Assessing the role of roughness on the frictional strength of faults and weakening by thermal pressurization

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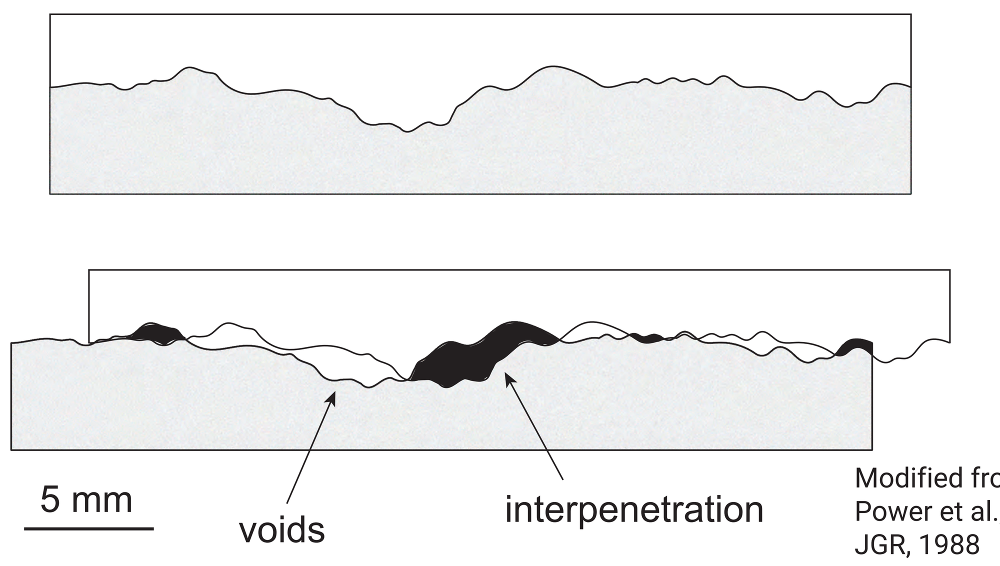
1. Introduction

- The assessment of physics-based constitutive equations that describe the frictional behavior of geologic materials during seismic slip is critical to advancing physics-based dynamic rupture models.
- Thermal pressurization (TP) occurs as frictionally heated pore-fluids thermally expand during seismic slip, which increases the pore pressure and decreases the effective normal stress, subsequently weakening the fault.
- The efficacy of thermal pressurization on rough faults is unclear as increases in pore space with slip could accommodate volumetric increases in pore fluids.



Modified from Power et al., JGR, 1988

- Here, we investigate thermal pressurization in laboratory experiments on rough and flat sliding surfaces using a high-pressure rotary shear apparatus.

