

## Project Report: Understanding Precursory Locking Using Unique Laboratory Fault

**Introduction:** The goal of this project was to develop a better understanding of the earthquake cycle, the repeated, long-term pattern of locking, loading, and slip that faults experience. This cyclic behavior is observed for both seismogenic earthquakes (Brace & Byerlee, 1966; Kanamori & Brodsky, 2004) and slow slip events (Bürgmann et al., 2005; Truttmann et al., 2024; Perfettini et al., 2010).

We have developed a system to study this cyclic process on heterogeneous faults that both evolve their normal stress heterogeneity through slip, and have ruptures that do not fail the entire interface with each event, and thus build up residual stresses over many earthquake cycles. We are able to do this by studying them in a biaxial friction system that employs faults made of transparent rubber with a layer of mobile sand in between. The transparent rubber (PDMS) affords a number of unique advantages:

- 1) It allows us to embed tracer particles below the frictional interface and directly measure displacements and thus calculate the slip velocity and strain fields across the entire interface at every moment.
- 2) It allows the control of normal stress heterogeneity through the size and distribution of sand used
- 3) The compliance of the rubber means that earthquake cycles encompass only a few seconds, and ruptures are predominantly confined within the edges of the system, and thus the fault can build up residual stresses over many earthquake cycles

Interestingly, these features lead the fault to follow many traditional earthquake statistics including the Gutenberg-Richter relationship, Omori's Law, and for events to have both magnitude and normal stress-invariant stress drops. Previously, we had used the ability to directly image slip dynamics on this system to observe and measure a precursory locking phase that precedes slip events on the system that occurs over a critical length scale and, on average, carries information about the size, timing, and location of future slip, described in more detail below. In this SCEC funded project, we have developed a deeper understanding of the origins of this scale and its intimate connection to stress heterogeneity.

**Methodology:** The motion of the tracer particles is imaged with a high speed camera (Phantom VEO), and displacements at each time step are determined through Particle Image Velocimetry (PIV), a standard image cross-correlation technique. This displacement is differentiated through time to calculate instantaneous velocity fields across the entire interface at all times. The velocity X-Y-T velocity field is then thresholded and contiguous volumes are identified as individual slip events where we can calculate a range of seismological and geometric parameters including the slip area, moment, and hypocenter for every event in the catalog. A complete description can be found in Steinhardt et al., 2023.

For every event, we calculate the average velocity on the eventual slip patch for all times before and throughout the event. For experiments performed under identical conditions, all events within a given size range are aligned with their hypocentral nucleation time set to  $t = 0$ . The mean patch velocities then are averaged for all of these events to calculate a mean slip velocity,  $\langle v_{\text{patch}} \rangle$ , for a given moment bin. Previously we had observed that  $\langle v_{\text{patch}} \rangle$  oscillates around zero for most of the time preceding the event, but starting at  $\sim 1.75$ s prior to nucleation, there is a sustained period where  $\langle v_{\text{patch}} \rangle$  is exclusively in the direction of loading. We refer to

this as a precursory locking phase and the time over which it occurs as  $\langle t_{\text{lock}} \rangle$ , and observed that it is independent of the moment bin of events, i.e events varying by 4 orders of magnitude have the same locking duration. This is easier to see when measuring  $\langle v_{\text{patch}} \rangle$  normalized by the mean patch area, where you can also see that all the data collapses onto a single common curve, as shown in Figure 1. This locking duration is also associated with a decrease in the event rate by  $\sim 28\%$  over a similar time scale.

We had also previously shown that the locking phase is predictive of the size of the eventual slip event. We calculate  $\langle v_{\text{patch}} \rangle$  for a range of event moments, and find that each shows a precursory locking phase before nucleation. We compared the total integrated locking distance,  $d_{\text{lock}}$ , during the locking phase to the moment of the eventual slip event, and found that for both individual events as well as the averages within a given moment range there is a linear increase in moment with  $d_{\text{lock}}$ , implying that the locking has predictive information about the size of the subsequent slip event.

Finally we had observed that  $\langle t_{\text{lock}} \rangle$  is constant at a given loading rate regardless of the eventual slip event size. However,  $\langle t_{\text{lock}} \rangle$  decreases inversely with increasing loading rate, as seen in Figure 1. The locking duration as a function of loading rate is well fit by  $v_{\text{load}} = L / t_{\text{lock}}$ , indicating a critical length scale of  $L = 0.9 \pm 0.1$  mm. This fit suggests a fixed length scale controls the duration of the locking phase. Given the similarity of this length scale to the grain size in the system (420-565 microns), we postulated that this might control the critical locking length scale. **The goal of this proposal was to understand whether this was true, and if so how the locking length scales with heterogeneity size, and what effect it has on other aspects of the fault's behavior.**

