Earthquakes Under the Lens of Rock Physics

From Analog Materials in the Lab to Rocks in the Field

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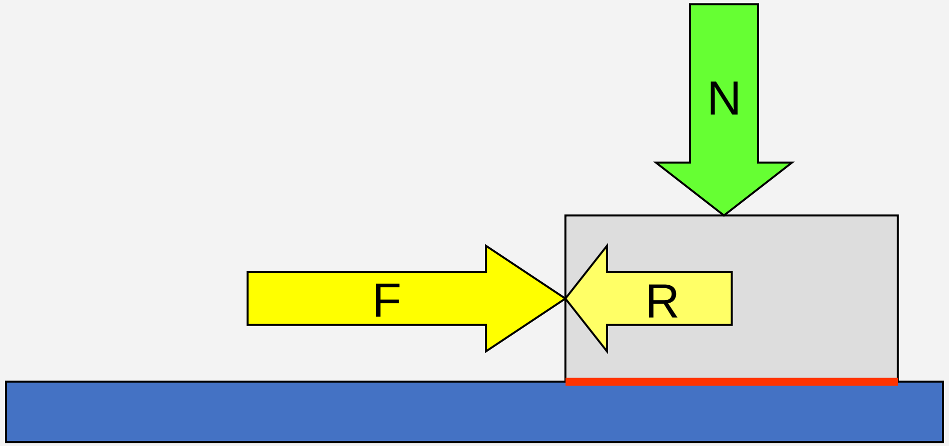
TEXAS Geosciences
The University of Texas at Austin
Jackson School of Geosciences

A new way to simulate Earthquakes reveals the influence of Weakening/Strengthening processes on Slip Velocity and Seismic Signature

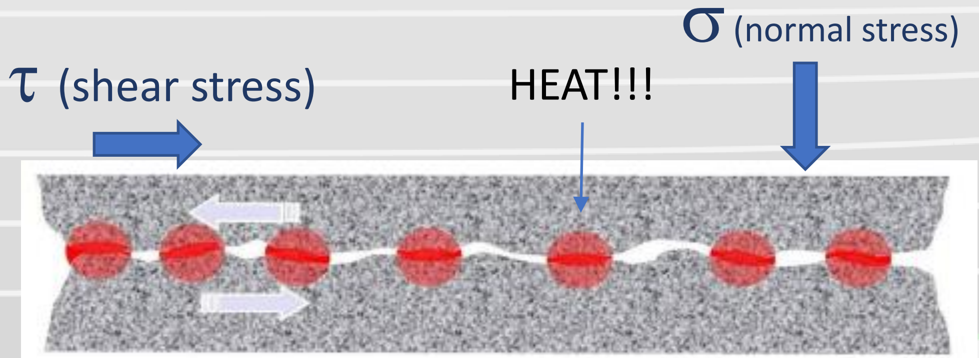
Conrad et al., 2022, JGR-SE, Influence of Frictional Melt on the Seismic Cycle: Insights from Experiments on Rock Analog Material

On the same page…

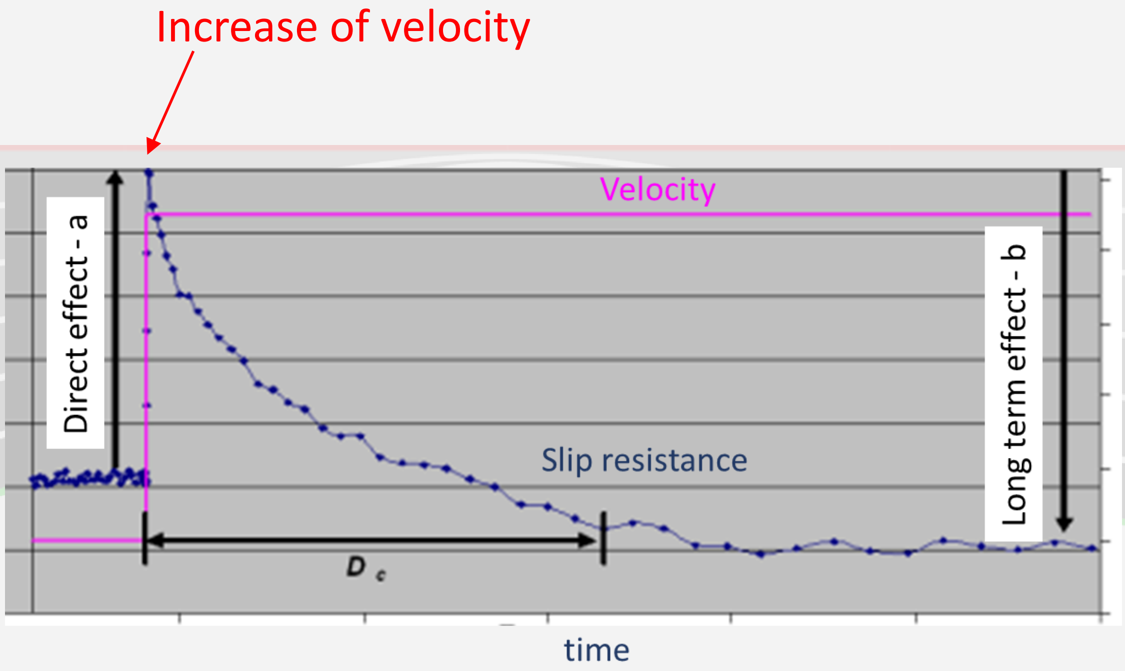
Friction coeff. (μ) = Resistance (R) / Normal load (N)



$$\mu=\tau/\sigma$$

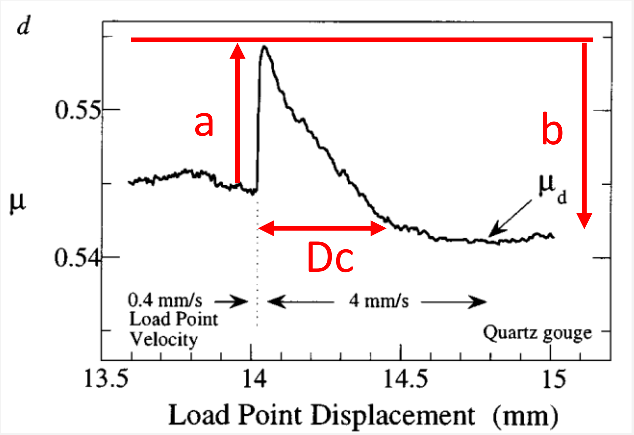


e.g.,Flash Heating and Weakening, Rice, 1999, 2006



Stiffness influences stable vs unstable behavior

$k\ (\sim elastic\ stiffness)$



critical weakening rate with slip

$$k_c = \frac{\sigma_n' \,(b-a)}{D_c}$$

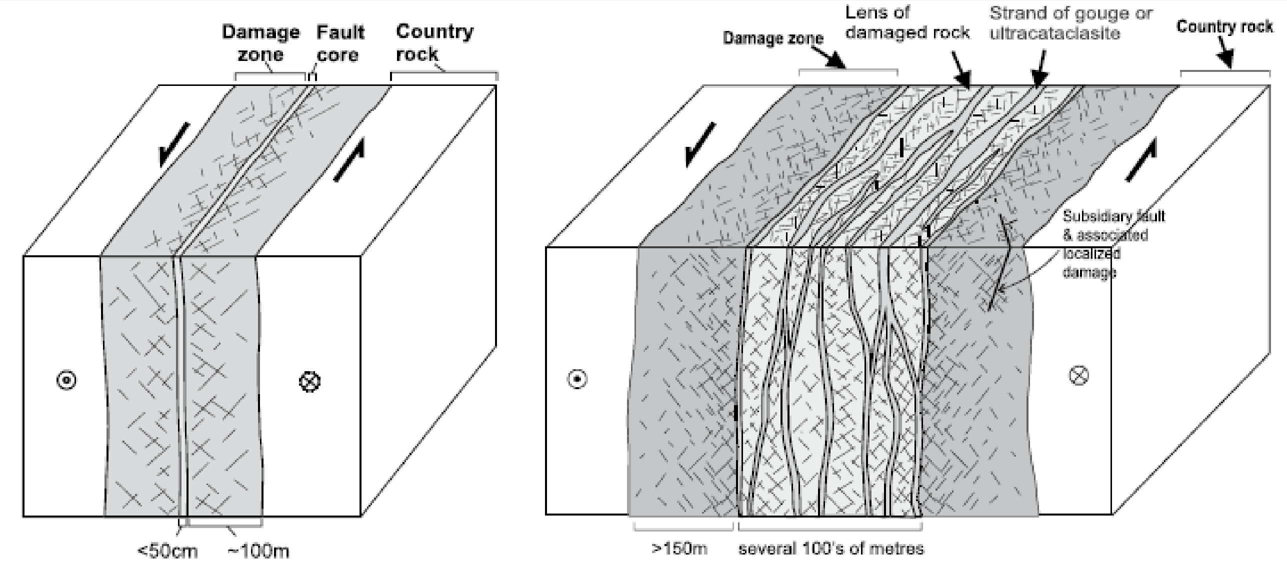
$$when\ k < k_c\ the\ system\ is\ unstable\ producing\ large\ slip\ events$$

Leeman et al., 2016: For $\kappa < 1$ ($\kappa = k/k_c$), the system will be unstable, storing elastic strain energy and then releasing it dynamically (e.g., Gu et al., 1984; Rice, 1983).

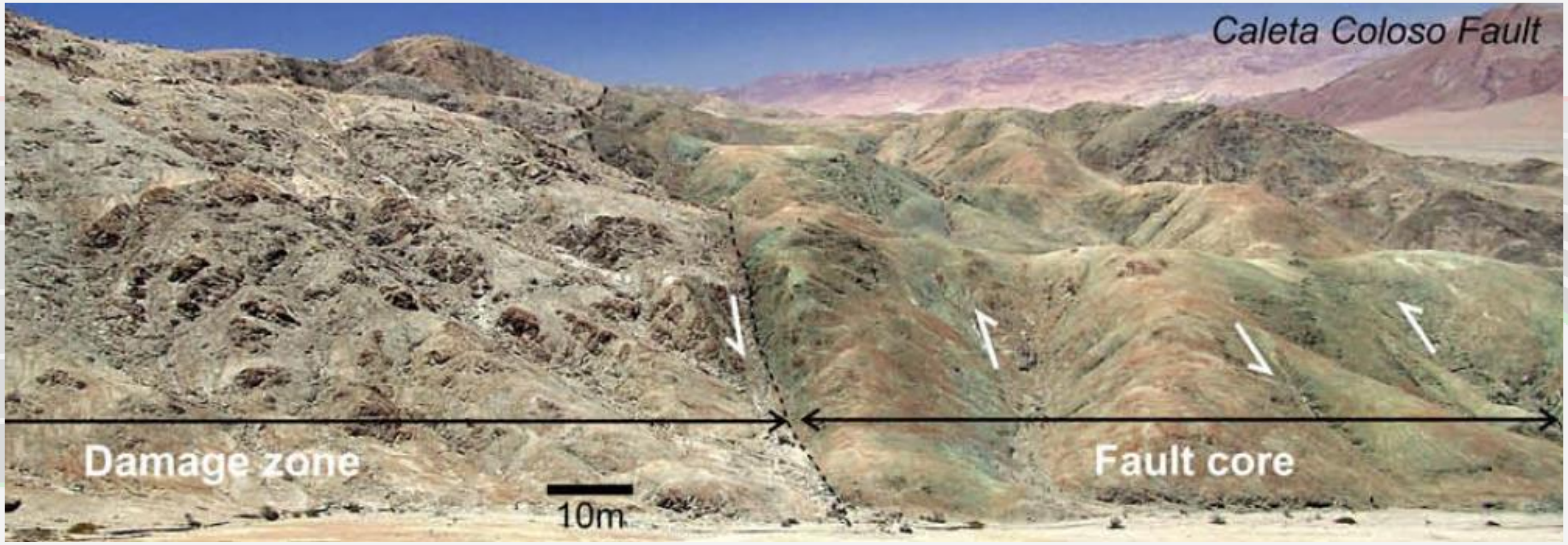
$$W = \frac{1}{2} k\, x^2 \,(\text{work and stored energy})$$

σ_n' ~normal stress
D_c critical slip distance

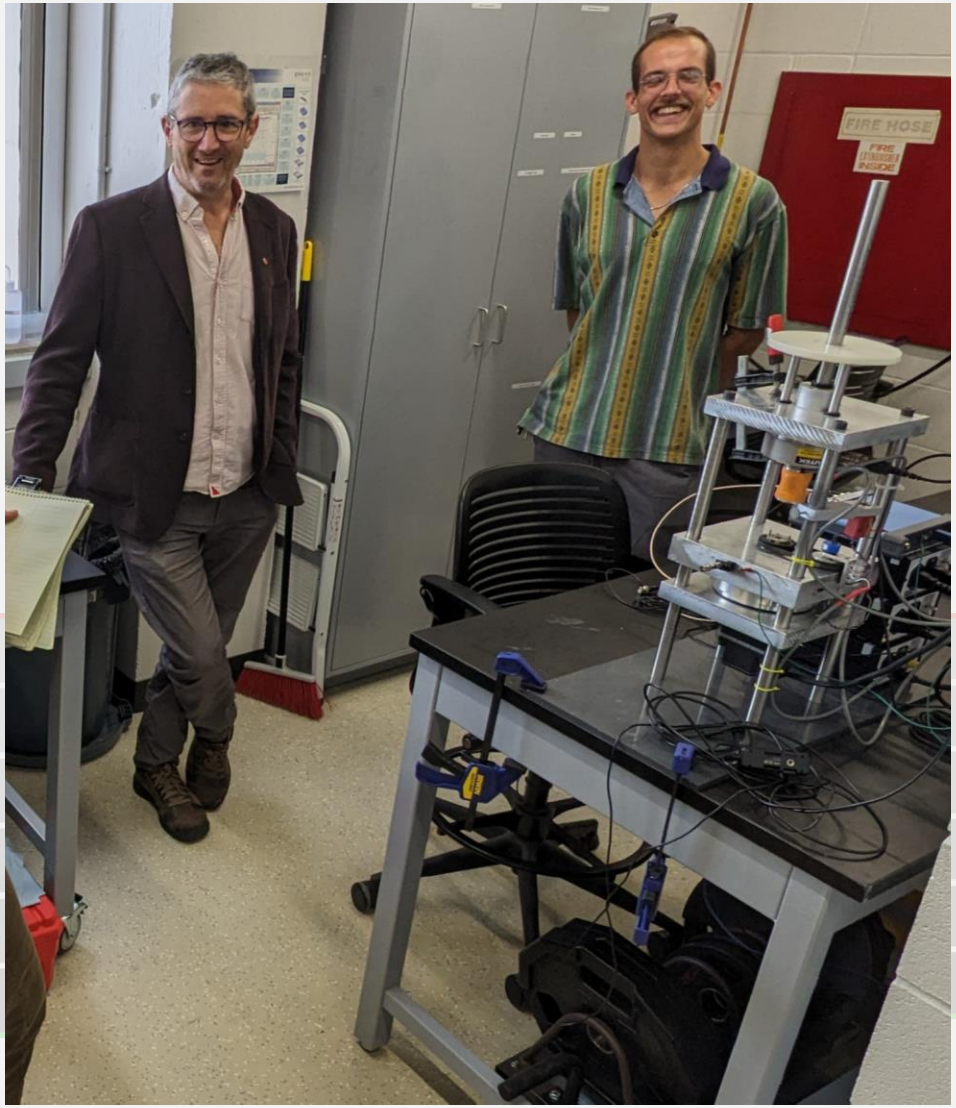
Gu et al., 1984; Rice, 1983

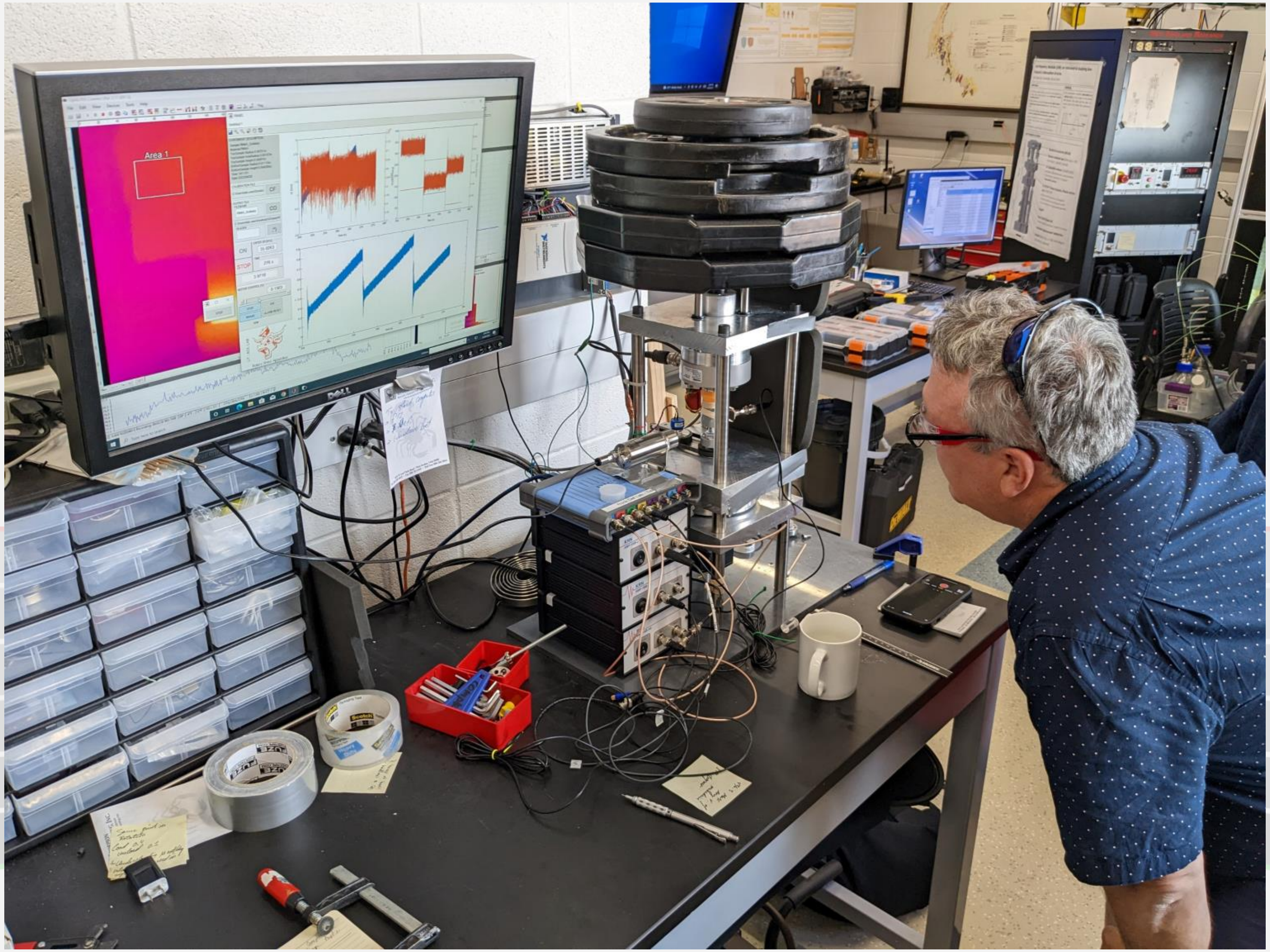


Mitchell and Faulkner, 2009 … and many others



Stick-slip and Rotary shear experiments





Slow vs fast

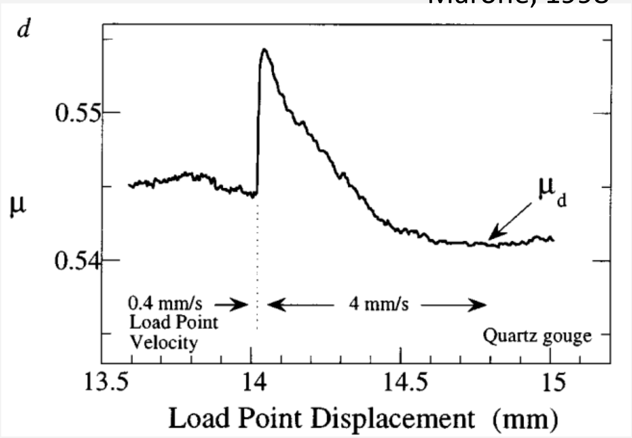
- At **slow slip rates**, the friction coefficient (**μ**) in many crustal rocks is **roughly 0.6** (e.g., Byerlee, 1978; Marone, 1998)
- **Much higher than** the values observed at **high slip rates** (e.g., Di Toro et al., 2011)
- **Low μ** is supported by field observations, e.g., **lack of thermal anomaly** around seismogenic faults suggesting that **weakening mechanisms "lubricate" faults** (e.g., Lachenbruch, 1980;Rice, 2006; Noda & Lapusta, 2013; Pozzi et al., 2019)

Slow

Stick–slip {to study friction instability}

- Brace & Byerlee, 1966; Dieterich, 1978; Ruina, 1983; Marone, 1998; Carpenter et al., 2015 …(and many others)

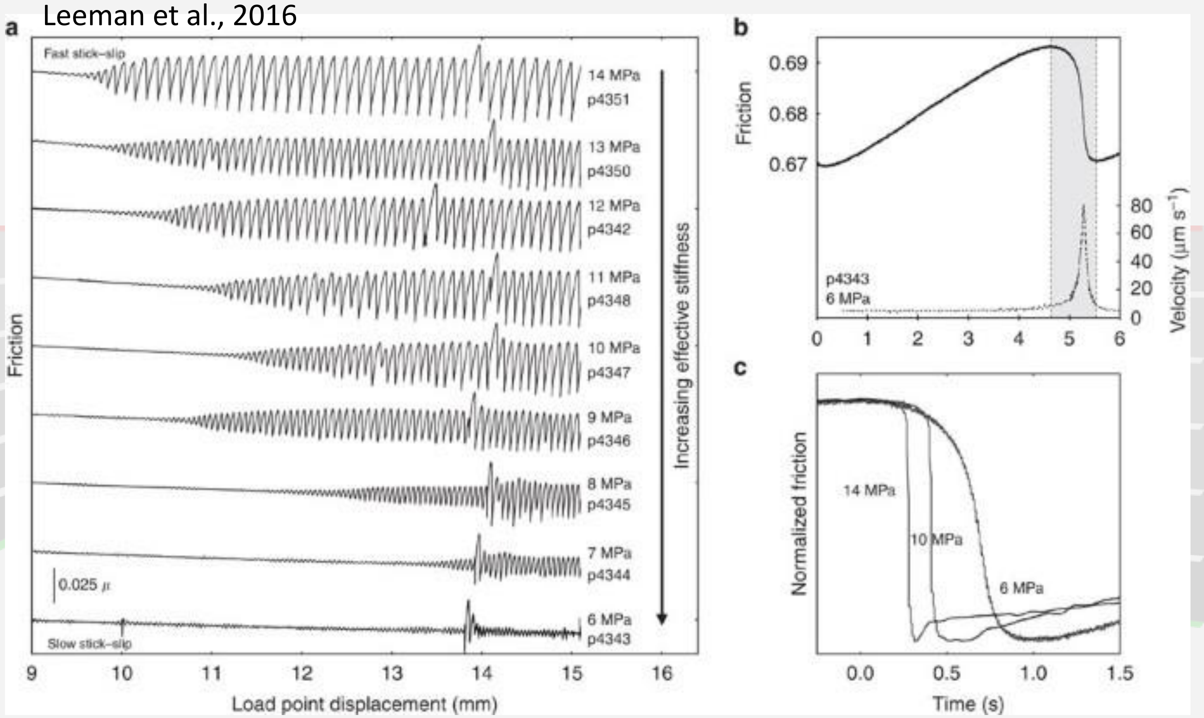
Marone, 1998



- **~Spontaneous slip**
- **Small velocity and slip (<mm/s <mm)**

- Leeman et al., 2016: proposed to tune the machine stiffness to change the slip response

