# Laboratory Earthquake Precursors and Prediction
## (for the Spectrum of Fault Slip Modes)


Chris Marone, The Pennsylvania State University, USA

Bryan Kaproth, John Leeman, Marco Scuderi, Cristiano Collettini, Elisa Tinti, Srisharan Shreedharn, Chas Bolton, Jacques Rivière, Bertrand Rouet-Leduc, Claudia Hulbert, and Paul Johnson


**Slow Earthquakes, Preseismic Velocity Changes, and the Origin of Slow Frictional Stick-Slip**

Bryan M. Kaproth and C. Marone

Science, 2013

**Machine Learning Predicts Laboratory Earthquakes**

Bertrand Rouet-Leduc[1,2], Claudia Hulbert[1], Nicholas Lubbers[1,3], Kipton Barros[1], Colin J. Humphreys[2], and Paul A. Johnson[4]

[1]Theoretical Division and CNLS, Los Alamos National Laboratory, Los Alamos, NM, USA, [2]Department of Materials Science and Metallurgy, University of Cambridge, Cambridge, UK, [3]Department of Physics, Boston University, Boston, MA, USA, [4]Geophysics Group, Los Alamos National Laboratory, Los Alamos, NM, USA

nature geoscience — LETTERS

PUBLISHED ONLINE: 8 AUGUST 2016 | DOI: 10.1038/NGEO2775

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nature geoscience — ARTICLES

https://doi.org/10.1038/s41561-018-0272-8

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**Journal of Geophysical Research: Solid Earth**

RESEARCH ARTICLE

10.1002/2016JB013545

Special Section: Slow Slip Phenomena and Plate Boundary Processes

**On the evolution of elastic properties during laboratory stick-slip experiments spanning the transition from slow slip to dynamic rupture**

E. Tinti[1], M. M. Scuderi[1,2], L. Scognamiglio[1], G. Di Stefano[1], C. Marone[3], and C. Collettini[1,2]

*7 Mar. 2019*


erc European Research Council — European Research Council, Seventh Framework Programme, "Ideas" Starting Grant, GLASS: 259256

US NSF IGPPS/CSES

RESEARCH & INNOVATION — Marie Skłodowska-Curie actions

INGV, Roma

SAPIENZA UNIVERSITÀ DI ROMA

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changes in some physical property of a fault zone prior to failure

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changes in some physical property of a fault zone prior to failure

prediction of that failure

spectrum of failure modes ranging from aseismic slip to slow earthquakes to low frequency earthquakes and fast, ordinary earthquakes dictated by elastodynamic rupture

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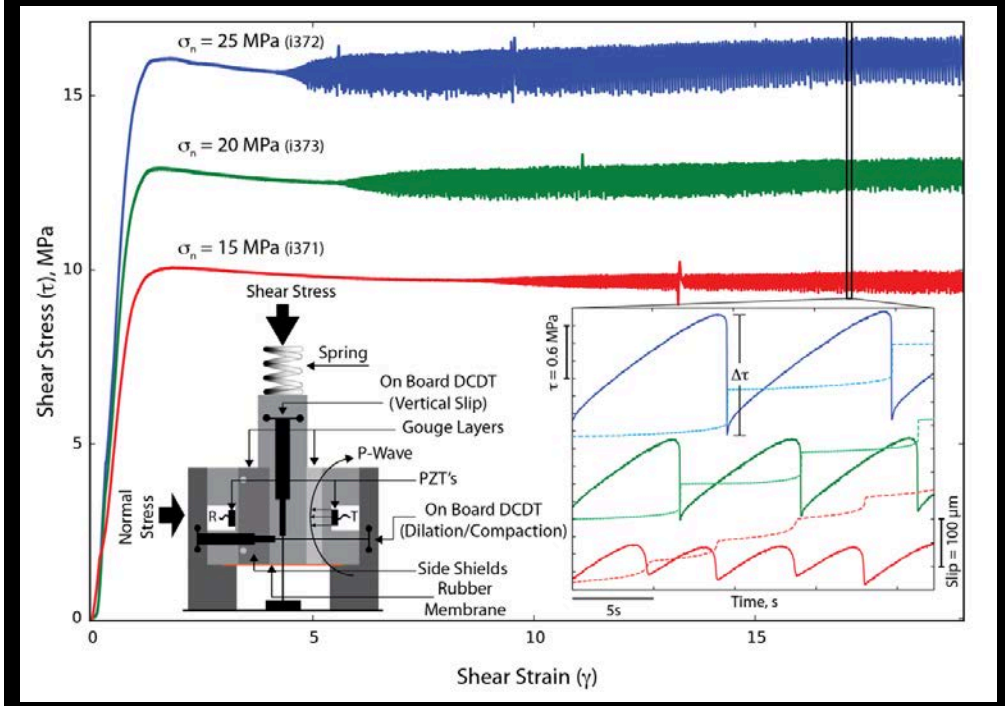
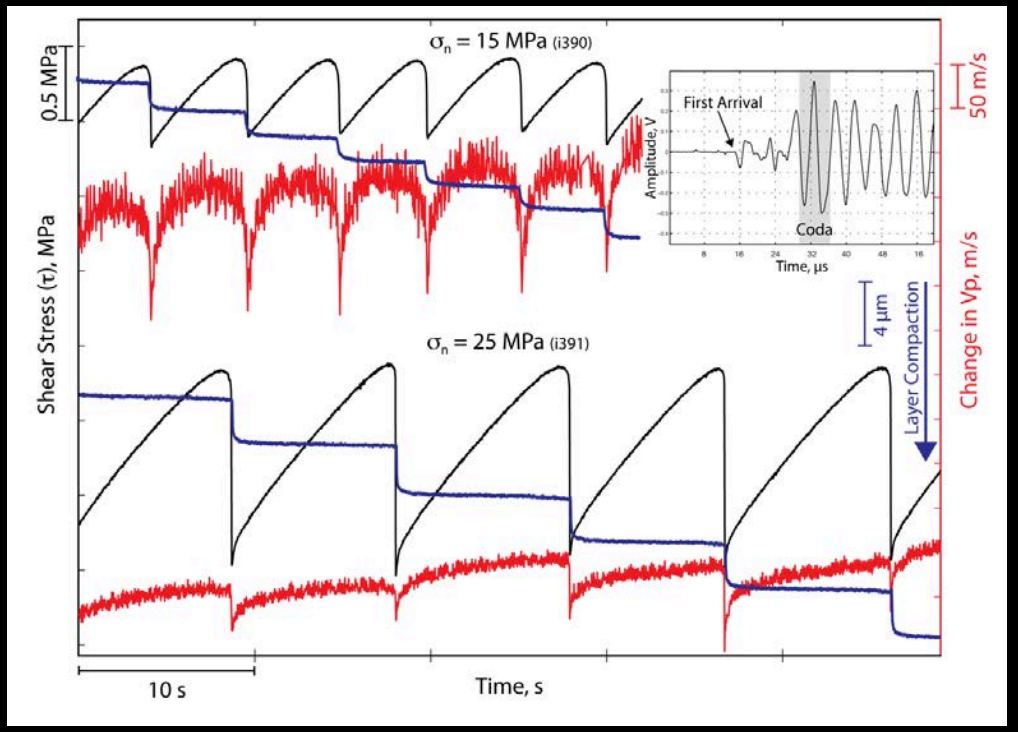
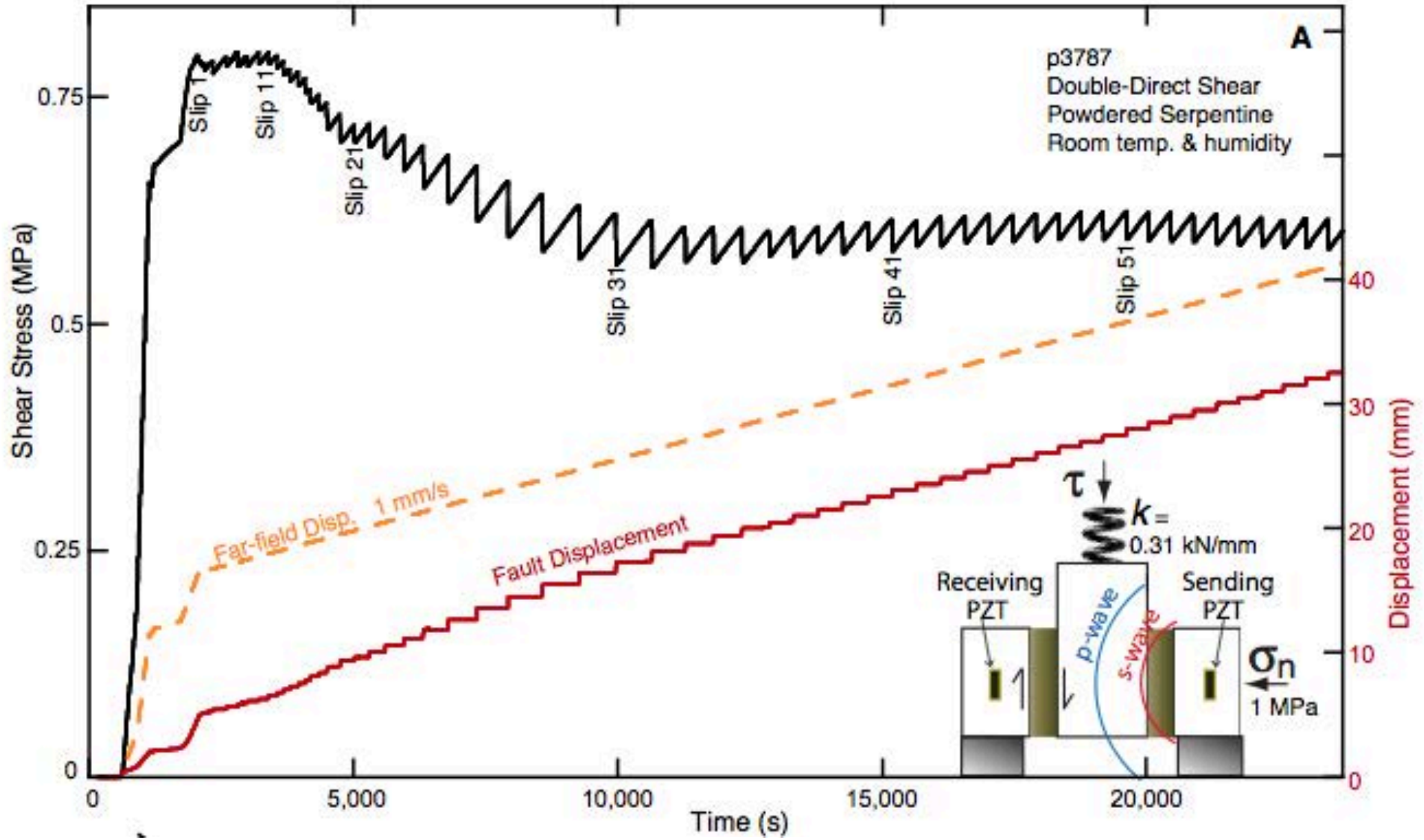


