The Role of Stiffness in the Dynamics of Frictional Stick-Slip Failure: Insights from Lab Experiments

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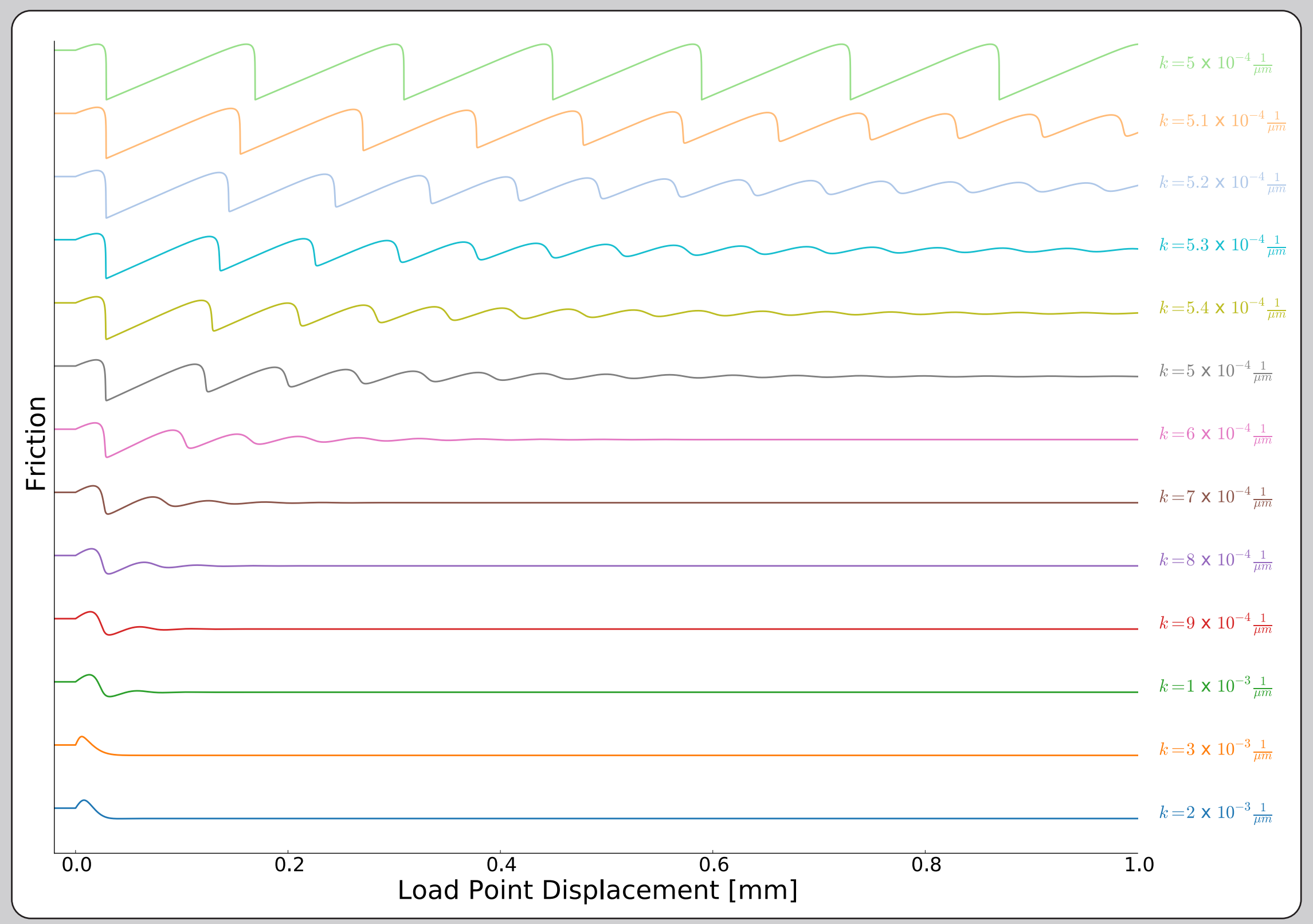
Frictional Stability and System Stiffness

The underlying mechanisms governing slow earthquakes remain a topic of debate, though they have been observed in many tectonic settings, including subduction zones and transform faults. What causes strain energy to be released across a wide-range of failure behaviors is not understood, and is made more difficult by the limited methods of observation on natural faults. Laboratory stick-slip is often used to model and study repeating earthquake behavior. Frictional stability of a system is predicted to bifurcate at a critical stiffness, k_c. For systems in which $k > k_c$, linearly stable response is expected, while systems with $k < k_c$ are dynamically unstable. Behavior at and near k_c is poorly characterized, but transitional behaviors such as sinusoidal stress variations and slow-slip have been observed.

