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

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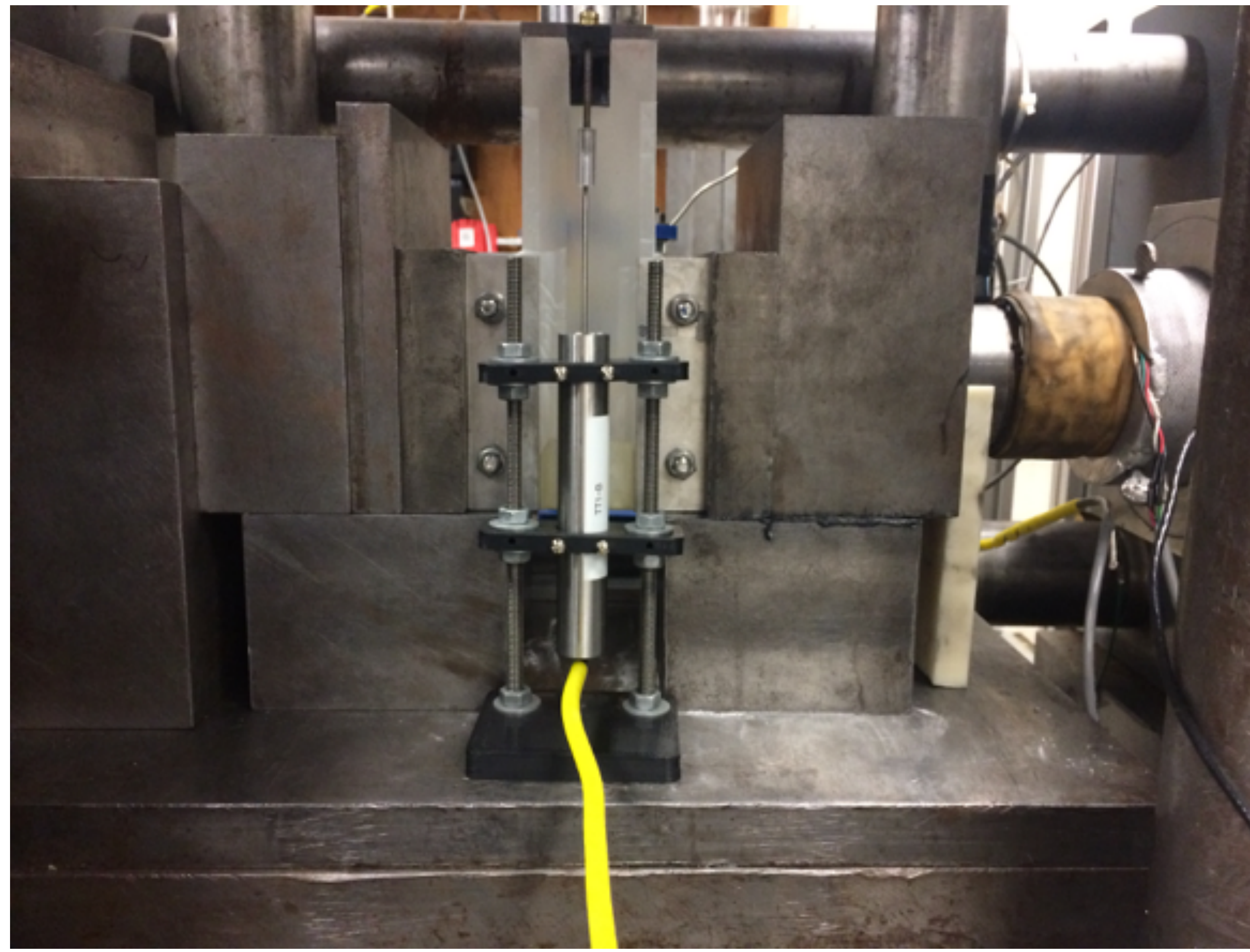
Department of Geosciences
The Pennsylvania State University

March 20, 2015



Penn State Rock and Sediment Mechanics Laboratory

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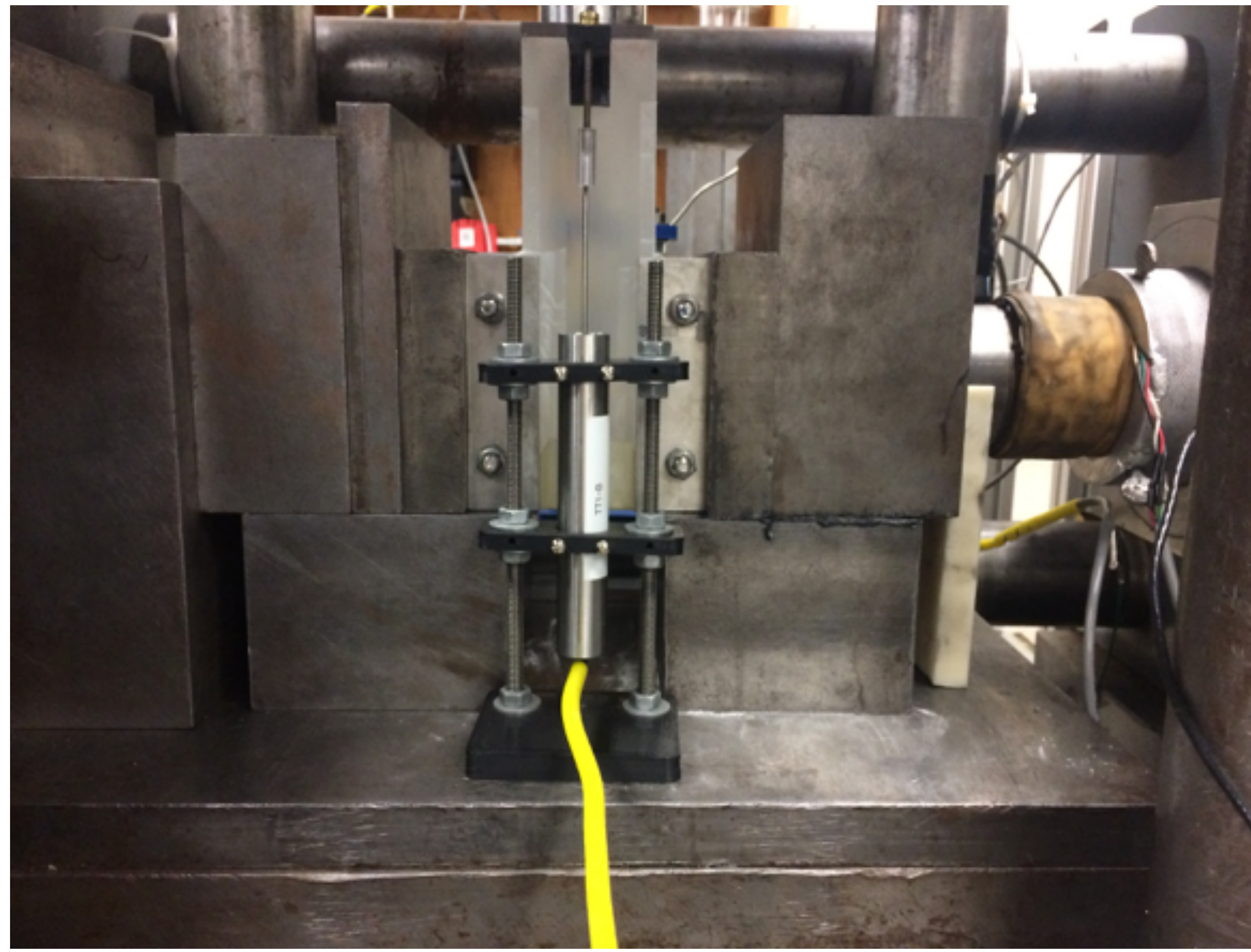

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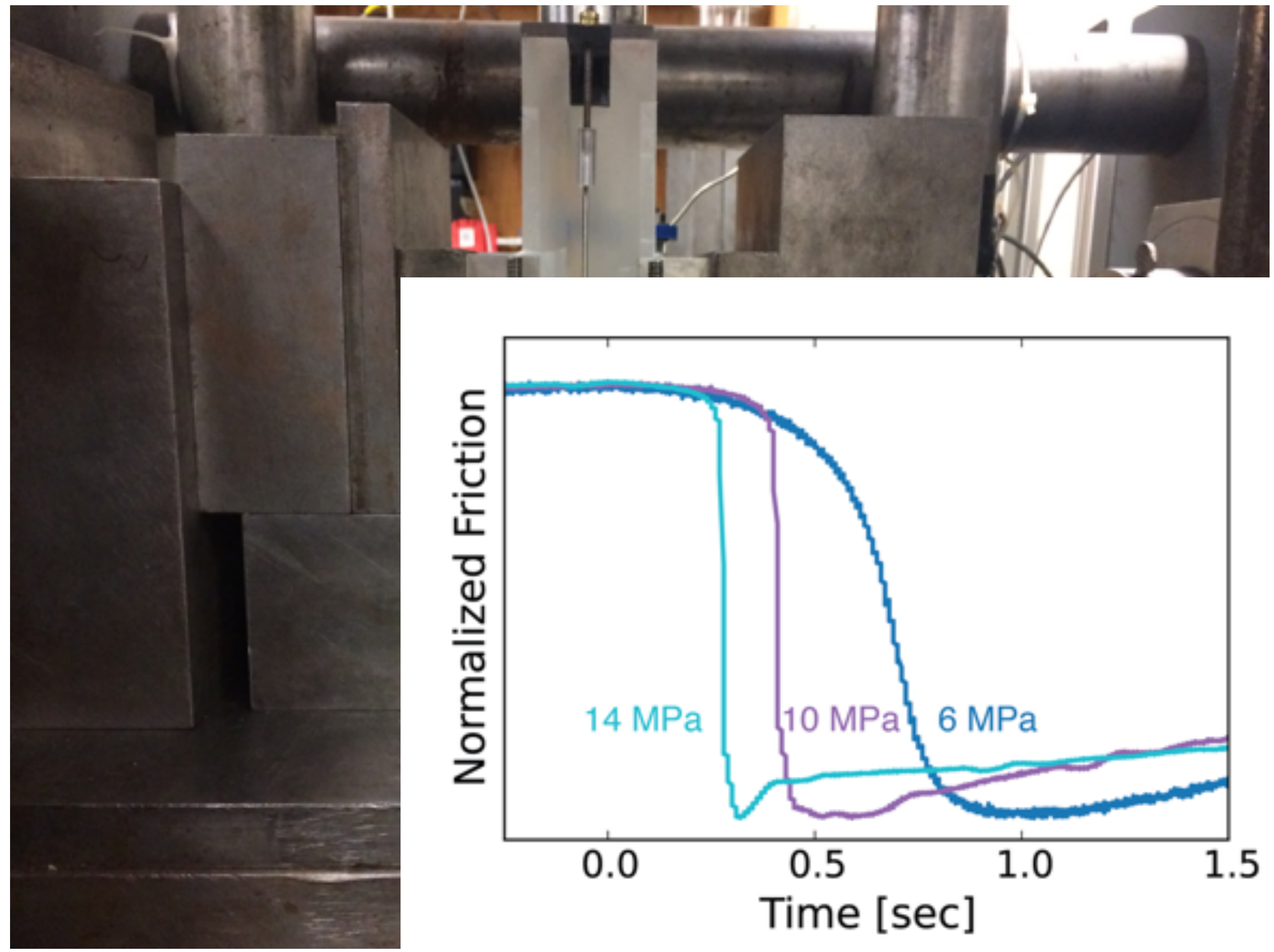

PENN STATE ROCK AND SEDIMENT MECHANICS LABORATORY

Traditionally, we have viewed faults as failing in one of two modes, defined by a phase boundary or bifurcation at Kc

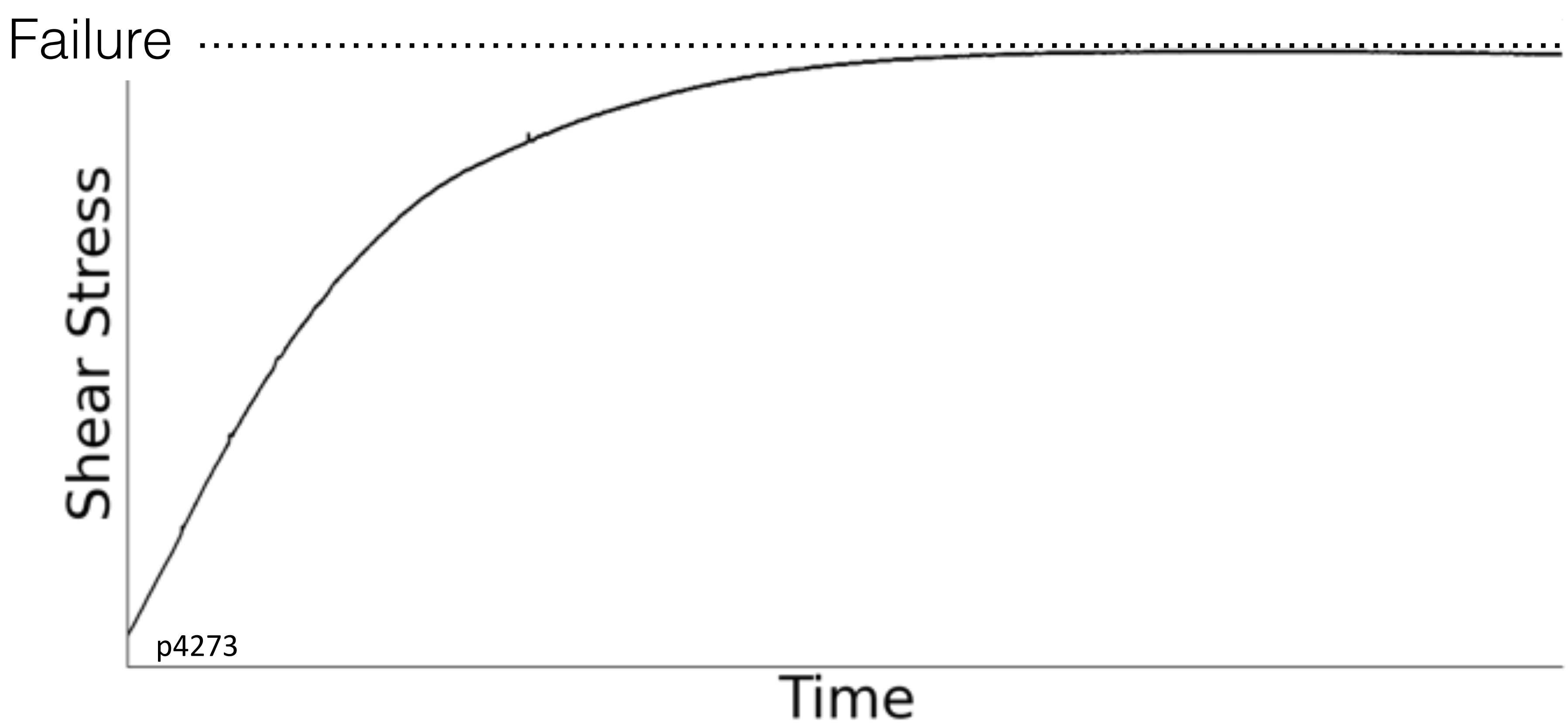

Photo: bbc.co.uk

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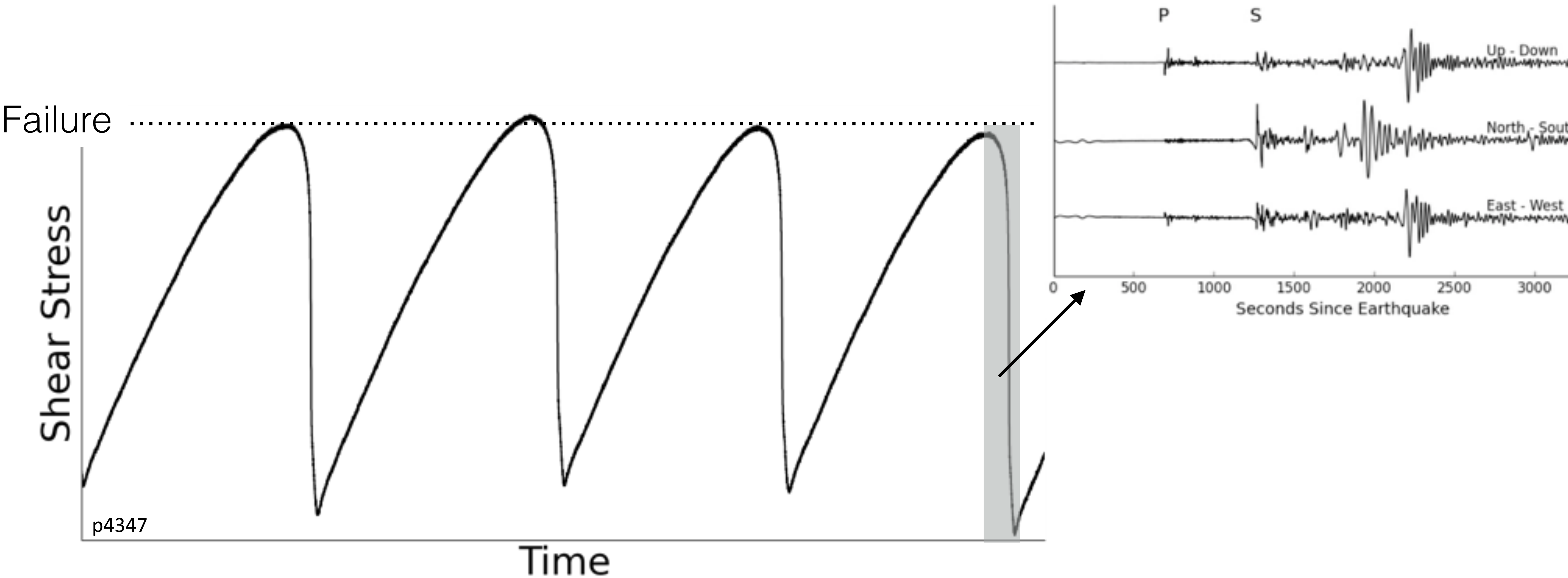

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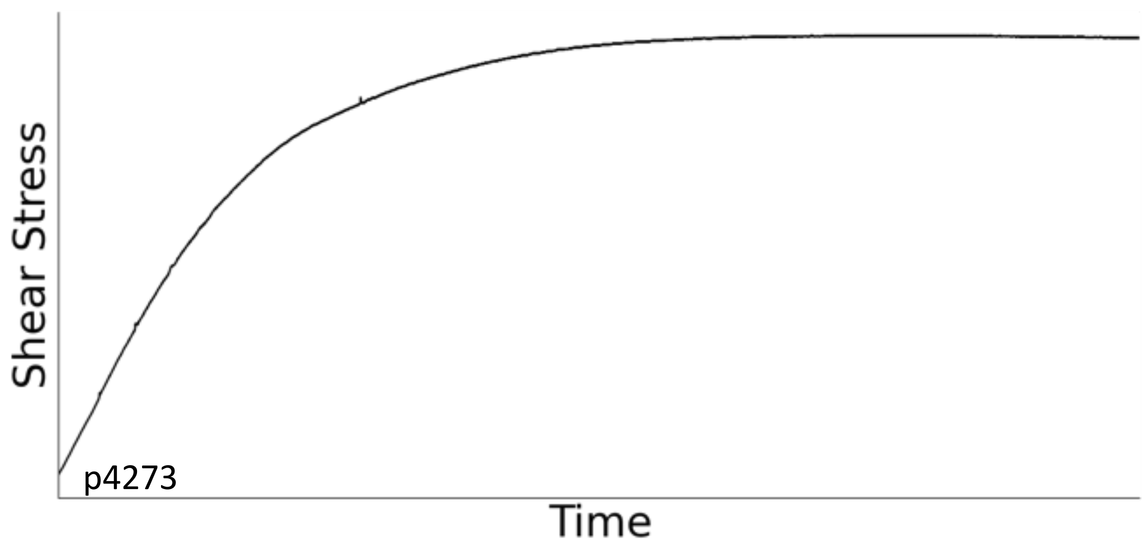
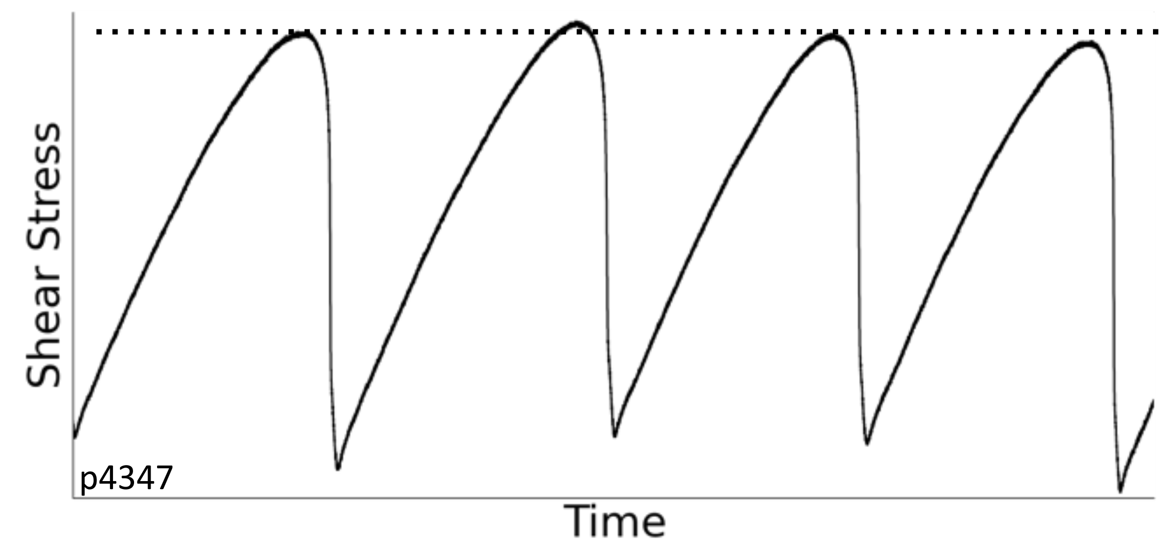
Stable

Kc

Unstable





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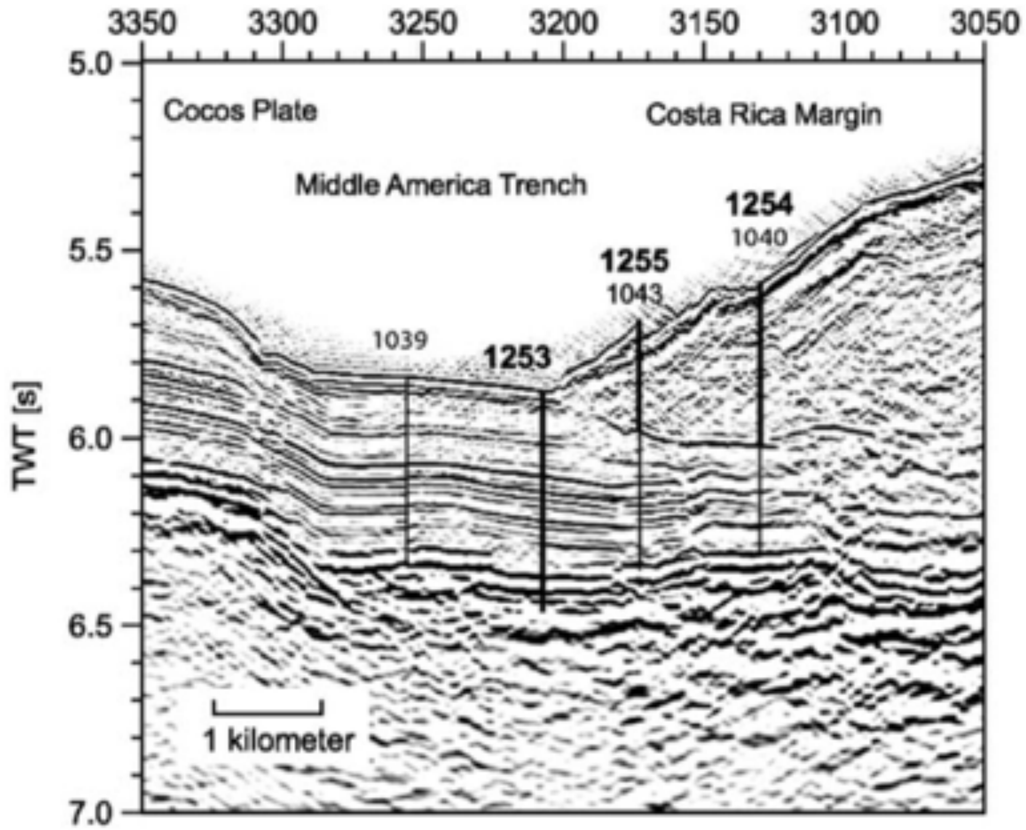
We are going to examine natural and predicted behavior of the slip spectrum, then compare it with lab observations



Davis et al., 2006

Nature

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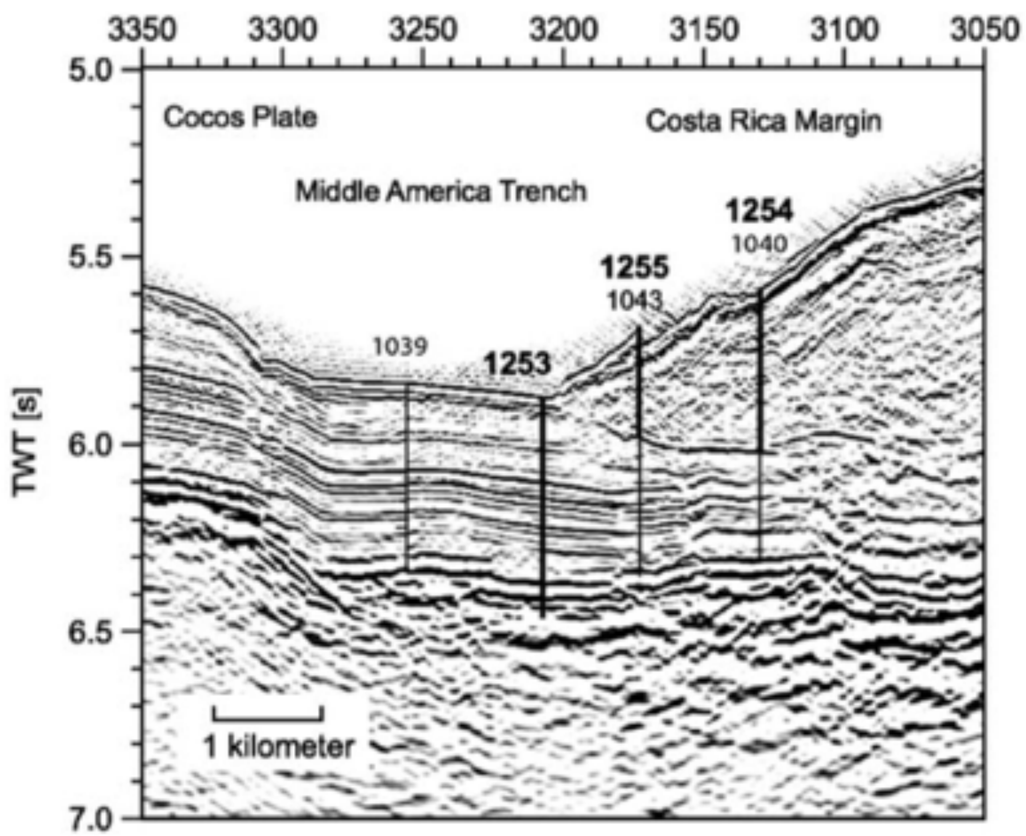

