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

J.R. Leeman
D.M. Saffer
C. Marone

Department of Geosciences
The Pennsylvania State University

March 20, 2015
Laboratory observations of the full spectrum of fault slip modes: implications for the mechanics of slow earthquakes

J.R. Leeman
D.M. Saffer
C. Marone

Department of Geosciences
The Pennsylvania State University

March 20, 2015
Laboratory observations of the full spectrum of fault slip modes: implications for the mechanics of slow earthquakes

J.R. Leeman
D.M. Saffer
C. Marone

Department of Geosciences
The Pennsylvania State University

March 20, 2015
Traditionally, we have viewed faults as failing in one of two modes, defined by a phase boundary or bifurcation at Kc.
Traditionally, we have viewed faults as failing in one of two modes, defined by a phase boundary or bifurcation at Kc.
Traditionally, we have viewed faults as failing in one of two modes, defined by a phase boundary or bifurcation at $K_c$. 

**Stable**

Shear Stress vs. Time

**Unstable**

Shear Stress vs. Time

Photo: bbc.co.uk
We are going to examine natural and predicted behavior of the slip spectrum, then compare it with lab observations.
We are going to examine natural and predicted behavior of the slip spectrum, then compare it with lab observations.

Davis et al., 2006

Rubin, 2008

Nature

Theory
We are going to examine natural and predicted behavior of the slip spectrum, then compare it with lab observations.
In reality, there is a spectrum of fault behavior, but the mechanics and causes of these failure modes are unknown.
Scaling differences between slow and non-traditional earthquakes question the fundamental mechanisms

Ide et al. (2007)
LFEs and tremor are contain much more low frequency energy.

Shelly et al. (2007)
Jiang et al. (2012)
A variety of explanations of slow slip have emerged, but they are not as general as we would like.
A variety of explanations of slow slip have emerged, but they are not as general as we would like.

High Pore Pressure
A variety of explanations of slow slip have emerged, but they are not as general as we would like.

High Pore Pressure

Designer Friction

Ikari et al, 2009
A variety of explanations of slow slip have emerged, but they are not as general as we would like.

High Pore Pressure

Designer Friction

Ikari et al, 2009

Material Properties
To study stability, we first have to define two necessary conditions that allow us to cross the stability phase boundary.
Small changes in stiffness can completely change the behavior of even the simplest system

\[ k > k_c \]
Small changes in stiffness can completely change the behavior of even the simplest system

\[ k < k_c \]
We can define $kc$ experimentally from velocity step inversions in experiments with stable behavior.

\[ \mu = \mu_0 + a \ln \left( \frac{V}{V_0} \right) + b \ln \left( \frac{V_0 \theta}{D_c} \right) \]
We can define $kc$ experimentally from velocity step inversions in experiments with stable behavior.

$$
\mu = \mu_0 + a \ln \left( \frac{V}{V_0} \right) + b \ln \left( \frac{V_0 \theta}{D_c} \right)
$$
We can define $kc$ experimentally from velocity step inversions in experiments with stable behavior.

\[ \mu = \mu_0 + a \ln \left( \frac{V}{V_0} \right) + b \ln \left( \frac{V_0 \theta}{D_c} \right) \]
We can define $kc$ experimentally from velocity step inversions in experiments with stable behavior.

\[ \mu = \mu_0 + a \ln \left( \frac{V}{V_0} \right) + b \ln \left( \frac{V_0 \theta}{D_c} \right) \]
We can define $kc$ experimentally from velocity step inversions in experiments with stable behavior.

$$\mu = \mu_0 + a \ln \left( \frac{V}{V_0} \right) + b \ln \left( \frac{V_0 \theta}{D_c} \right)$$
We can define $kc$ experimentally from velocity step inversions in experiments with stable behavior.

$$\mu = \mu_0 + a\ln\left(\frac{V}{V_0}\right) + b\ln\left(\frac{V_0\theta}{D_c}\right)$$
We can define $k_c$ experimentally from velocity step inversions in experiments with stable behavior.

\[ k_c = \sigma_n \frac{b - a}{D_c} \]
Single State Variable produces either stable, decaying, or unstable behavior
Models have been able to produce regions of sustained oscillations that represent transitory behavior.
The Penn State biax is setup for double direct shear for all experiments.
The Penn State biax is setup for double direct shear for all experiments
Min-U-Sil is a quartz fault gouge simulant that provides a reproducible laboratory test material.
Min-U-Sil is a quartz fault gouge simulant that provides a reproducible laboratory test material.
We modify the system stiffness by changing the normal load and the center block material.
In unstable experiments we observe emergent stick-slip behavior from which we can measure system stiffness.
We can measure stiffness in two different ways, but they give comparable results.
We can measure stiffness in two different ways, but they give comparable results.
We can measure stiffness in two different ways, but they give comparable results.
We can measure stiffness in two different ways, but they give comparable results.
We see a transition between behaviors as a function of $k/k_c$, not a sharp bifurcation.
There is a clear division between stable and unstable experiments that aligns with $k_c$, but the unstable behavior itself is complex.
Both peak velocity and slip duration scale linearly with $k/k_c$, but the inertial limit is close at hand.
Both peak velocity and slip duration scale linearly with $k/k_c$, but the inertial limit is close at hand.
Gain comminution is occurring, but appears to be relatively constant despite the applied normal stress.
We see a transition between behaviors as a function of $k/k_c$, not a sharp bifurcation.
We also observe some of the complex behavior predicted by numerical models.
Experimentally we have shown that critical stiffness supports the arguments made for the spectrum observed in natural systems.
Planned work includes audio analysis and energy budget calculations based on elastically stored strain energy.