Experimental Investigation of Fault Healing Processes Under Coseismic Conditions

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Introduction

- In typical earthquake cycles, tectonic stress slowly builds up along faults during interseismic periods (spanning years to centuries), and is suddenly released during coseismic periods (lasting seconds to minutes).
- Laboratory experiments consistently demonstrate coseismic re-strengthening following dynamic weakening, with considerable shear stress recovery observed, ~ 50% in double direct shear tests (Figs. 1a, 1b) and approaching 100% in rotary shear tests (Fig. 1c).
- Coseismic re-strengthening plays a critical role in controlling earthquake processes, influencing the magnitude of coseismic stress drop, the overall energy budget, fault healing process, and earthquake recurrence intervals.
- This work will address the dynamic fault re-strengthening process using stick-slip friction tests under different loading configurations of direct shear and rotary shear. We present stress and velocity evolution along with microstructural analysis to explore physical mechanisms govering coseismic fault re-strengthening.

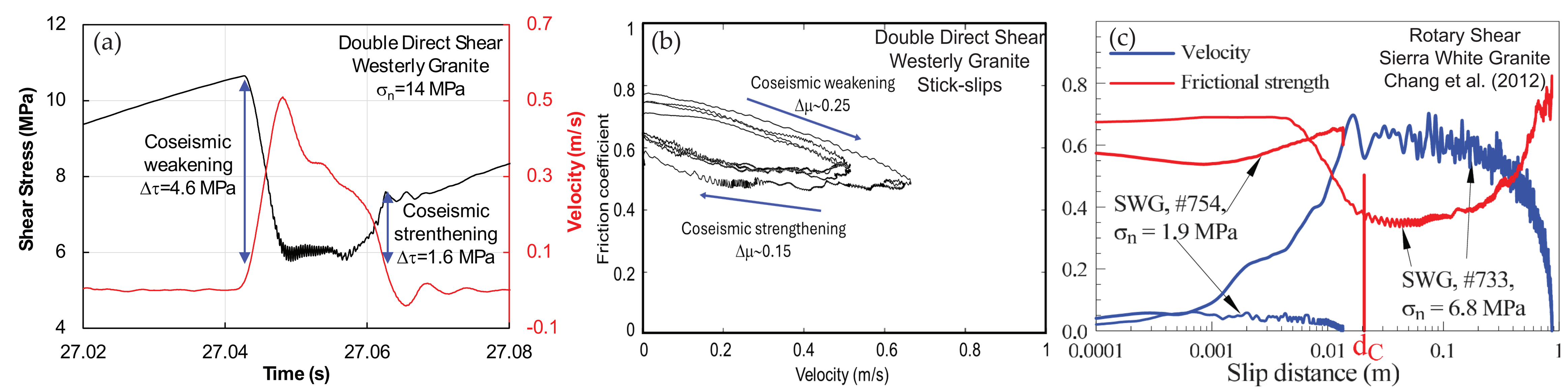


Figure 1. Fault regain strength during coseismic periods in rock friction experiments. (a) A typical stick-slip experiment from the double direct shear (DDS) apparatus on a Westerly Granite fault, showing 35% stress recovery following peak velocity of 0.5 m/s. (b) Similar results from (a) plotted in the friction-velocity space, showing consistent stress recovery. (c) Rotary shear experiments on granite fault showing full coseismic stress recovery.

Experimental setup

- **Rotary Shear**
  - High-speed motor replaced by stepper motor for μm/s loading
  - Near-field accelerometers for seismic radiation monitoring
  - Strain gauge rosette array for dynamic rupture monitoring
  - Data acquisition utilizes low-f platform (kHz) for mechanical data and high-f ADC platform (MHz) for acceleration and strain field measurements
- **Double Direct Shear**
  - Pneumatically powered loading frame enables fast acceleration and quick load point response
  - Continuous data acquisition at 50 kHz rate
  - Infrared camera allows real-time fault surface temperature monitoring at sub-mm scale