$$k_c = \frac{b-a}{D_c}$$

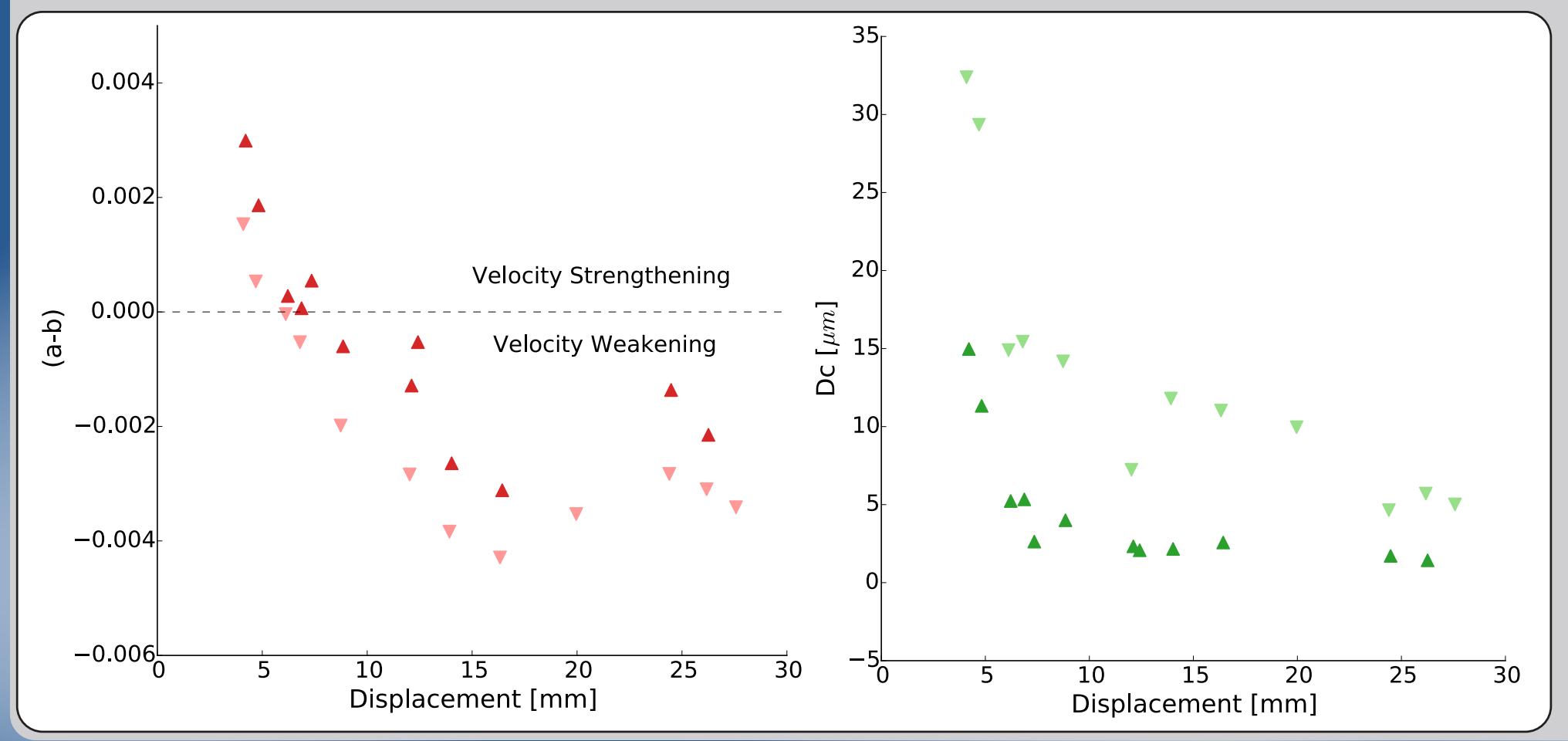
Frictional models commonly employ the rate-and-state friction framework. Elastic coupling in the model is parameterized as a spring-slider system with 1-D linear elastic terms. Simple 1-D rate-and-state frictional models have trouble predicting and reproducing the observed behavior near the system critical stiffness. This suggests that either the frictional constitutive relation needs to be modified, the coupling in inadequate, or both.



1-D rate-and-state model responses to an order of magnitude velocity perturbation on the system for various stiffnesses. Only when the stiffness is equal to the critical stiffness does repeating, self-sustaining stick-slip emerge.

