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Overview: Friction in the Lab and Field

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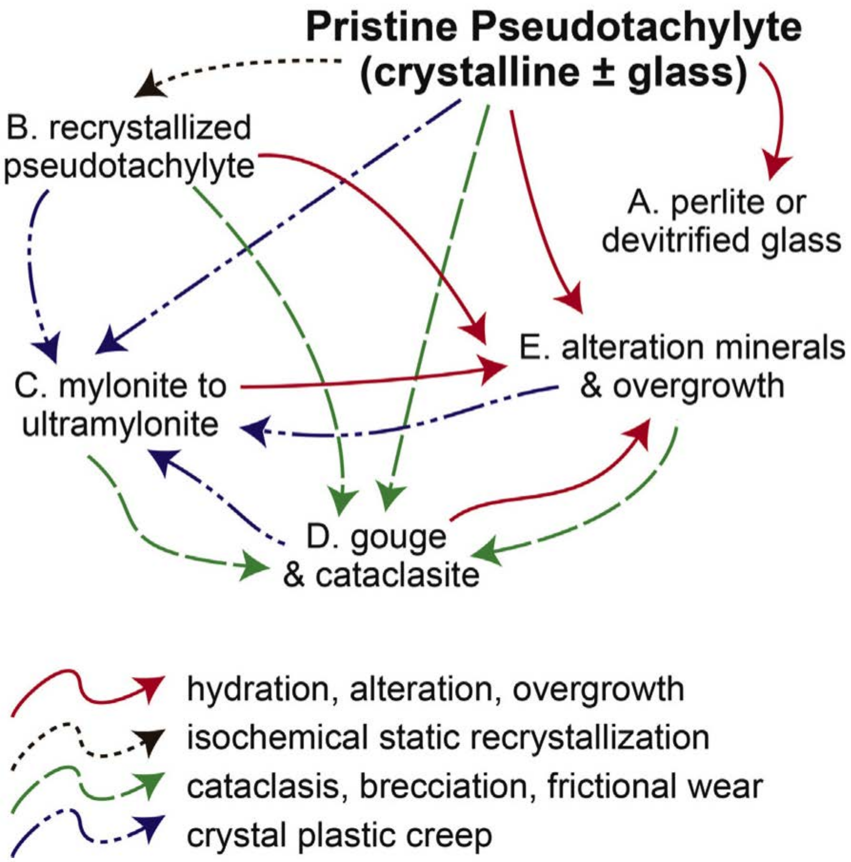
Evidence of seismic faulting in the rock record

- EQ energy budget includes considerable frictional work
  - Byerlee friction, and fast, localized slip in rock, expect melting
- There are pseudotachylytes associated with fault slip zones
  - Mostly in crystalline rocks, but also accretionary prism sedimentary rock
  - Association with mylonites and cataclasites at base of seismogenic zone
  - Melting of cataclasite and gouge, role of water and depressurization
- Record of frictional heating to below melt temperatures
  - Dissociation and devolatilization, decarbonation in carbonates
  - Loss of water and lattice collapse in clays
  - Mineral transformation; trace element mobility, concentration
  - Isotopic changes, clumping
  - Oxidation state of transition metals on slickenside surfaces
  - Thermal maturity of organic matter near faults
  - Direct measure of temperature in earthquake slip zones

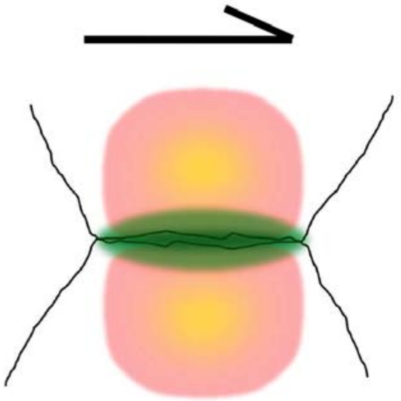
Pseudotachylyte formation and preservation

- Several processes for modification or destruction of friction melt
  - Cataclasis, alteration
  - Mylonitization and recrystallization at deeper levels
- Significance of melting underestimated?
- Occurs only if the other likely coseismic weakening mechanisms are insufficient
  - Flash weakening
  - Thermal fluid pressurization
  - Others? Phase transformation, GBS, diffusion, acoustic fluidization, vibrations, slip-surface smoothing, powder lubrication, powder rolling…