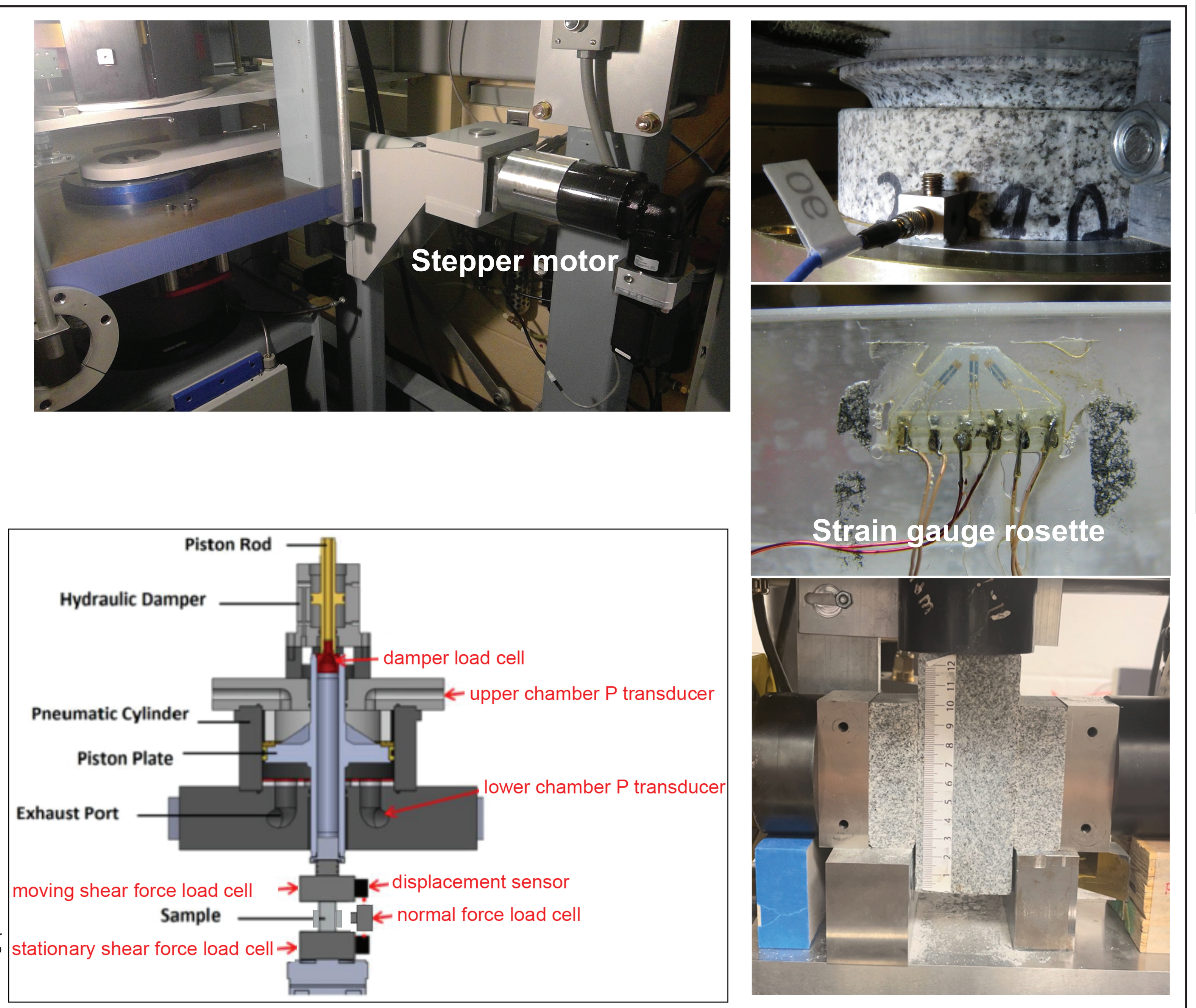


Figure 2. The rock friction test apparatus. (a) The Rotary Shar apparatus at University of Oklahoma. (b) The High-speed Biaxial (HSB) Double Direct Shear apparatus at Texas A&M University.