2. Methods

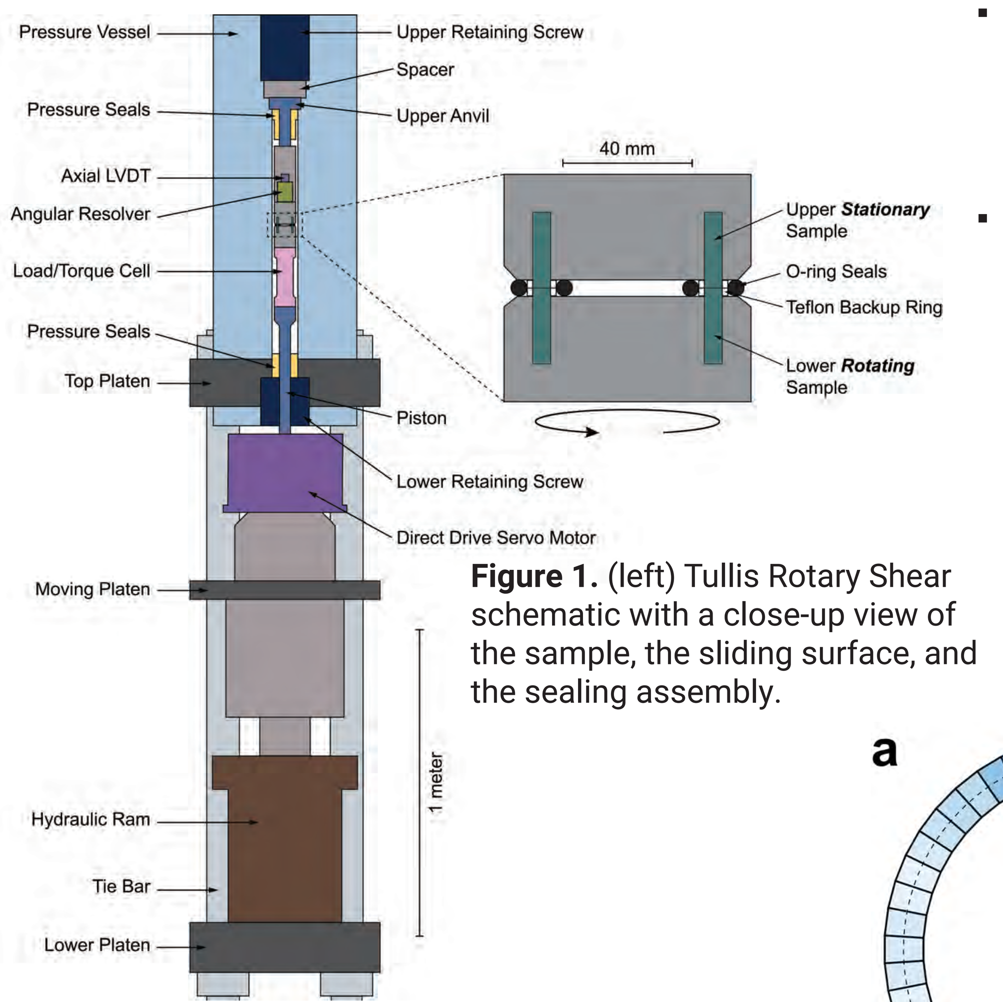


Figure 1. (left) Tullis Rotary Shear schematic with a close-up view of the sample, the sliding surface, and the sealing assembly.

- Experiments were conducted on Frederick diabase samples using a rotary shear apparatus.