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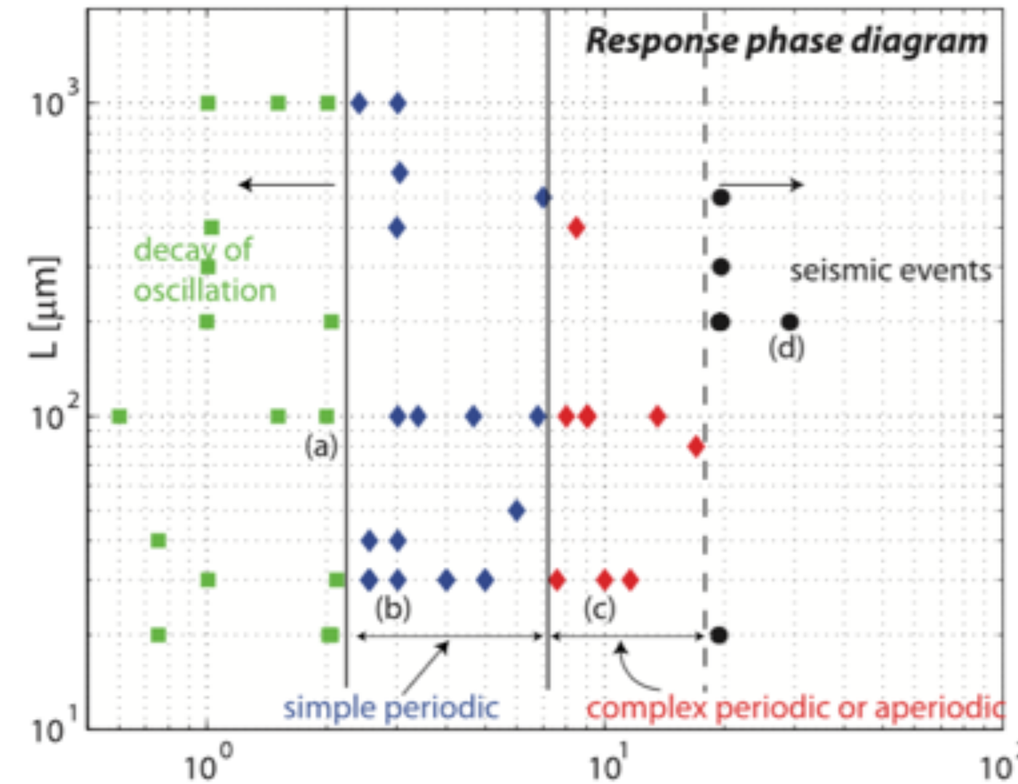

Rubin, 2008

Theory

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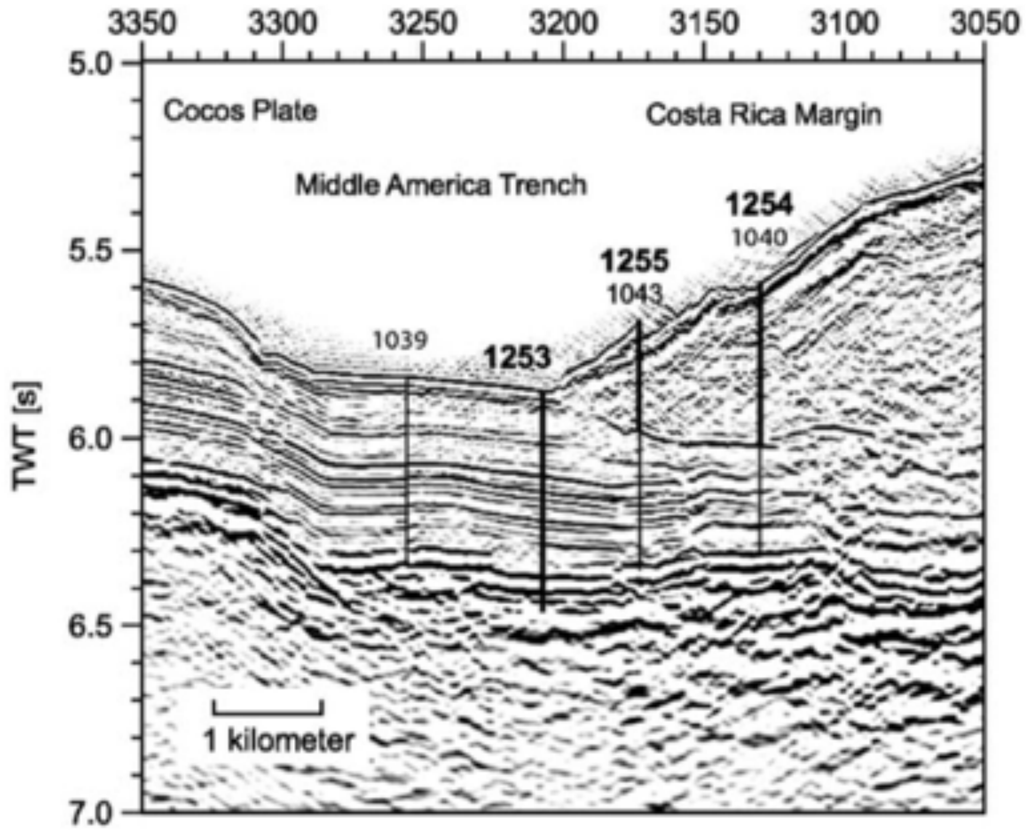

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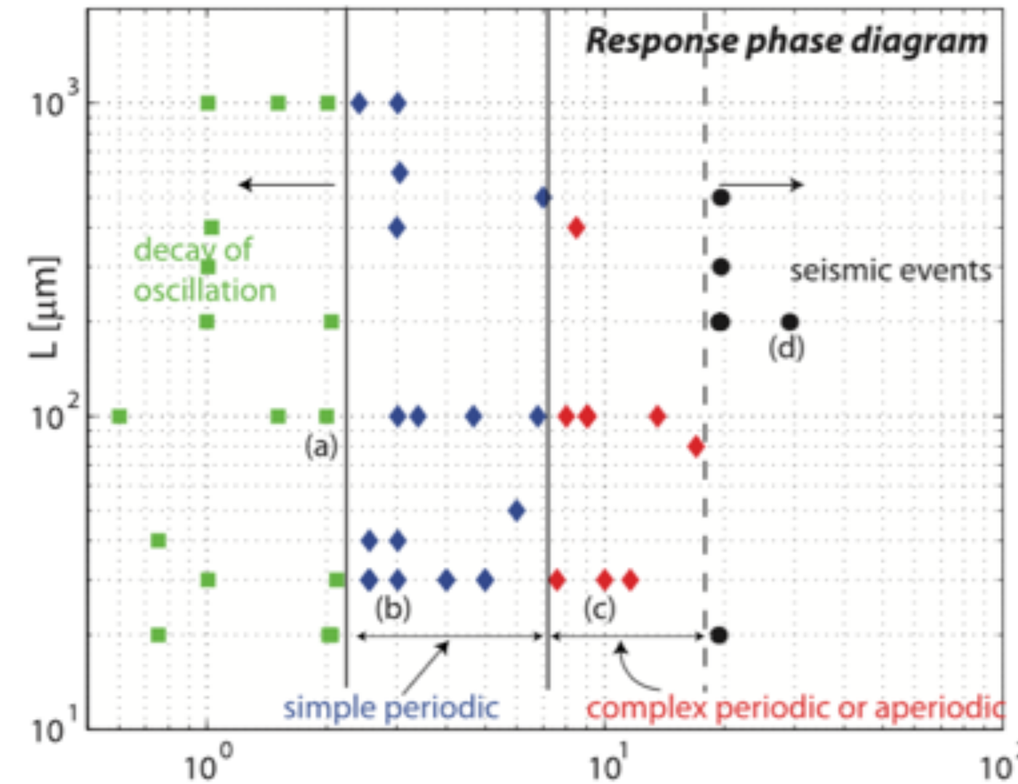
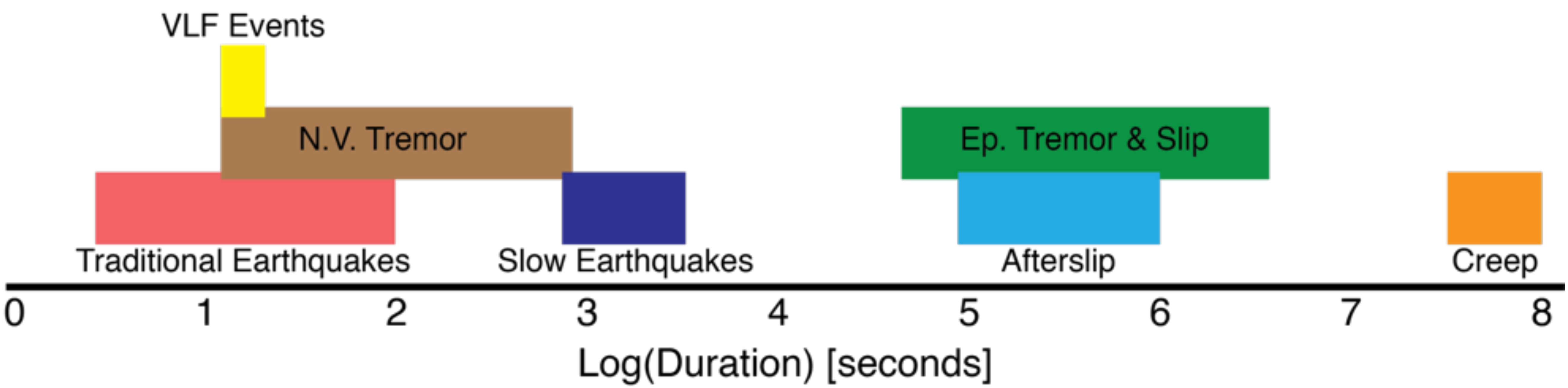


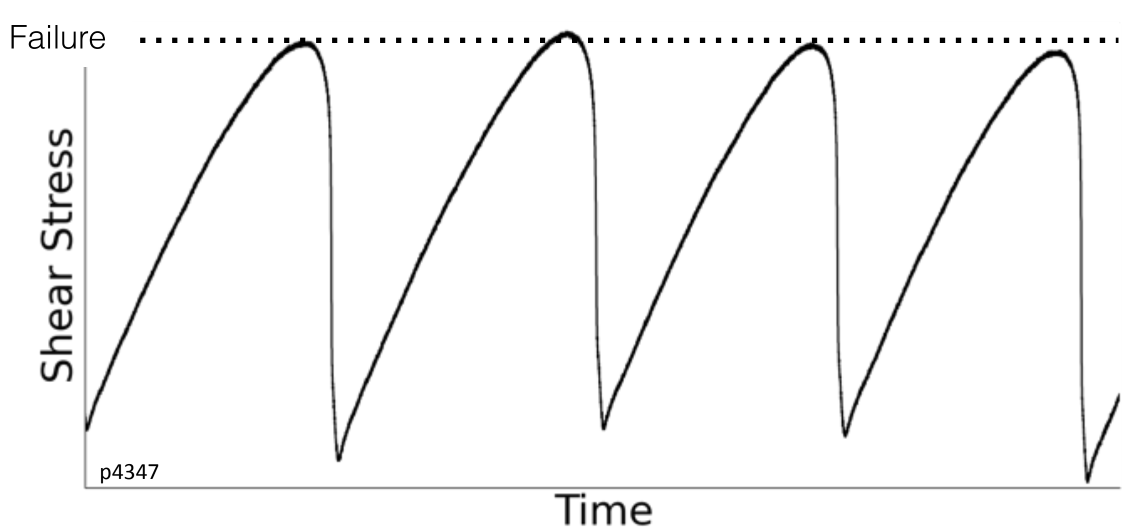
Rubin, 2008

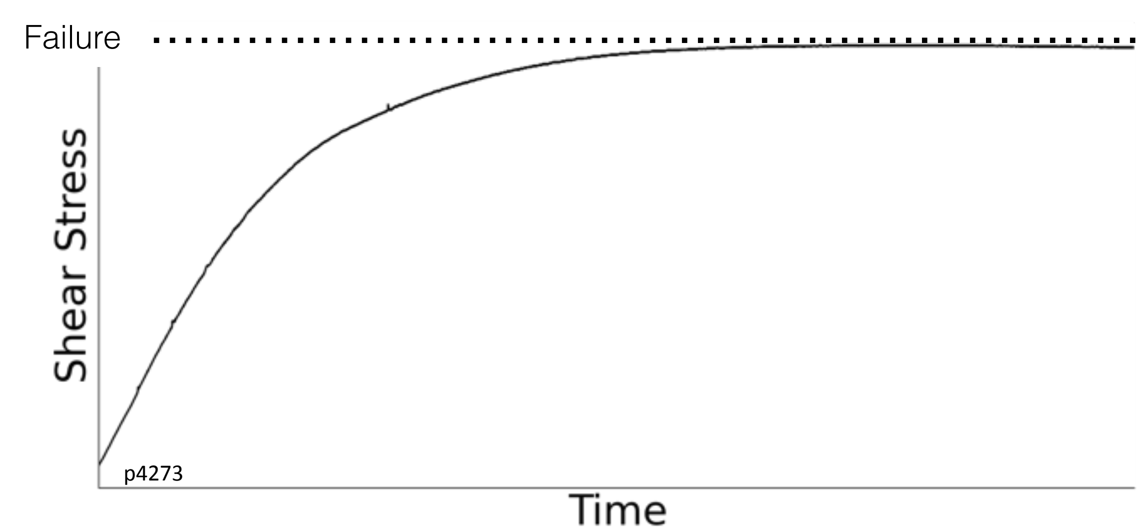
Theory

Laboratory

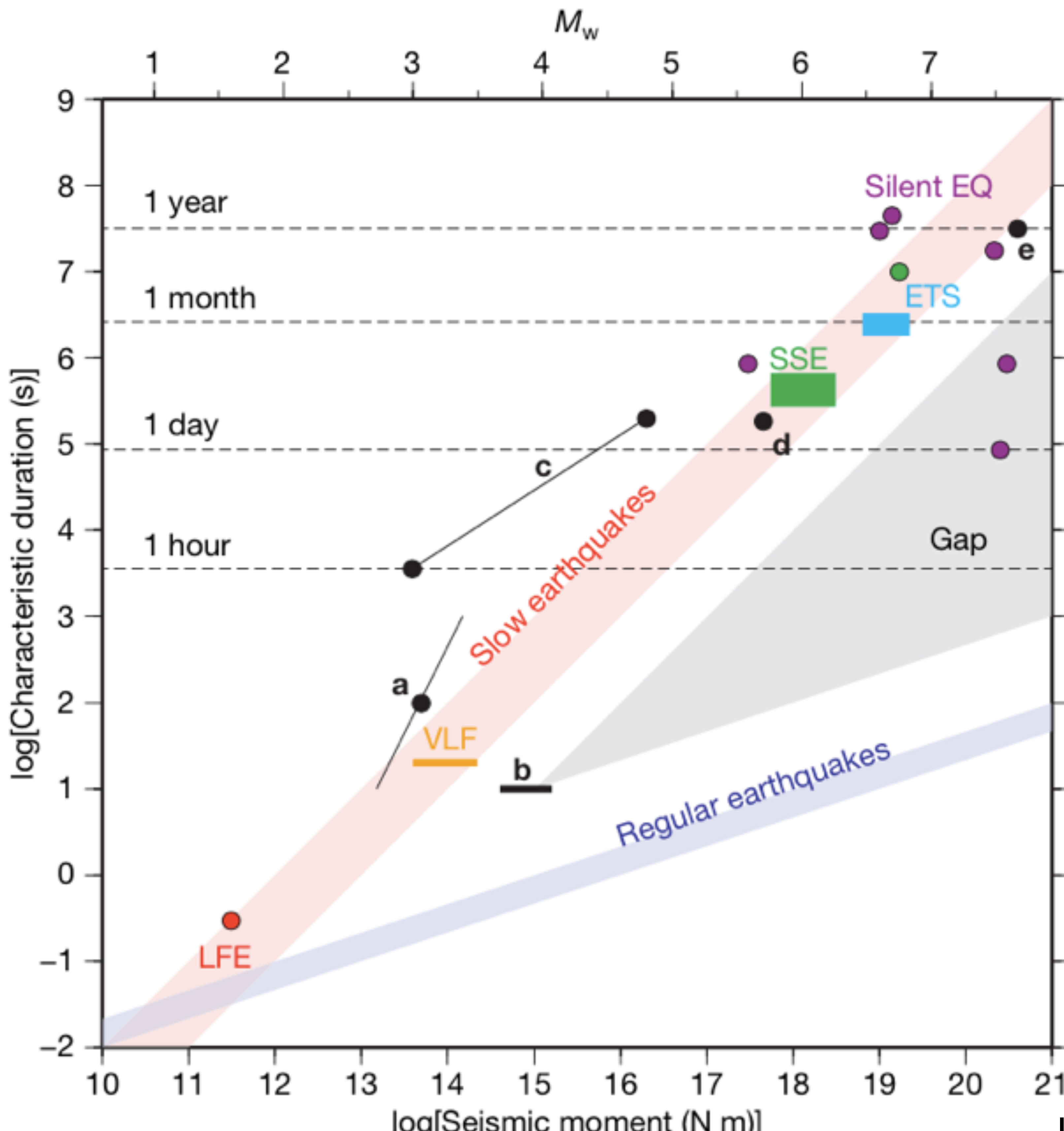
In reality, there is a spectrum of fault behavior, but the mechanics and causes of these failure modes are unknown





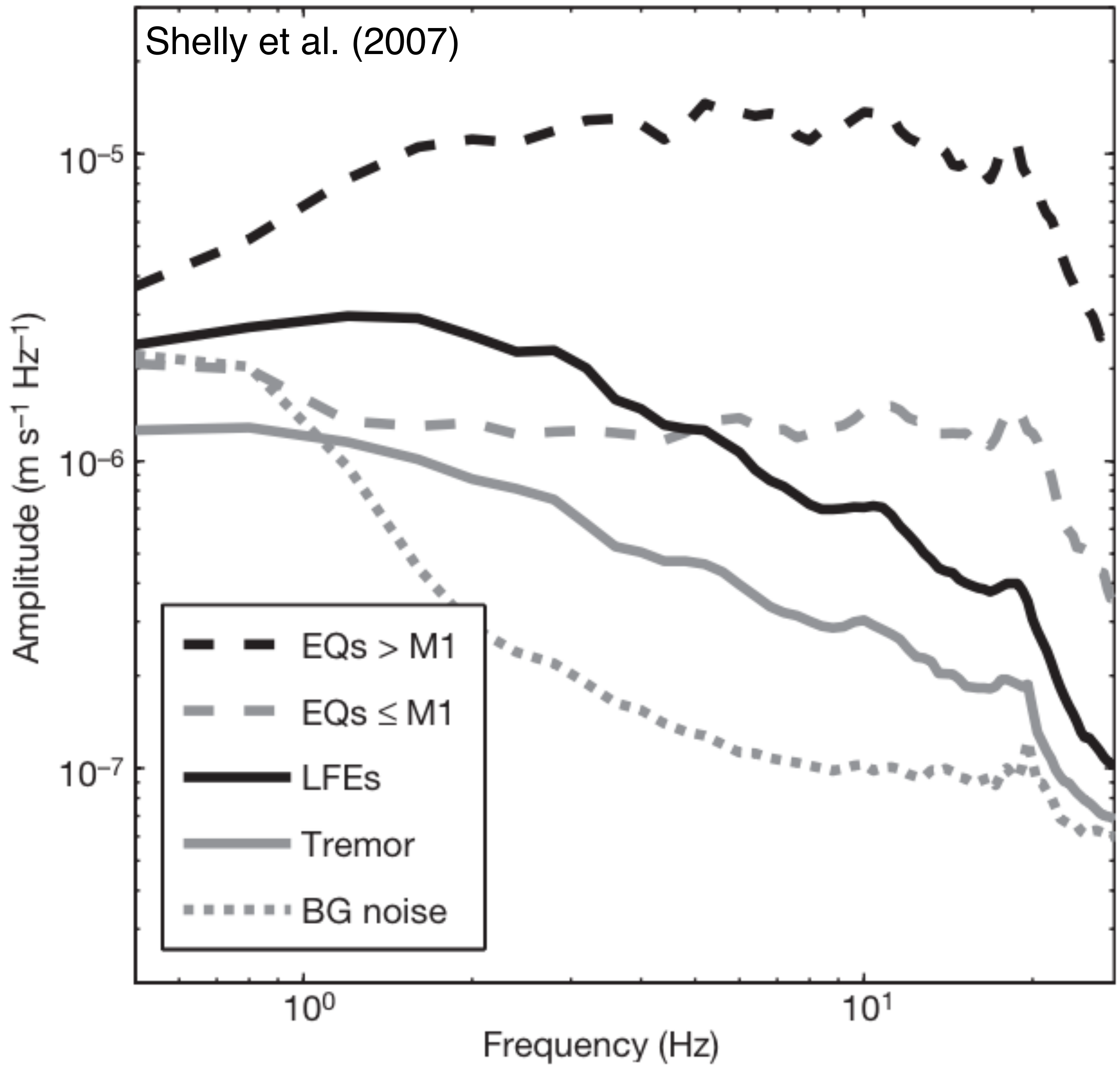


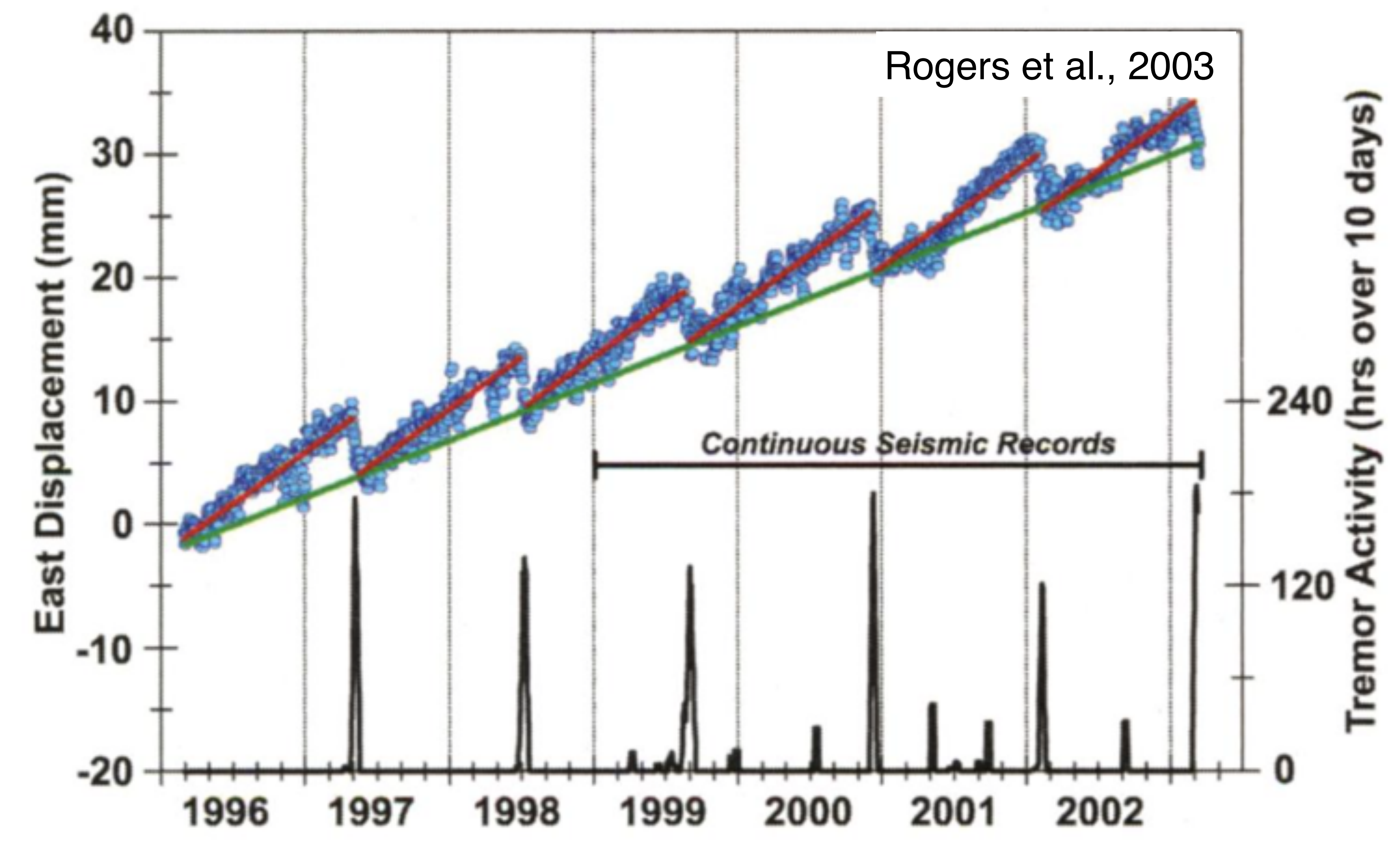
Scaling differences between slow and non-traditional earthquakes question the fundamental mechanisms



Ide et al. (2007)

LFEs and tremor are contain much more low frequency energy




Rogers et al., 2003
East Displacement (mm)
Tremor Activity (hrs over 10 days)
Continuous Seismic Records
40
30
20
10
0
-10
-20
240
120
0
1996
1997
1998
1999
2000
2001
2002

