New data on the stick-slip mechanics of seismogenic faults from rotary shear experiments

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Abstract

Rotary shear (RS) experiments have been used to characterize the deformational behavior of materials and attempt to understand earthquakes. Typical RS experiments test materials under a prescribed slipping velocity and normal load. Yet, in natural earthquakes, fault nucleation, growth, termination, and slipping velocity are not predefined, but a result of the stored and released energy around the seismic fault. Here we present new measurements performed with a RS apparatus designed to be more representative of a natural system. The device uses a clock spring that when loaded by a motor imposes a linearly increasing torque to the sample. Thus, events occur spontaneously when the shear stress exceeds the static shear stress acting on the surfaces in contact. We report the results of experiments using solid poly(methyl methacrylate) (PMMA) and granular samples of polyvinyl chloride powder (figure), glass microbeads, silica powder, and crushed quartz. PMMA experiments were started at a spring loading rate (SLR) of ˜2.5 RPM, where we observed low amplitude stick-slip events occurring at regular recurrence intervals. The SLR was then increased to ˜12.5 RPM where after a transition period, temperatures during slip events exceeded the melting point of PMMA (˜160ºC). This formed a melt layer that cooled and bonded the slipping surfaces. The friction coefficient just before rupture and the amount of weakening increased as a function of the amount of melt produced. Granular experiments were conducted at a SLR of ˜2.5 RPM and variable normal stresses (0.1-0.5 MPa). The granular samples show strain hardening just before rupture, followed by strain softening and marked changes in behavior with varying water content. Since the behavior of PMMA is comparable to that of rocks at depth (McLaskey and Glaser, 2011), results of PMMA tests yield insight into precursory and coseismic events, fault strengthening/weakening mechanisms, and perhaps, the formation of pseudotachylite glass. Experiments with granular samples allow us to characterize each material's behavior in response to variable water content, SLR, and normal stress. We conclude that analog materials are valuable to simulate the behavior of the seismogenic brittle lithosphere. From such experiments, we can gain insight into stick-slip mechanisms relevant to earthquakes.

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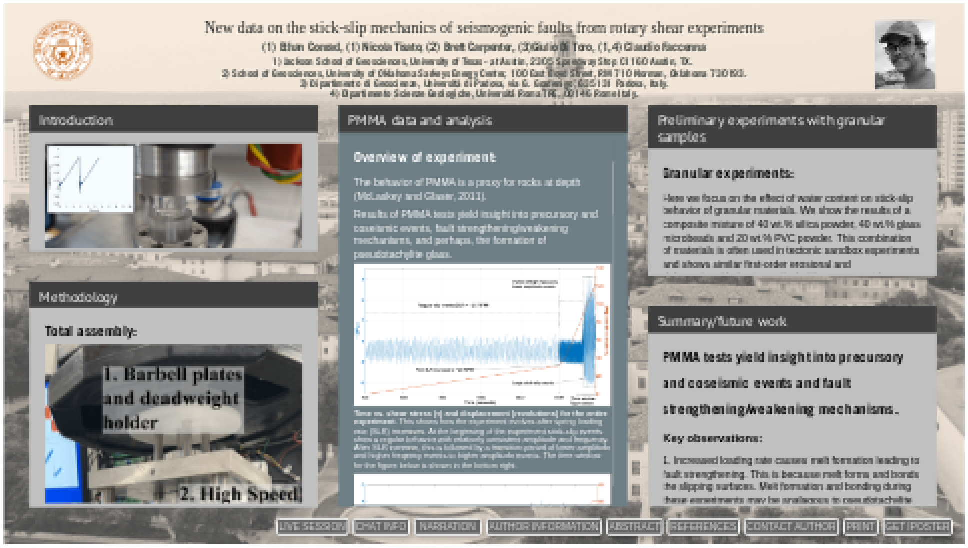

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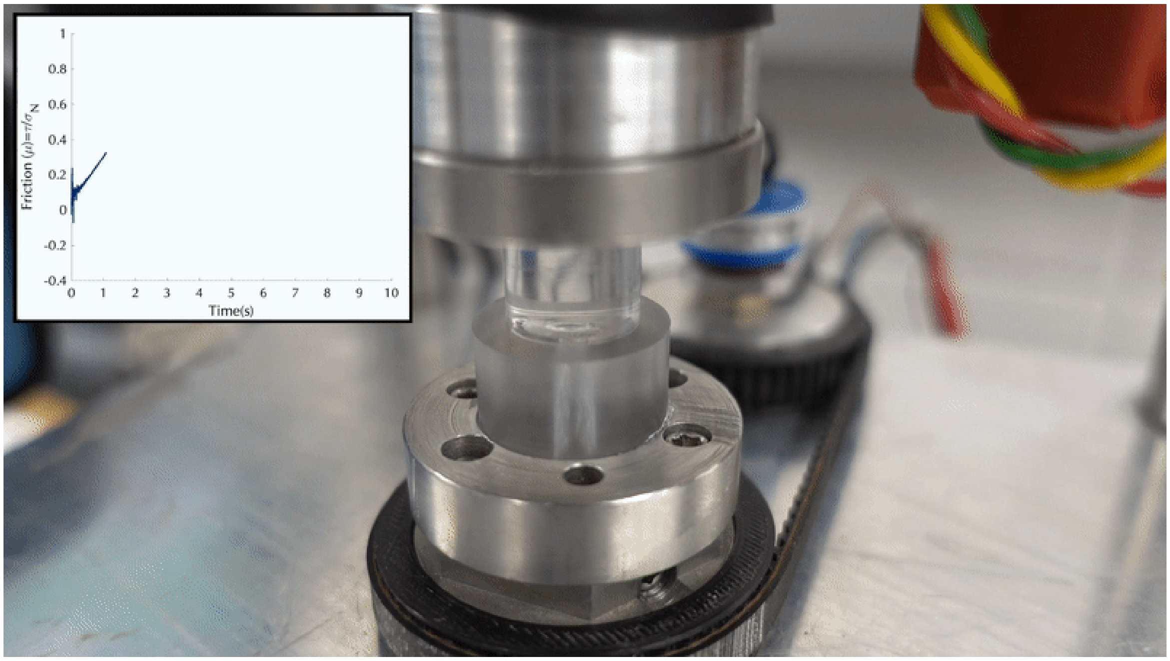
PRESENTED AT:

INTRODUCTION



Introductory example of an experiment with PMMA showing stick-slip behavior. Pay attention to the interface between the upper and lower sample and how it changes with each event.

- Rotary shear (RS) experiments have been used to characterize the deformational behavior of materials and attempt to understand earthquakes. Conventional rotary shear tests impose a predefined slipping velocity to materials in contact under a predefined load.