Results

- **Temporal resolution limit**
  - Stress drops can last from ~0.01s to ~1s depending on compliance and normal stress conditions, with peak velocity ranges from μm/s to mm/s (Fig. 3b, 3c)
  - Stick-slip events occur during the stress drop period for HSB tests (Fig. 3b), with duration range ~0.01s and peak velocity ~1cm/s
  - Seismicicity can occur on both locked faults (Fig. 1a) and creeping fault (Fig. 3b)
  - Sampling rate of stress and displacement below kHz could not resolve fast stick-slips (Fig. 3a)

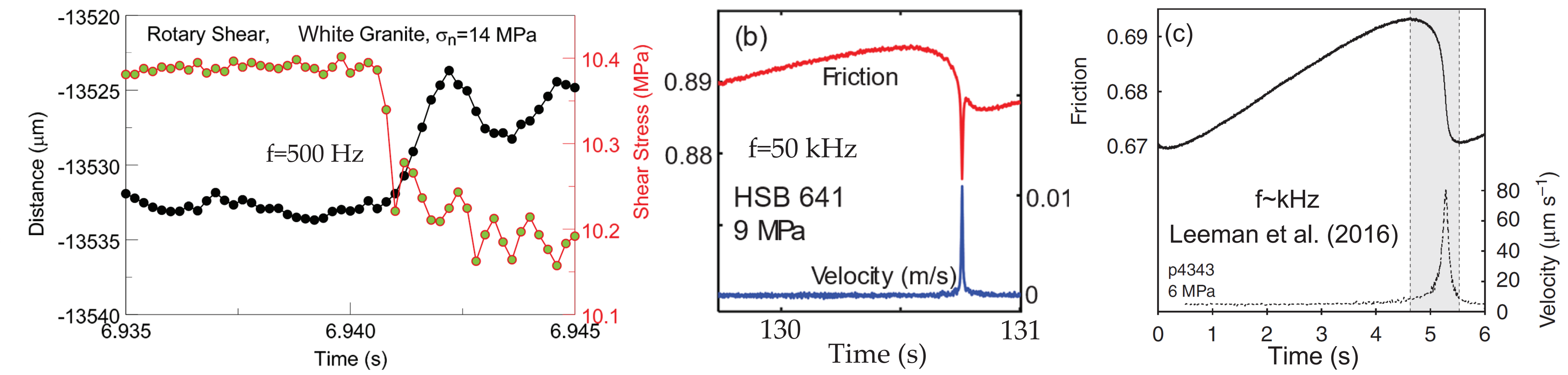
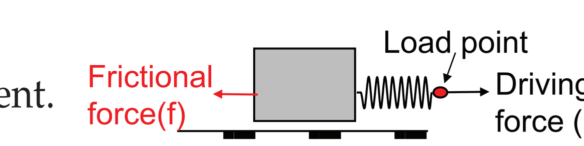


Figure 3. Stress and displacement (velocity) records from experimental stick–slip events. (a) Enlarged view of a stick–slip event in a rotary shear test on Sierra White Granite, acquired at a relatively low sampling rate (500 Hz), resulting in limited resolution of the stress drop. (b) Stick–slip event from a Westerly Granite fault in the HSB apparatus, recorded at 50 kHz, illustrating pronounced dynamic weakening followed by re-strengthening. (c) Gouge shear experiment in the Penn State double direct shear apparatus, showing a slow stick–slip event with a duration of ~1 s.

- **System setup and load point response**
  - Many experimental setups measure shear stress and fault displacment at the load point, resulting in unloading compliance equal to rig compliance.
  - Ensure measured shear stress equal to true fault shear stress (inertial force correction). Ensure measured displacement equal to true fault displacement.
  - When load point driving speed is comparable with fault movement speed, load cell reading reflects true fault friction.



- **Fault surface microstructure**
  - Wear of asperities produces gouge layer coverage with slip striation patterns (Fig. 4). Gouge particles aggregate to form mm-scale flake pieces. Gouge flakes peel off from surface as they cool off and dry after exposing the fault surfaces. Overall shear process smoothens slip surface (Fig. 4b).
  - SEM images show cohesionless particles with brittle fracturing features covering slip surface (Fig. 5a). Areas with thick gouge coverage show sintering/melting features flattening and bonding gouge particle grains together (Figs. 5b-5f).