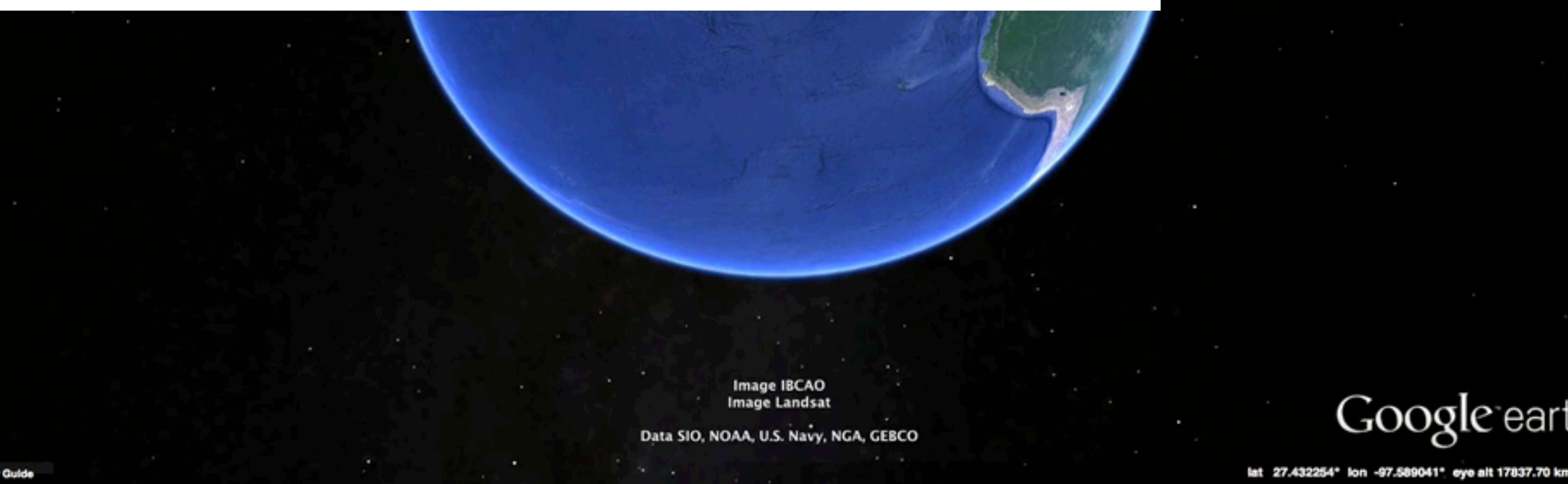
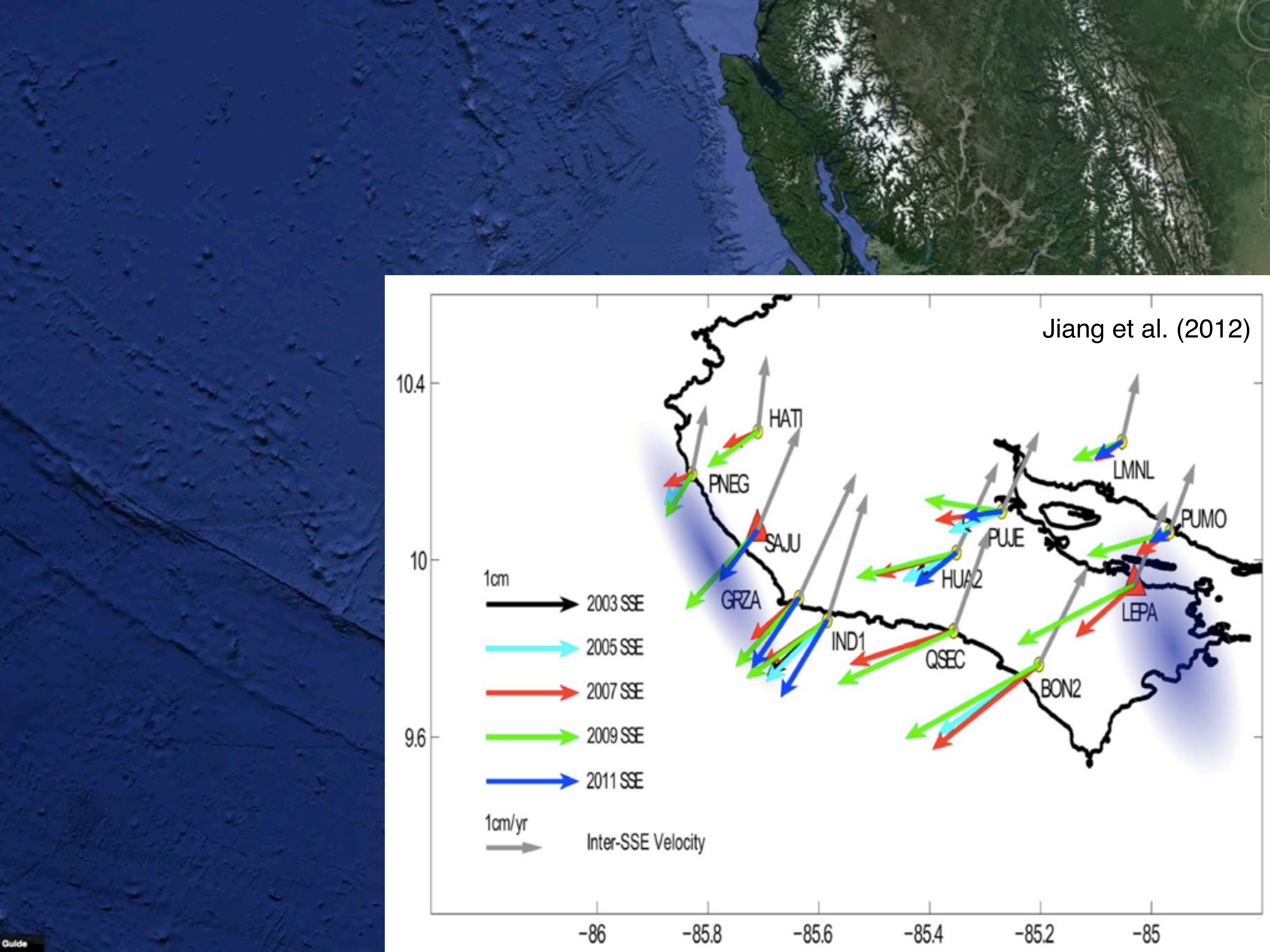
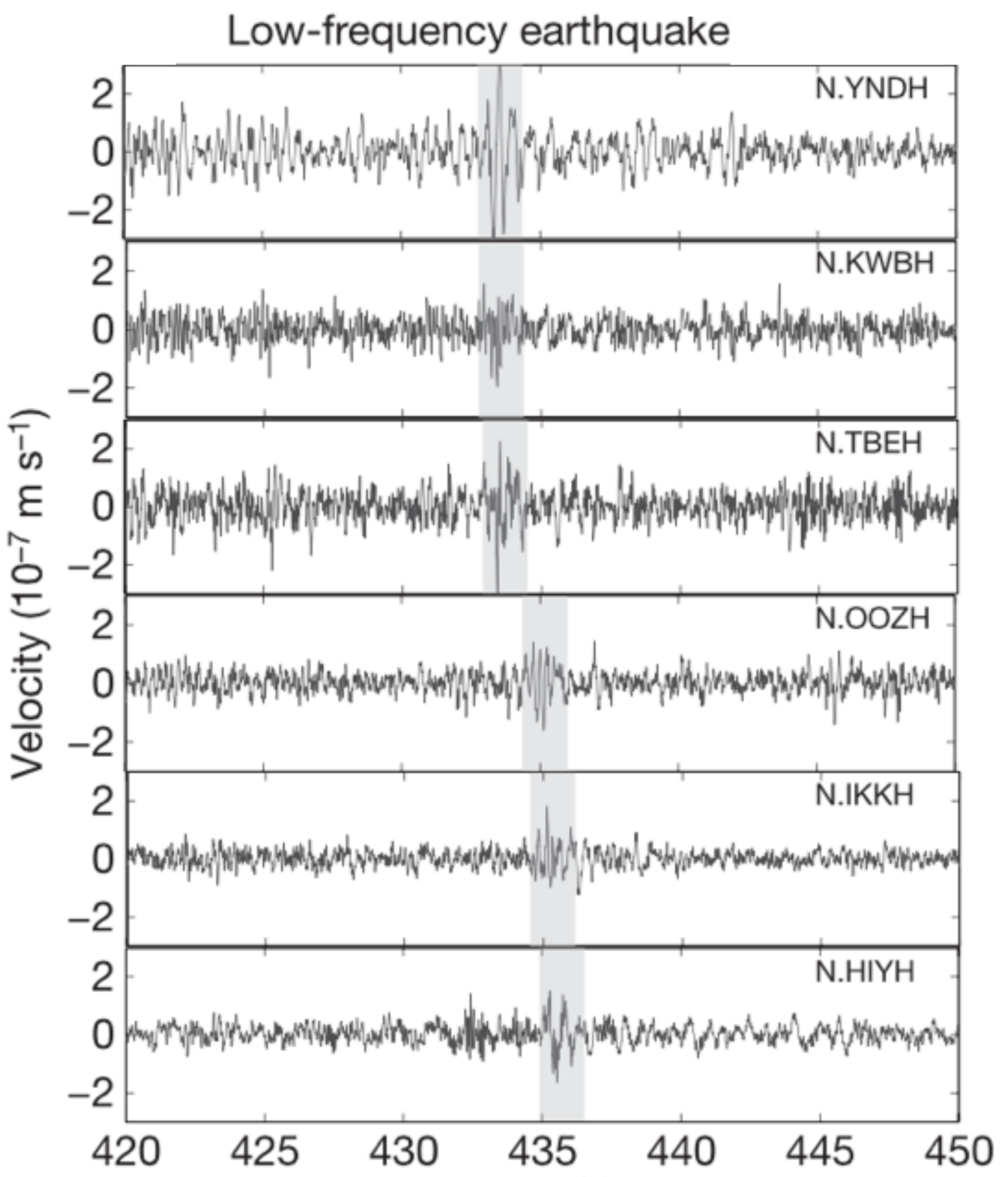


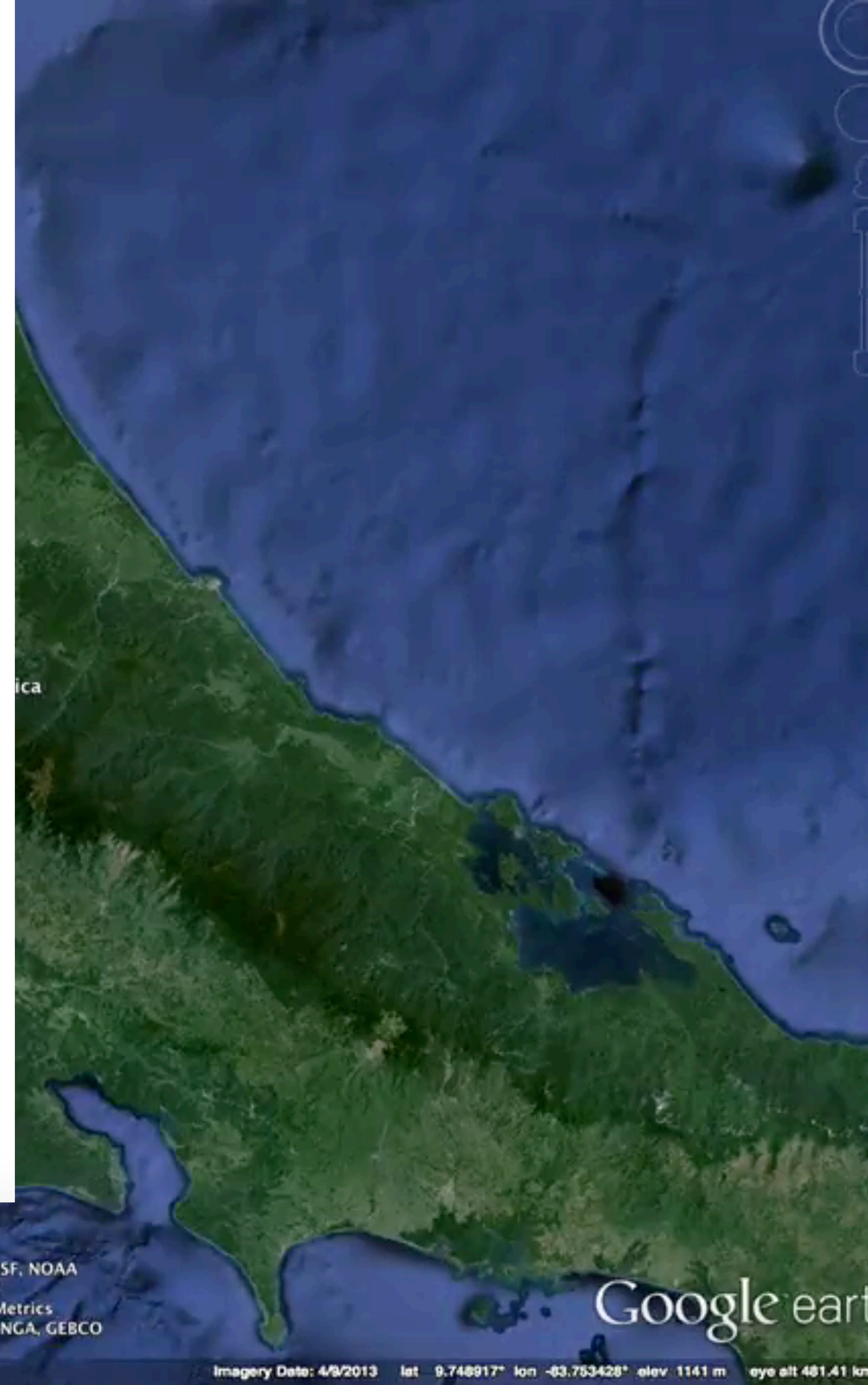
Image IBCAO
Image Landsat
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Google earth
Guide
lat 27.432254° lon -97.589041° eye alt 17837.70 km



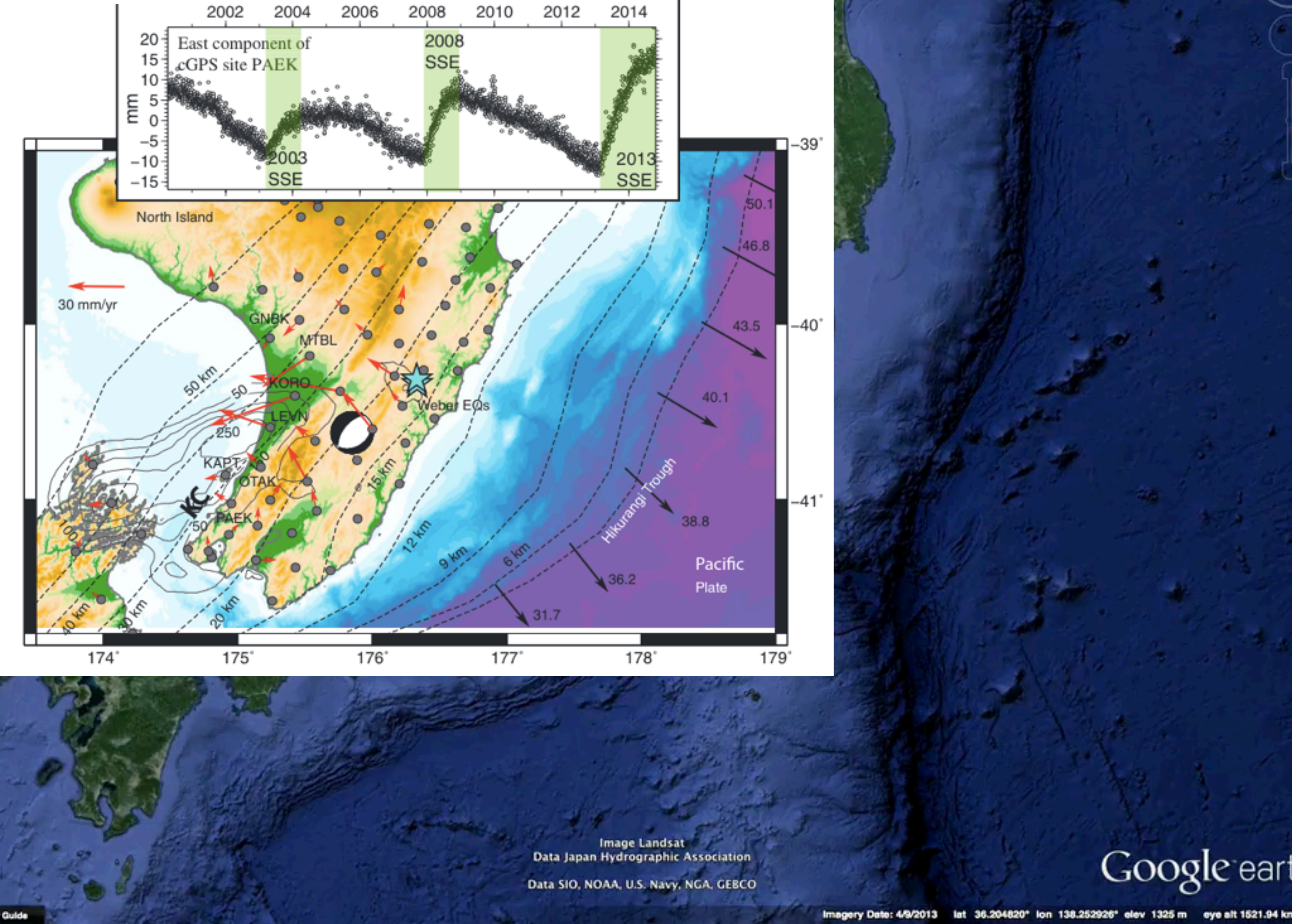
Jiang et al. (2012)
HATI
PNEG
SAJU
GRZA
IND1
QSEC
BON2
PUJE
HUA2
LMNL
PUMO
LEPA
1cm
2003 SSE
2005 SSE
2007 SSE
2009 SSE
2011 SSE
1cm/yr
Inter-SSE Velocity
10.4
10
9.6
-86
-85.8
-85.6
-85.4
-85.2
-85



Shelly et al. (2006)



Wallace et al., 2014



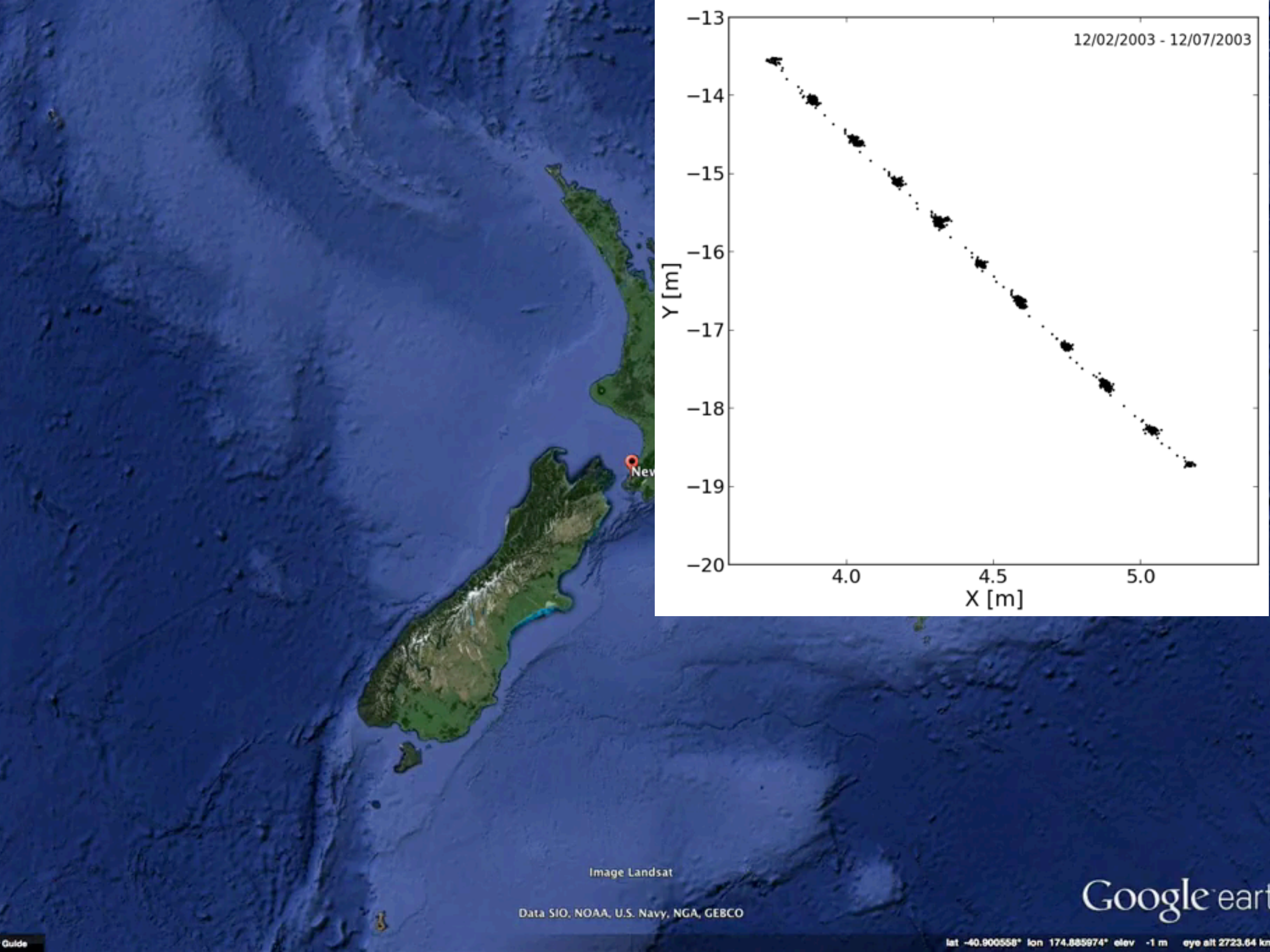


Image Landsat
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Guide
lat -40.900558° lon 174.885974° elev -1 m eye alt 2723.64
12/02/2003 - 12/07/2003
Y [m]
−13
−14
−15
−16
−17
−18
−19
−20
X [m]
4.0
4.5
5.0

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

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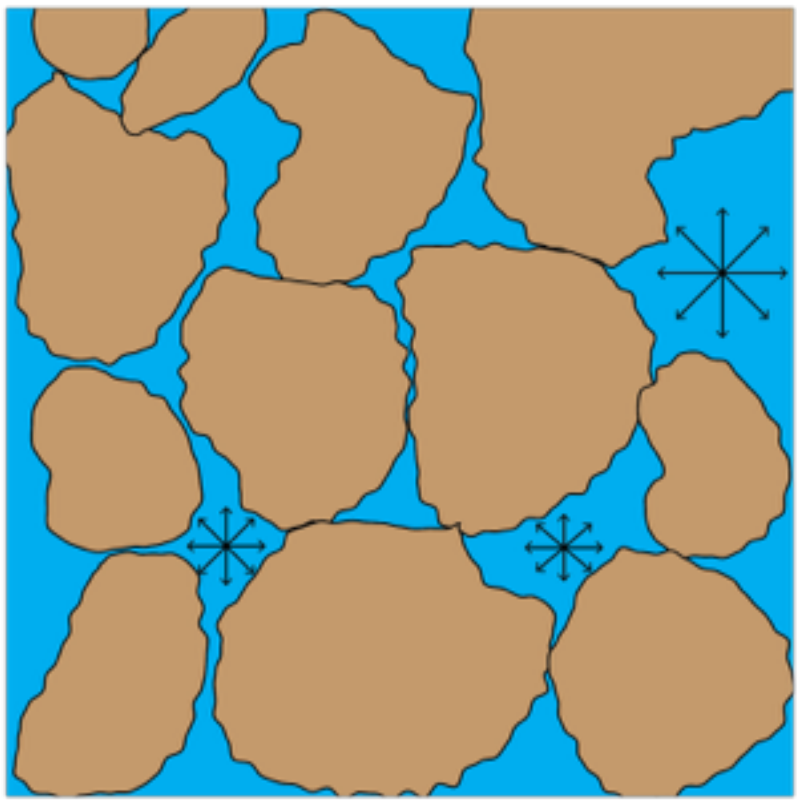
High Pore Pressure



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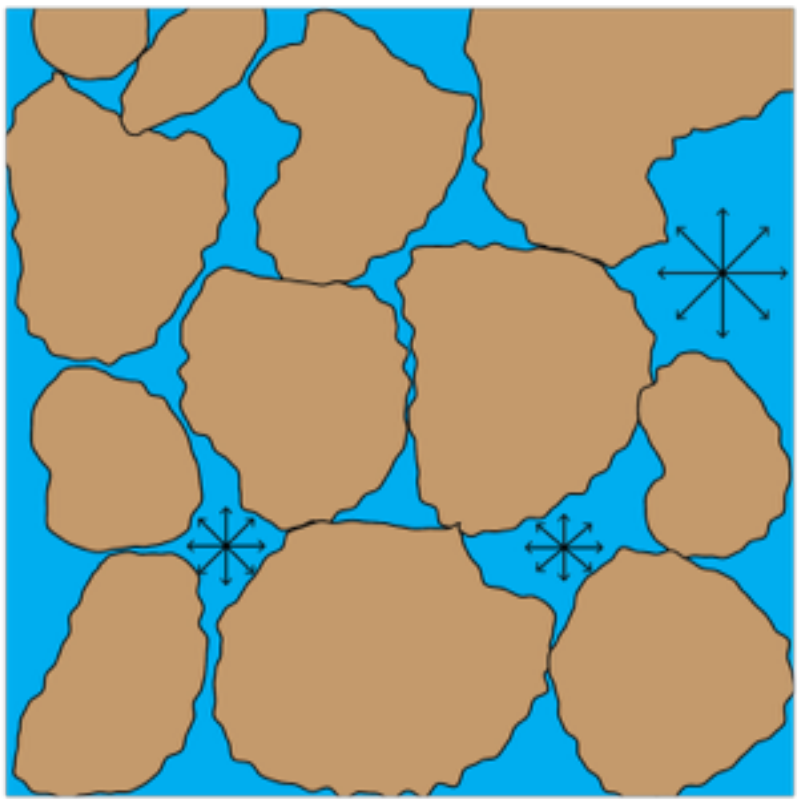
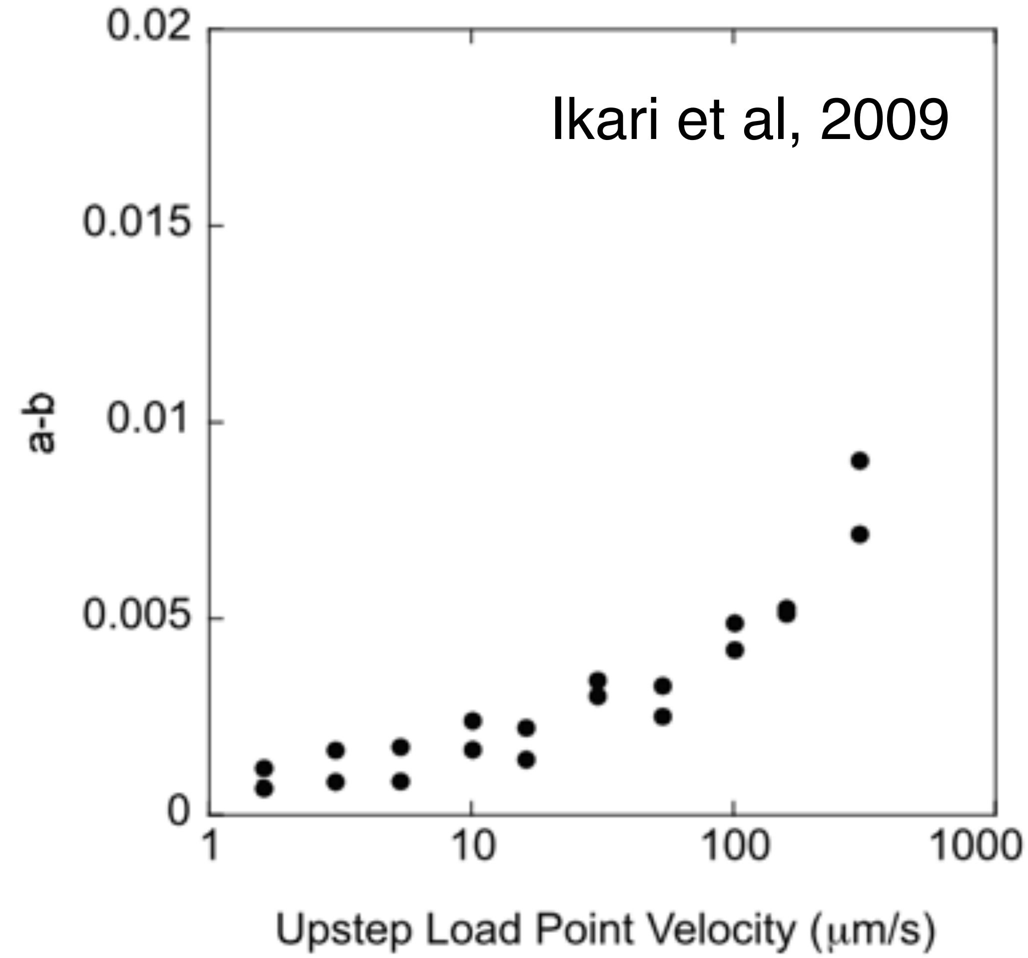