- We performed velocity steps (VS) from 1 µm/s to 6-10 mm/s under 20 MPa effective normal stress:
  - σ_n 45 MPa, c_p 43 MPa, p_p 25 MPa
  - σ_n 20 MPa, c_p 18 MPa, p_p 0 MPa

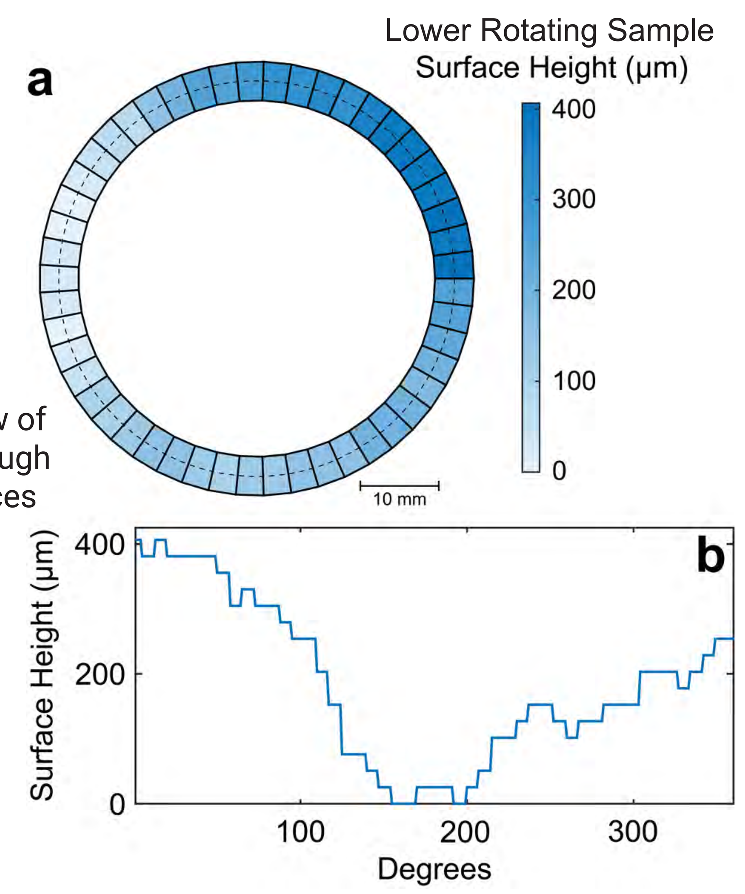
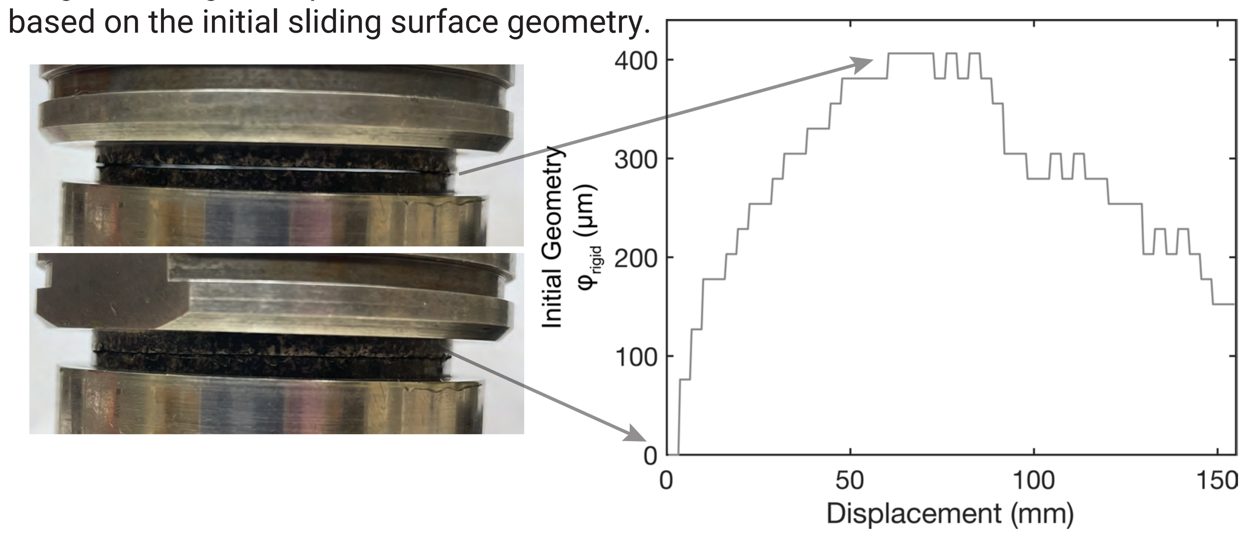