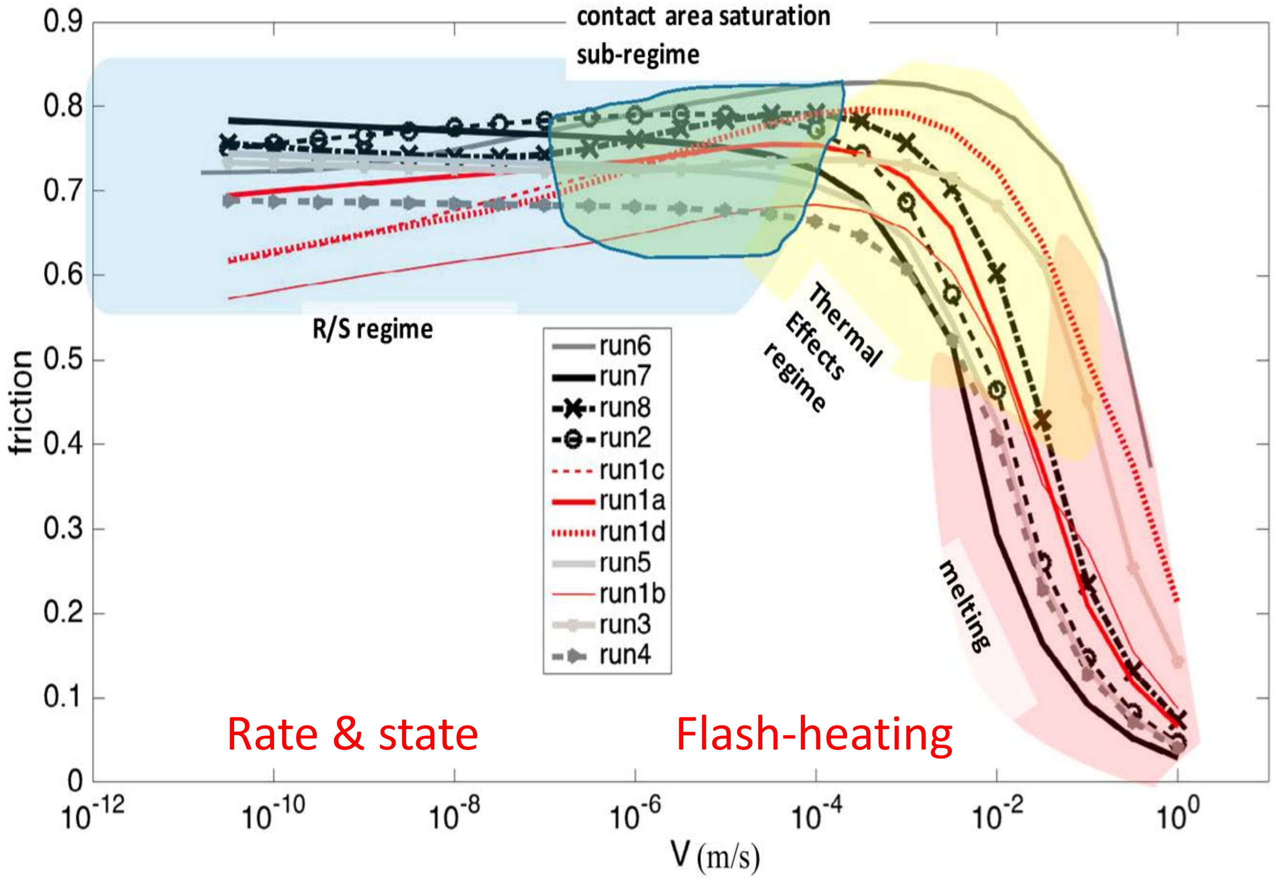
Kirkpatrick & Rowe, 2013

Adhesion theory of friction



Aharonov & Scholz, 2018

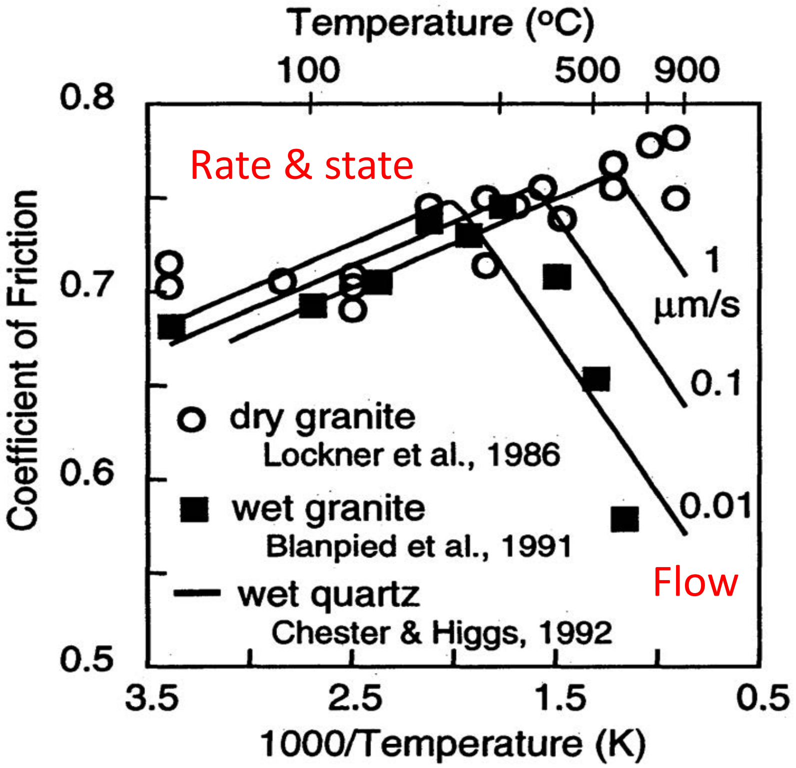
- Basis for understanding rate and state friction, flash weakening
- Micrometer-scale contact junctions
- For sliding, contact area depends on contact lifetime
- Aharonov & Scholz theoretical model for friction transition to high speed (2018) and to BPT creep (2019).
- Assumes contact area growth and contact shear follow low-T high-stress creep relations (exponential)
- Captures transition from rate weakening to contact melting by flash heating