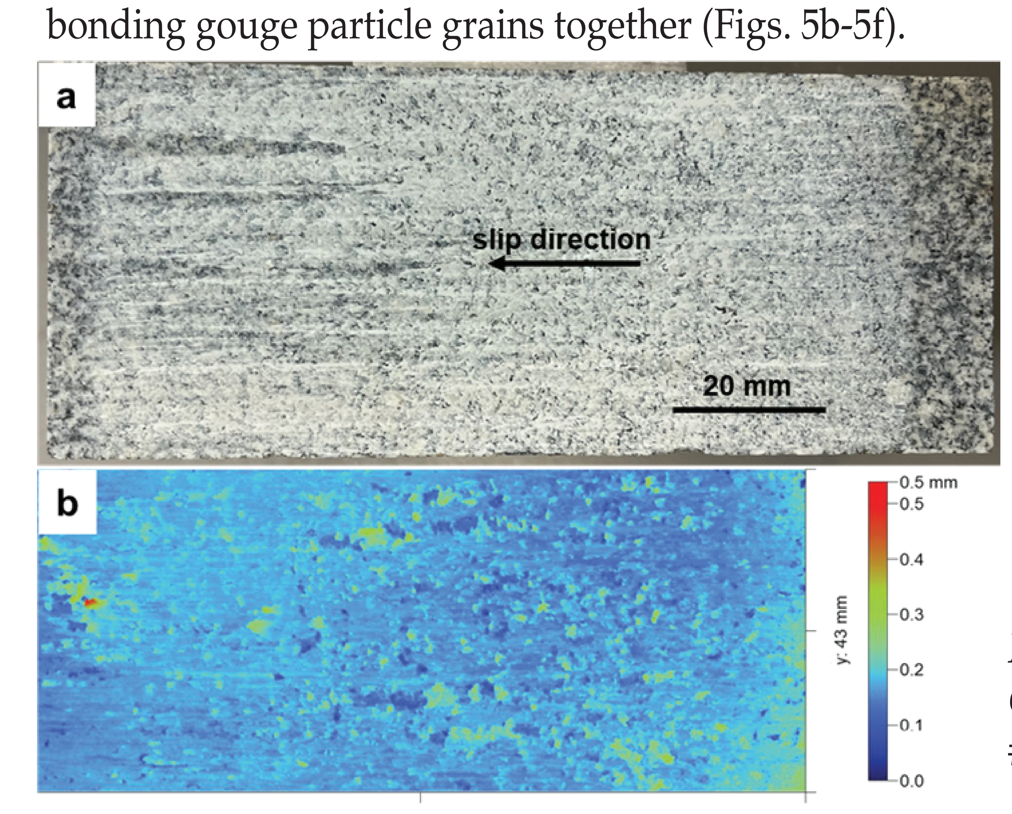


Figure 4. Optical image (a) and surface height profile (b) of the Westerly Granite central fault block after stick-slip run #649 under a normal stress of 18MPa. The slip direction is marked with the arrow.

