Laboratory observations of the full spectrum of fault slip modes: implications for the mechanics of slow earthquakes

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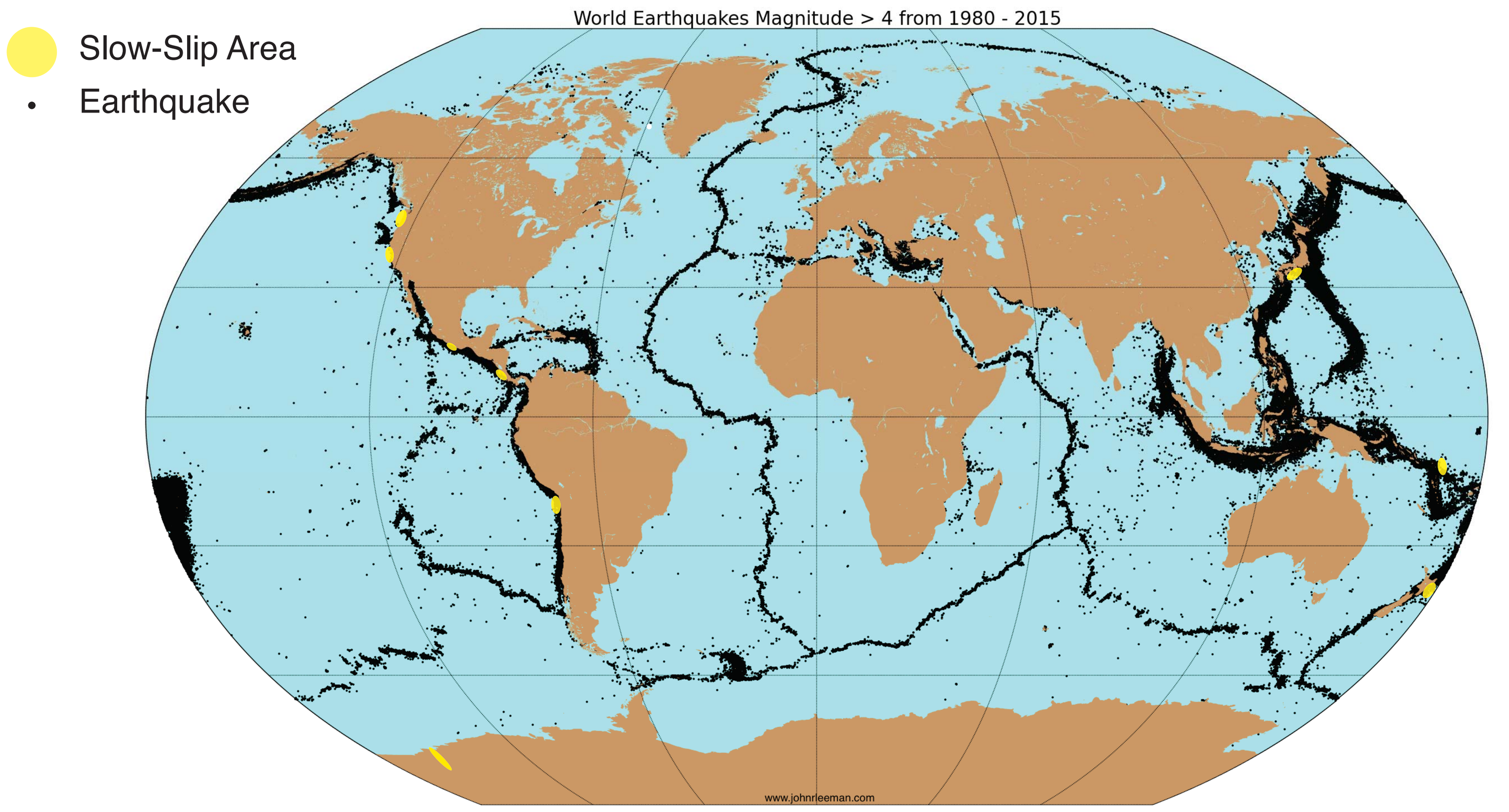
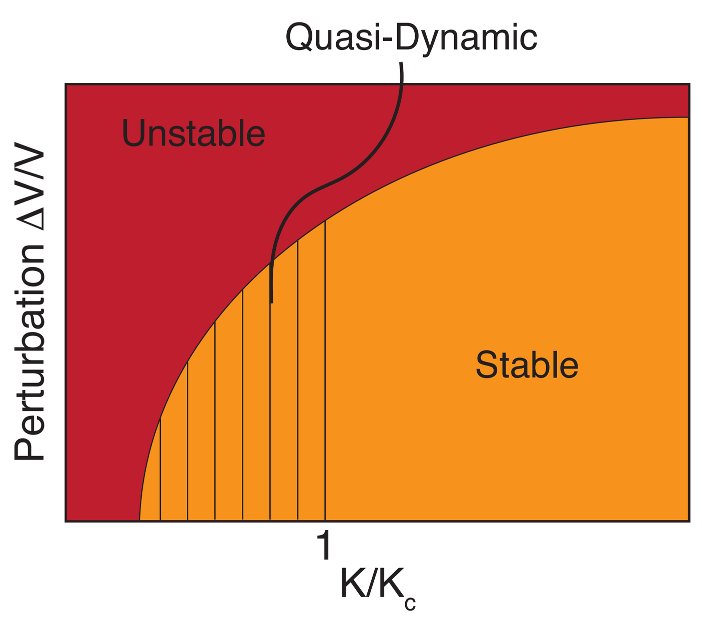
Introduction

