# Shaking up Faults: Insights from the Lab on Earthquake Triggering

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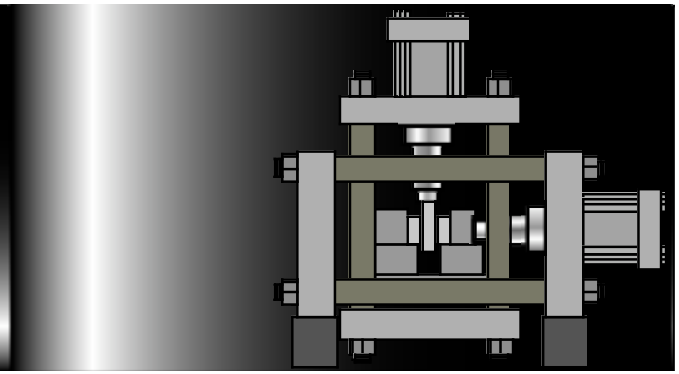
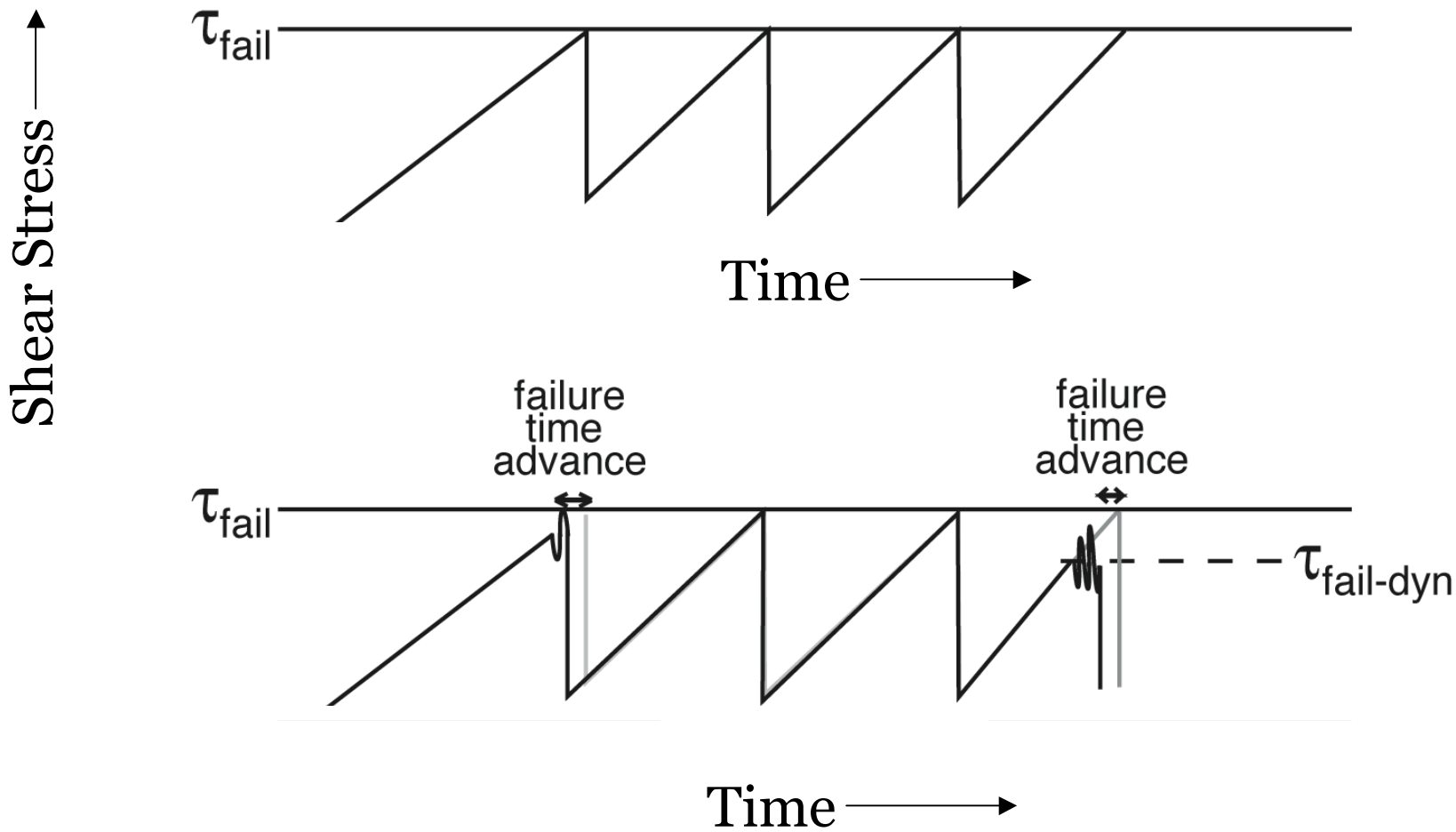
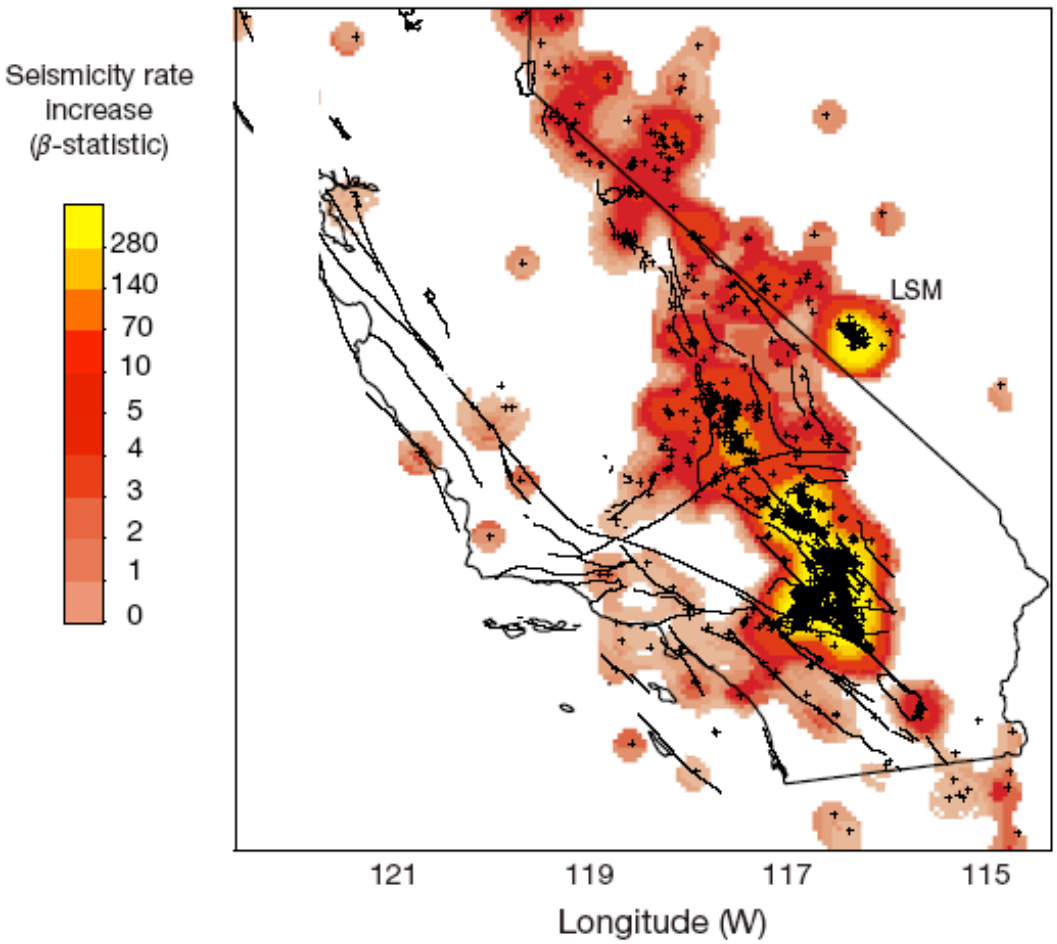


# What is Earthquake Triggering?

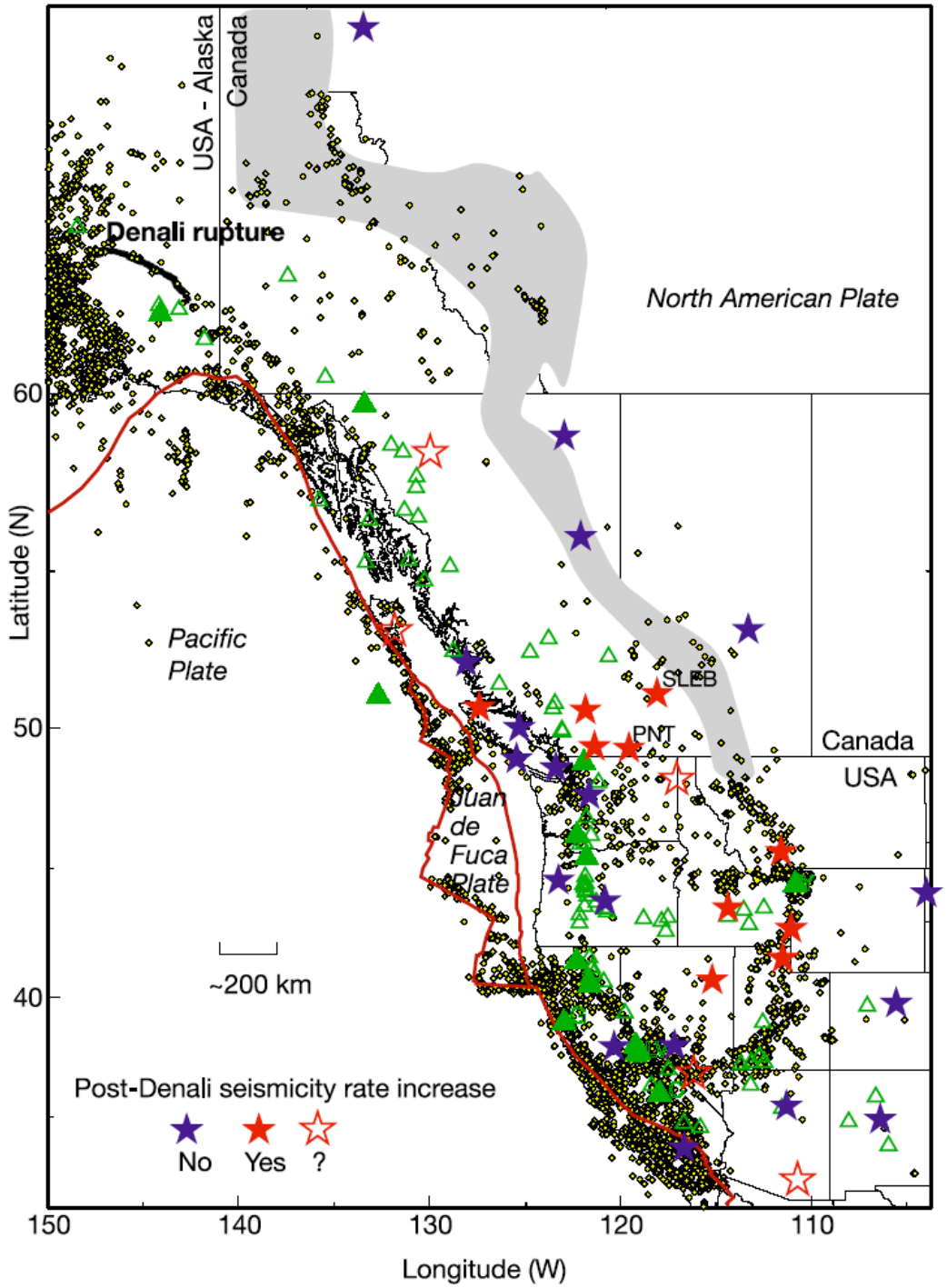





*Gomberg et al. 2001*

# Examples of Seismic Wave Triggering: Landers Earthquake 1992

- M 7.3
- First example of remotely triggered seismicity
- Strongly uni-directional



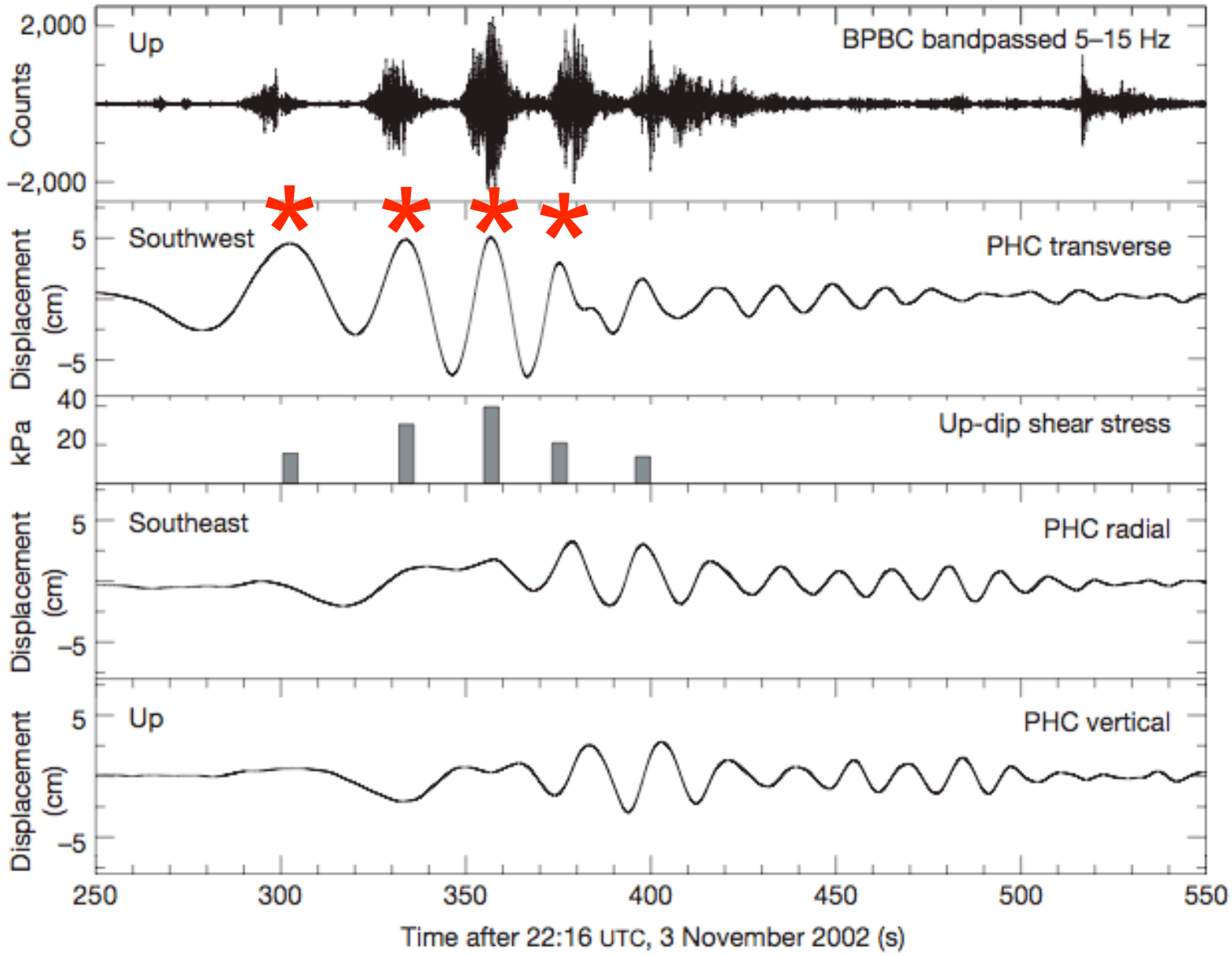

# Denali Earthquake 2002

- M 7.9
- Triggered earthquakes along propagation path over thousands of kilometers