# Slow Earthquakes, Preseismic Velocity Changes, and the Origin of Slow Frictional Stick-Slip

**Bryan M. Kaproth and C. Marone**

Earthquakes normally occur as frictional stick-slip instabilities, resulting in catastrophic failure



nature geoscience

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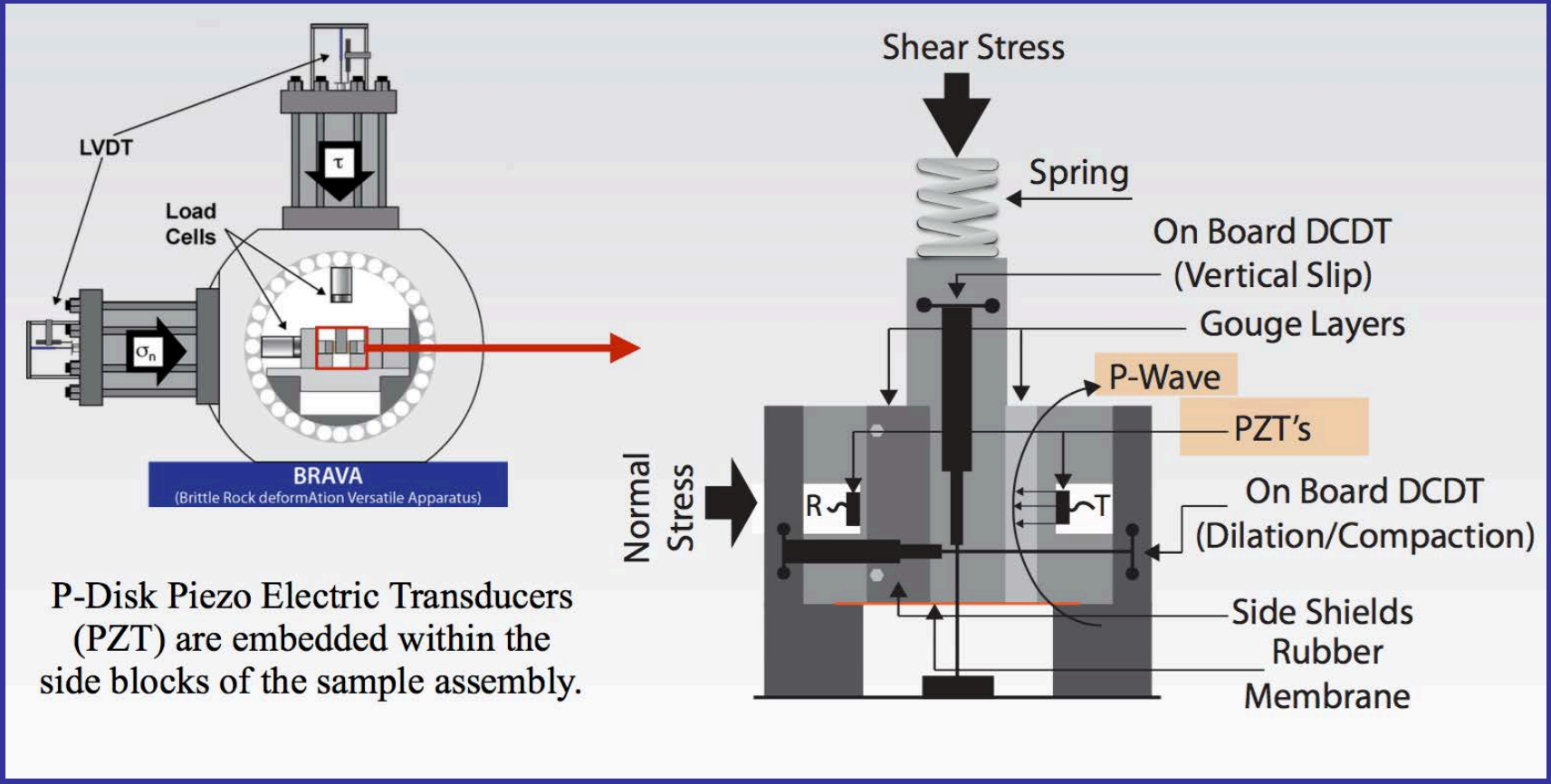
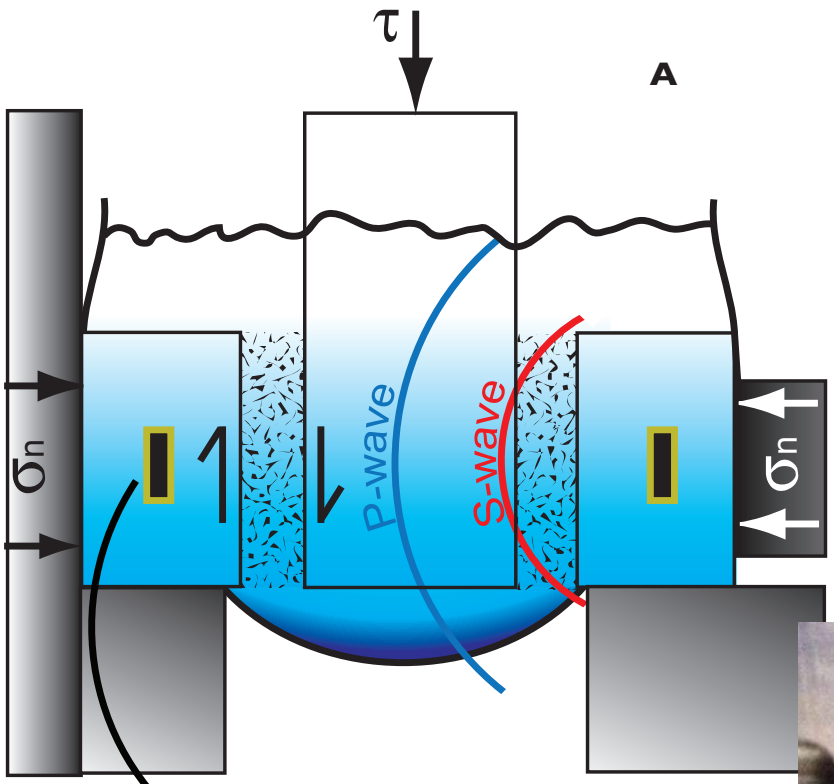
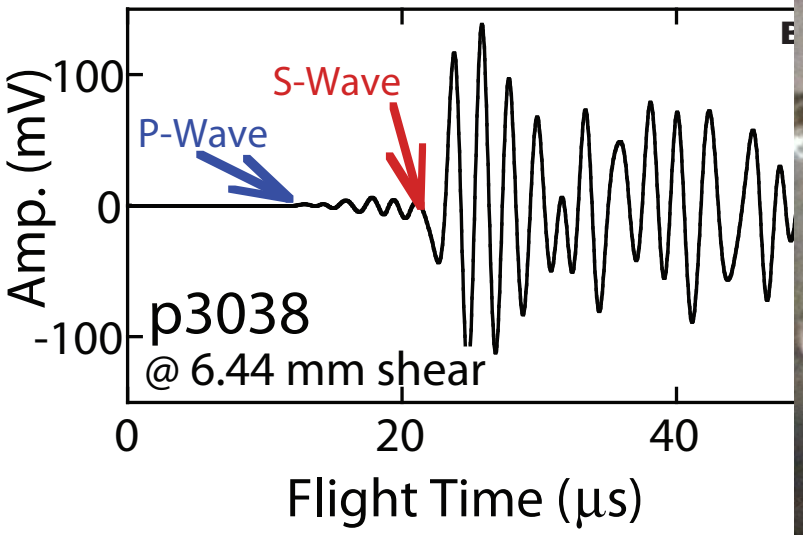
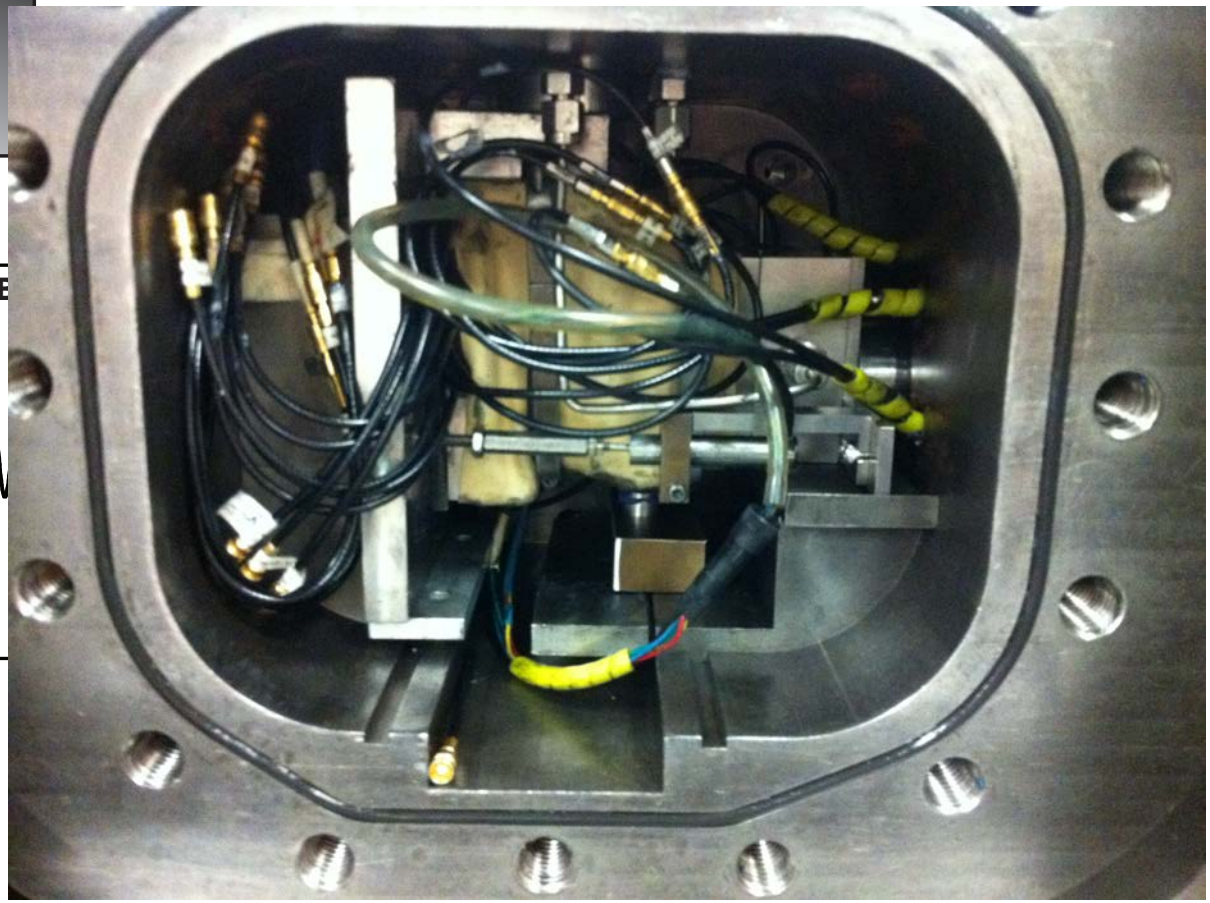