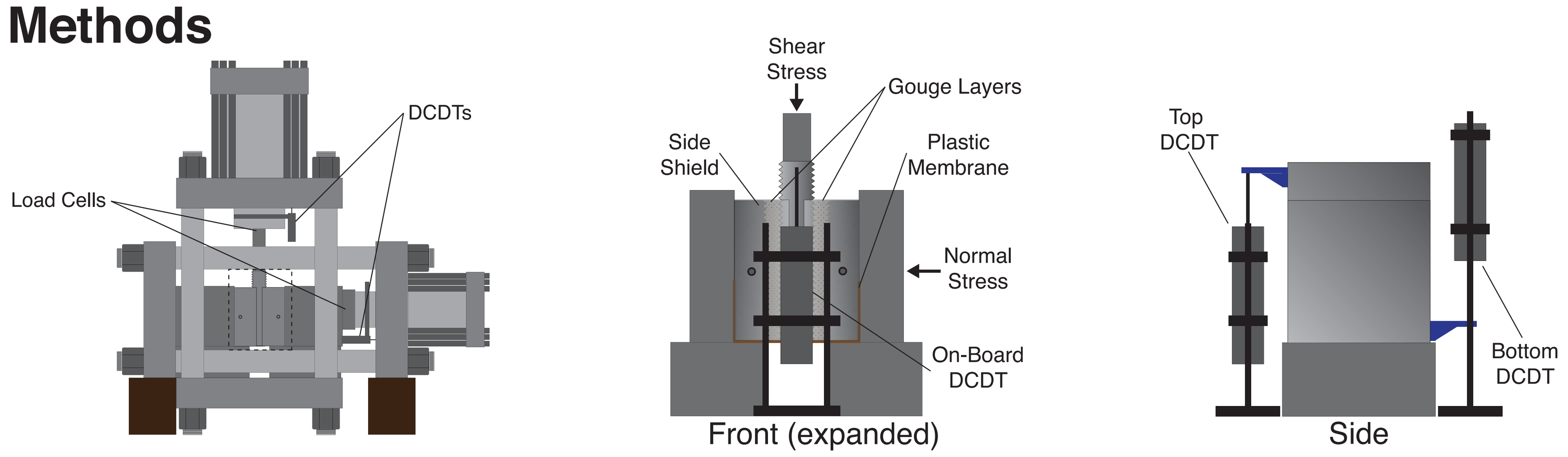
The classical view that faults fail in seismic or a-seismic fashion has been incomplete since observations of tremor and slow-earthquakes in a wide range of geologic settings almost a decade ago. Faults fail in a spectrum of slip behavior as demonstrated by slow slip events, slow and low-frequency earthquakes, episodic tremor and slip, and non-volcanic tremor. The underlying causes of this spectrum of behavior and the processes that control the failure mode of a particular fault are poorly understood, and constitute one of the most pressing conundrums of the field. Field observations provide documentation of slow-slip events at many different locations, but provide little insight into their mechanism. Laboratory observations provide idealized physical models of fault zones, but have historically been unable to reproduce slow-slip events in a systematic and controllable way. We have demonstrated the full range of the seismic slip spectrum in the laboratory and present that data in the context of natural observations.