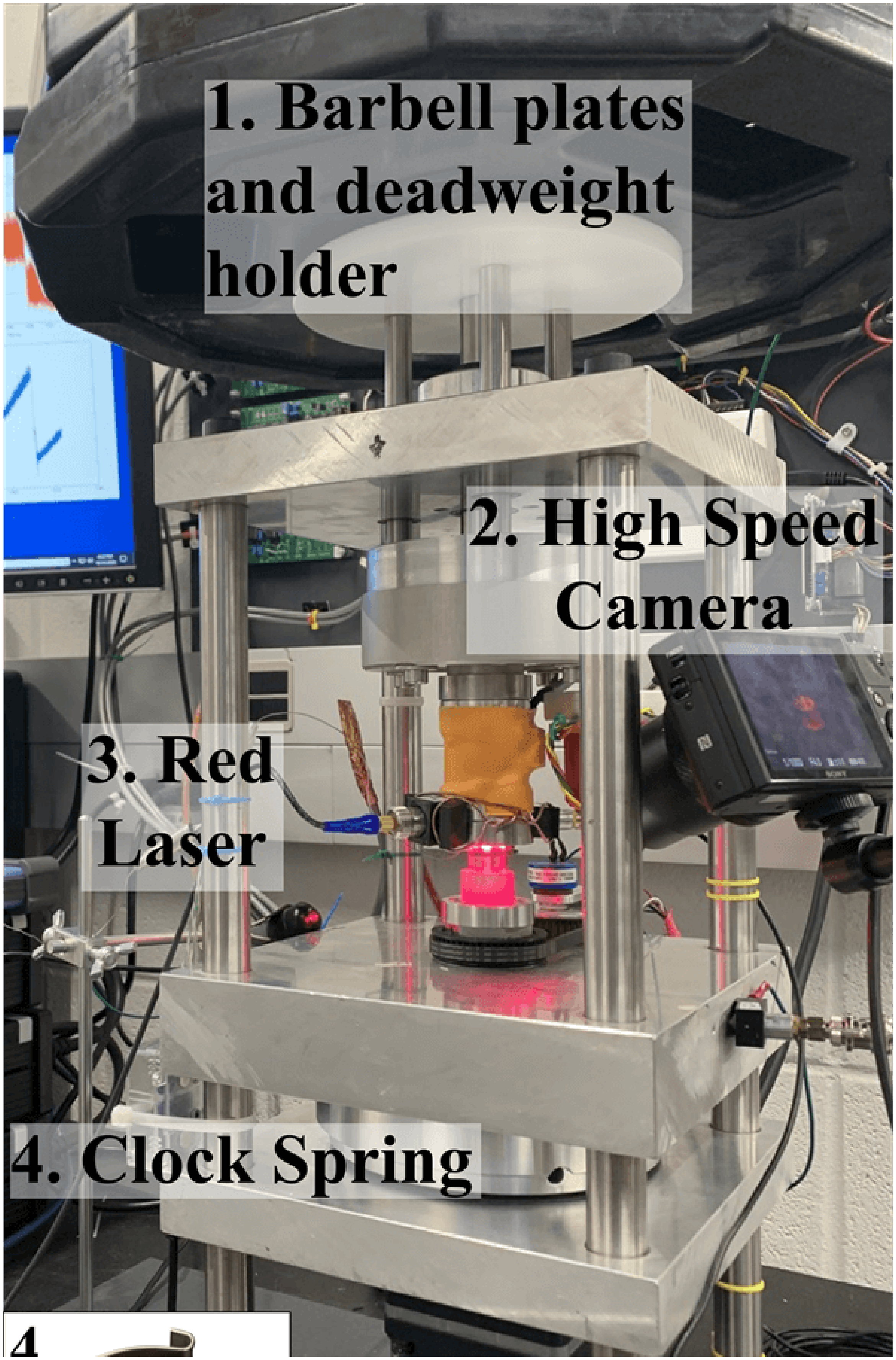
- In natural earthquakes this is not the case.

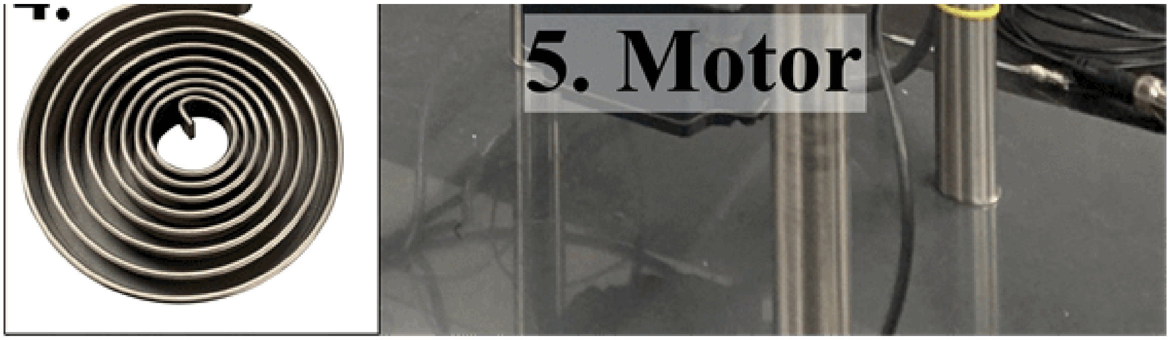
- Our unique rotary shear apparatus implements a clock spring that imposes a linearly increasing torque to the sample. Like a natural earthquake, the material surface interactions control when slip occurs, the velocity of slip and the total displacement. Thus, events occur spontaneously when the shear stress exceeds the static shear stress acting on the surfaces in contact (Rieger et al., 2013; Tisato et al., 2017).

- This new method allows us to study both the precursory and co-seismic events that resemble natural earthquakes.

METHODOLOGY

Total assembly:





