small oscillations of vertical stress indicating oscillatory slip in a region between steady stable sliding and stick-slip (from ref. 37). b) blowup of the displacement record showing oscillatory sliding between steady sliding and stick-slip (from ref. 37). c) a similar experiment that also shows a region of period doubling between oscillatory slip and stick-slip (from ref. 39).

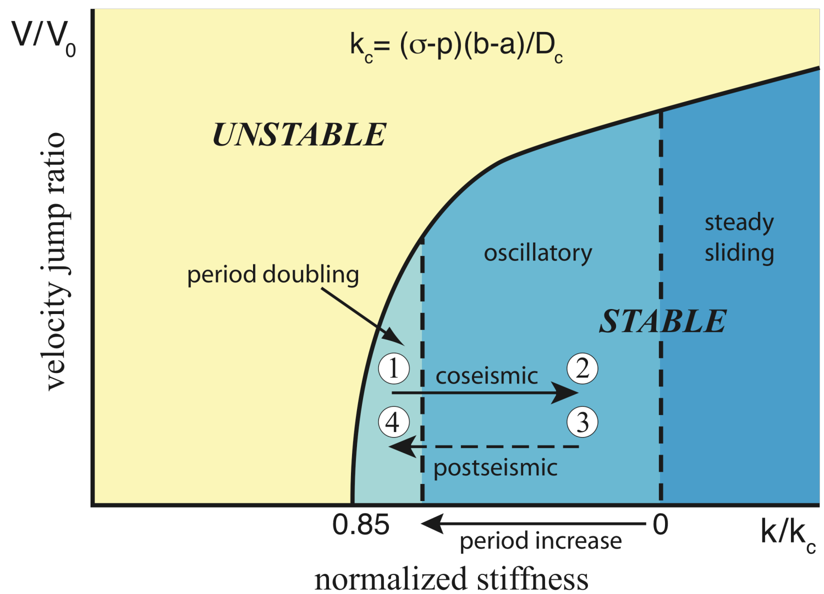

Figure 3. Stability diagram for the 2-state variable friction law (from ref. 38). Numbers 1-4 indicate possible paths for coseismic and postseismic response of LFEs south of Parkfield, California to the 2004 M6 Parkfield earthquake.