Controls on Fault Zone Stability and the Mechanics of Slow Earthquakes

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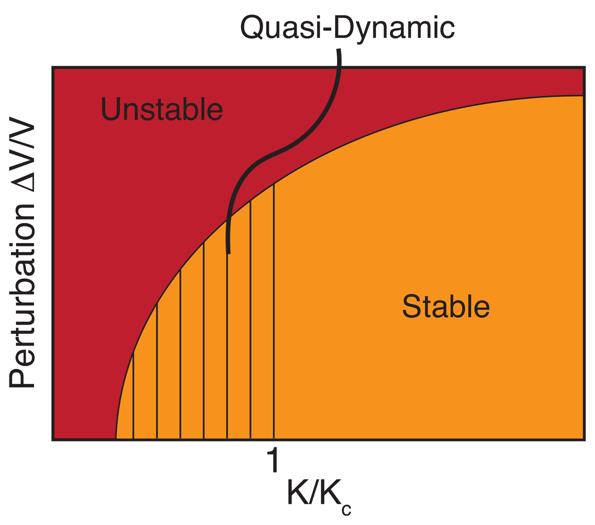
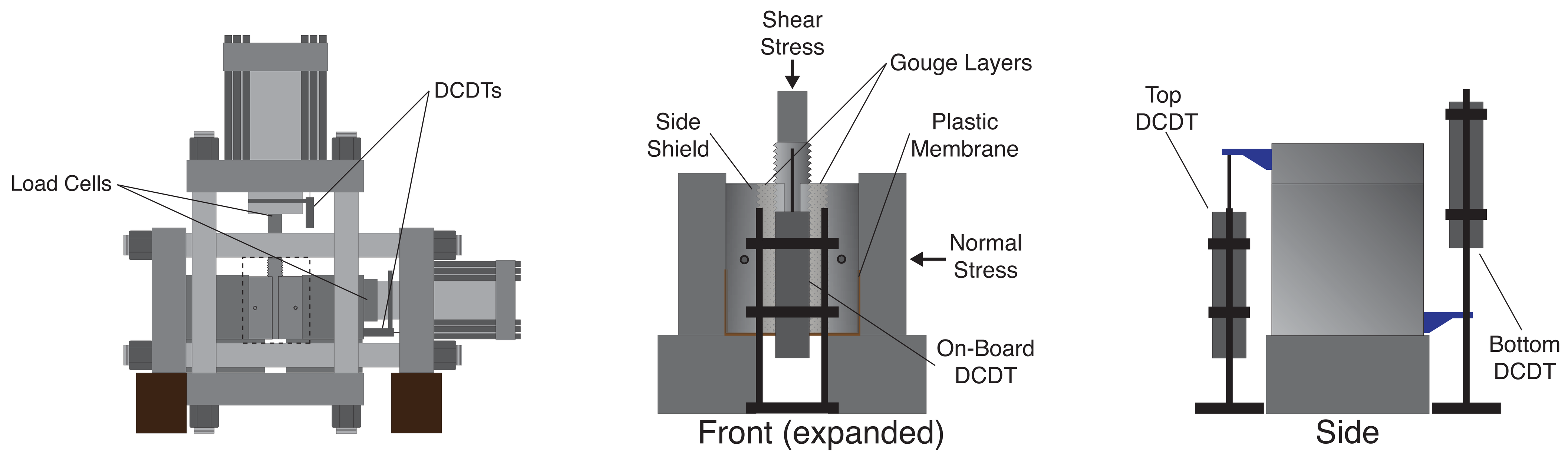
Introduction

The classical view that faults fail in seismic or a-seismic fashion has been invalidated by observations of tremor and slow-earthquakes in a wide range of geologic settings. Faults fail in a spectrum of slip behaviors 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 in geophysics. 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 seismic slip spectrum in the laboratory (Leeman et al., 2016). Here we present that data, along with new work, in the context of natural observations.