1. Deadweight holder loaded with barbell plates: used to apply normal stress on the slipping surface.

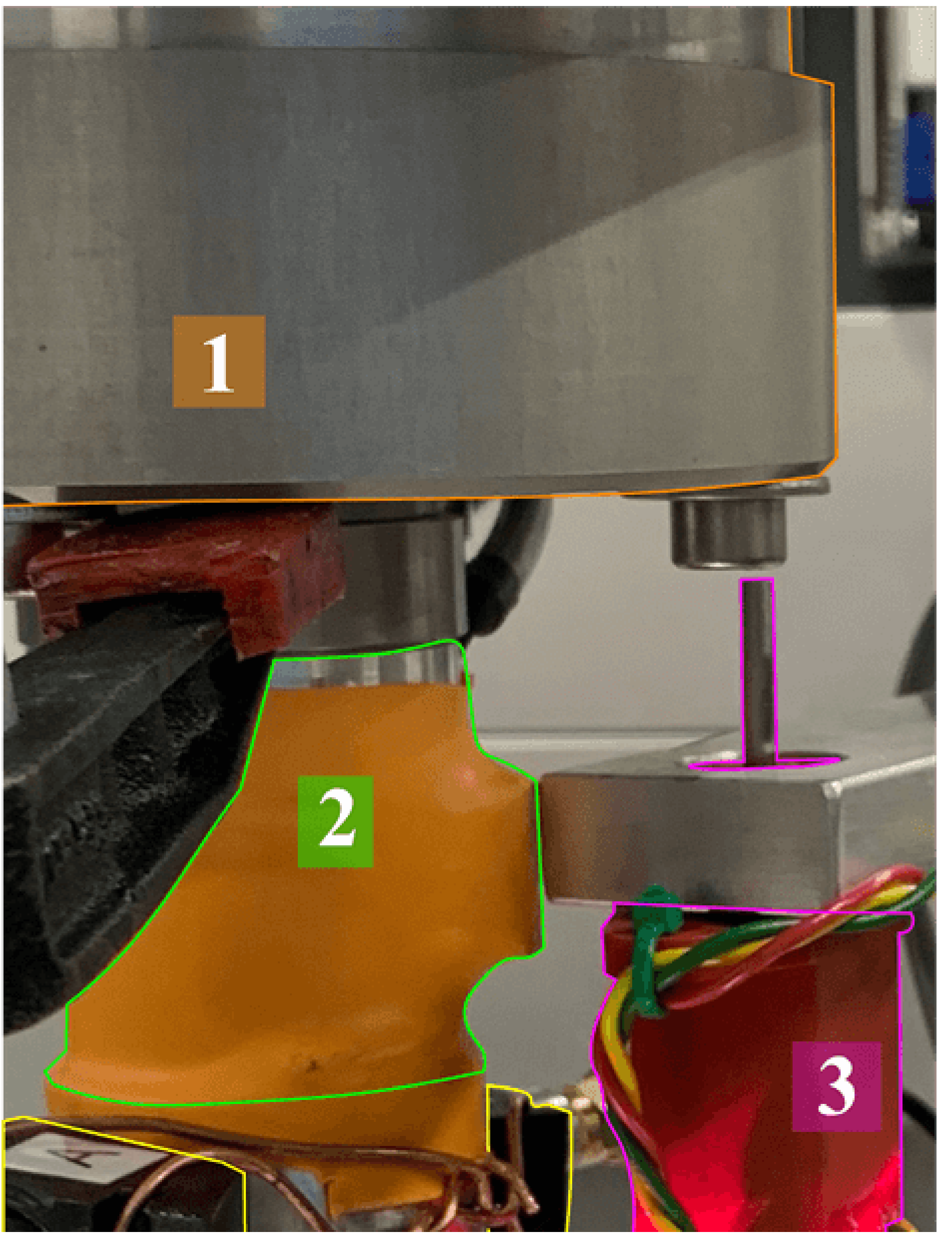
2. Highspeed camera (Sony - DSC-RX100M5A): records 960 fps video of the experiment.

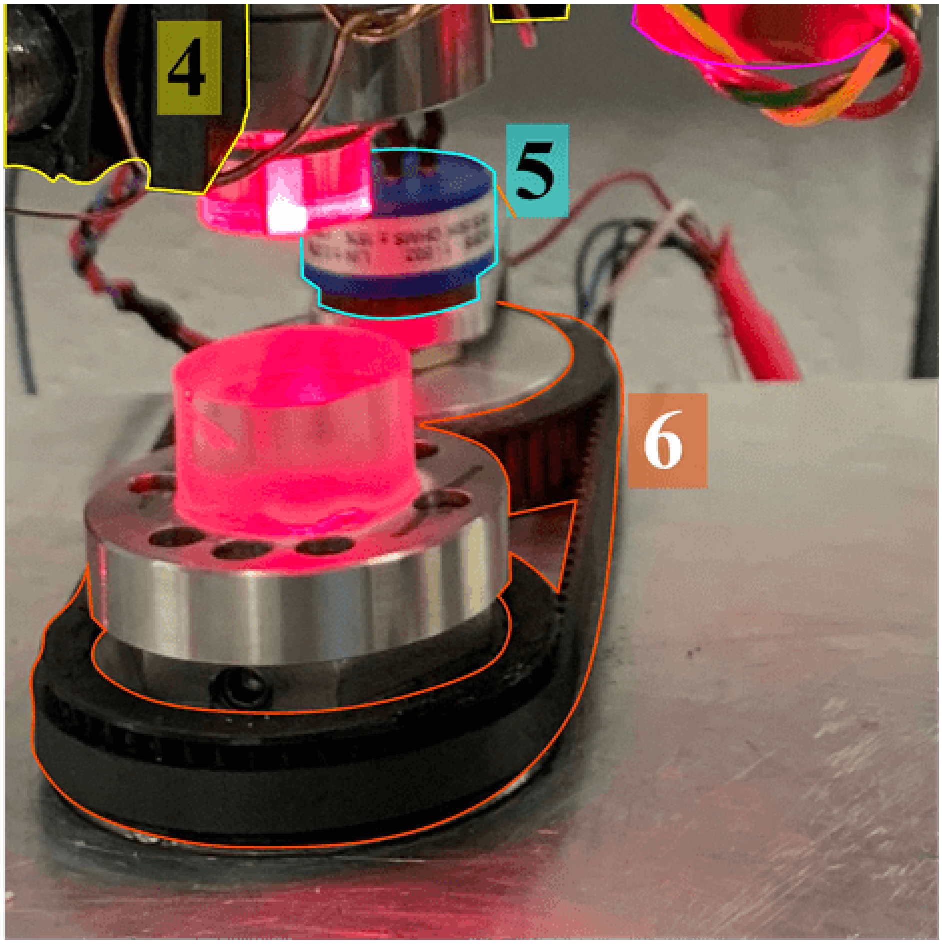
3. Red laser: illuminates the sample and slipping surface

4. Clock spring: applies linearly increasing torque to the sample

5. Motor: loads the clock spring

Solid sample assembly:





Method for presented experiment:

Sample: PMMA: poly-(methyl) methacrylate a.k.a. plexiglass or acrylic glass.

- Normal force constant at ~3.3 MPa.
- Started at a spring loading rate (SLR) of ~2.5 RPM.
- SLR then increased to ~21 RPM > ~23.5 RPM > 35 RPM.

Assembly:

1. Load cell: measures the normal force.

2. Torque cell: measure the torque which can be converted to shear force.

3. Vertical displacement sensor: measures sample dilation.

4. Acoustic emmision sensor

5. 2 multiturn potentiometers: measures rotational displacement.