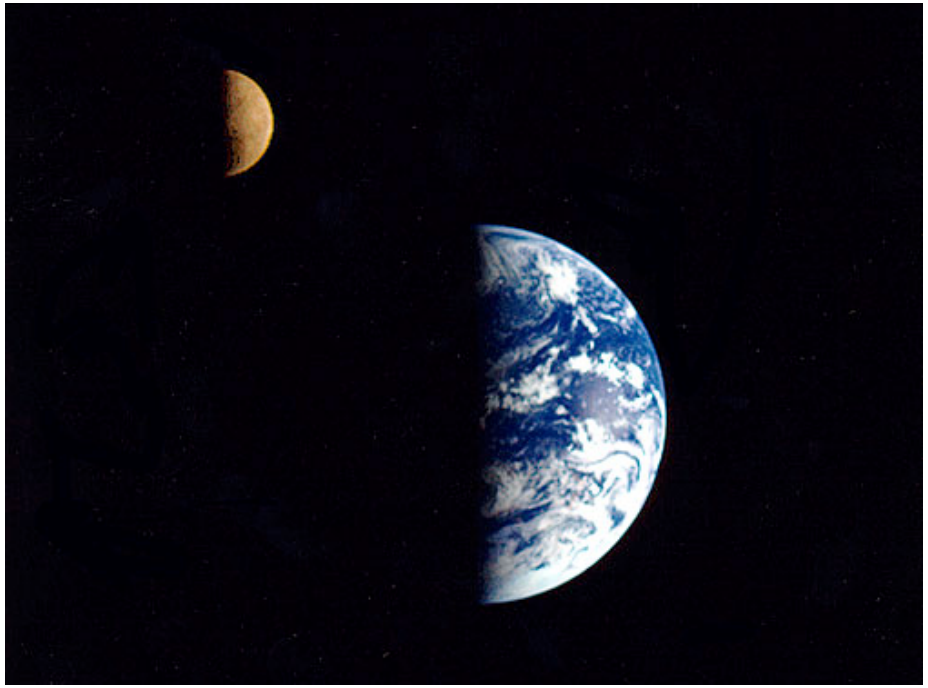
*Gomberg et al. 2004*

# Tremor Triggered by Love Wave Shear Stress, Denali

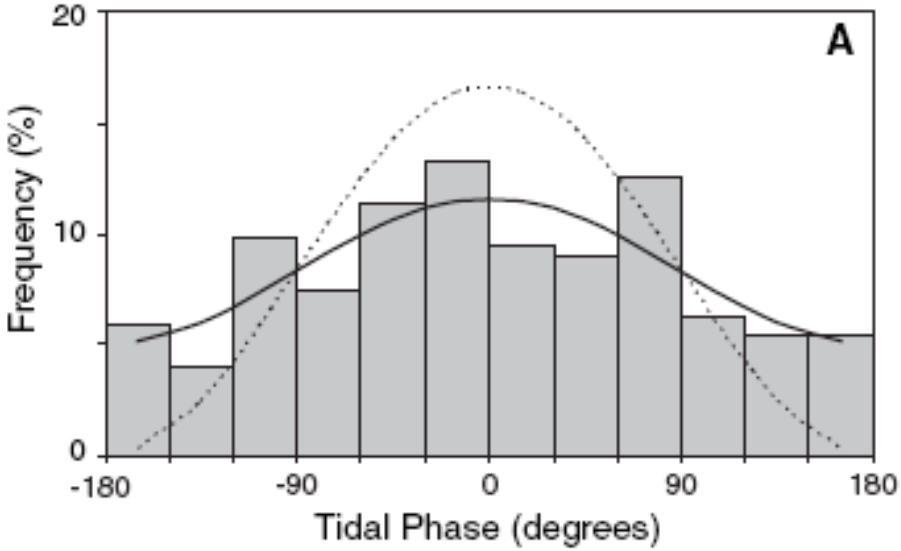
*Rubinstein et al. 2007*



# Tidal Oscillations



http://www.physicalgeography.net/fundamentals/images/earth_moon.jpg

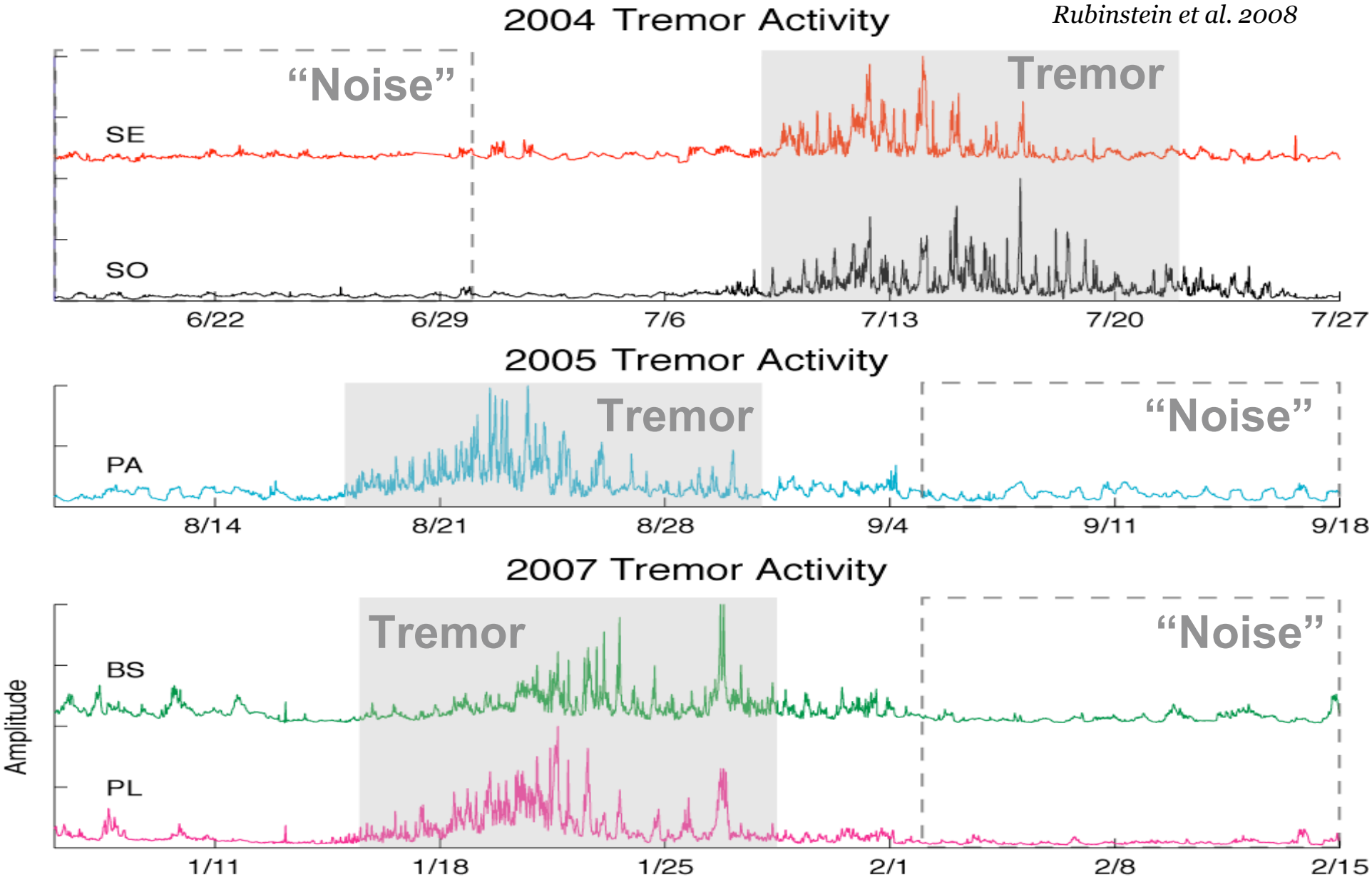



*Cochran et al., 2004*

# Last 3 ETS Episodes - Tremor Modulated by Tides

*Local Seismic Array*

*Rubinstein et al. 2008*



# Tidal Oscillations and the West Antarctic Ice Sheet

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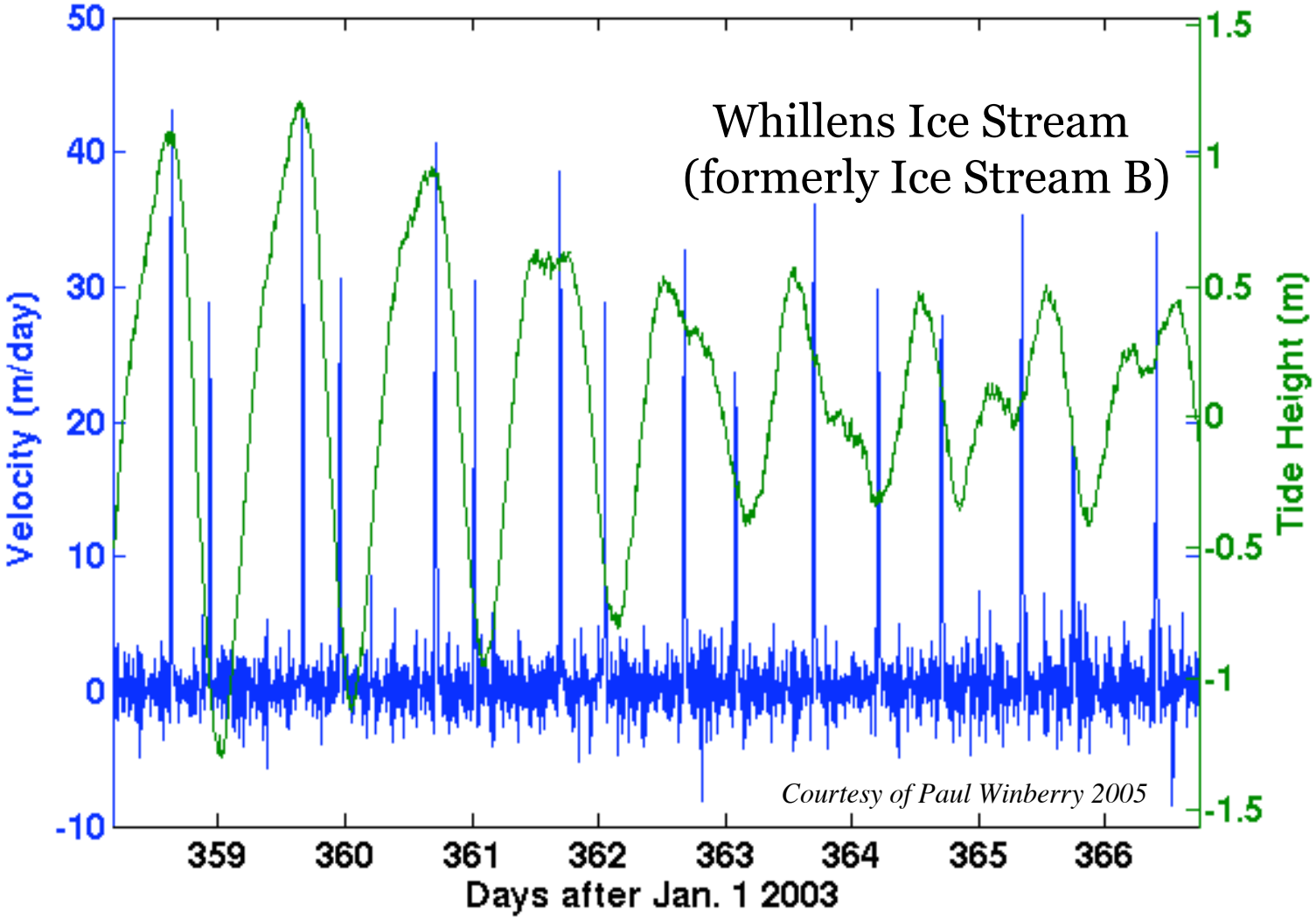
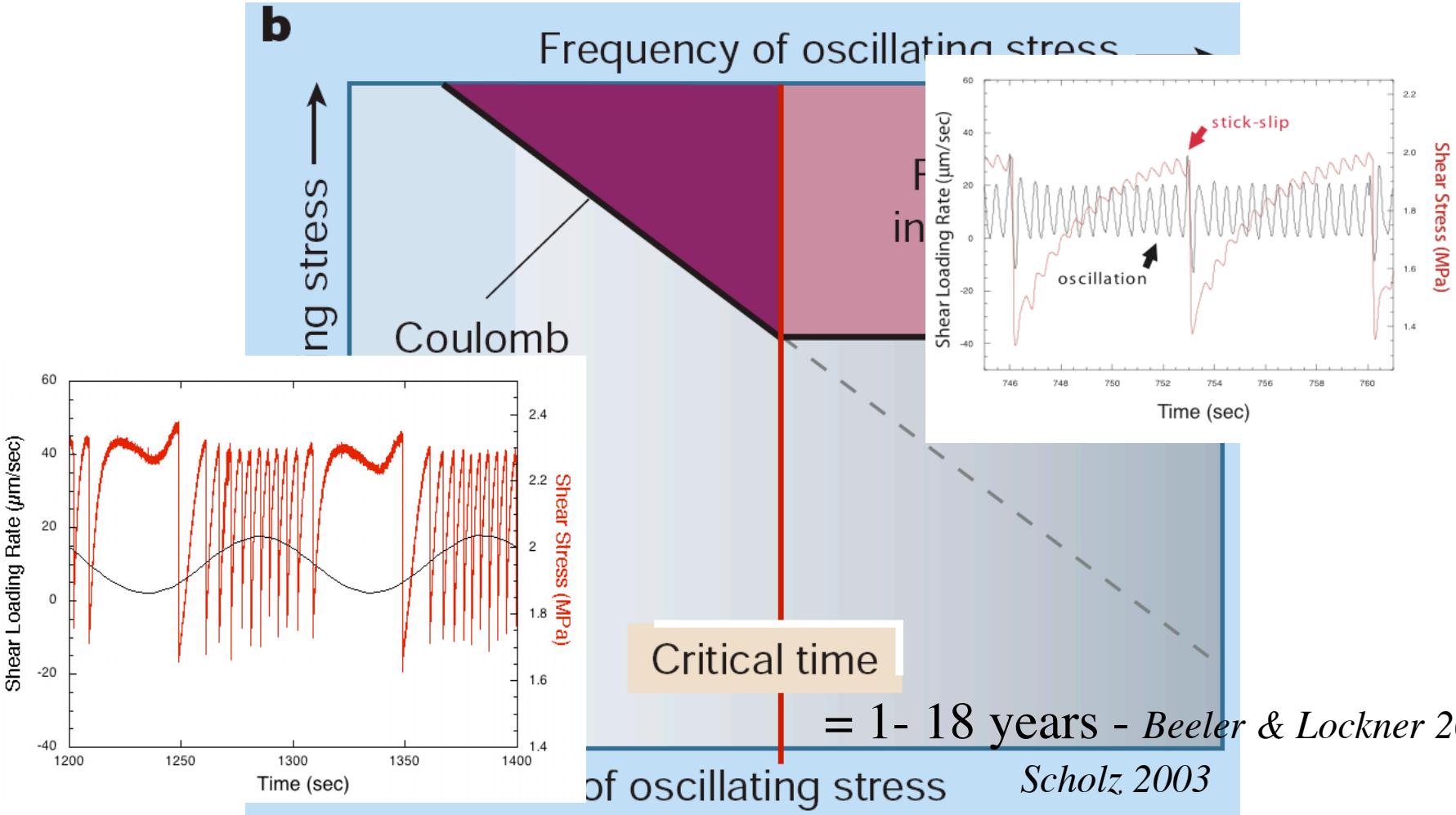


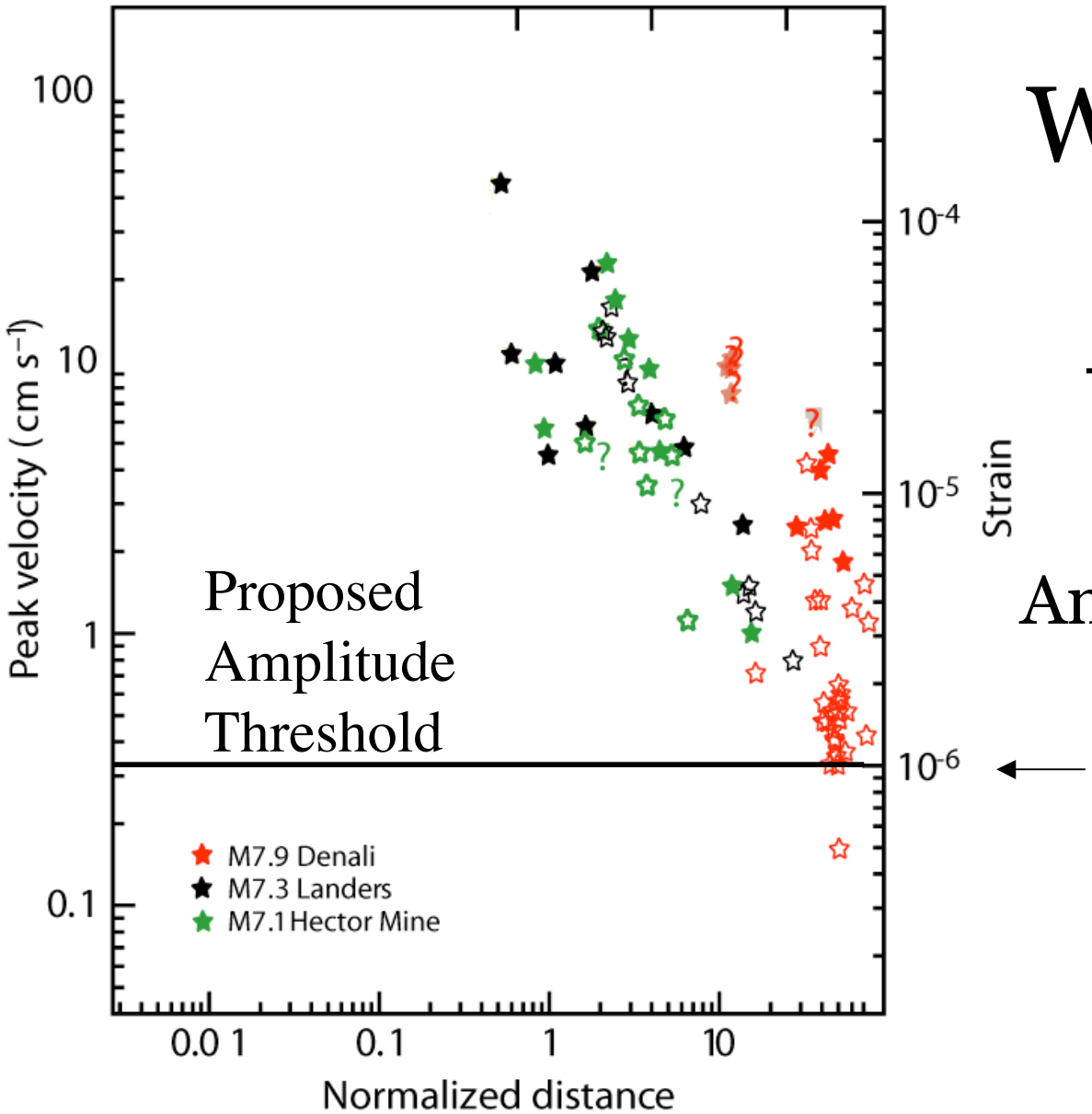
# What Controls Triggering Thresholds?