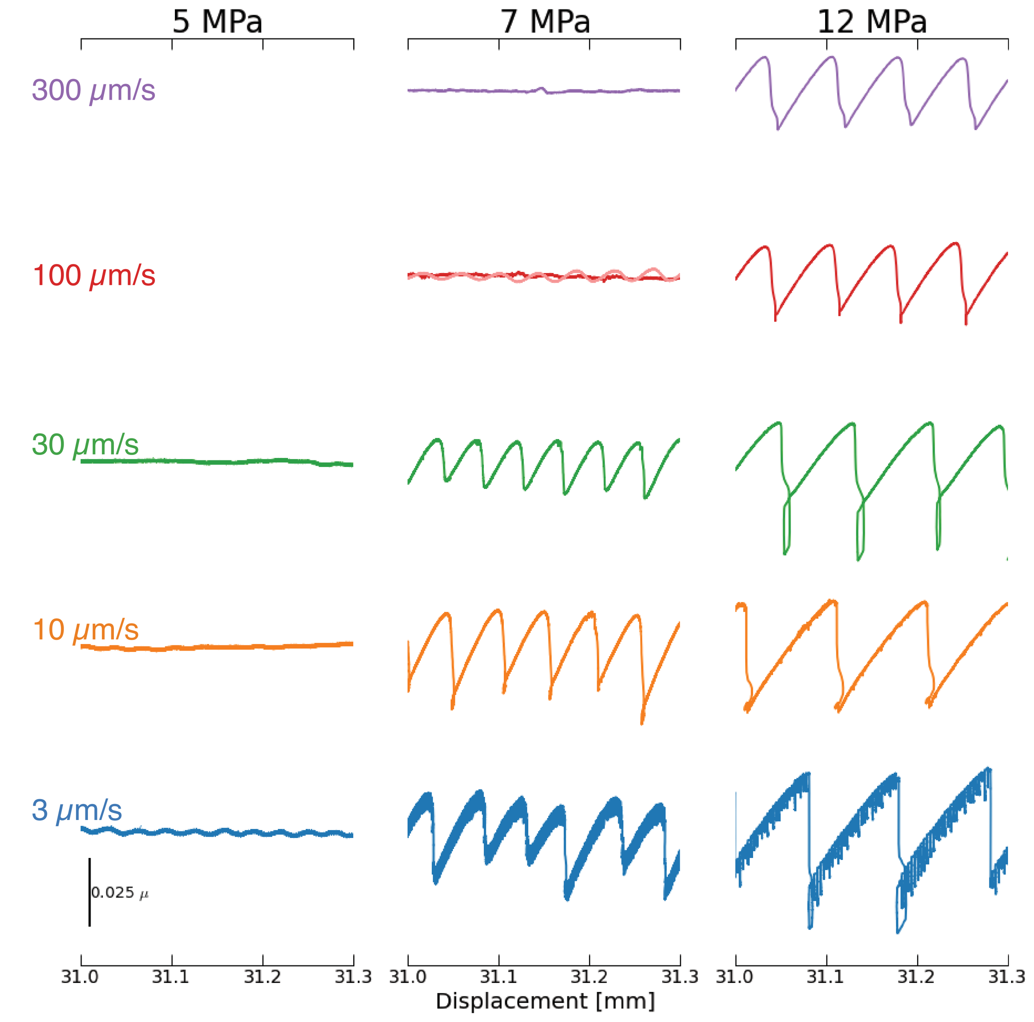


Single state variable rate-and-state frictional theory suggests that when $k' < k_c'$ the system behaves in an unstable fashion with the velocity of the slider going to infinity (neglecting inertia). When $k' > k_c'$, the system is intrinsically stable to velocity and stress perturbations and slides in a stable manner. For the special case of $k' = k_c'$ 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.