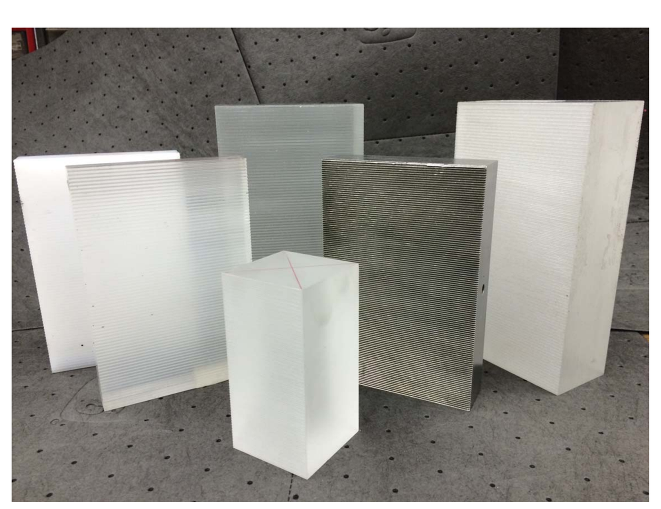


Single state variable rate-and-state frictional theory suggests that when k'< kc' the system behaves in an unstable fashion with the velocity of the slider going to infinity (neglecting inertia). When k'> kc', the system is intrinsically stable to velocity and stress perturbations and slides in a stable manner. For the special case of k'= kc' we can produce emergent slow-slip behavior that was previously thought to be explained only by two state variable systems or a more complicated set of governing equations. We also show that the event type and slip velocity can be controlled by varying the effective stiffness (k') of the system around the critical effective stiffness (kc') predicted from basic frictional stability theory.