= 1- 18 years - *Beeler & Lockner 2003*

*Scholz 2003*

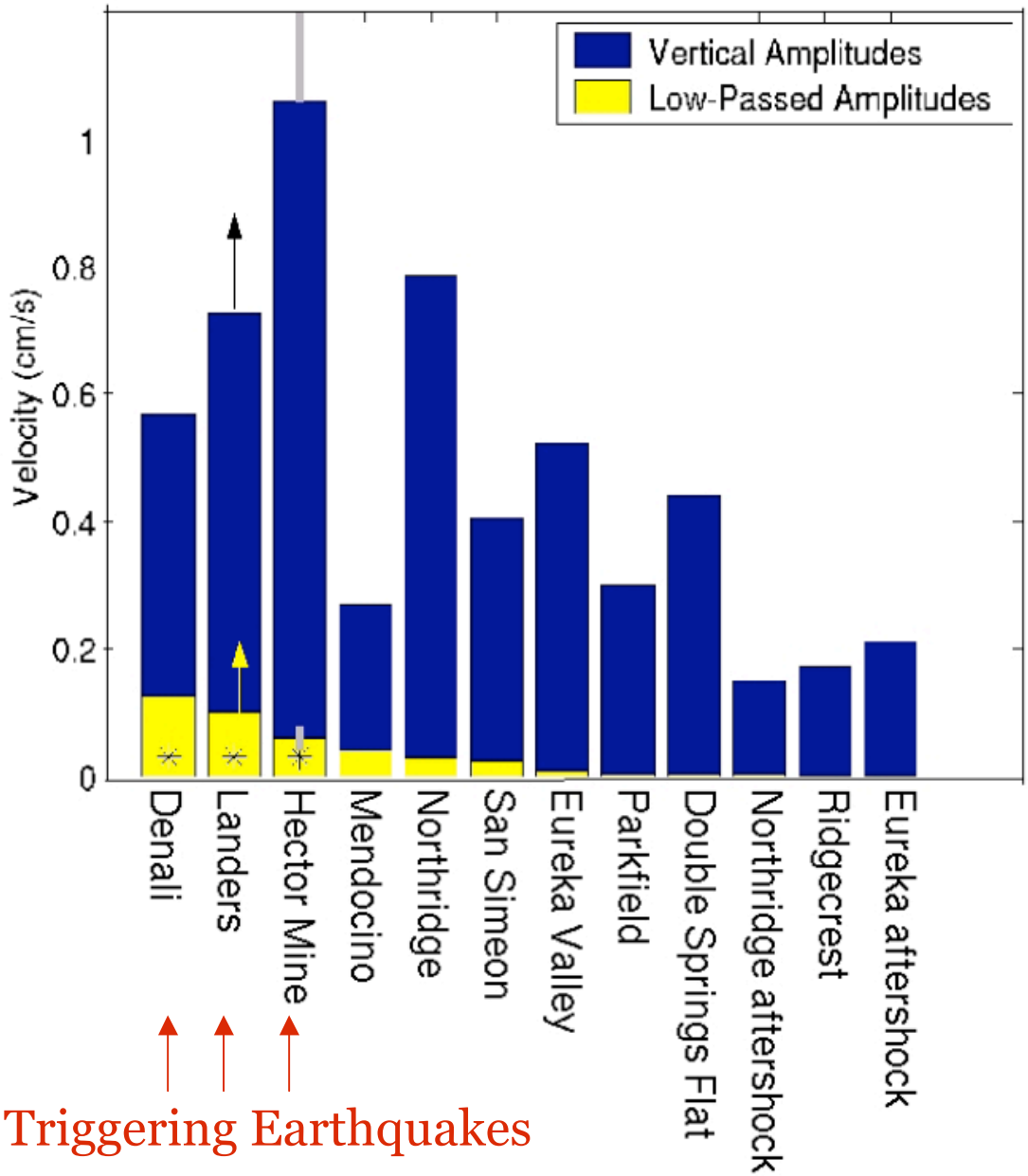
Friction change (e.g. weakening) requires finite slip & time




# What controls triggering thresholds?

Amplitude trigger

*Gomberg & Johnson 2005*




# What controls triggering thresholds?

Frequency trigger

*Brodsky & Prejean 2005*

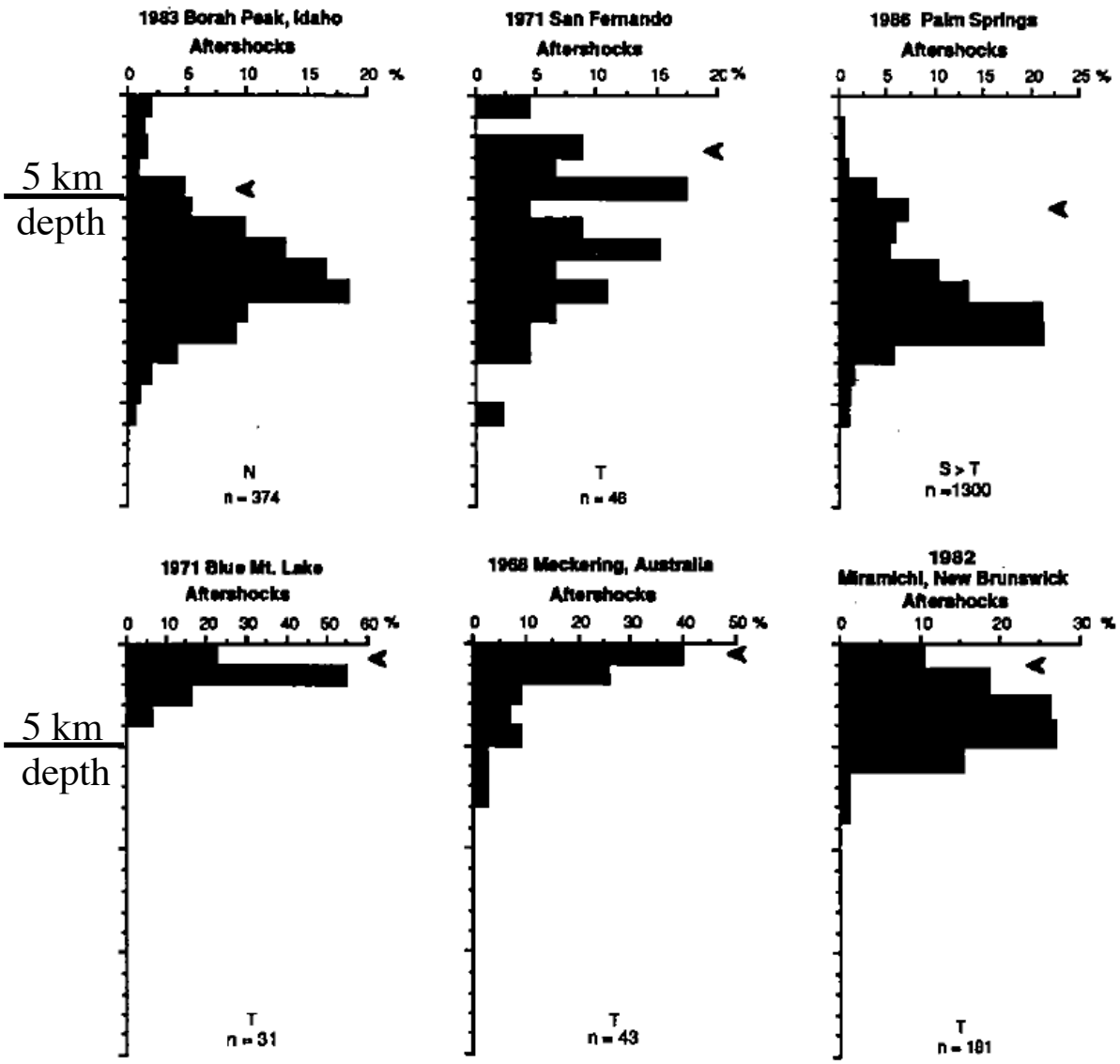
# Earthquake Triggering

- Seismological evidence for both amplitude and frequency triggering thresholds
- Thresholds vary between geographic locations -- does tectonic setting matter?
- Do frictional properties of the fault affect triggering potential?

# Fault Zone Architecture

*Courtesy of Ray Fletcher*

*Courtesy of Nick Hayman*

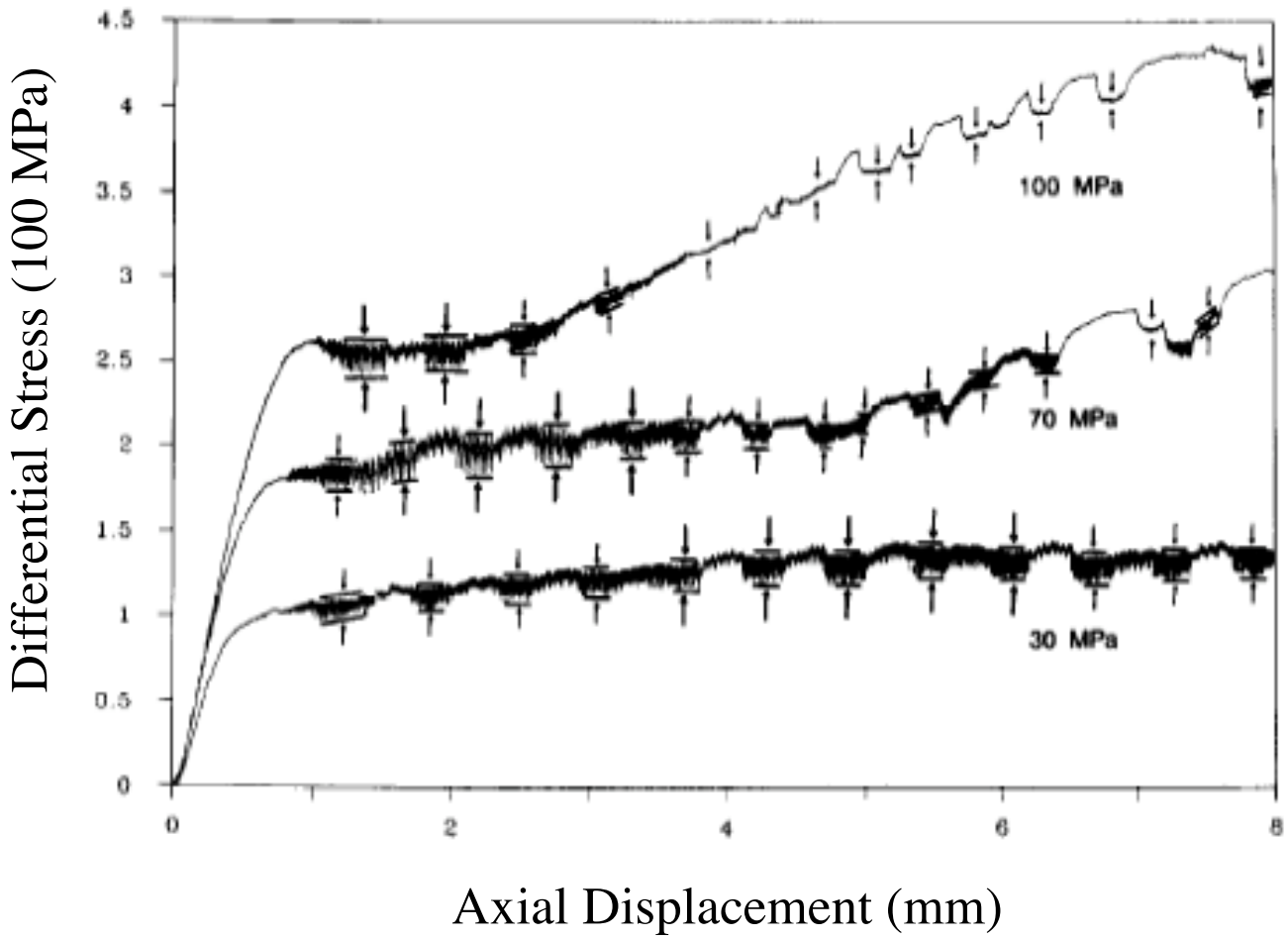



Interplate faults

Intraplate faults

*Marone and Scholz 1988*

# Fault Stability and Architecture: Laboratory Studies




*Faults stabilize with increasing displacement, Wong and Zhao 1990*

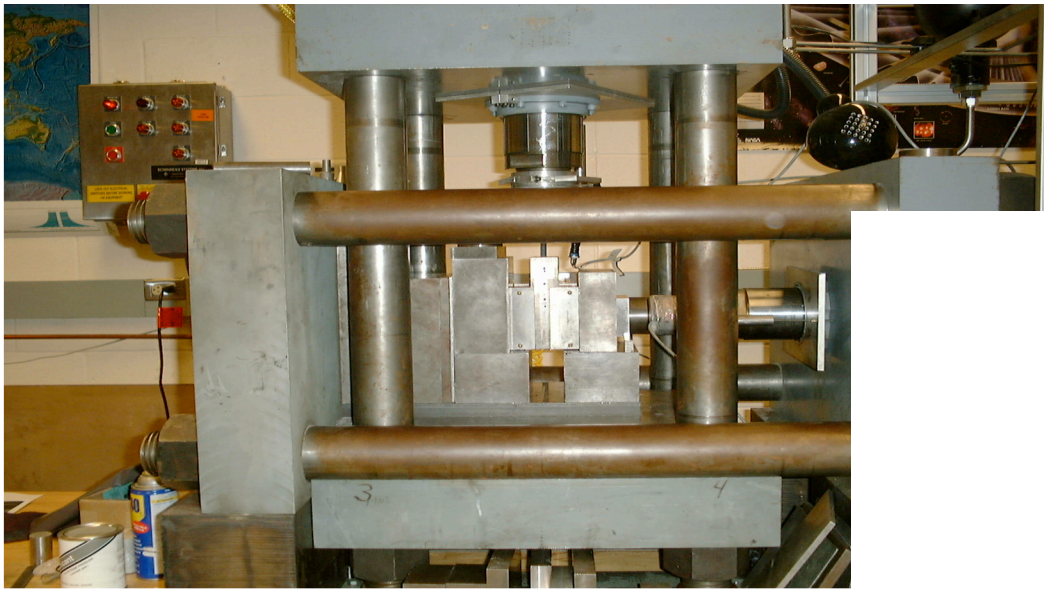
# Research Question

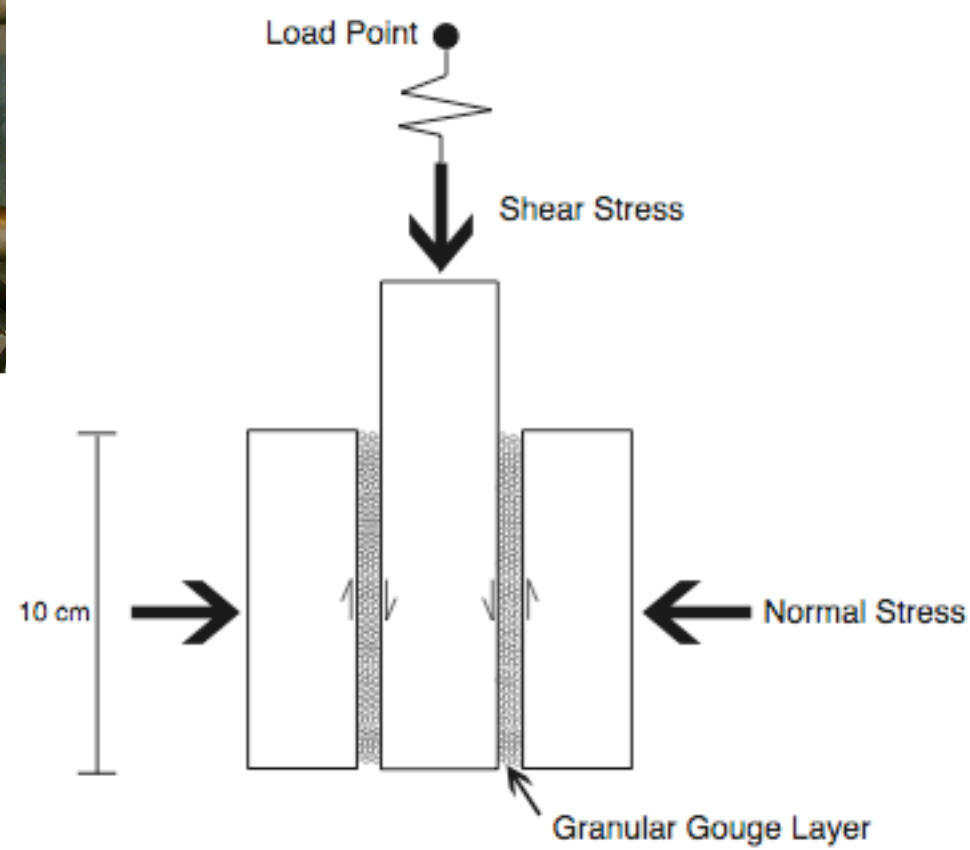
- Oscillating stresses trigger earthquakes
- Gouge stabilizes fault slip
- Does gouge have stabilizing effects during oscillating stress (e.g. seismic waves)?

# Testable Parameters in the Laboratory

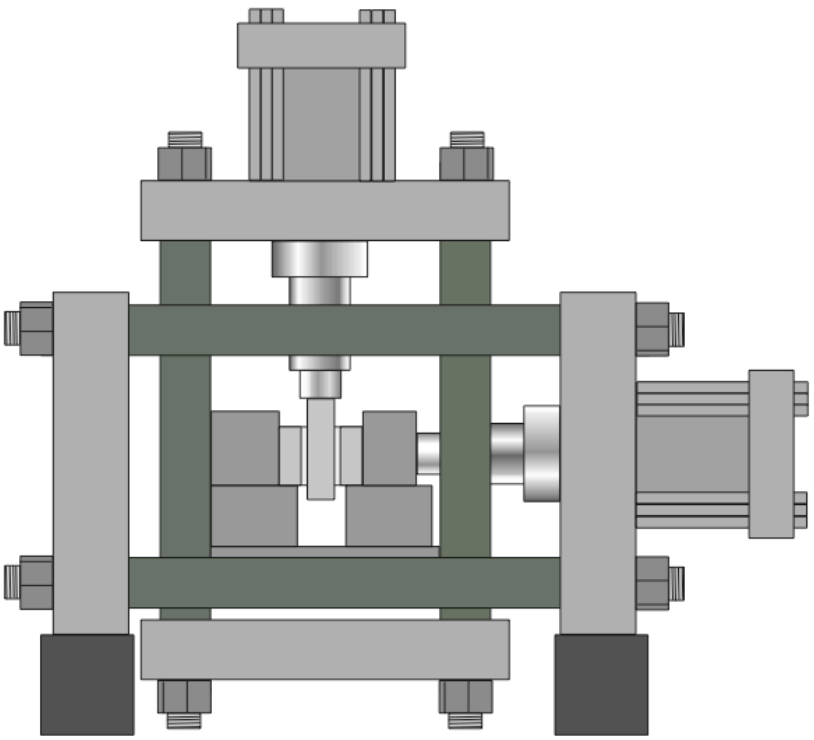
- Properties of the seismic wave:
  - Amplitude
  - Frequency
  - Duration
- Properties of the fault:
  - Fault zone architecture (presence or absence of gouge zone, thickness of gouge zone)
  - Fault state (timing in the interseismic cycle)