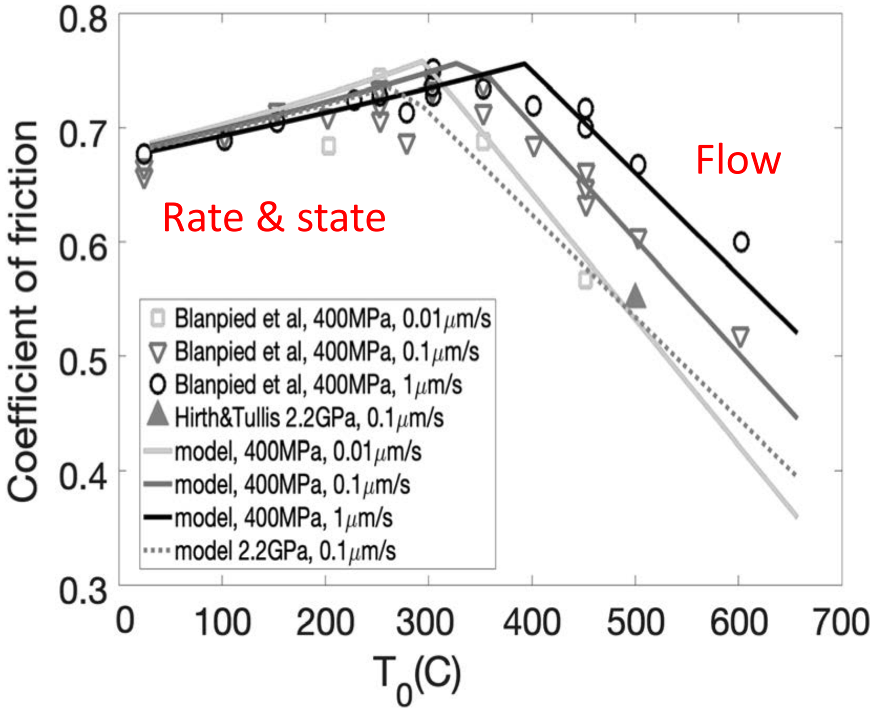
Adhesion theory – Friction across the BPT

- At high T and low slip rates, asperity creep increases true contact area with transition to ductile flow
- Aharonov & Scholz theoretical model (2019) compared to lab data.

  Wet quartz (Chester & Higgs, 1992) and granite (Blanpied et al., 1995).
- Captures transition from rate weakening friction to fully ductile flow
- Model does not treat chemical/bonding (e.g., water) at low rates or other process besides low-T plasticity and melting at high rates (e.g., mineral transformations)