Figure 2. (right) a) Schematic view of lower sample sliding surface in rough experiments. Rough sliding surfaces were generated by stacking six wavelengths (154 - 4.8 mm) and rounding to the nearest 1/1000". b) Corresponding surface profile.

Figure 3. (below) Images of rough samples oriented for maximum and minimum fault opening (φ) based on the initial sliding surface geometry.



3. Results from Flat and Rough Experiments

- Along flat faults, dramatic weakening occurs in the first VS but quickly diminishes to an average Δμ of 0.2.
- Along rough faults, weakening is not typically observed in the first 2-3 VS, but becomes more frequent with increasing VS. When weakening occurs, the average Δμ is 0.2, matching flat VS.
- The frequency of weakening increases with total displacement for both geometries, though the frequency is reduced by ~40% for rough samples when compared to flat samples (Figure 6).

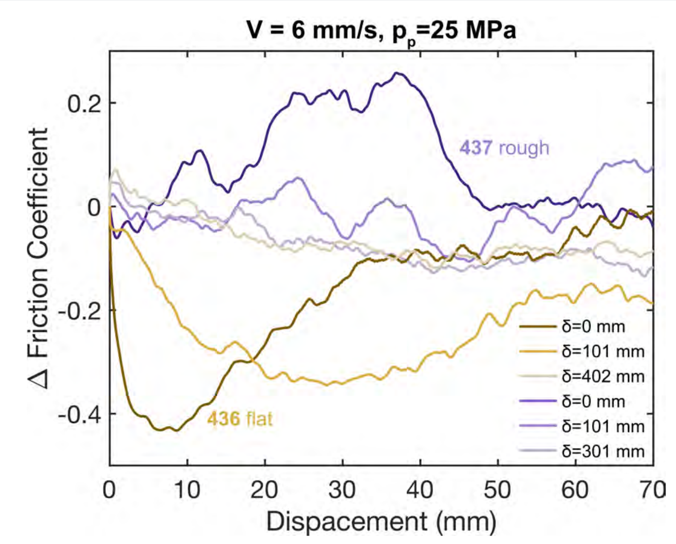


Figure 5. (above) Changes in friction coefficient during VS in rough (purple) and flat (yellow) experiments as total displacement increases.