Methods

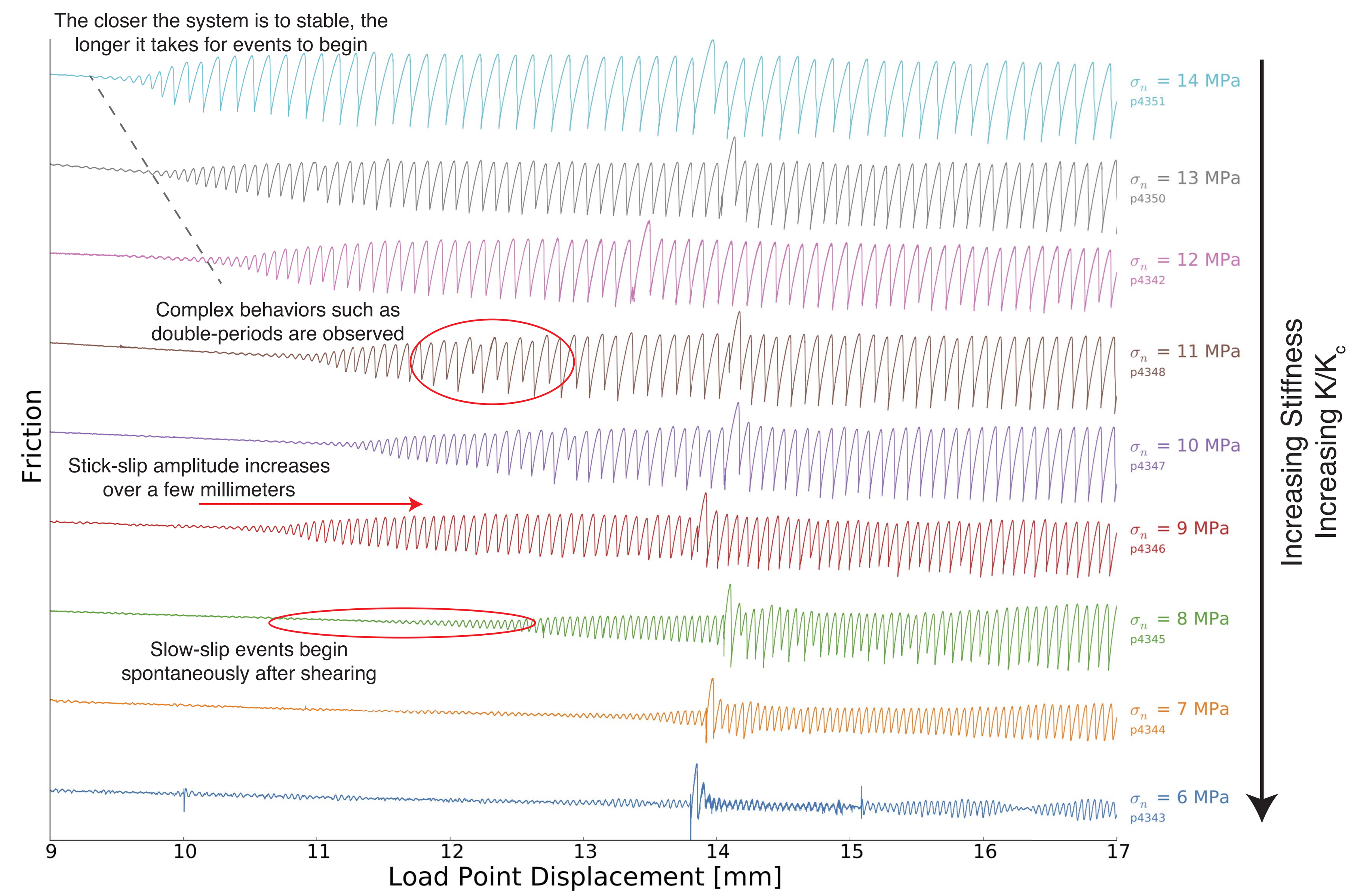


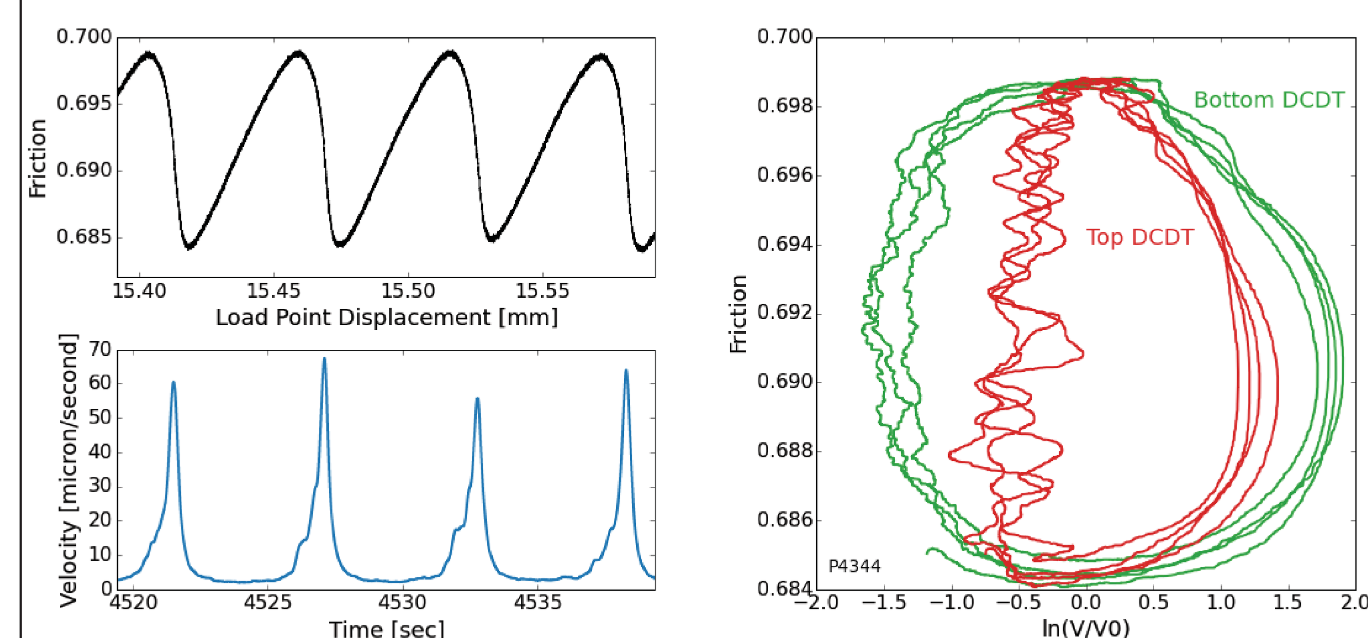
Samples were prepared using steel or titanium side blocks and steel or acrylic (PMMA) central shearing blocks. We used Min-U-Sil 40 powdered silica (U.S. Silica Co.) to simulate granular fault gouge. Samples were constructed as 3-mm thick layers, and with 10 cm x 10 cm frictional contact area. Layers were prepared and sheared under 100% relative humidity at room temperature.



Shear was induced by imposing a displacement rate on the central forcing block, using a feedback servo control. The displacement rate was maintained constant at 10 µm/s for the majority of our experiments, and velocity step tests were used to determine the friction rate parameters (a-b) and Dc. We used a range of shear loading stiffnesses (k) given by the summation, in series, of the apparatus stiffness, the stiffness of the loading blocks, and the stiffness of the layers of fault gouge. The effective loading stiffness of the testing machine ($k' = k/\sigma_n'$) was altered by using a compliant central forcing block (PMMA) and by changing the applied normal stresses. We measured k in experiments using a least-squares linear fit to friction vs. shear displacement for the interval µ = 0.3 – 0.4 and from the elastic loading portion of stick-slip events. Rate-and-state friction parameters were determined using an iterative singular value decomposition technique.