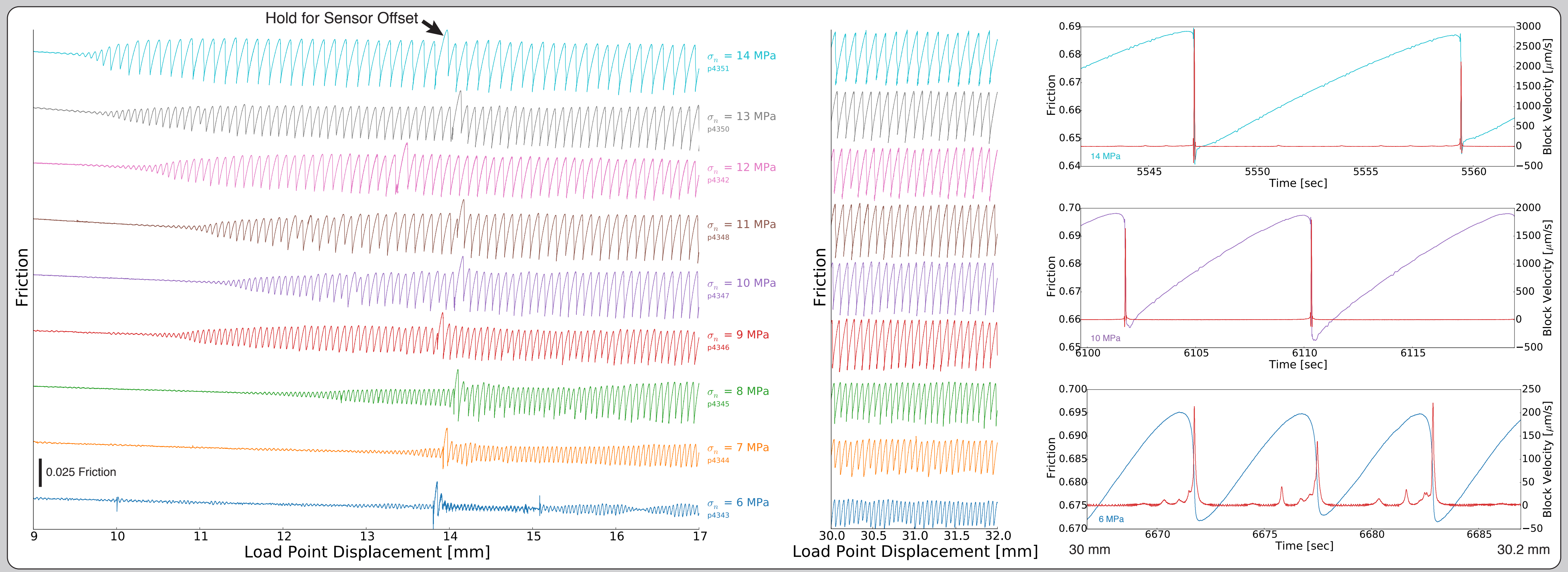
$$\mu = a\ln\left(\frac{V}{V_0}\right) + b\ln\left(\frac{V_0\theta}{D_c}\right)$$

$$\frac{d\mu}{dt} = k\left(V - V_0\exp\left[\frac{\mu - \mu_0 - b\ln\left(\frac{V_0\theta}{D_c}\right)}{a}\right]\right)$$