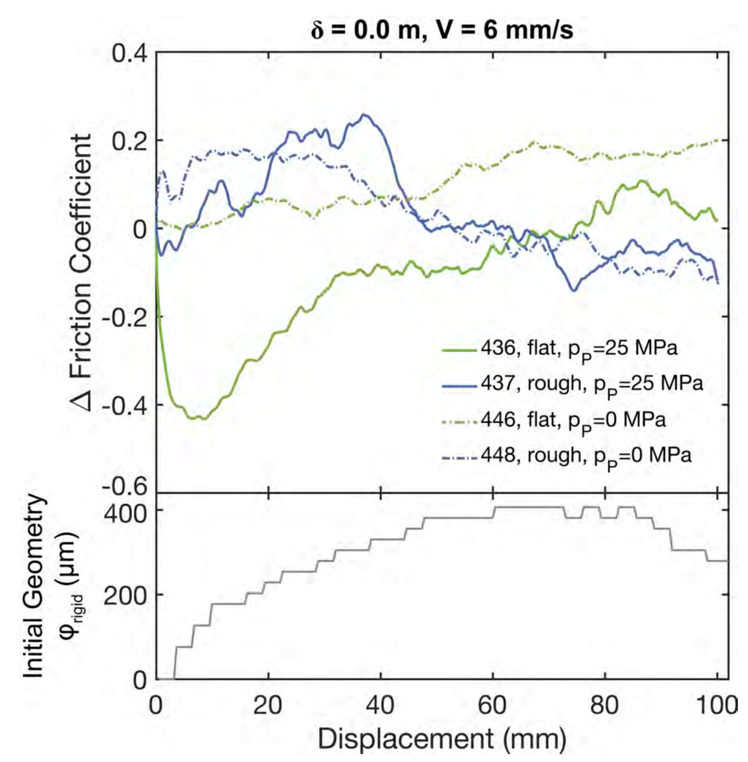


Figure 4. (left) Mechanical data from the first VS in 4 experiments.

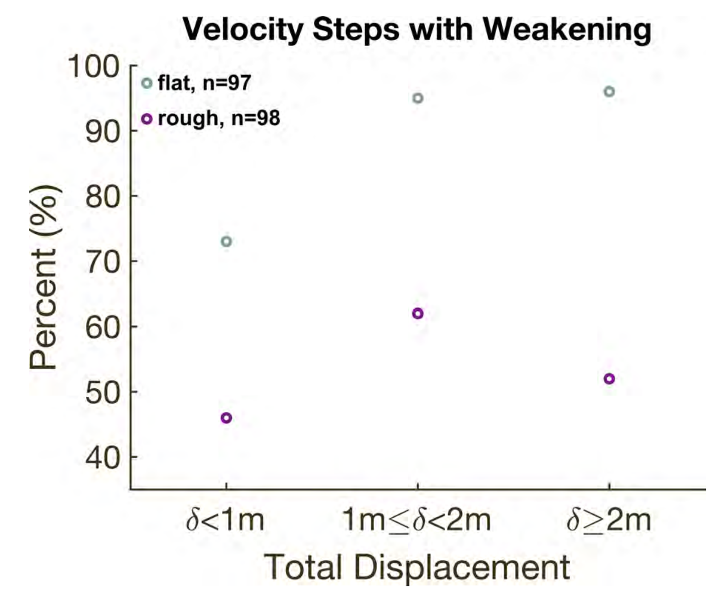


Figure 6. (above) Frequency of weakening in rough and flat VS as total displacement increases.