6. Thermocouple (not visible): measures the outer sample temperature

Granular sample assembly:

Method for presented experiments:

- SLR constant at ~2.5 RPM
- Normal force constant at ~120 KPa

Assembly:

1. Upper sample holder (fixed): lowered to compress powder.

2. Lower sample holder (mobile): with powder trough: contains the powder.

3. Teflon ring: seals sample holder. Torque contribution minimal and removed during post processing.

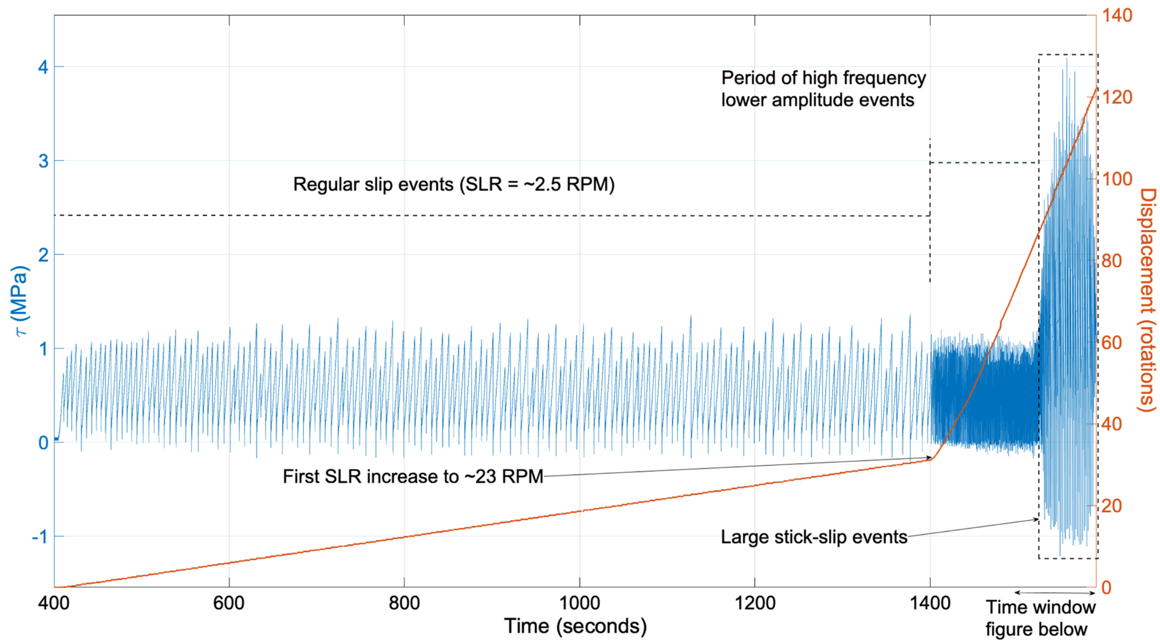
4. 2 carpet disks: ensures that slip occurs within the powder layer and not at the interface between the powder and the sample holders.

PMMA DATA AND ANALYSIS

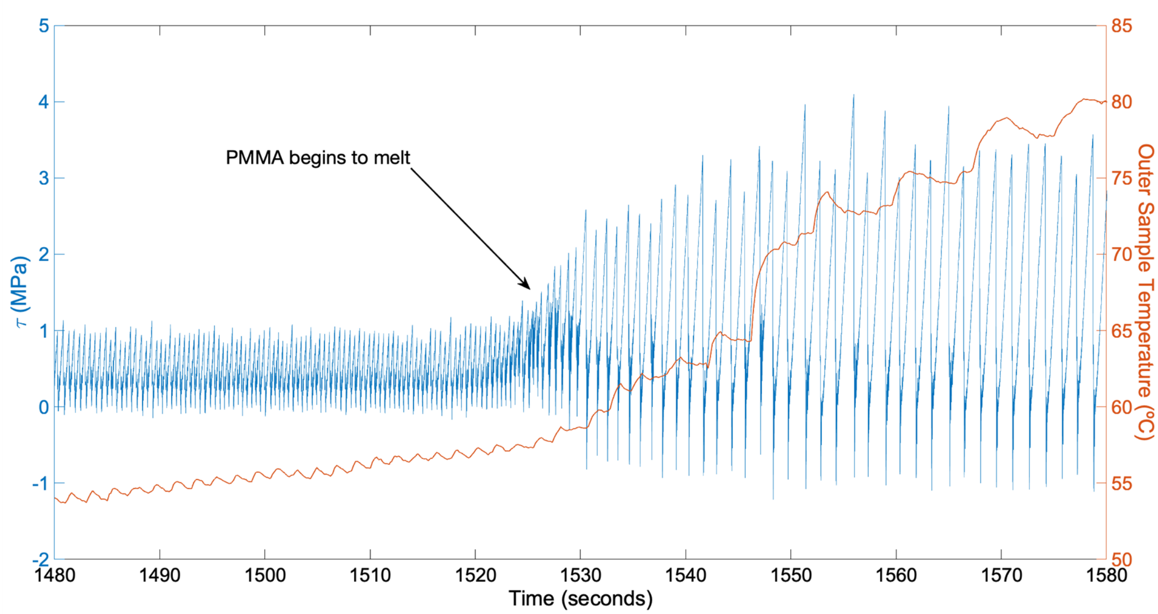
Overview of experiment:

The behavior of PMMA is a proxy for rocks at depth (McLaskey and Glaser, 2011).

Results of PMMA tests yield insight into precursory and coseismic events, fault strengthening/weakening mechanisms, and perhaps, the formation of pseudotachylite glass.



Time vs. shear stress (τ) and displacement (revolutions) for the entire experiment. This shows how the experiment evolves after spring loading rate (SLR) increases. At the beginning of the experiment stick-slip events show a regular behavior with relatively consistent amplitude and frequency. After SLR increase, this is followed by a transition period of lower amplitude and higher freqency events.to higher amplitude events. The time window for the figure below is shown in the bottom right.



Data cropped to after the initial SLR increase (time window shown in figure above). Here we show time (seconds) vs. shear stress (τ) and the measured outer sample temperature. While 80 ^{0}C is well below the metling temperature of PMMA, we assume that the temperature at asperity tips is high enough to initiate melting. More work must be done to refine our method for temperature acquisition.