Laboratory Results

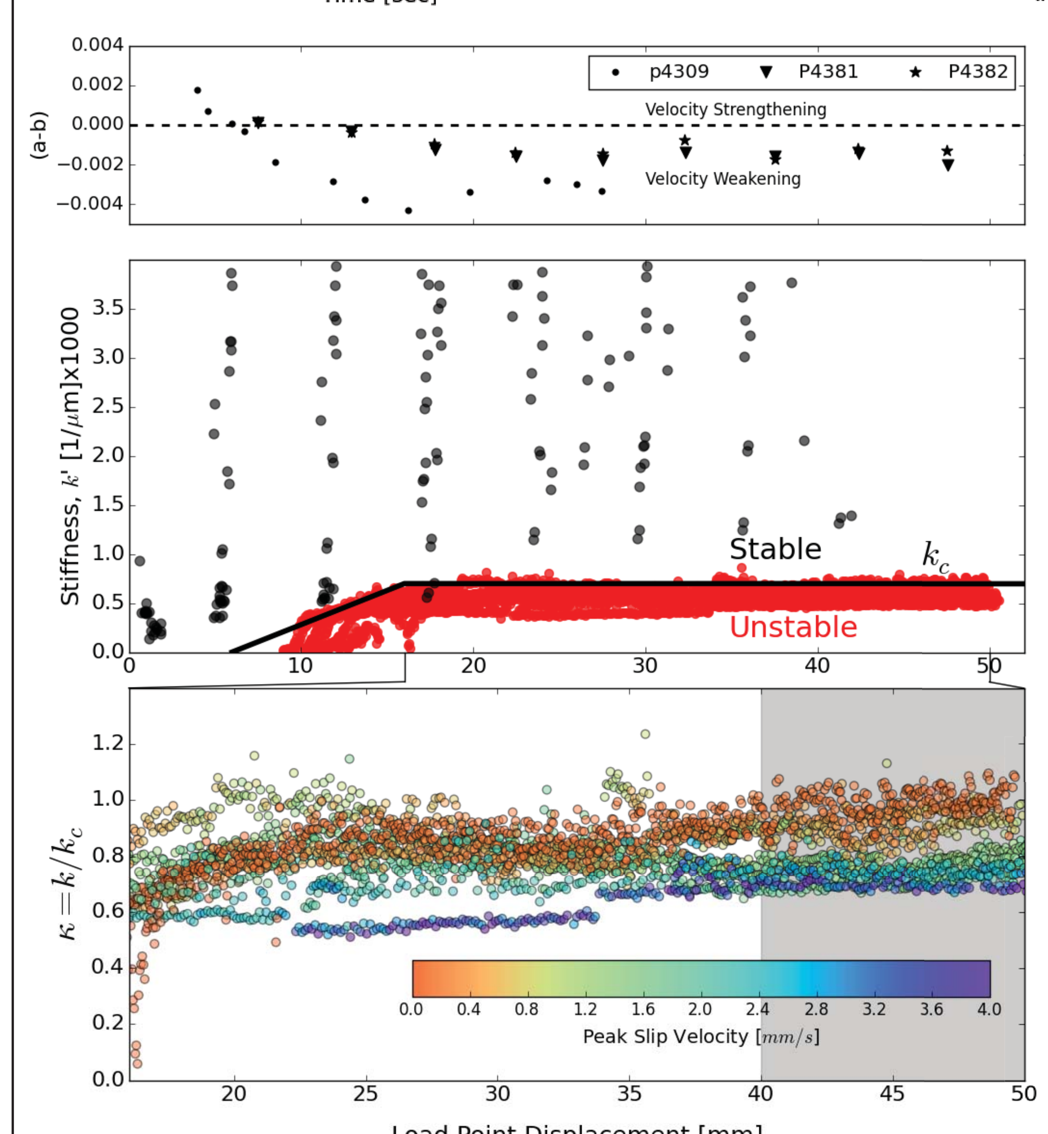




- The top DCDT continues to move near the loading velocity, but the bottom almost stops. This is due to strain energy being stored in the elastic center block.

- Velocity profiles for all events are very similar

- Experimental phase plots are similar to model results, but with some noise at low velocities

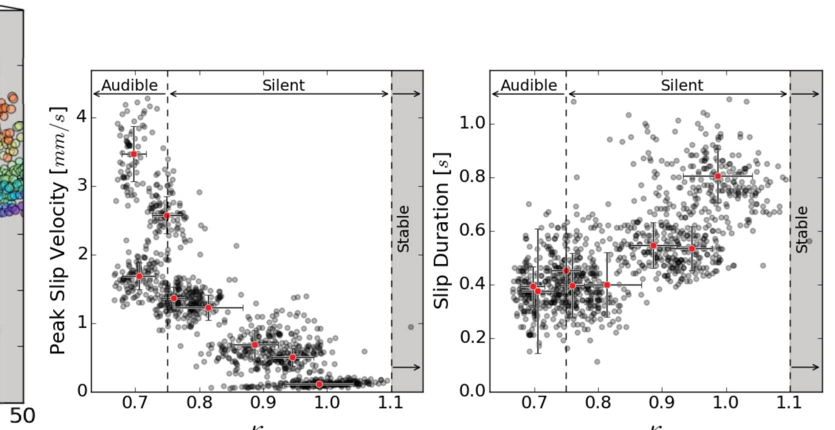


- The stability boundary (black line) predicted by theory well separates experimental data into stable and unstable regions.