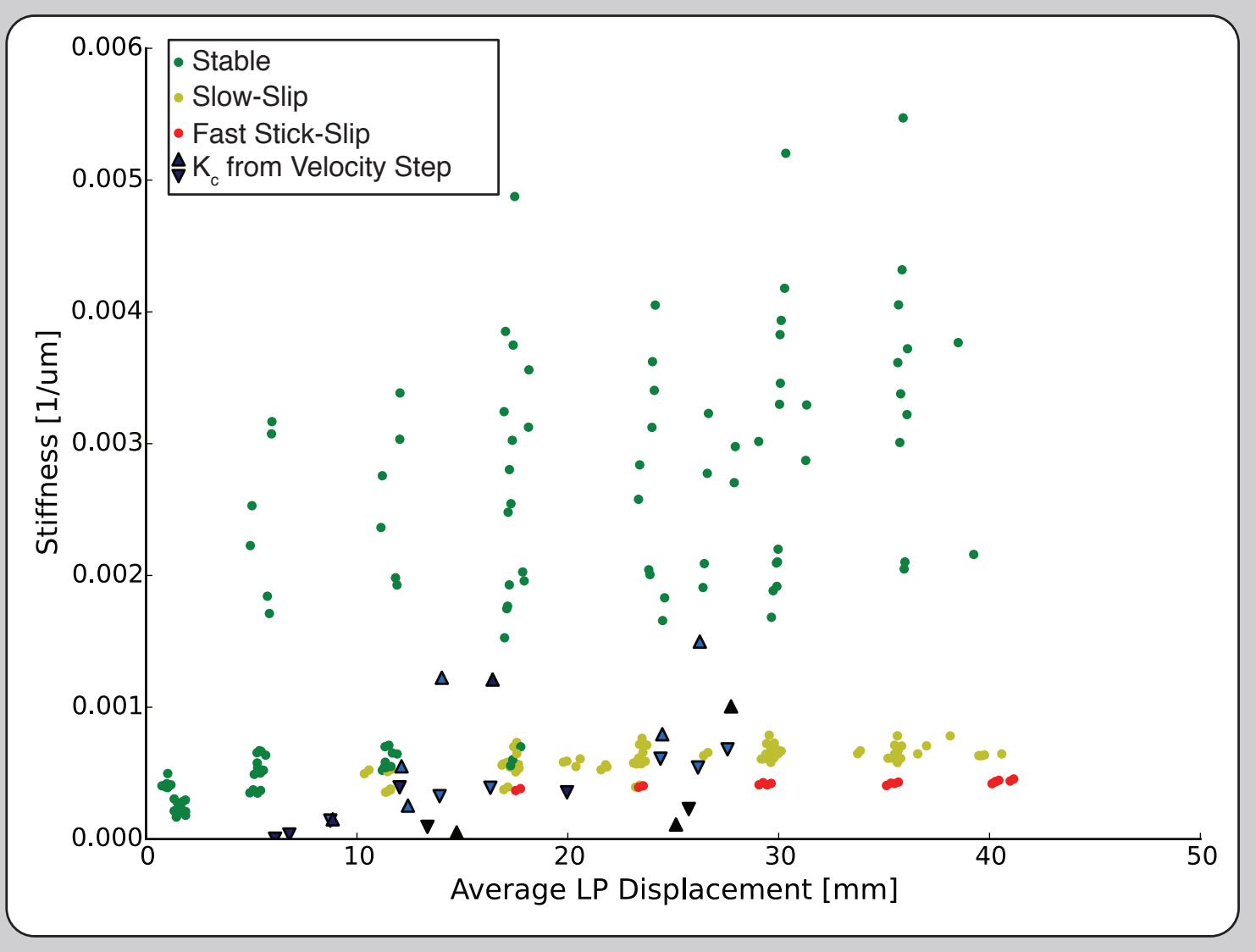


(left) Rate-and-state parameters evolve with shear during an experiment, indicating that the critical stiffness is a dynamic quantity and that fault behavior may change with accumulated slip.

Laboratory Results and Discussion



Laboratory data from identical Min-U-Sil experiments with increasing normal stresses. As effective stiffness is reduced, frictional instability onset is earlier, faster, and produces larger stress drops.



- Slip transitions from stable to unstable, both with displacement (fabric development) and decreasing stiffness.

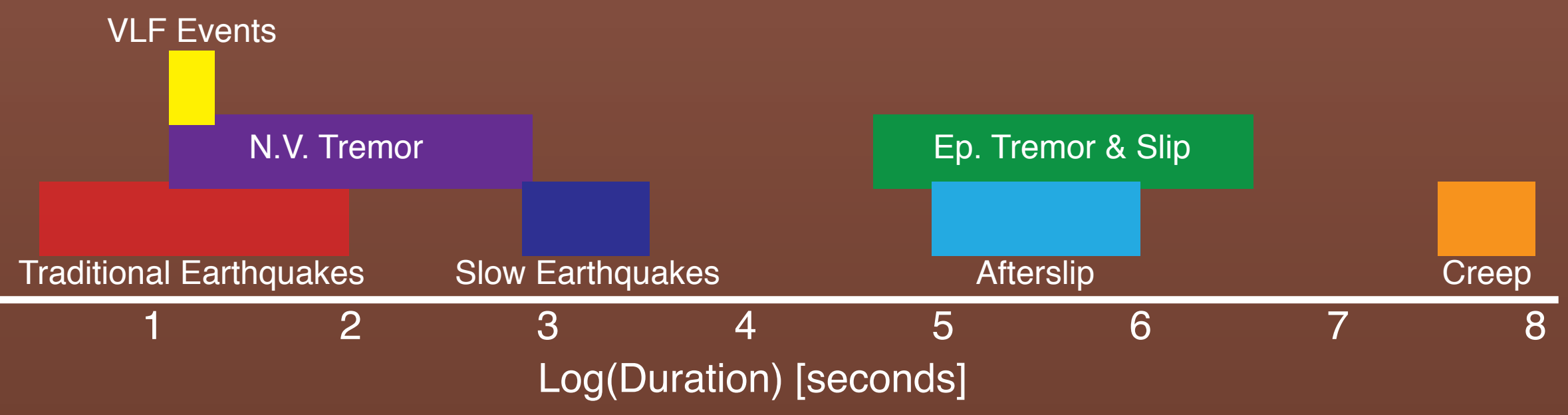
- Experiments with lower stiffness showed faster and larger stick-slip events. Fast events were audible, while slow events were silent. The transition occurs as the system stiffness approaches, then crosses the critical stiffness.

- We find similar behavior with steel blocks at low normal stress and acrylic center blocks and high normal stress, which yield similar stiffnesses.

- Individual slip events become shorter in duration as shearing progresses, and as the system stiffness is reduced.

The Stick-Slip Spectrum

Faults can fail in a continuum of failure behavior ranging from stable creep to unstable, dynamic stick-slip. The controlling processes are currently poorly understood and mostly inferred from frictional models.