# Laboratory Setup



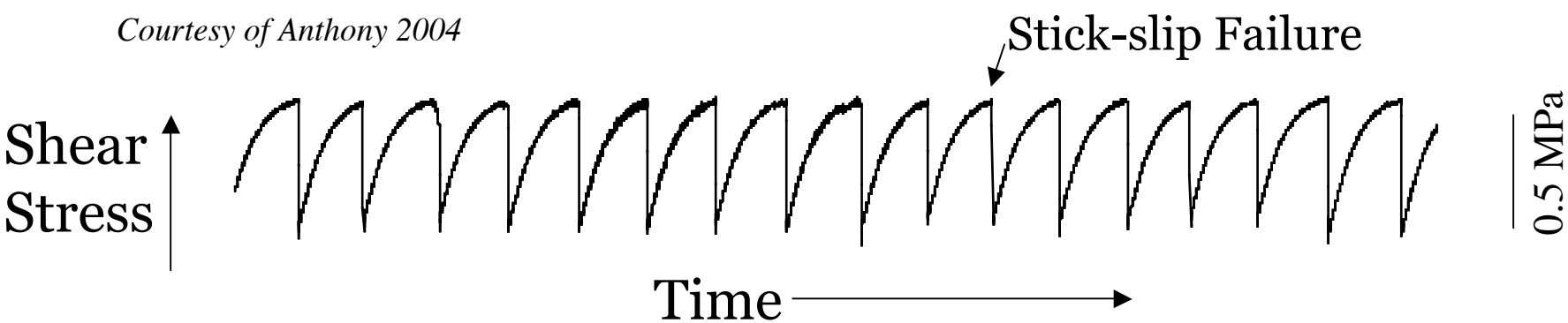


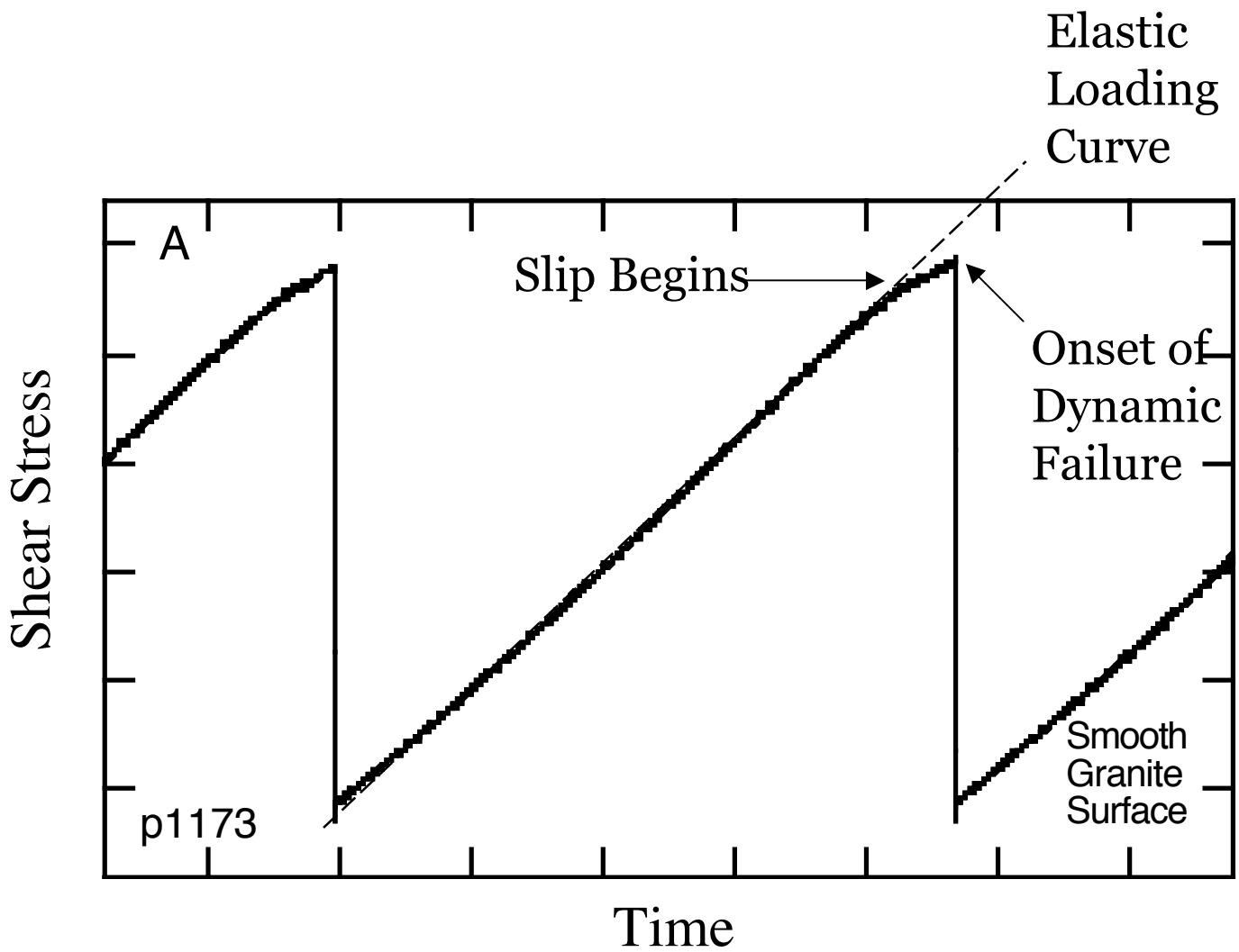
# Laboratory Setup



*Courtesy of Anthony 2004*

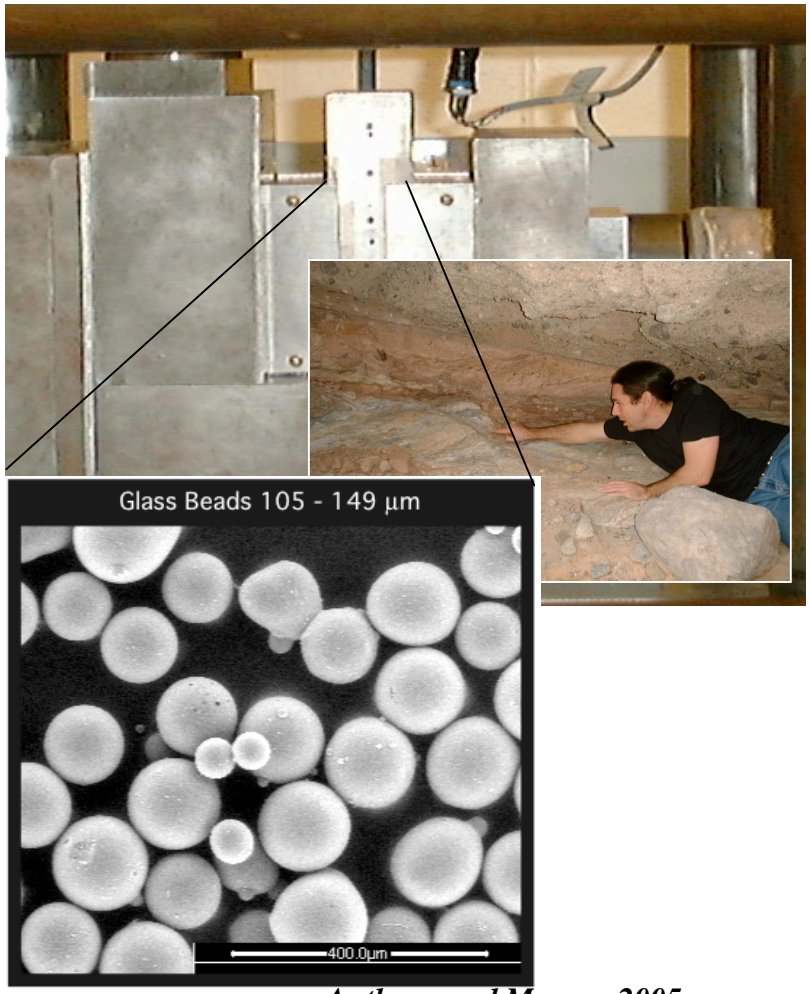
- 5 MPa normal stress
- Tectonics stress: background shear loading rate of 5 μm/s






*Modified from Scholz 2003*

# Fault Zone Materials




*Anthony and Marone 2005*

Granite surface

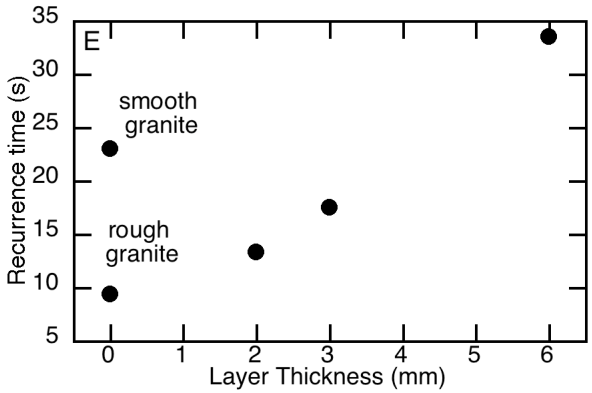
Smooth

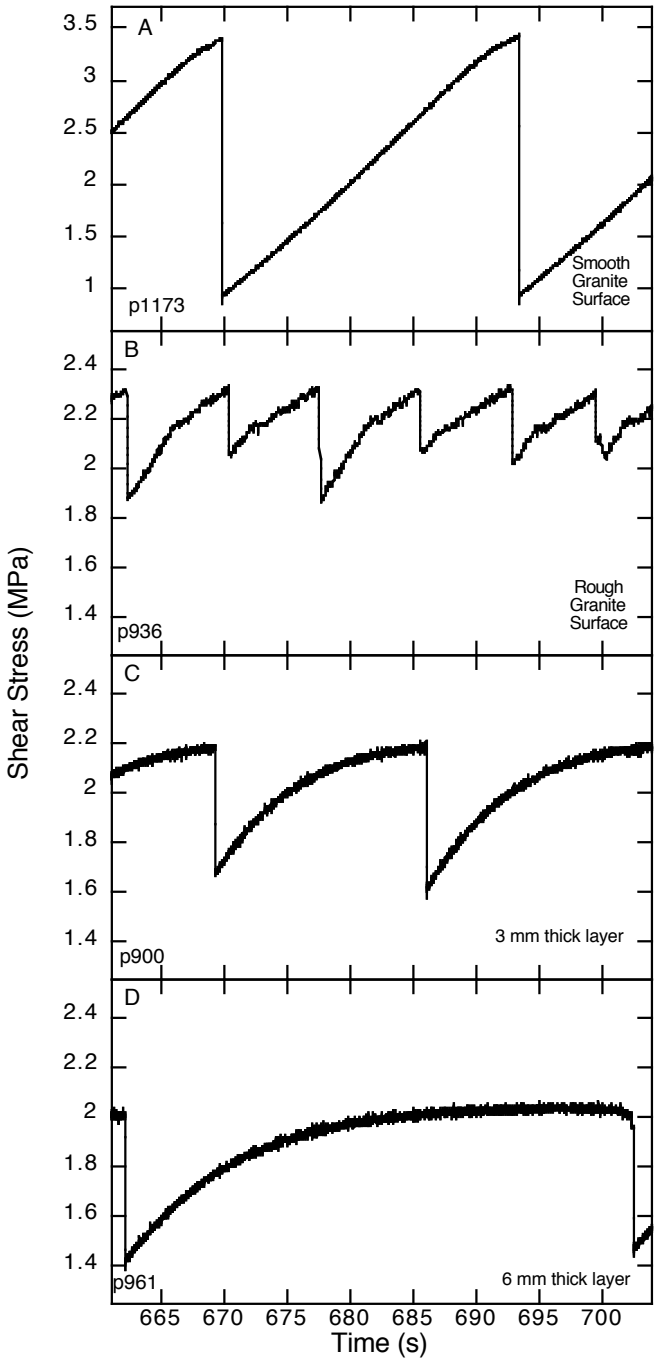
Rough

Glass bead layer

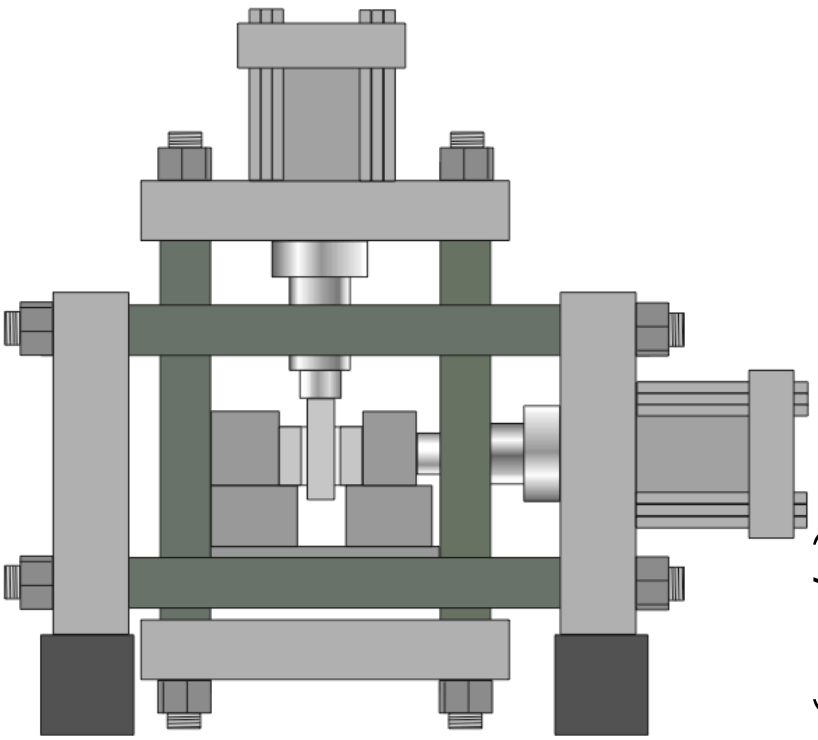
3mm

6mm



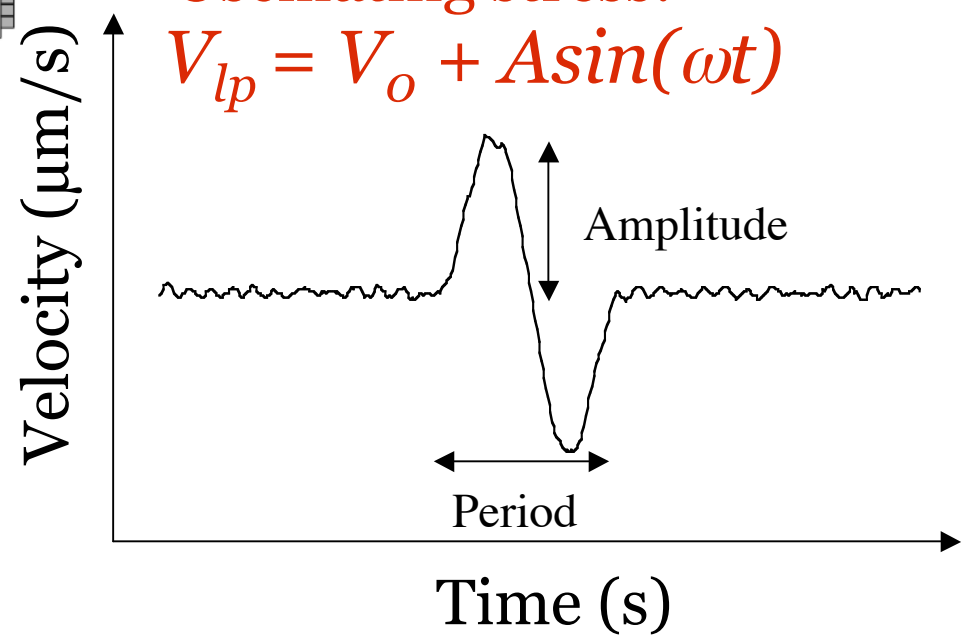
# Laboratory Setup



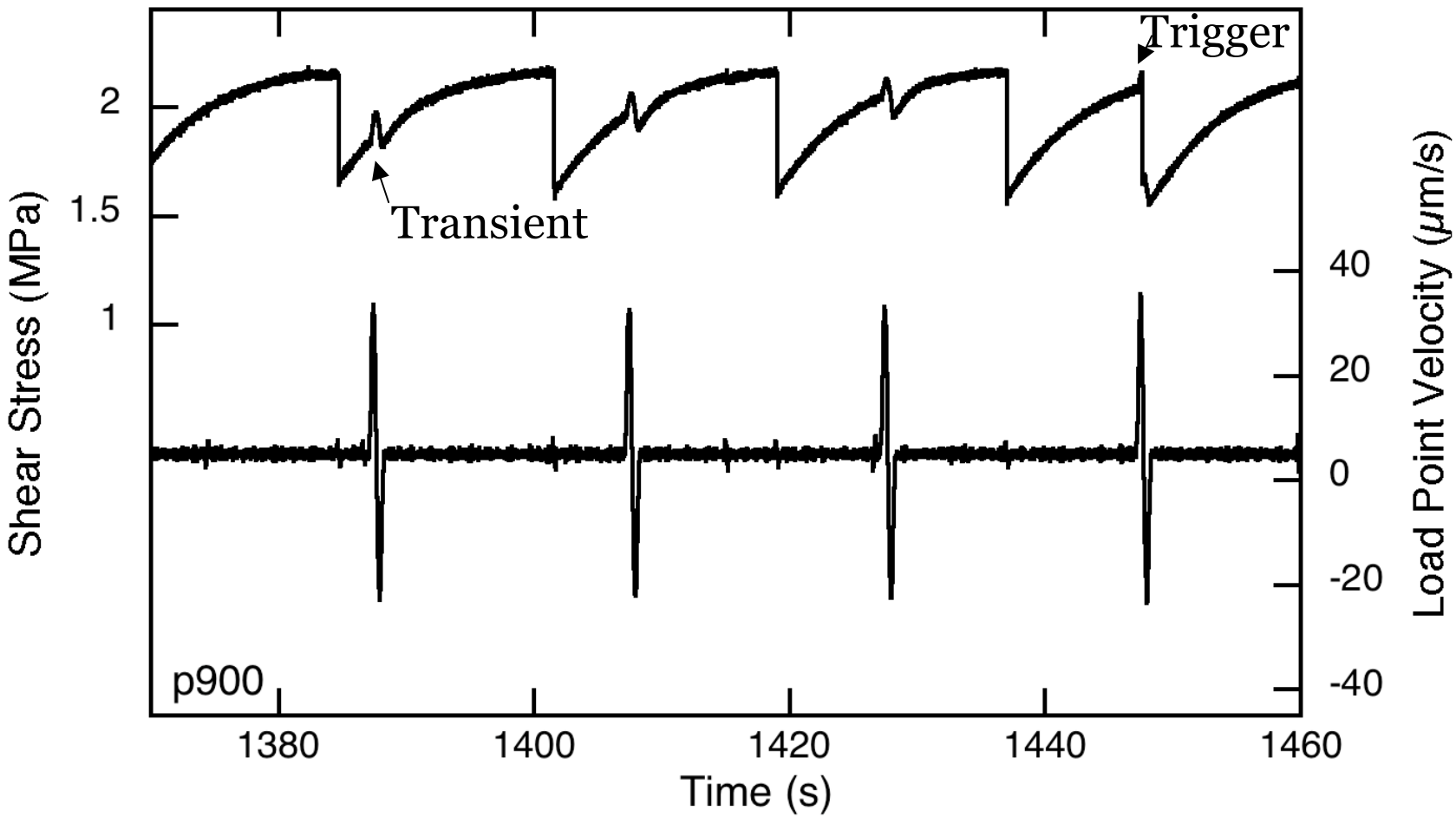
*Courtesy of Anthony 2004*

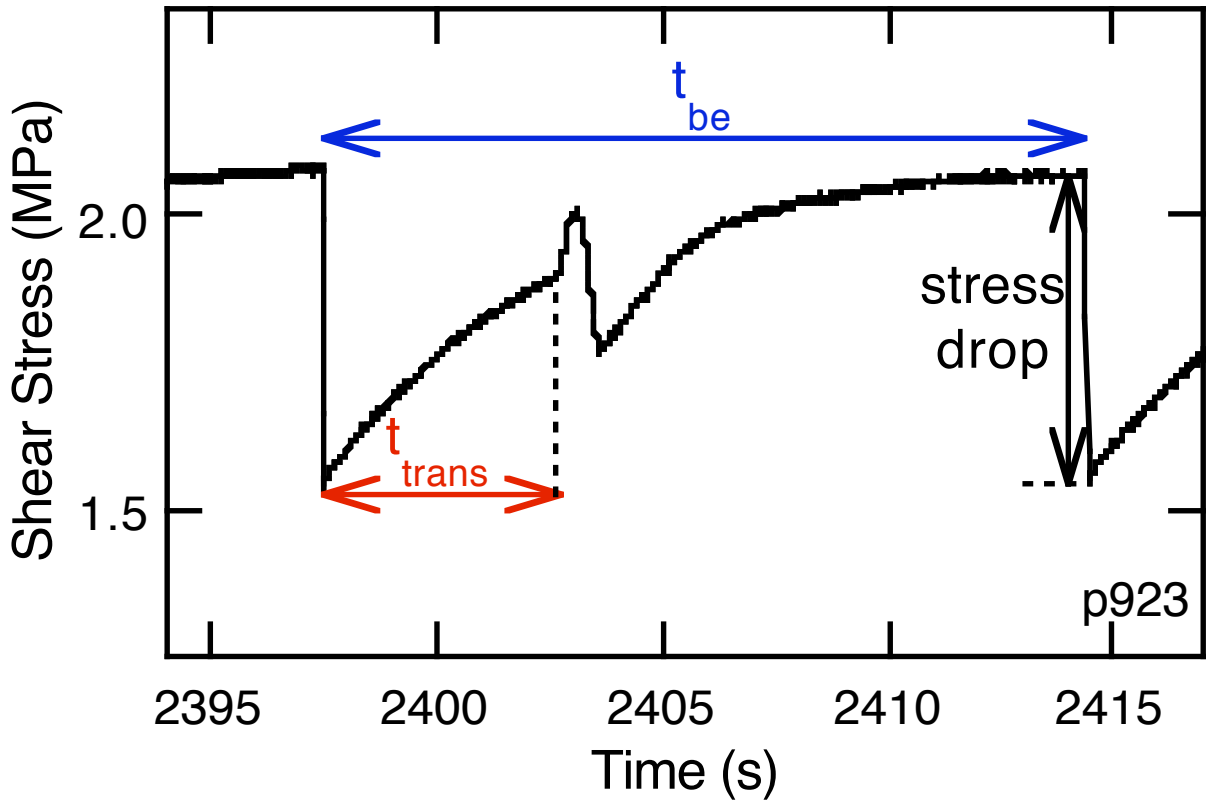
- 5 MPa normal stress
- Tectonics stress: background shear loading rate of 5 μm/s
- Oscillating stress:

$$V_{lp} = V_o + A\sin(\omega t)$$



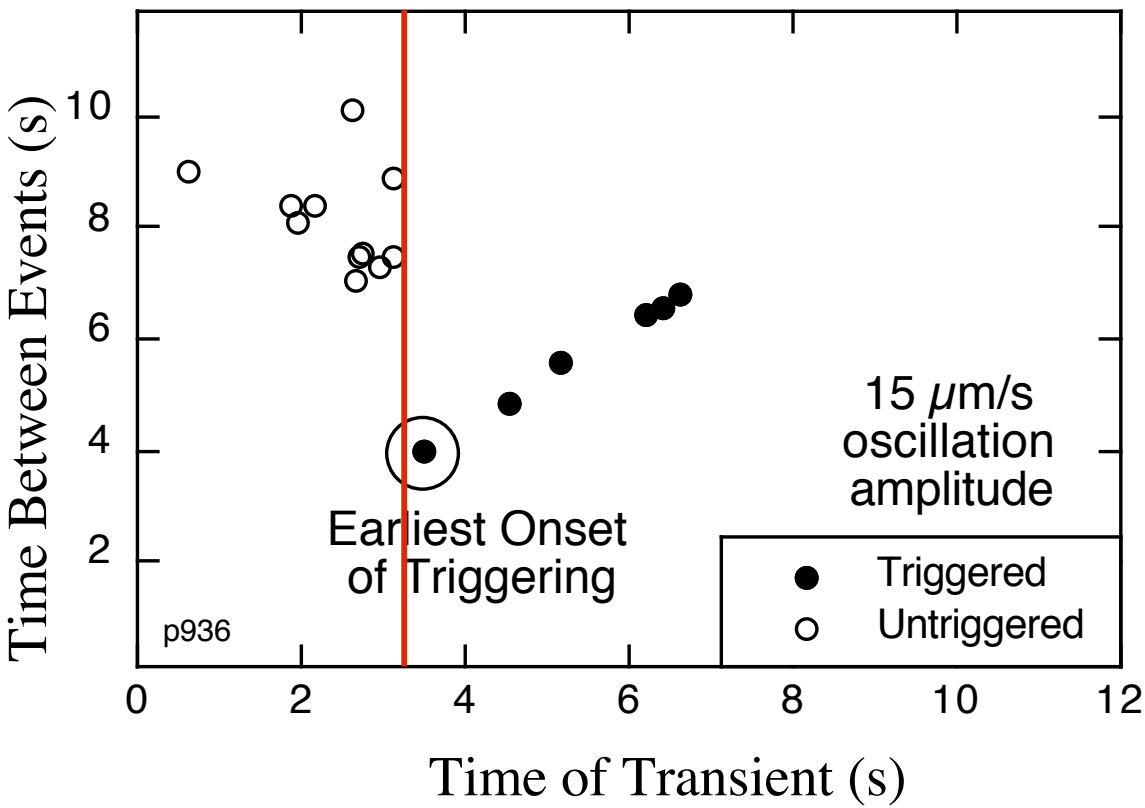
# Stick-Slip Triggering





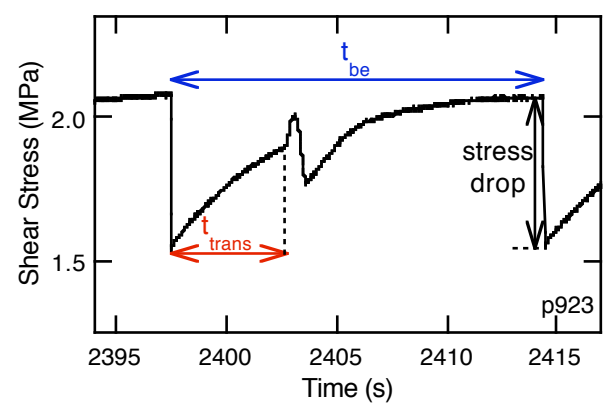

$t_{be}$ = Time Between Events

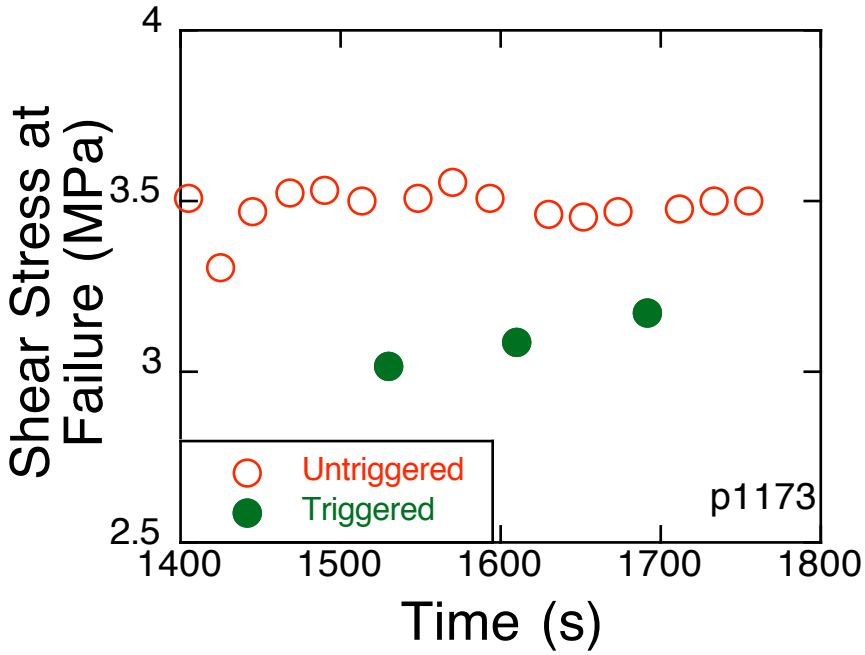
$t_{trans}$ = Time of Transient: Timing of Oscillation Relative to Last Failure



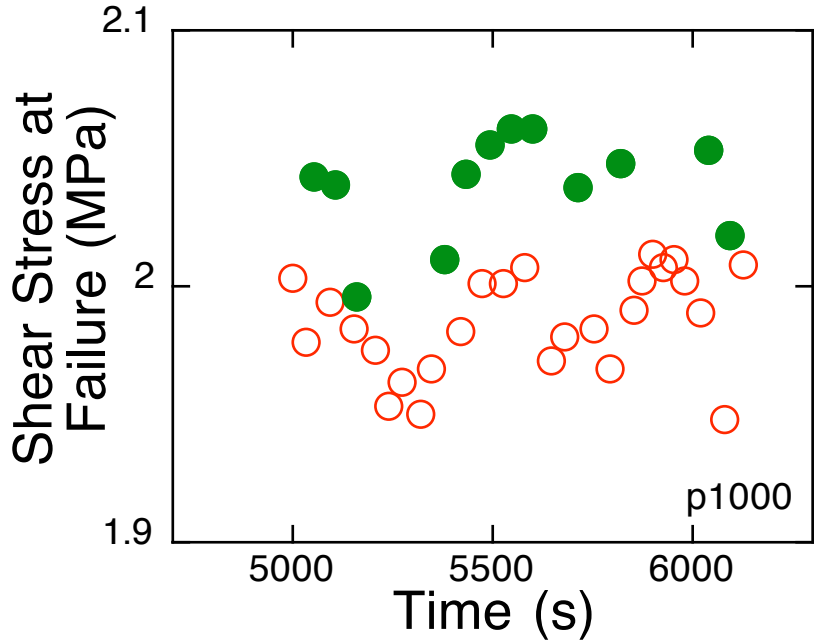

# Triggering Definition:

1. The failure occurs during the transient
2. The inter-event time of the earliest triggered event must be two standard deviations from the average recurrence