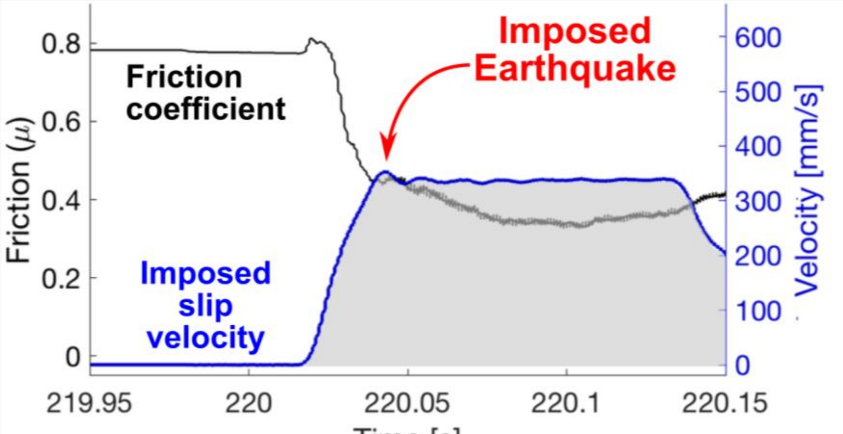
Leeman et al., 2016



Fast

Rotary {to study weakening mechanisms}

- Di Toro et al., 2011; Goldsby & Tullis, 2011; Hayes et al., 2011; Hirose &Shimamoto, 2005; Reches & Lockner, 2010; Tisato et al., 2012…(and others)



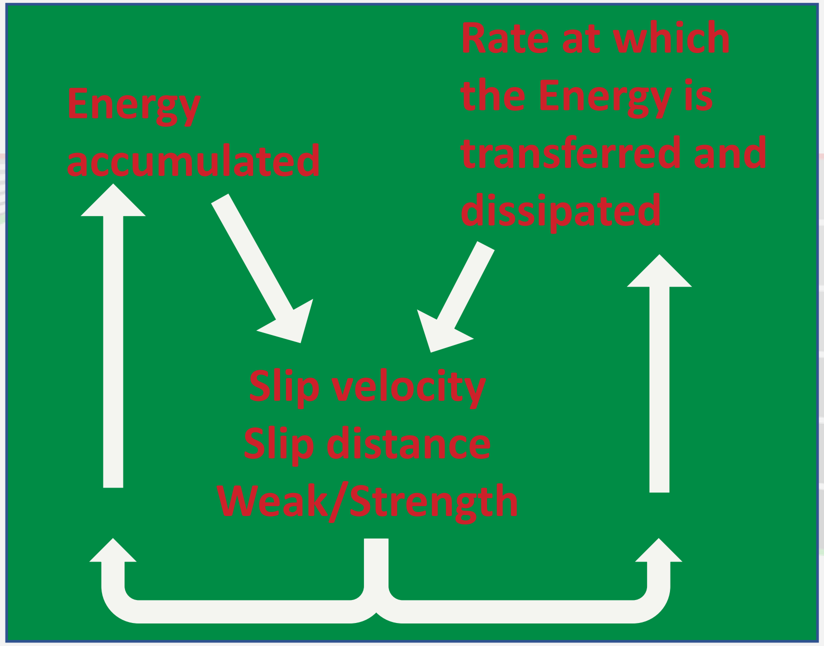
Tisato et al., 2012

- **Co-seismic velocity and slip distance (m/s, m)**

- **No spontaneous slip***

vs

The co-seismic feedback

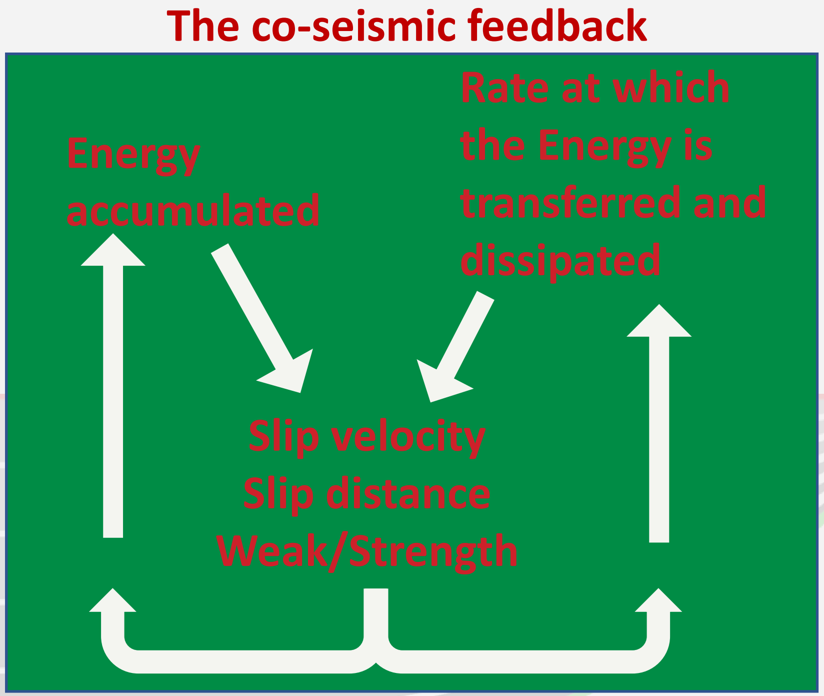


- But some have tried energy and torque boundary conditions to rotary shear (Chang et al., 2012; Reches & Lockner, 2010; Rieger, 2013; Spagnuolo et al., 2012)

*** As borrowed from engineering**

Hypothesis: Slip behavior and friction are a

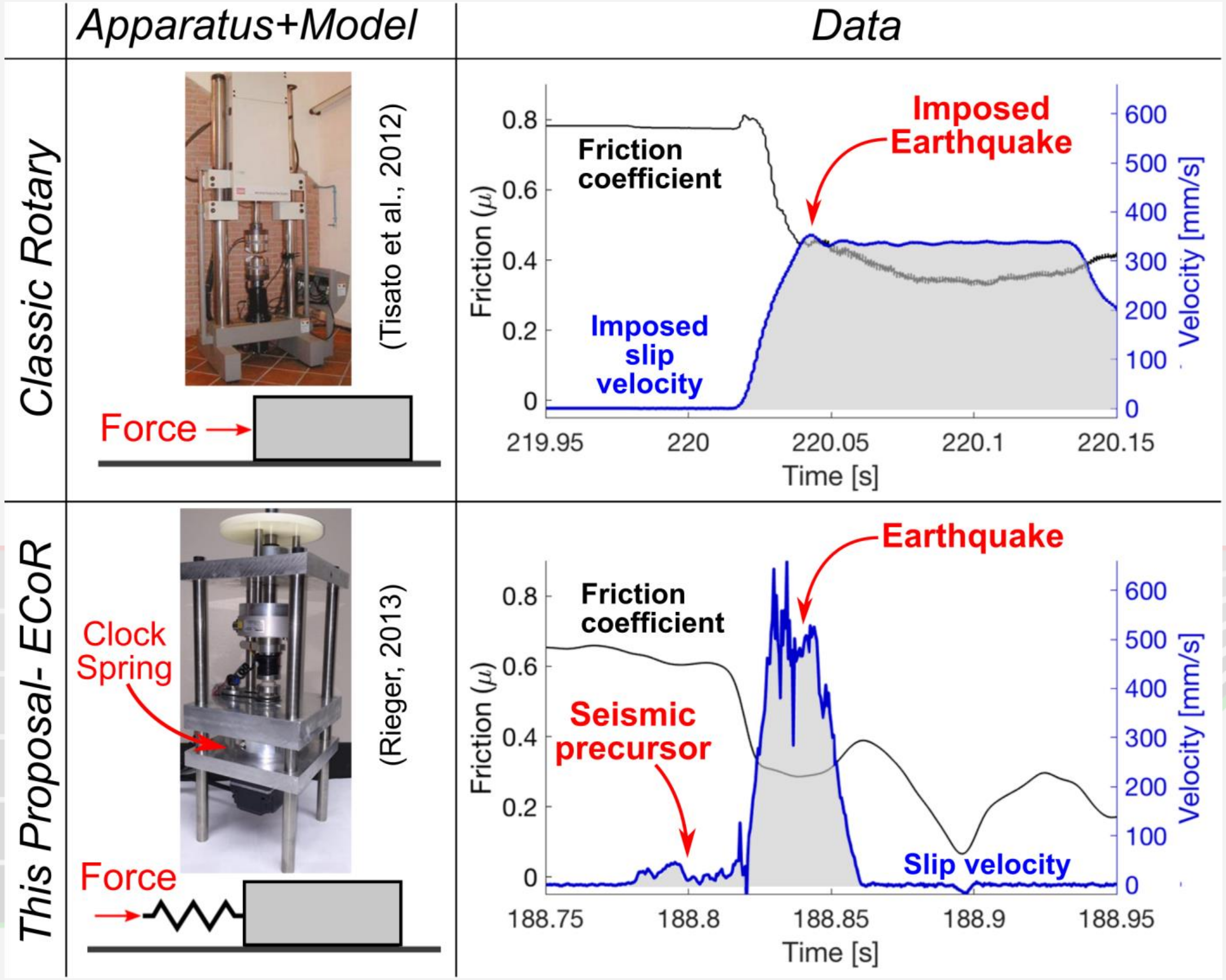
- function of the weakening and strengthening mechanisms activated at high slip rate

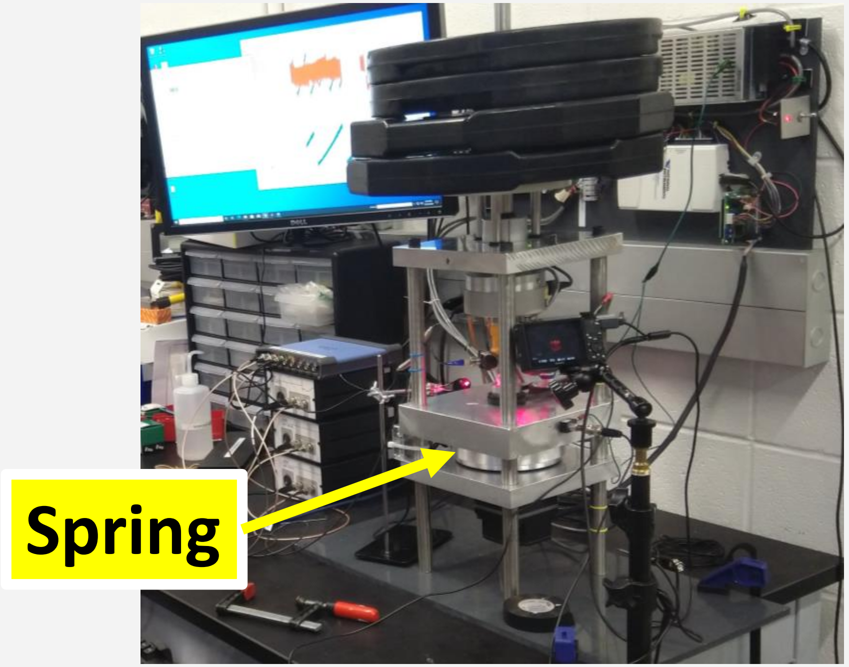


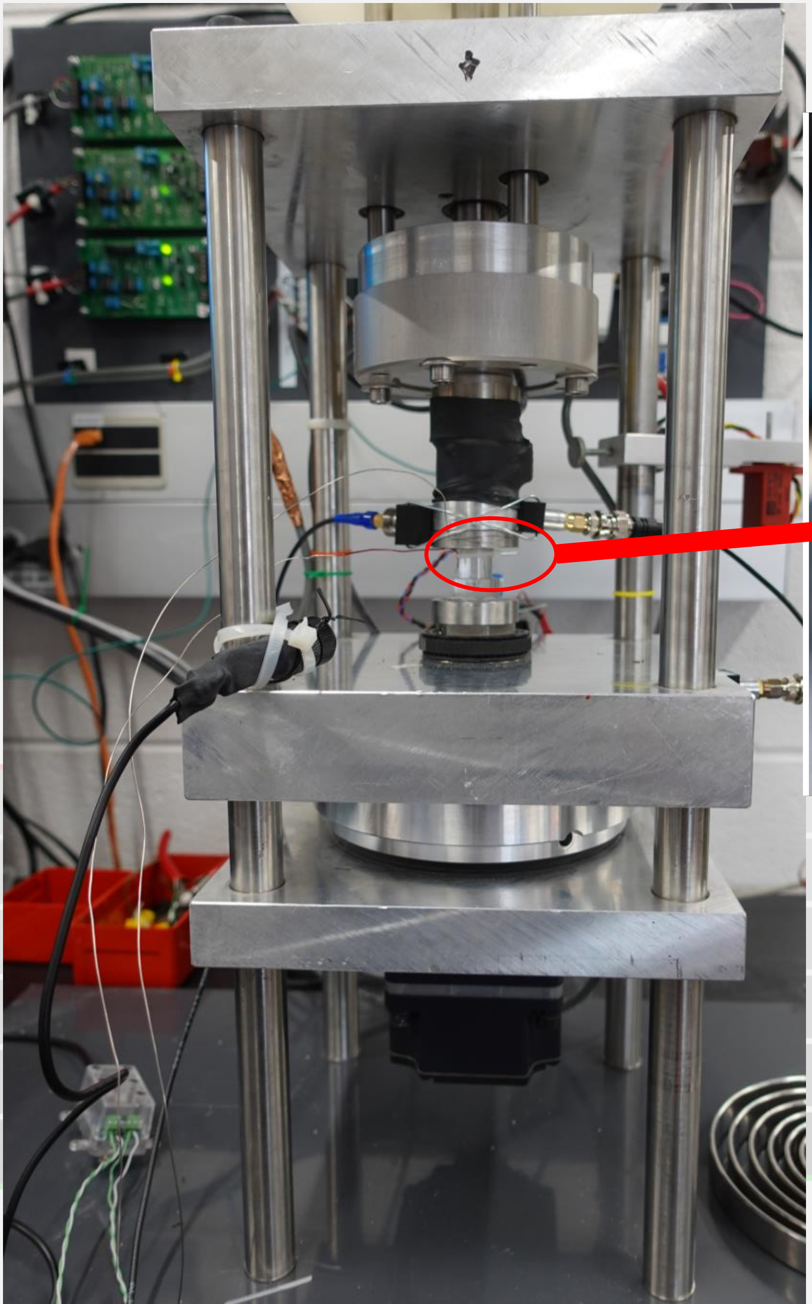
**Is it a Mass (Energy) Optimal Transport problem?*

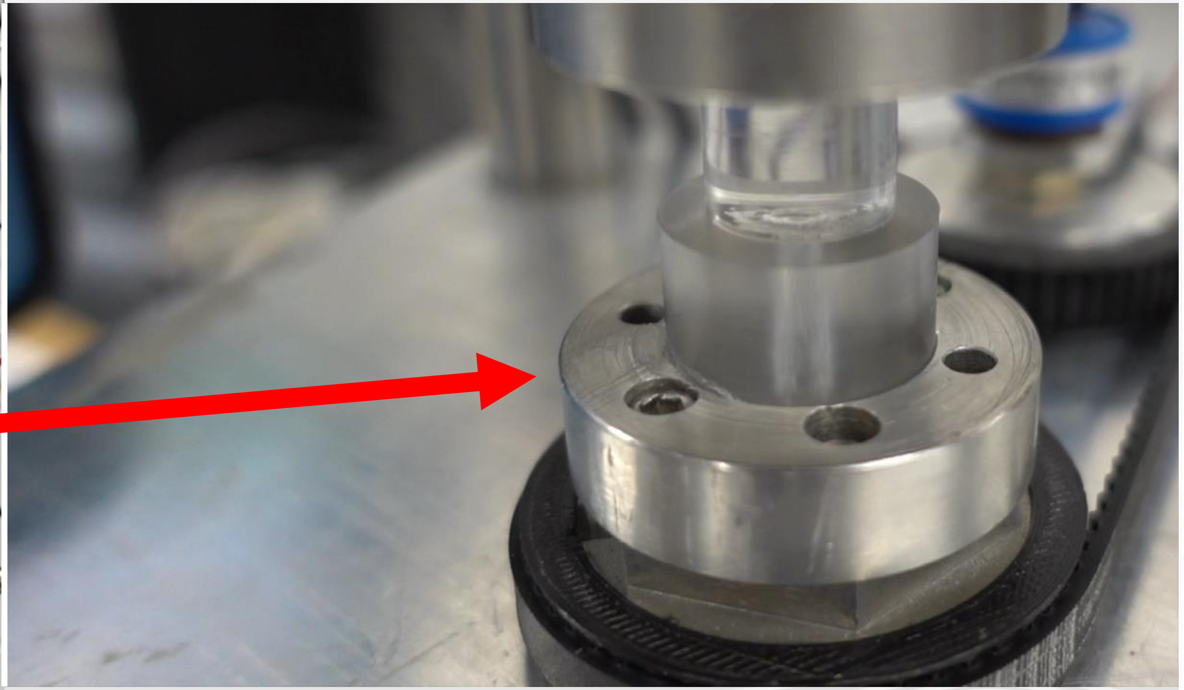
Energy Controlled Energy Rotary Shear apparatus (ECoR)