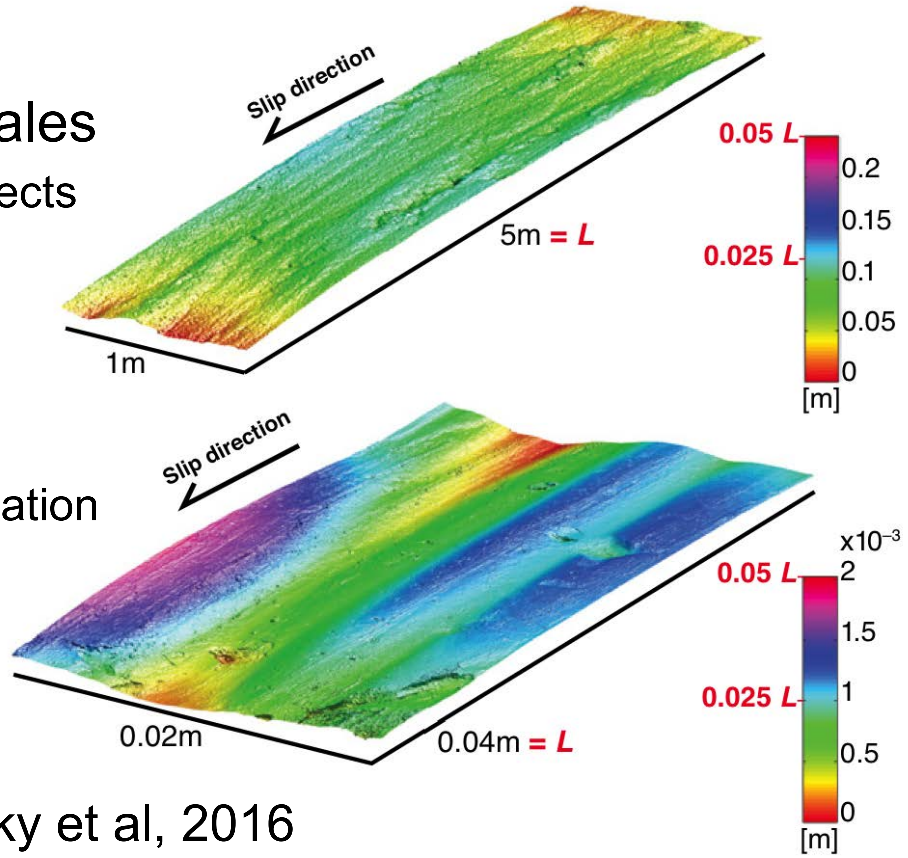
Chester, 1995



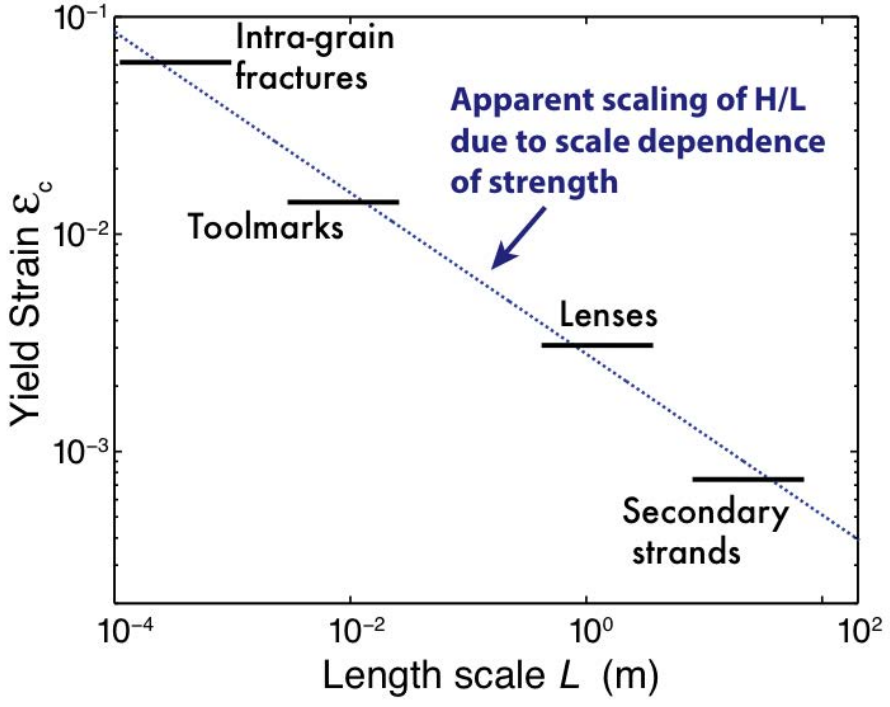
Aharonov & Scholz, 2019

Geometry of fault slip surfaces

- Anisotropic, smoother in slip direction
- Self affine, rougher at smaller length scales
  - Isotropic roughness at micrometer scale reflects adhesion contacts?
- Slip on surfaces necessarily sets up inhomogeneous stress
  - Observations that natural surfaces mated to small scale roughness suggests stress relaxation in bounding rock after seismic slip events?