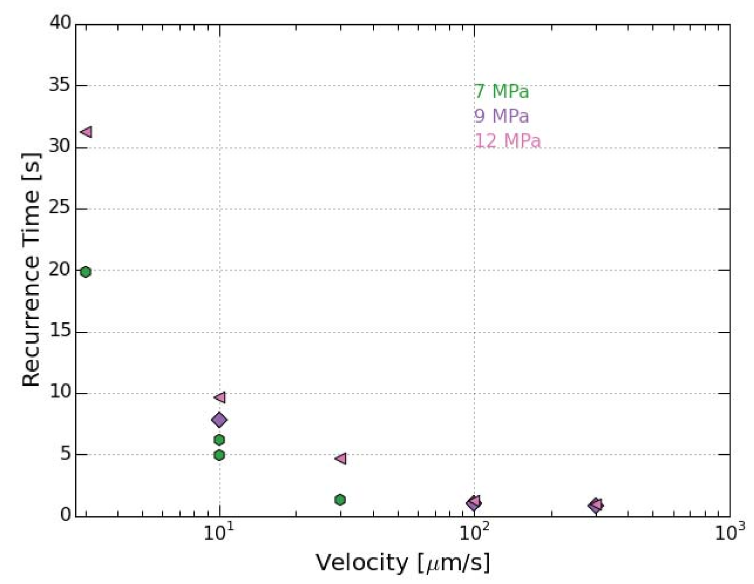
Samples were prepared using steel or titanium side blocks and steel or acrylic (PMMA) central shearing blocks. We used Min-U-Sil 40 powdered silica (U.S. Silica Co.) to simulate granular fault gouge. Samples were constructed as 3-mm thick layers, and with 10 cm x 10 cm frictional contact area. Layers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