Designer Friction



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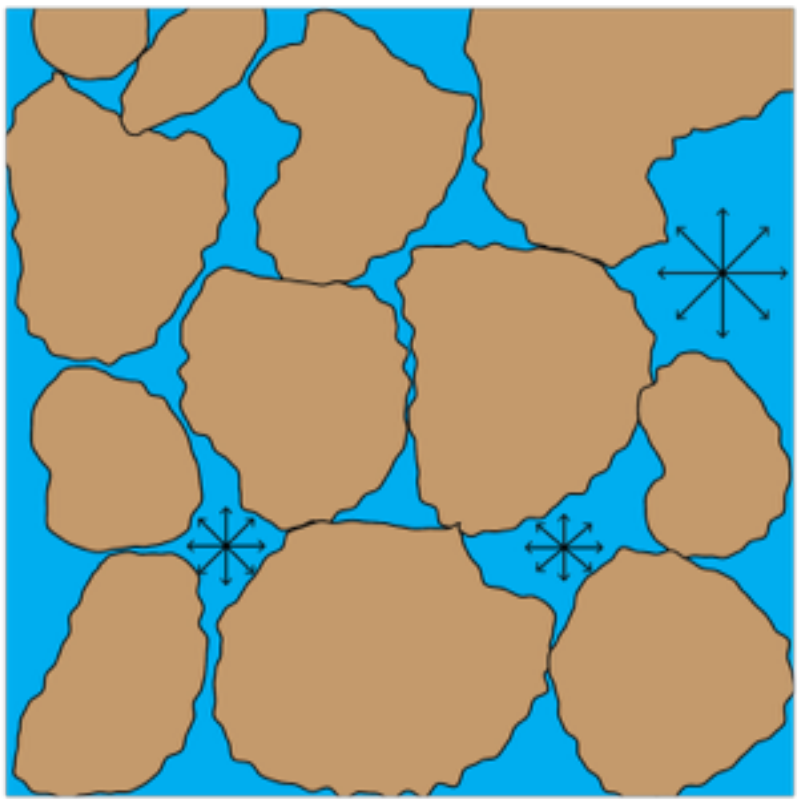
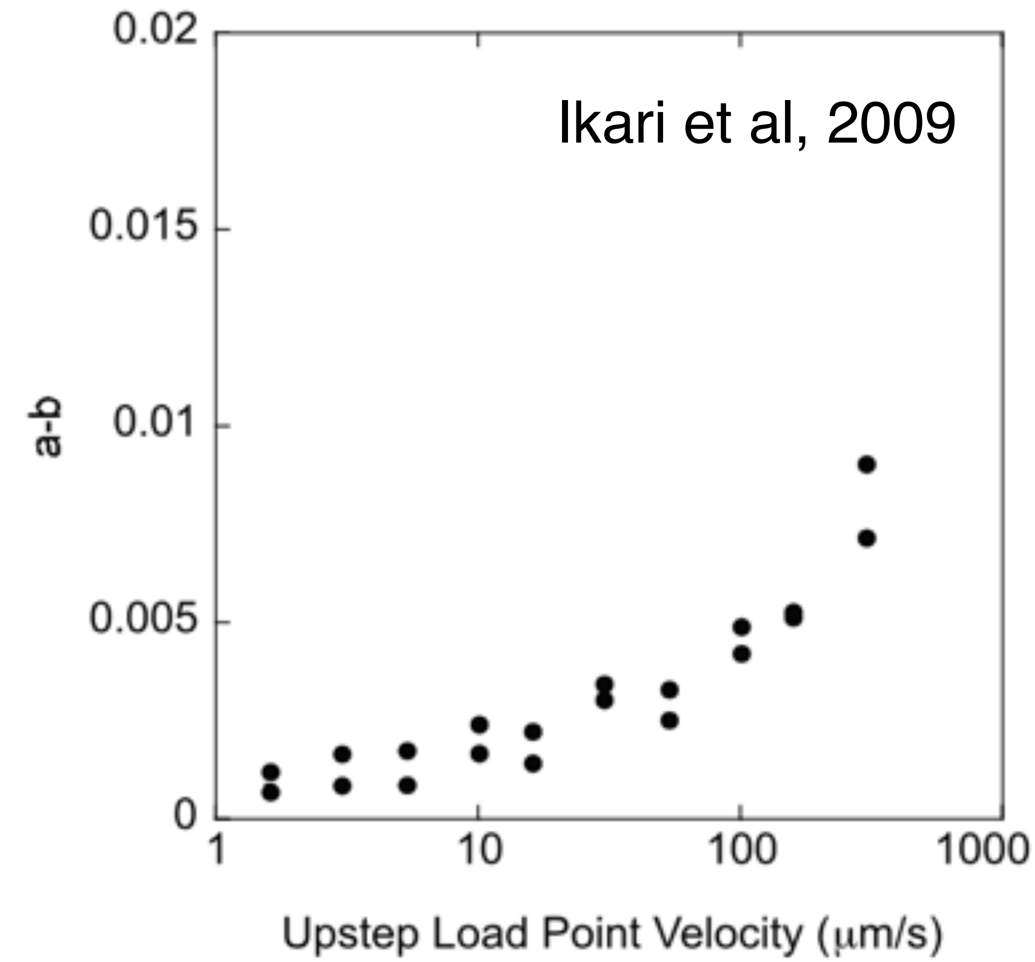
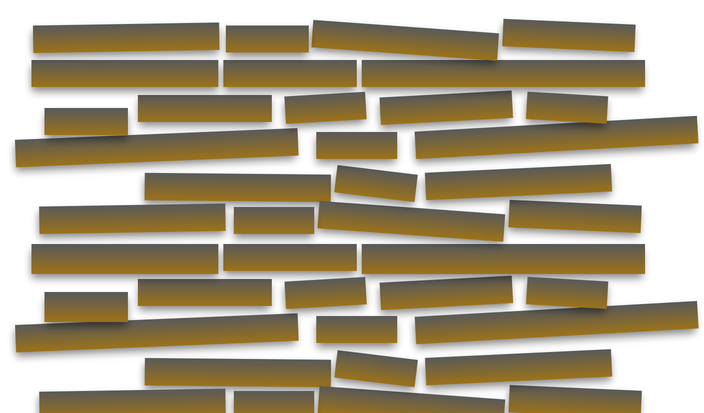


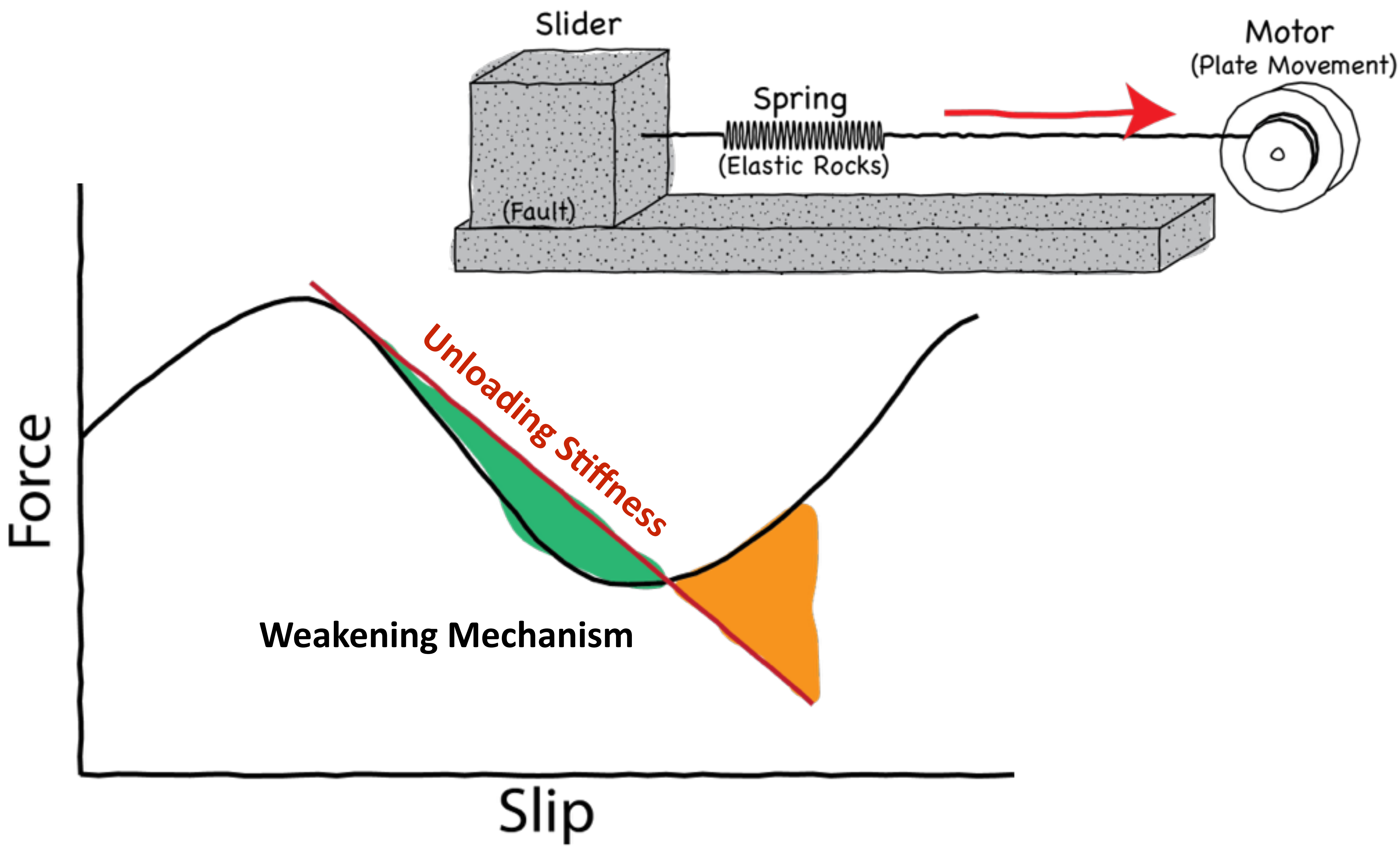
Designer Friction





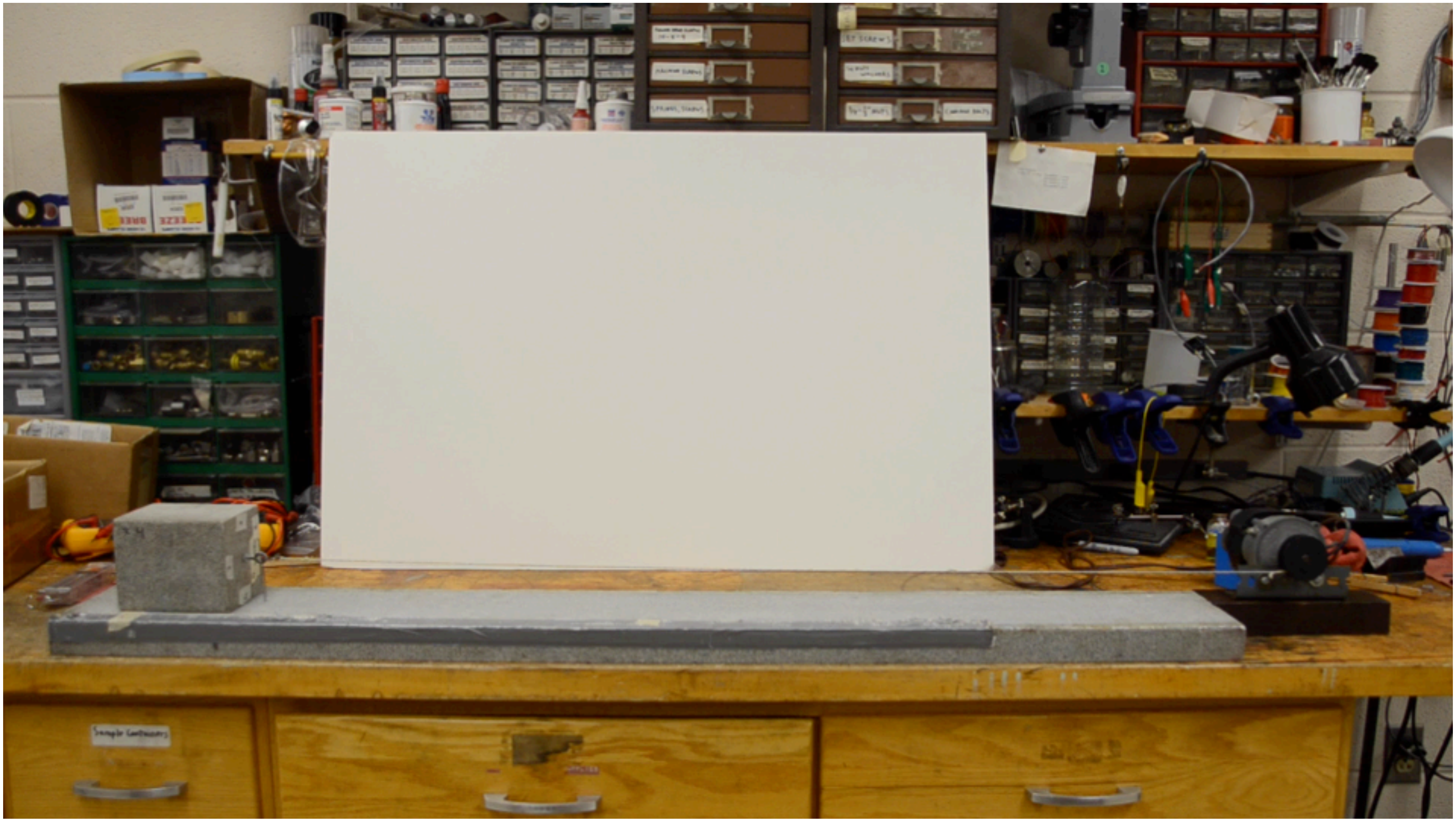
Material Properties

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

$k > k_c$



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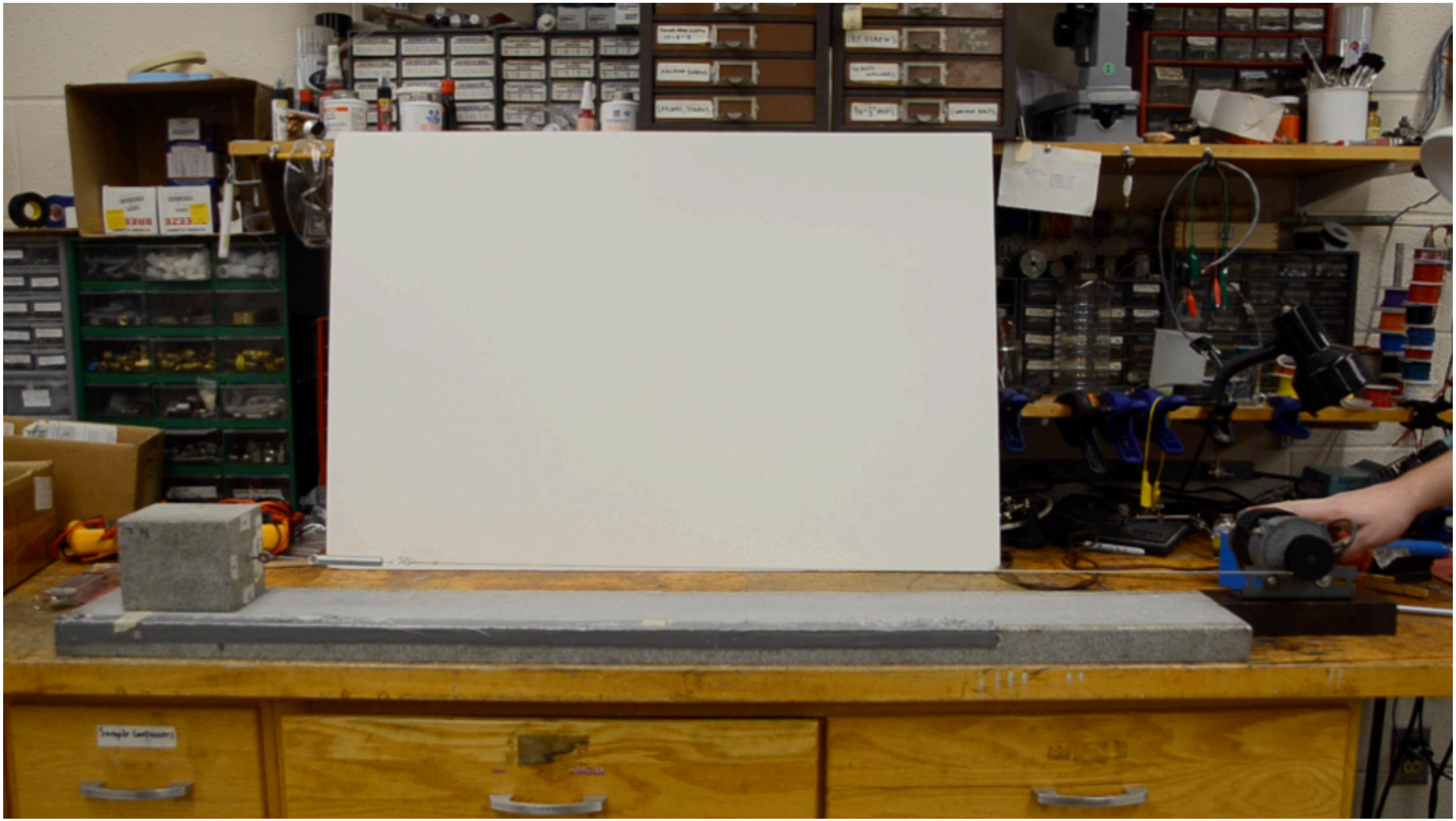
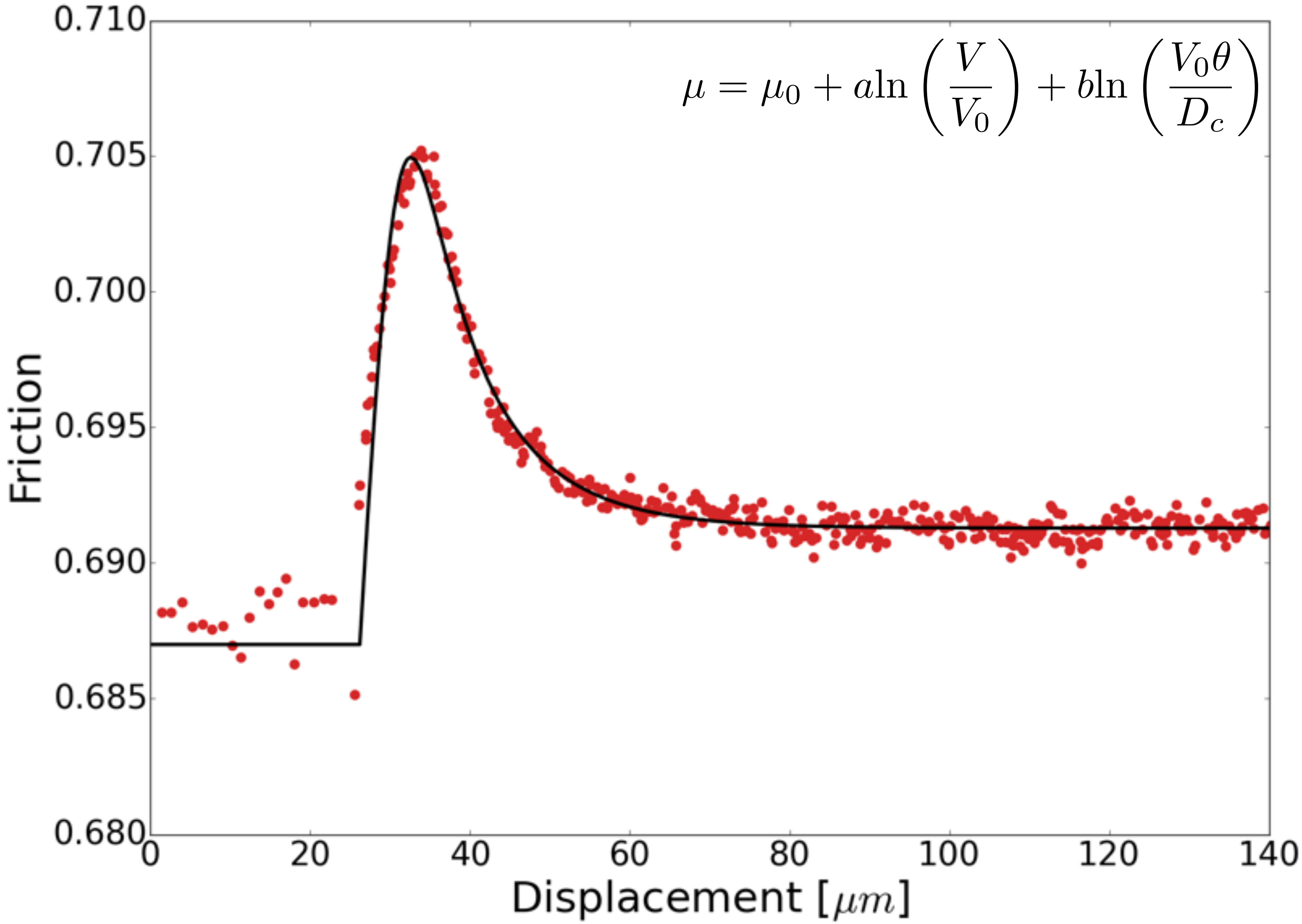


We can define kc experimentally from velocity step inversions in experiments with stable behavior



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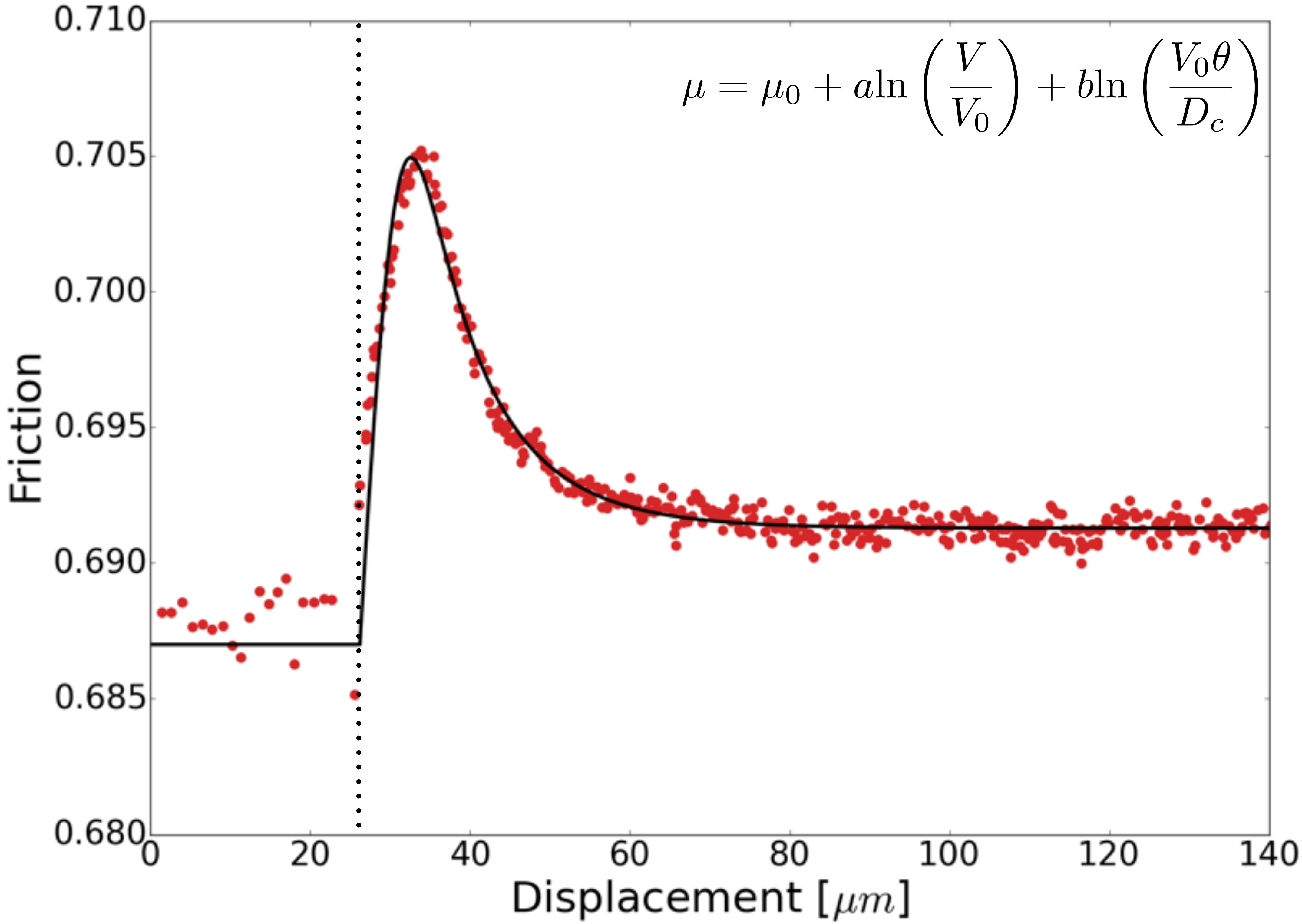

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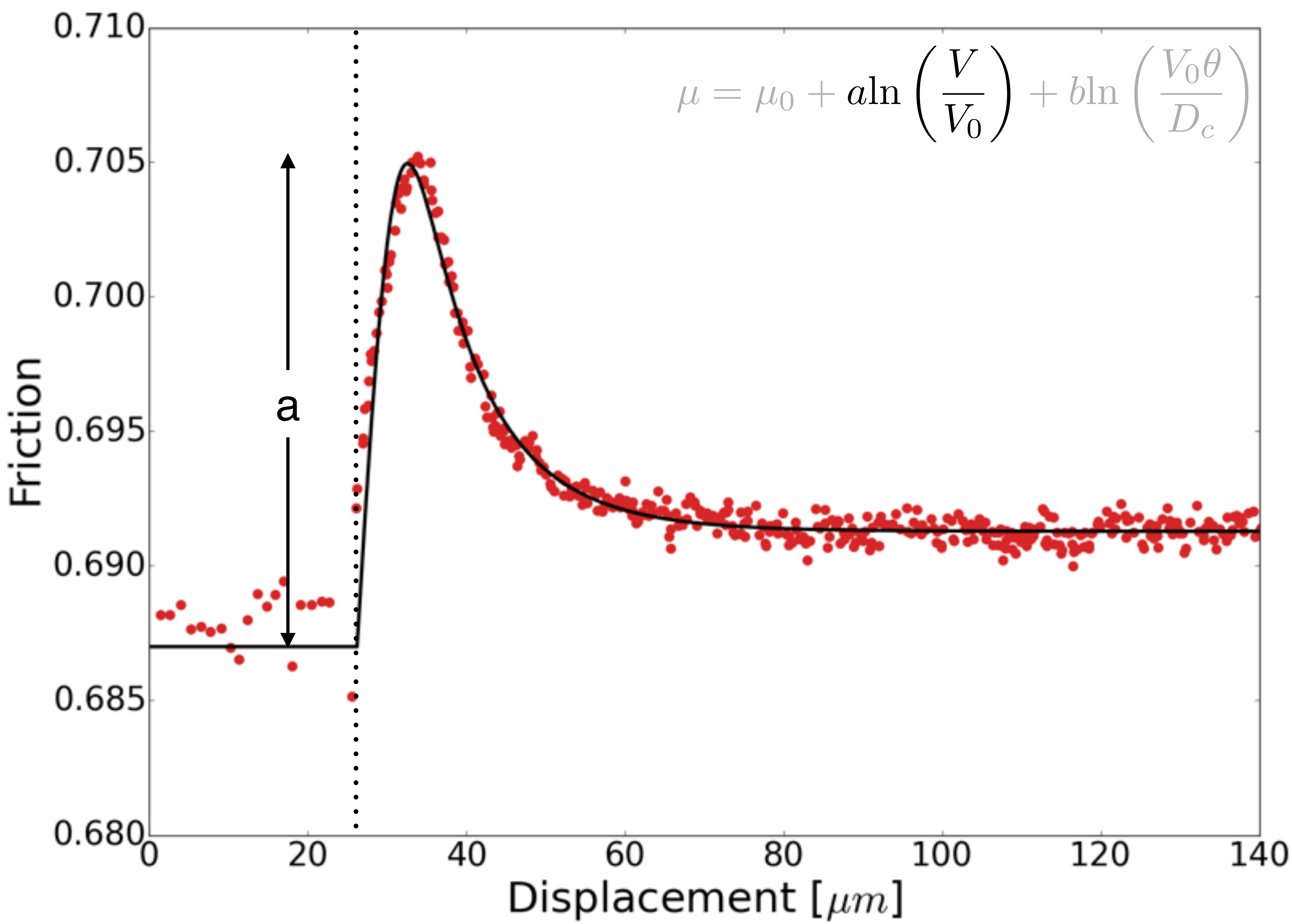