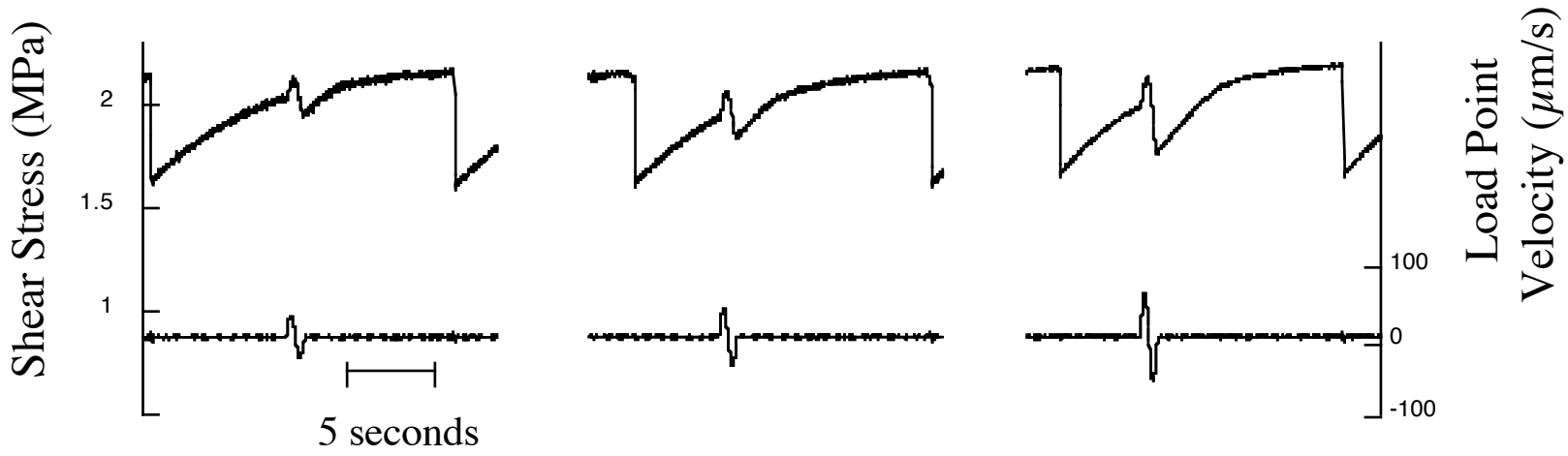



Granite

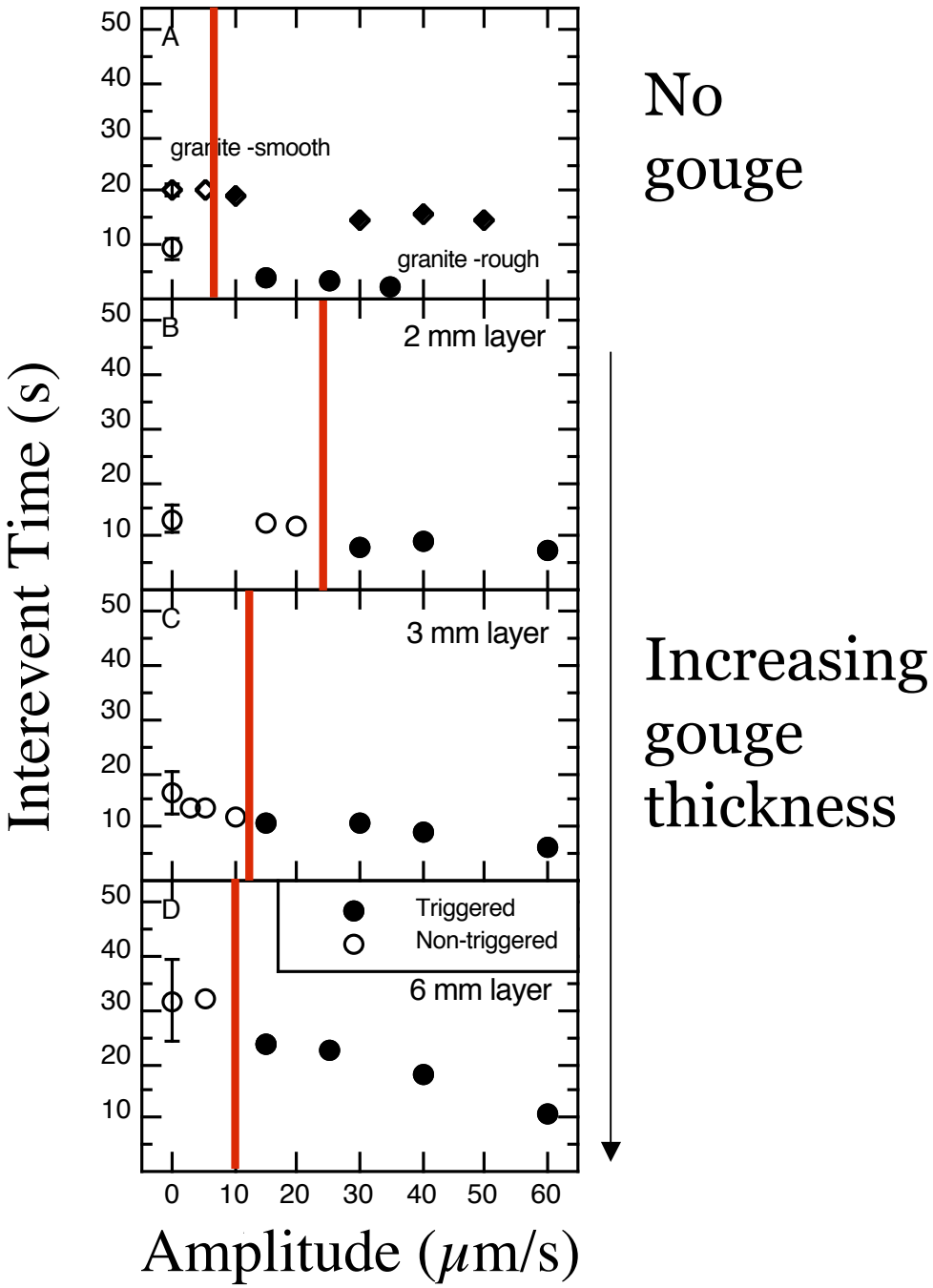



Glass Beads

# Amplitude Dependence

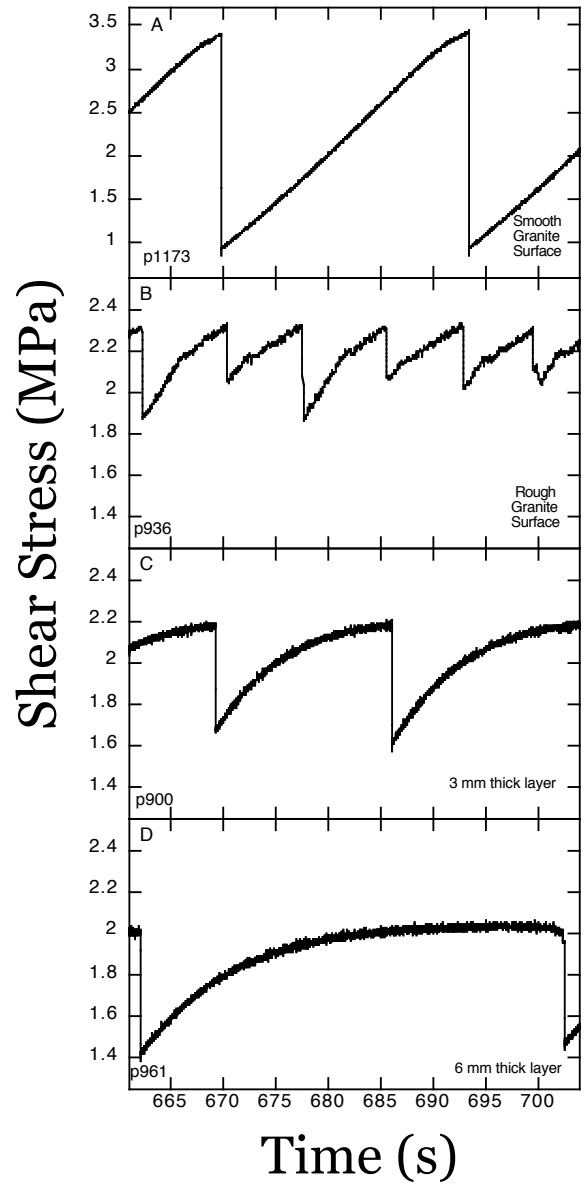


# Amplitude Dependence

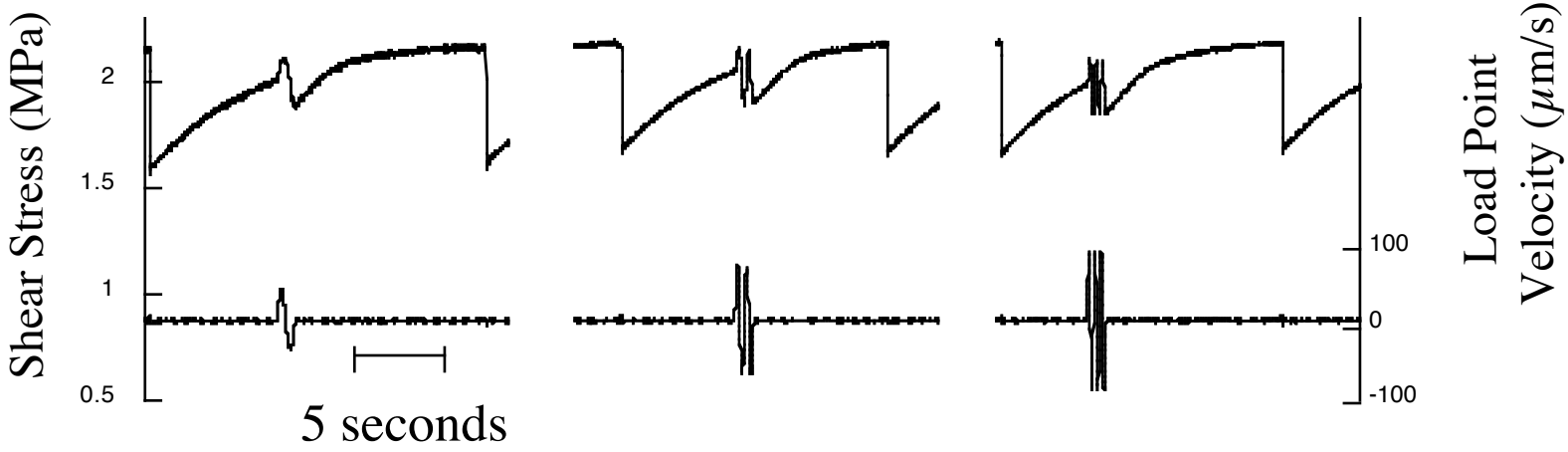



No gouge

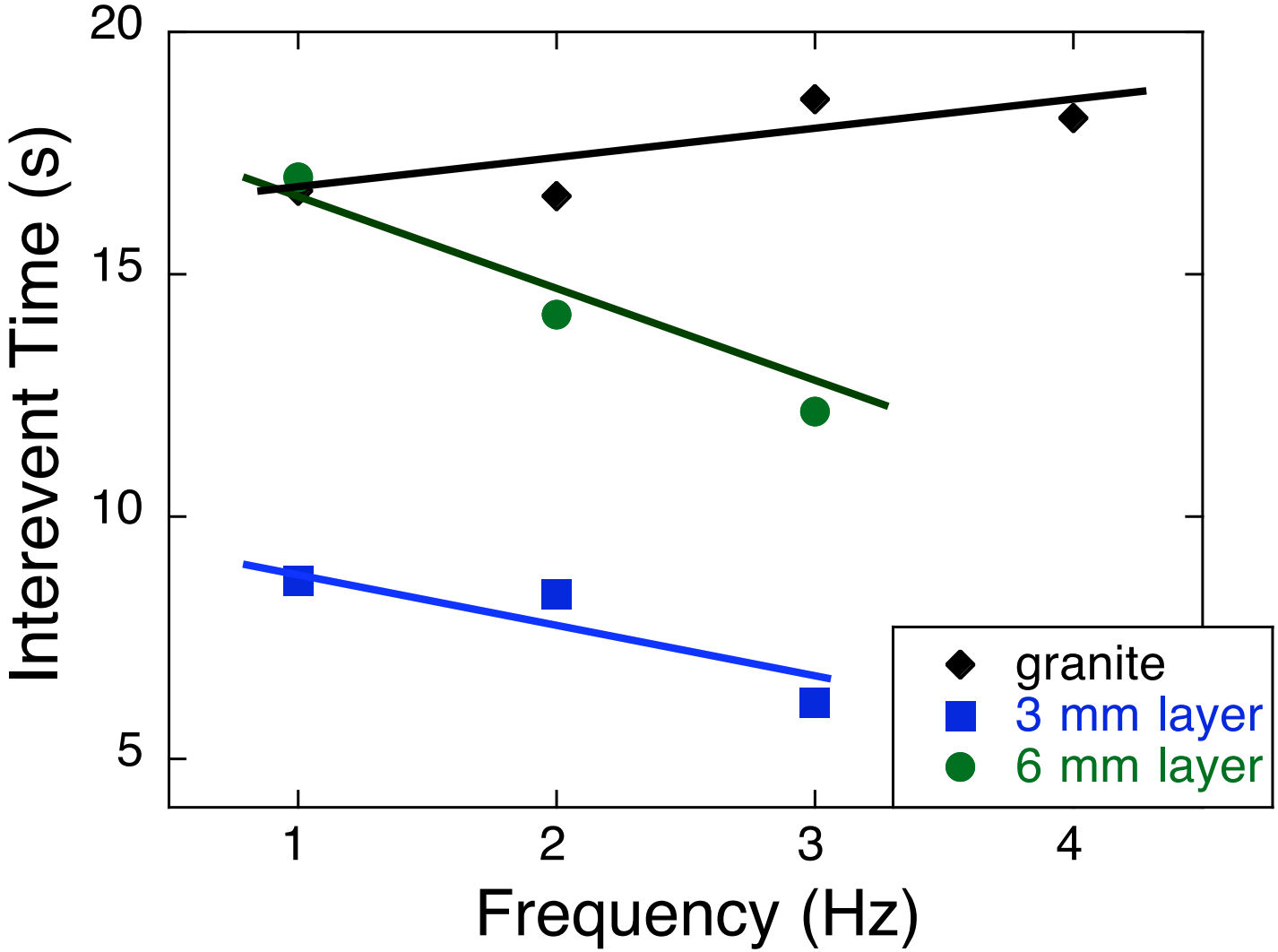
Increasing gouge thickness



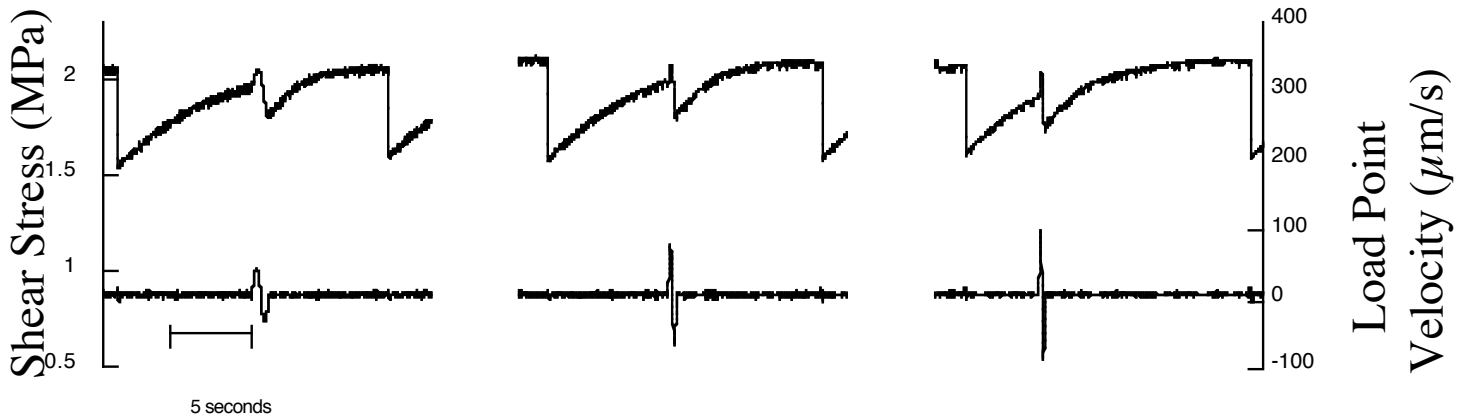
# Frequency Dependence

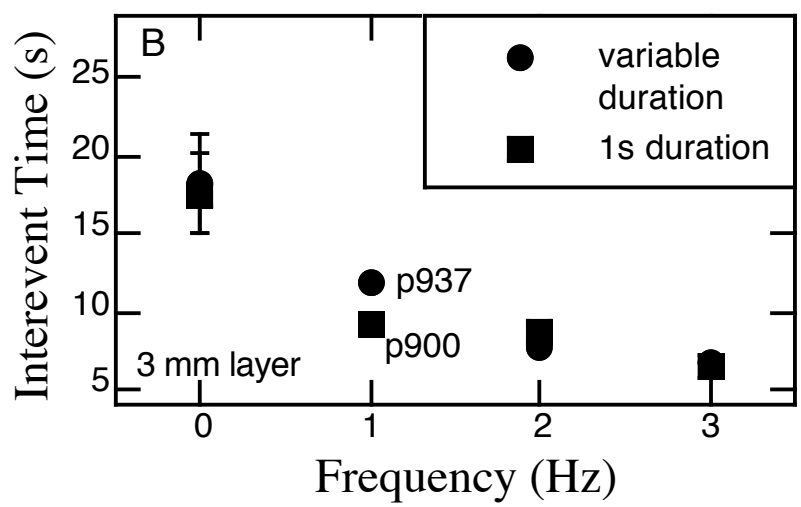


# Frequency Dependence

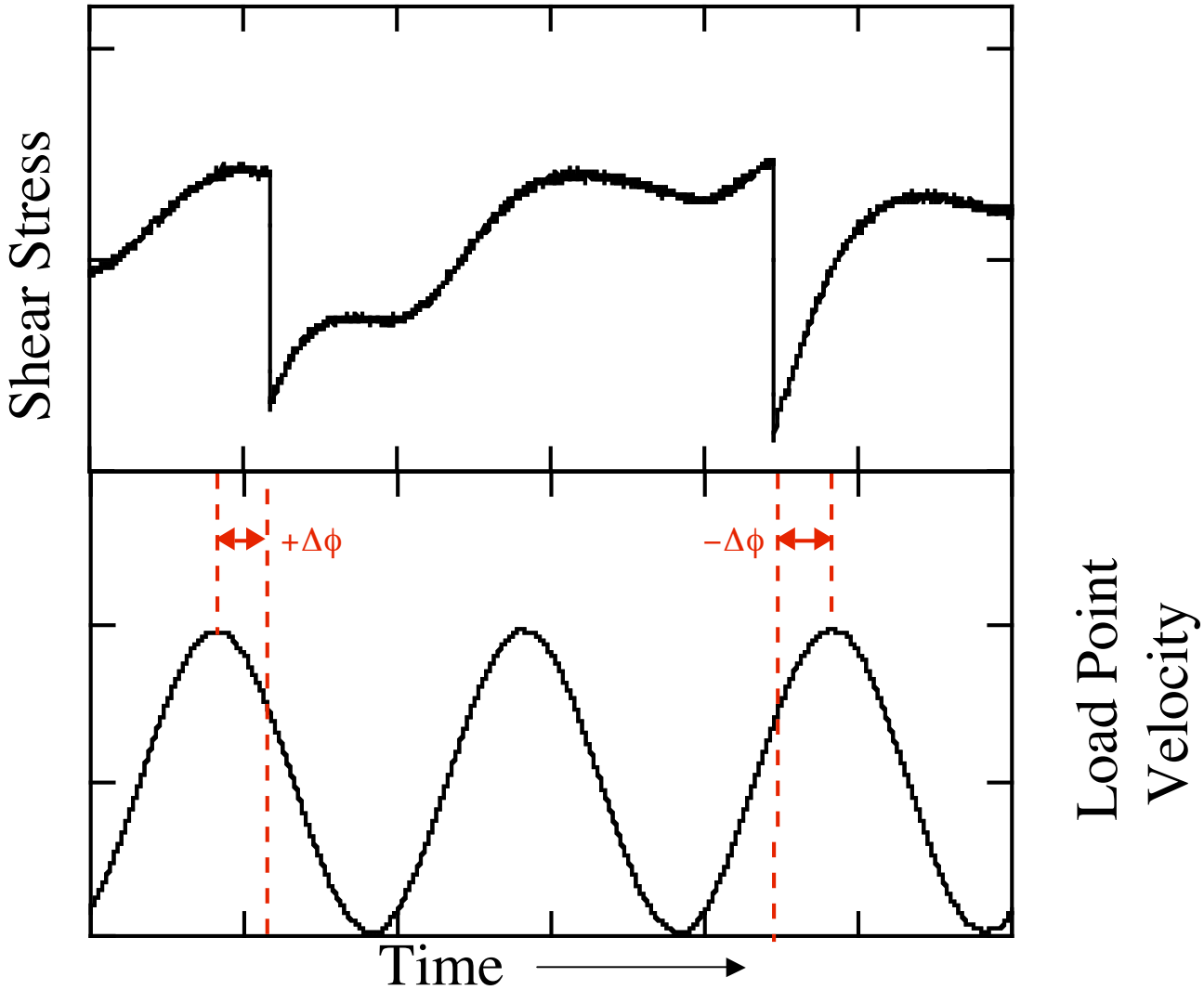


# Duration Effects

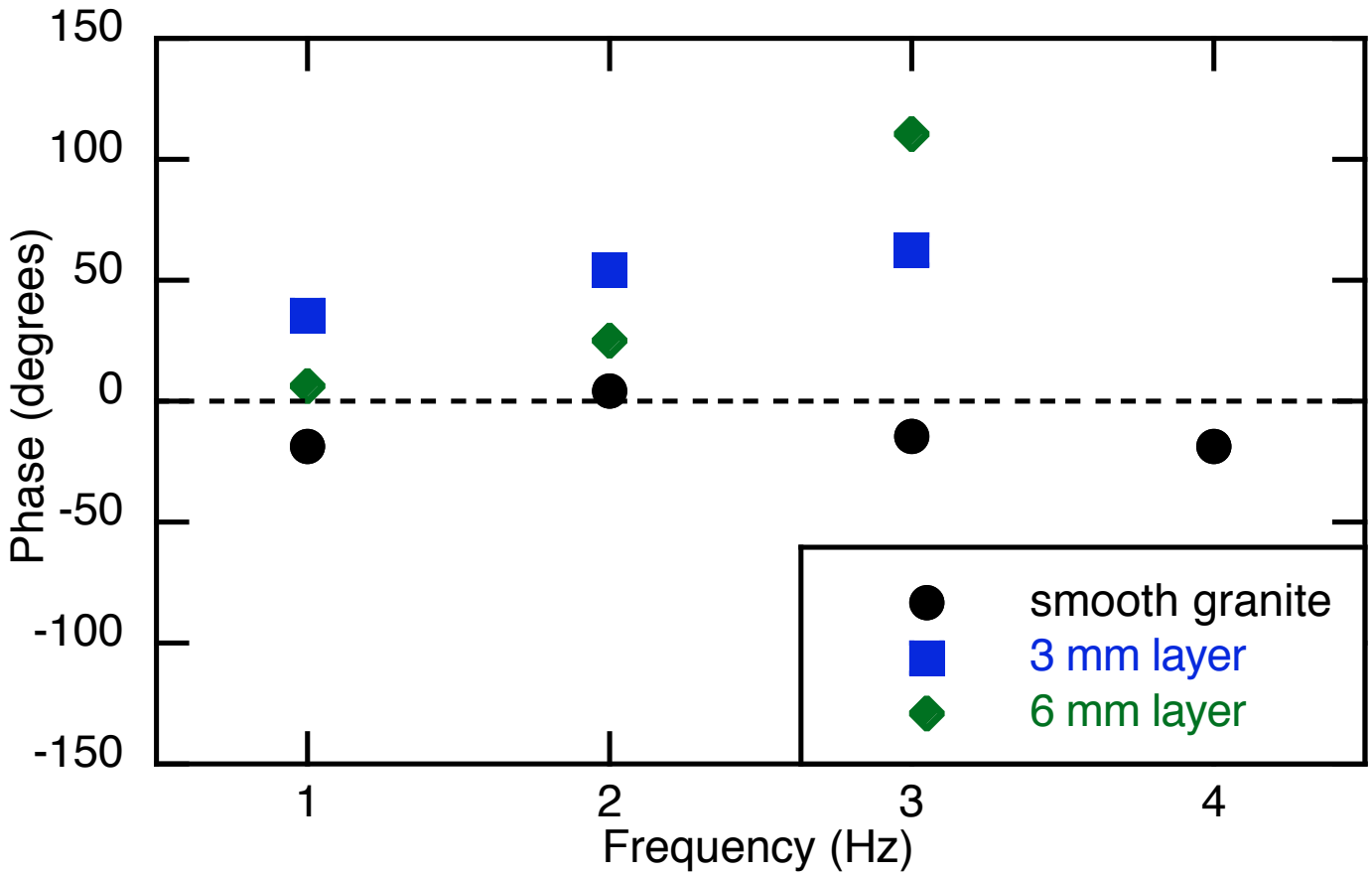


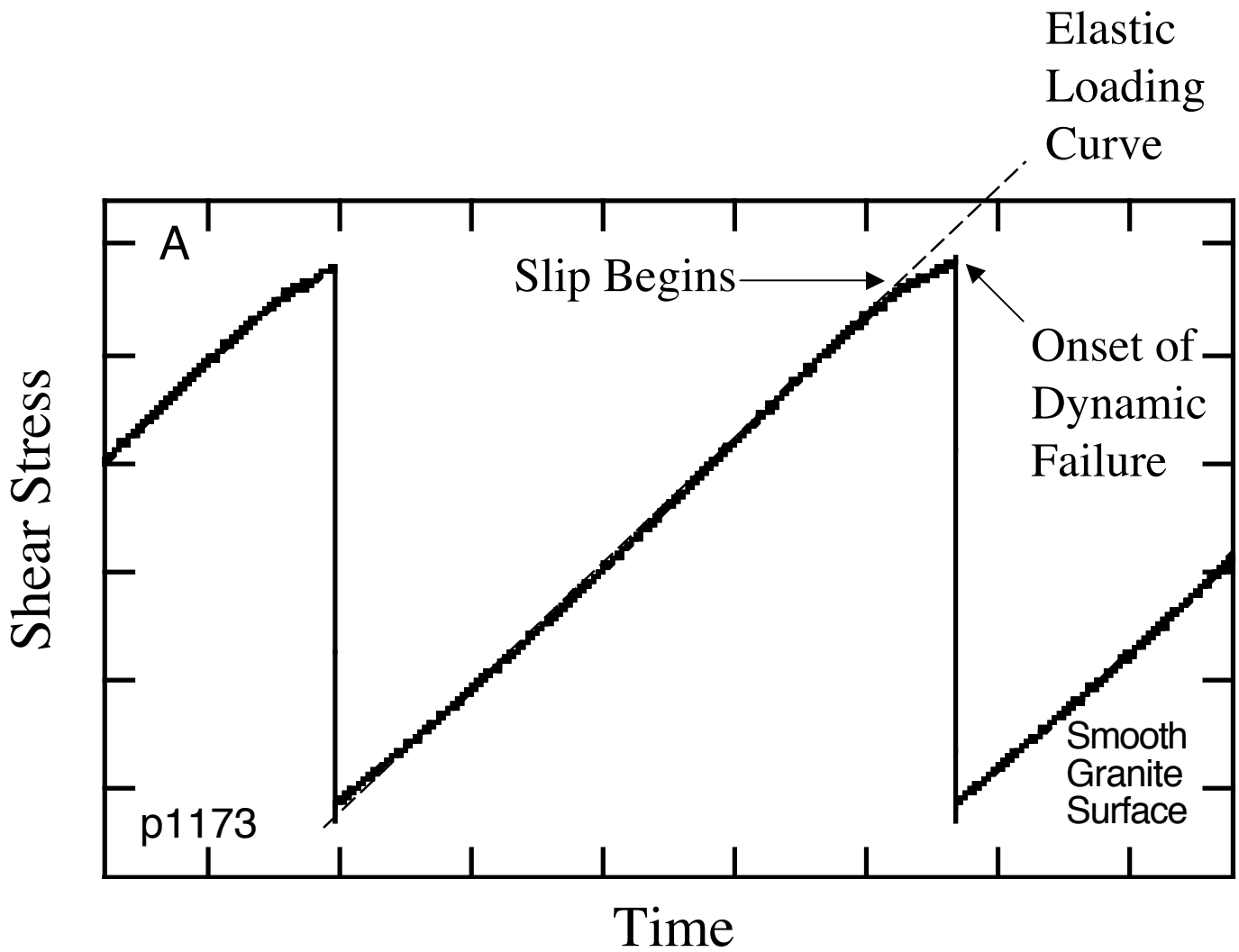