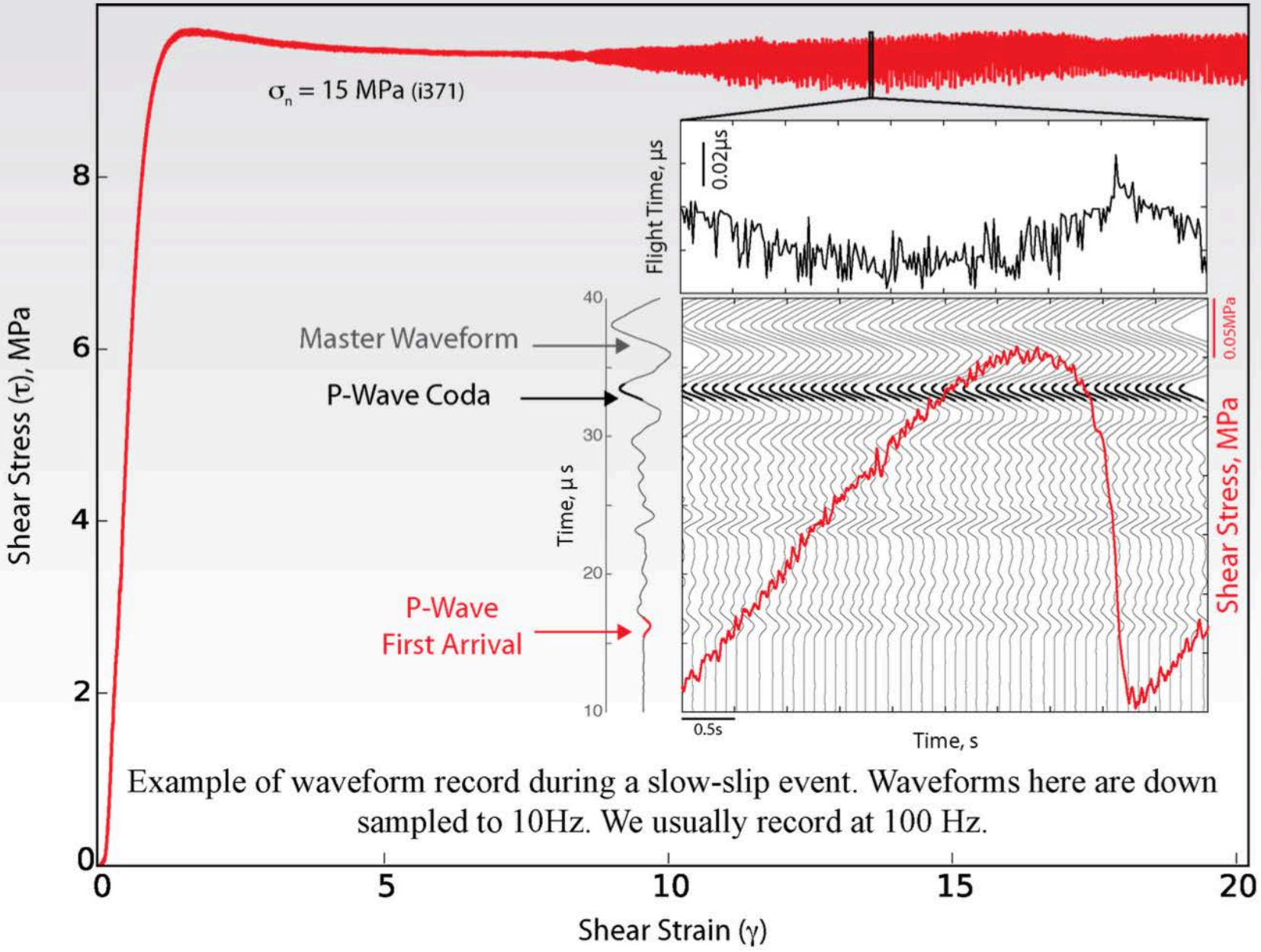

P-Disk Piezo Electric Transducers (PZT) are embedded within the side blocks of the sample assembly.


τ
A
σn
σn
P-wave
S-wave


B
100
0
-100
Amp. (mV)
P-Wave
S-Wave
p3038
@ 6.44 mm shear
0
20
40
Flight Time (μs)