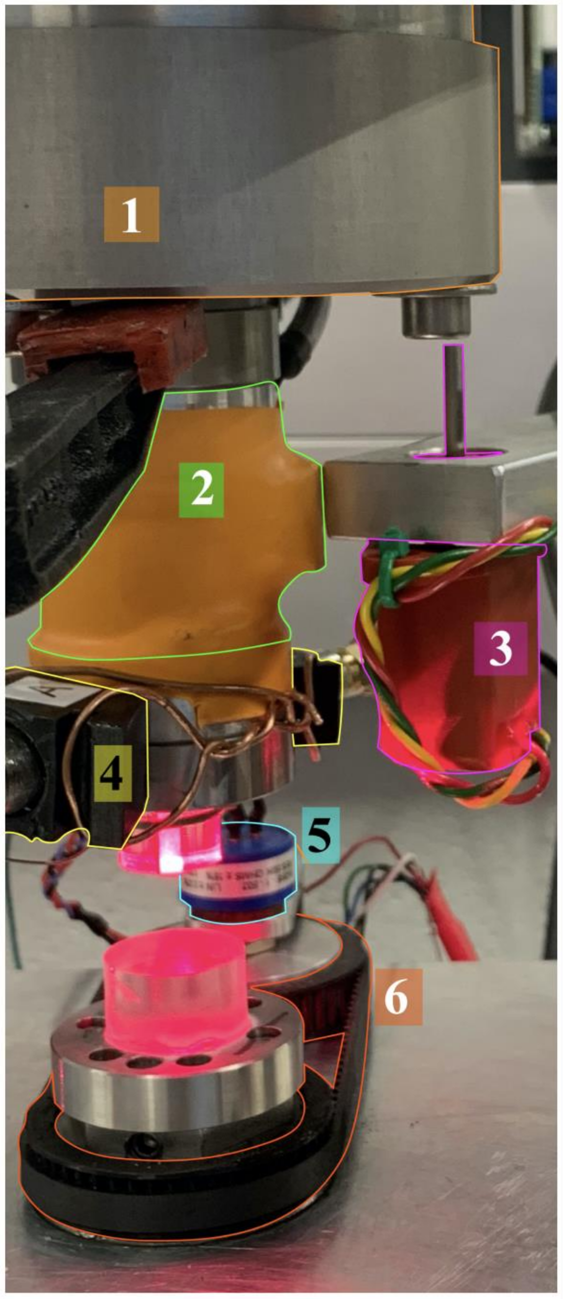
Thanks to Dr. Cordonnier



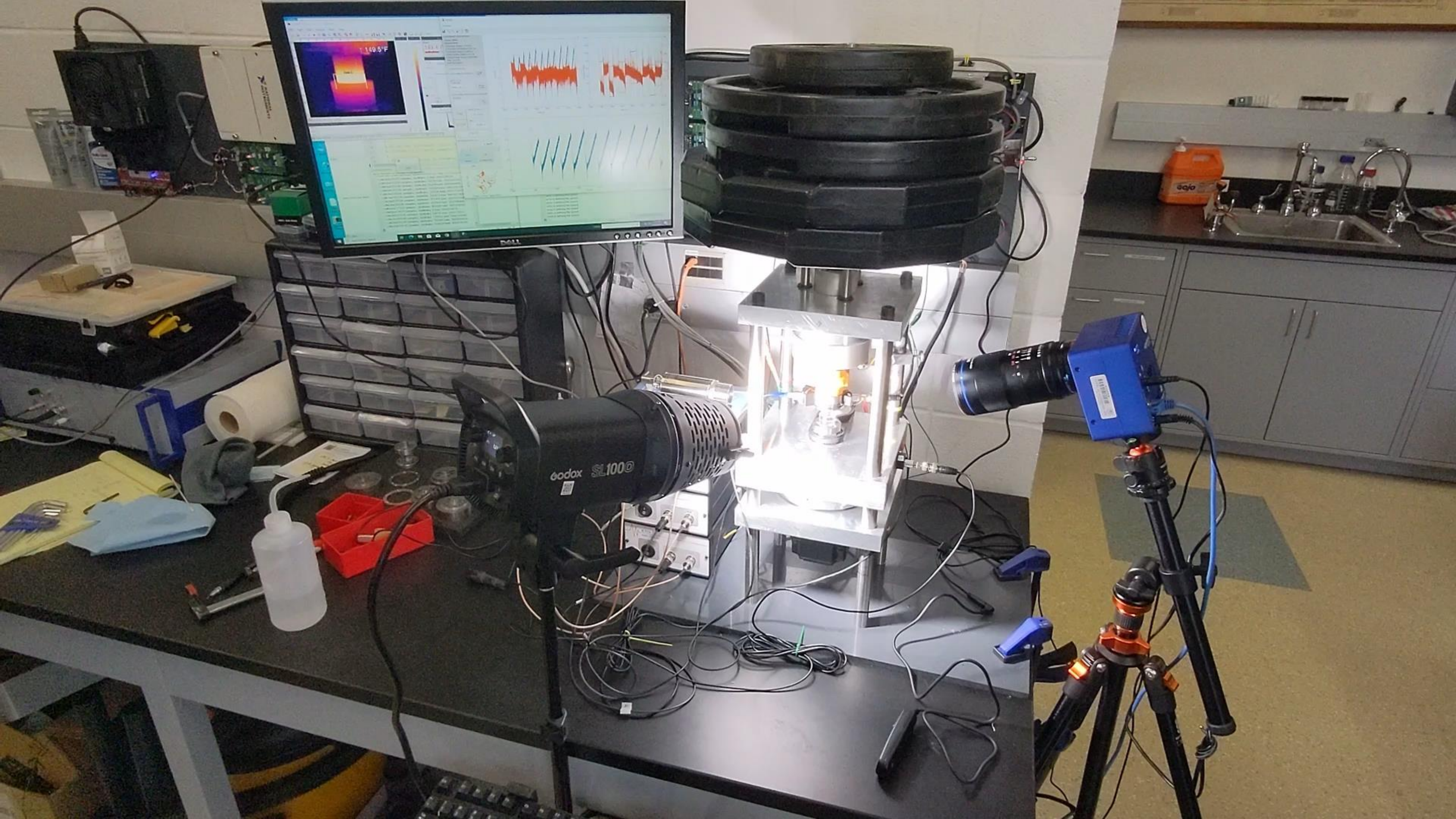






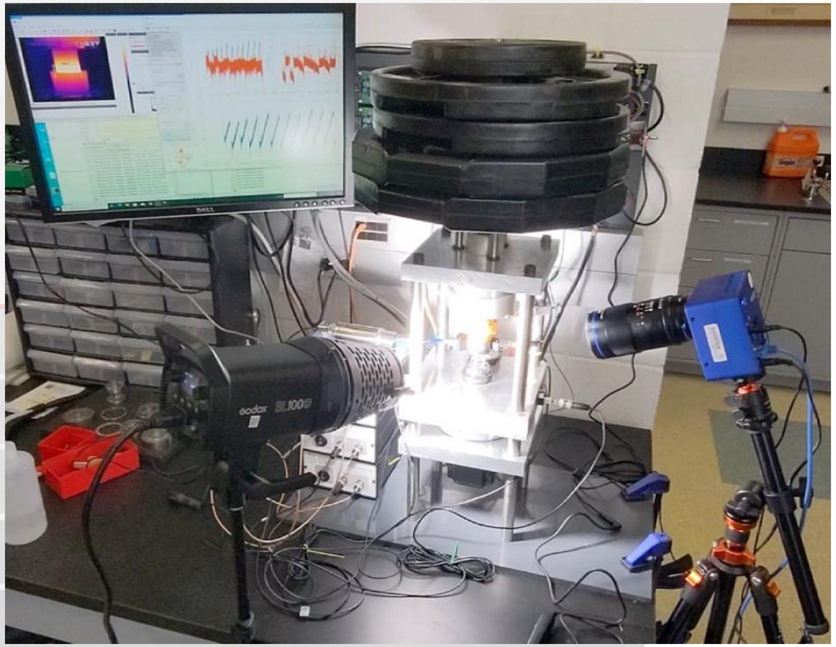


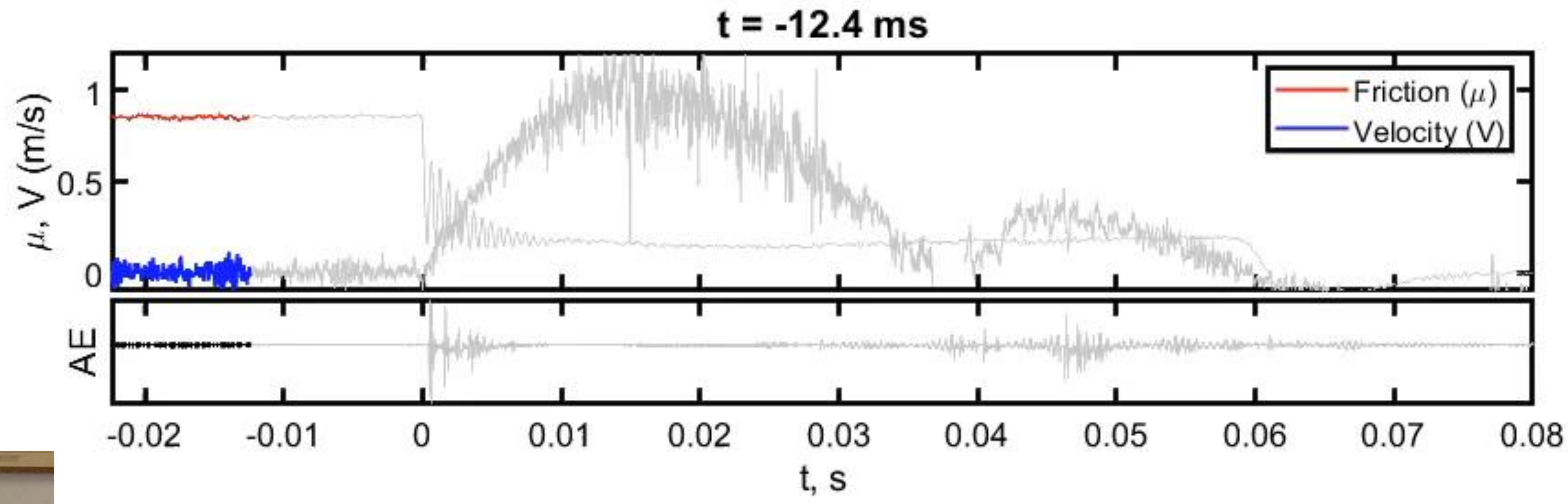
LEGEND
1: Load cell
2: Torque cell
3: Vertical displacement sensor
4: Acoustic Emission sensor
5,6: Slip distance sensor

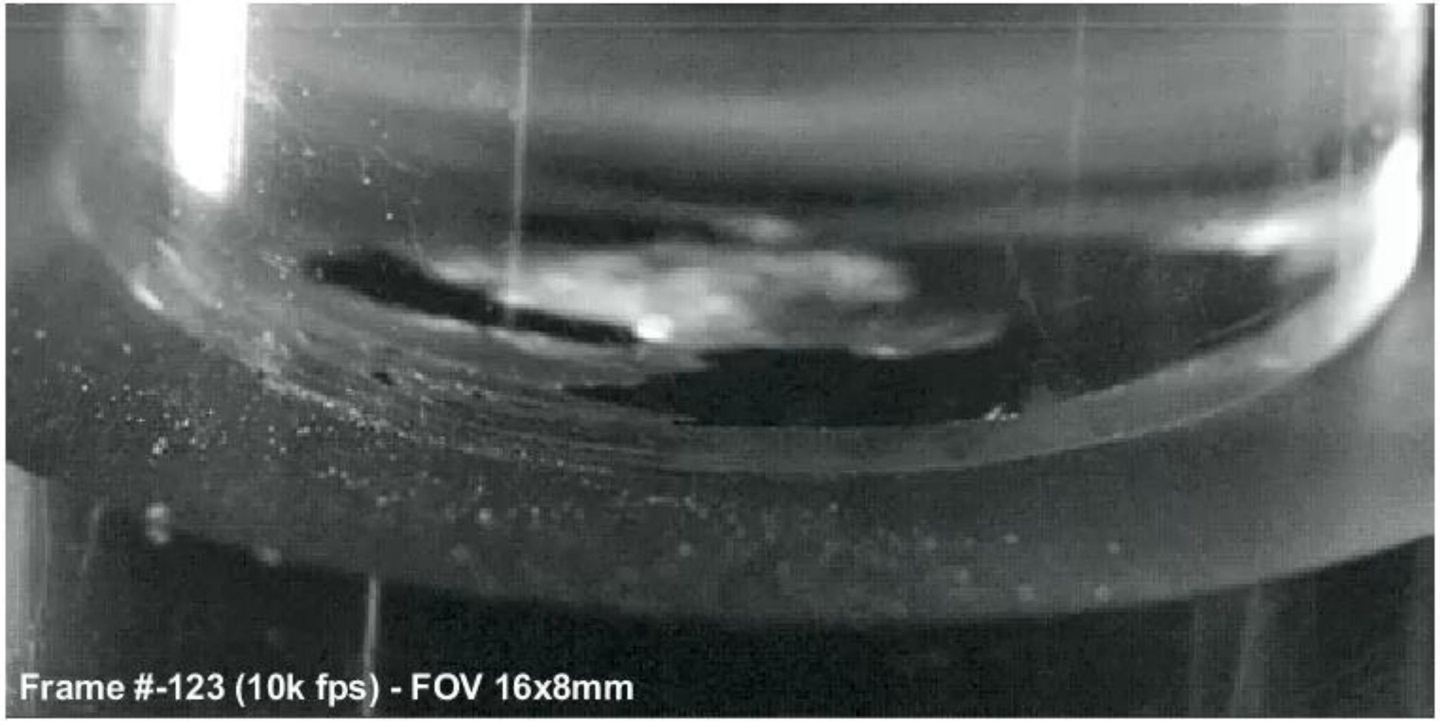

149.5°F
DELL
Godox
SL100D
GOJO

At a glance...

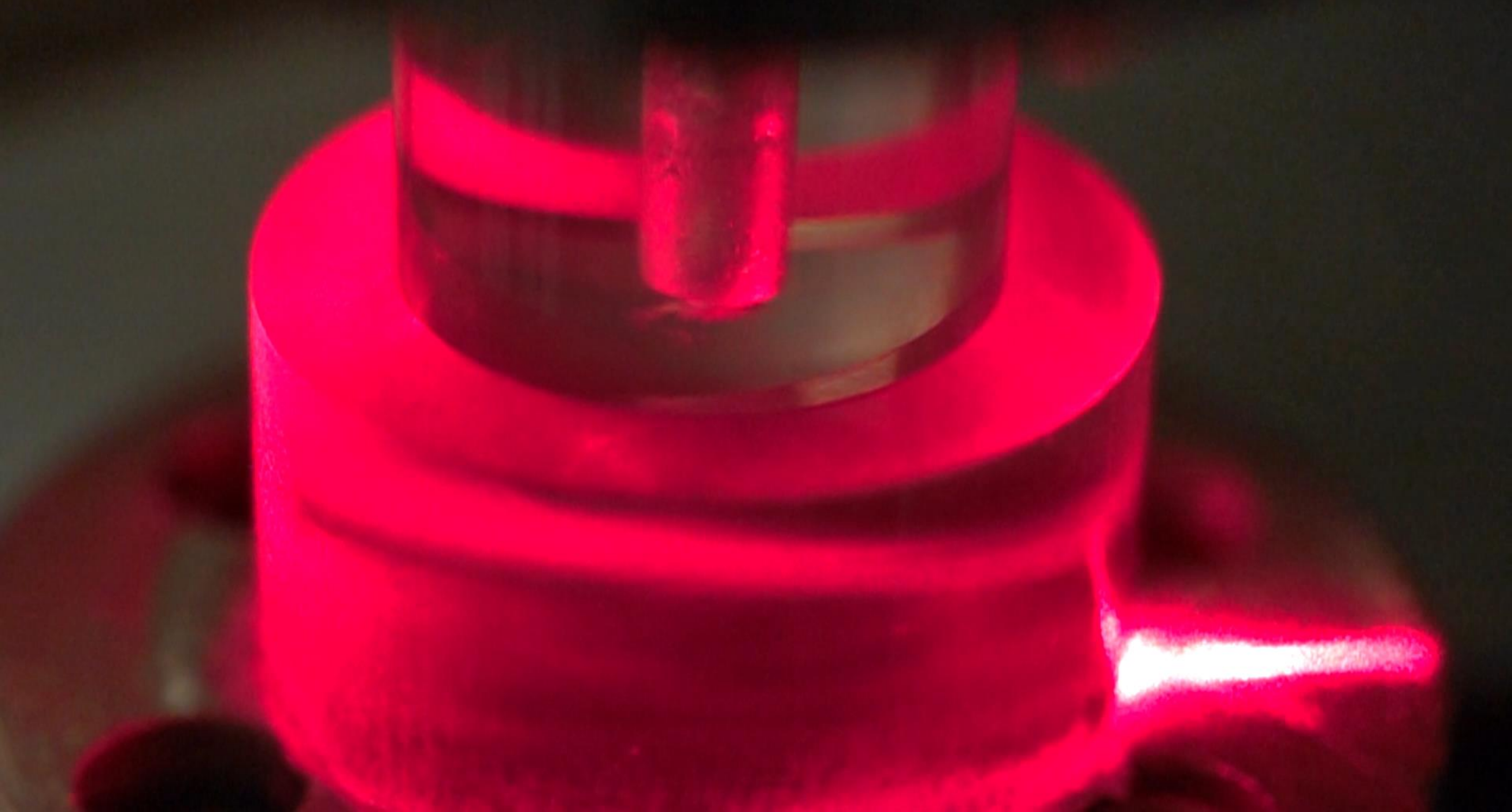
High Speed recording 10k fps + mechanical data







Phase C @960 fps



PMMA - Poly(methyl methacrylate)

PMMA resembles crustal rocks (McLaskey & Glaser, 2011; McLaskey et al., 2012)

Homologous temperature $T_h = \frac{ambient\ T}{melting\ T}$

PMMA at STP conditions $T_{h\ PMMA} = \frac{293\ K}{418\ K} = 0.7$

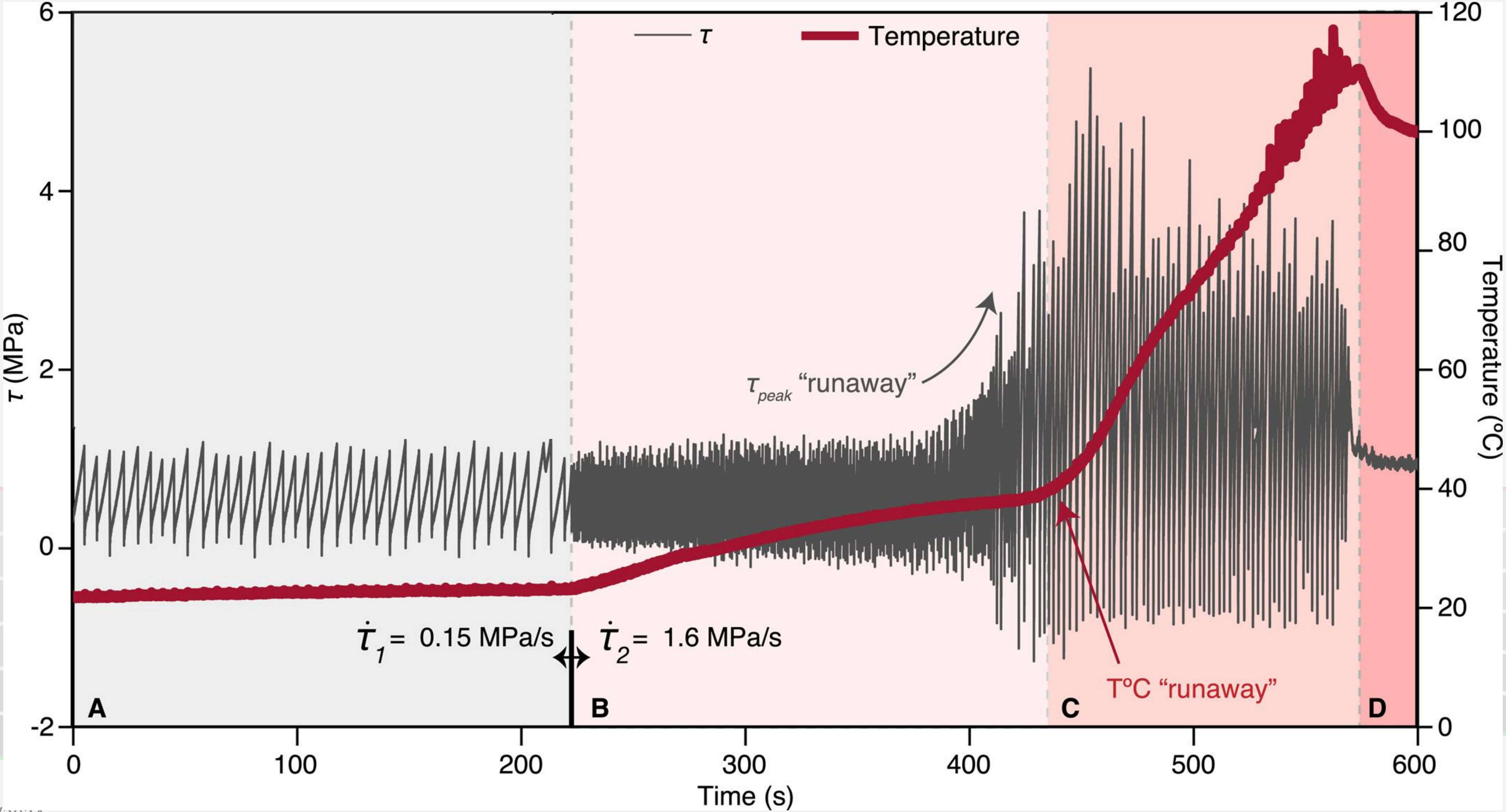
~27 degC/km at 17 km depth

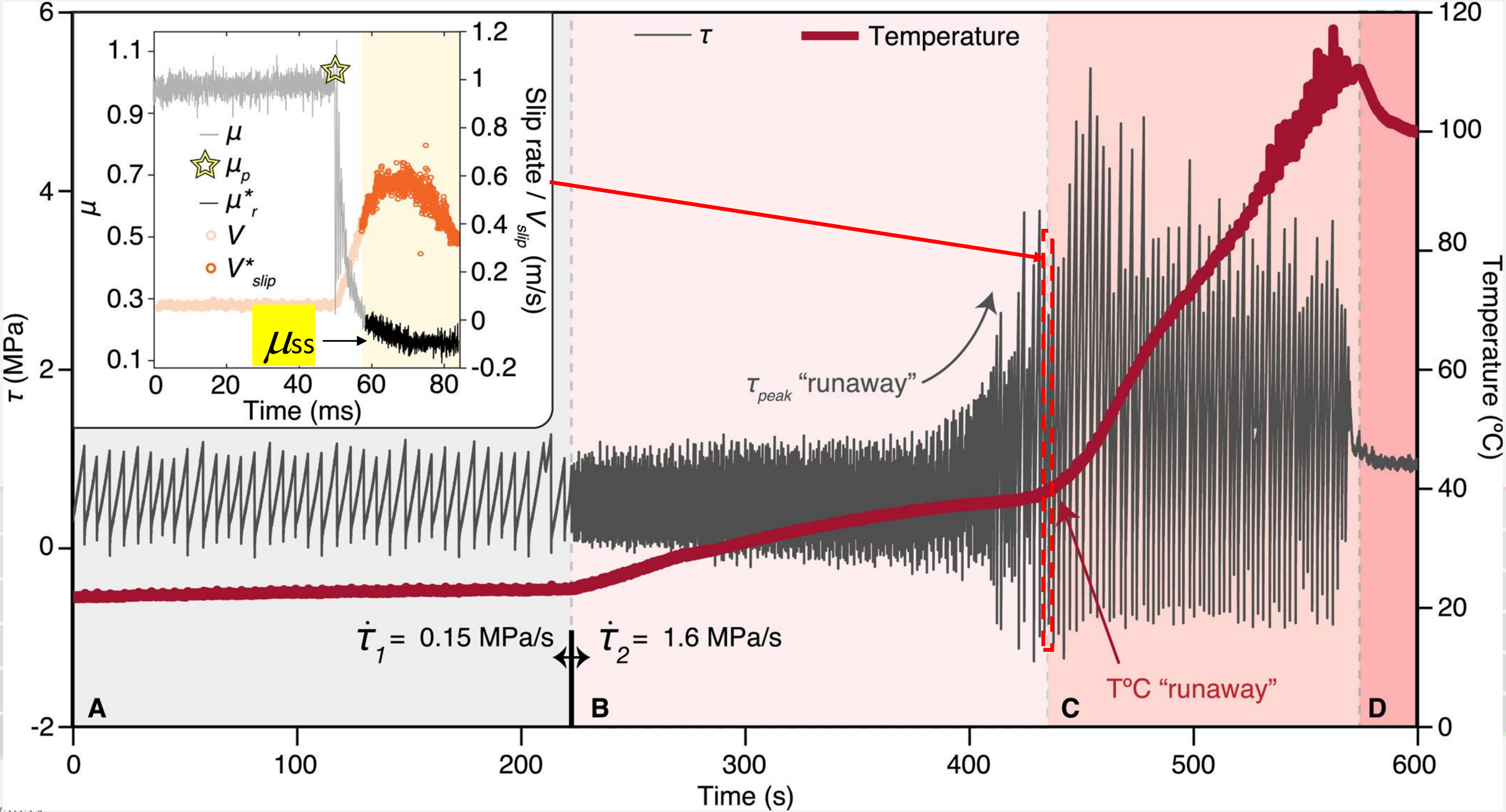
Rocks with granitic compositions at seismogenic depths $T_{h\ Granite} = \frac{750}{1023} \sim 0.7$

Low strength, low melting point, it is transparent

Experiment parameters	
Sample material	PMMA
Melting point	160ºC
Radius 1	15 mm
Radius 2	20 mm
Normal load	3.6 MPa
Loading rate (initial)	0.15 MPa/s
Loading rate (final)	1.5 MPa/s

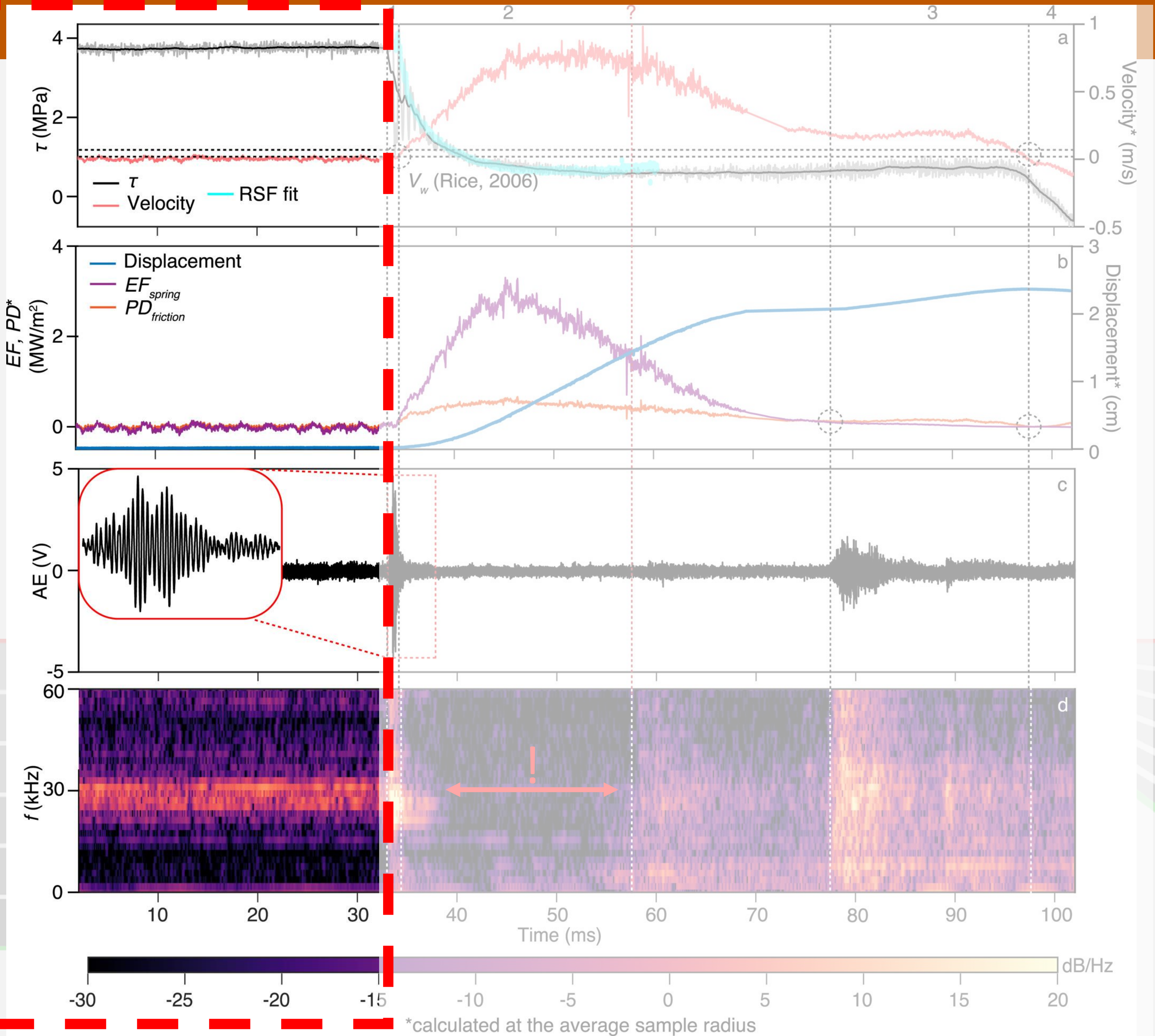
Surfaces were prepared with a lathe and then polished for 1 min with increasingly finer grit silicon carbide abrasive paper (600 grit–1,200 grit–3,000 grit–3,000 grit with water), then cleaned with alcohol