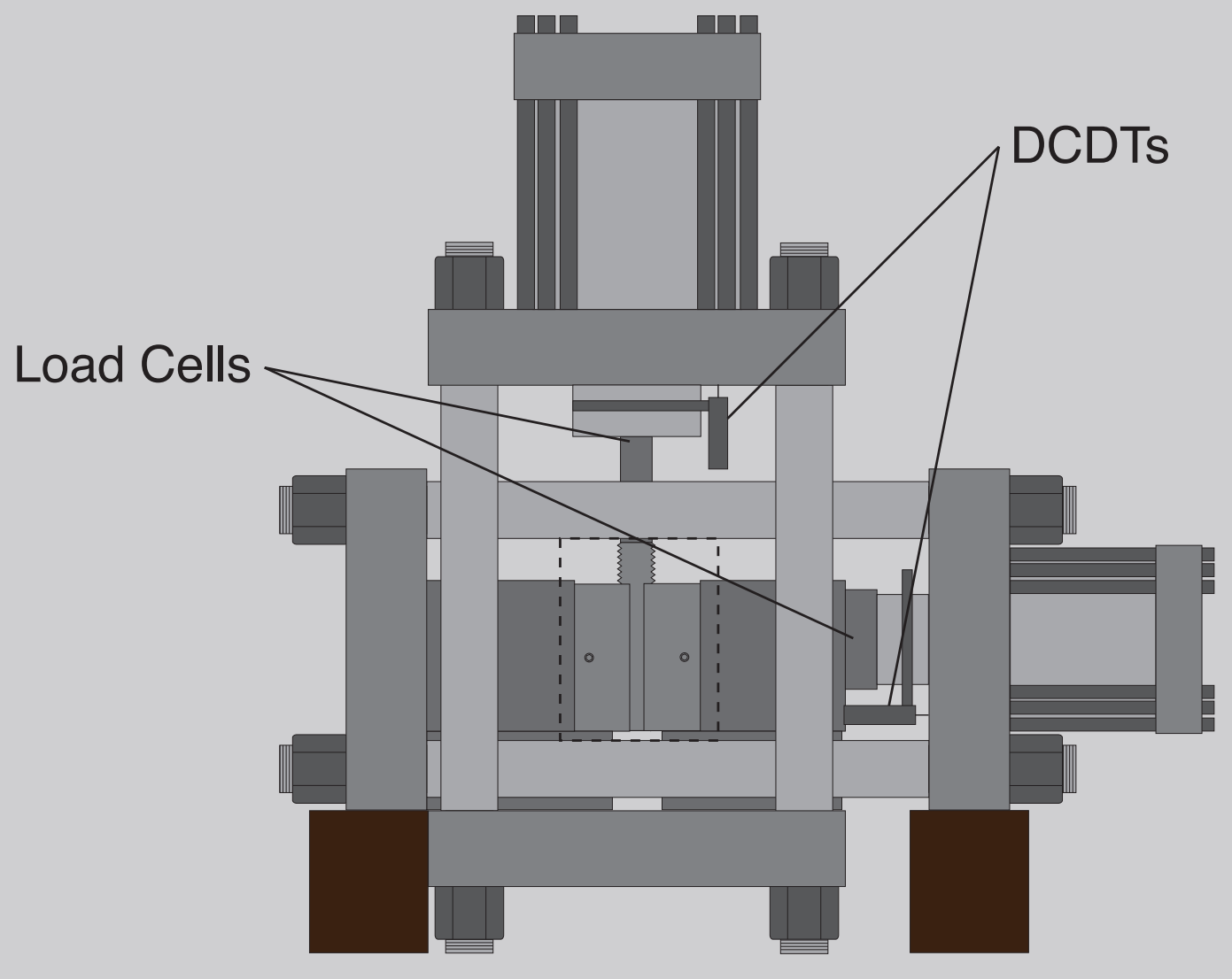


Fundamental Questions:

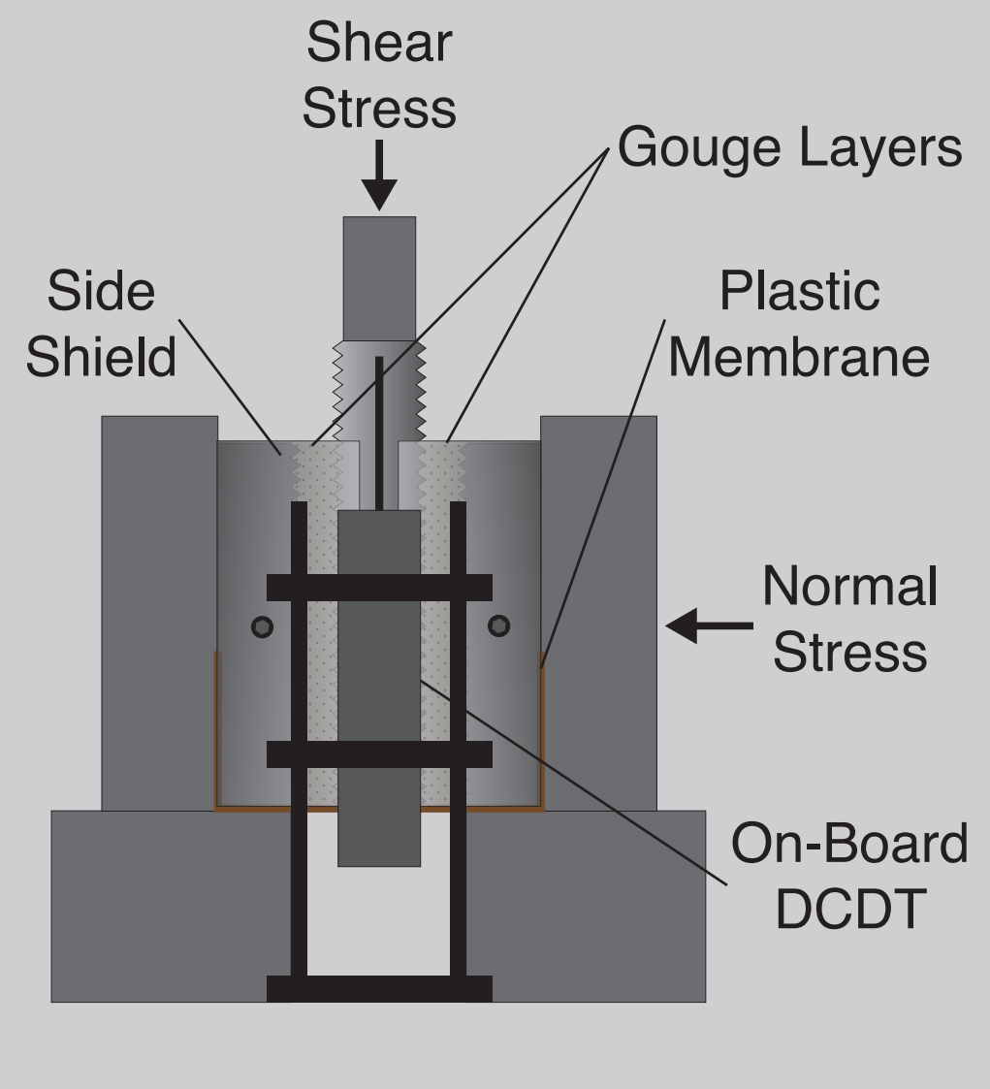
- Is stiffness the controlling factor in determining slip behavior?
- Is critical stiffness an adequate estimate of stability?
- What role does the coupling of stiffness play?
-How does system stiffness evolve?

Experimental Methods

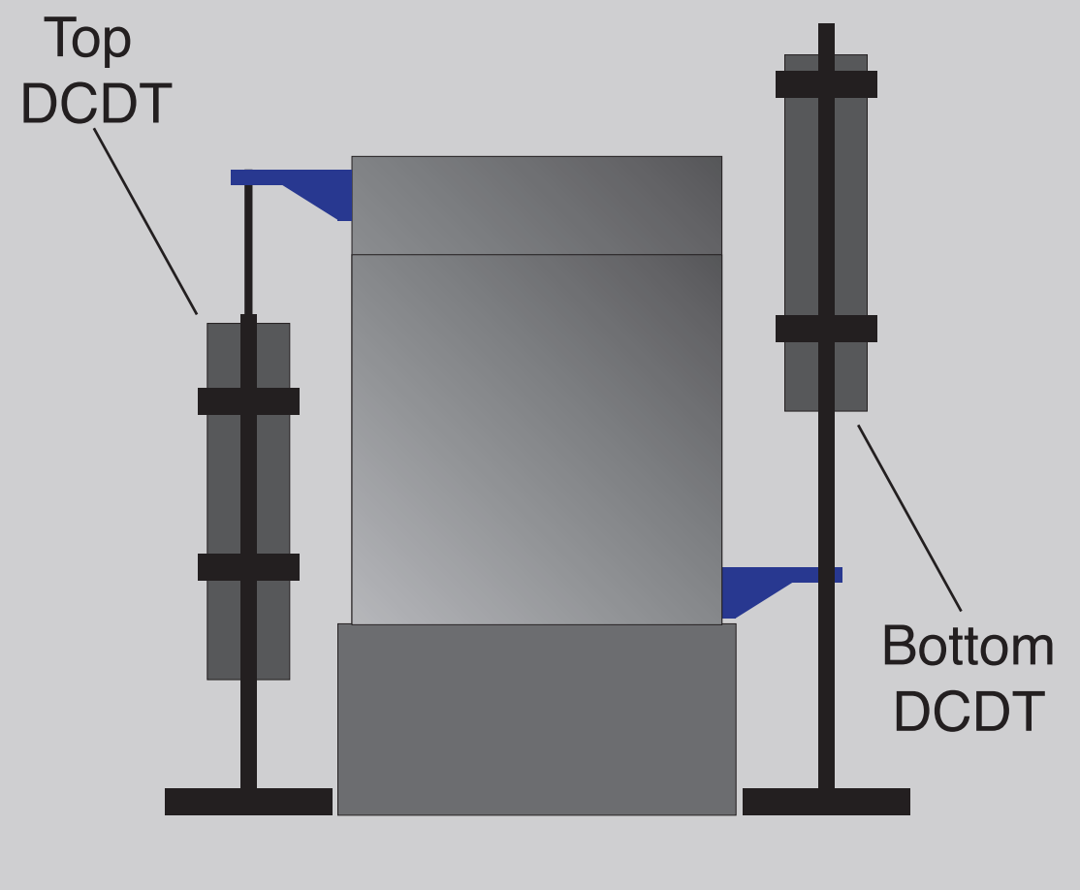
Layers of quartz powder (Min-U-Sil) were sheared with a bi-axial load frame in a double direct shear geometry. Sample materials were conditioned in a 100% relative humidity environment to eliminate environmental variation. Displacement was measured at the top and bottom of the central forcing block, as well as at the end of each hydraulic ram. Displacement and force data were recorded at 1 kHz with a 24-bit analog to digital converter.