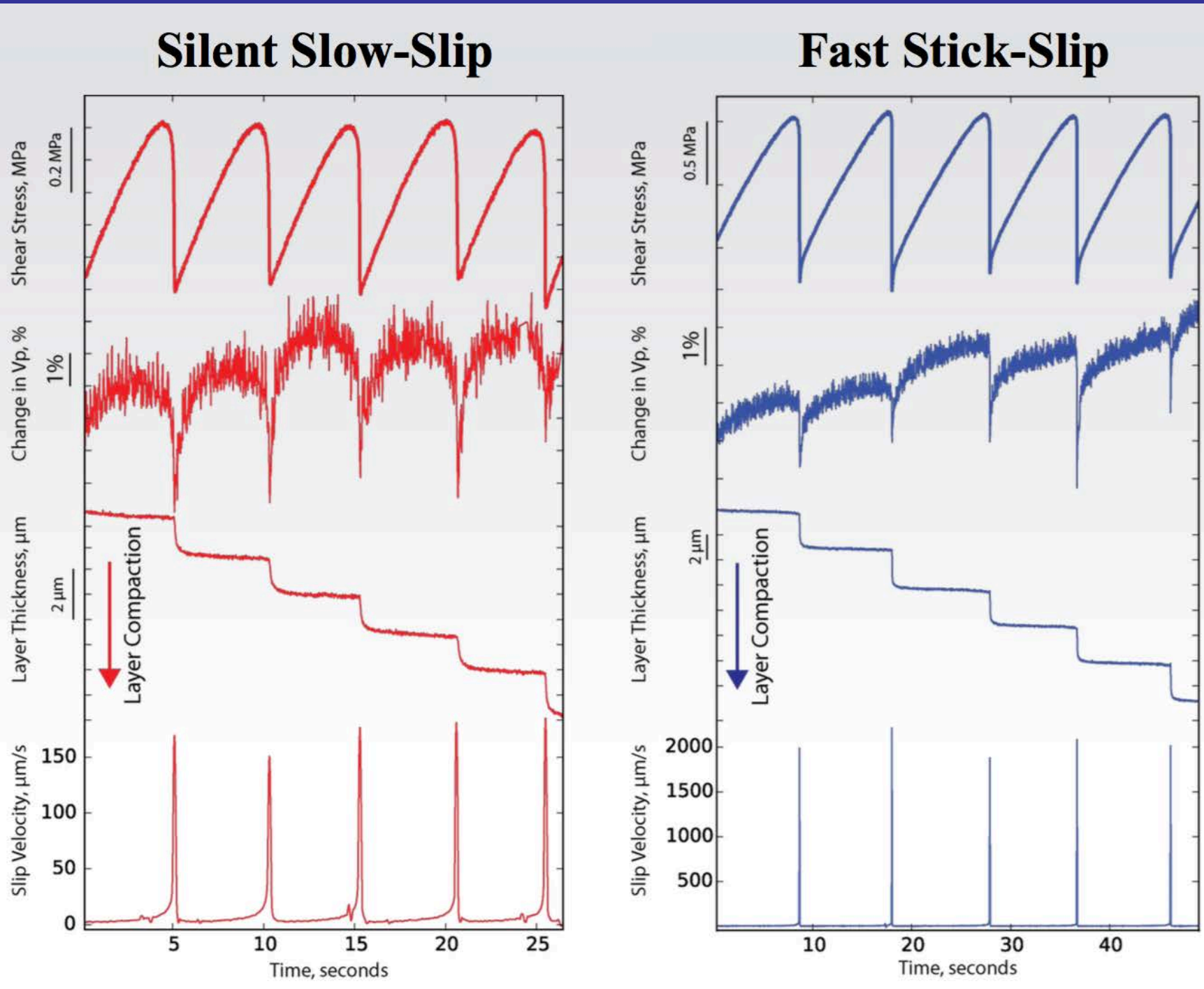


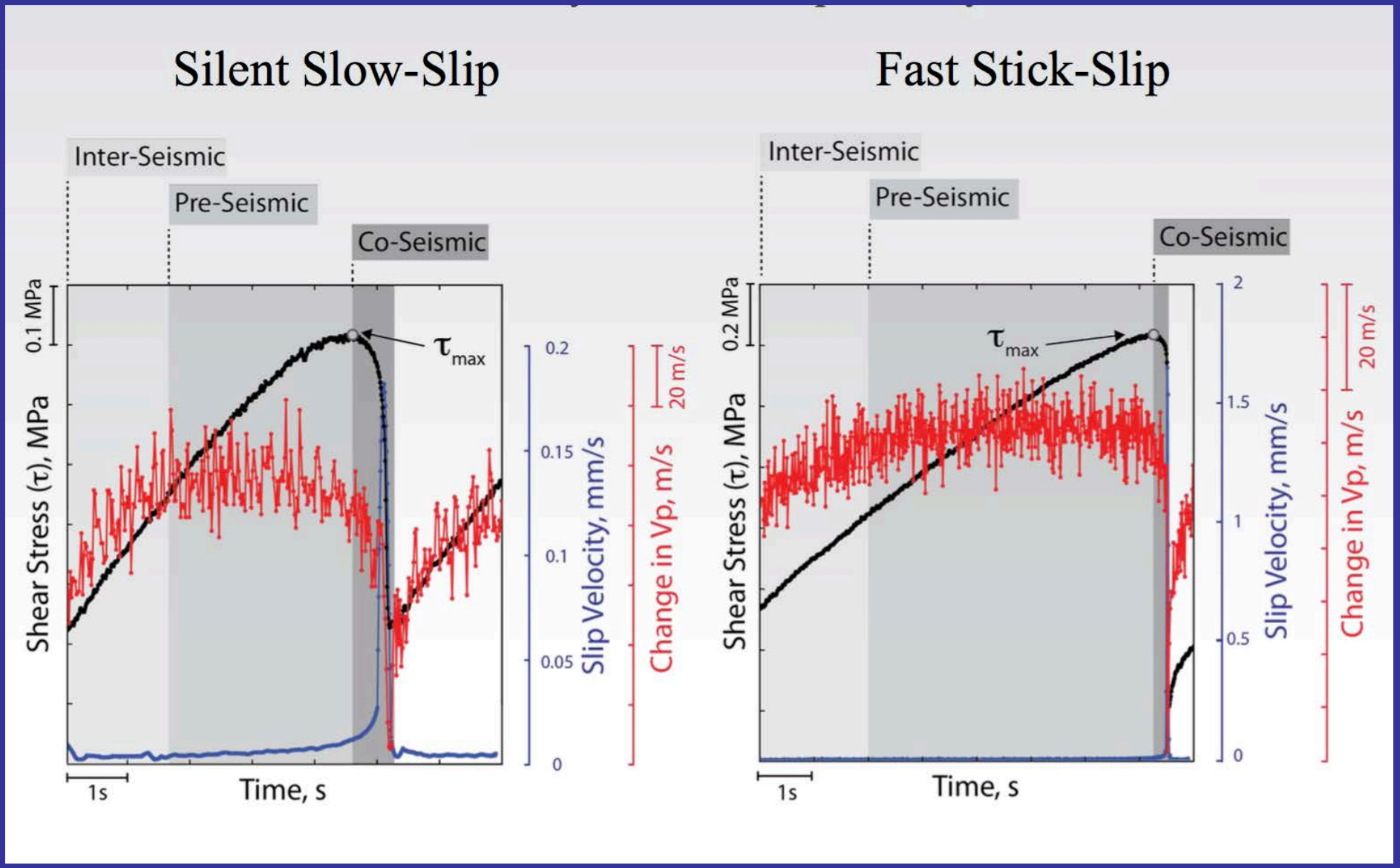
# Ultrasonic Measurements




Example of waveform record during a slow-slip event. Waveforms here are down sampled to 10Hz. We usually record at 100 Hz.

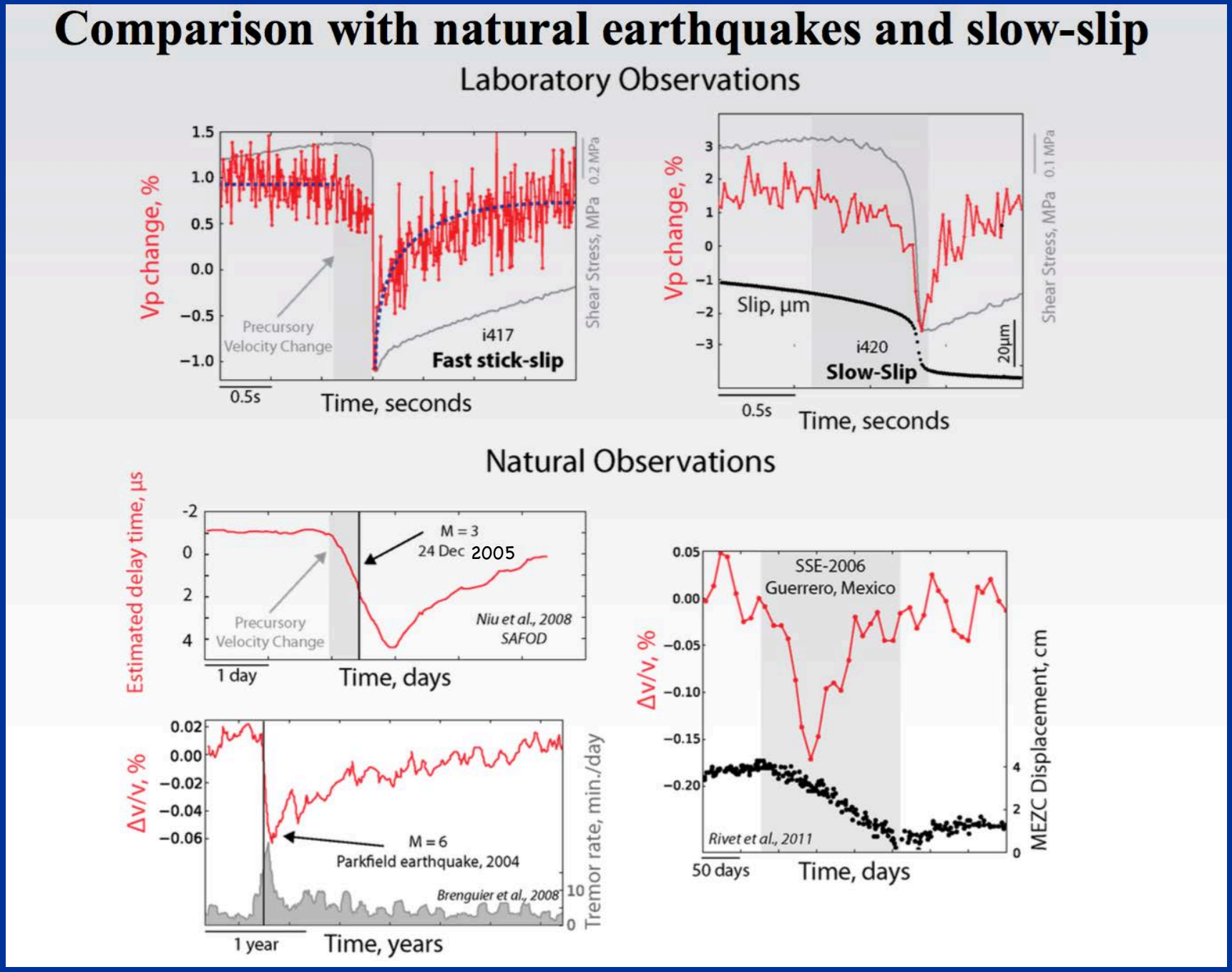
Scuderi et al., 2016


Silent Slow-Slip
Fast Stick-Slip
Shear Stress, MPa
0.2 MPa
0.5 MPa
Change in Vp, %
1%
Layer Thickness, µm
2 µm
Layer Compaction
Slip Velocity, µm/s
150
100
50
0
2000
1500
1000
500
5
10
15
20
25
10
20
30
40
Time, seconds
Time, seconds




Scuderi, Marone, Tinti, Di Stefano, & Collettini, *Nature Geosc.*, 2016

# Comparison with natural earthquakes and slow-slip




Scuderi, Marone, Tinti, Di Stefano, & Collettini, *Nature Geosc.*, 2016

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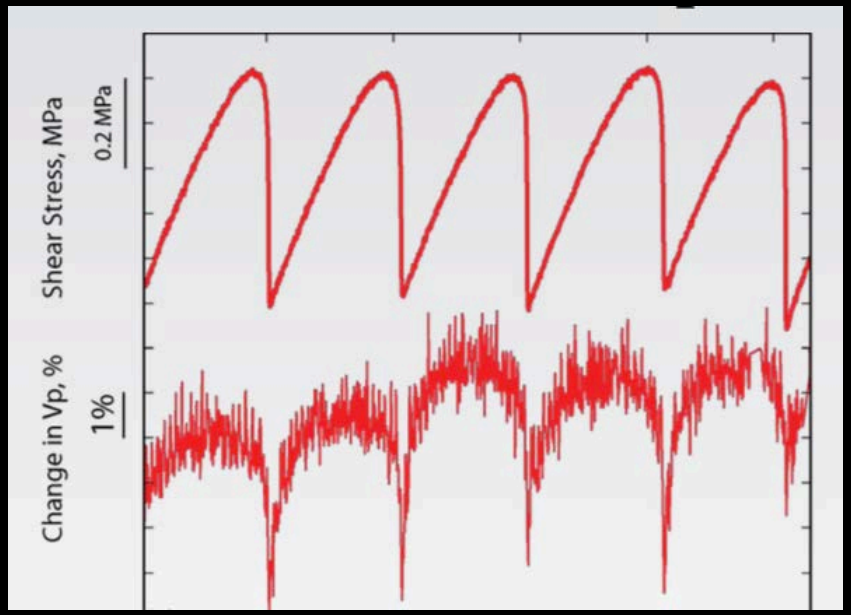
Precursors to failure

1. Lab earthquakes are preceded by changes in elastic wave speed that occur within the fault zone
2. Acoustic emissions in lab earthquakes exhibit power law frequency magnitude (Gutenberg-Richter) scaling that evolves systematically during the lab seismic cycle



Bulletin of the Seismological Society of America. Vol. 58, No. 1, pp. 399–415. February, 1968