τ
Temperature
τ (MPa)
Temperature (°C)
Time (s)
τ_peak "runaway"
T°C "runaway"
τ̇_1 = 0.15 MPa/s
τ̇_2 = 1.6 MPa/s
A
B
C
D
6
4
2
0
-2
120
100
80
60
40
20
0
100
200
300
400
500
600


τ
Temperature
τ (MPa)
Temperature (°C)
Time (s)
μ
Slip rate / V slip (m/s)
Time (ms)
μ
μp
μ*r
V
V*slip
μss
τpeak "runaway"
T°C "runaway"
τ̇1 = 0.15 MPa/s
τ̇2 = 1.6 MPa/s
A
B
C
D

Experiment 021622

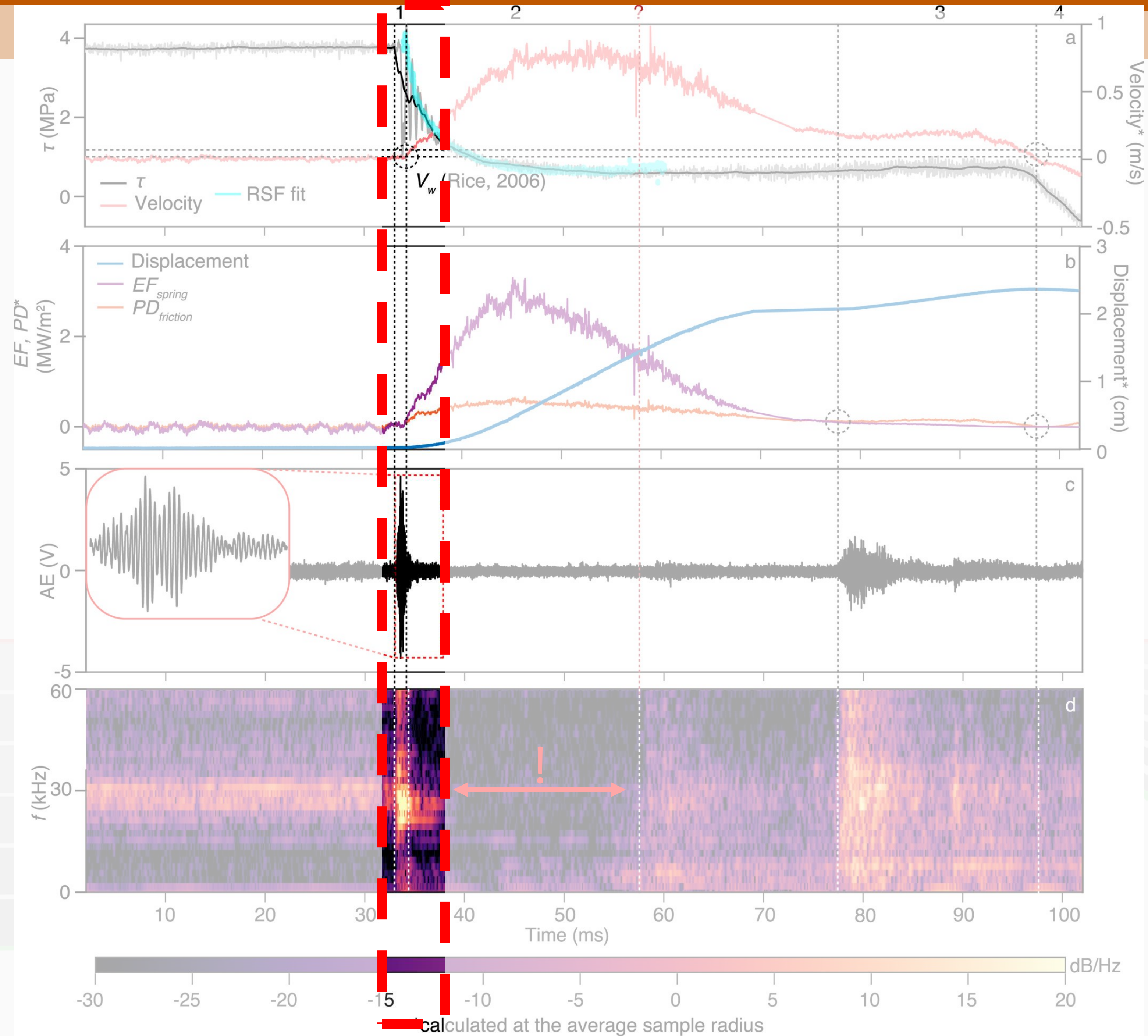
Slow rupture
Low F,
continuos AE



Experiment 021622

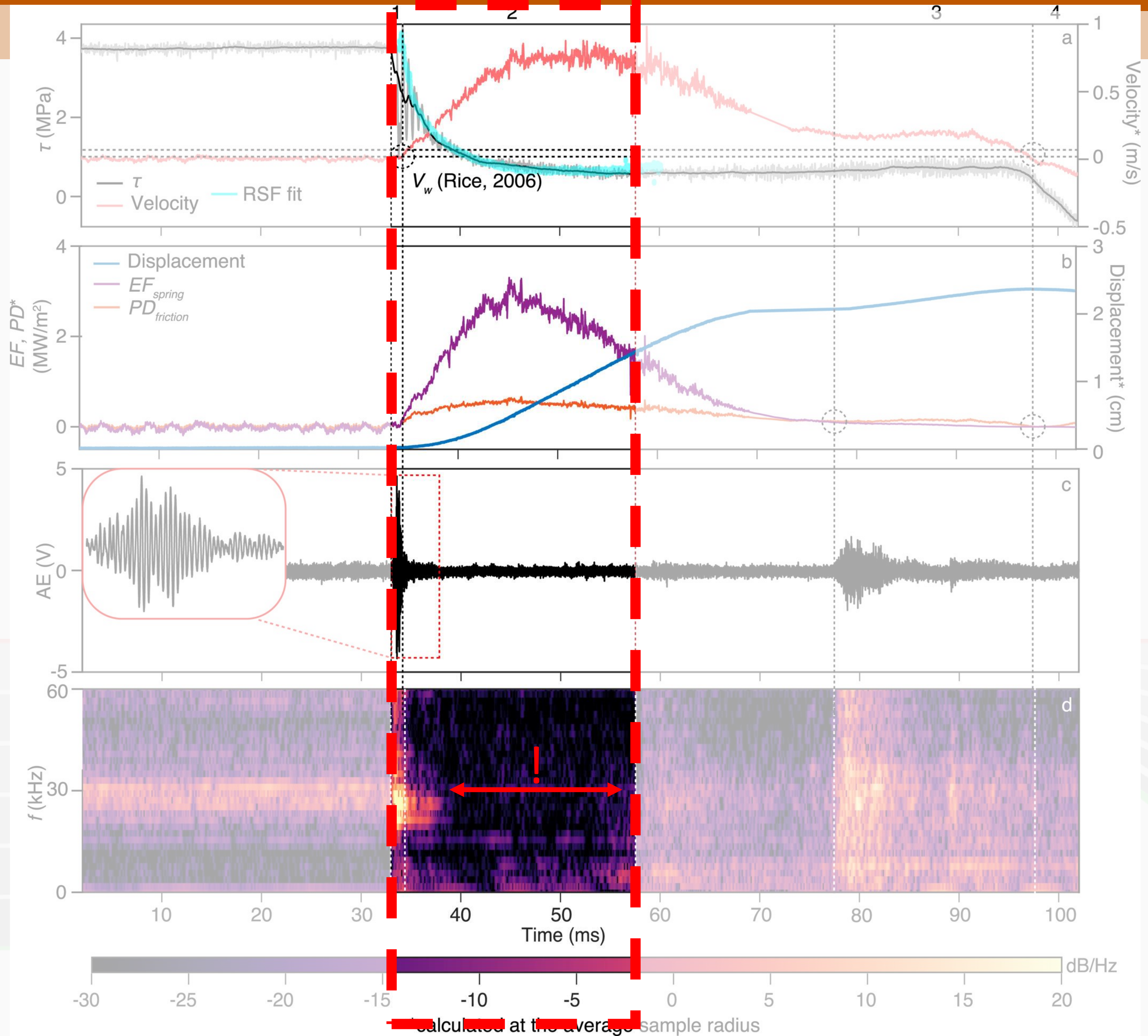
Failure

Loud AEs



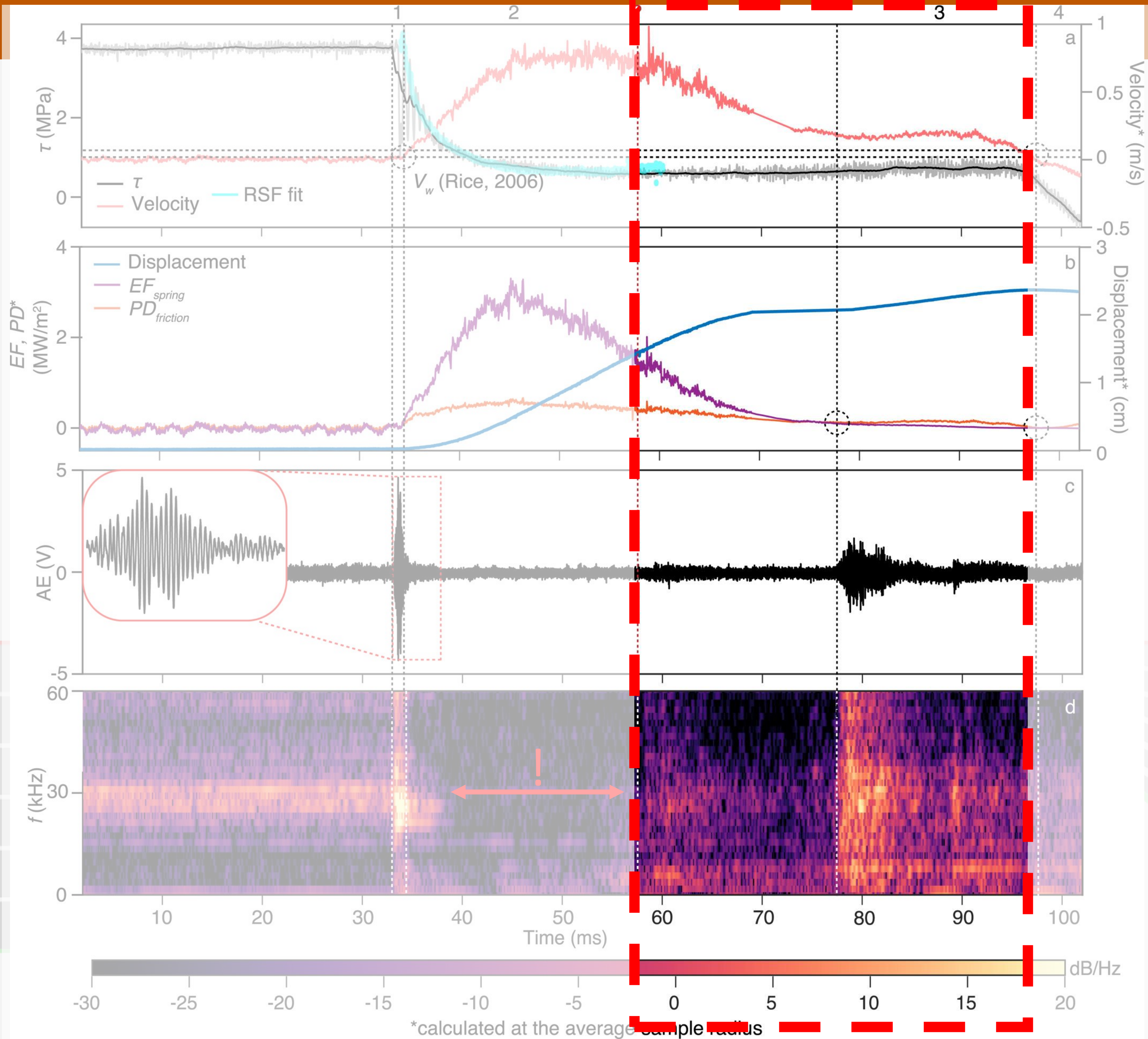
Experiment 021622

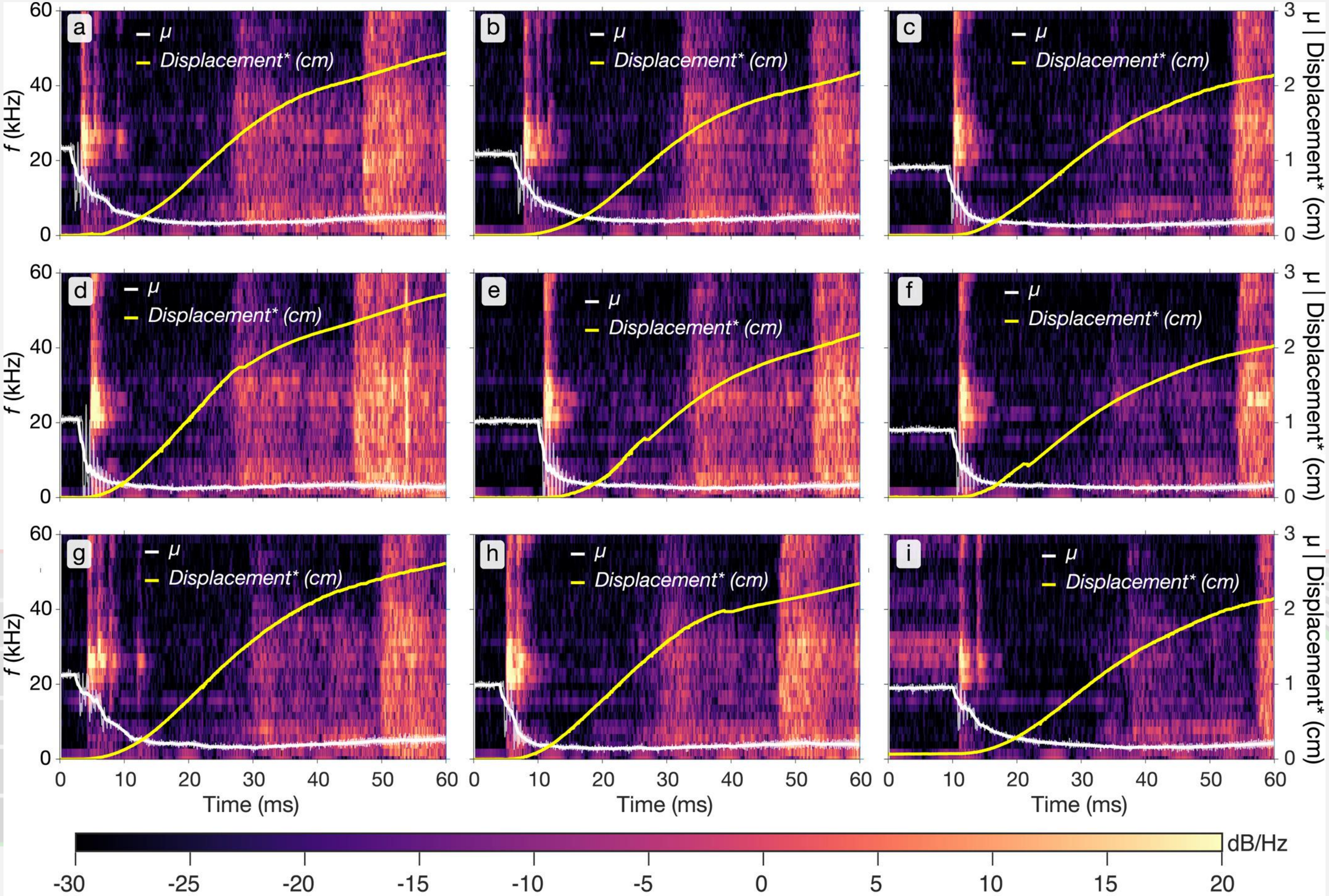
Melt Lubrication
No AEs



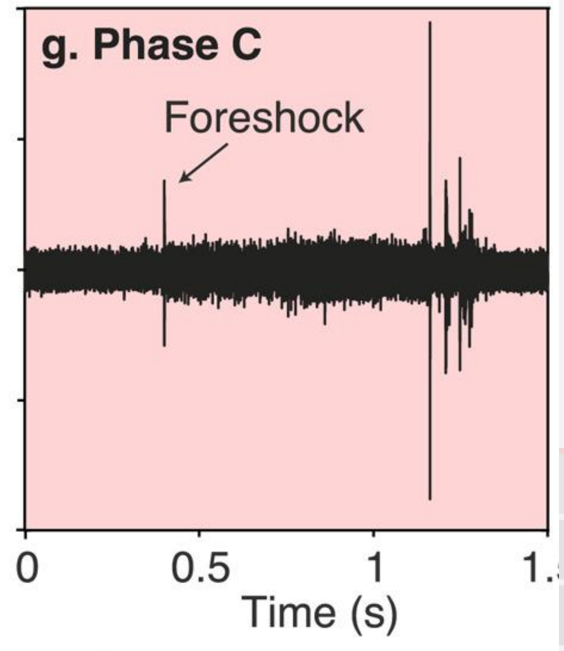
Experiment 021622

Viscous Braking
Loud AE

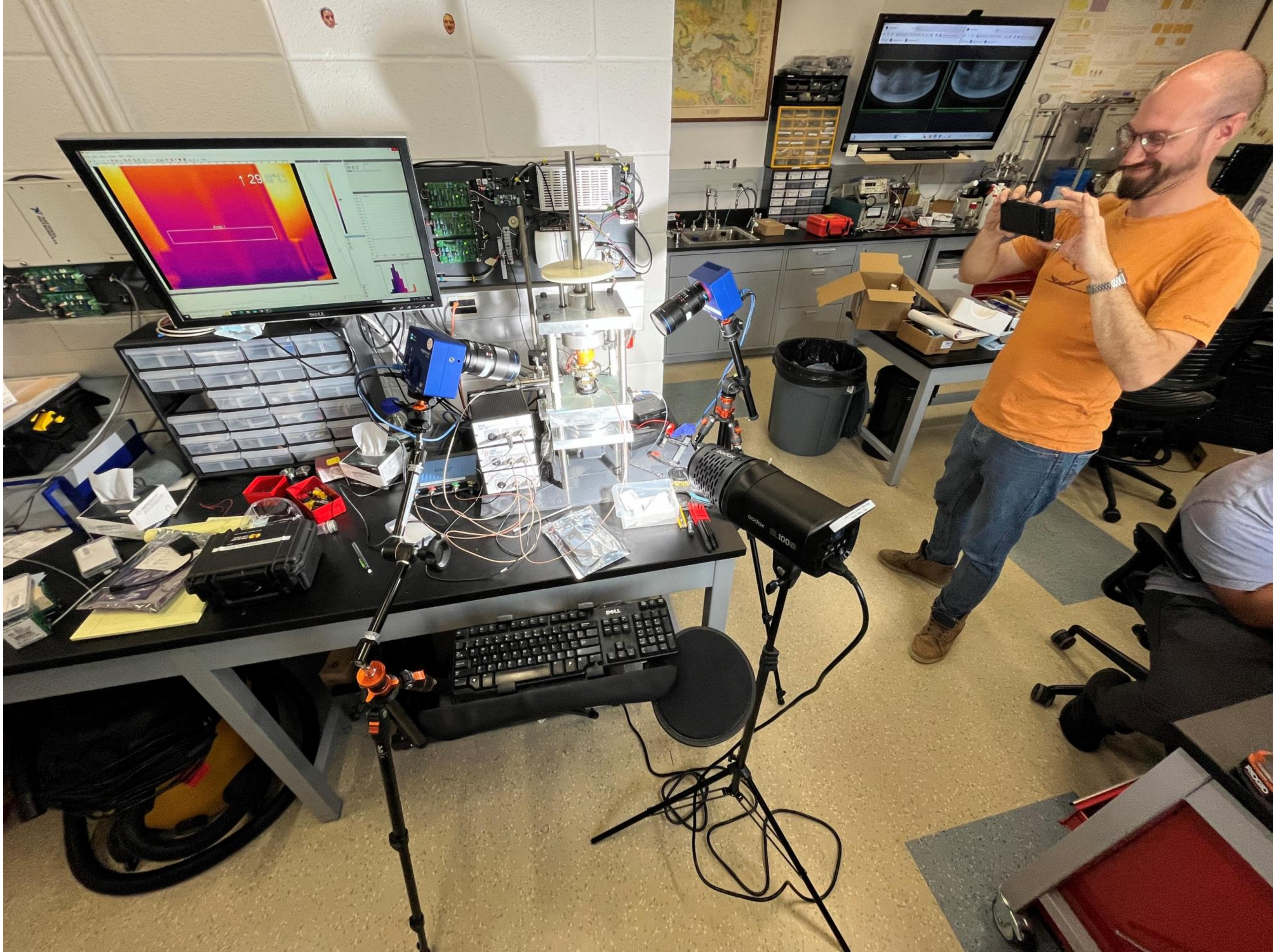




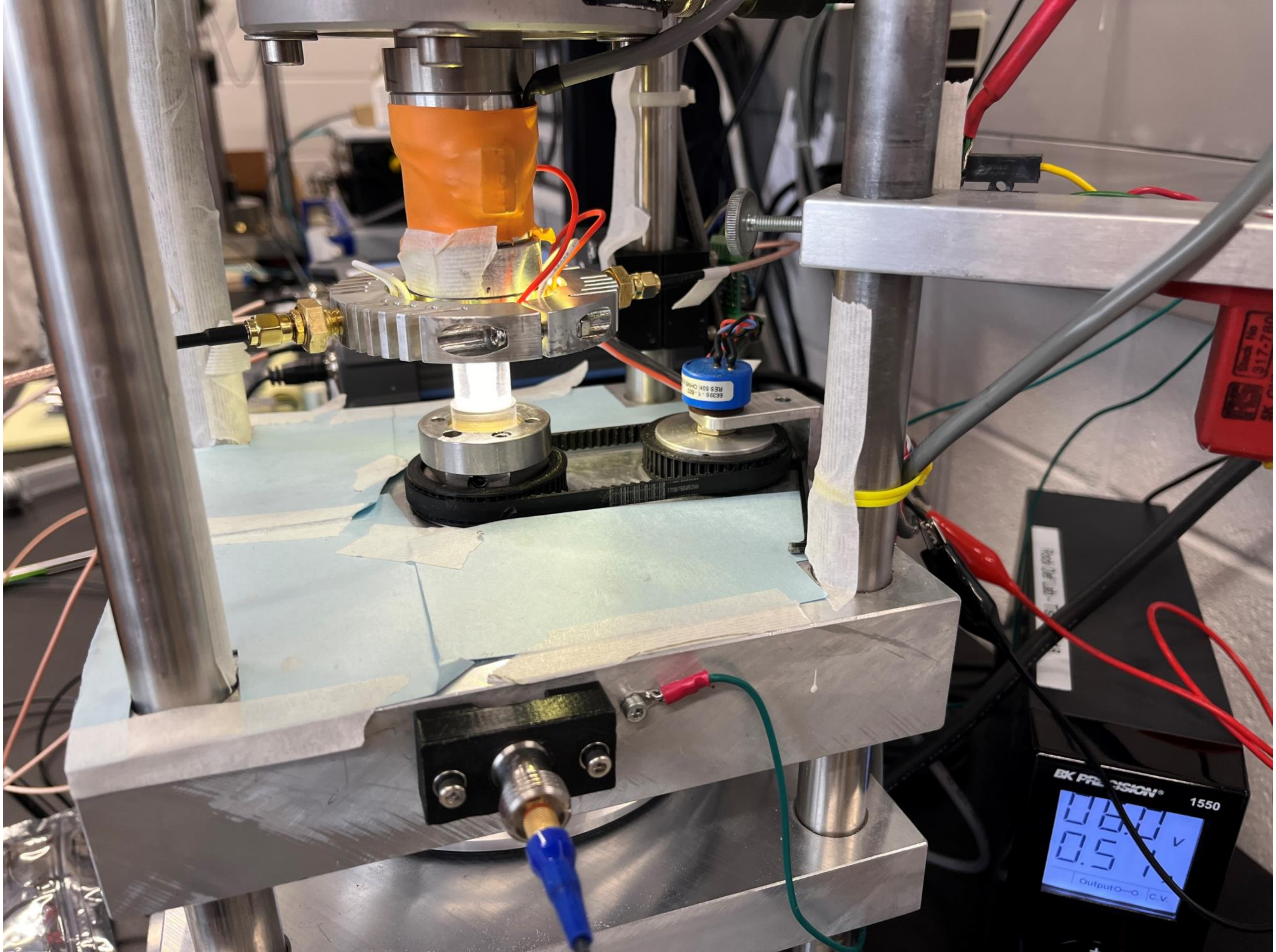
*calculated at the average sample radius