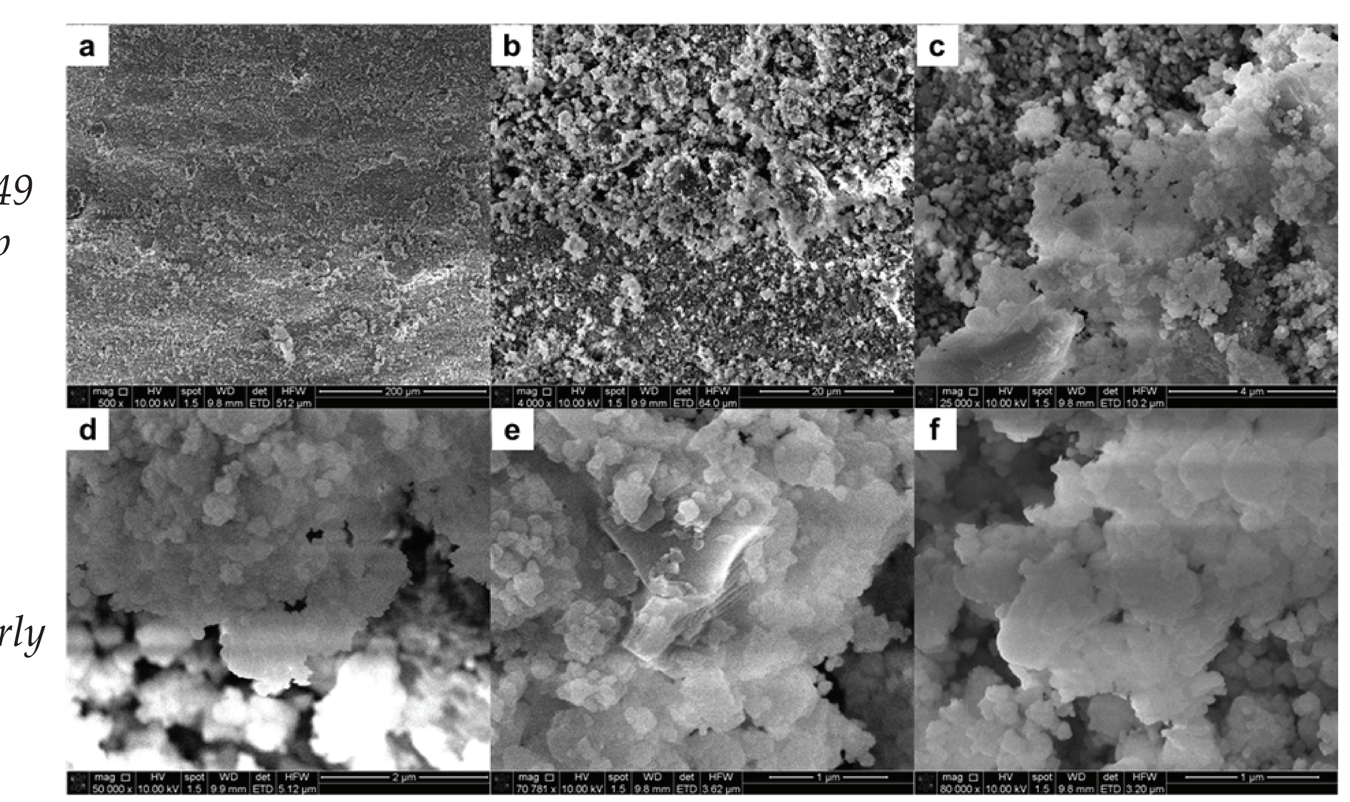
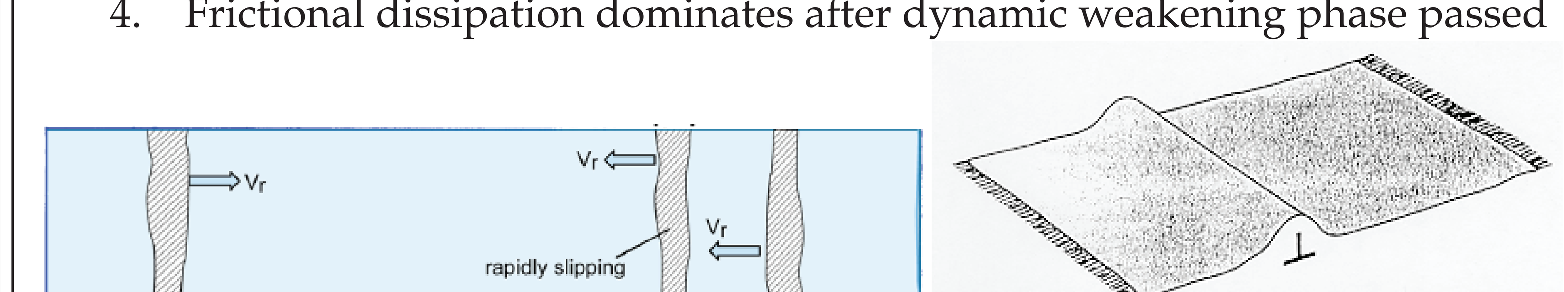


Figure 5. SEM images of the same Westerly Granite shear surface post stick-slip run #649.

Discussion

- **Processes in the coseismic period**
  1. Nucleation and dynamic rupturing traverses fault surface (~10s of μs)
  2. Near-field seismic energy radiation (~100 μs)
  3. Entire fault sliding, from acceleration with dynamic weakening till deceleration with continued coseismic restrengthening
  4. Frictional dissipation dominates after dynamic weakening phase passed



- **Mechanisms and Implications**
  - The friction–velocity relation (Fig. 1b) is characteristic of flash heating, consistent with a friction-controlled weakening–restrengthening process during the later stage of coseismic slip.
  - Negligible fault surface temperature rise from IR monitoring yet local sinter/melting observed for post-shear surfaces suggest highly localized frictional process govering coseismic behavior.
  - Existance of coseismic re-strengthening decreases overall coseismic stress drops, reduces coseismic slip magnitude, and shortenes earthquake occurance interval.
  - Post-mortum microstructural observations could not separate dynamic weakening process from coseismic re-strengthening.

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