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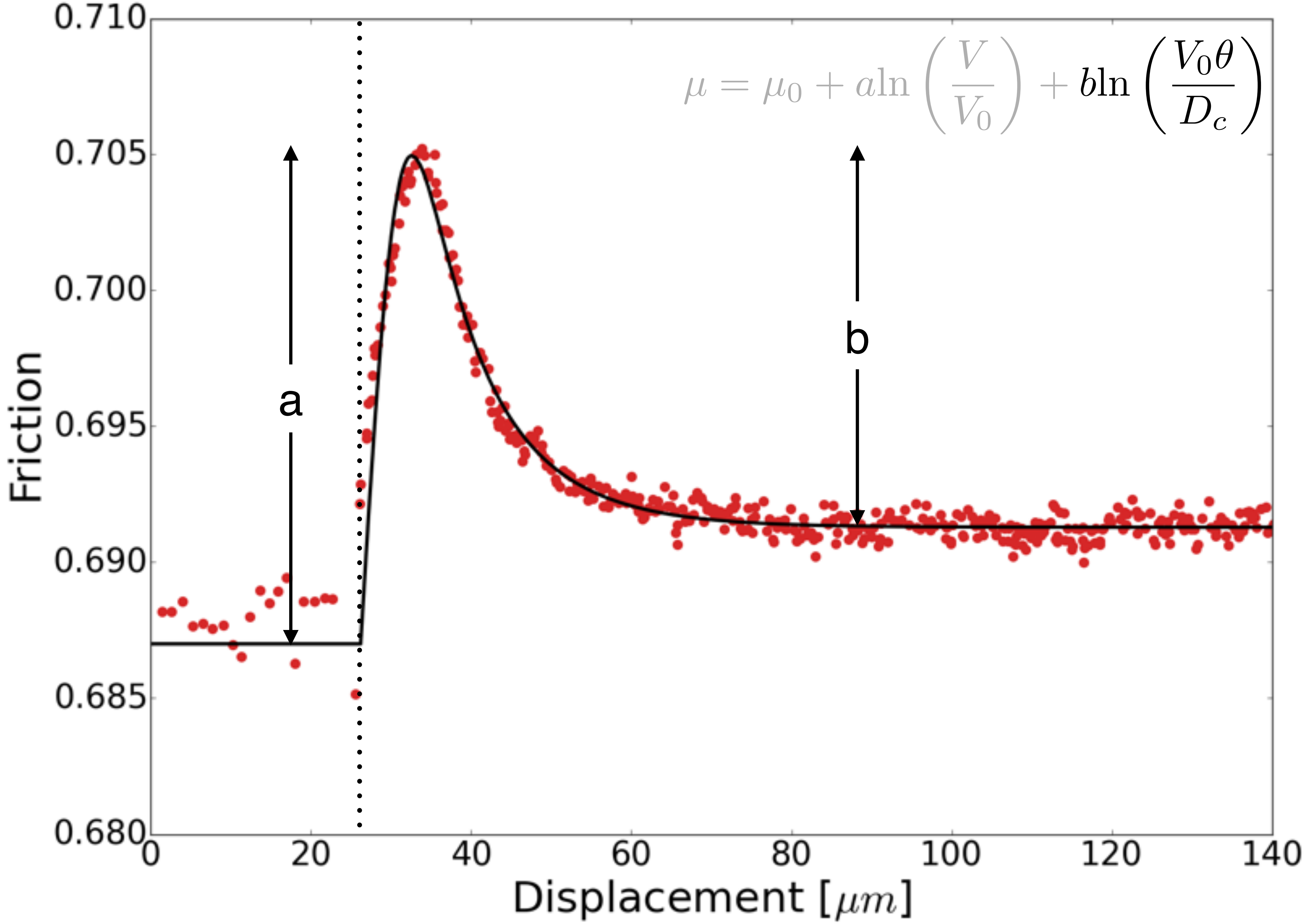

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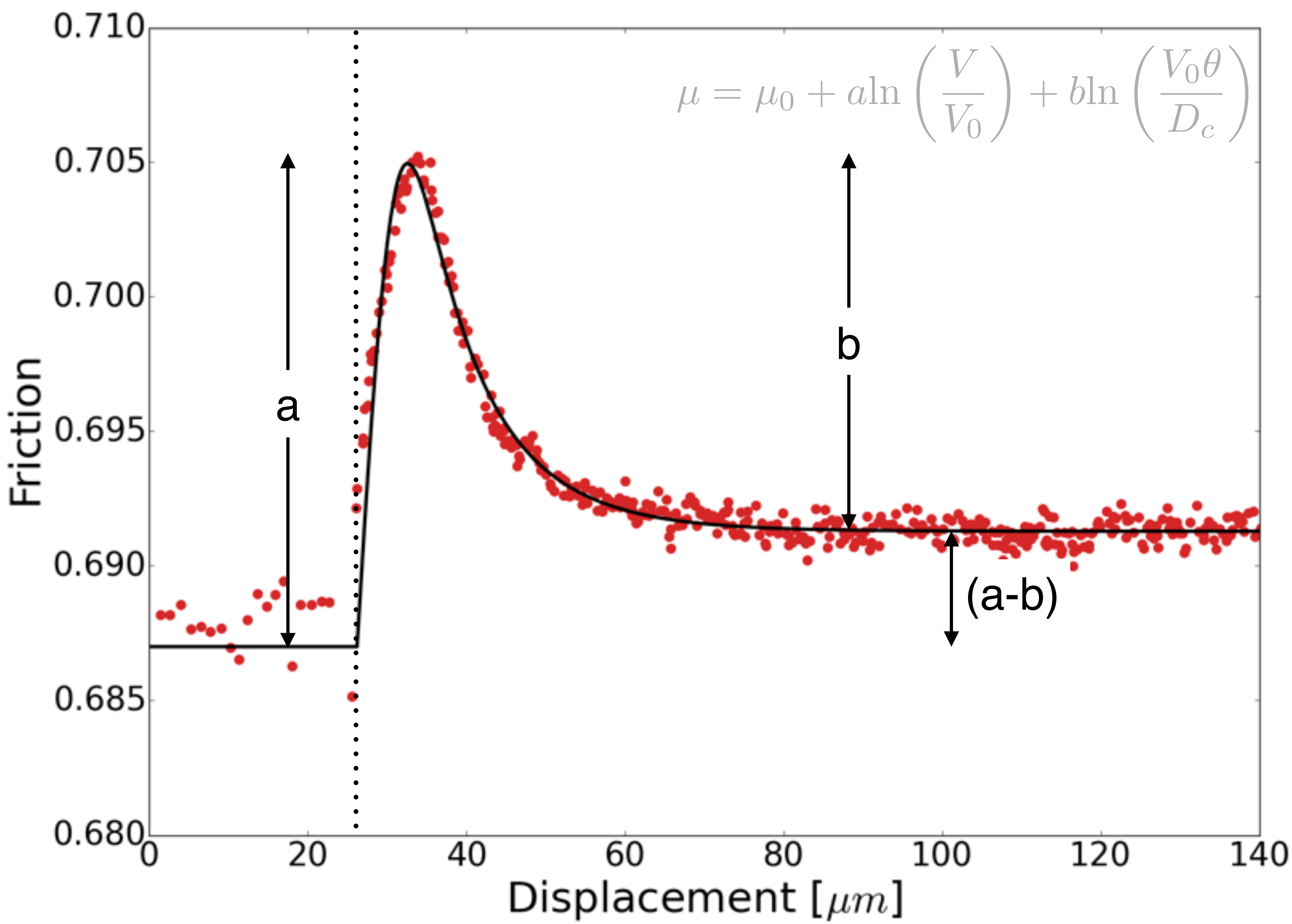

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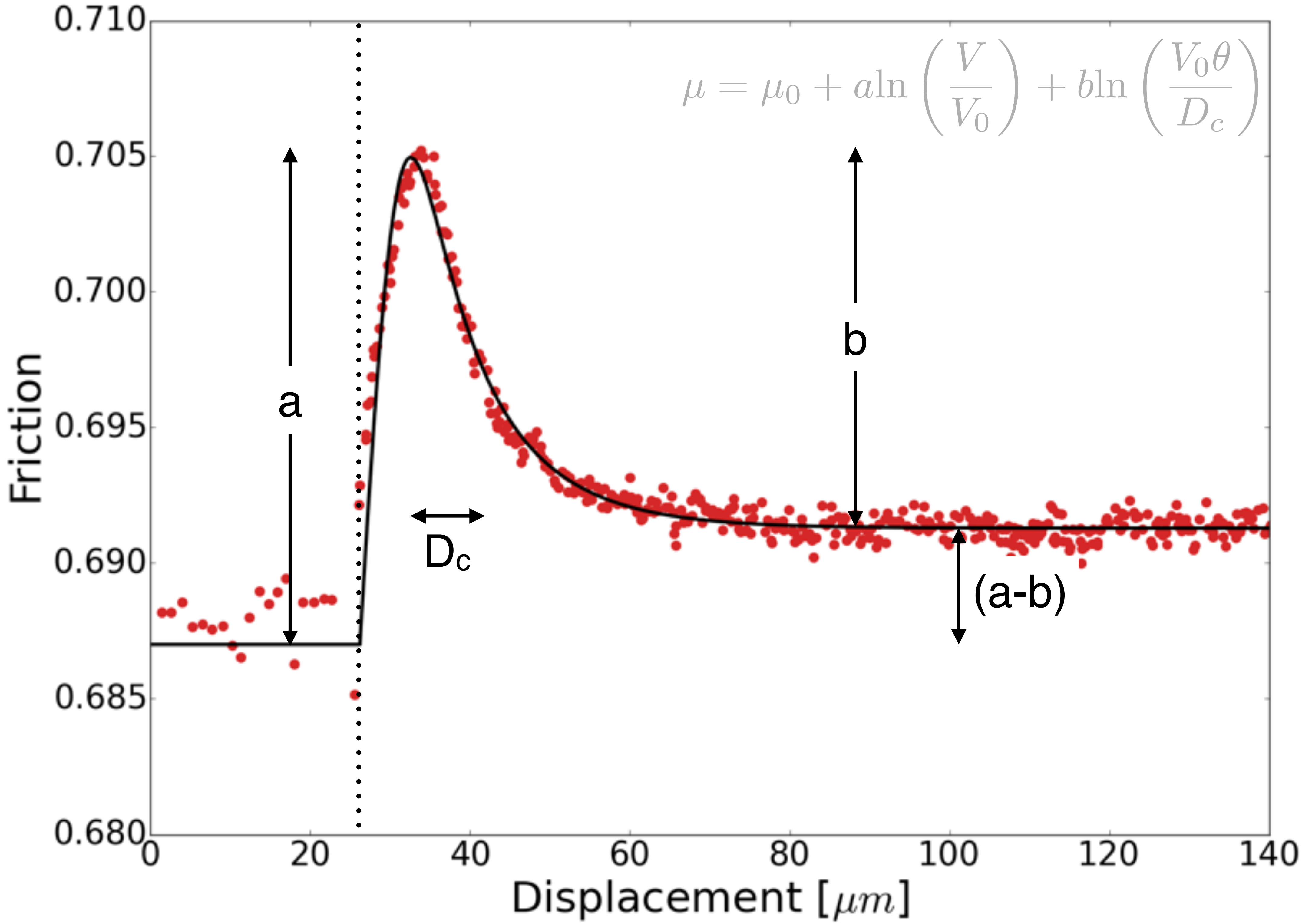

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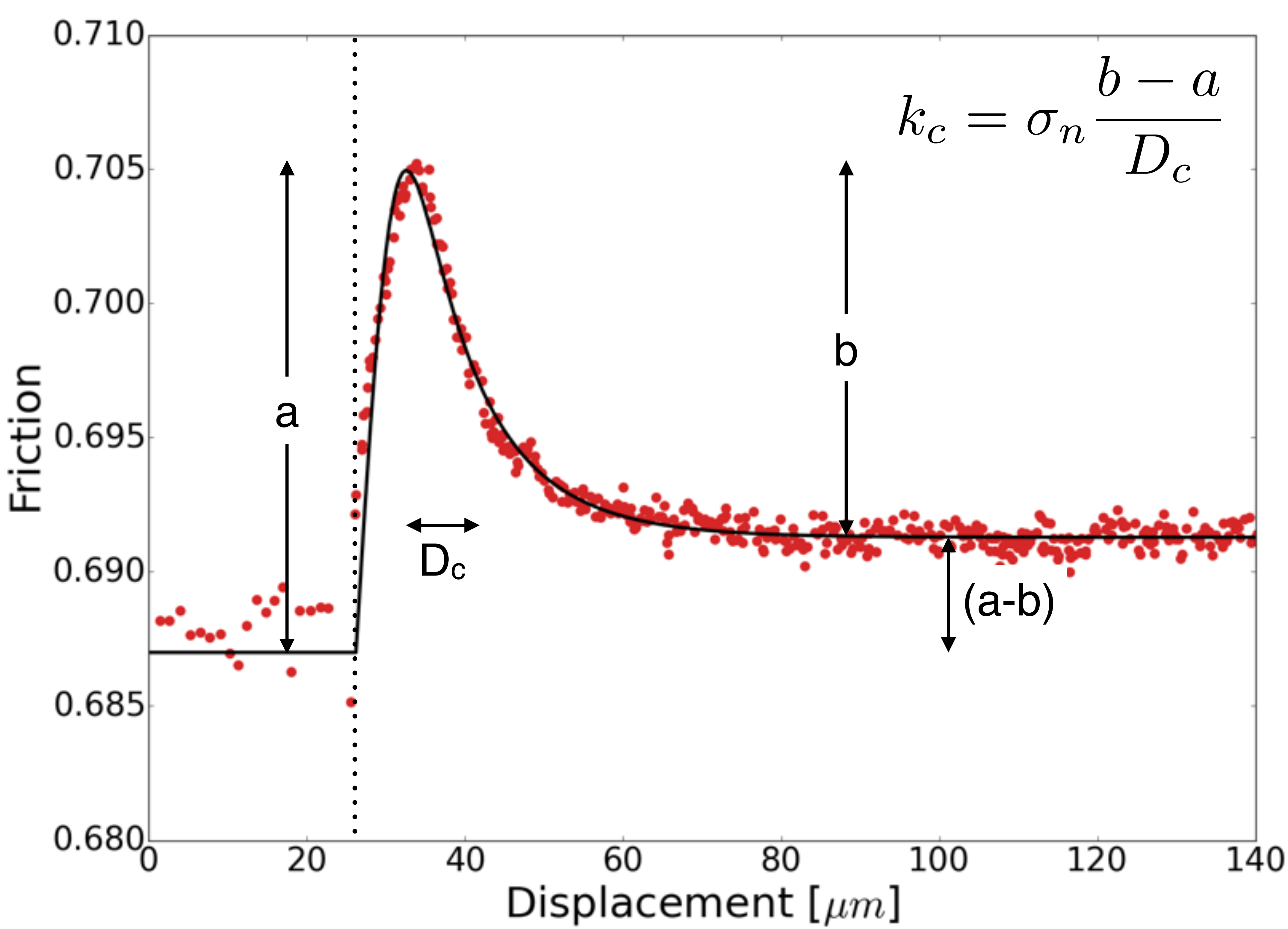
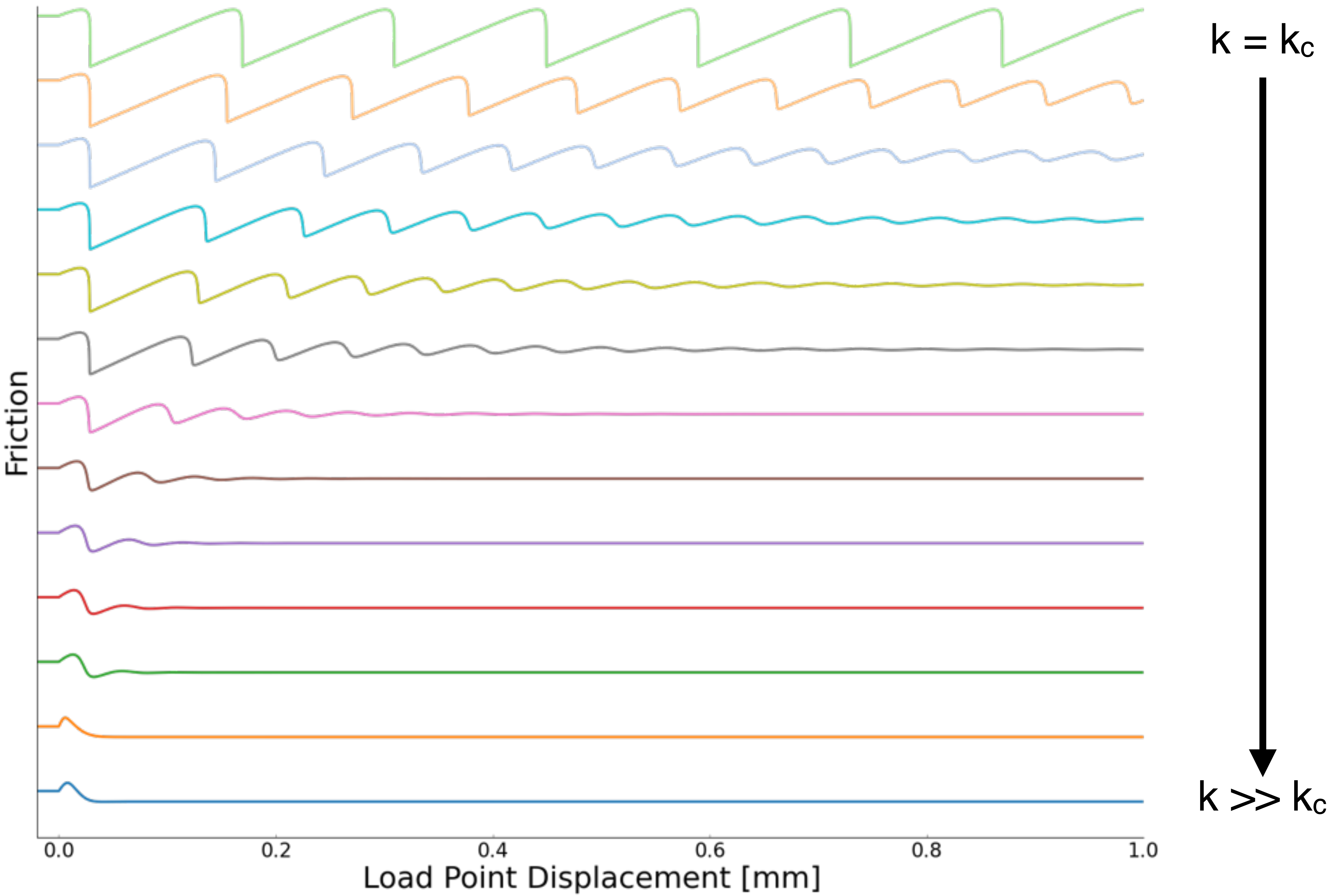
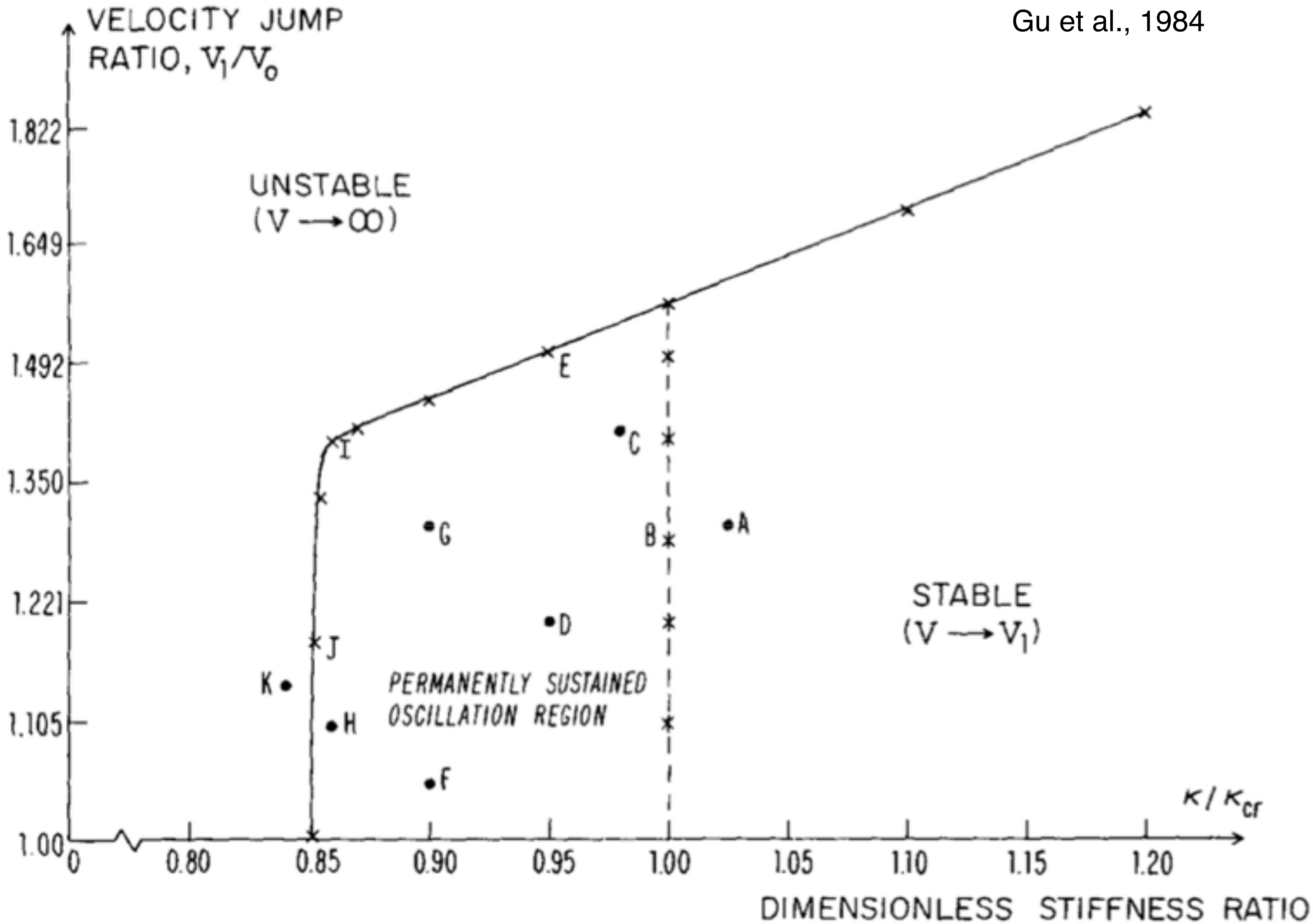


Single State Variable produces either stable, decaying, or unstable behavior

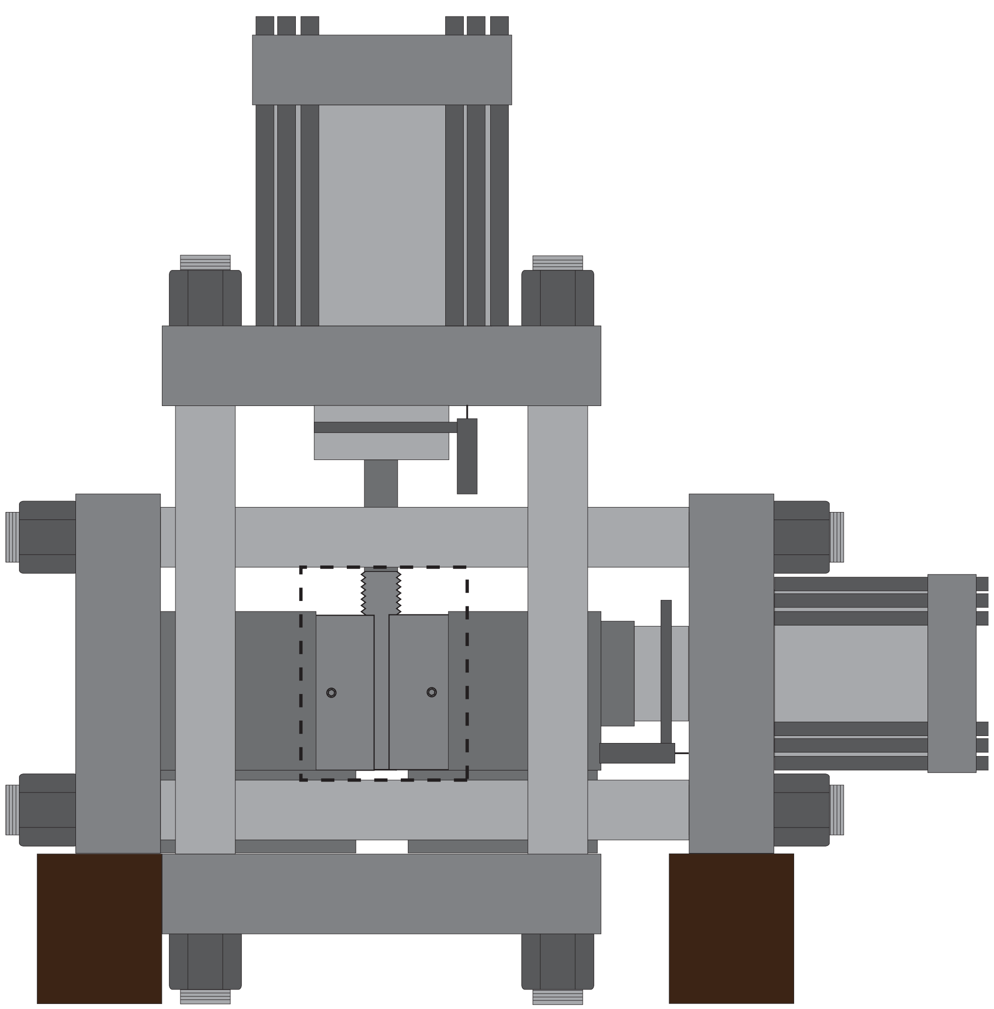


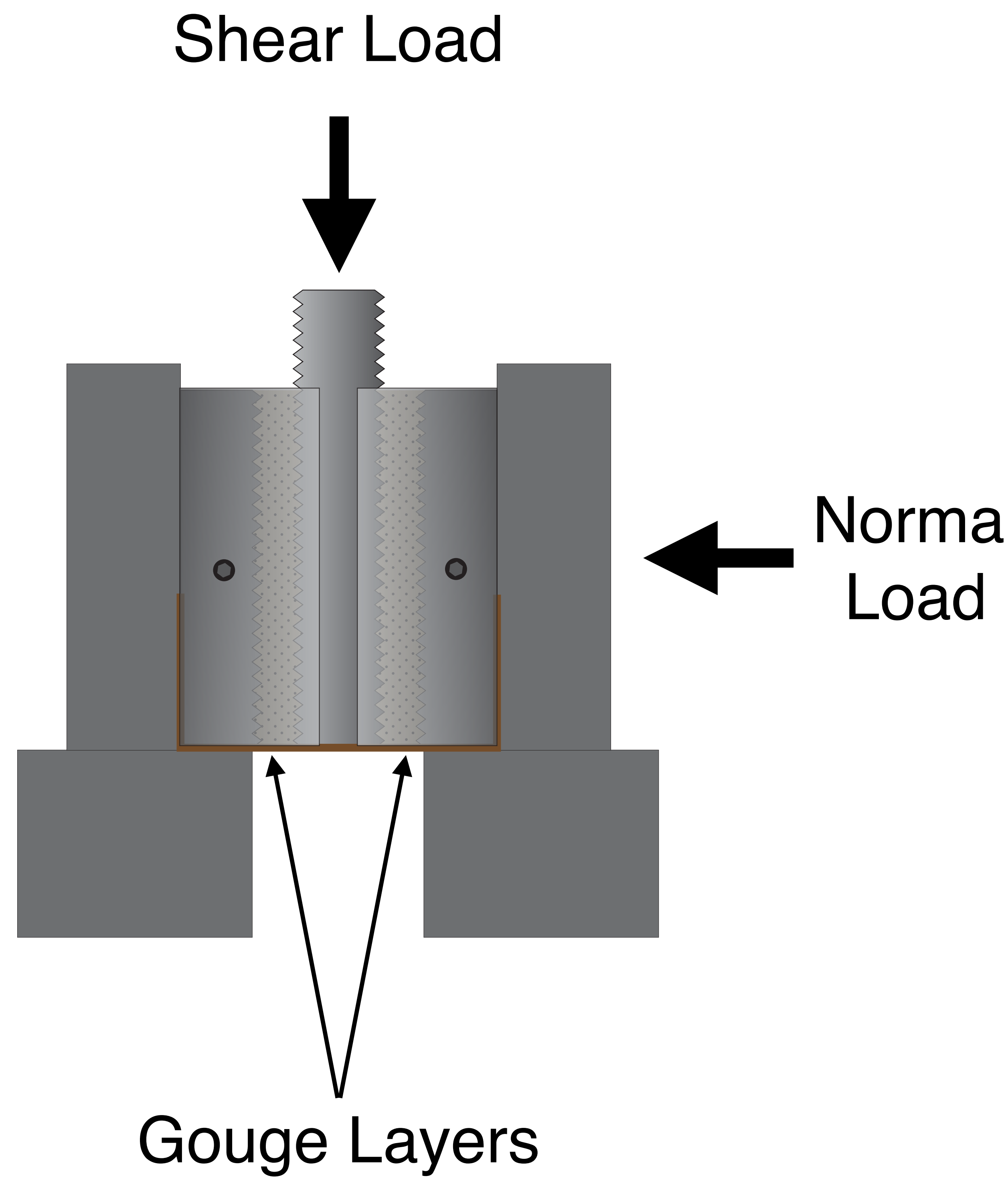
Models have been able to produce regions of sustained oscillations that represent transitory behavior