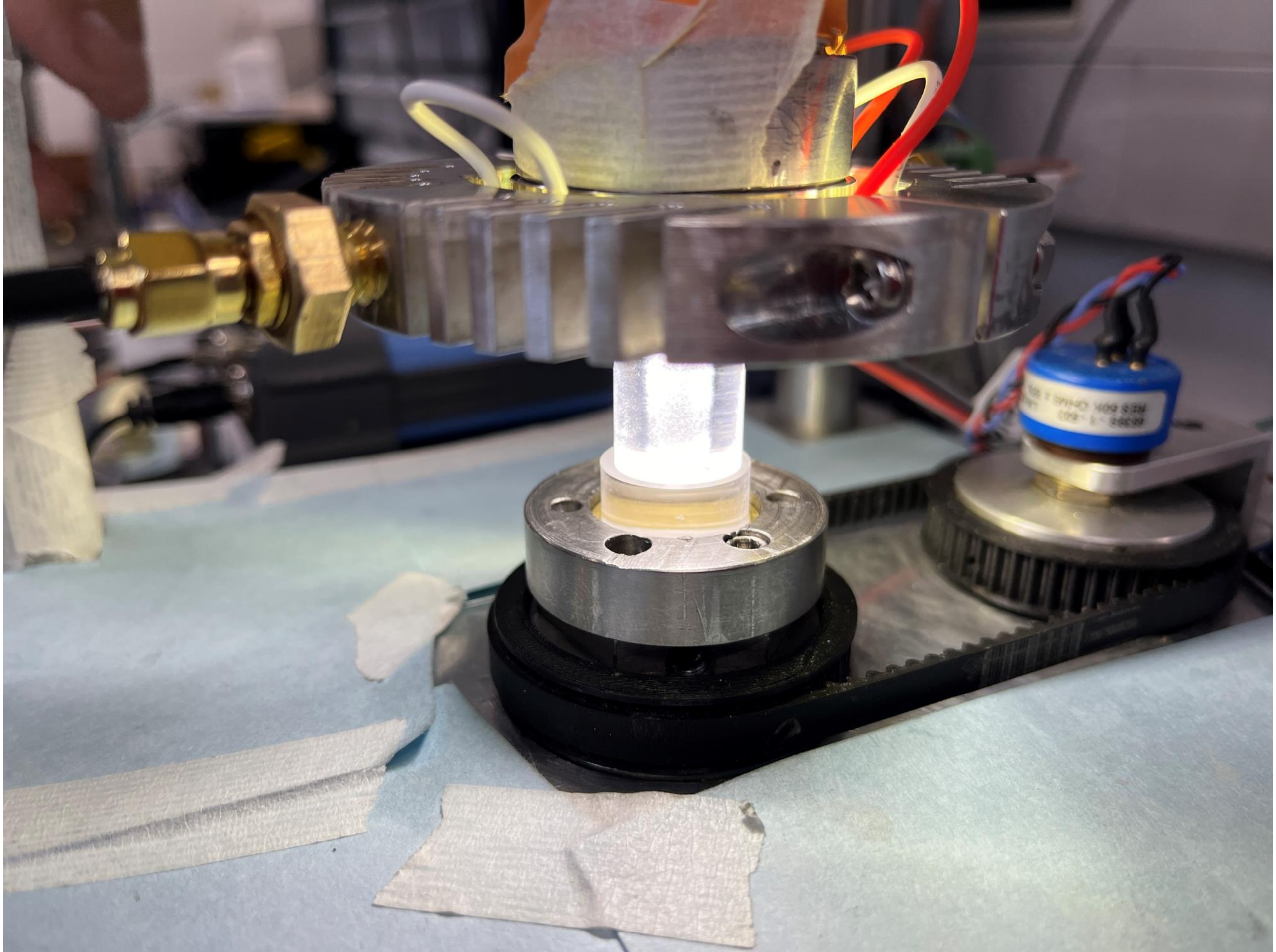


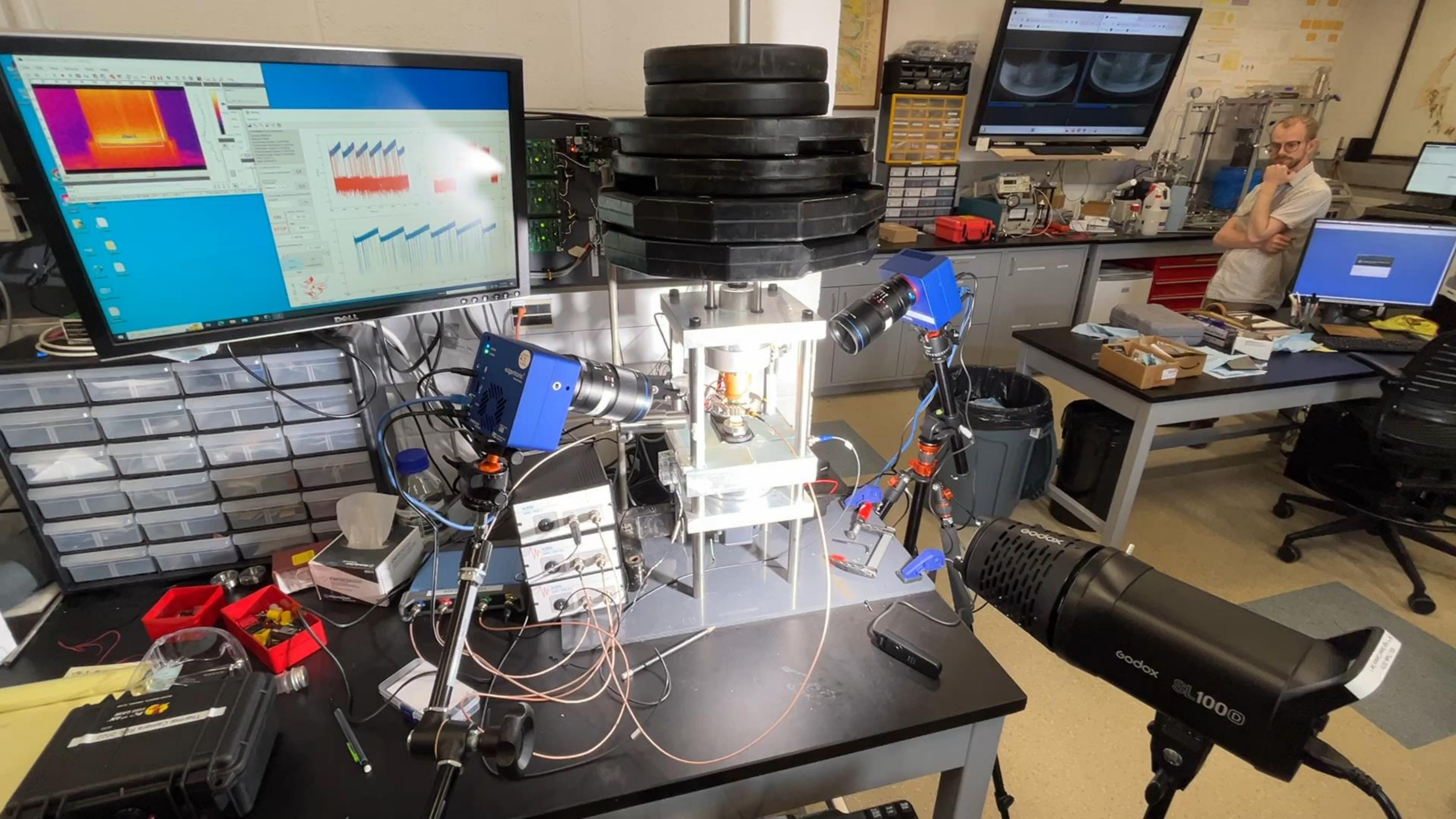
Rotary shear experiments

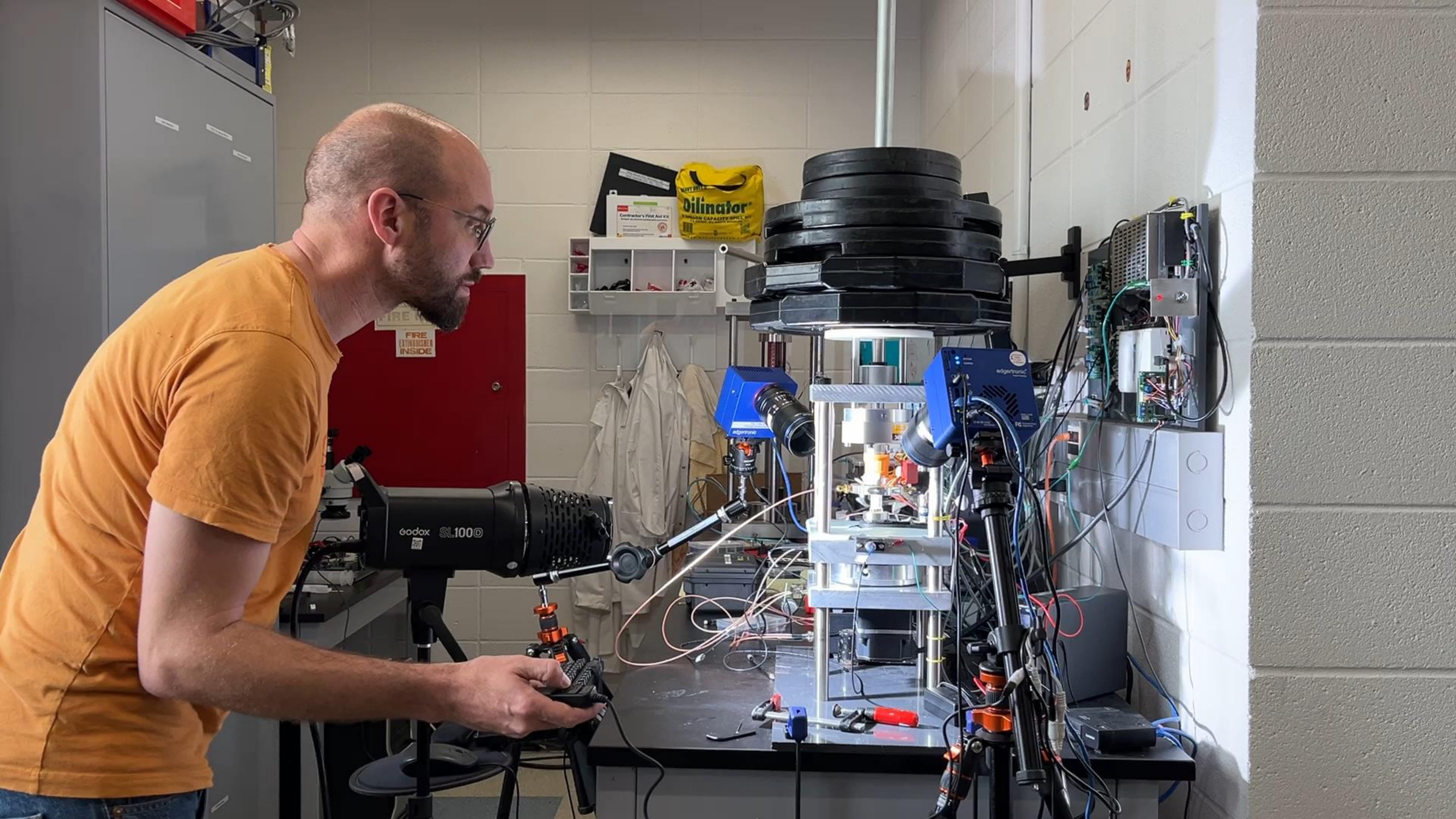

DELL
godox


THE BEDROCK GEOLOGY OF THE WORLD
EXIT


BK PRECISION
1550
C.V.



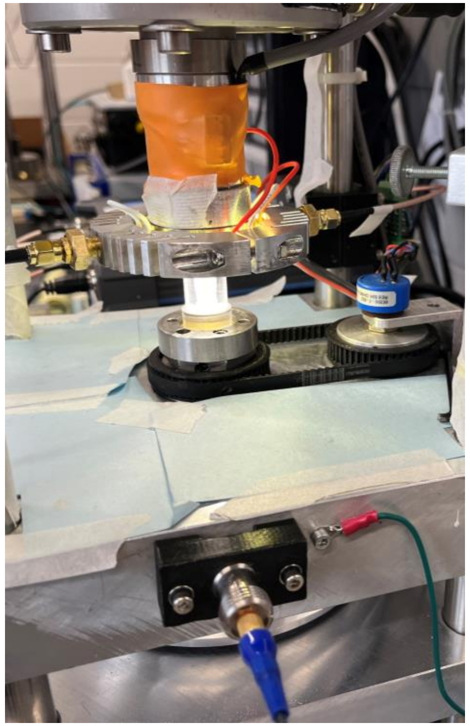

DELL
Godox
Godox
SL100D

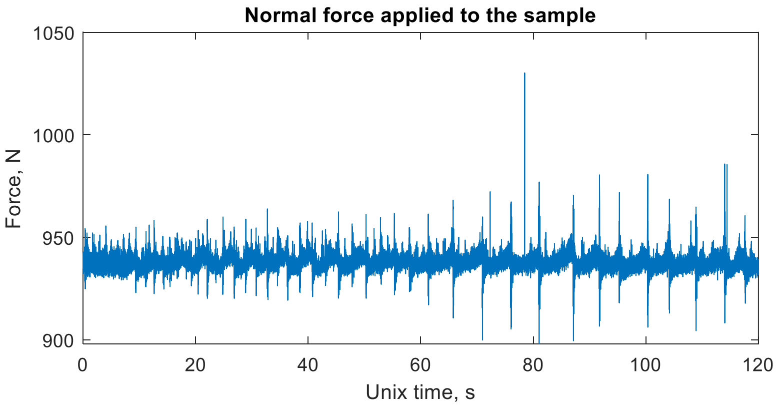

Dilinator
Contractor's First Aid Kit
FIRE EXTINGUISHER INSIDE
Godox SL100D
edgertronic
edgertronic

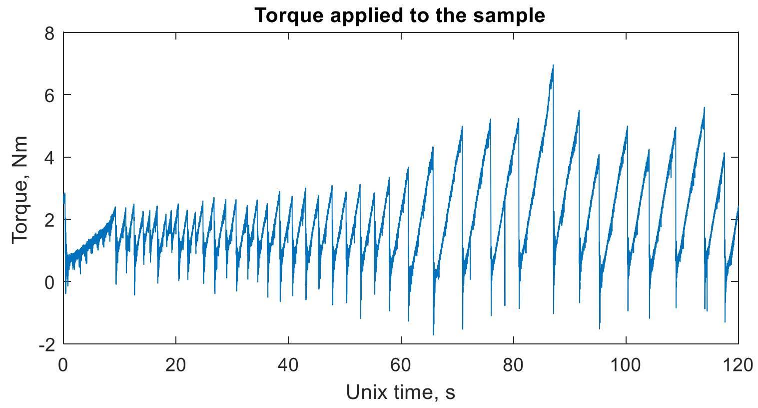
Which data are we dealing with

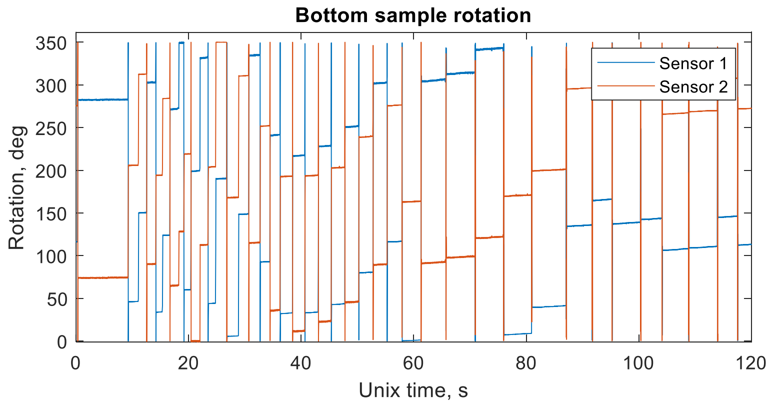
1) Mechanical data
2) Acoustic Emissions
3) Slow motion Videos