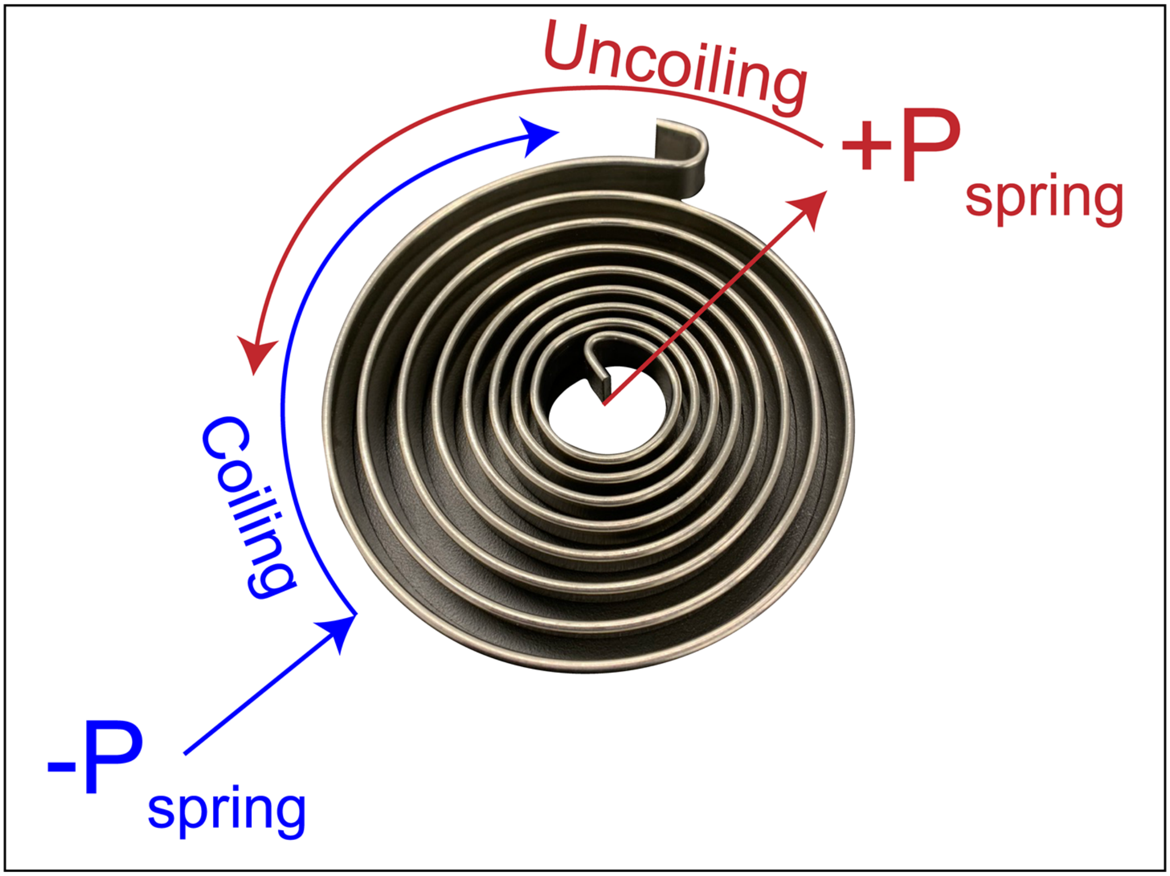
After PMMA begins to melt and form experimental PST, we observe fault strengthening. This occurs because heat cannot dissipate rapidly enough between events and the temperature at aperity tips exceeds the melting point of PMMA (160℃).

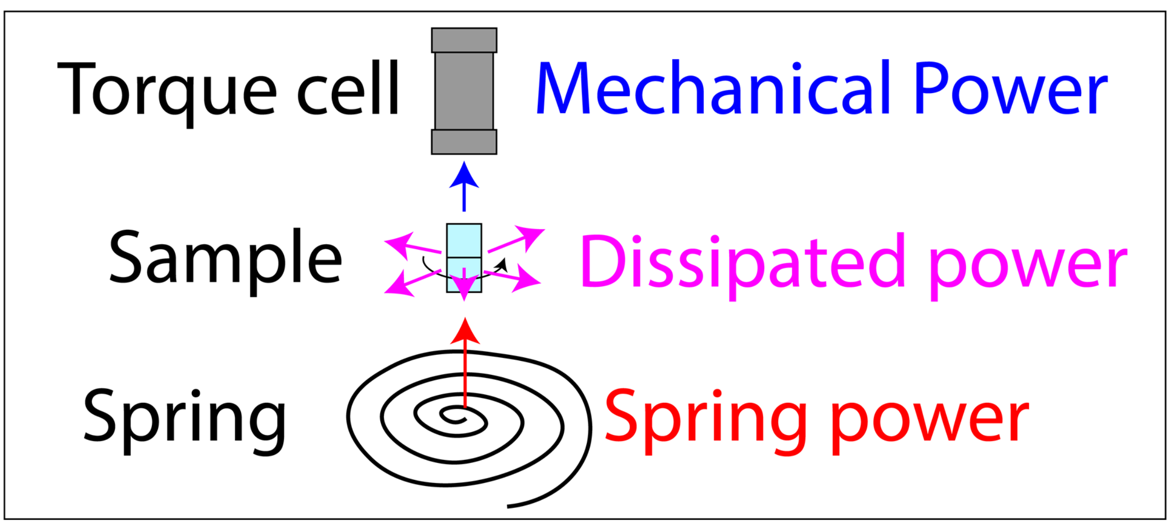
Power analysis:

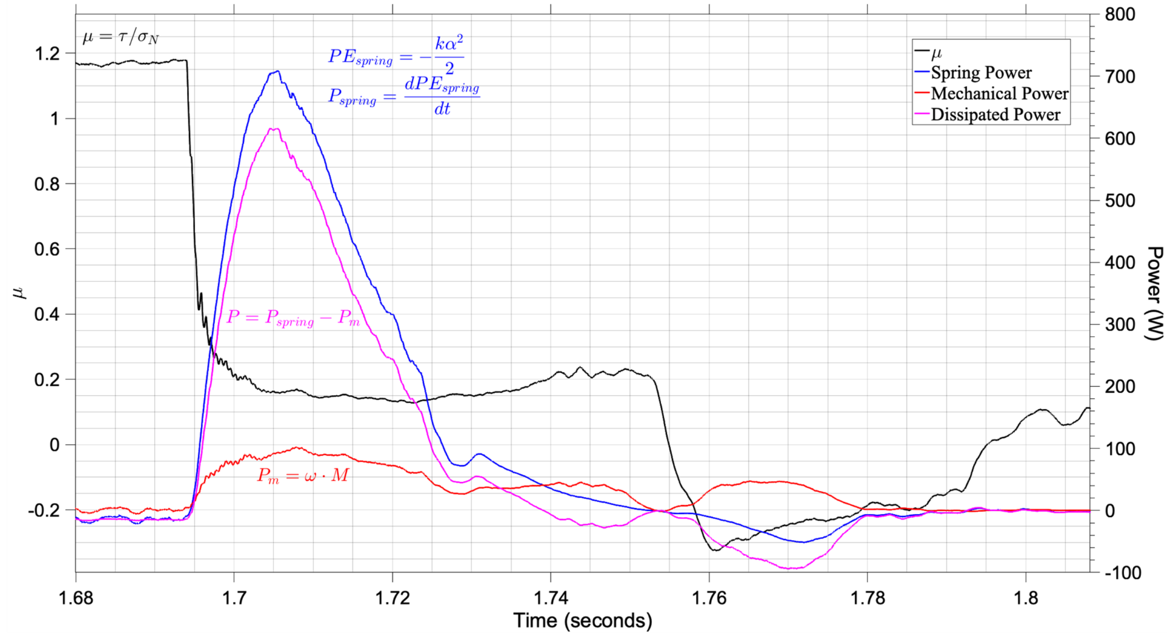
Reches et al. (2019) suggests that the energy flux during fault slip may control the slip style of natural fault systems.

Here we investigate their hypothesis using PMMA in our solid sample assembly.