# THE FREQUENCY-MAGNITUDE RELATION OF MICROFRACTURING IN ROCK AND ITS RELATION TO EARTHQUAKES

By C. H. Scholz

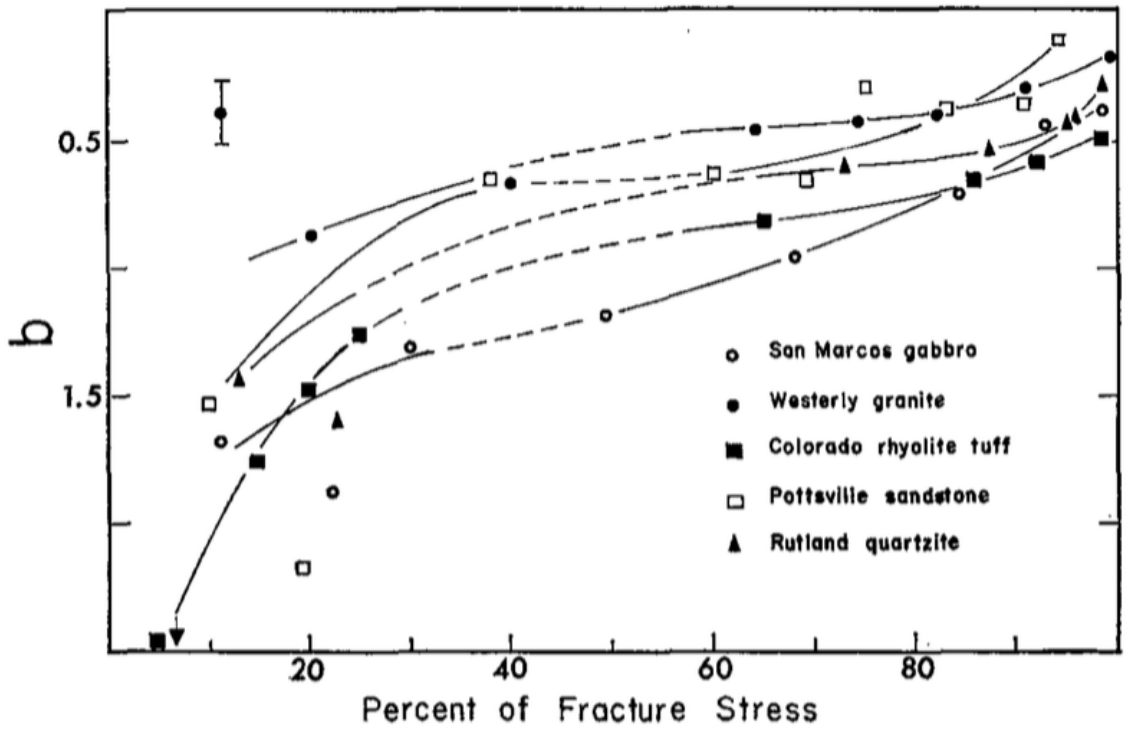
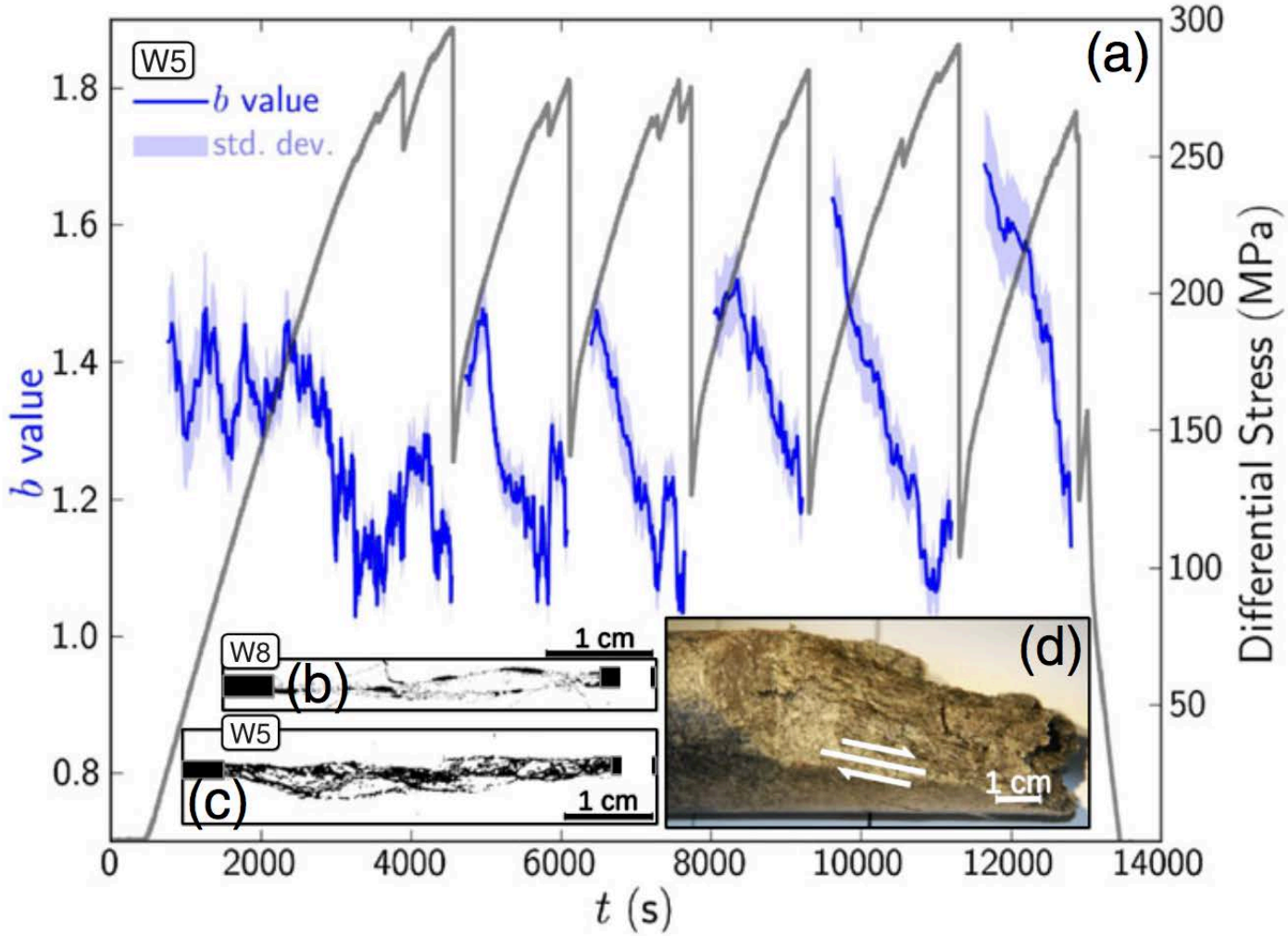



Fig. 3. $b$ as a function of normalized stress for five rocks in uniaxial compression. The dashed part of the curves are in the region where few events were detected.

GEOPHYSICAL RESEARCH LETTERS, VOL. 40, 2049–2054, doi:10.1002/grl.50507, 2013

# Acoustic emissions document stress changes over many seismic cycles in stick-slip experiments

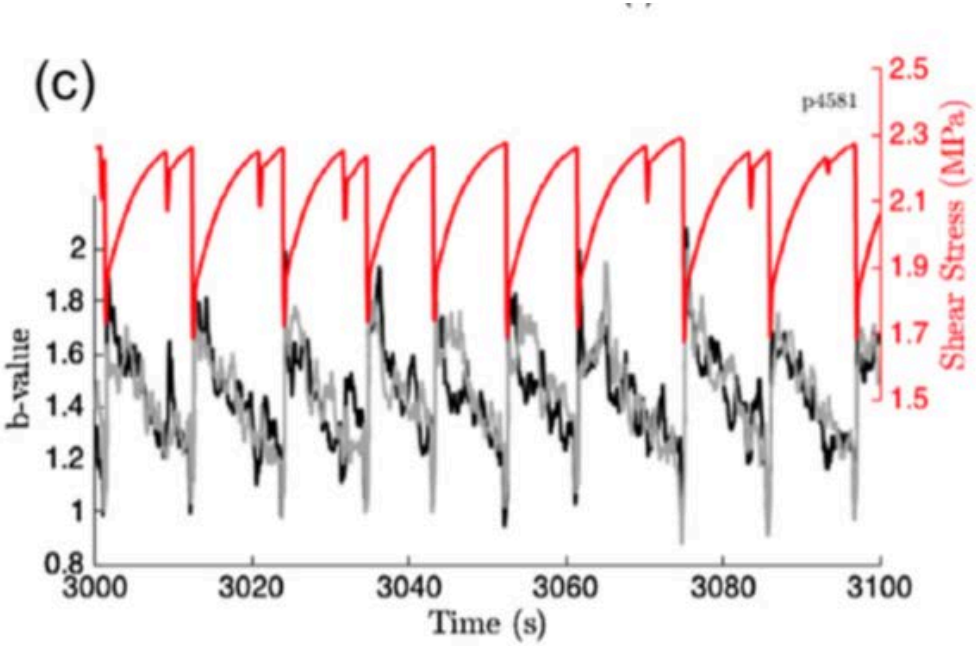
T. H. W. Goebel,[1] D. Schorlemmer,[2] T. W. Becker,[1] G. Dresen,[3] and C. G. Sammis[1]

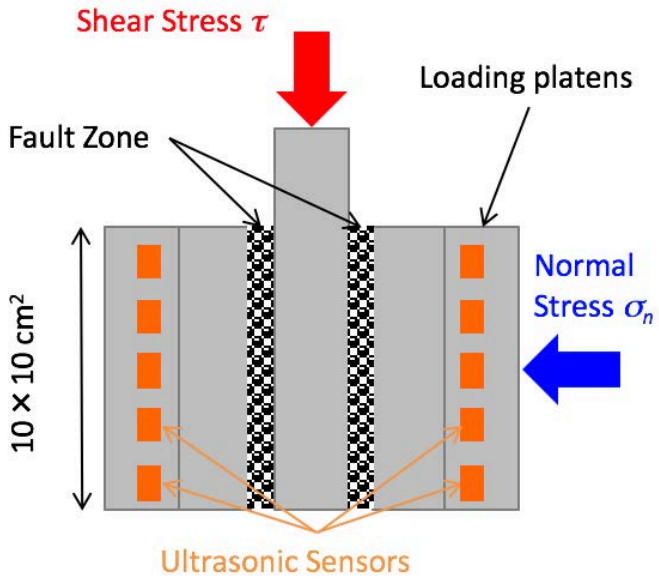


# Evolution of *b*-value during the seismic cycle: Insights from laboratory experiments on simulated faults

EPSL, 2018

J. Rivière [a,b,*], Z. Lv [c,b], P.A. Johnson [d], C. Marone [b]




(seismicity at the lab scale)