- During an experiment, the system stiffens, drawing closer to the stability threshold.

- Peak slip velocity is a nearly linear function of the critical stiffness ratio: the closer to stability the system is, the slower the system fails.

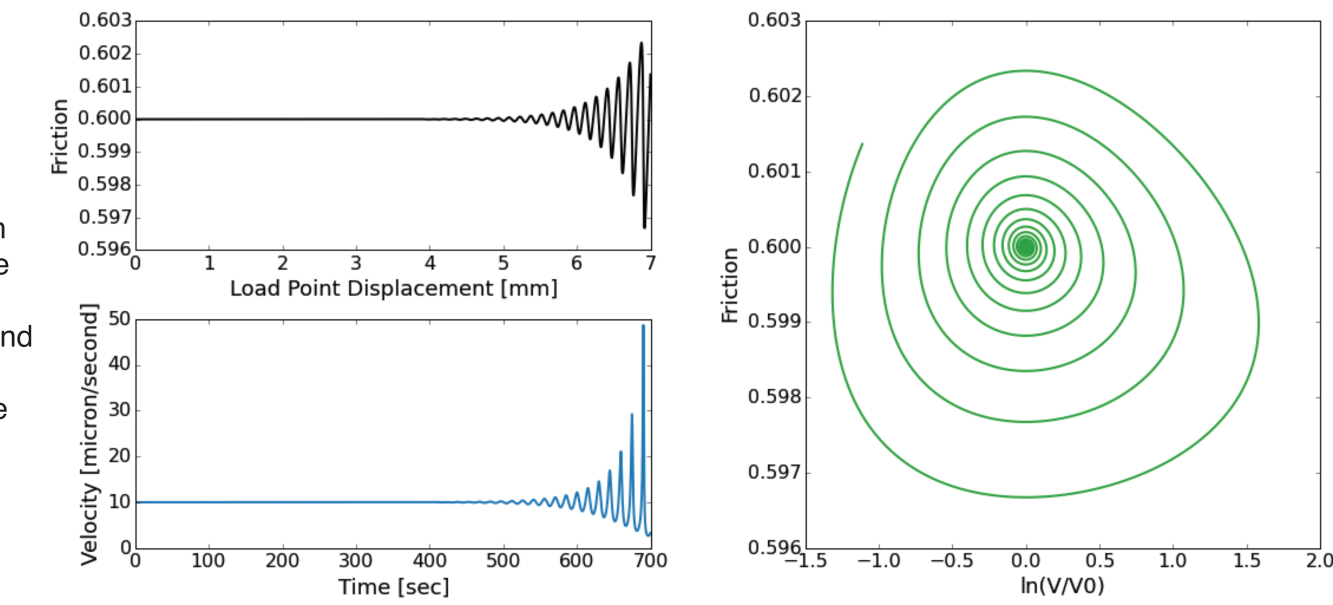
- Slip duration is also a nearly linear function of the critical stiffness ratio: the closer to stability the system is, the longer the slip duration is.