We compare the power contributed by spring loading and the mechanical power to attempt to understand the evolution of slip style during each event. The difference between the two powers is the dissipated power.

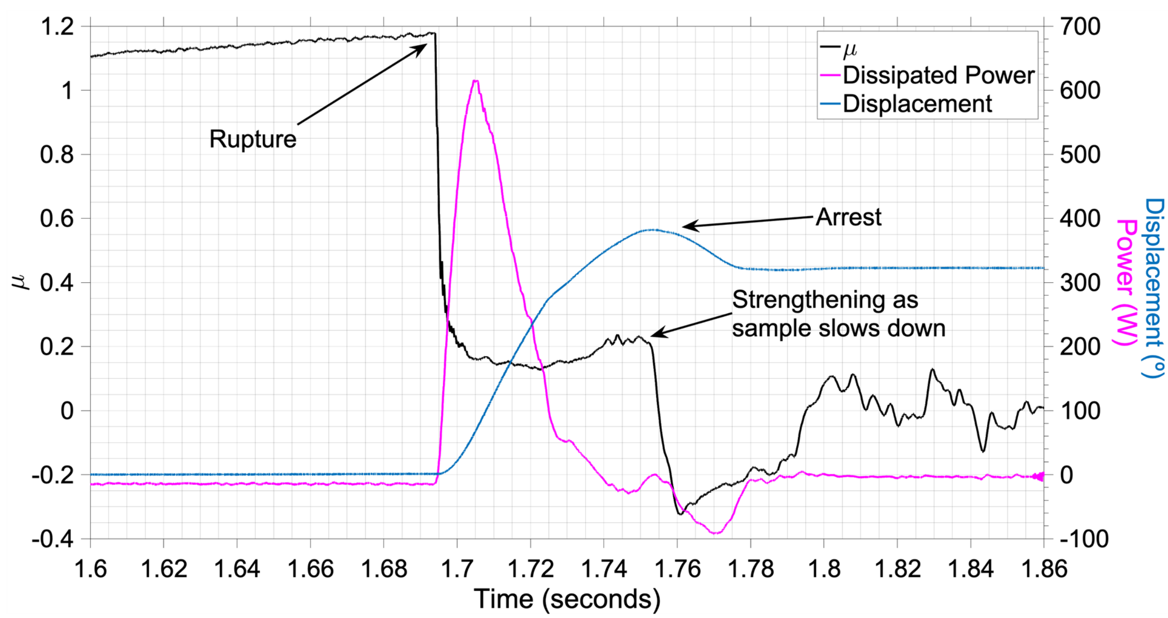






Time vs. friction and calculated powers.

k = spring coefficient (N•M/radian), α = difference between the angular displacement of the motor and the angular displacement of the sample, PE_{spring}= potential energy stored in the spring, P_{spring}= spring power, P_m= mechanical power, ω = angular displacement of the sample, M = torque.



Time (seconds) vs. friction coefficient and dissipated power.

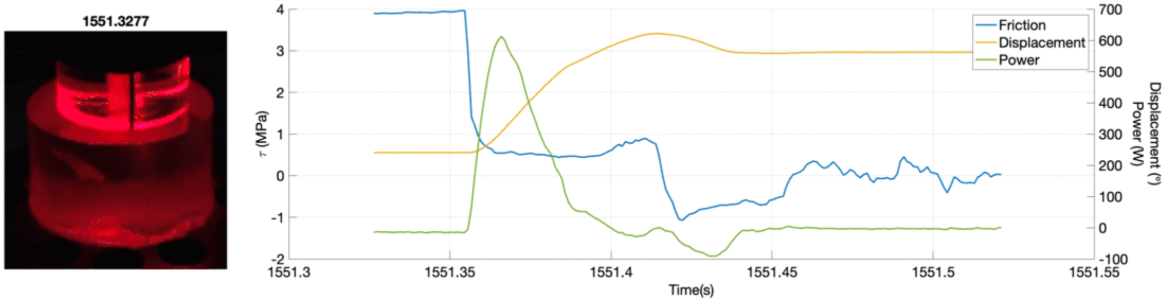
Observations:

1. The sudden dissipation of power (700 W) corresponds to the sharp reduction in the friction coefficient. This may reflect flash heating (e.g. Rice, 2006) and the rapid formation of melt.

2. As the melt layer grows and the sample slows down, there is a slight increase in the friction coefficient as the event comes to an end.The velocity and rate of power dissipation decrease. One possible explaination could be that at this point the layer begins to cool, increasing the viscosity of the melt layer and strengthening the bond between the slipping surfaces. This may explain the inflection in velocity and power dissipation.

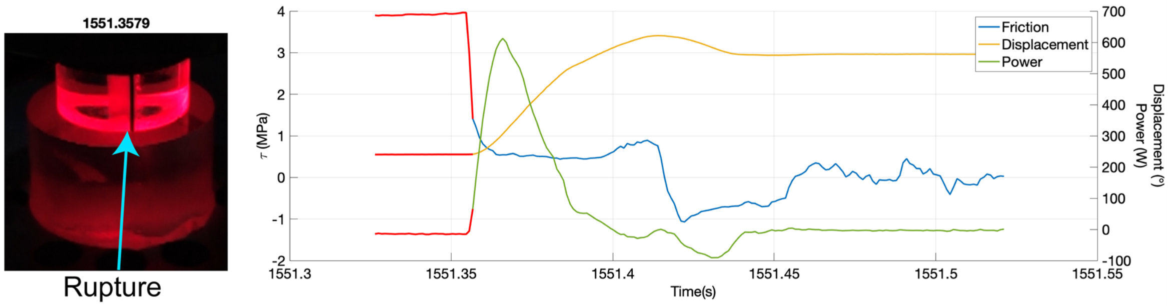
3. Slipping in this direction (CCW) eventually stops. Due to the rotational inertia the sample recoils, rotating in the opposity direction.

The evolution of the slip surface is apparent in our high frame rate recording:

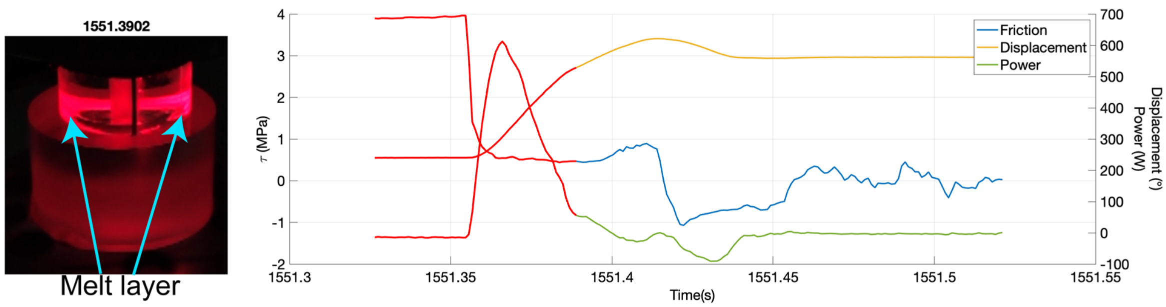


Key snapshots:

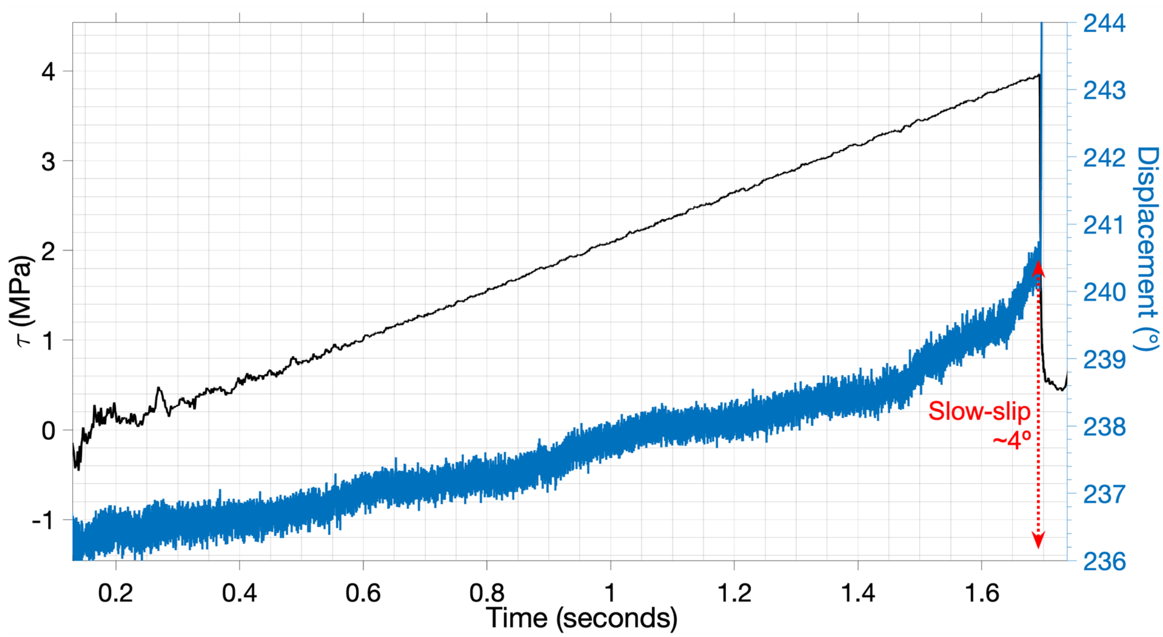
Rupture and initiation of first slip style:



Melt layer growth:



Precursory slow slip before each event:



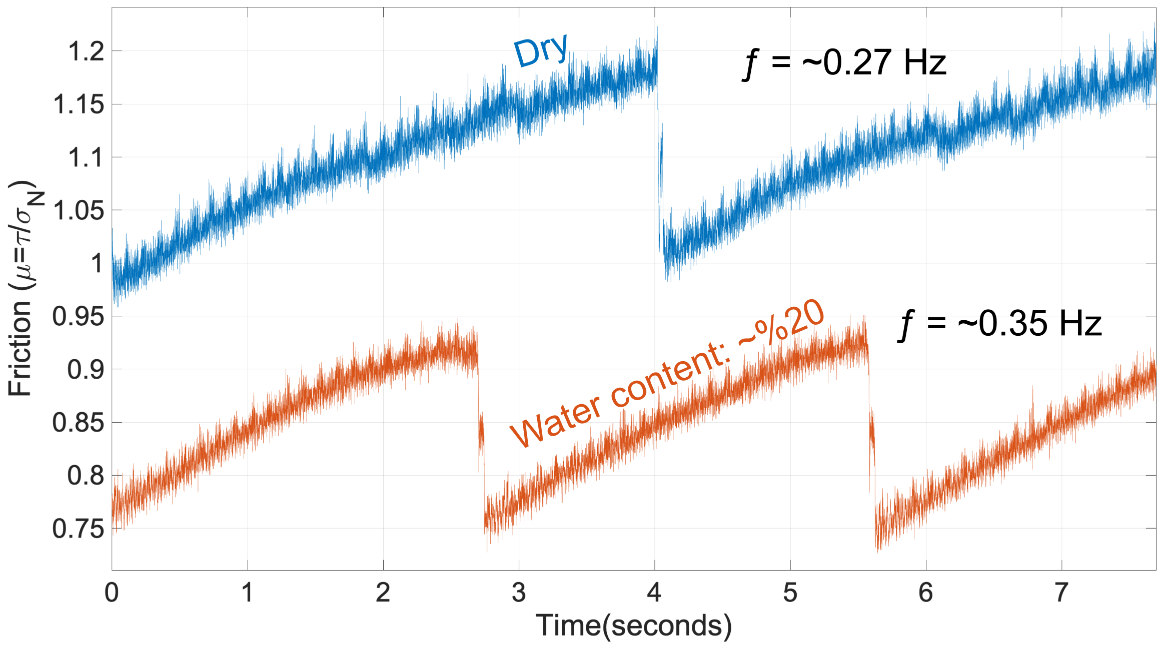
Time (seconds) vs. shear stress (τ, MPa) and angular displacement (^{0}).

The slow slip before this event is ~4^o, this is unique to our method and highlights the significance of allowing the “fault” plane to control when and how much slip occurs.

PRELIMINARY EXPERIMENTS WITH GRANULAR SAMPLES

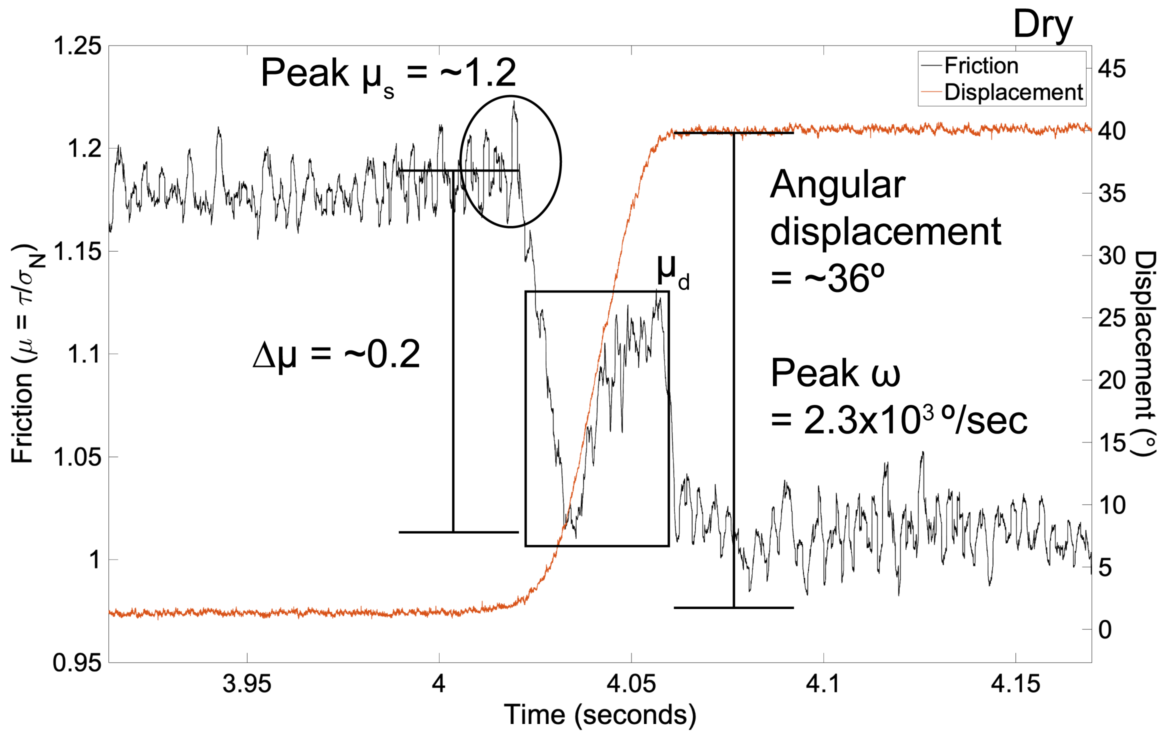
Granular experiments:

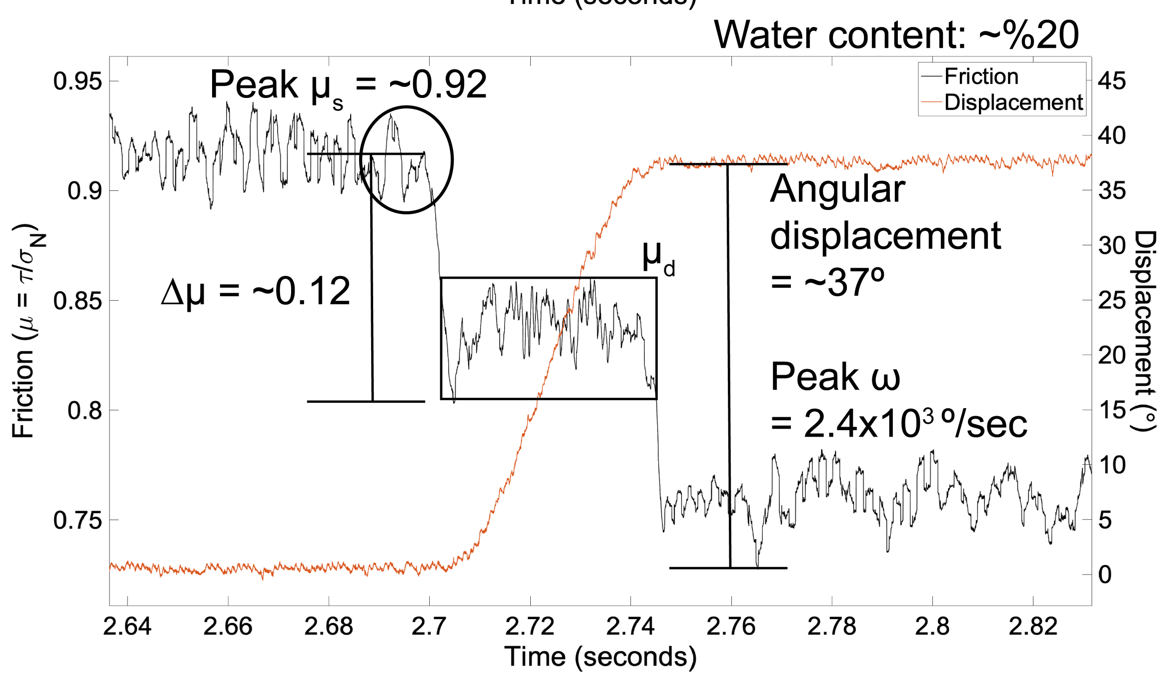
Here we focus on the effect of water content on stick-slip behavior of granular materials. We show the results of a composite mixture of 40 wt.% silica powder, 40 wt.% glass microbeads and 20 wt.% PVC powder. This combination of materials is often used in tectonic sandbox experiments and shows similar first-order erosional and deformational behavior as the brittle upper crust (e.g. Reitano et al. 2020). For "wet" experiments, 20 wt. % water was added to the sample.



Time (seconds) vs. friction ($\mu=\tau/\sigma_N$) for both dry and wet experiments.

Dry experiments show higher static and dynamic friction coefficients and events occur at a lower frequency.





Data cropped to show the difference between individual stick-slip events. μ_s = static friction, μ_d = dynamic friction, $\Delta\mu$ = friction drop, ω = angular displacement.

From these experiments we see that static friction, dynamic friction and the friction drop decreases with increased water content.

SUMMARY/FUTURE WORK

PMMA tests yield insight into precursory and coseismic events and fault strengthening/weakening mechanisms.

Key observations:

1. Increased loading rate causes melt formation leading to fault strengthening. This is because melt forms and bonds the slipping surfaces. Melt formation and bonding during these experiments may be analagous to pseudotachylite formation in nature.

2. Changes in slip velocity and rate of power consumption are possibly related to the activation of multiple co-seismic strengthening and weakening mechanisms. This is apparent in the HFR video showing the evolution of the slip surface.

3. High amplitude experimental events are preceded by slow slip events analogous to precursory fault creep before high magnitude earthquake rupture. This observation is unique to our method and highlights the significance of allowing the "fault" plane to control when and how much slip occurs.

Experiments with granular samples allow us to characterize each material's behavior in response to variable water content.

Key observation:

Increasing the water content of a granular sample decreases the peak static friction coefficient, the friction drop and increases the frequency of stick-slip events. These experiments show the potential to optimize granular mixtures to better represent the brittle upper crust.

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Thesis advisor: Michael Perfit

ABSTRACT

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Plain Language Summary:

Geoscientists use machines that rotate two materials against each other to simulate earthquakes. Measurements made during these experiments yield insight into the mechanisms that control earthquake behavior. Here we present data acquired from a unique rotary shear device that instead of forcing rocks past one another, uses a spring to gradually increase the twisting force (torque) on the sample. With this method, sample rotation occurs at the exact moment the torque exceeds the resisting force (friction) between the two material surfaces.

Here we report the results of experiments using acrylic glass and a variety of granular samples. Experiments with the acrylic glass showed distinct events that resemble aspects of earthquake behavior. For example, our experiments generated temperatures high enough to melt the acrylic glass and weld the two opposing surfaces together. A similar phenomenon may be present in the natural places where rocks slide past one another (faults). Experiments with granular samples showed an increase in strength just before motion followed immediately by a decrease in strength and distinct changes in behavior with varying water content. Since rocks show similar behaviors, these experiments allow us to gain insight into processes that occur during the earthquake cycle.

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