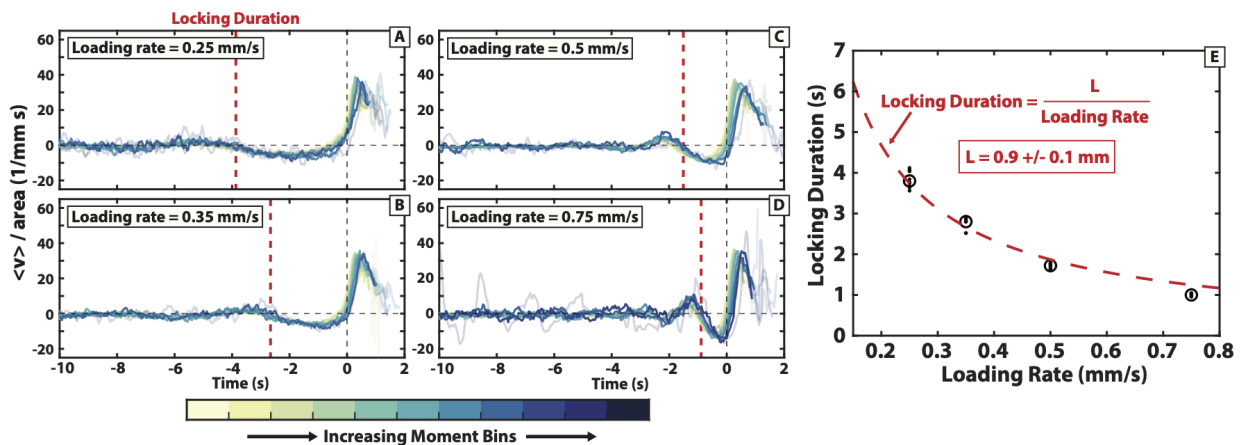


Figure 1: Precursory locking occurs over critical length scale (A-D) Mean slip patch velocity per unit area for loading rates of 0.25, 0.35, 0.5 and 0.75 mm/s at increasing event moment bins. Grayed out regions indicate an average of less than 10 total events. When normalized by area, each event bin shows a nearly identical pattern of locking and slip. For each set of experiments the locking duration is invariant as a function of event size, but decreases with increasing loading rate. (E) Locking duration as a function of loading rate. Small black dots represent each individual moment bin with the average indicated by the large circle. This data is well fit (red line) by a constant length scale  $L$  divided by the loading rate, where the best fit is  $L = 0.9 \pm 0.1$  mm. This represents a critical loading distance that is required to nucleate a slip event.

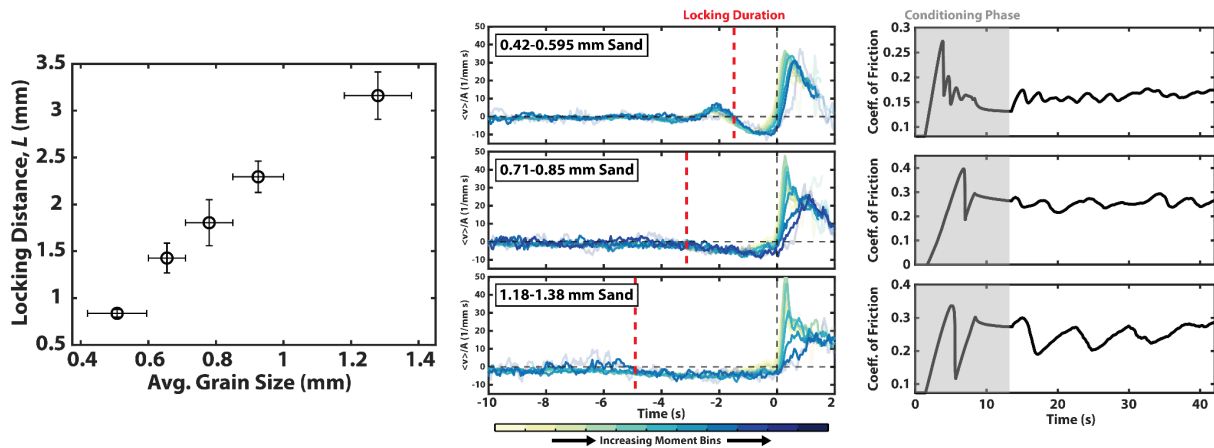
**Results:** We purchased bulk,  $\sim 0.5$ - $1.5$ mm sand and used a stack of sieves to separate it into  $\sim 100$  micron size bins. There was almost no sand that remained in the 1-1.2mm sieve, and thus we had 5 total sizes we were able to test. For each size bin, we performed 20 experimental runs, resulting in  $\sim 2000$  total events for each bin. For each bin, we separated the events into similar logarithmic size bins described above and then calculated the locking

duration for each. Since we had already shown that the locking duration corresponds to a critical length scale that can be calculated as  $L = v_{\text{load}} * t_{\text{lock}}$ , we performed all these experiments at the same loading rate and calculated  $L$  for each grain size at each moment bin.

We observed a clear, linear increase in  $L$  with the grain size, as shown in Figure 2. The ~500 micron sand was used for a larger suite of experiments and thus has significantly smaller error bars. This indicates that the critical locking length is directly controlled by the heterogeneity scale of the system, and scales linearly for the size range we observed.

In addition, we noticed another interesting and surprising observation: in addition to controlling the critical locking length scale, the grain size also affected the recurrence interval of large events in the system, as seen in Figure 2. This can be most easily seen in the bulk friction measurements where we observe fewer, larger drops in the friction over the course of experiments with increasing sand size. This indicates that the heterogeneity scale of a fault controls the critical locking length scale, which in turn controls the mean earthquake cycle timing.

**Significance:** Overall these results show that precursory locking is a critical element of the earthquake cycle, and that the scale of normal stress heterogeneity controls both this locking behavior and the recurrence interval of large events/earthquake sequences. While these results are measured on a scale laboratory system, they offer important insights into our understanding of the behavior of faults, and indicate that if we can find a way to measure the scale of heterogeneity on faults, we can significantly improve our assessment and prediction of hazard.



**Figure 2: Locking distance and recurrence interval are controlled by the grain size scale** (Left) Critical locking distance,  $L$ , as a function of the average grain size used between the samples. There is a clear, linear increase in  $L$  with increasing grain size. (Middle) Patch velocity normalized by mean slip patch area for increasing grain sizes (top to bottom) showing that the locking duration increases with grain size. (Right) Corresponding bulk friction measurements over course of typical experiments for the same grain sizes as in the middle column. After the initial conditioning phase (gray boxes) as the grain size increases, there are fewer cycles and each cycle shows larger drops in the friction.