# Phase Lag of Failure



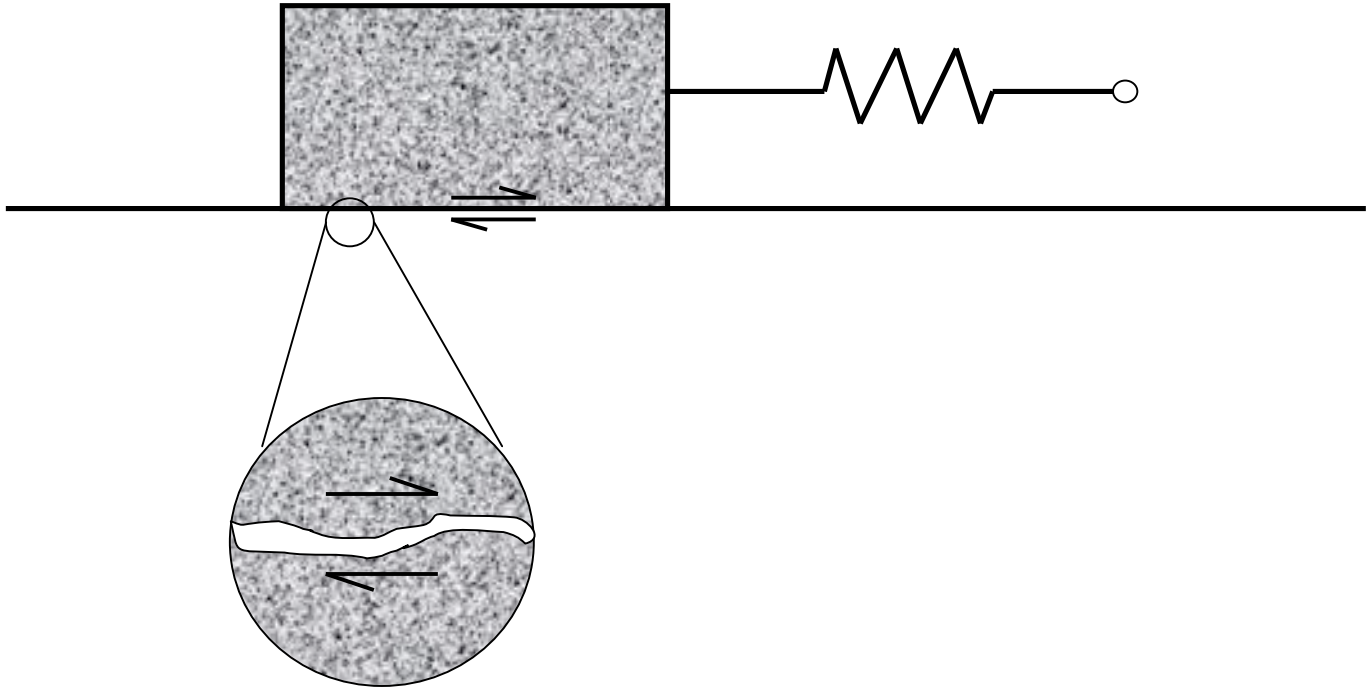
# Phase Lag at Failure



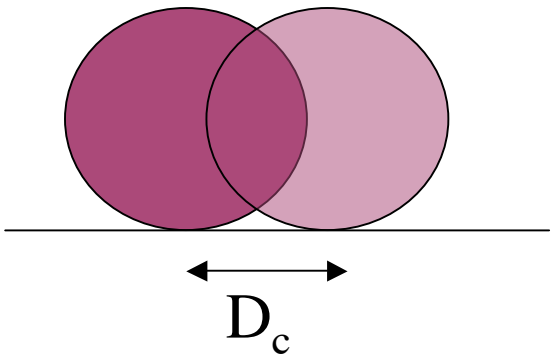



*Modified from Scholz 2003*

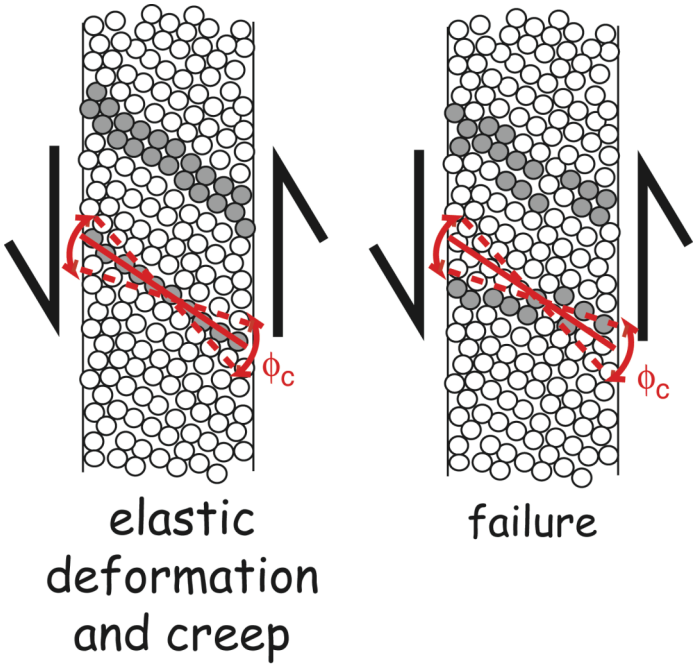
# Critical Slip Distance on Bare Surfaces: Asperity Contact



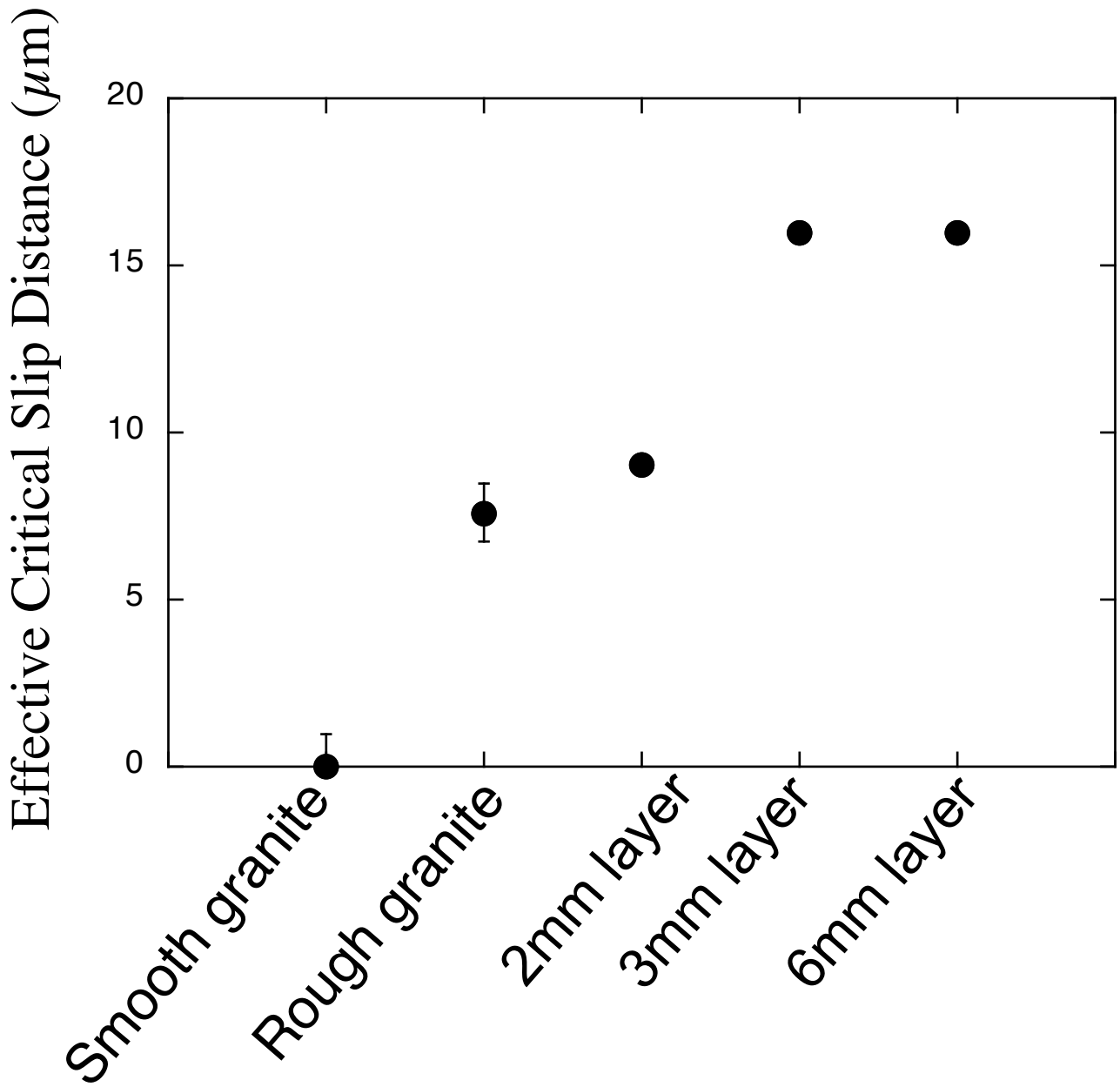
# Critical Slip Distance in Granular Layers



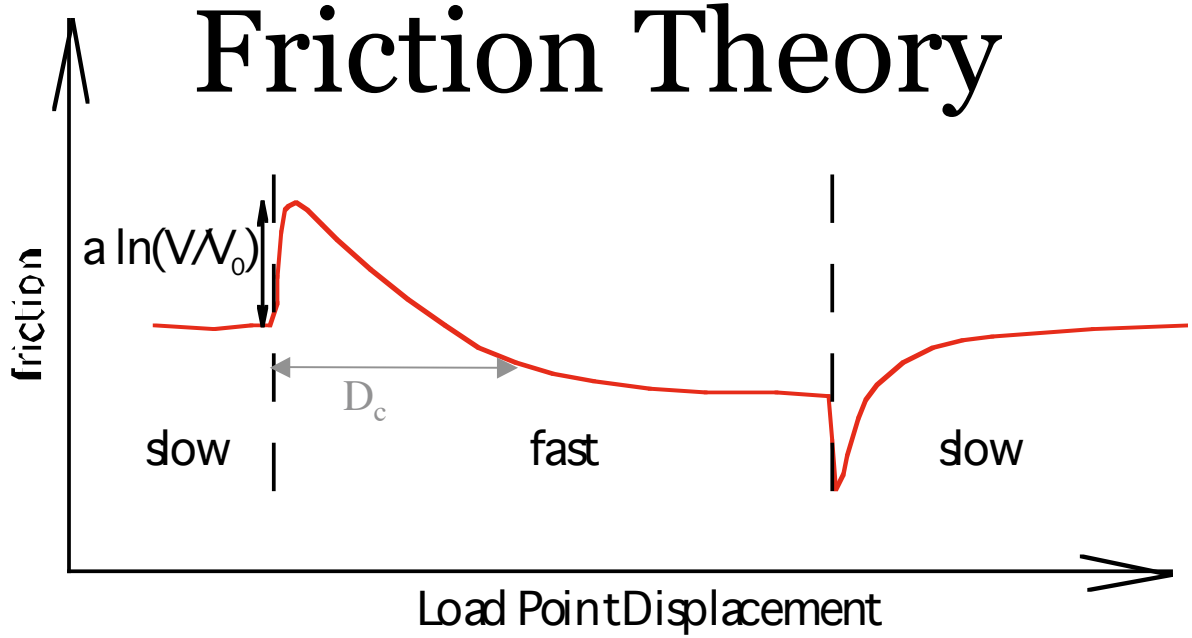

*Grain-Grain Contact*

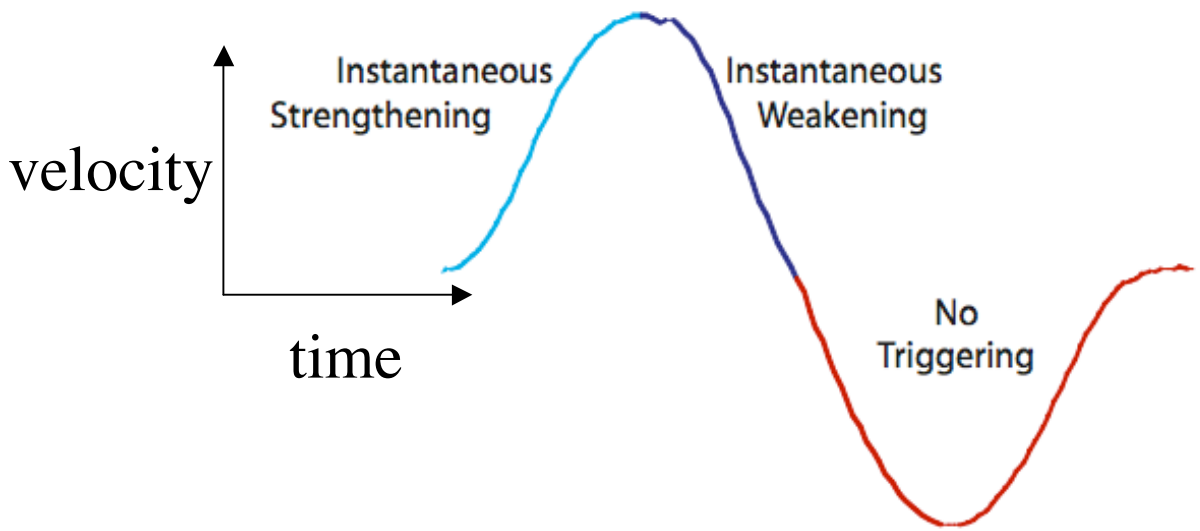



*Force Chains*

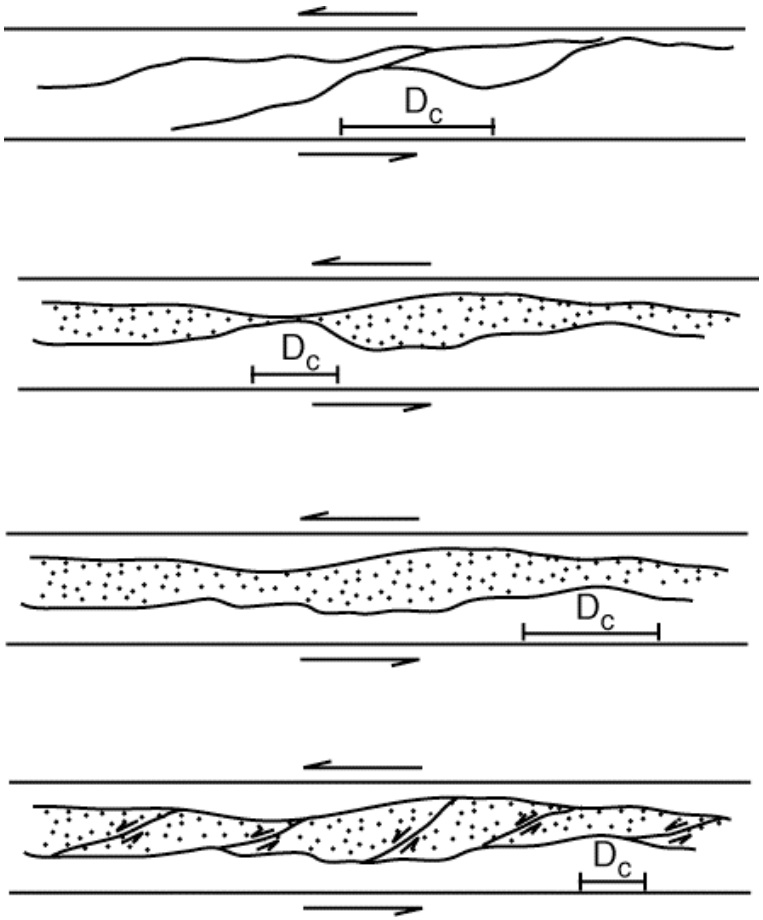

Effective Critical Slip Distance (μm)
20
15
10
5
0
Smooth granite
Rough granite
2mm layer
3mm layer
6mm layer