Front



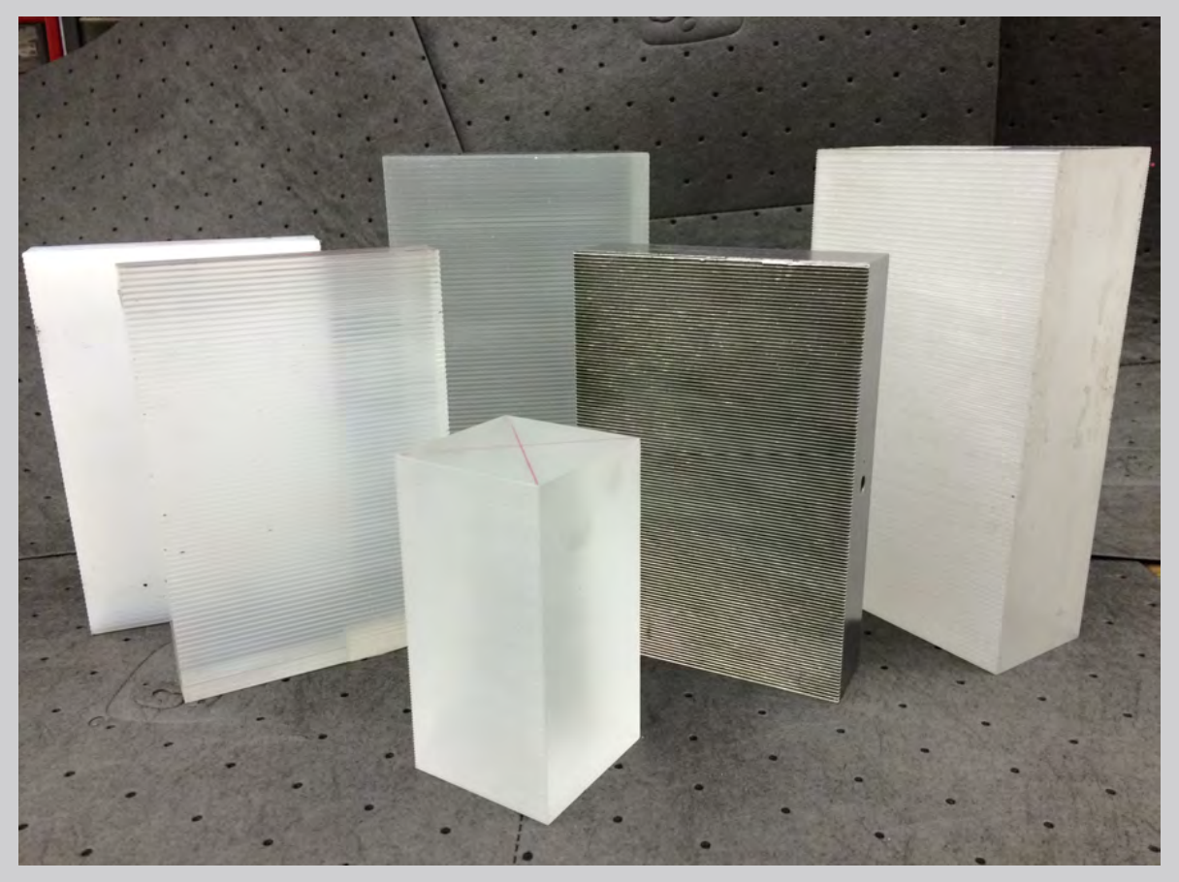
Front (expanded)



Side

System stiffness was modified by varying the normal stress applied to the sample and by using different center blocks; steel and cast acrylic blocks are used to simulate stiff and compliant systems respectively. Increasing the normal stress will decrease the effective stiffness (stiffness normalized by normal stress), tending to push the system towards conditionally unstable or unstable behavior.