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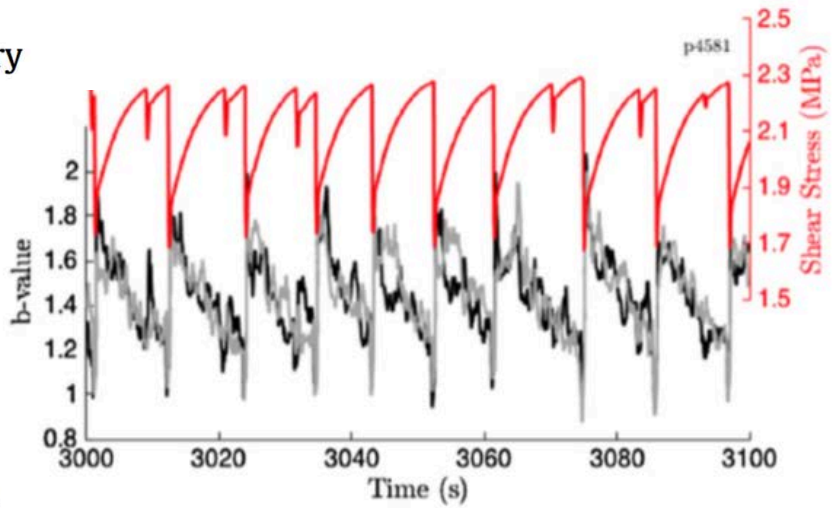
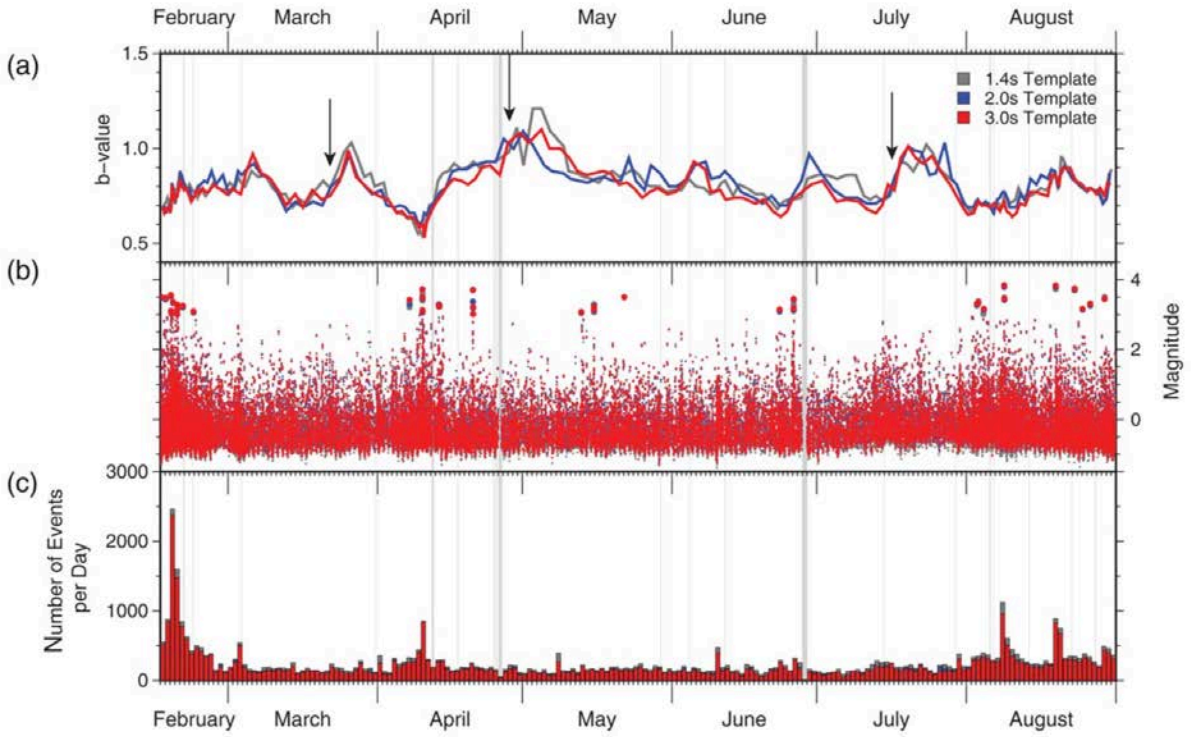



# *Hundreds of Earthquakes per Day: The 2014 Guthrie, Oklahoma, Earthquake Sequence*

**by Harley M. Benz, Nicole D. McMahon, Richard C. Aster, Daniel E. McNamara, and David B. Harris**

SRL, 2015



## Machine Learning Predicts Laboratory Earthquakes

GRL 2017

**Bertrand Rouet-Leduc[1,2], Claudia Hulbert[1], Nicholas Lubbers[1,3], Kipton Barros[1], Colin J. Humphreys[2], and Paul A. Johnson[4]**

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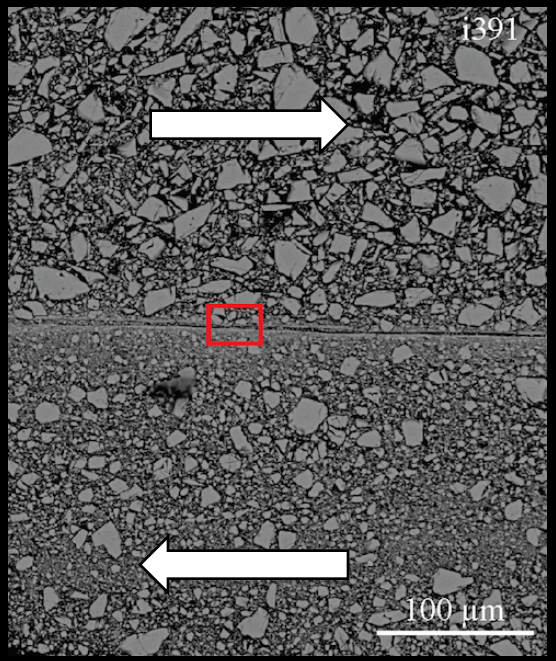
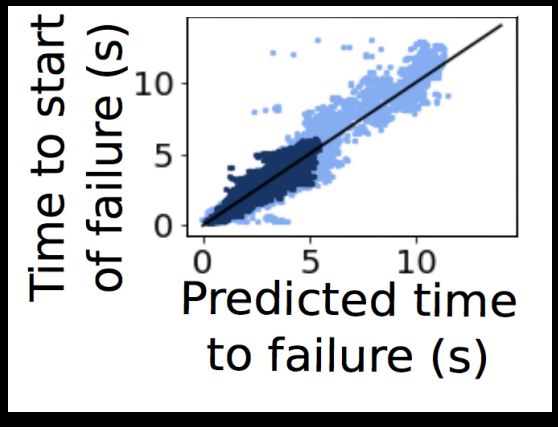
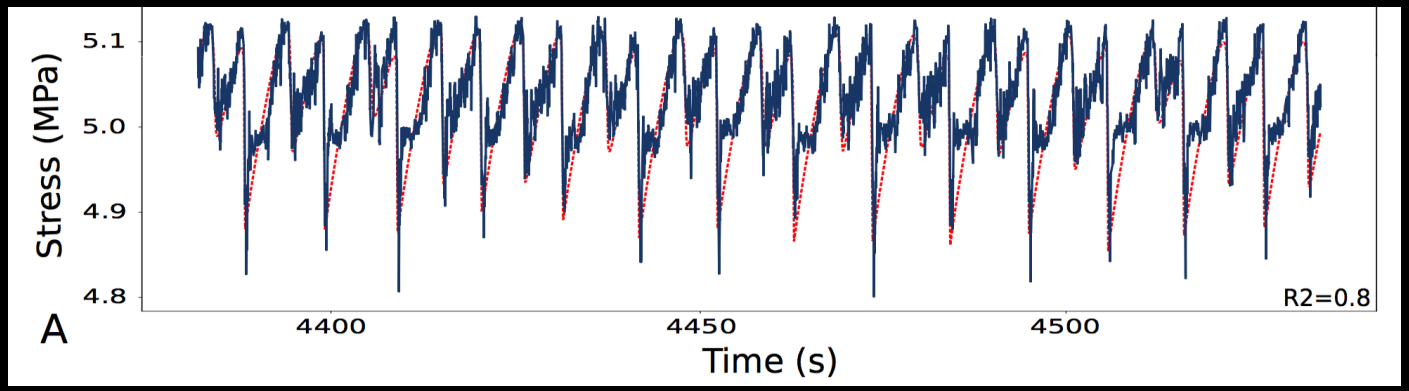
## Estimating Fault Friction From Seismic Signals in the Laboratory

GRL 2018

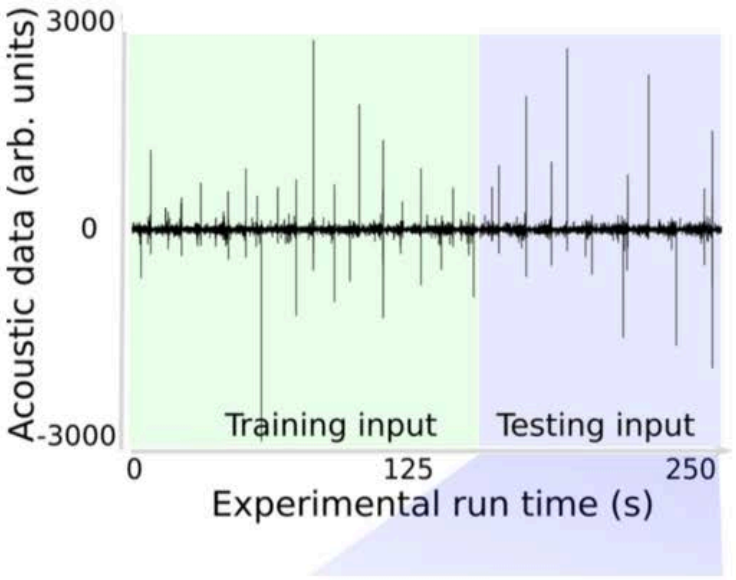
**Bertrand Rouet-Leduc[1], Claudia Hulbert[1], David C. Bolton[2], Christopher X. Ren[3], Jacques Riviere[2,4], Chris Marone[2], Robert A. Guyer[1], and Paul A. Johnson[1]**