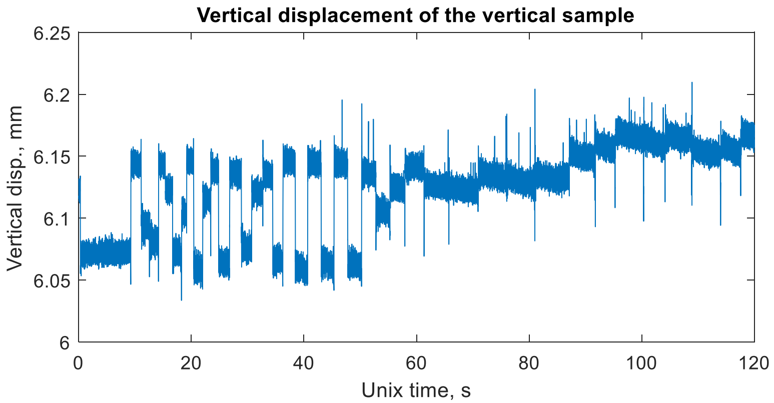
Mechanical data

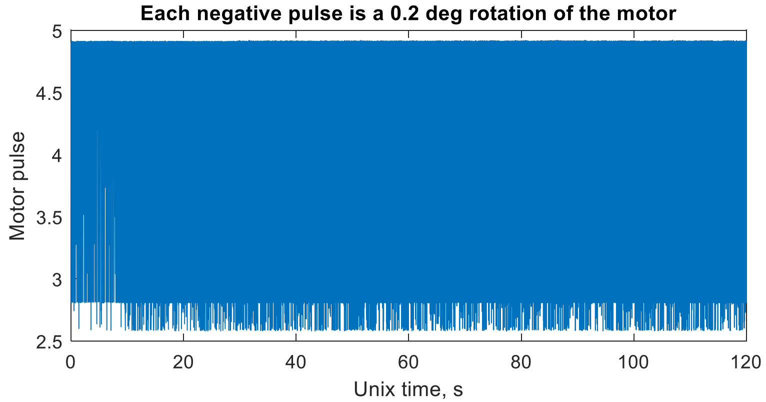


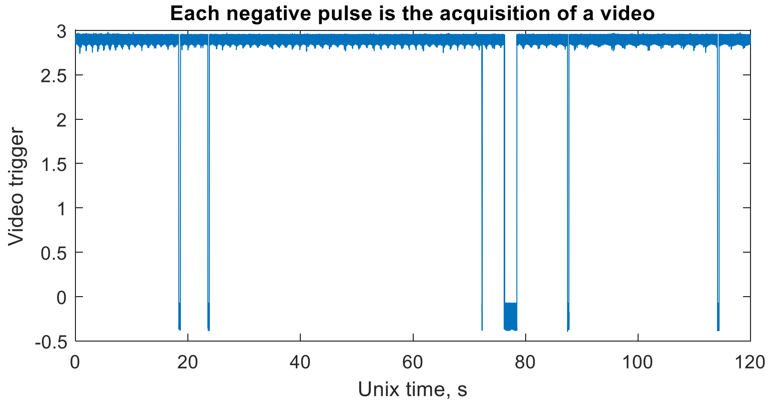






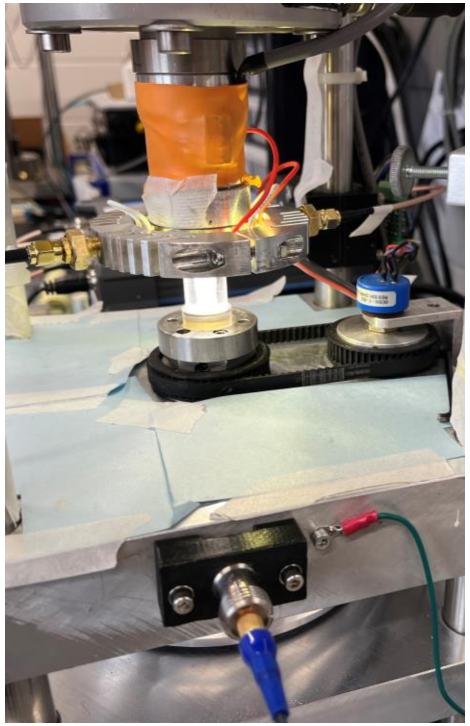


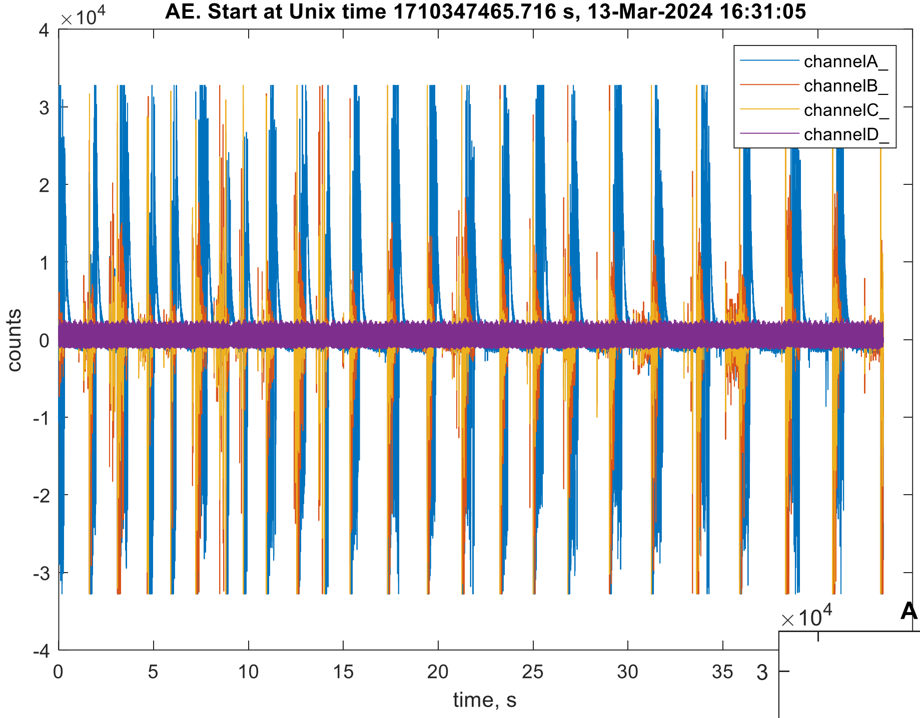


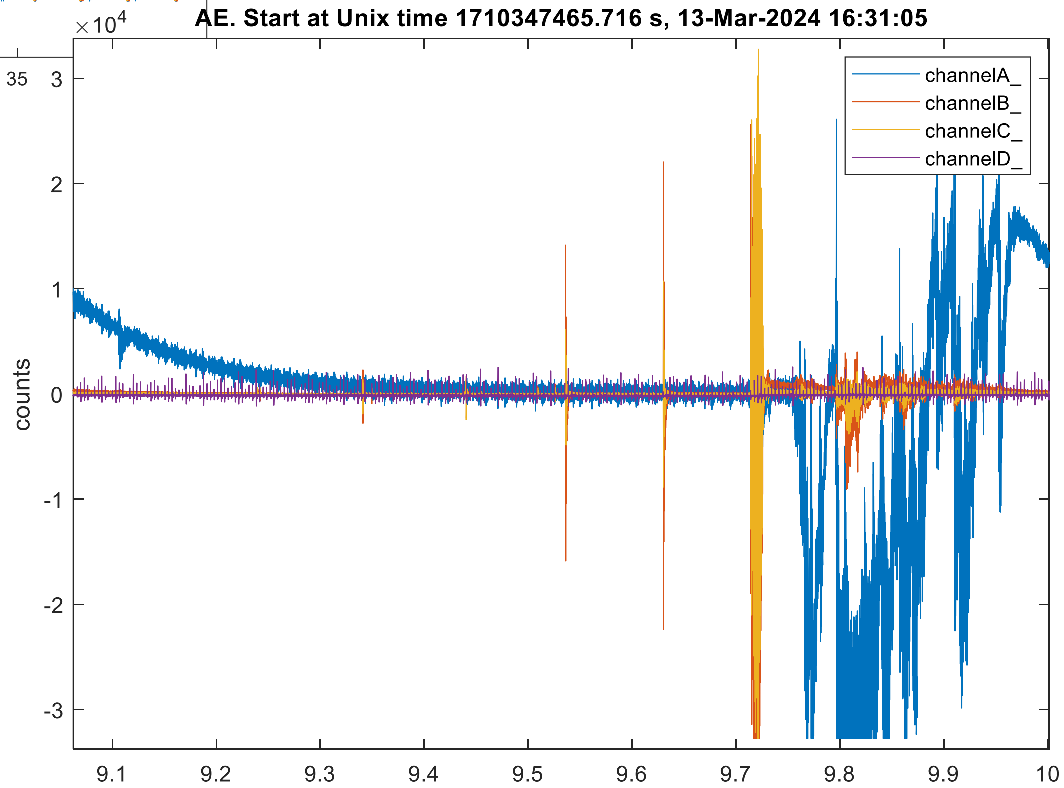


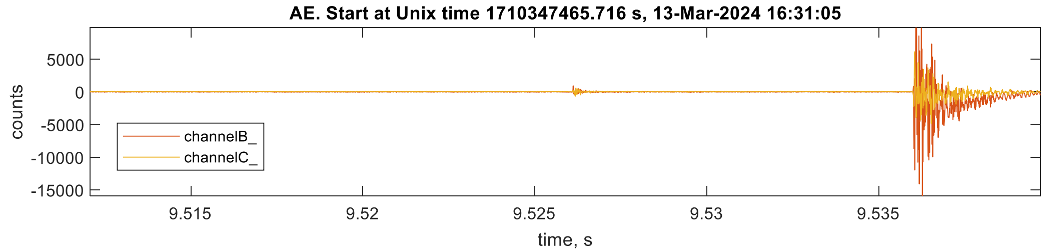
Acoustic emissions

AE and mechanical data have roughly the same UNIX time

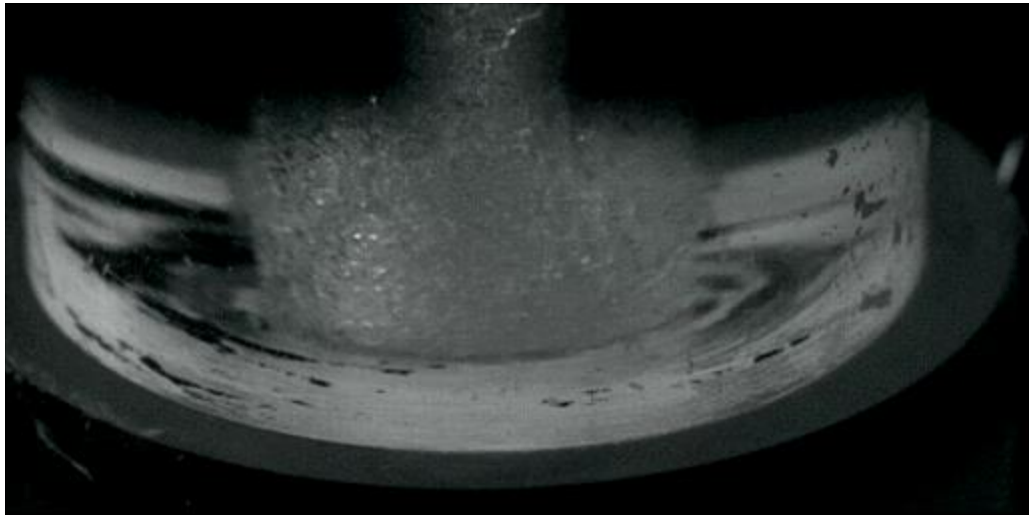


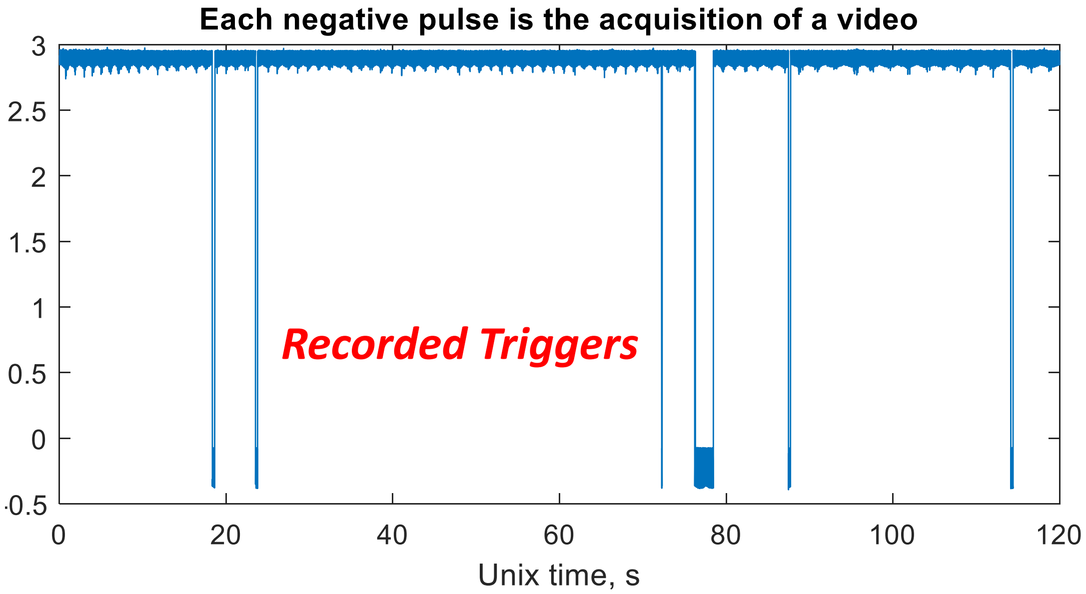




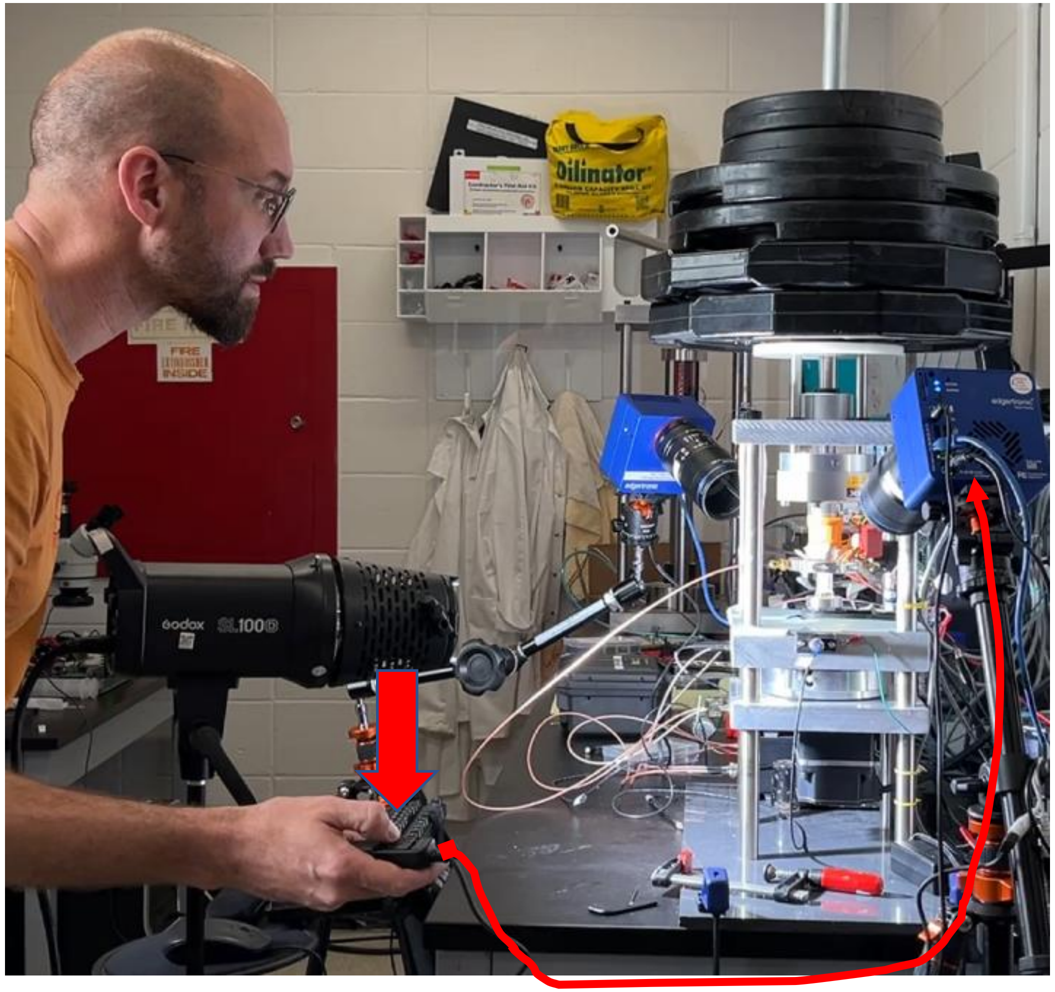


Slow motion (Slomo) video





Mechanical Data and Slomo video are synchronized through a recorded trigger



Analyze data and prepare the figures for your Poster

1) Find precursors…

- Watch the all slomo videos
- Select 1 video that shows precursors
- Move that video into the SlomoVideo folder
- If other videos have been taken around the time of the selected video, move also 1 to 3 videos taken before and after the selected video

UNIX time of trigger

GMT (Greenwich Time) when file was saved

Selected video

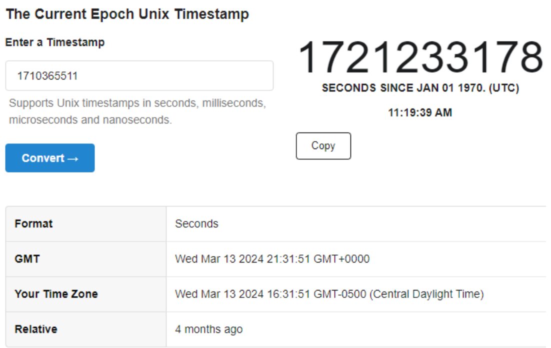
slomo_1710365506_26.mov	3/13/2024 9:36 PM	MOV File	88,865 KB
slomo_1710365506_26.txt	3/13/2024 9:36 PM	Text Document	3 KB
slomo_1710365511_27.mov	3/13/2024 9:39 PM	MOV File	89,262 KB
slomo_1710365511_27.txt	3/13/2024 9:39 PM	Text Document	3 KB
slomo_1710365564_28.mov	3/13/2024 9:42 PM	MOV File	96,164 KB
slomo_1710365564_28.txt	3/13/2024 9:42 PM	Text Document	3 KB
slomo_1710365575_29.mov	3/13/2024 9:44 PM	MOV File	97,073 KB
slomo_1710365575_29.txt	3/13/2024 9:44 PM	Text Document	3 KB

https://en.wikipedia.org/wiki/Unix_time

Video number

Posix or Unix time (GMT) = **Mar 13 2024 16:31:51 CDT**

1) Go to https://www.unixtimestamp.com/ or any other UNIX time converter
2) Type in the Unix time of the video
   E.g., 1710365511
3) Convert:

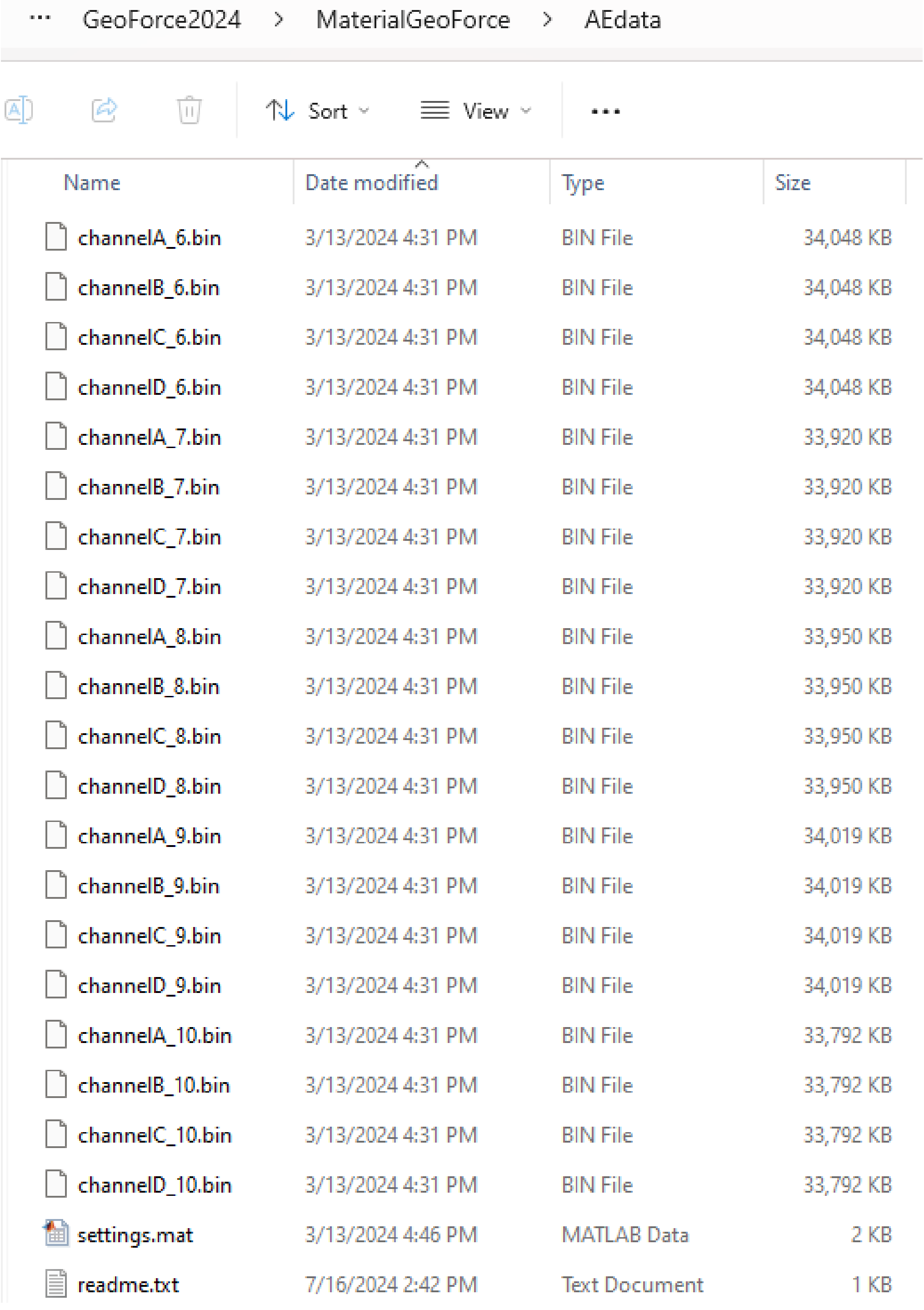


4) Look at the time (in your time zone) and search for the mechanical data that have been acquired around that time (a slomo video records 1 second at 10000 frames per second)
5) Move those 2-3 files into the folder "MechanicalData"

This file has been created at 4:32pm, and contains the data 1 minute prior to that moment

Name	Date modified	Type	Size
00070_4139.995860_4199.995767s.mat	3/13/2024 4:32 PM	MATLAB Data	61,131 KB
00071_4199.995800_4259.995707s.mat	3/13/2024 4:33 PM	MATLAB Data	61,121 KB

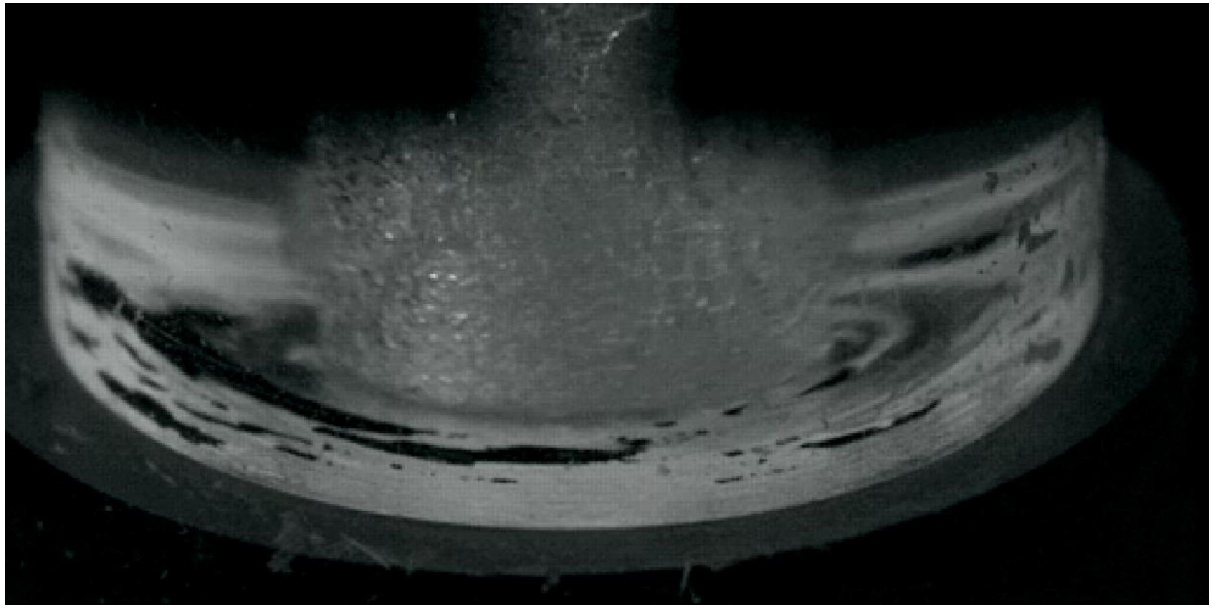
- Look for Acoustic Emission files that have been created around the time of video and mechanical data
- Copy all the channel files (e.g., channel_Y.bin) into the folder AE data
- Copy also the file settings.mat that you find in the same folder of the AE data



2) Find the frames of the precursor events

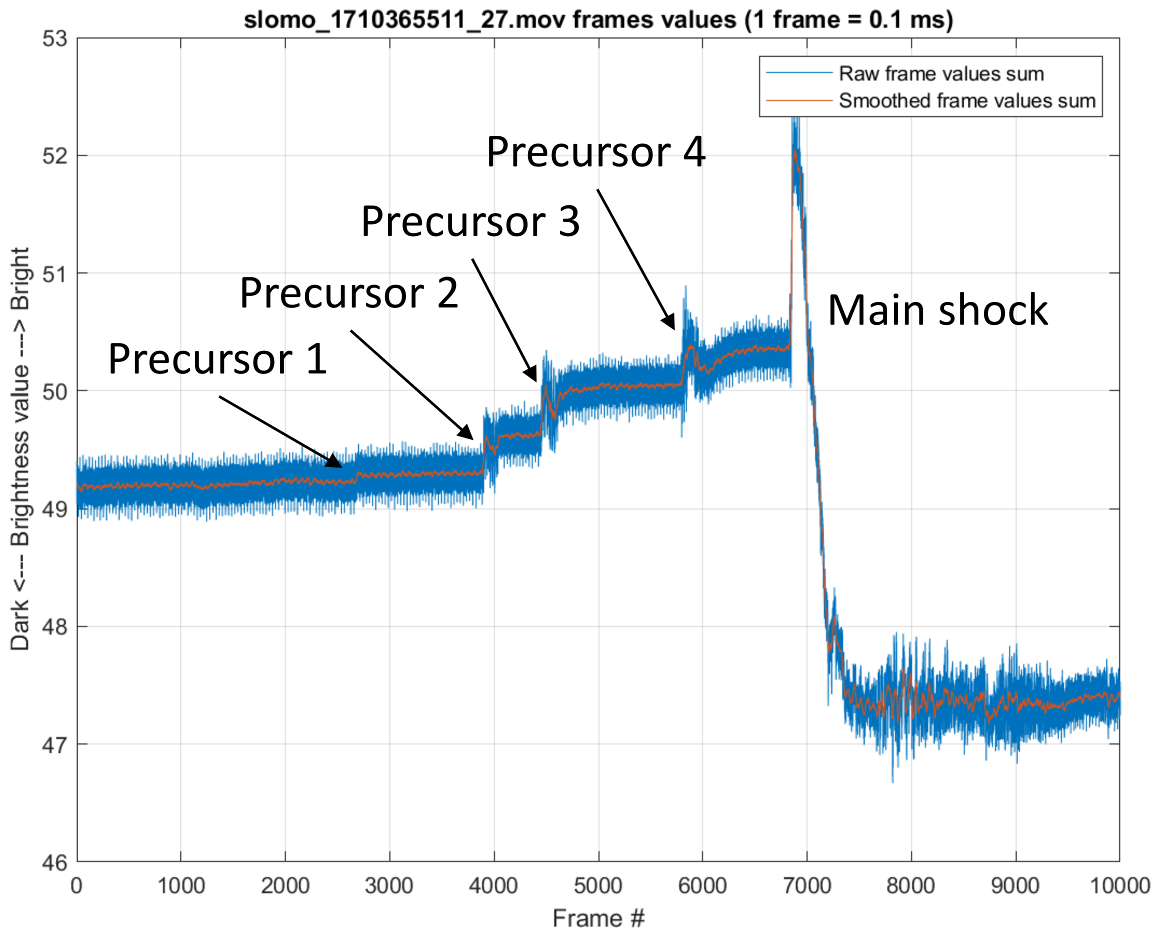
- Open the Matlab/Octave code: OpenSlomoVideo_v01.m
- Change the name of the video file changing the variable filename
- Run the code