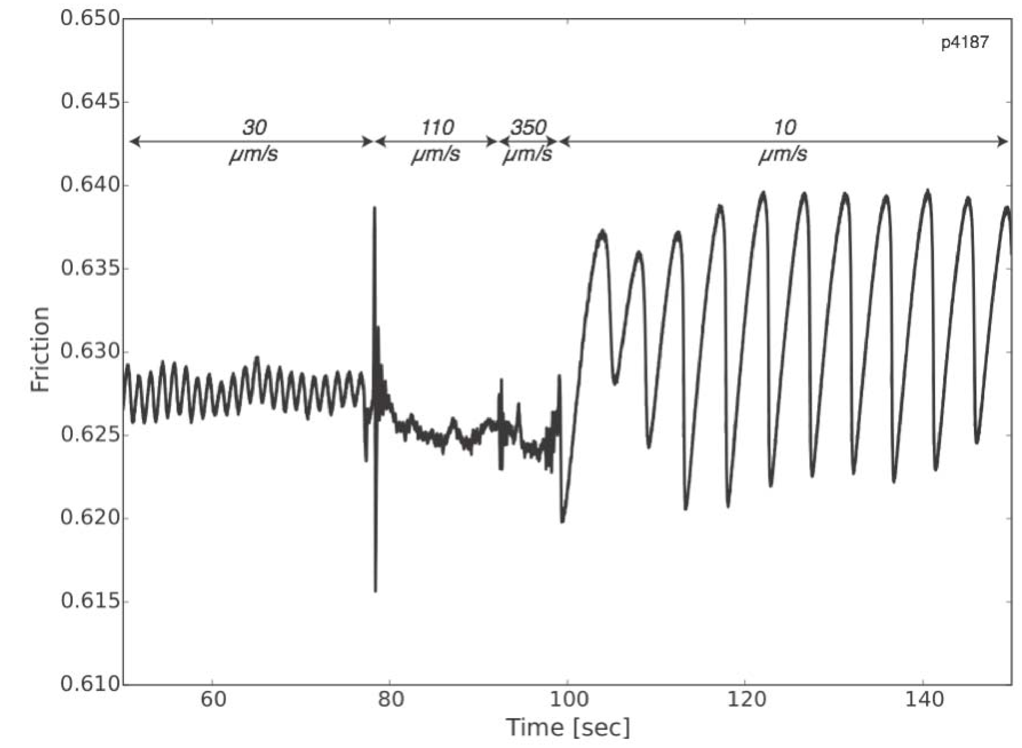
Velocity Effects



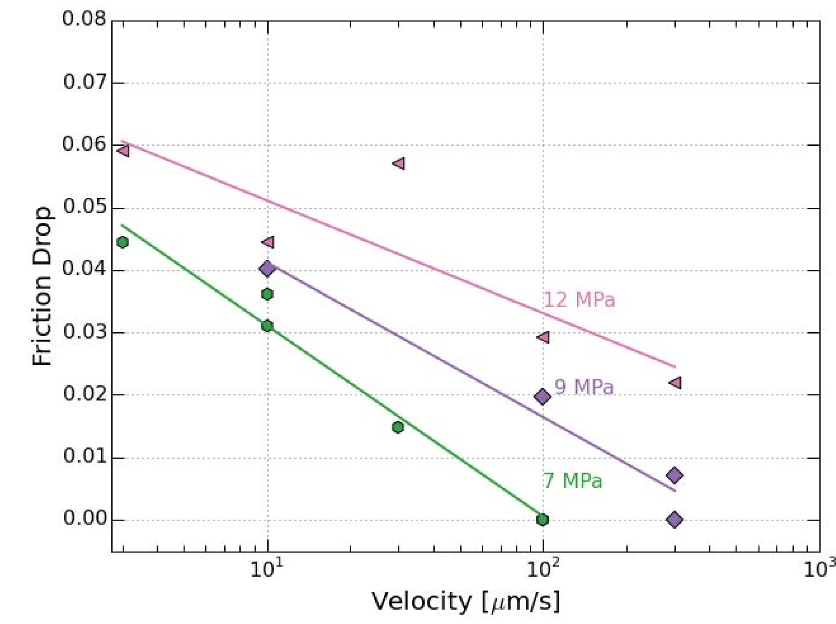
The effects of normal stress and loading velocity are apparent in this experimental matrix. Faster shearing rates produce more stable behavior compared to slower rates. At a normal stress of 7 MPa, the stability transition occurs between shearing rates of 30μm/s and 100 μm/s.

Recurrence time decreases exponentially with the log of driving velocity. There is a weak normal stress dependence as well.



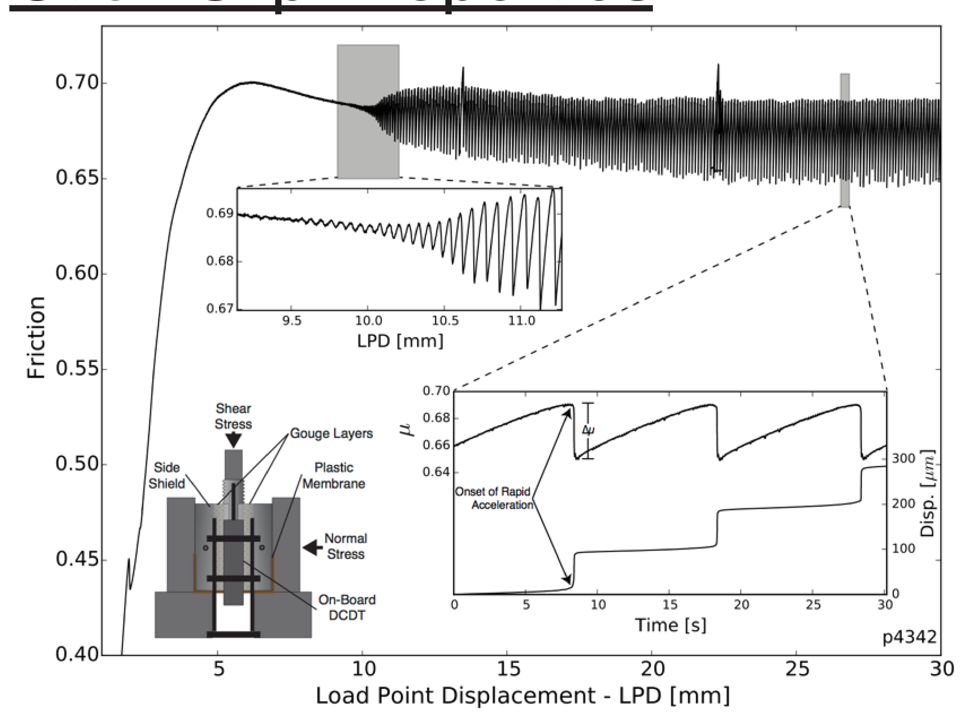


Velocity effects can also be observed in a single experiment, confirming that the inter-experiment comparison is valid.