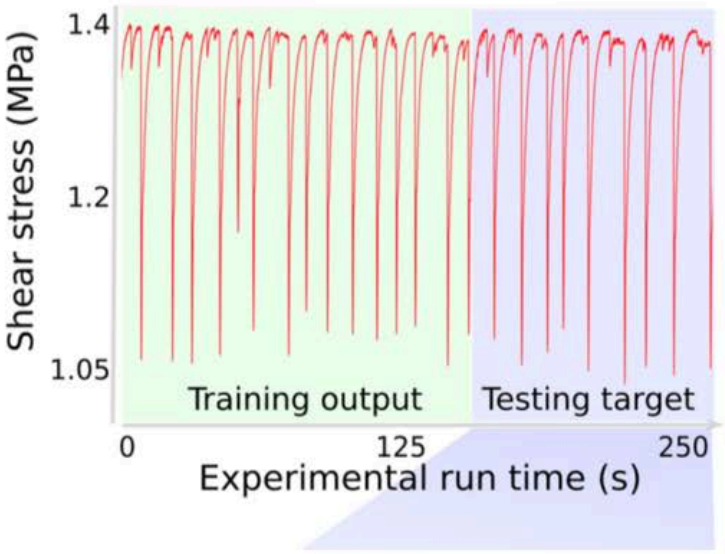


# Supervised machine learning to predict labquakes

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GRL
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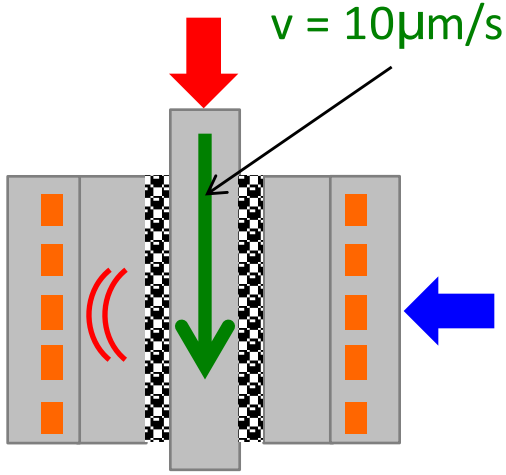

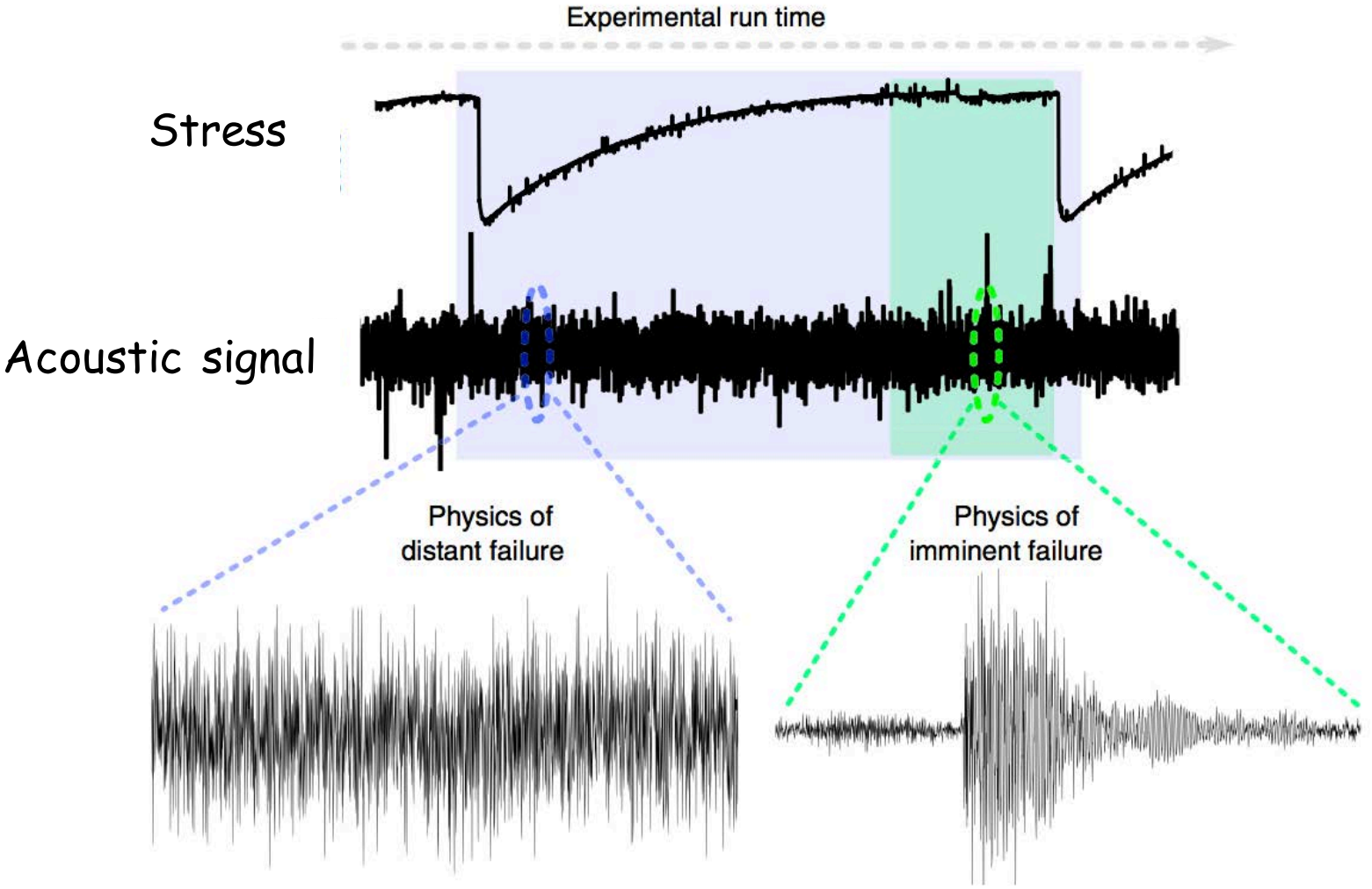


Rouet-Leduc et al., 2017

nature geoscience

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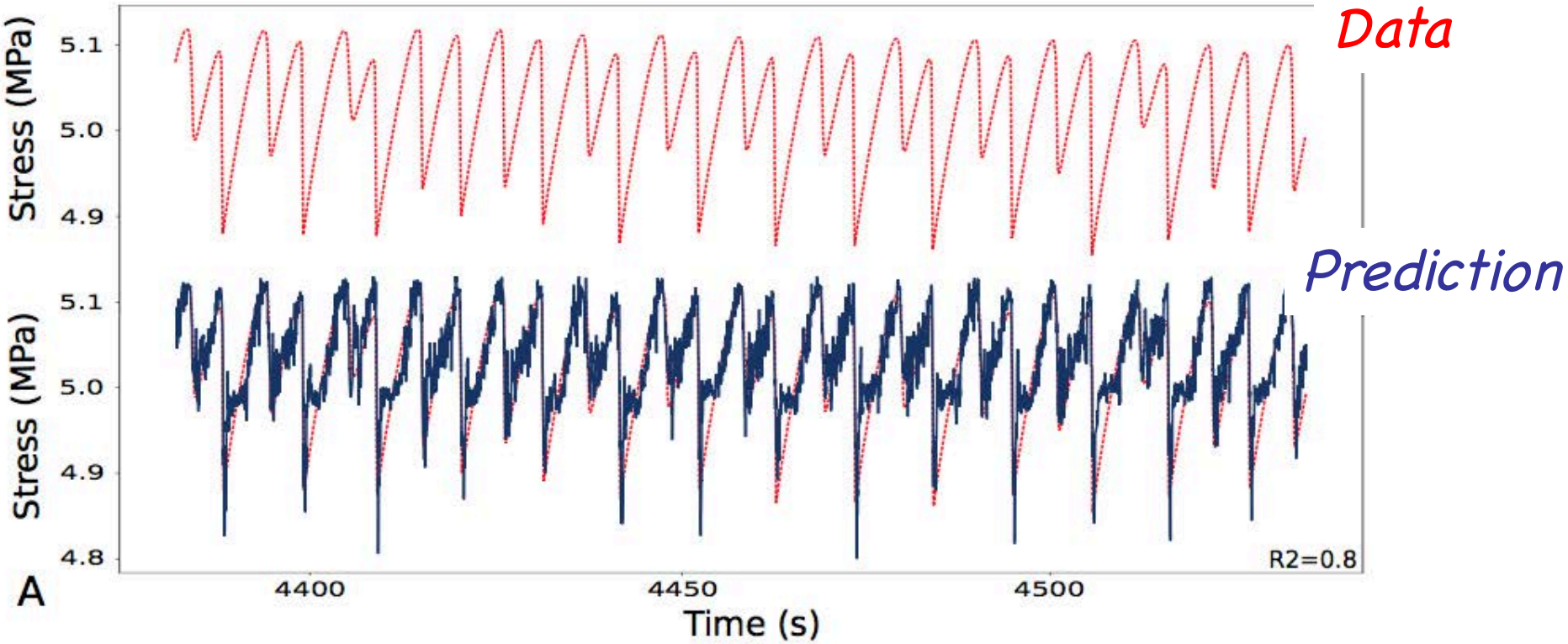
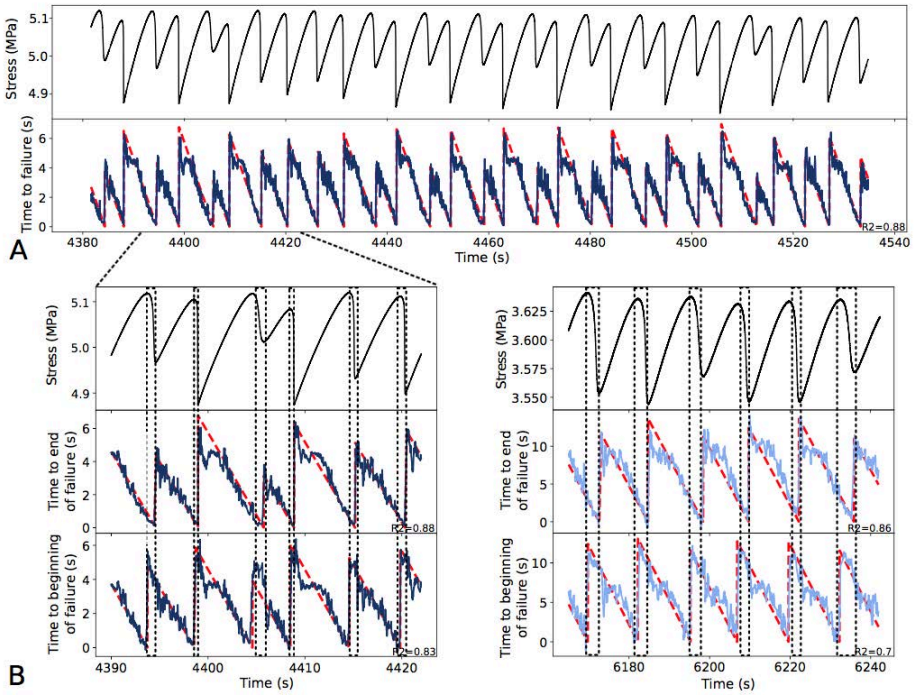
Claudia Hulbert[1]*, Bertrand Rouet-Leduc[1], Paul A. Johnson[1], Christopher X. Ren[1], Jacques Rivière[2], David C. Bolton[3] and Chris Marone[3]