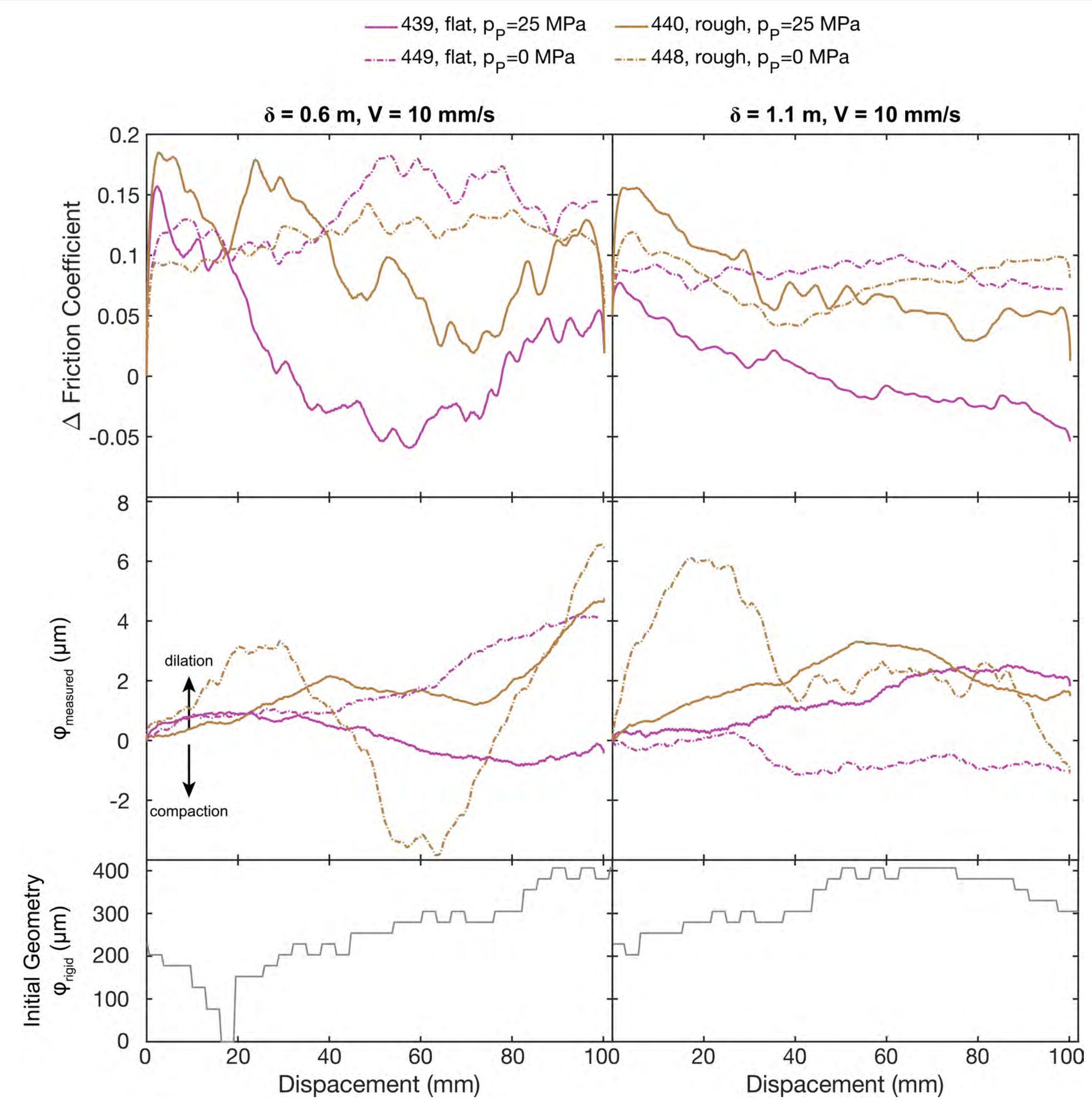


Figure 7. (above) Mechanical data from VS in 4 experiments on rough (brown) and flat (pink) sliding surfaces at total displacements of 0.6 and 1.1 m.

4. Model for Thermal Pressurization with Dilatancy

- Using a model by Brantut (2021) that combines thermal pressurization with dilatancy toughening, we model shear stress, τ, and temperature, *T*, as a function of slip following:

$$\tau(\delta) = \tau_0 \exp\left(\frac{\delta}{L^*}\right) erfc\left(\sqrt{\frac{\delta}{L^*}}\right) + \frac{\tau_D}{1+\frac{L^*}{\delta_D}}\left[-exp\left(\frac{\delta}{L^*}\right) erfc\left(\sqrt{\frac{\delta}{L^*}}\right) + exp\left(-\frac{\delta}{\delta_D}\right)\left(1+\sqrt{\frac{L^*}{\delta_D}} erfi\left(\sqrt{\frac{\delta}{\delta_D}}\right)\right)\right]$$

$$T(\delta) = T_0 + \frac{f_r}{\Lambda}\left(1+\sqrt{\frac{\alpha_{hy}}{\alpha_{th}}}\right)\left[\tau_0 - \tau(\delta) + \tau_D\sqrt{\frac{\delta_D}{L^*}} e^{\left(\frac{-\delta}{\delta_D}\right)} erfi\left(\sqrt{\frac{\delta}{\delta_D}}\right)\right]$$

$$\tau_D = \frac{f_r \Delta\Phi_{max}}{\beta^*}\frac{\delta_C}{\delta_D}\left(1+\sqrt{\frac{\alpha_{th}}{\alpha_{hy}}}\right)$$