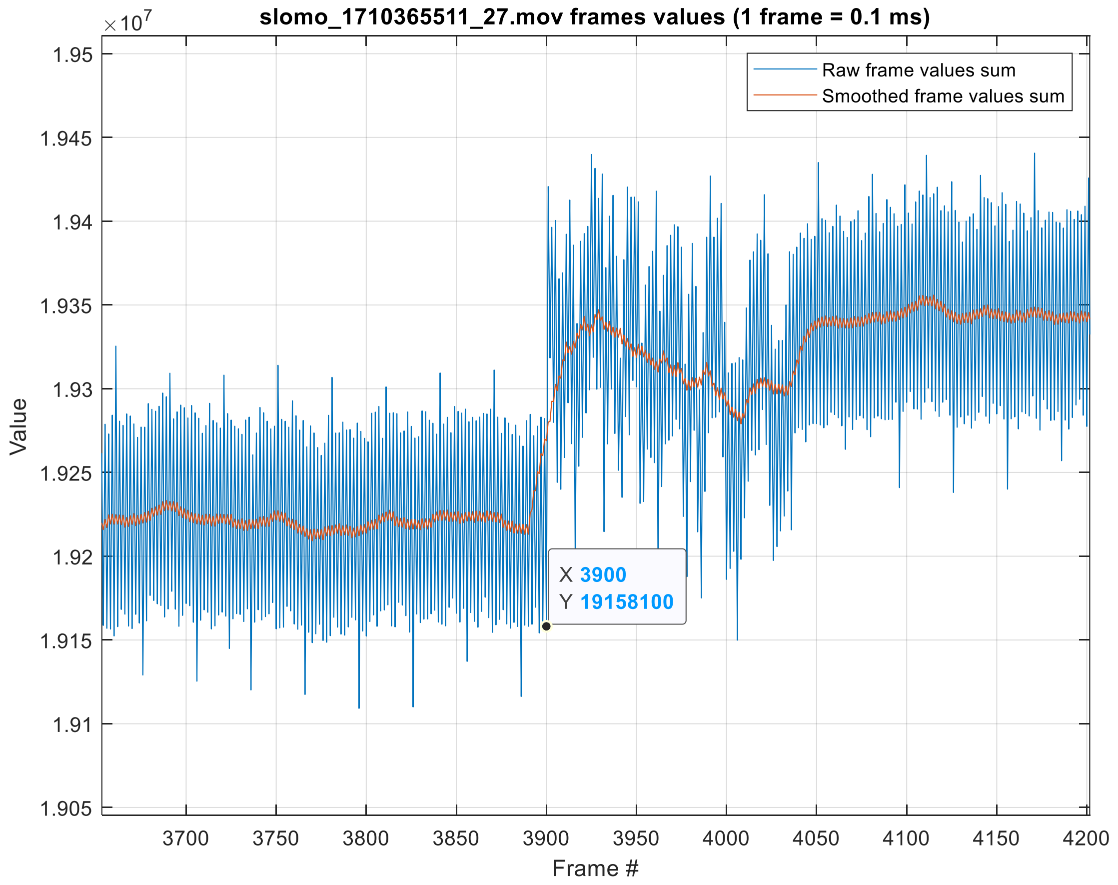
Frame: 7971/10000

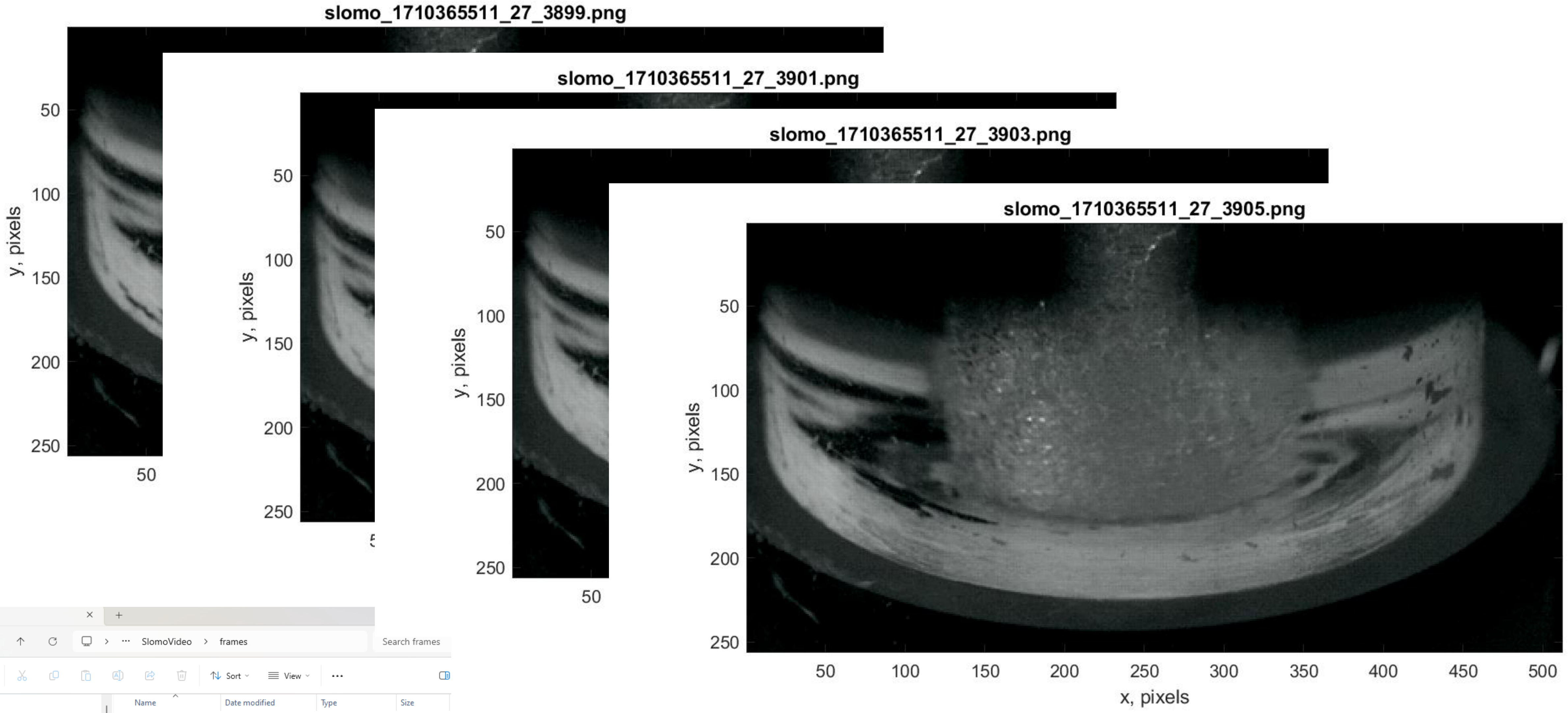


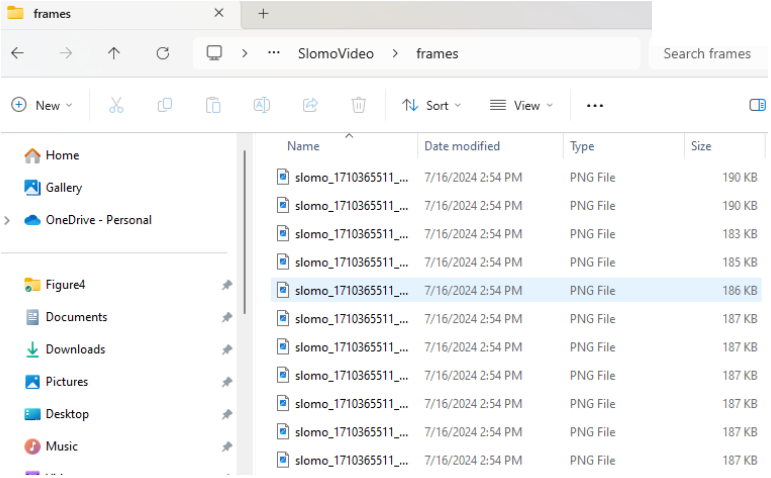
- Look at the figure 2: Brightness value

- Use the zoom and the cursor to determine the frames around a precursor (alternatively use the ginput command, e.g., ginput(1))
- Change the variable selFrames to select the frames
- Run the code and find the frames in the subfolder “frames”







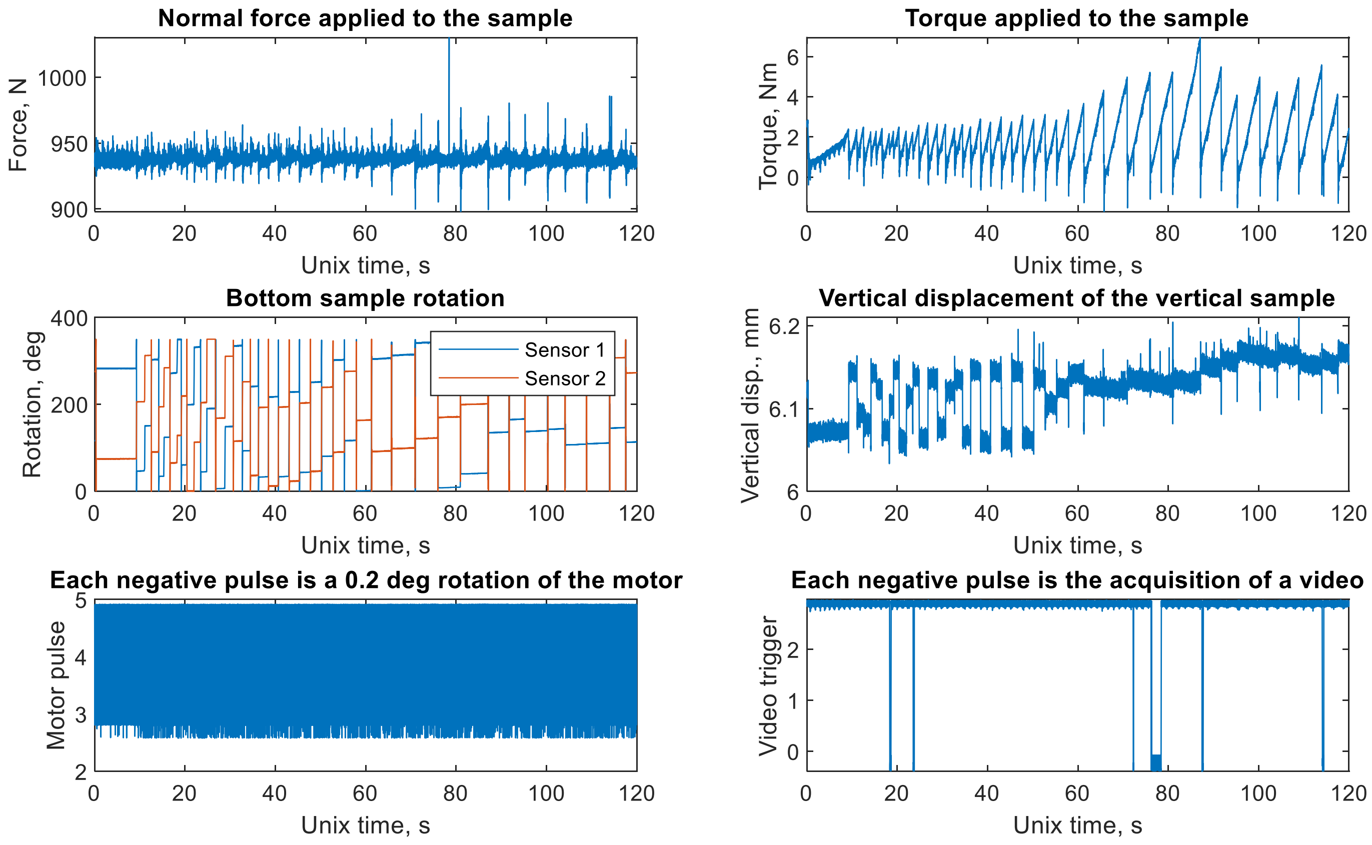


- Improve these figures for your poster…

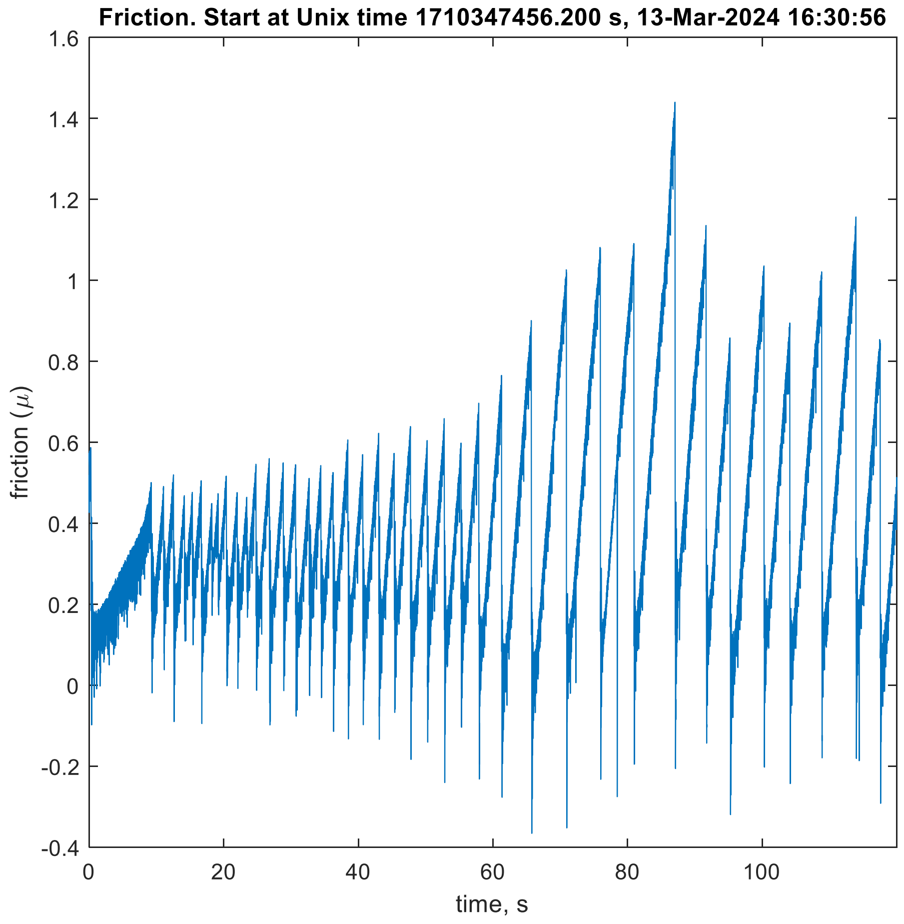
3) Check file data and time offsets

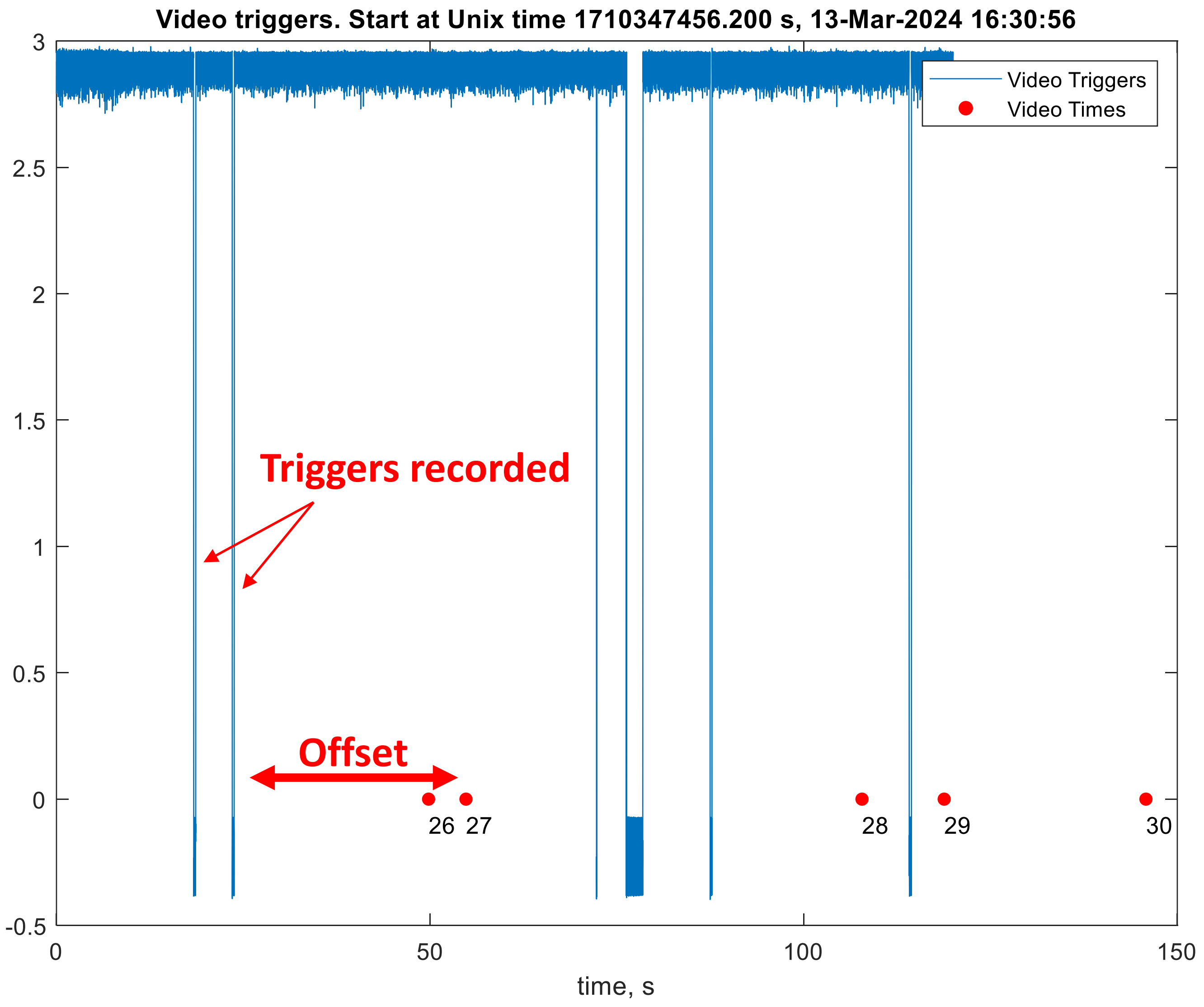
- Run the code DataOverview_01.m

Overall data

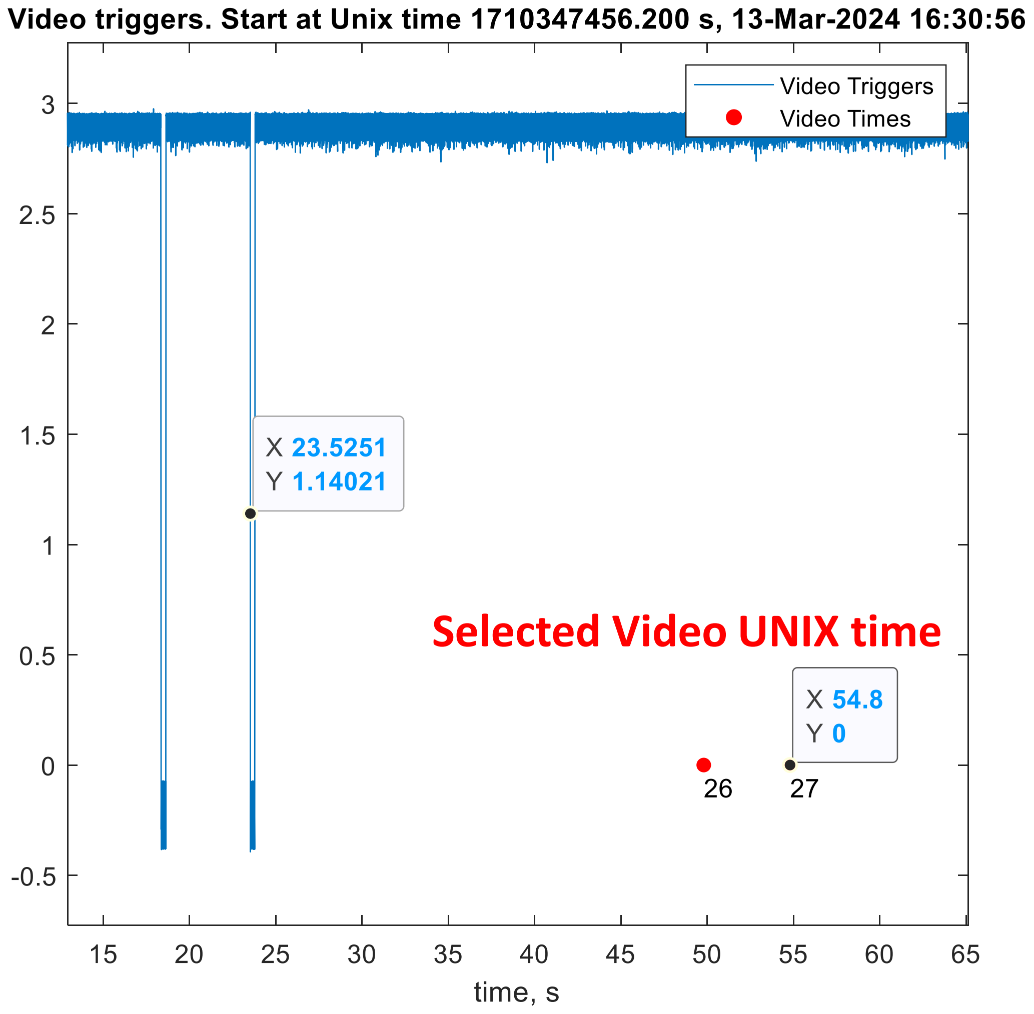


- Find the Offset time between Mechanical data and Videos



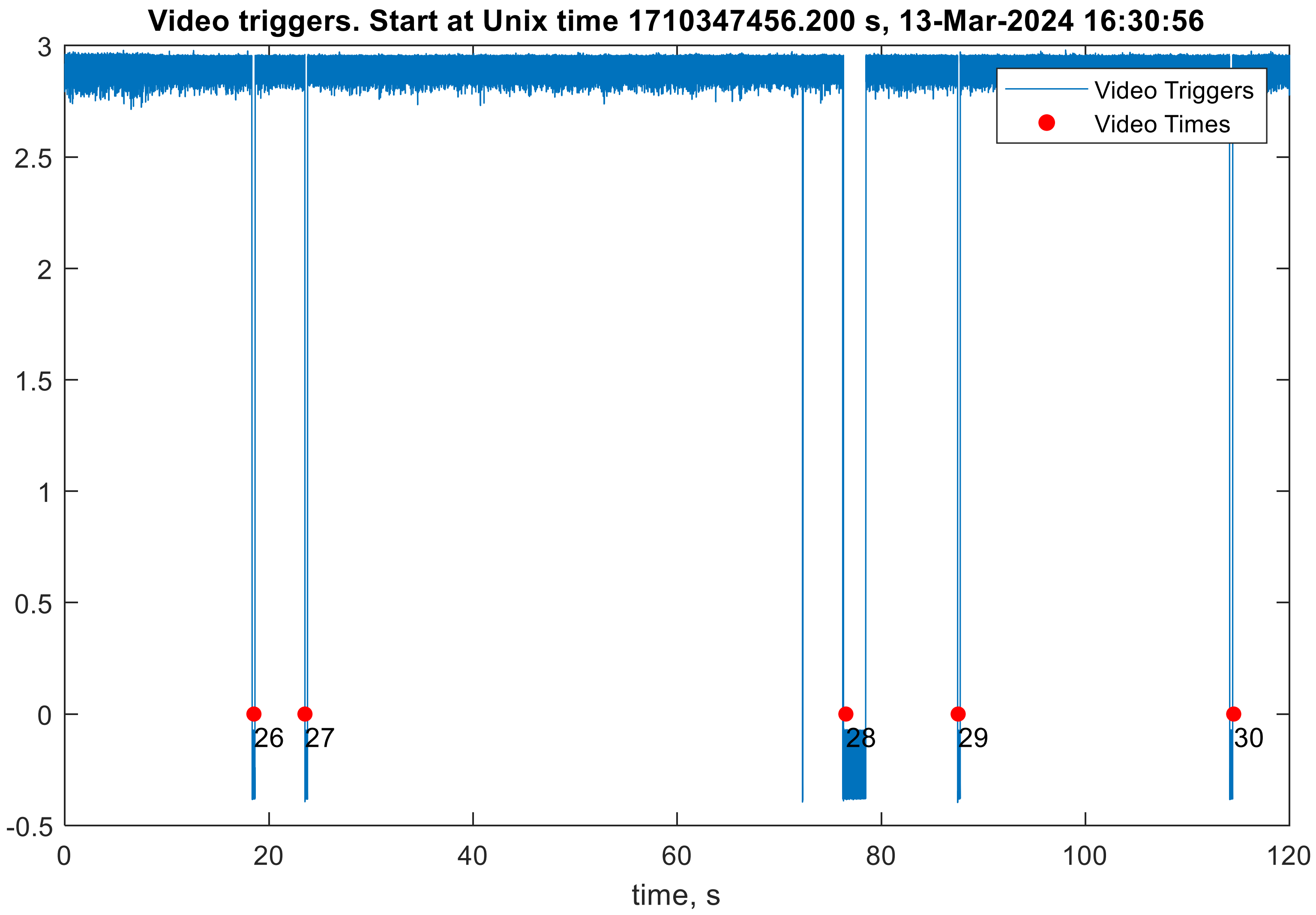


- Find the Offset time between the Trigger and the video – use the zoom and data tip or ginput
- Change the variable TimeOff_s with the difference between the Trigger and the video time