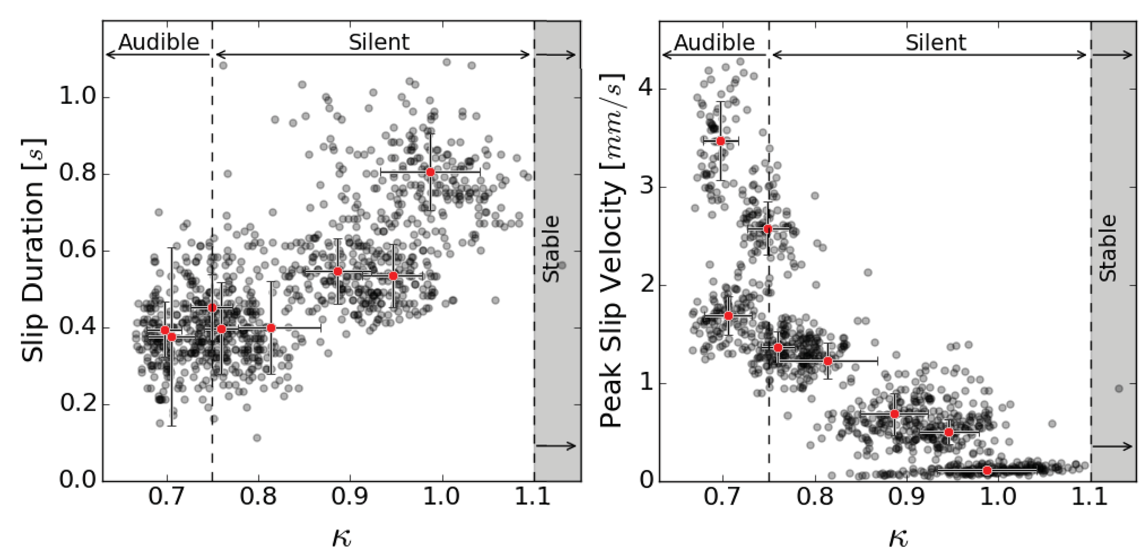


Friction drop scales logarithmically with load point velocity. As the normal stress increases and the critical stiffness ratio decreases, the systems become more unstable and have higher friction drops at a given velocity. The scaling constant appears to decrease with higher normal stress, suggesting that higher normal stresses the friction drop is more weakly dependent on velocity, possibly suggesting why there is such a small range of inferred stress drops in natural earthquakes.

Stick-Slip Properties

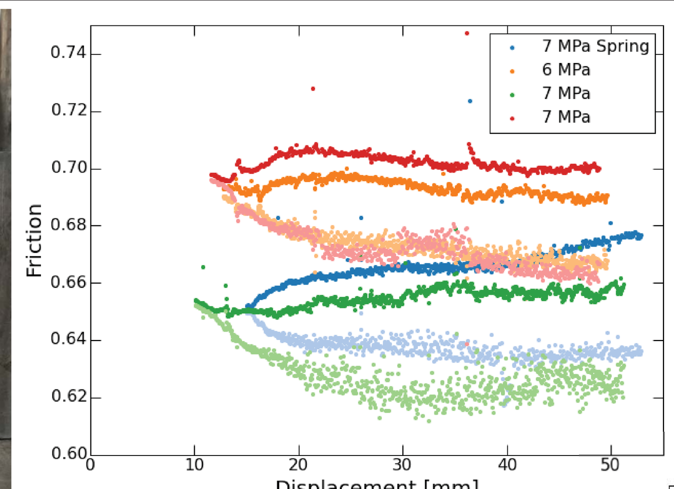


During the experiments, slow-slip events spontaneously emerge after ~10 mm shear displacement. The amplitude of the stick-slip events increases over a few millimeters of displacement, then reaches a steady value.

