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 Shreedhar, 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

Precursory changes in seismic velocity for the spectrum of earthquake failure modes
M. M. Scuderi1,2, C. Marone3, E. Tinti4, G. Di Stefano5 and C. Collettini1,2

On the evolution of elastic properties during laboratory stick-slip experiments spanning the transition from slow slip to dynamic rupture
E. Tinti1, C. Marone3, M. M. Scuderi1,2, L. Scognamiglio1, G. Di Stefano3 and C. Collettini1,2

Machine Learning Predicts Laboratory Earthquakes
Bertrand Rouet-Leduc1,2, Claudia Hulbert1, Nicholas Lubbers1,3, Kipton Barros1, Colin J. Humphreys2, and Paul A. Johnson4

Similarity of fast and slow earthquakes illuminated by machine learning
Claudia Hulbert1, Bertrand Rouet-Leduc1, Paul A. Johnson1, Christopher X. Ren1, Jacques Rivière2, David C. Bolton3 and Chris Marone3

US NSF IGPPS/CSES
INGV, Roma
changes in some physical property of a fault zone prior to failure
changes in some physical property of a fault zone prior to failure prediction of that failure
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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E. Tinti\textsuperscript{1} \textsuperscript{d}, M. M. Scuderi\textsuperscript{1,2} \textsuperscript{d}, L. Scognamiglio\textsuperscript{1} \textsuperscript{d}, G. Di Stefano\textsuperscript{1} \textsuperscript{d}, C. Marone\textsuperscript{3} \textsuperscript{d}, and C. Collettini\textsuperscript{1,2} \textsuperscript{d}
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.
Precursory changes in seismic velocity for the spectrum of earthquake failure modes

M. M. Scuderi\textsuperscript{1,2*}, C. Marone\textsuperscript{3}, E. Tinti\textsuperscript{2}, G. Di Stefano\textsuperscript{2} and C. Collettini\textsuperscript{1,2}

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

![Graphs showing Silent Slow-Slip and Fast Stick-Slip](image-url)
Silent Slow-Slip

Inter-Seismic
Pre-Seismic
Co-Seismic

Fast Stick-Slip

Inter-Seismic
Pre-Seismic
Co-Seismic

Shear Stress ($\tau$), MPa

Changes in $V_p$, m/s

Shear Stress ($\tau$), MPa

Slip Velocity, mm/s

0.1 MPa
20 m/s
0.2 MPa
20 m/s

Comparison with natural earthquakes and slow-slip

Laboratory Observations

Natural Observations

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
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.
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. Sammis1
Evolution of $b$-value during the seismic cycle: Insights from laboratory experiments on simulated faults

J. Rivière$^{a,b,*}$, Z. Lv$^c,b$, P.A. Johnson$^d$, C. Marone$^b$

(seismicity at the lab scale)
Evolution of $b$-value during the seismic cycle: Insights from laboratory experiments on simulated faults

J. Rivière$^{a,b,*}$, Z. Lv$^c$, P.A. Johnson$^d$, C. Marone$^b$

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

Bertrand Rouet-Leduc, Claudia Hulbert, Nicholas Lubbers, Kipton Barros, Colin J. Humphreys, and Paul A. Johnson

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Estimating Fault Friction From Seismic Signals in the Laboratory

Bertrand Rouet-Leduc, Claudia Hulbert, David C. Bolton, Christopher X. Ren, Jacques Riviere, Chris Marone, Robert A. Guyer, and Paul A. Johnson

Time to start of failure (s)
Predicted time to failure (s)

Stress (MPa)

Time (s)
Supervised machine learning to predict labquakes

Estimating Fault Friction From Seismic Signals in the Laboratory

Bertrand Rouet-Leduc¹, Claudia Hulbert¹, David C. Bolton², Christopher X. Ren³, Jacques Riviere², Chris Marone², Robert A. Guyer¹, and Paul A. Johnson¹

GRL 2018
Acoustic signal

Stress

Experimental run time

Physics of distant failure

Physics of imminent failure

Rouet-Leduc et al., 2017
Similarity of fast and slow earthquakes illuminated by machine learning

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

2019
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)?
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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
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