Model Inputs and Parameters

α_{hy}	Hydraulic diffusivity
α_{th}	Thermal diffusivity
β^*	Hydraulic Storage Capacity
$\Delta\Phi_{max}$	Maximum inelastic porosity change
δ	Displacement +
δ_C	Slip weakening distance for thermal pressurization
δ_D	Characteristic slip distance for porosity change
Λ	Undrained thermal pressurization factor
τ	Shear stress +
τ_0	Initial shear stress +
f_r	Residual friction
L^*	Thermal pressurization weakening length parameter
T_0	Initial temperature
+ measured data	

Takeaways

Weakening from thermal pressurization occurs on flat and rough faults, but the **frequency is reduced on rough faults**.

When weakening occurs, the **magnitude does not vary** between rough and flat faults.

Figure 8. (right) Thermal pressurization model results alongside mechancial data from a flat VS.

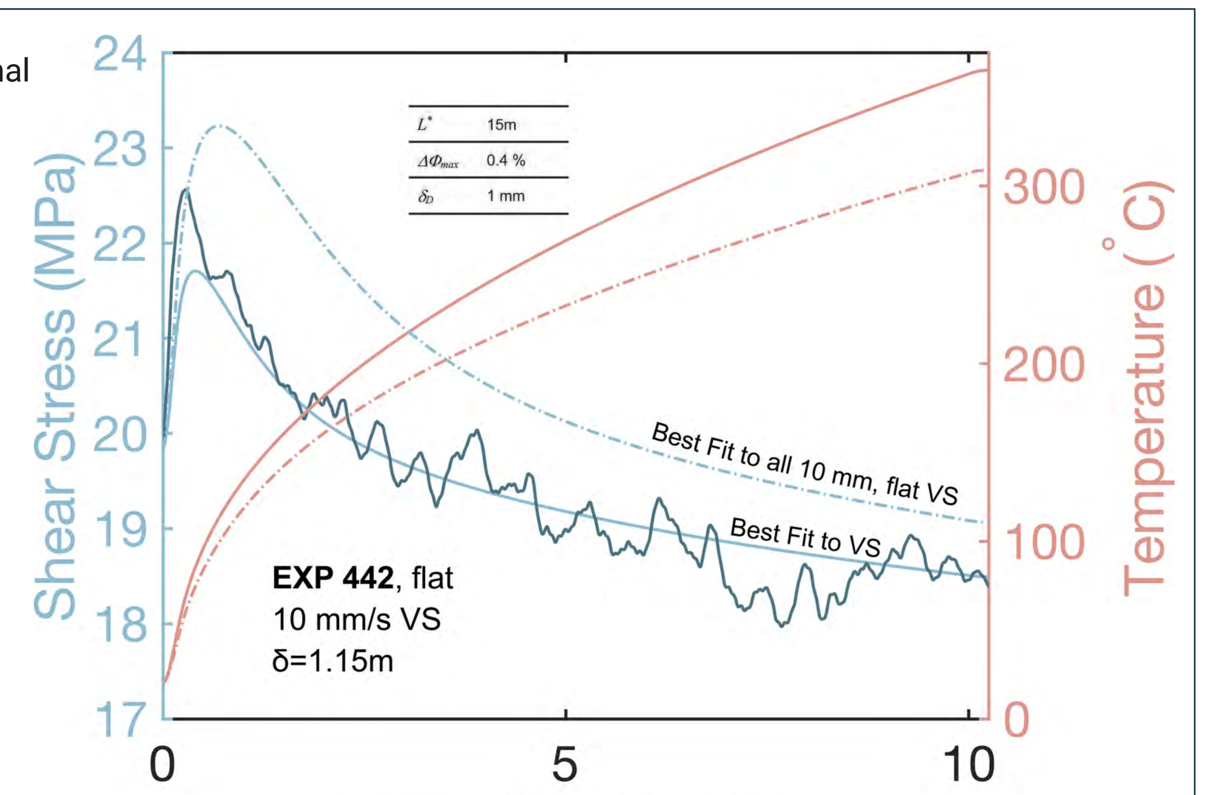
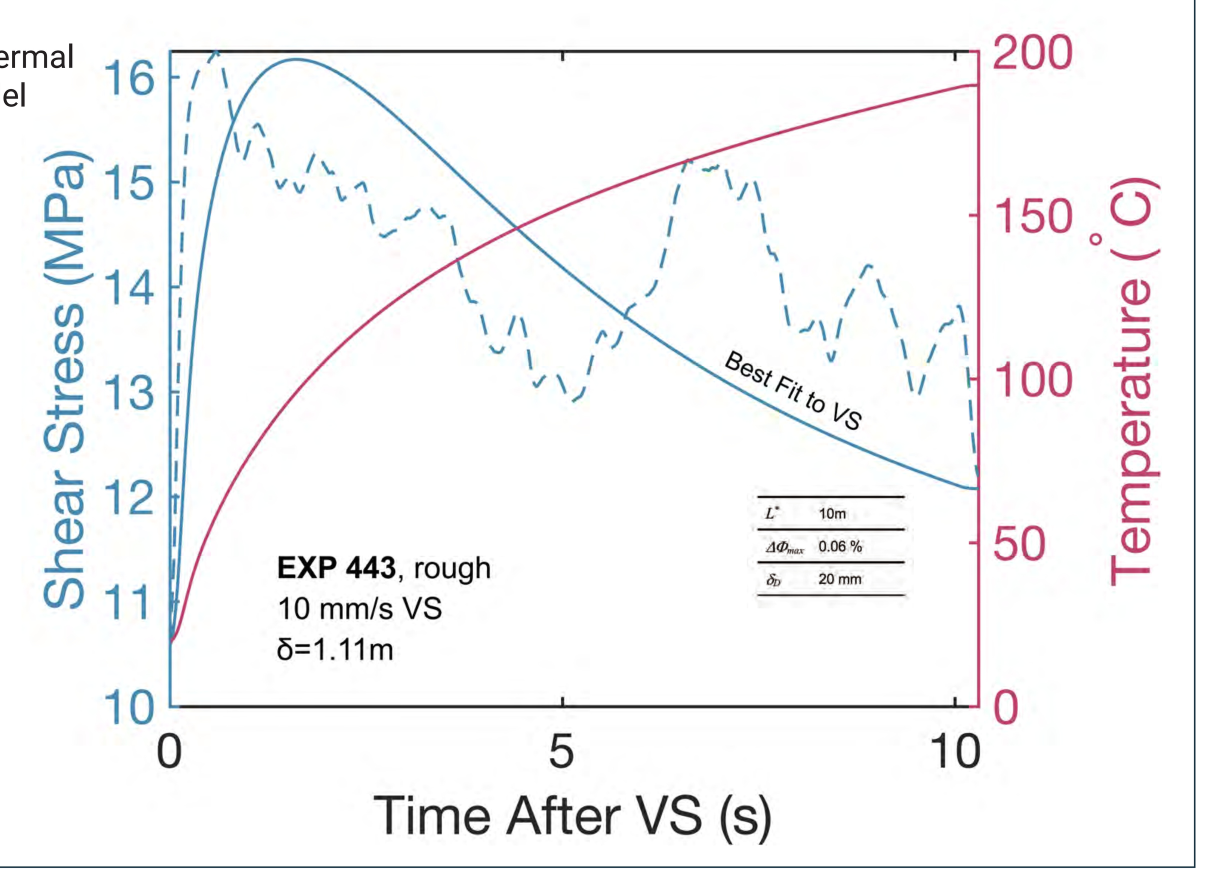


Figure 9. (right) Thermal pressurization model results alongside mechanical data from a rough VS.



5. References

Brantut, N. (2021). Dilatancy toughening of shear cracks and implications for slow rupture propagation. Earth and Planetary Science Letters, 538, 116179. https://doi.org/10.1016/j.epsl.2020.116179.

Power, W., Tullis, T.E., & Weeks, J.D. (1988) Roughness and wear during brittle faulting. JGR Solid Earth, 93(B12), 14757-15344. https://doi.org/10.1029/JB093iB12p15268

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