Acrylic Block
More Compliant
14 MPa
←→
Steel Block
More Stiff
2 MPa



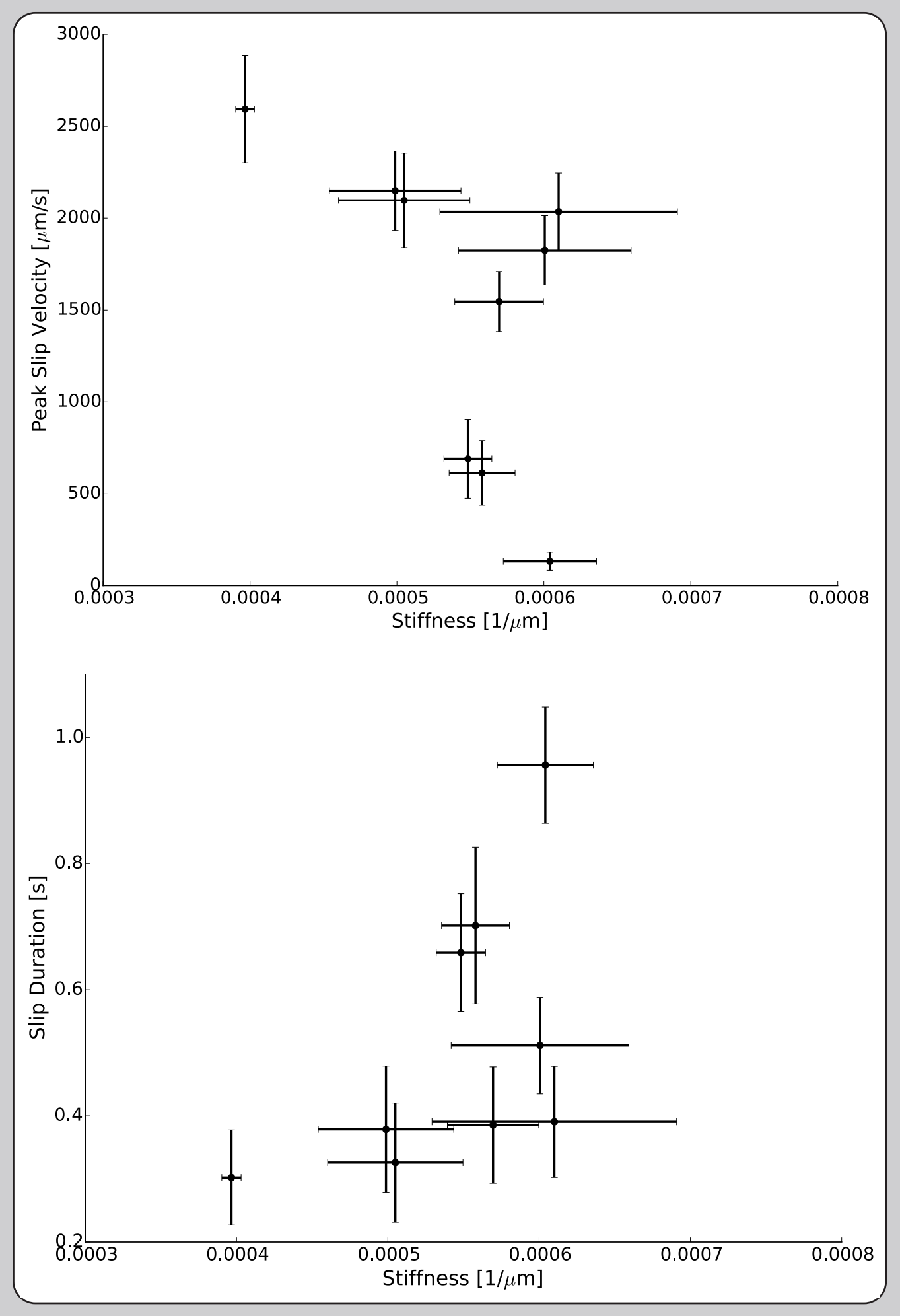
All experiments had a starting layer thickness of 3 mm before the application of normal load. Samples were allowed to compact before shearing began. Shearing was accomplished at a constant loading rate of 10 μm/s for the entire 45 mm of displacement.

Conclusions and Future Work

- We show, for the first time, a systematic study of the entire spectrum of slip behaviors in the lab by exploring the relation of the stiffness of the fault compared to the critical stiffness (k/k_c).

- Factors such as pore pressure and material frictional response are important, they are already factored into the stiffness comparison.

We observe that the critical stiffness of a system evolves as a fabric is developed, suggesting that accumulation of shear can change the behavior of a fault during its lifetime. Further, a scaling relationship has begun to emerge indicating that the further below the critical stiffness a system is, the faster and larger the resulting stress drop is. Refining this relationship and resolving it with fabric development will greatly enhance our understanding of fault zone behavior and the evolution of a fault as the damage zone is developed and the country rock stiffness lowered.



Future work includes further processing of the existing dataset to examine the properties of each individual stick-slip event, inspecting the audio emissions from slip events, and equipping the center block with strain gages or optical strain indicators to record how the rupture begins and propagates in a laboratory sized sample. We also plan to look at any fabric the developed during shear, as well as grain comminution at higher normal stresses.

Take Home Conclusions

- Critical stiffness is a good first-order predictor of system stability
- The entire range of stick-slip behavior is observed as the system stiffness approaches and crosses the critical stiffness
- Single variable rate-and-state friction relations with 1-D linear elastic coupling are too simplistic to fully capture the natural behavior
- Slow slip may be driven by strain energy stored locally next to the fault zone
- Slip duration and slip velocity scale with the stiffness of the system

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