Modeling Results

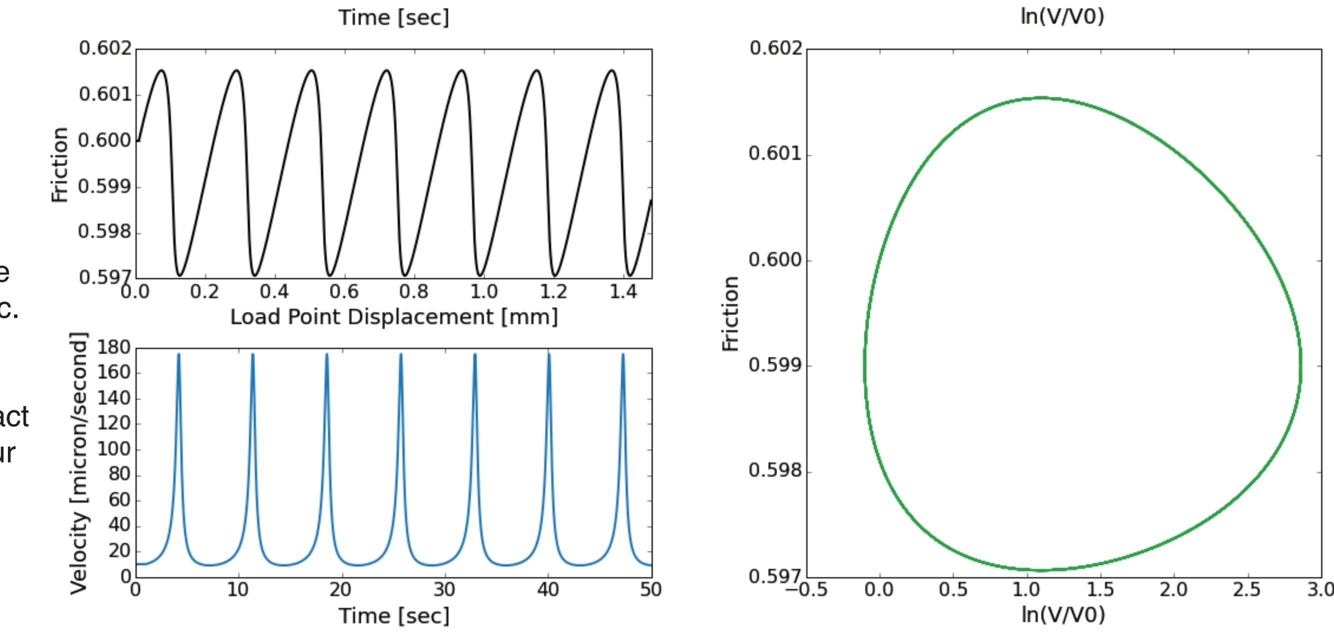
$K/K_c = 0.8$
$V_f/V_0 = 1$
Small Perturbation

Single state variable models can reproduce emergent instability with small perturbations while below the critical stiffness. These models eventually become fully dynamic and unstable. While inertia or evolving RSF parameters are required to be valid during dynamic fast stick-slip events, this model well represents the beginning of our experiments