Gu et al., 1984



The Penn State biax is setup for double direct shear for all experiments





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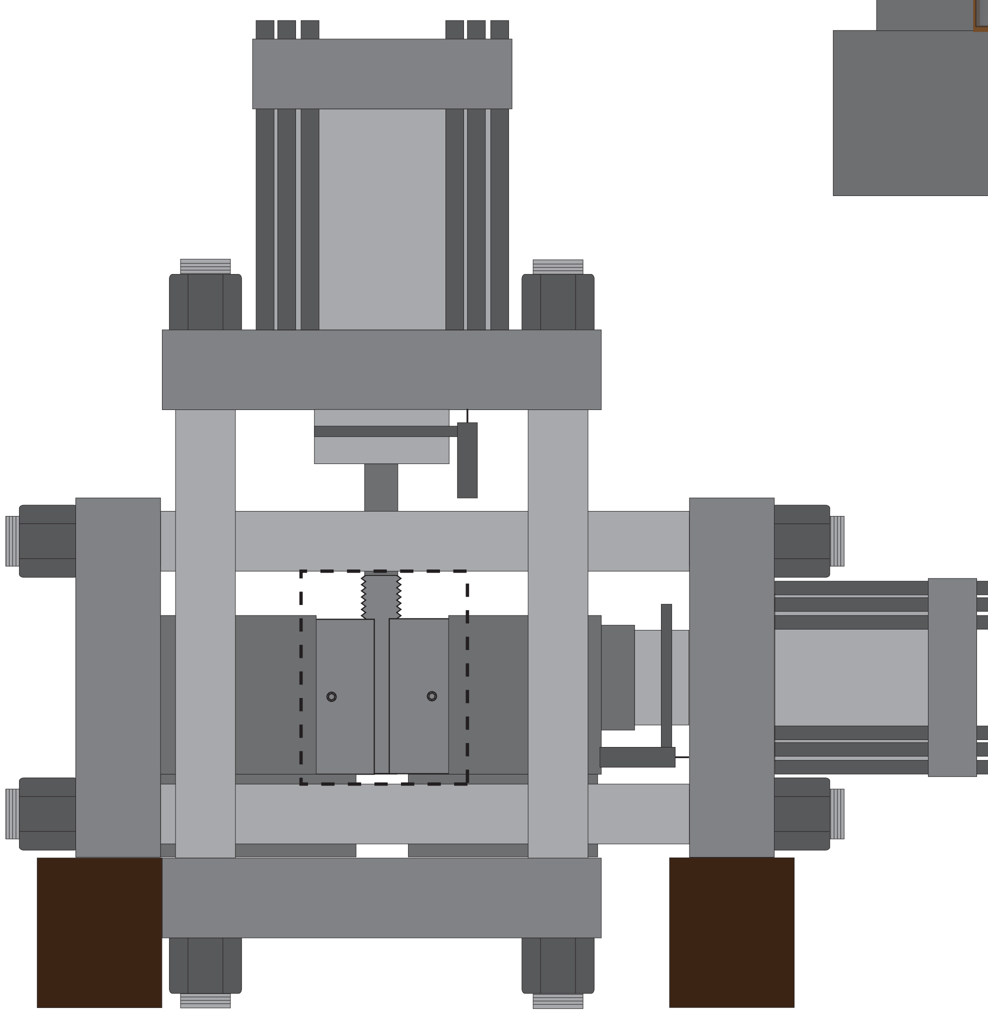
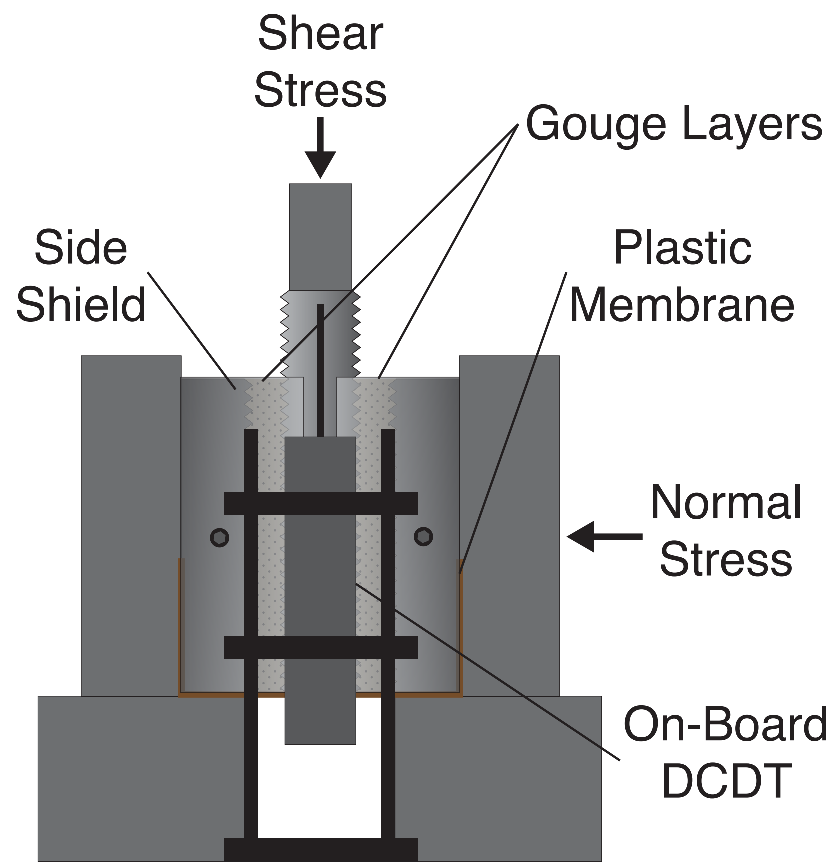
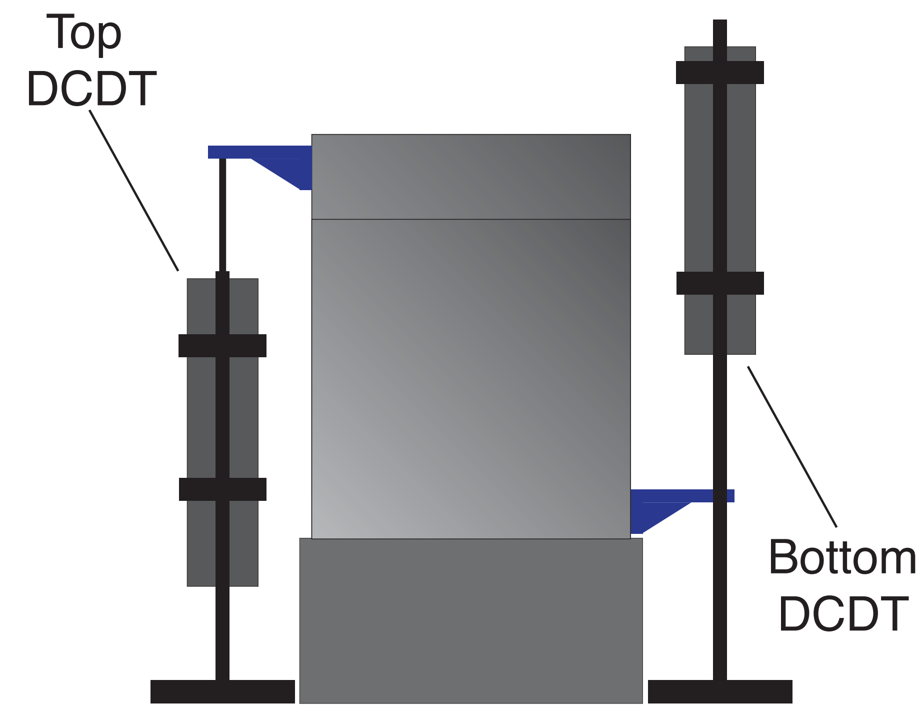
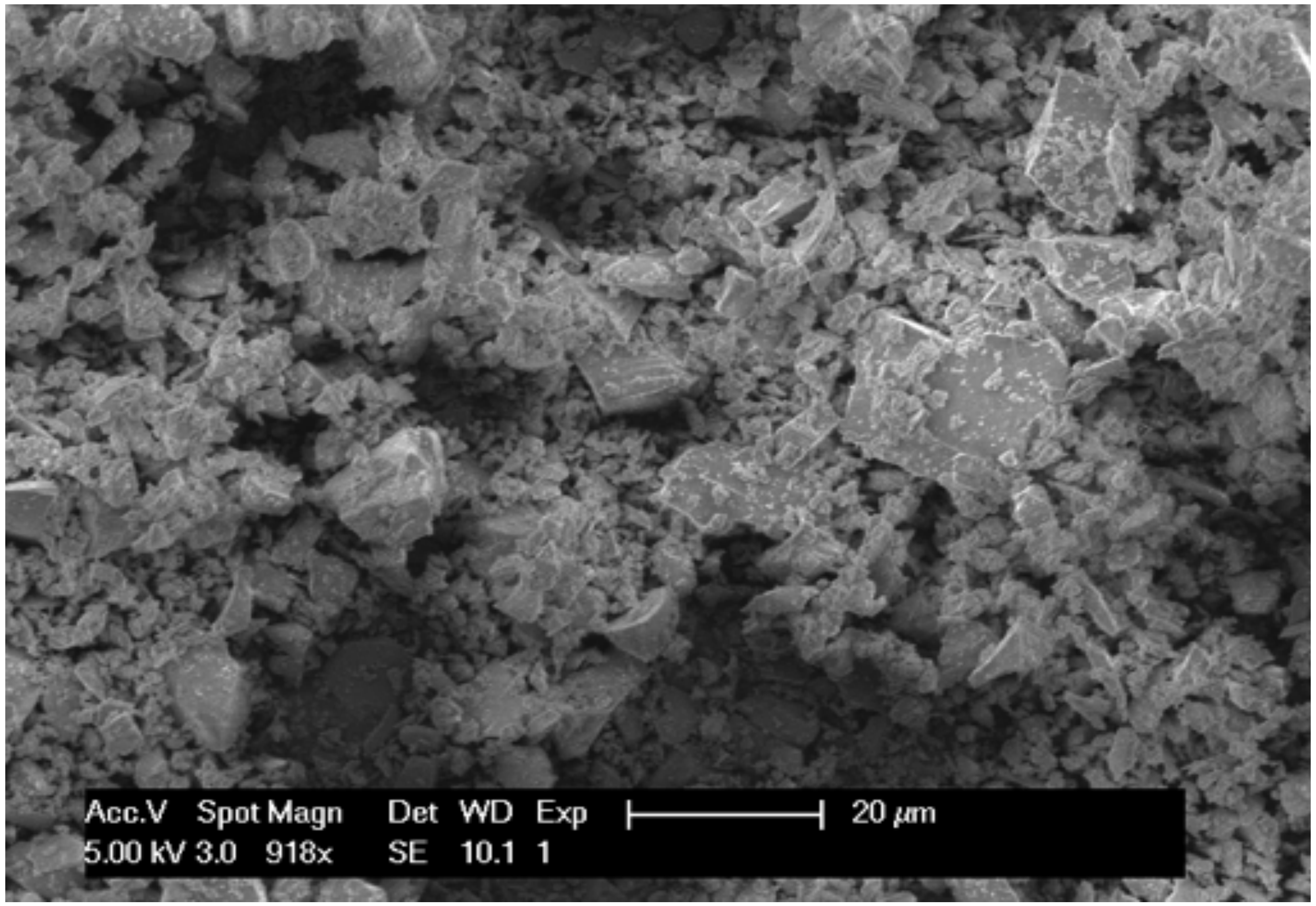
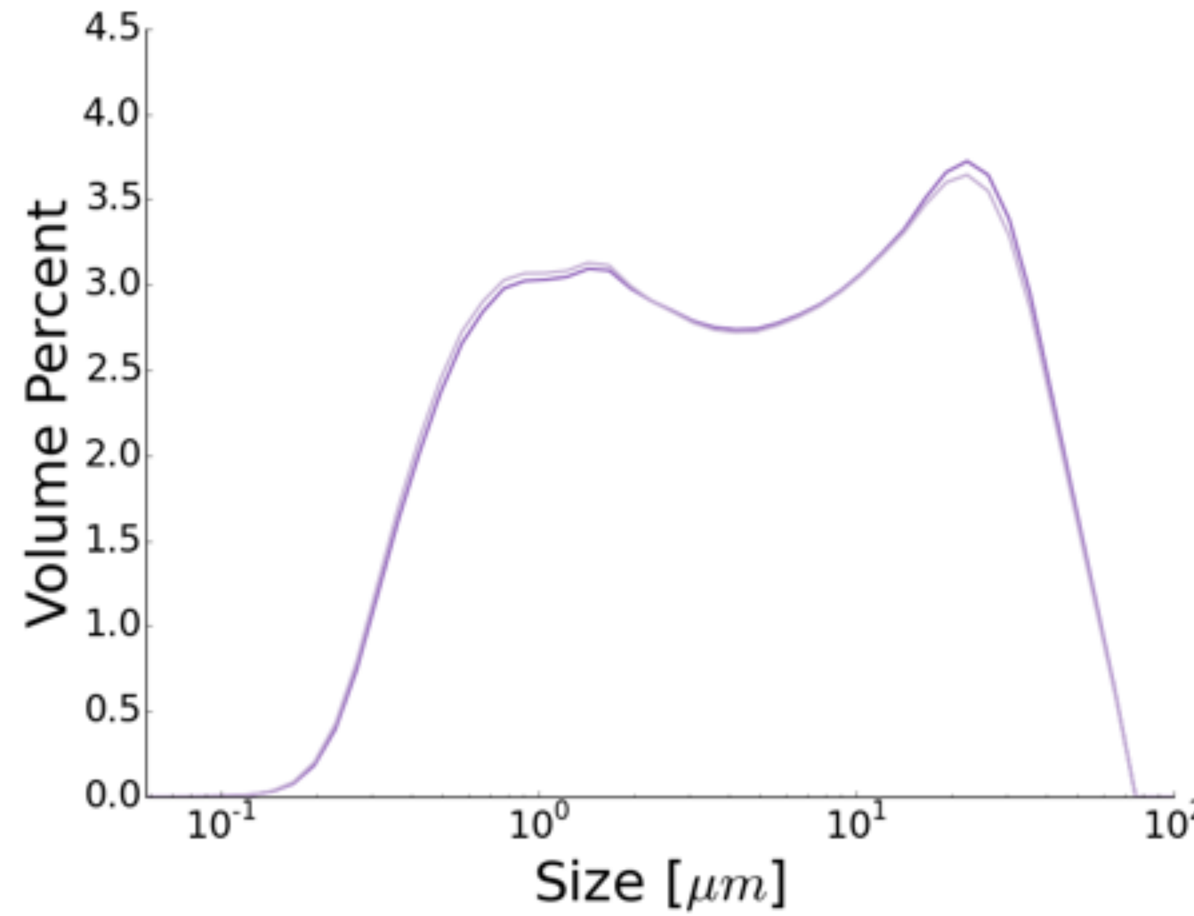






Min-U-Sil is a quartz fault gouge simulant that provides a reproducible laboratory test material





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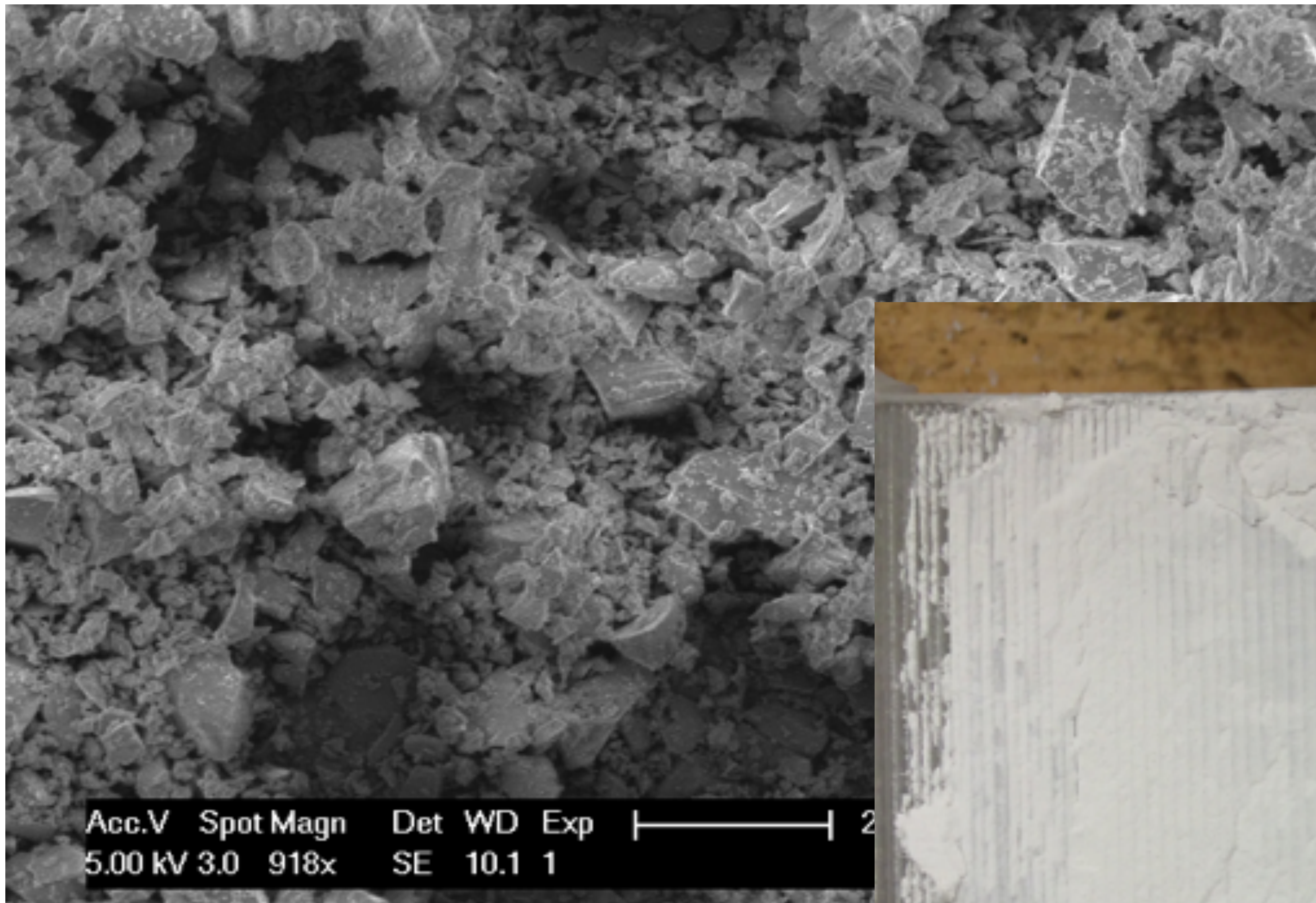
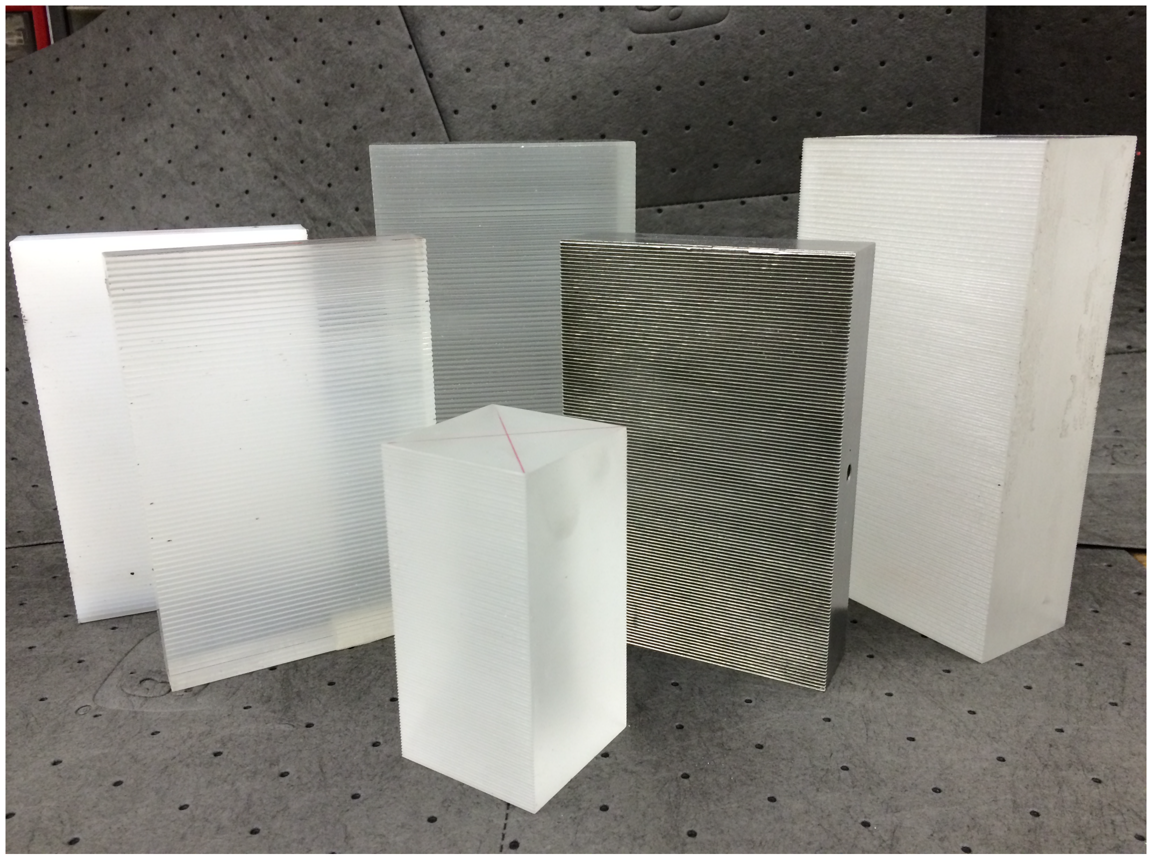
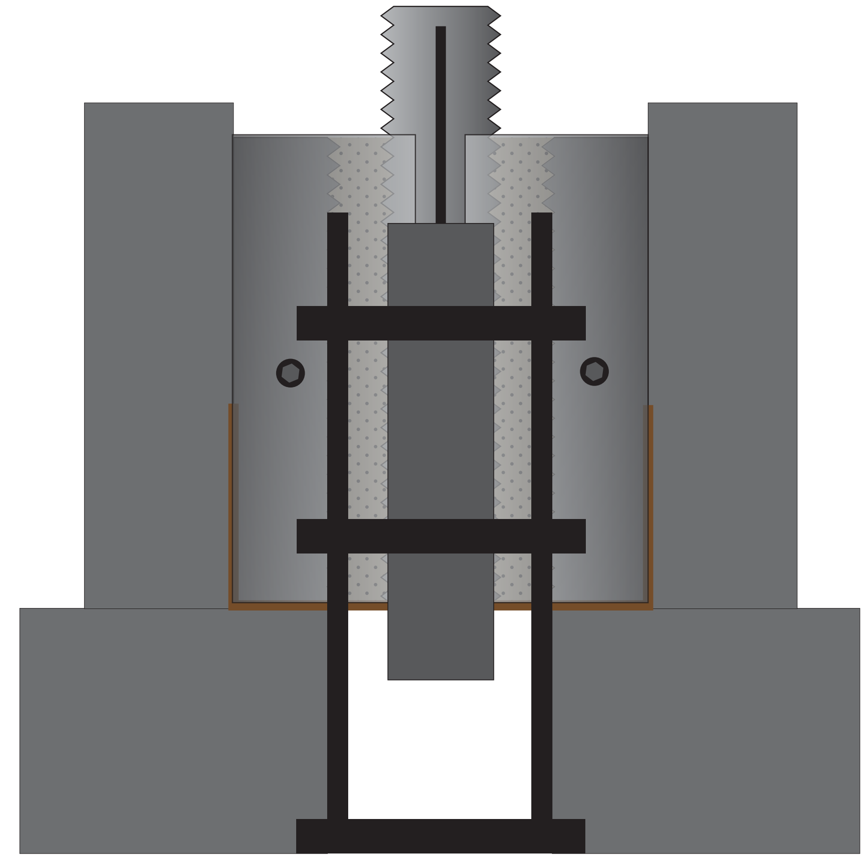


We modify the system stiffness by changing the normal load and the center block material