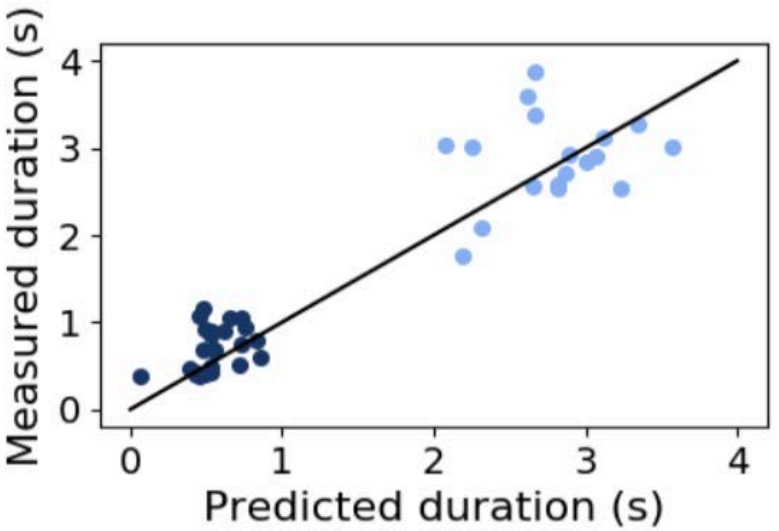
*2019*

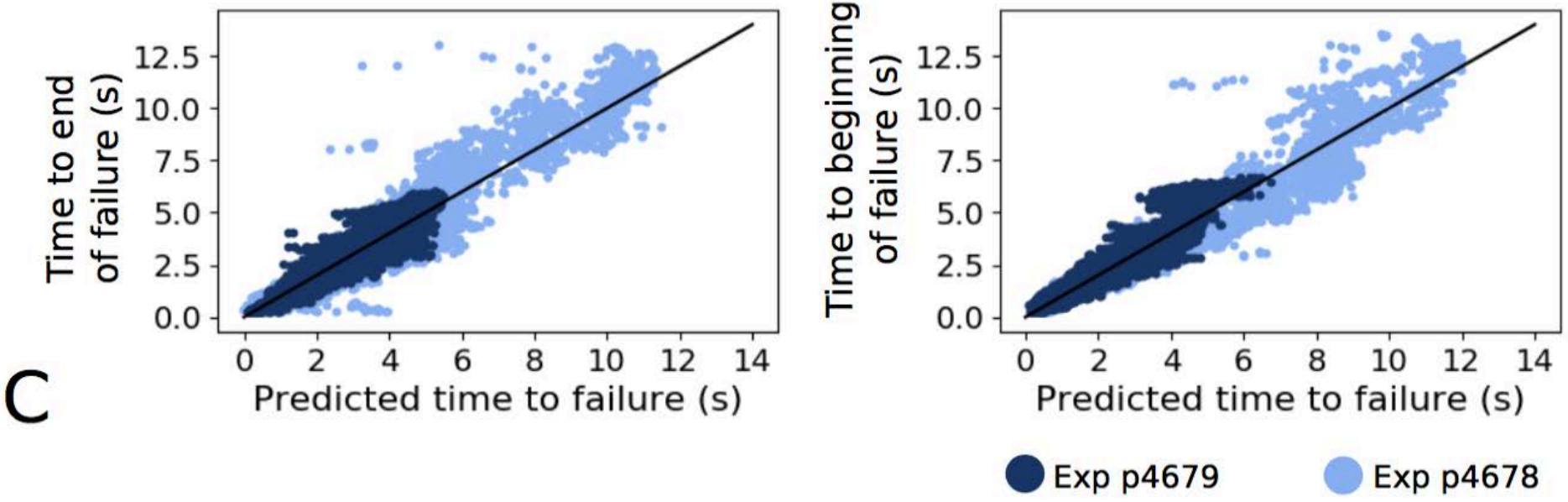



Data

Prediction



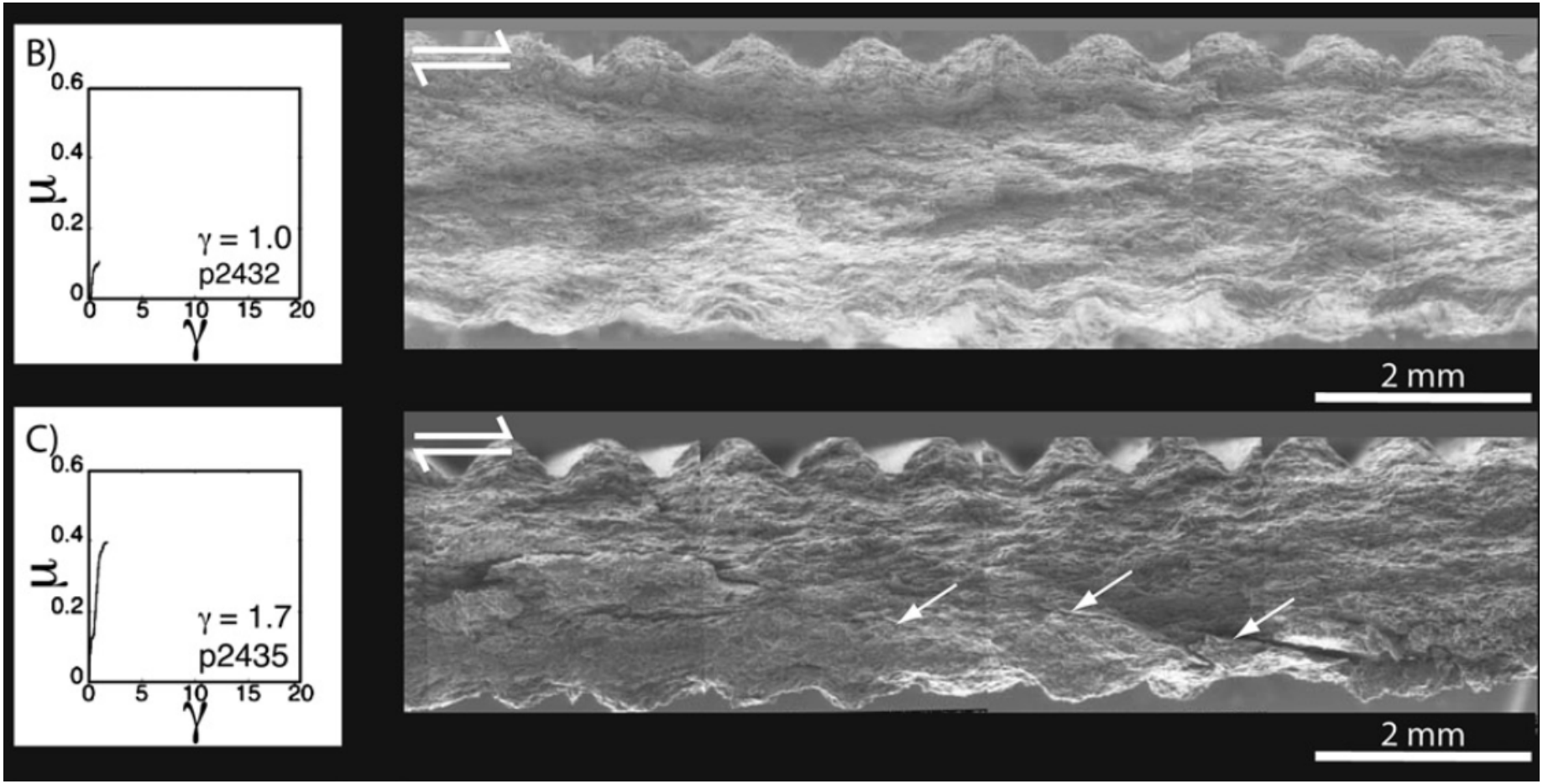




Hulbert et al., 2019

**Physics of laboratory earthquake prediction**.
Do microfailure events define a geometric structure that evolves into catastrophic fault failure?

**Physics of earthquake precursors**.
What are the mechanisms and where do they occur (fault zone, damage zone, wall rock)?



# Laboratory Earthquake Precursors and Prediction
## (for the Spectrum of Fault Slip Modes)

### Precursors to failure

1. Lab earthquakes are preceded by changes in elastic wave speed that occur within the fault zone
2. Changes in b-values are precursors to failure

### Lab earthquake prediction

3. Lab earthquakes are preceded by a cascade of micro-failure events (AE) that radiate elastic energy in a manner that foretells catastrophic failure
4. ML predicts the fault zone stress state, the failure time and in some cases the magnitude of lab earthquakes

# Thank You

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