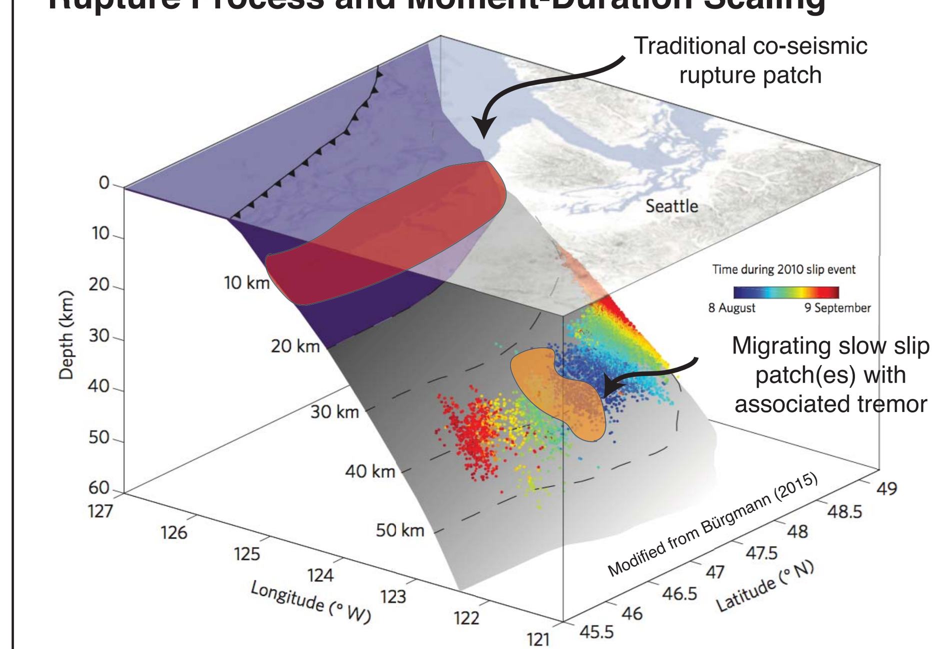
$K/K_c = 1$
$V_f/V_0 = 3$
Velocity Step

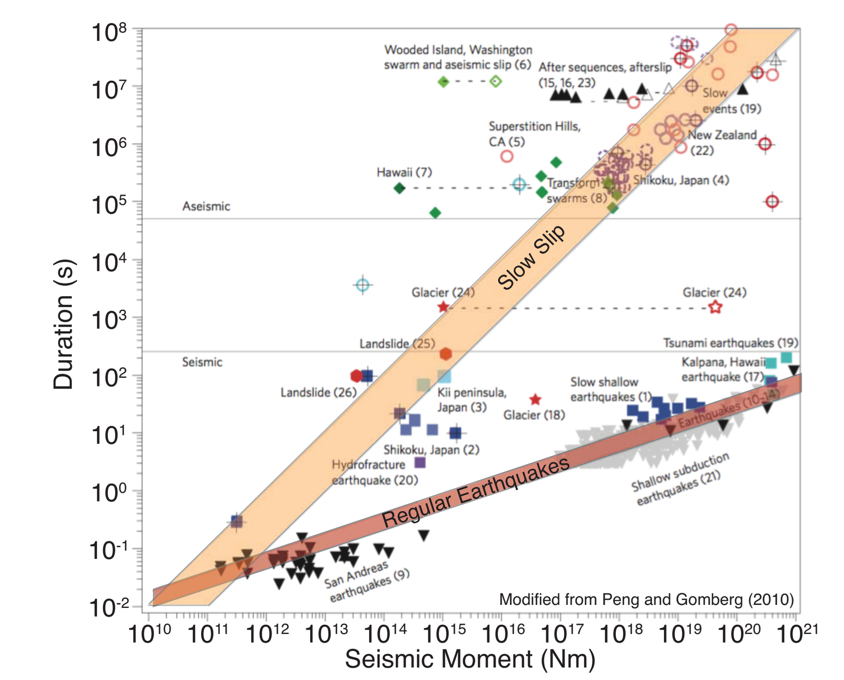
Repeated slow-slip events can be modeled by setting the stiffness equal to the critical stiffness. These events never become fully dynamic. Velocity perturbations from the emerging instability (above) and increasing system stiffness could act in concert to effectively stabilize our slow-slip experiments in approximately these conditions.

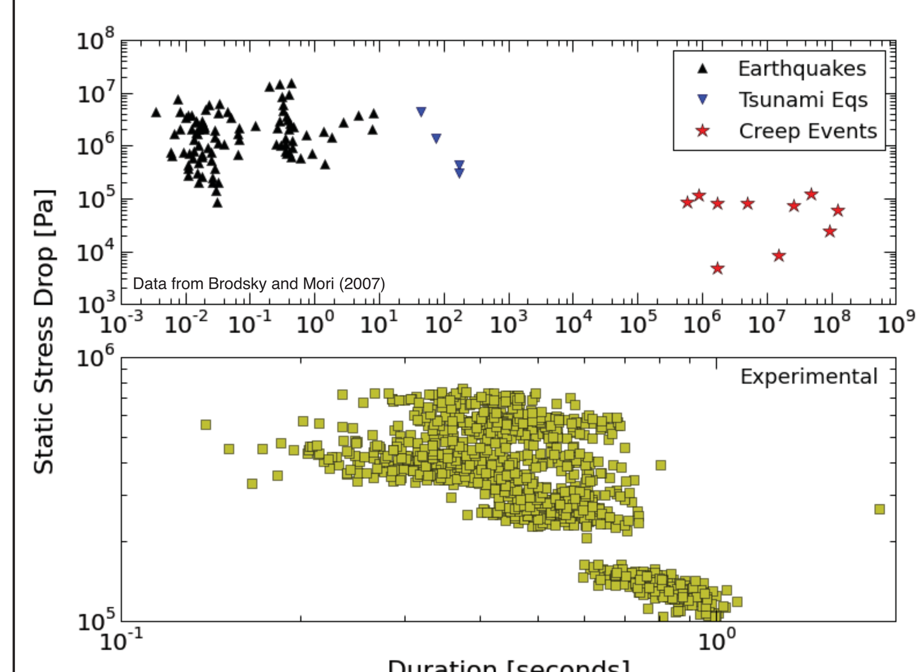


Connection to Natural Earthquakes

Rupture Process and Moment-Duration Scaling







Regular Earthquakes
Seismic patch ruptures in 10's of seconds at most. Slip scales with size of the patch.

$$M_0 \propto T^3$$

Slow Earthquakes
Rupture propagates as a patch of fixed size for hours to years. Slip scales with patch size, not total rupture size.

$$M_0 \propto T$$

We observe the commonality that stress drop scales with duration in a power-law form for both laboratory and natural events (both slow and fast). This further supports a fundamental and common physical mechanism that can produce slow and fast slip events.

Take Home Conclusions

- The stiffness of the system with respect to the critical stiffness controls the failure behavior
- Peak slip velocity and duration of slip vary systematically with distance from the stability boundary
- Arguments such as high pore pressure, weak faults, and designer friction are all consistent with this idea
- Single state variable models are capable of reproducing many of the observed behaviors
- The stability argument can be applied to the many diverse areas where slow slip is observed
- Laboratory faults are reasonable representations of real faults with similar characteristics

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