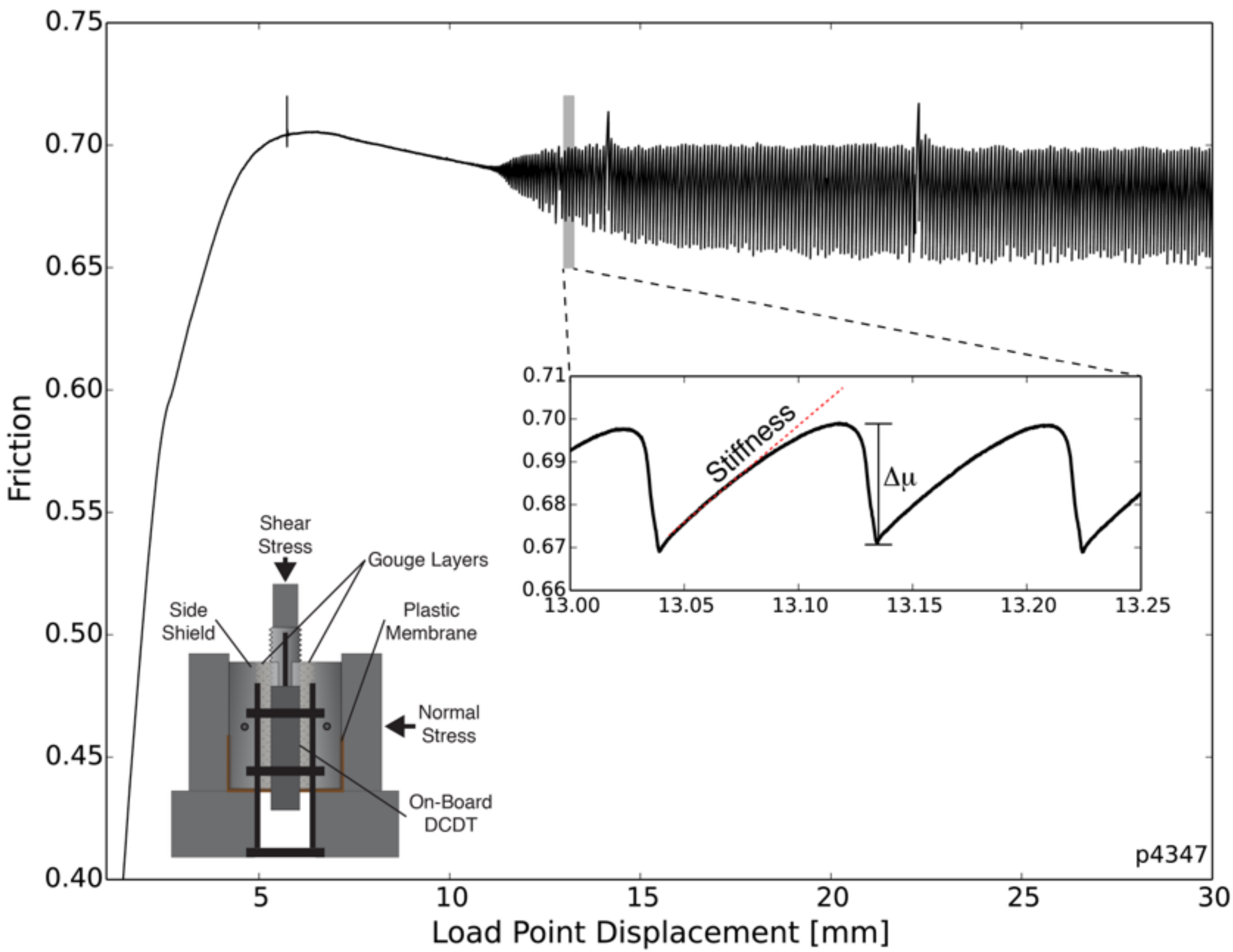


Block Material

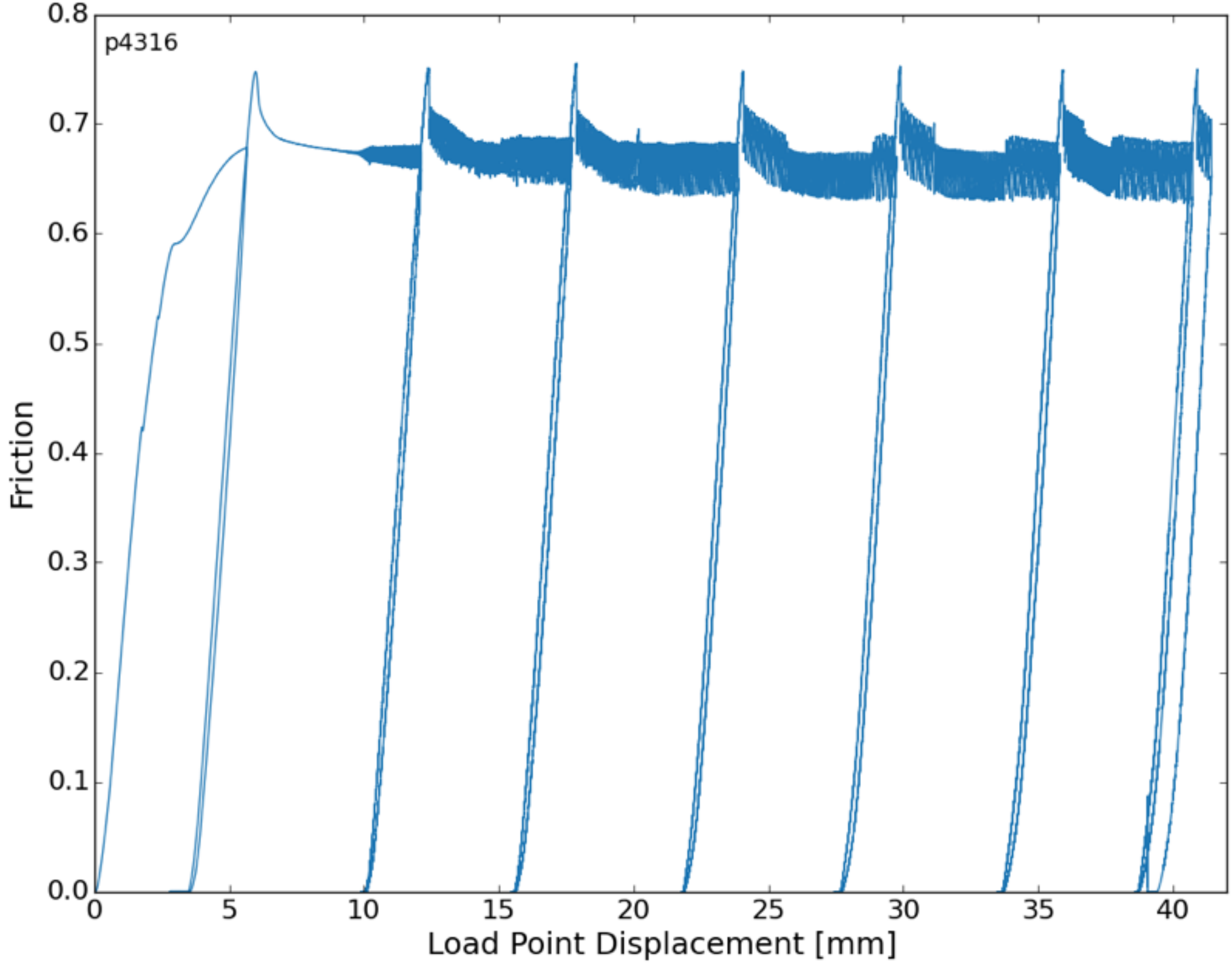


Normal Stress

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



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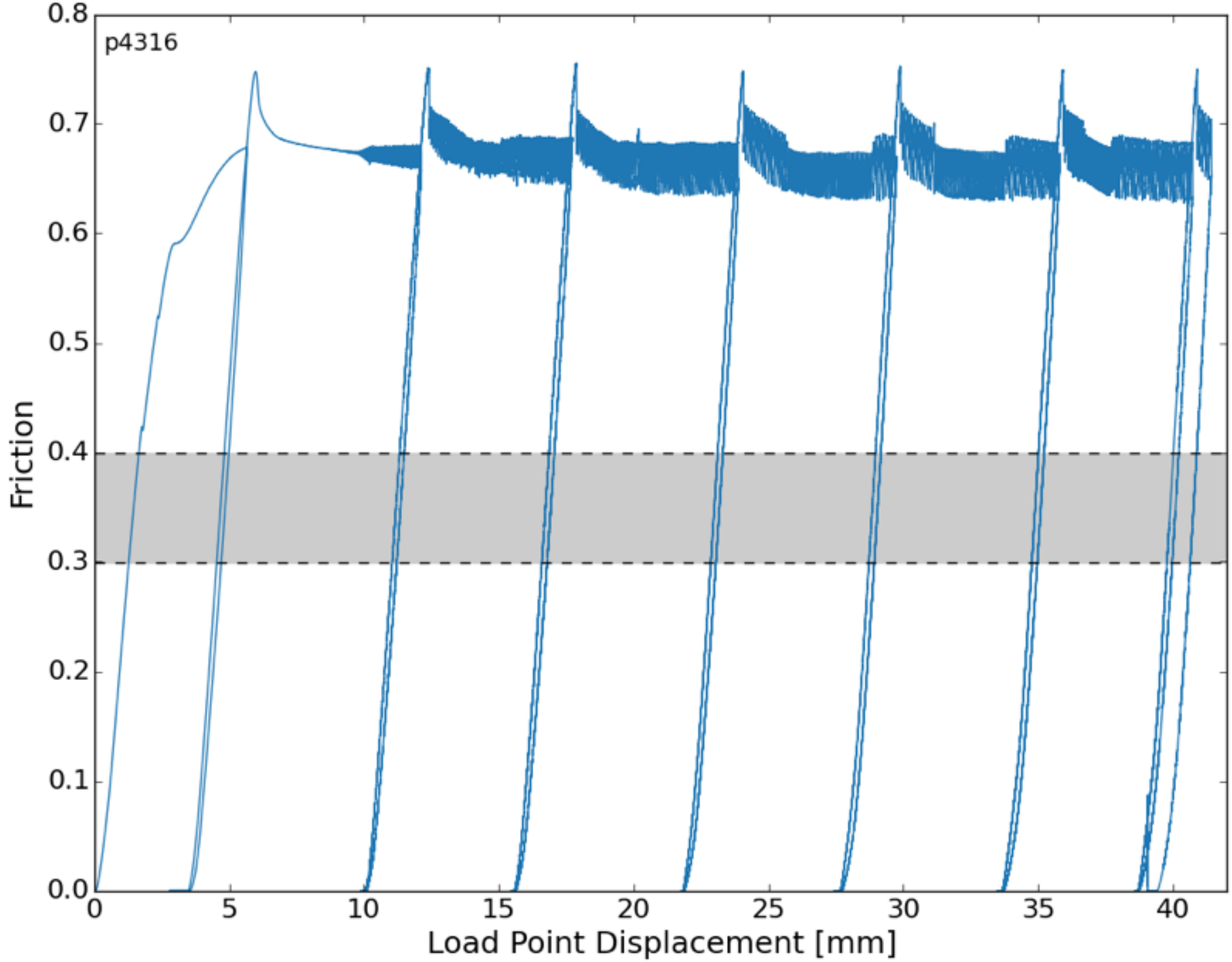

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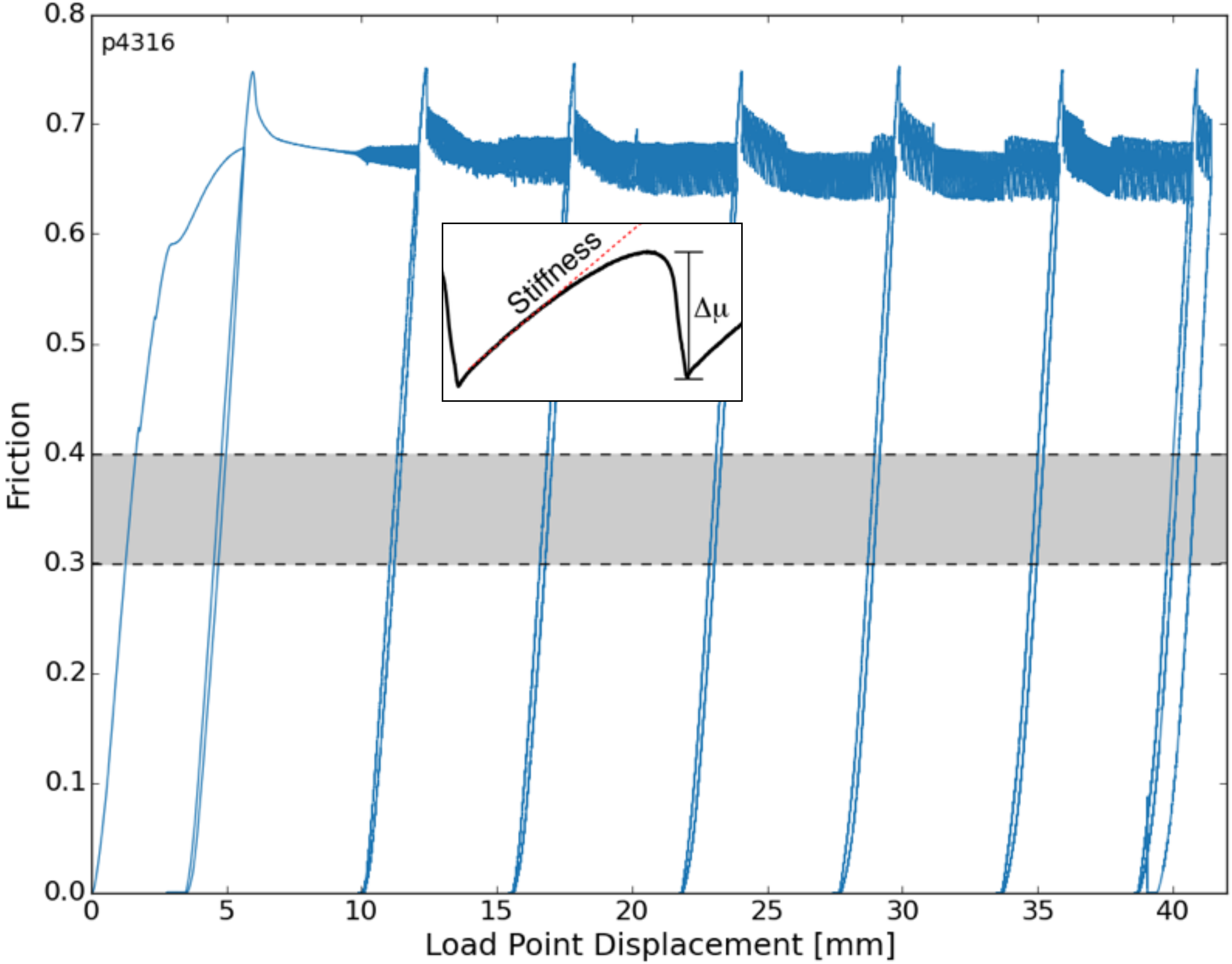

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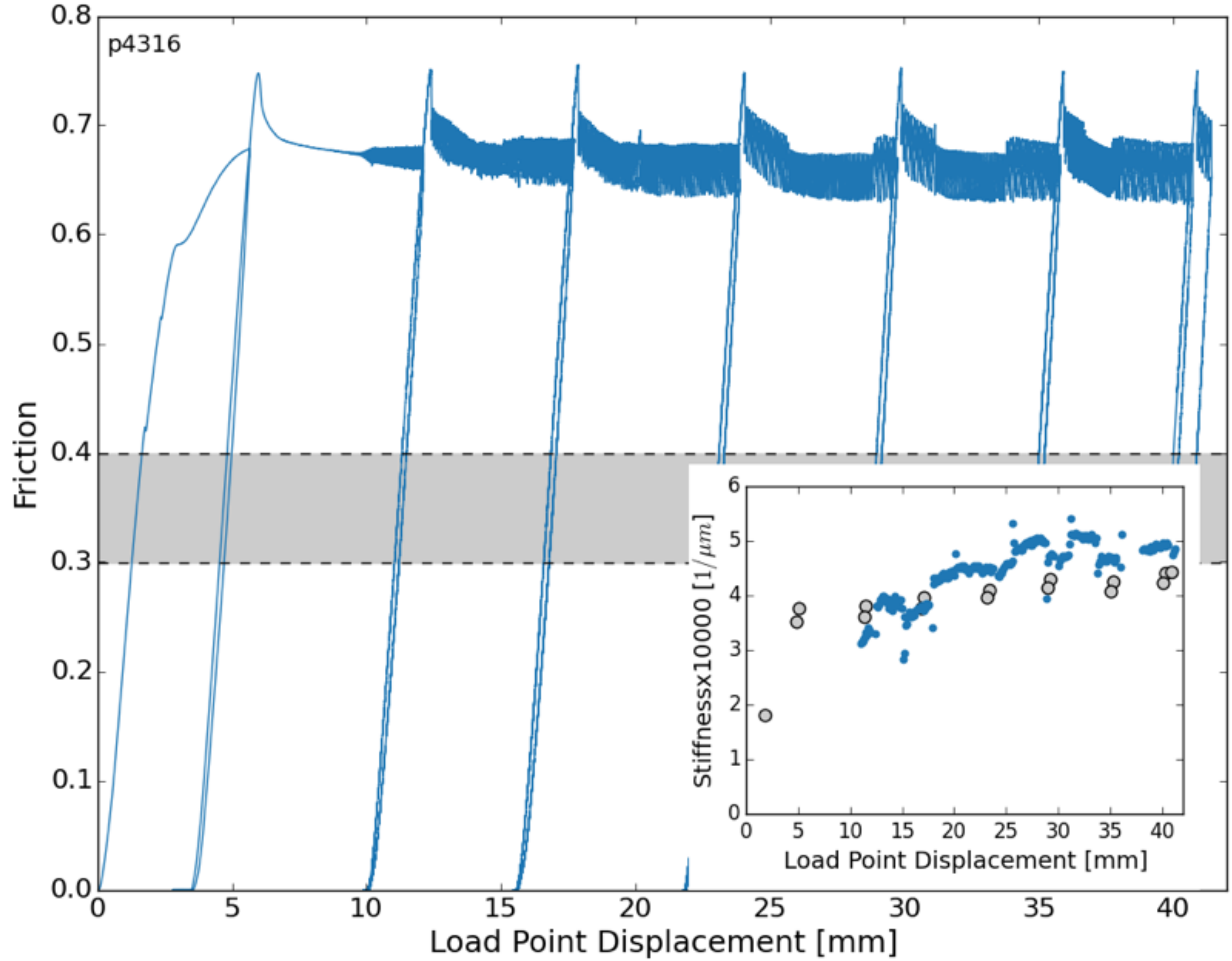
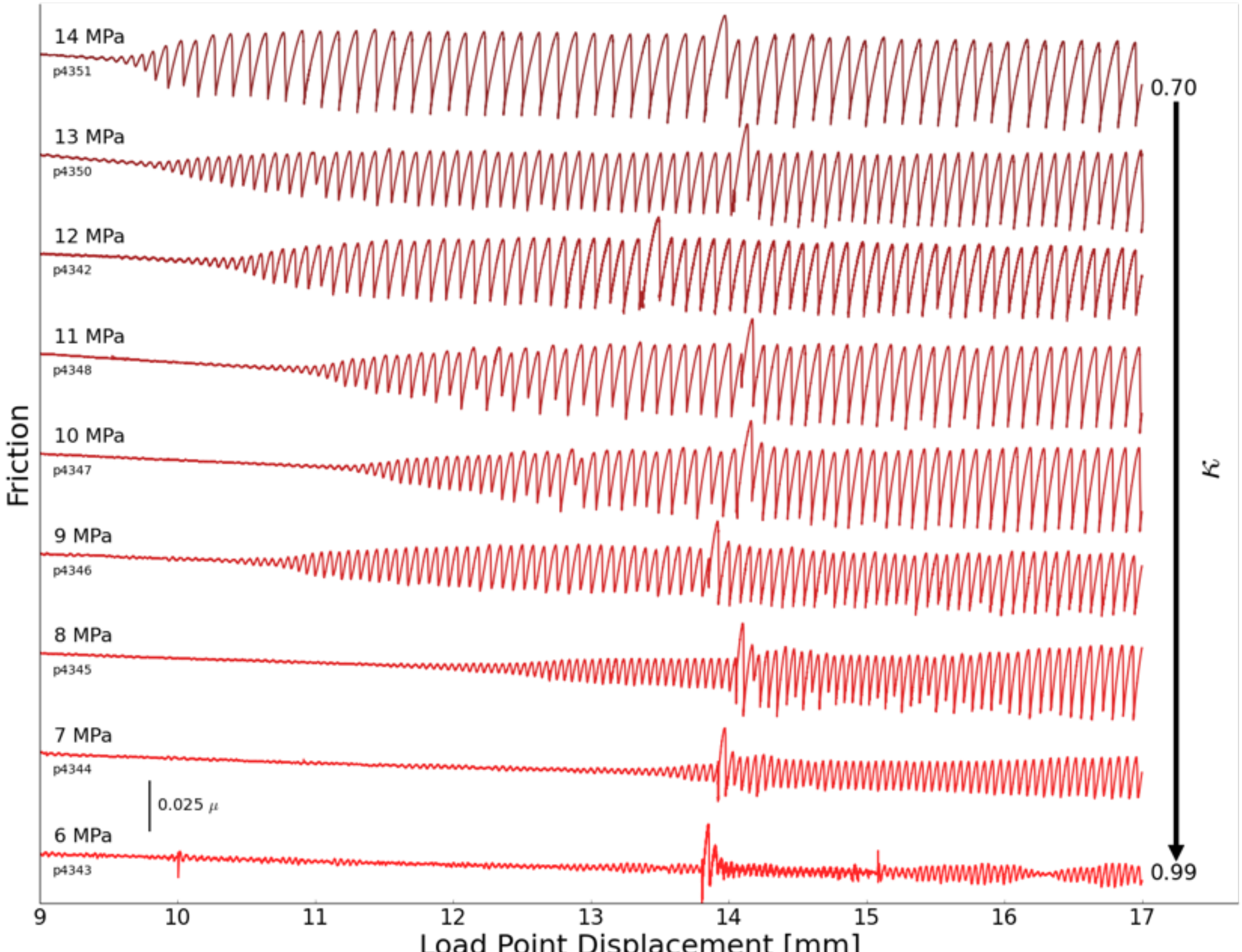
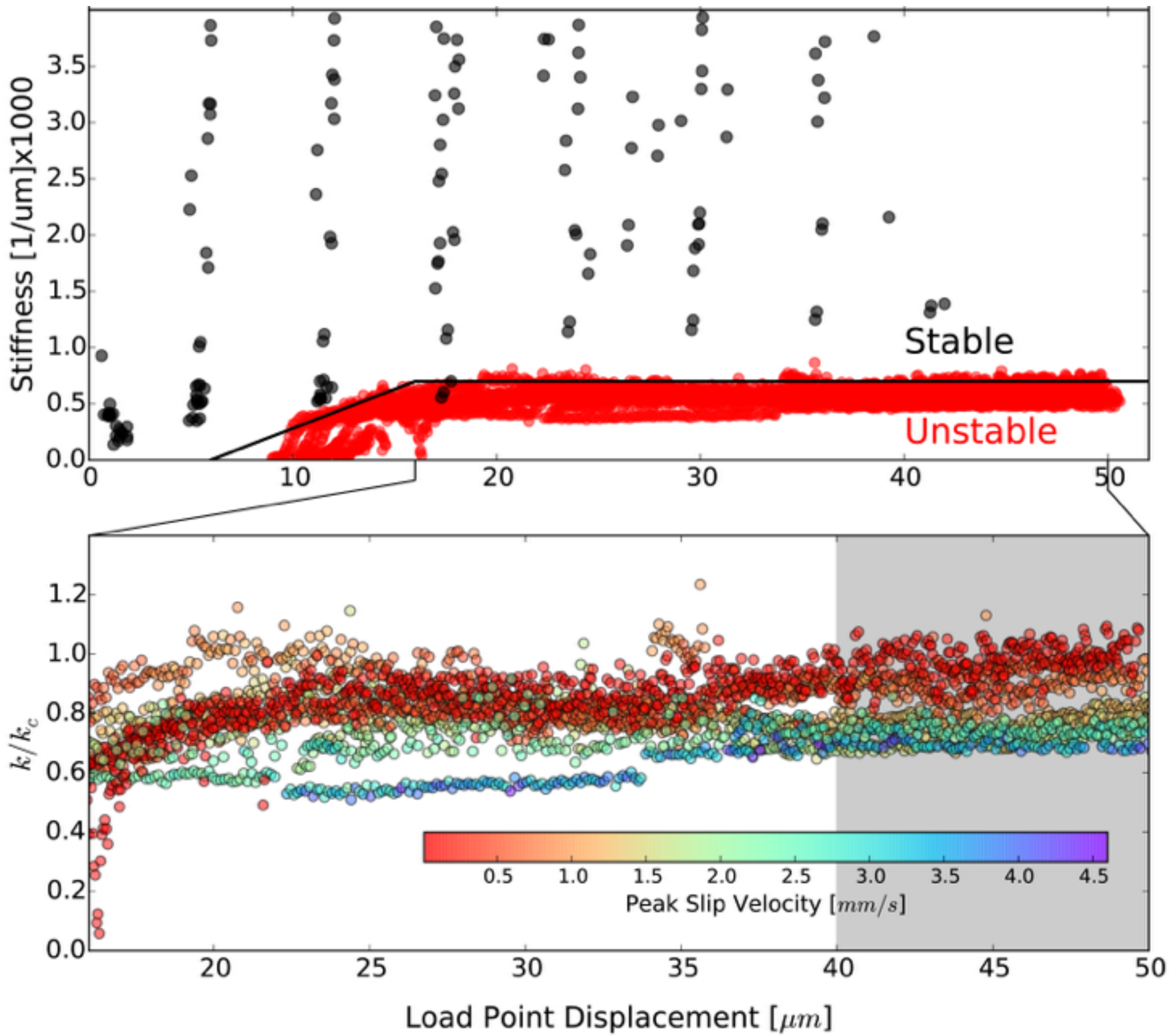


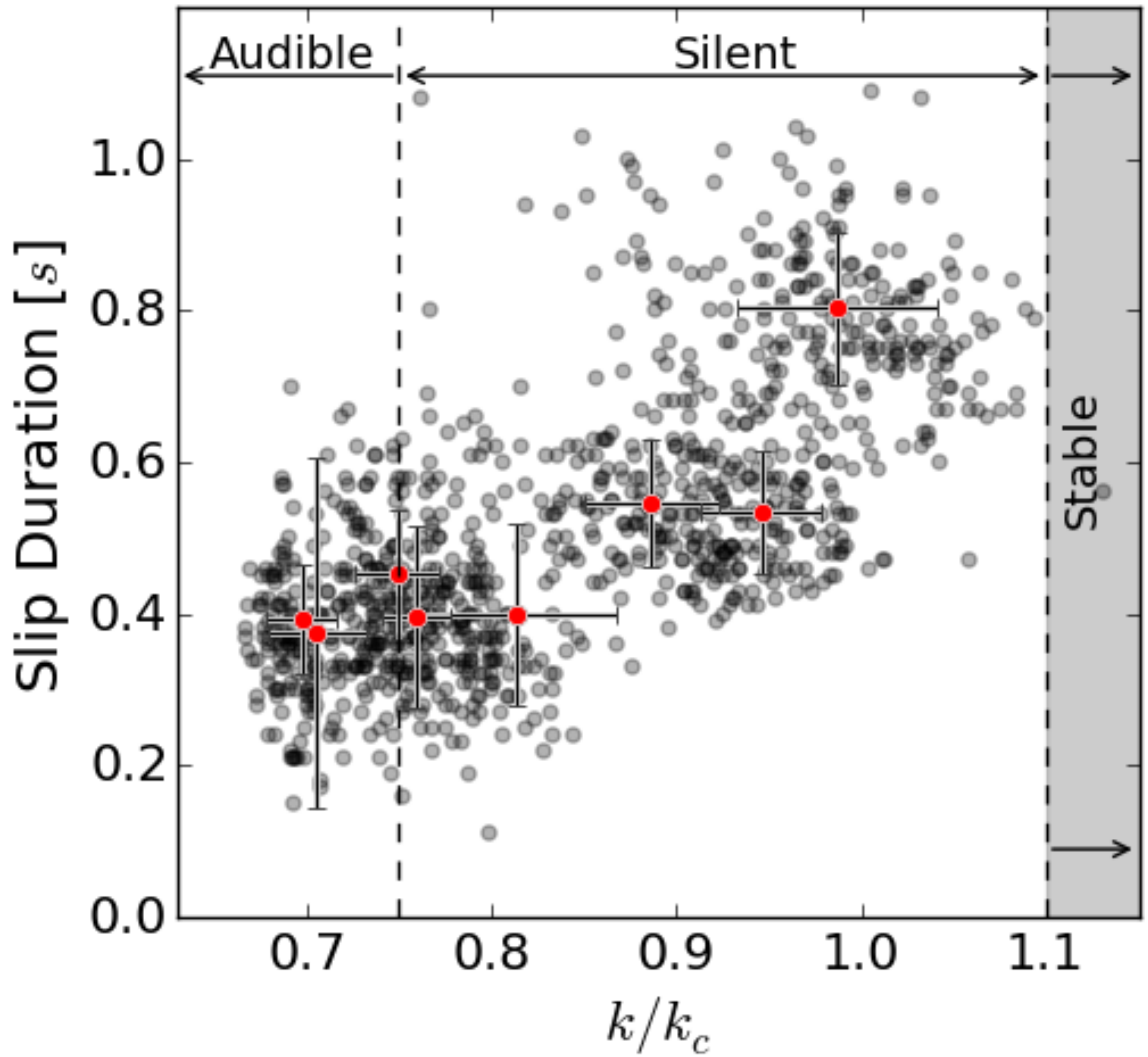
We see a transition between behaviors as a function of k/kc, not a sharp bifurcation



There is a clear division between stable and unstable experiments that aligns with kc, but the unstable behavior itself is complex



Both peak velocity and slip duration scale linearly with k/kc, but the inertial limit is close at hand