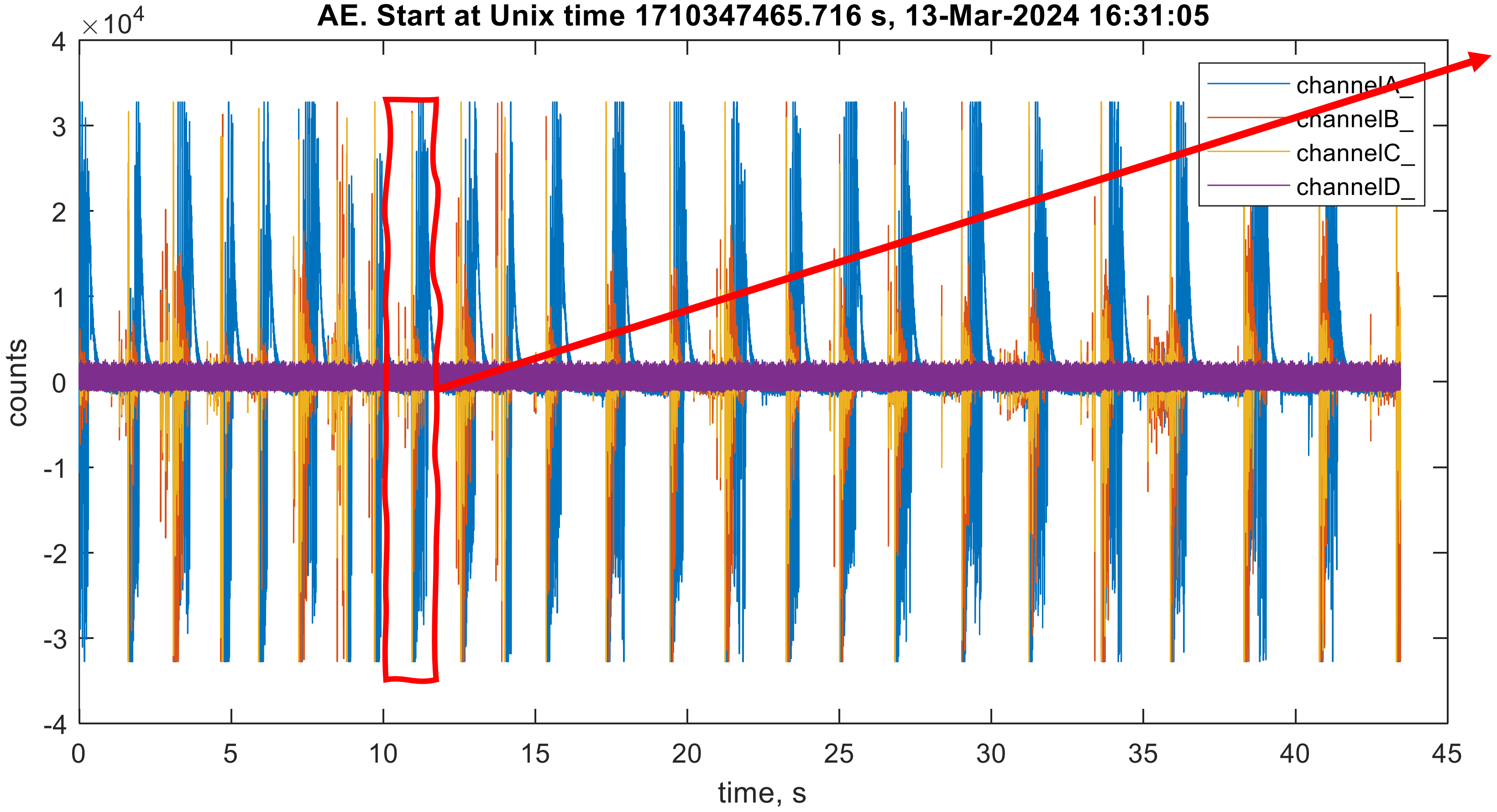

```
%% THIS CODE ALLOWS TO FIND THE VIDEO-MECHANICAL DATA TIME OFFSETS
clear; close all; clc
%% graphics
% available_graphics_toolkits % OCTAVE
% graphics_toolkit('gnuplot'); % OCTAVE

%% parameters to be changed
shiftGMT_h = 5; % hour shift between GMT and Austin time
r1_m = 0.5*15e-3; % sample outer radius, m
r2_m = 0.5*3e-3; % sample inner radius, m
TimeOff_s = 54.8-23.5251; % time offset between video and mechanical data
```

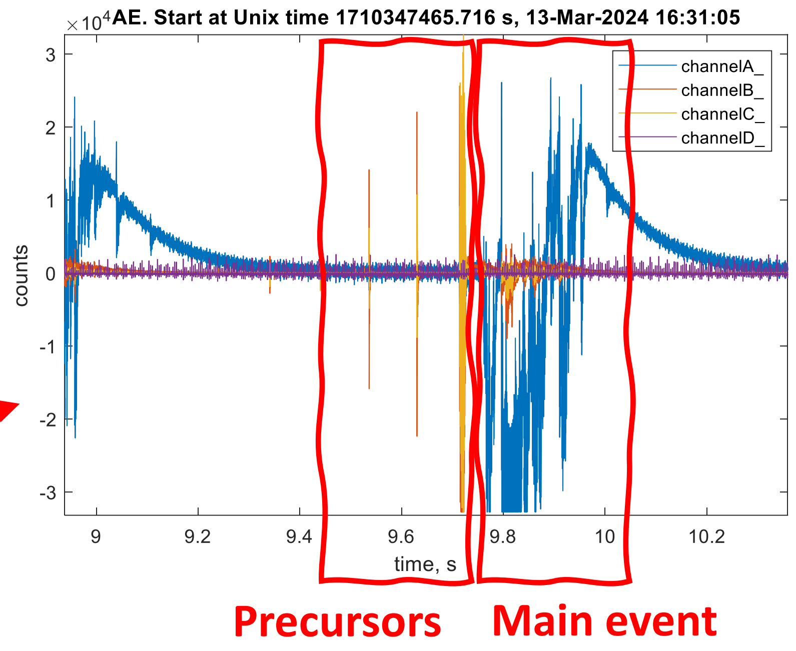
- Run again DataOverview_v01.m. You should obtain something like this
- Take note of the “Dataset starts at UNIX time” and “Camera-mechanical data time shift” that are shown in the Command Window



3) Check AE Data

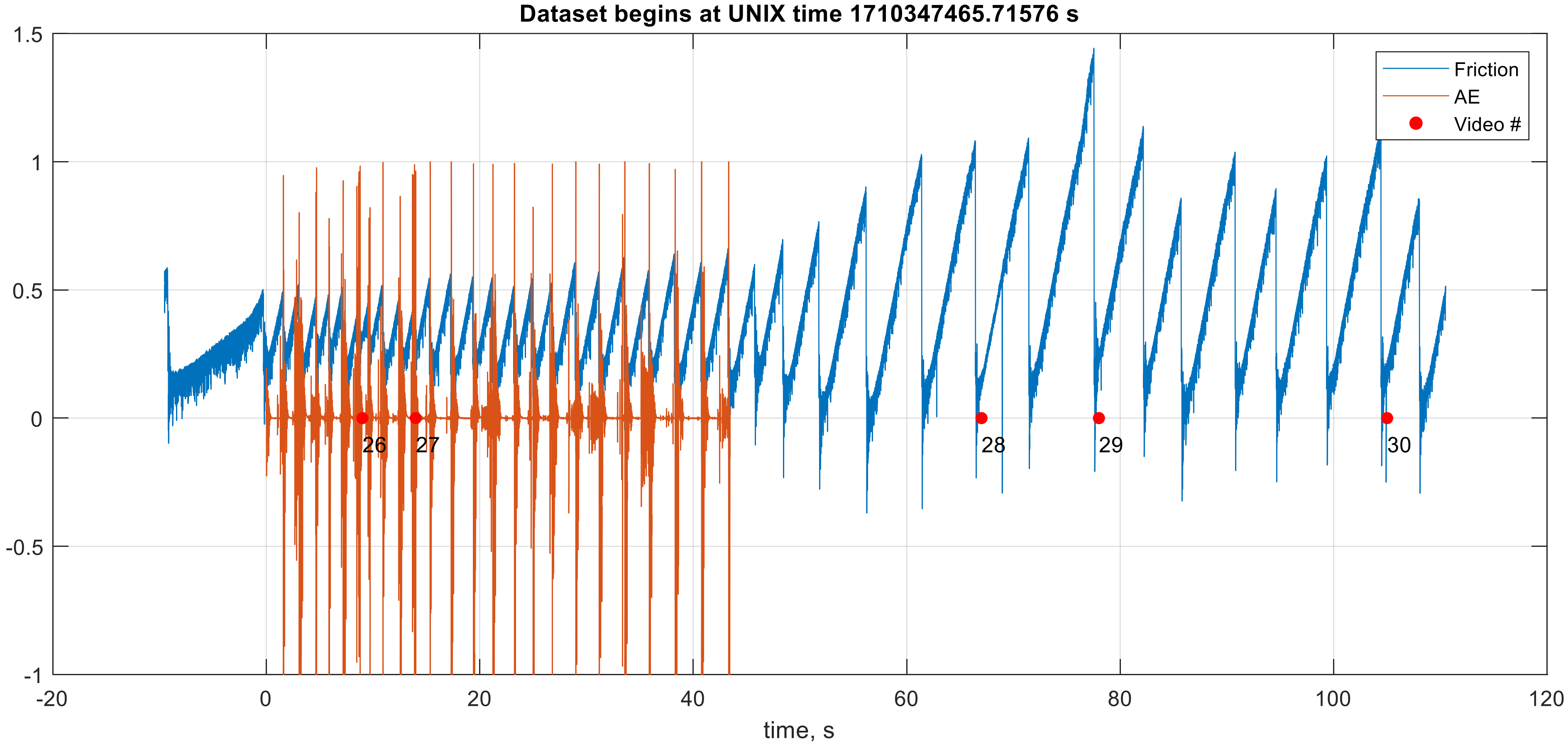
- Run the code OpenAcousticEmissions_v01.m



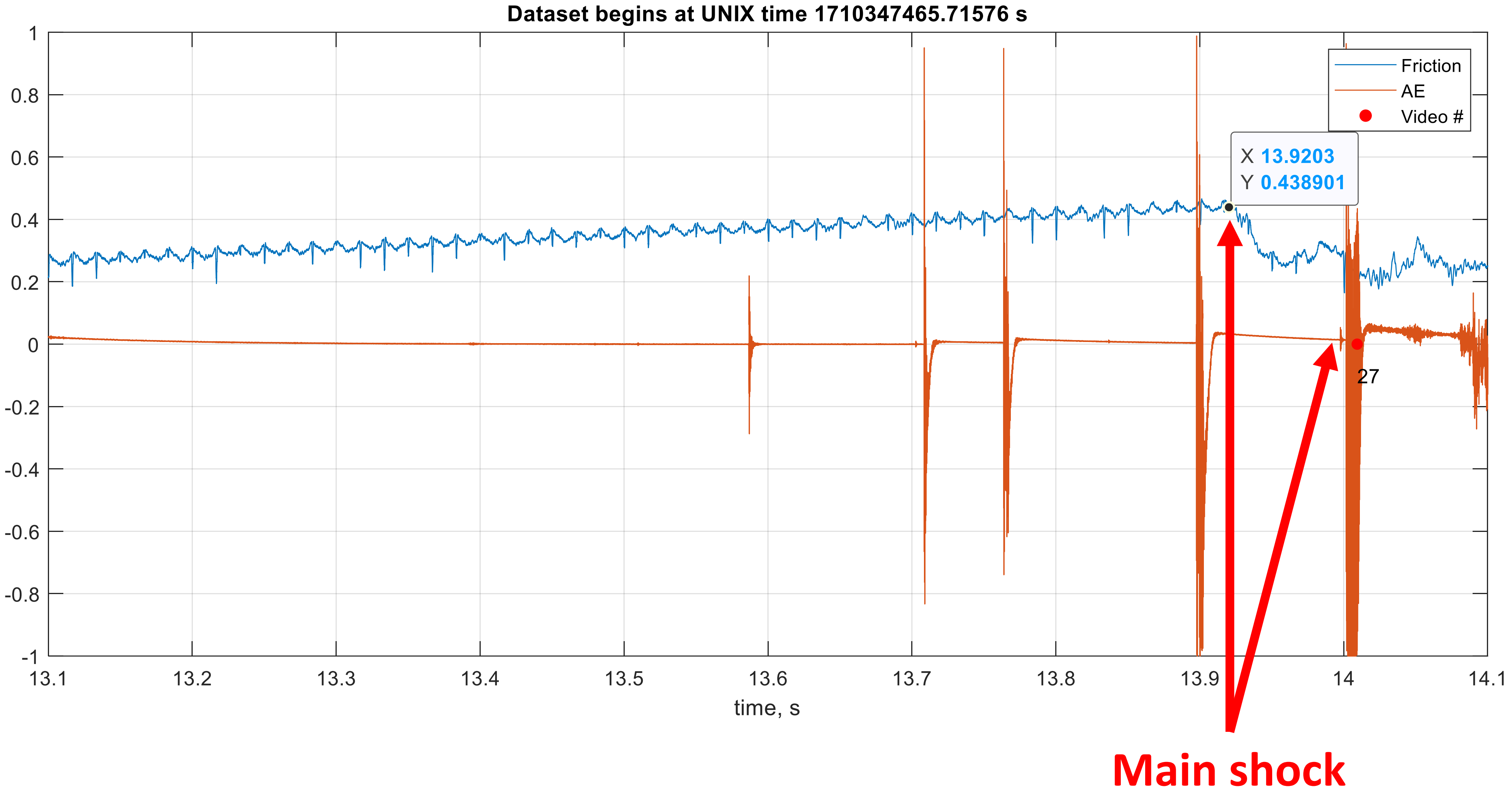


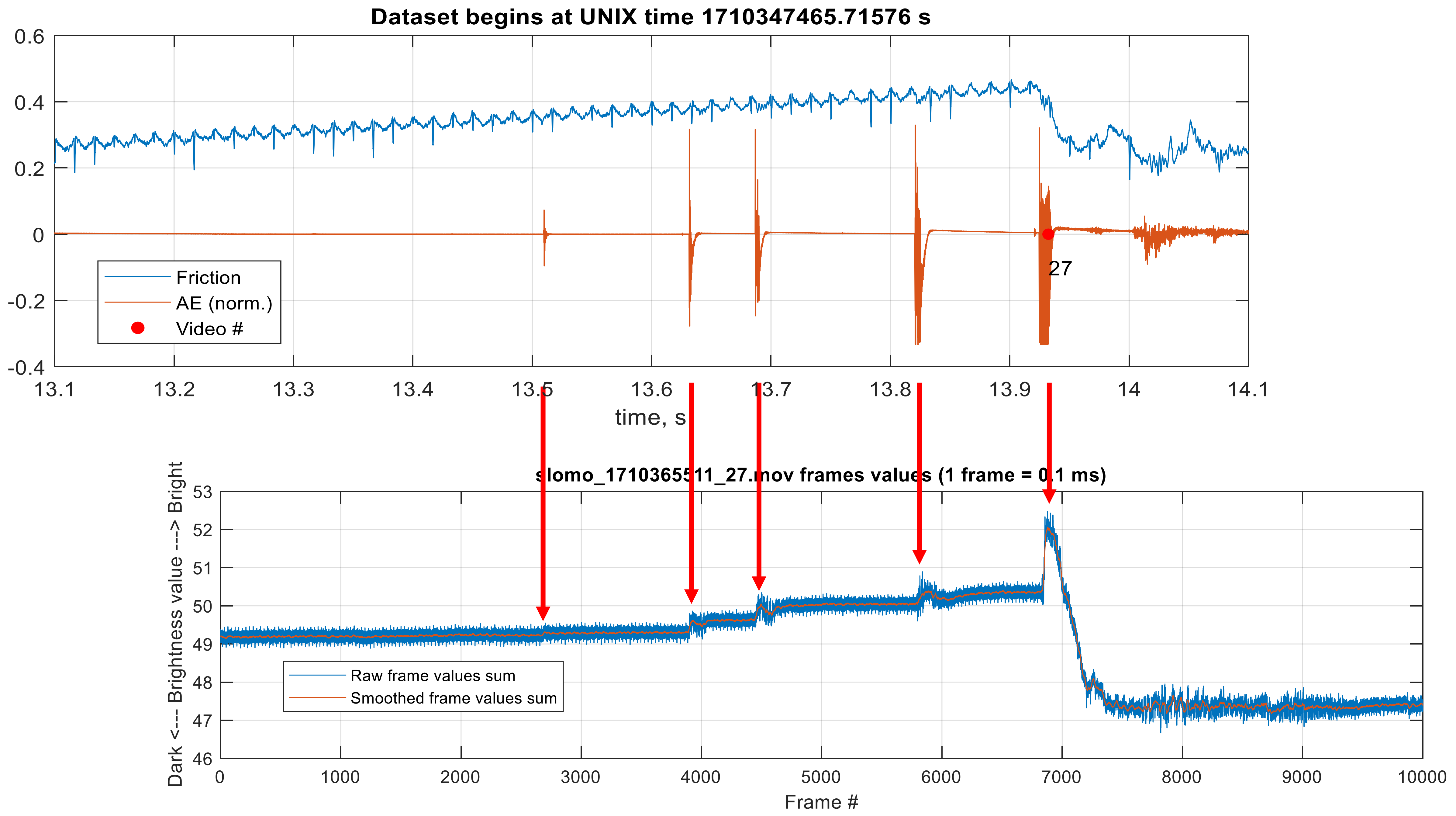
4) Try to produce the final figure (mech-AE data)

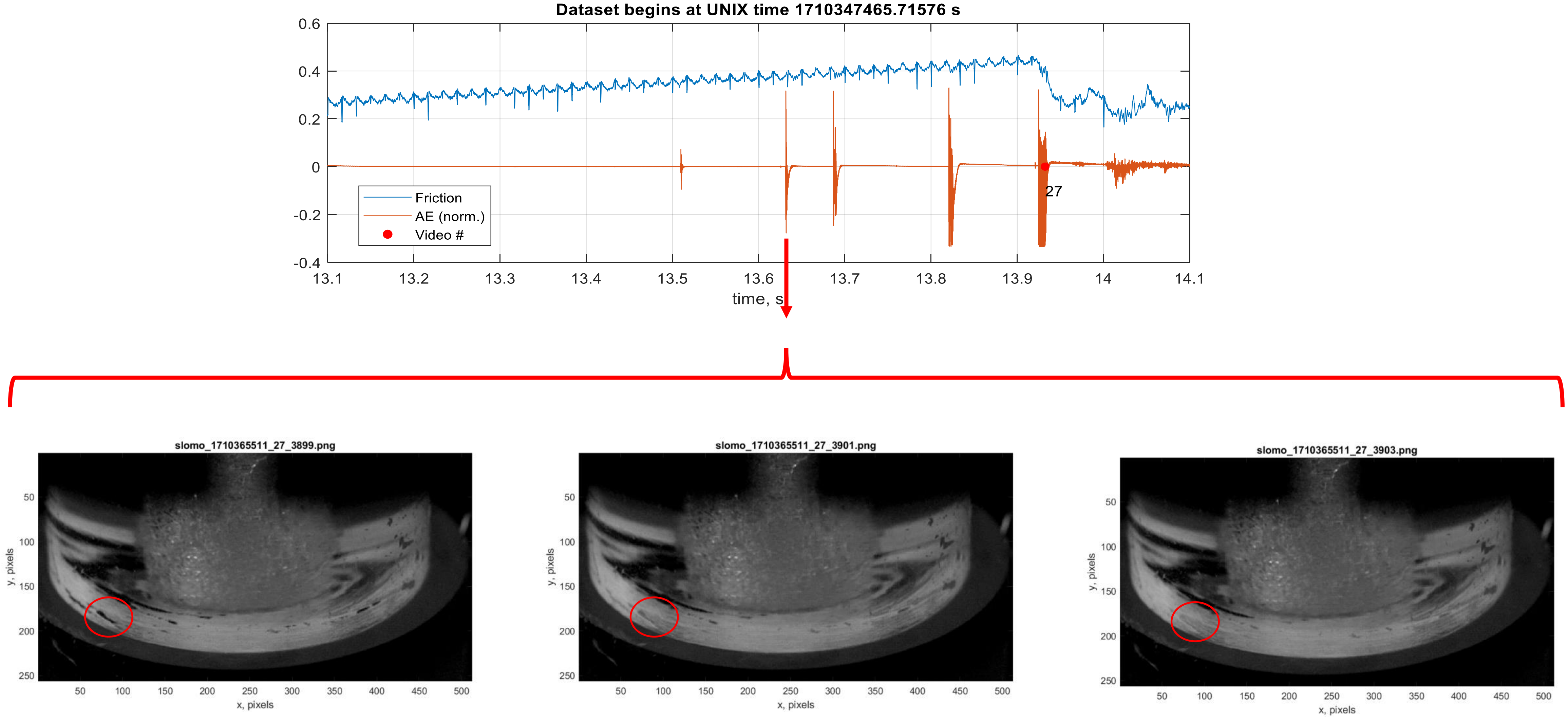
- Run code MakeFigures_v01.m



- Zoom into data around the selected video (e.g., 27)
  - Use xlim in your code to keep the zoom (e.g., xlim([13.1 14.1]);
- Use datatips or ginput to estimate the offset between mechanical and AE data – change the variable AEoff to align AE and mechanical data (in this case it is 0.077 s)




Dataset begins at UNIX time 1710347465.71576 s
Friction
AE (norm.)
Video #
27
time, s
slomo_1710365511_27.mov frames values (1 frame = 0.1 ms)
Dark <--- Brightness value ---> Bright
Raw frame values sum
Smoothed frame values sum
Frame #



To further elaborate the images you can use Matlab or software such as Fiji (https://imagej.net/software/fiji/)

Extra Info

Add video package to open mov files

- pkg install -forge video
- pkg load video