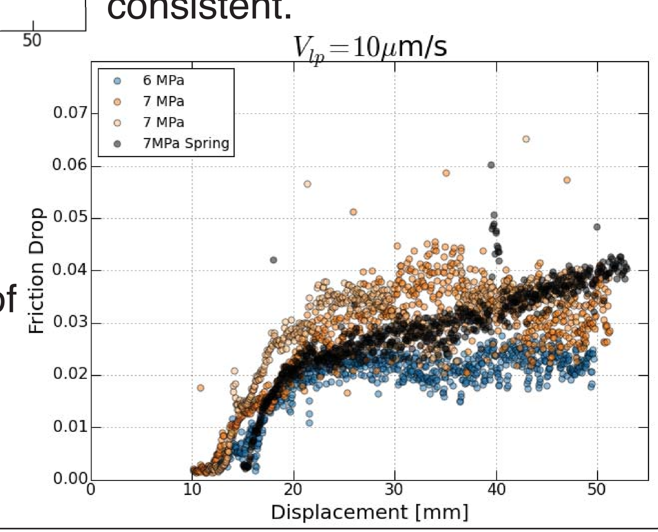


The slip duration and peak slip velocity of the stick-slip events scales with how close the system is to the stability boundary ($k/k_c = \kappa = 1$). All experiments shown were conducted at a shearing rate of 10 μm/s with an acrylic center block. The normal stress was changed to modify the critical stiffness ratio; higher normal stresses push the system further into the unstable regime. The silent events are laboratory analogs of slow earthquakes, while audible events are considered regular earthquake analogs.

Most of the experiments shown were conducted by destiffening the shearing apparatus using an acrylic center forcing block (left). Similar results have been obtained by destiffening the system using an acrylic block as a spring above an all steel forcing block setup (right). Block wear is also much less of a concern using this technique.

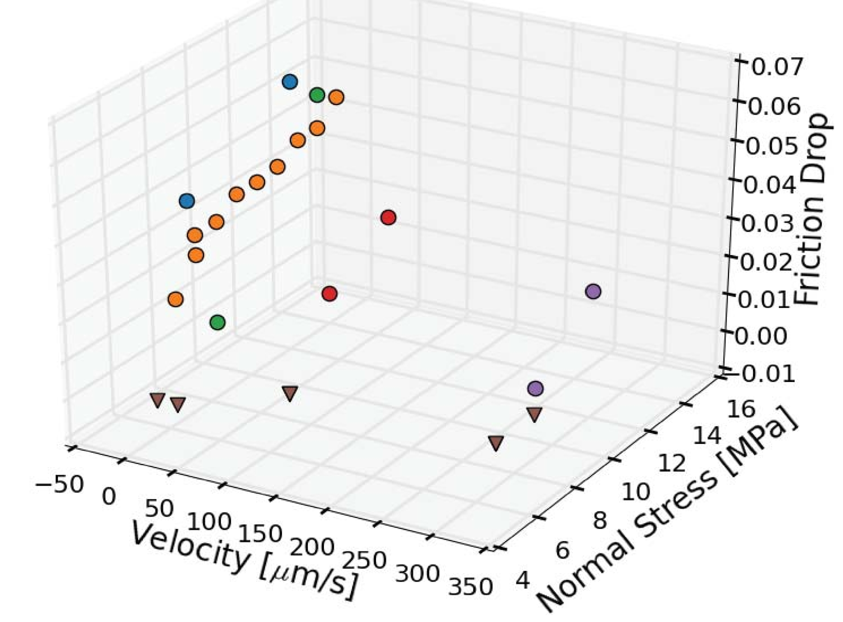


The minimum and maximum friction values for each stick-slip event. The trends for experiments with the acrylic center block and acrylic spring are very similar. Minimum and maximum values for each experiment are remarkably consistent.