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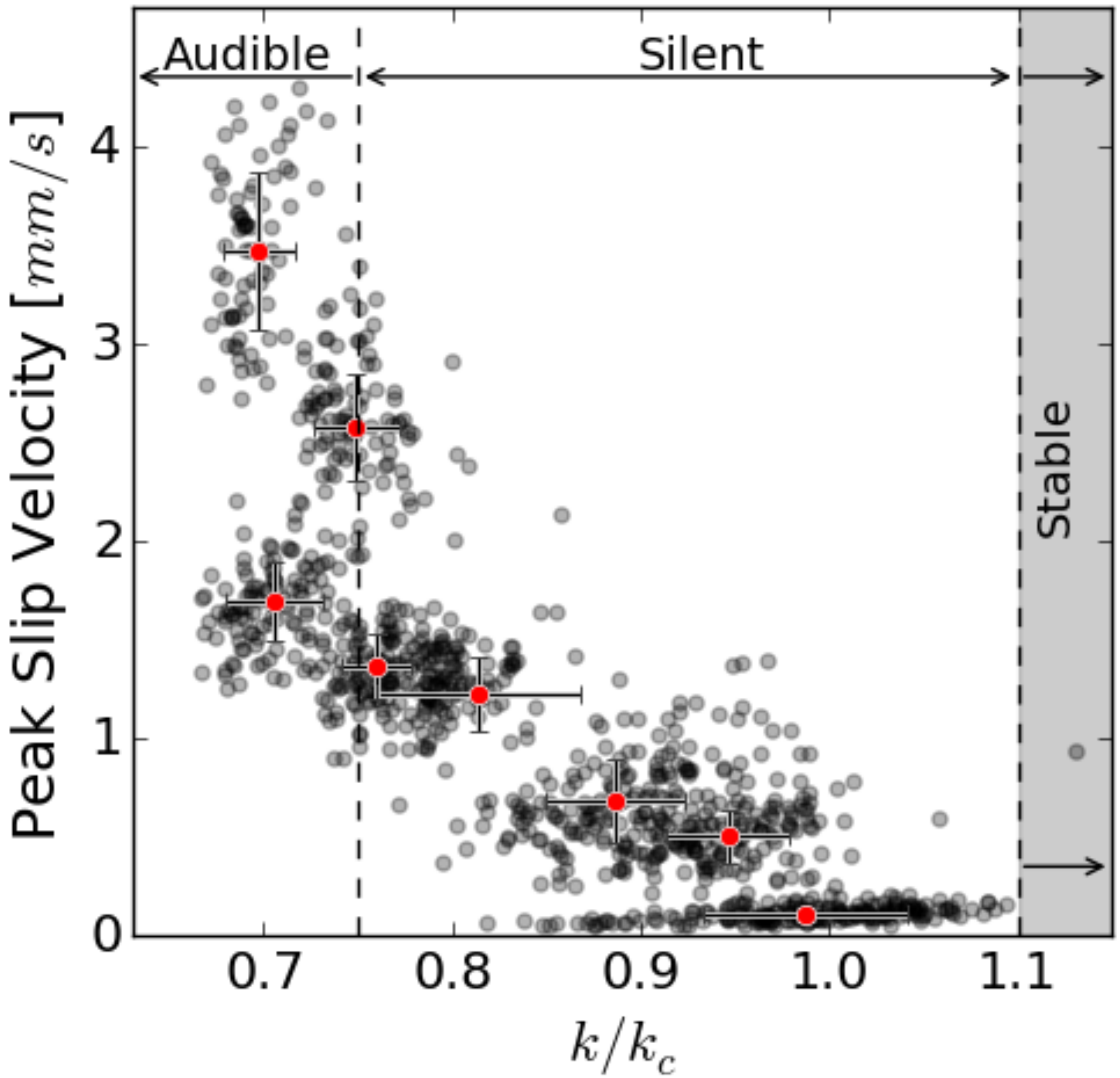
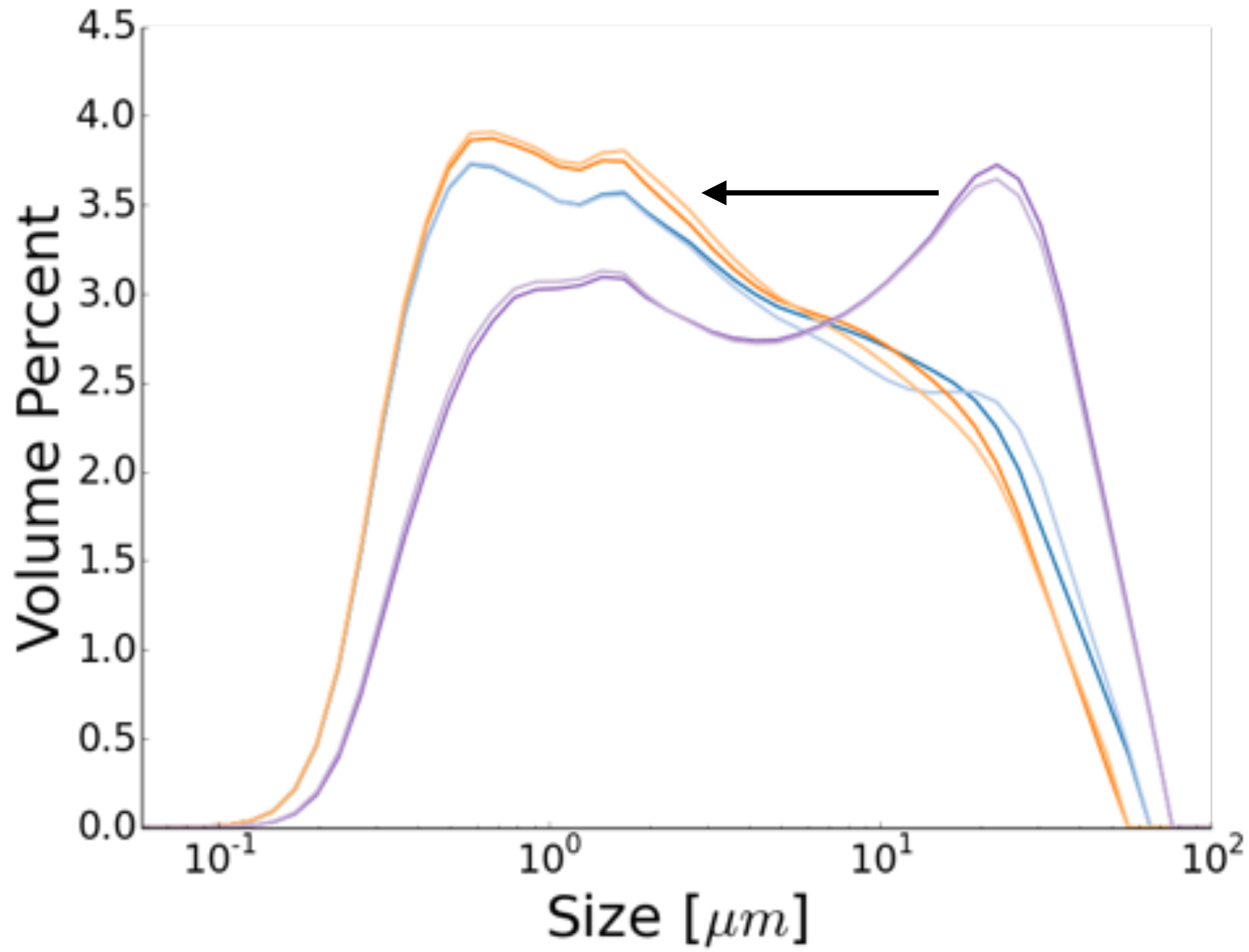
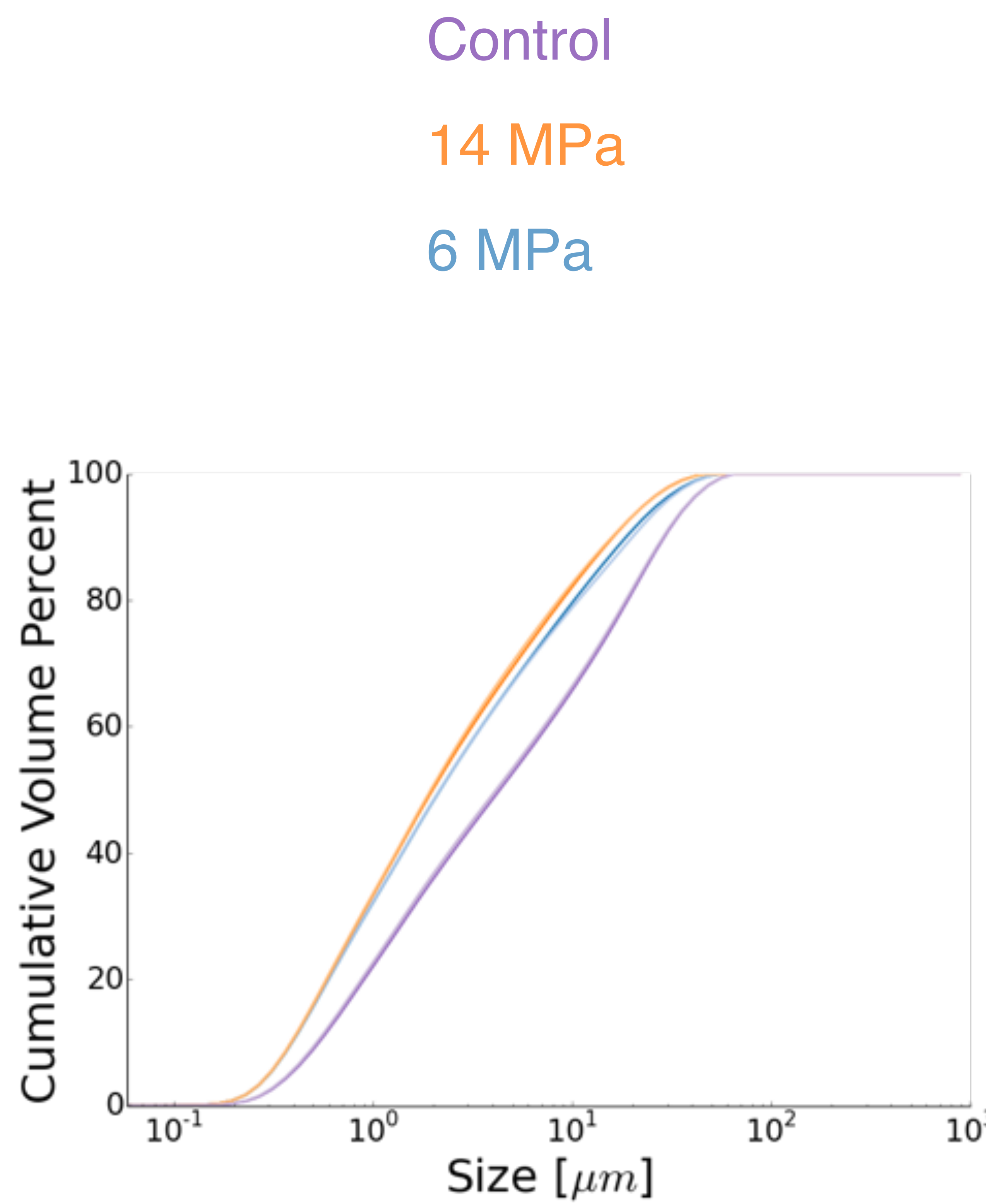
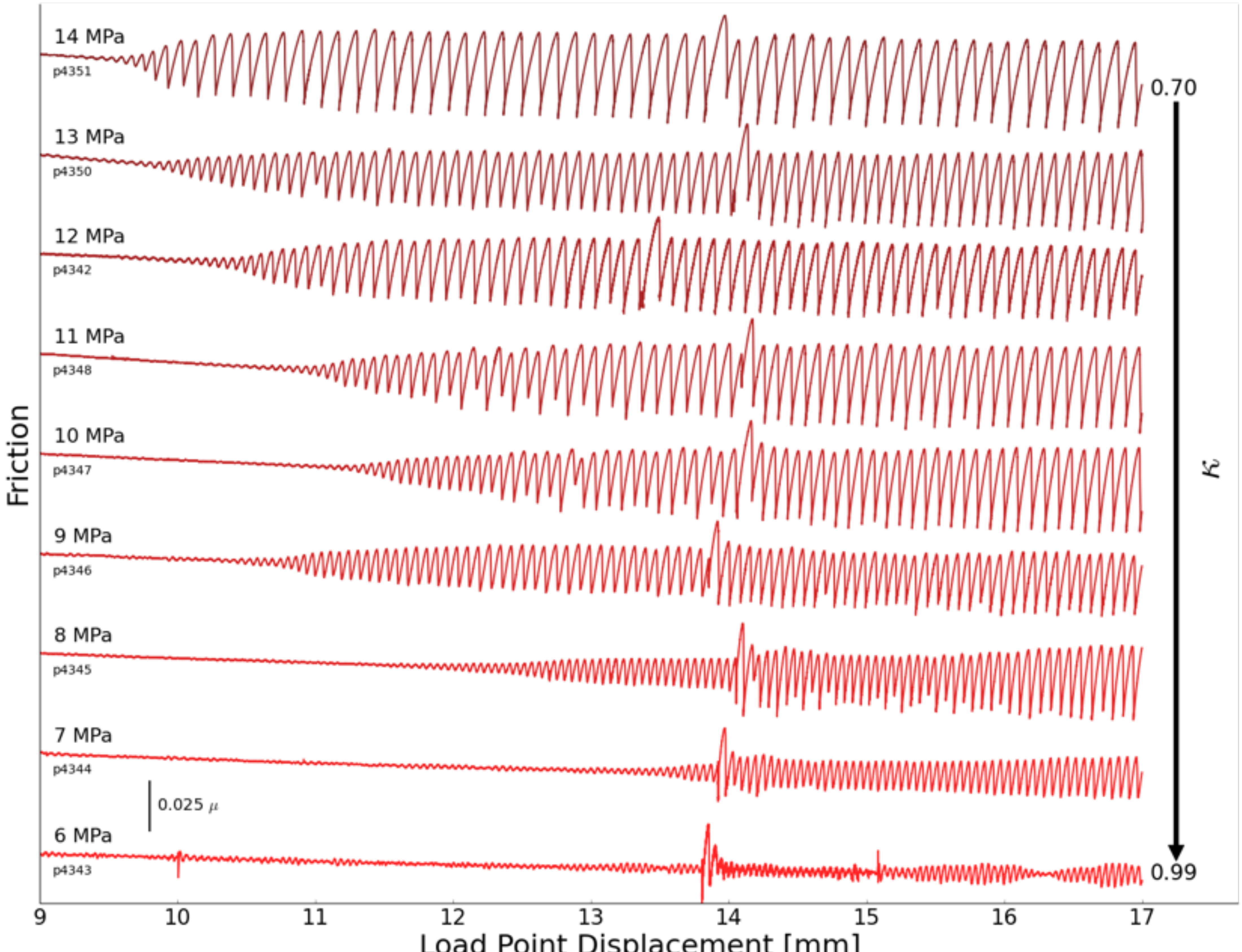


Gain comminution is occurring, but appears to be relatively constant despite the applied normal stress

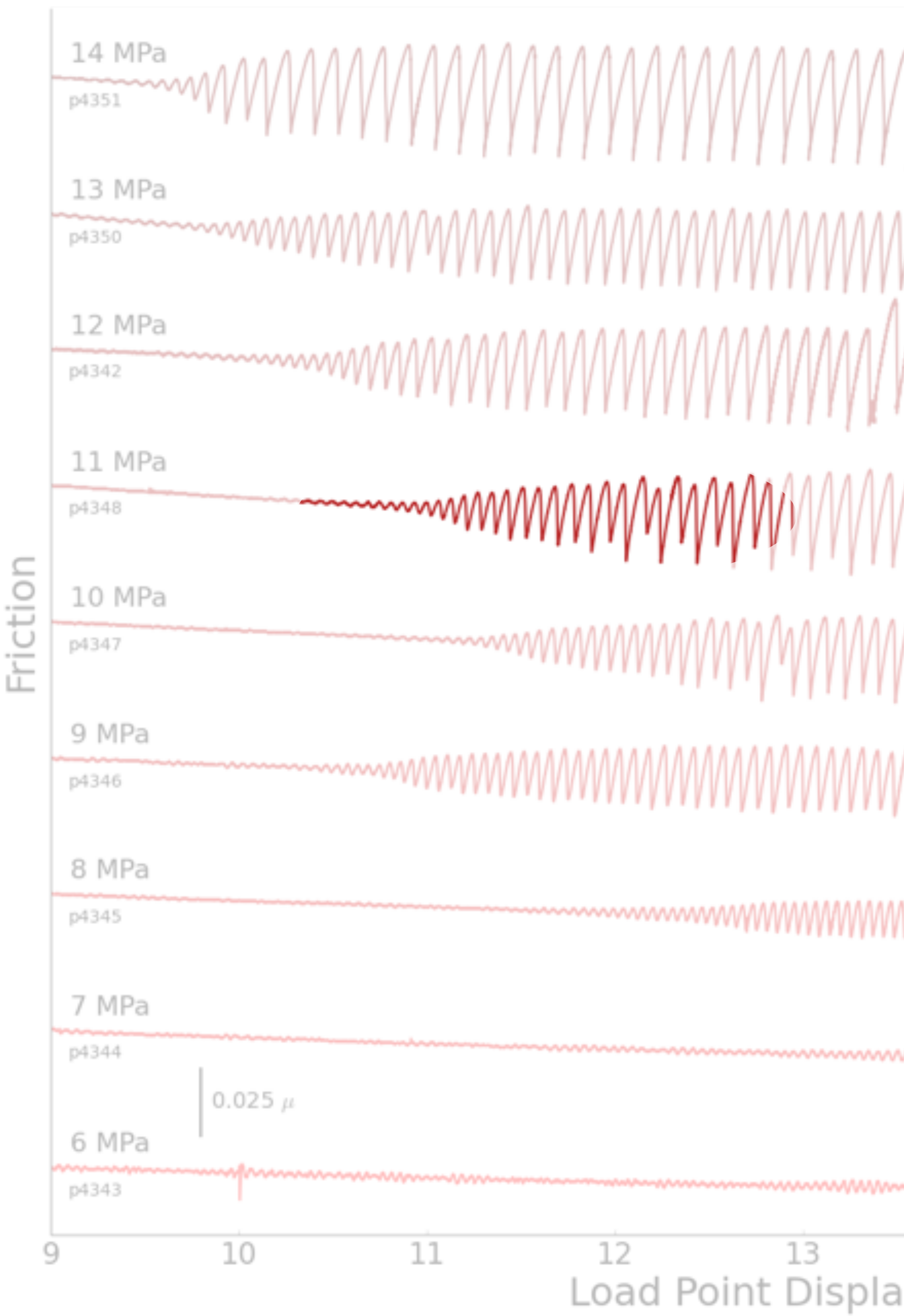


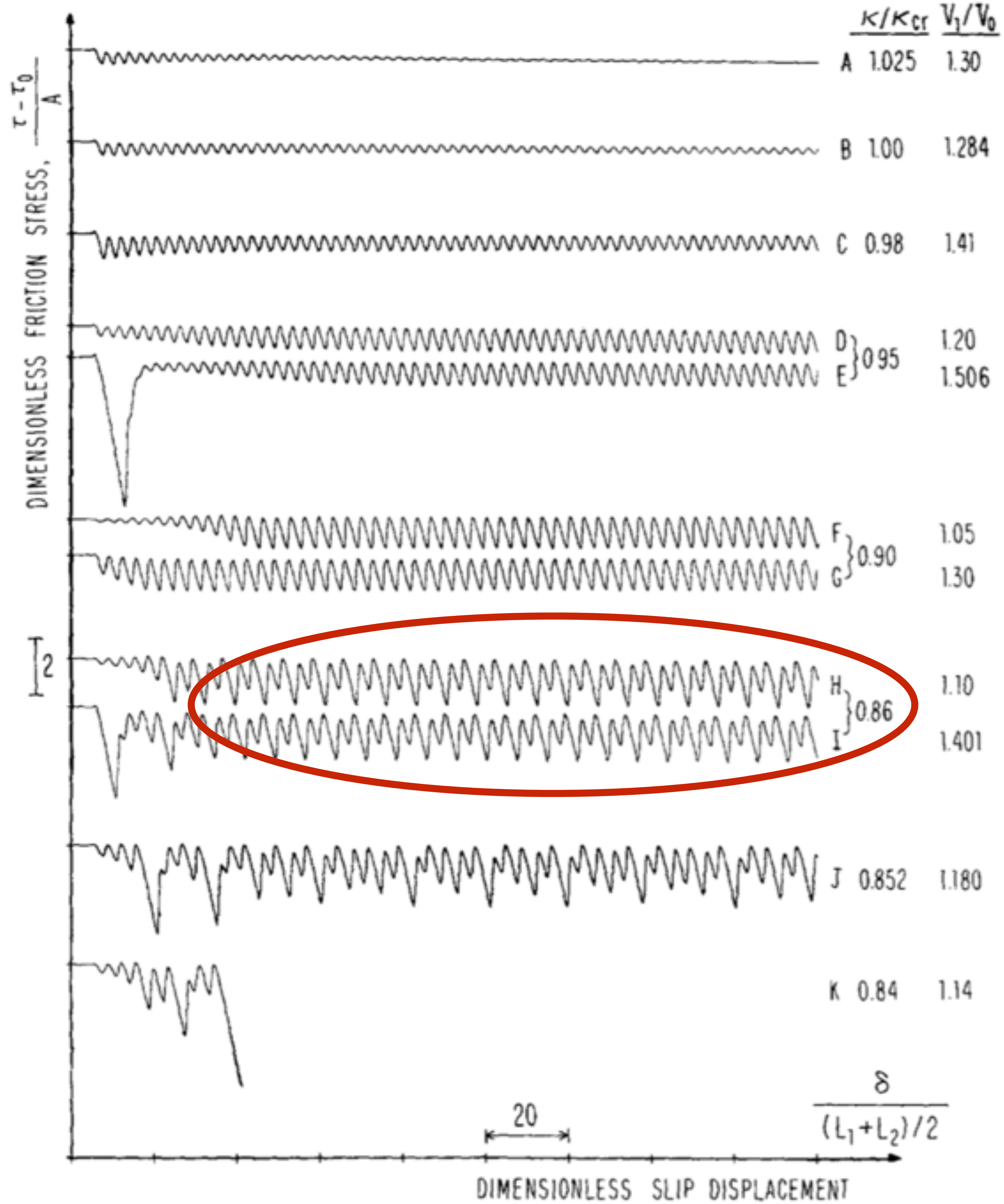


We see a transition between behaviors as a function of k/kc, not a sharp bifurcation

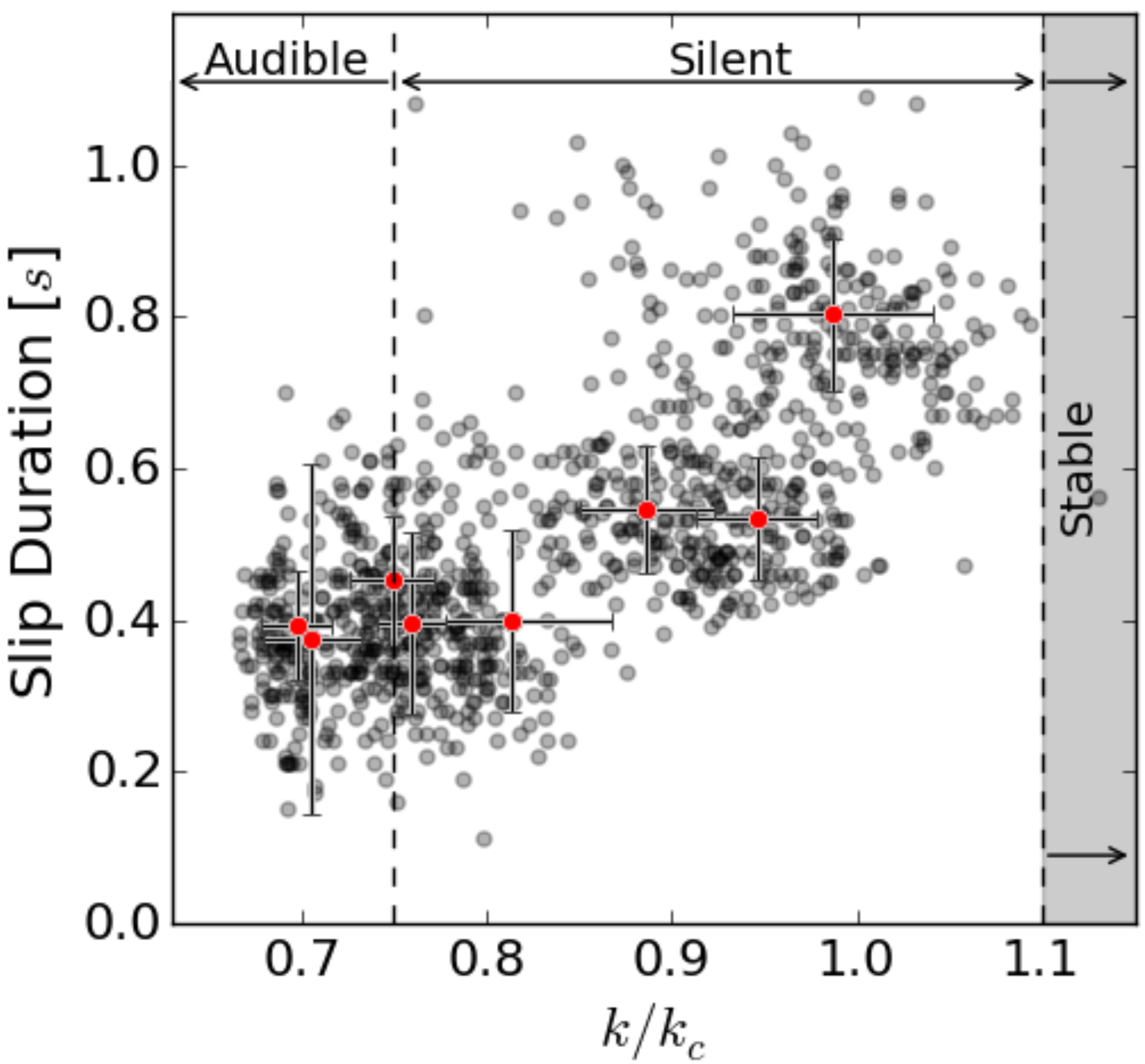


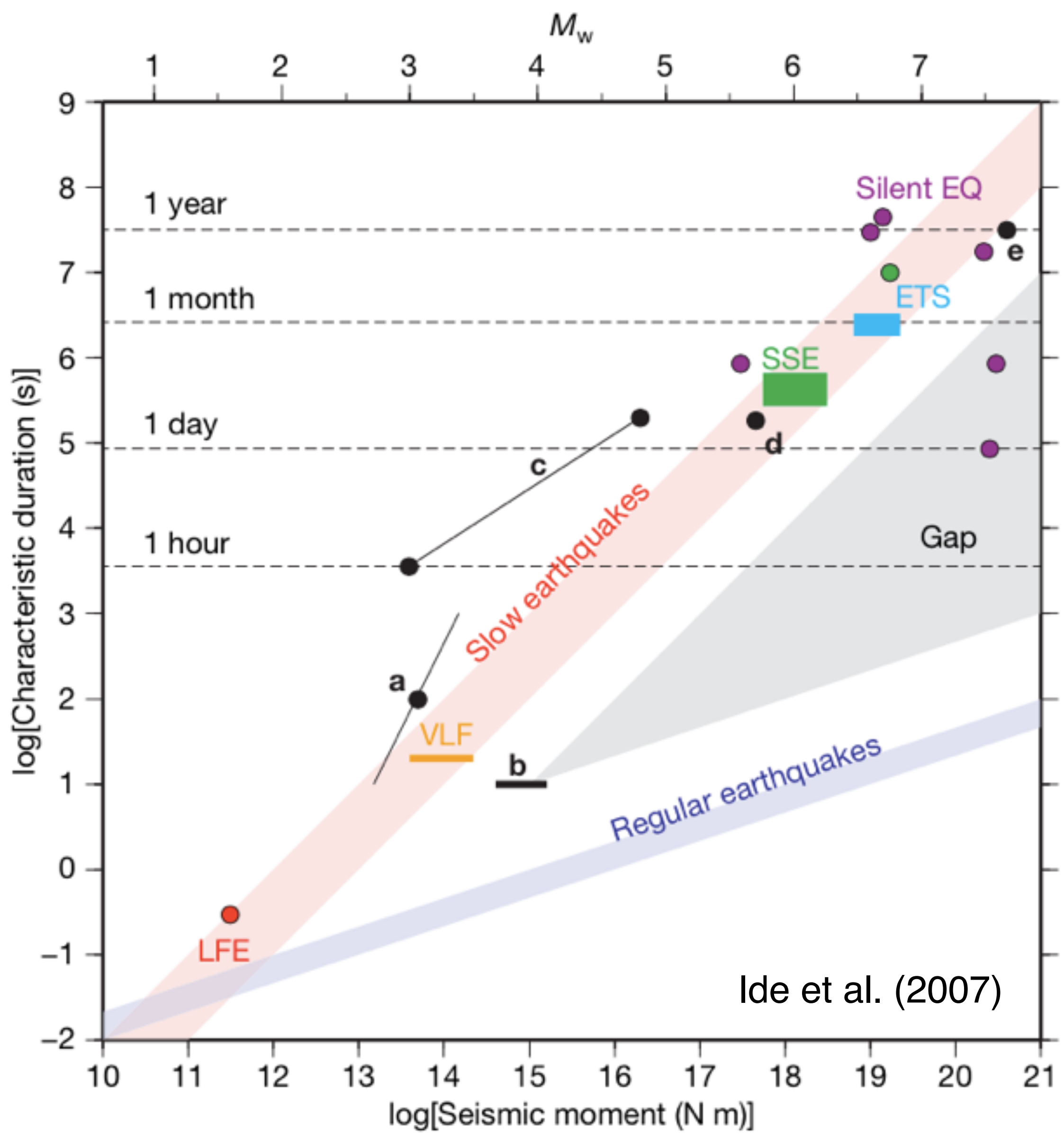
We also observe some of the complex behavior predicted by numerical models





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