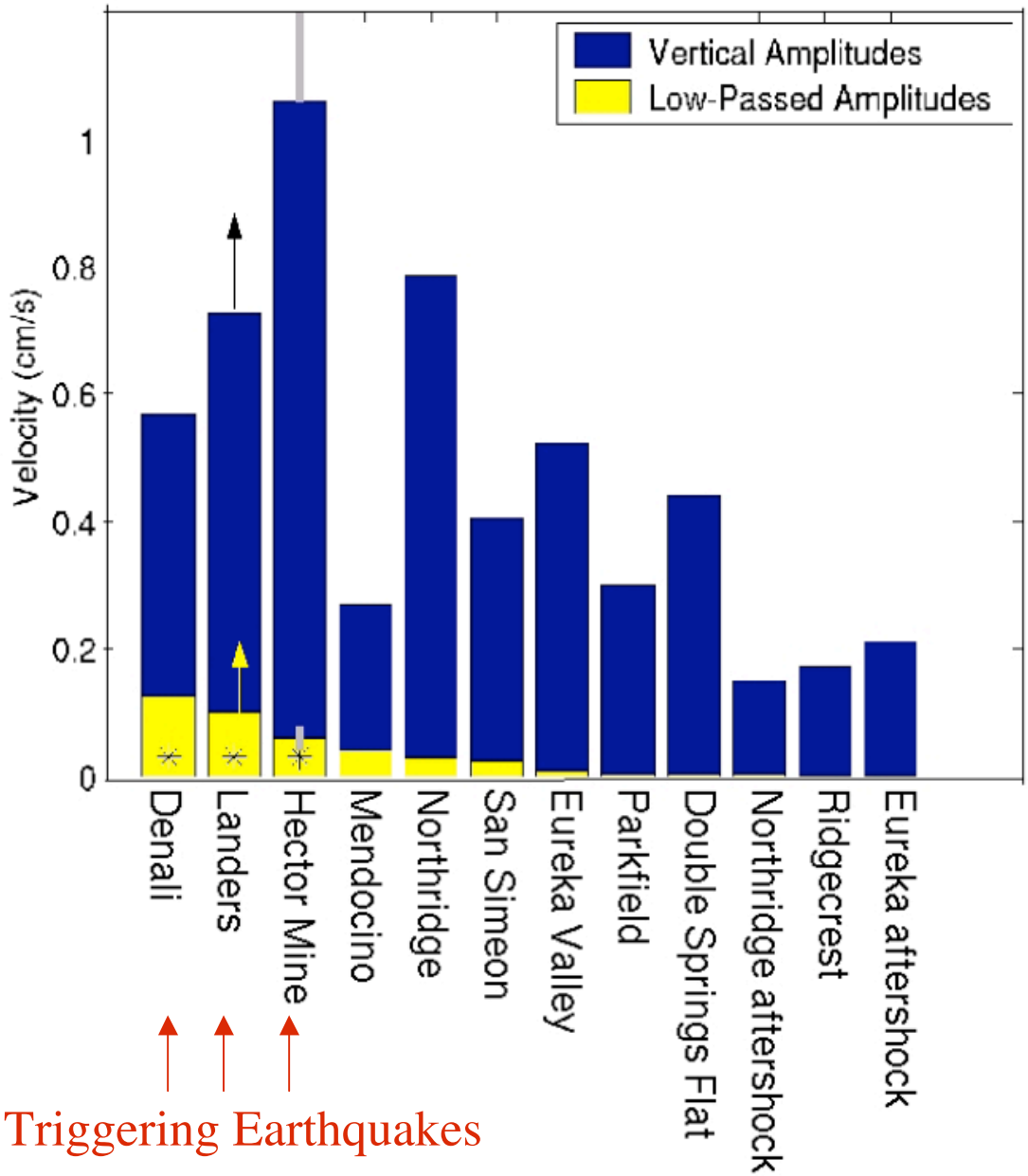
# Direct Effect of Rate and State Friction Theory



# Implications: What type of fault is more susceptible to triggering?



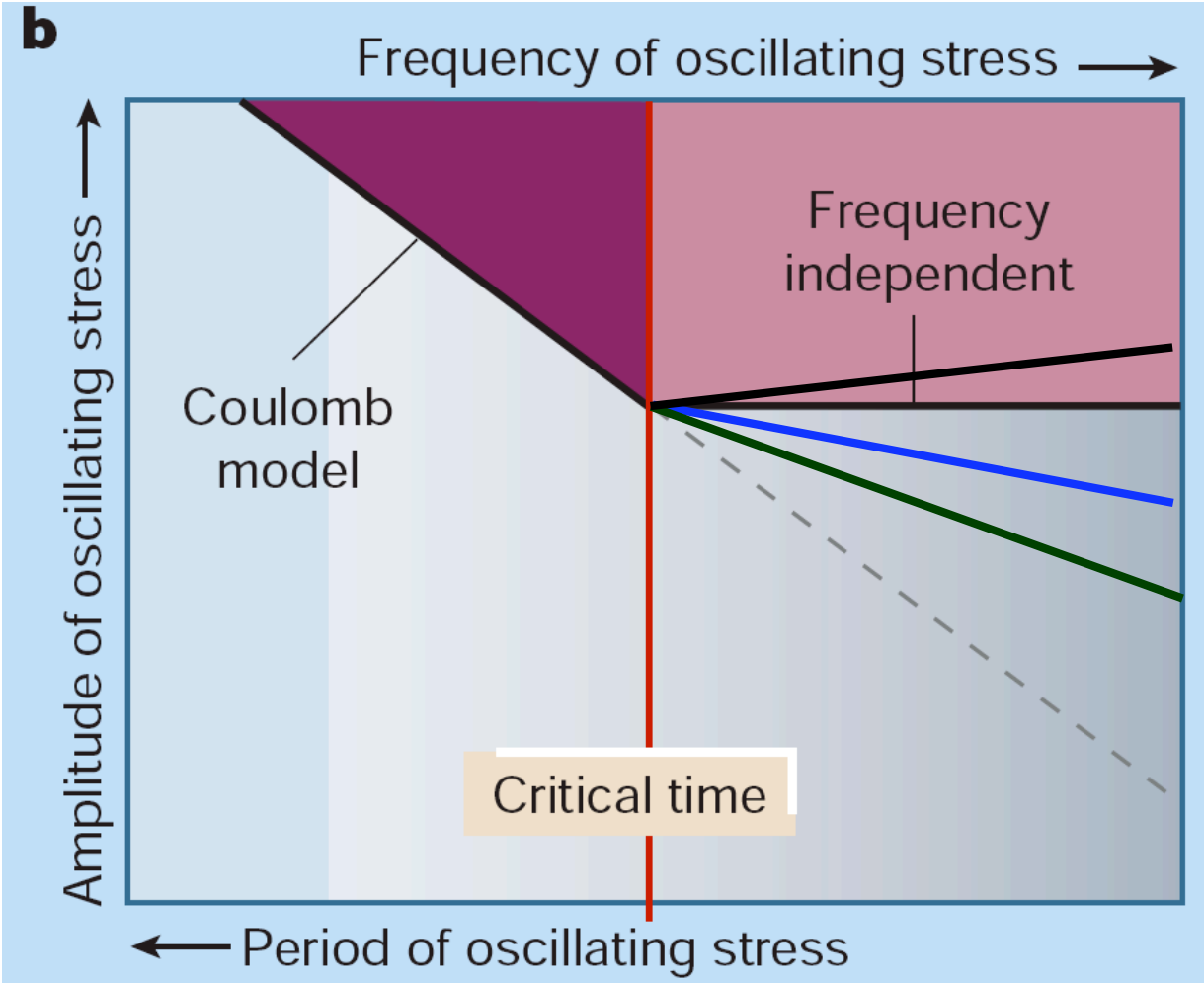



# What controls triggering thresholds?

Frequency trigger

*Brodsky & Prejean 2005*

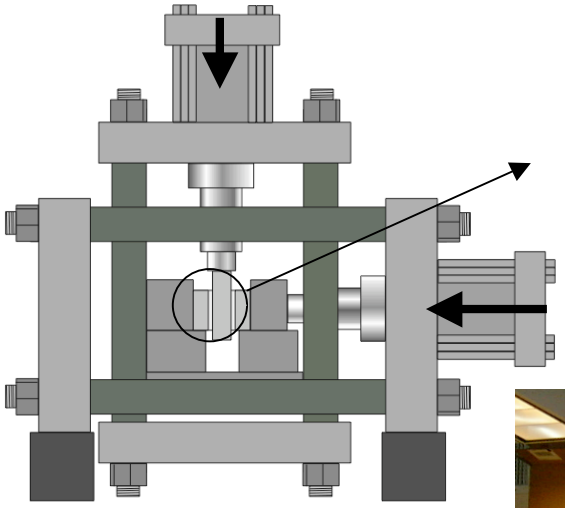
# Implications: Triggering Thresholds

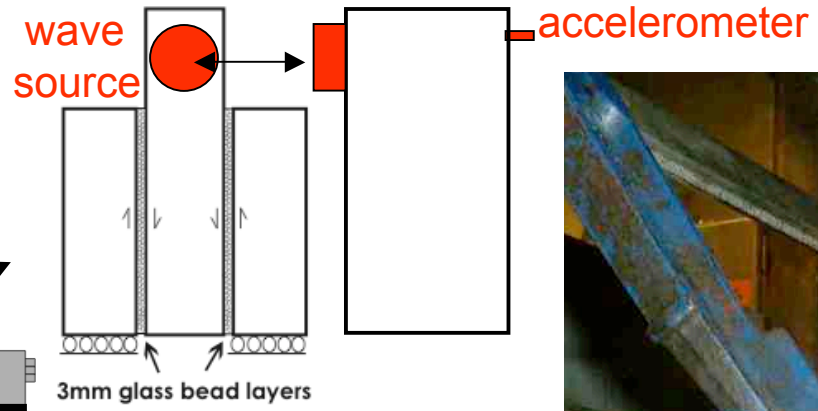



*Scholz 2003*

# Effects of acoustic waves on stick–slip friction

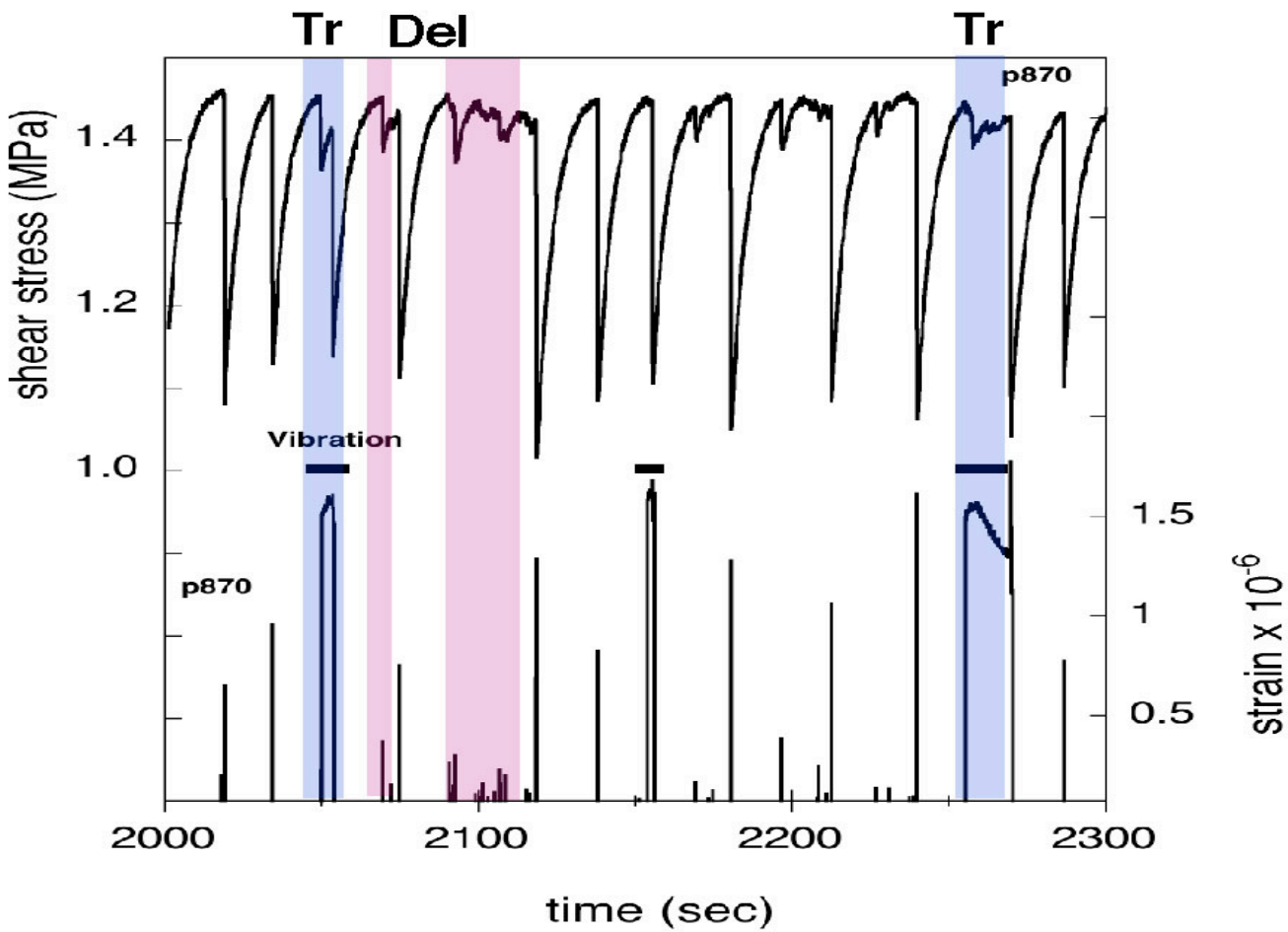
Johnson, Savage, Knuth, Gomberg & Marone, Nature, 2008



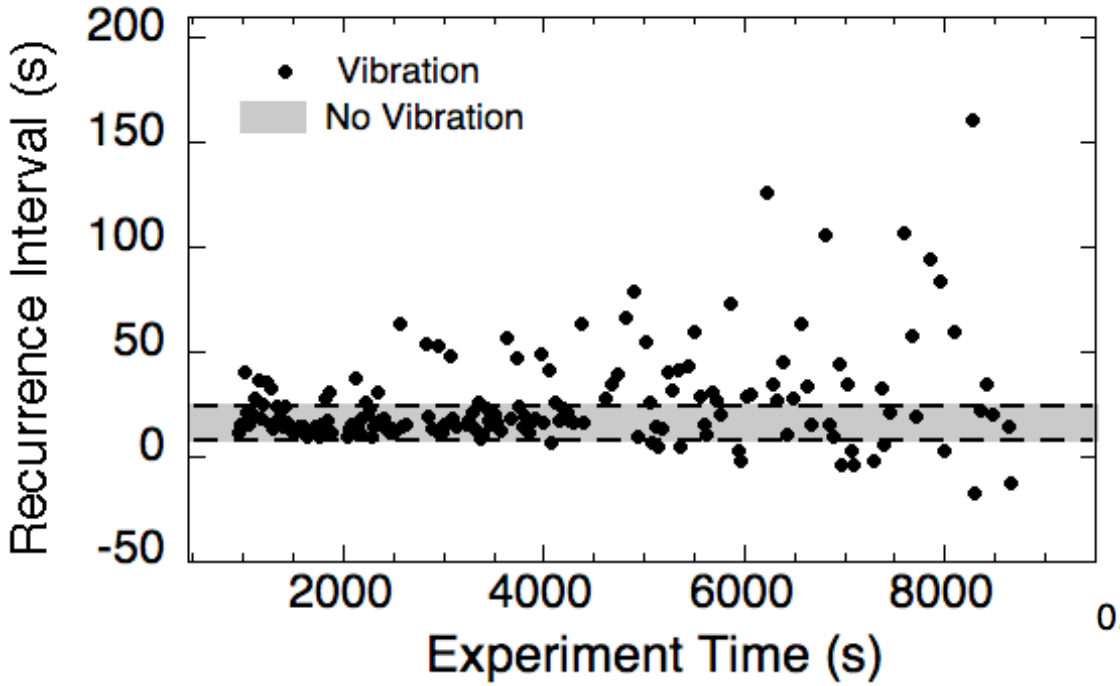



- 4 MPa normal stress
- background shearing rate of 5 μm/sec

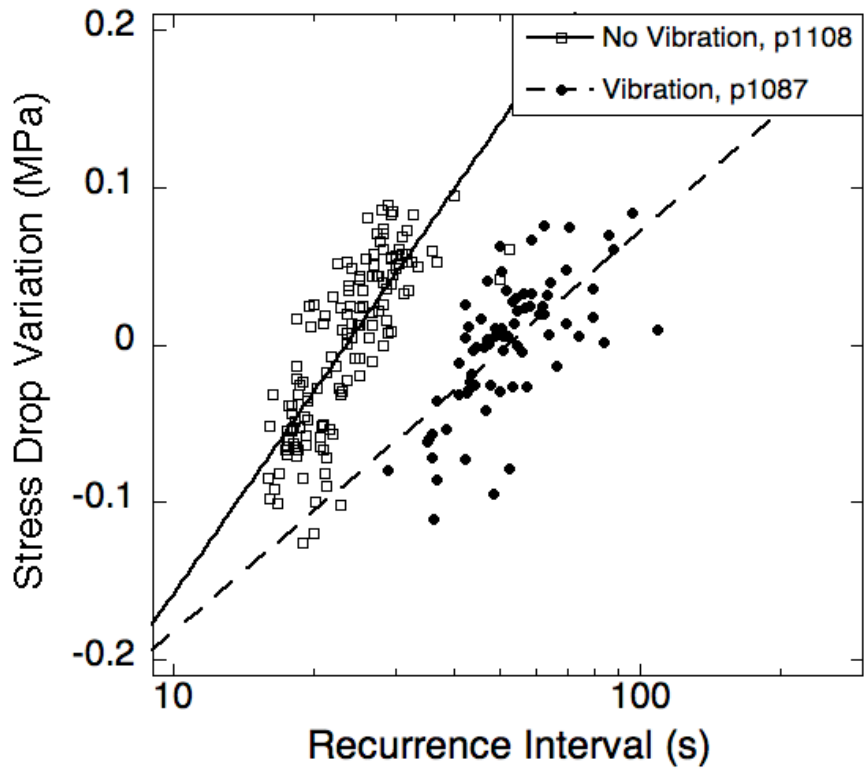
# Effects of acoustic waves on stick–slip




Johnson et al., Nature, 2008




Johnson et al.,
Nature, 2008




# Acoustic Vibration disrupts regular stick slip, leads to smaller stress drop

# Conclusions

- Triggering thresholds vary as a function of fault type - possibly as a function of $D_c$
- Increasing gouge thickness makes a fault more susceptible to triggering because of increased creep in the interseismic period
- Triggering threshold is most likely a function of amplitude, frequency in the high-frequency regime

# Modeling Microfriction

- Incorporating critical slip distance into failure thresholds for faults will allow for testing delayed failure behavior
- Varying critical slip distance lengths is important to model fault maturity
- Some indication that the dependence of strength on velocity will also be important