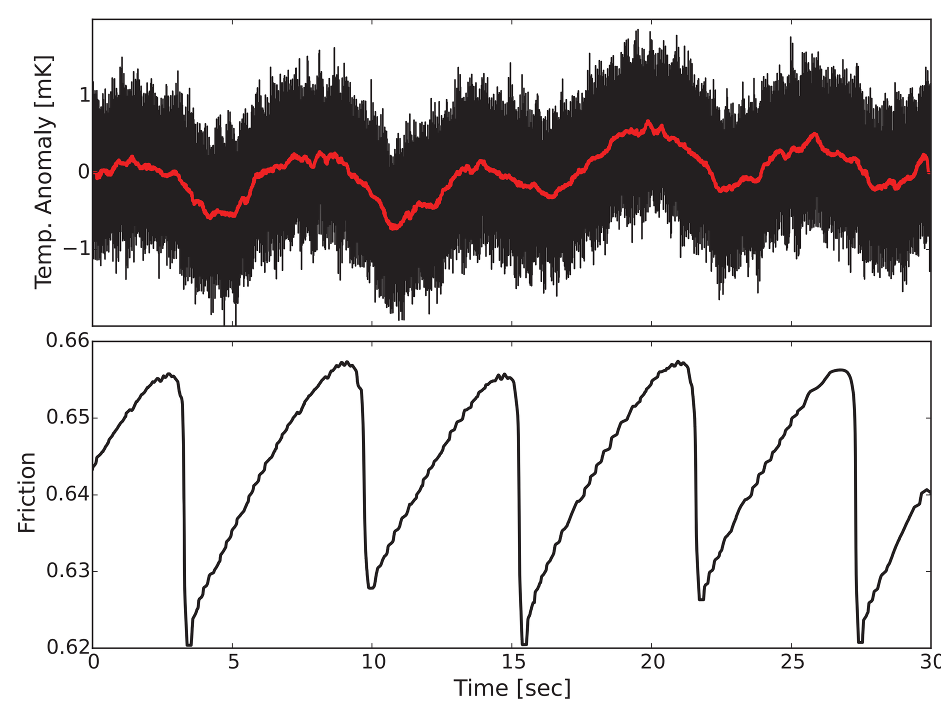


The friction drop for the acrylic spring experiment appears to monotonically increase with displacement for the duration of the experiment unlike acrylic center block experiments.

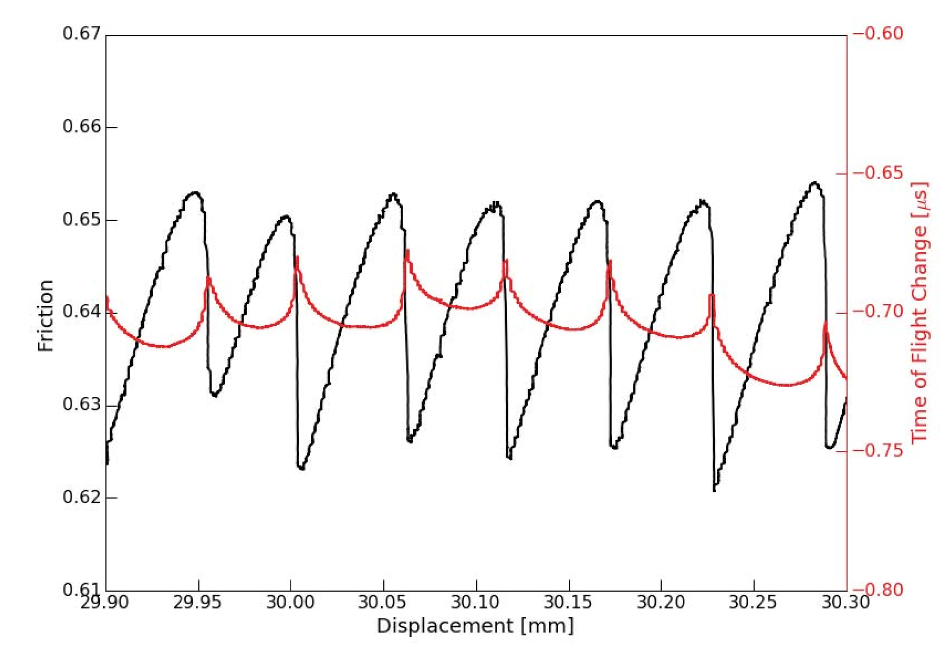
Conclusions and Implications



We have begun to map out the stability surface, showing that it is not simply a boundary between stable and unstable, but an envelope going from stable to growing stick-slip events. Triangles represent stable (zero friction drop) experiments. Each color is a constant shearing velocity.



Heat pulses from individual slow-slip events have been observed in our experiments. The anomalies are on the order of 1 mK and can be matched by a shear-heating/multi-layer thermal conduction model.



The acoustic time of flight (P-wave velocity) through the layers of fault gouge increases well before failure occurs, consistent with Kaproth and Marone (2013) and Scuderi et al., (2016). The results are also similar to observations of seismic velocity decreases before natural earthquakes.

Take-Home Messages

* The mode of fault slip (ranging from aseismic to seismic) is controlled by the conditions on the fault and the stiffness of the surrounding rock.

* The complete spectrum of slip behaviors observed in nature can be simulated in the laboratory, including acoustic and thermal anomalies.

* Fault zone elastic stiffness is a function of time and shear strain. Stiffness is not a static property of the system.

* The stability of frictional sliding depends on the shearing velocity, with higher velocities producing a more stable response.

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