Brodsky et al, 2016



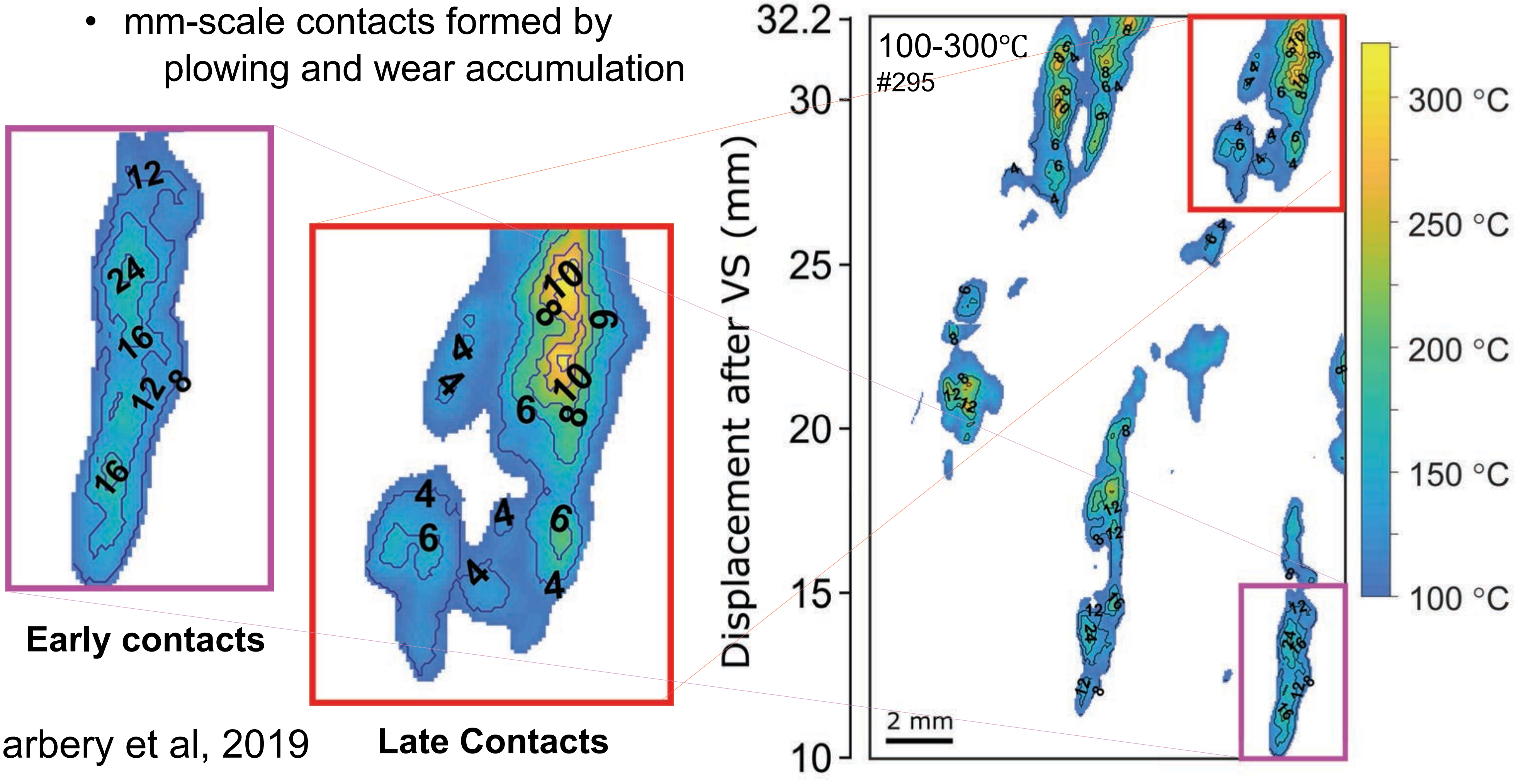
- Interpretation is that formation of roughness features at different length scales reflect different failure processes.
- Lower roughness at longer length scales reflects scale dependence of strength

Scale dependence of friction?

- Critical slip distance for rate-state and flash-weakening
  - Adhesion theory with micrometer-scale contact junctions
- For typical laboratory experiments (engineered surfaces)
    - For single sliding surface, ~ dimensions of contacts
    - For shear of gouge layer, a critical shear strain
  - Friction is a macroscopic description at cm and larger scales
  - Critical slip distance does not scale
- For natural faults
  - Self affine or self-similar roughness with correlated or uncorrelated surfaces
    - Are larger scale failure processes important to friction behavior?
    - At what scale can we assume critical slip distance is fixed
- For coseismic flash-weakening processes
  - At contact scale weakening is essentially instantaneous
  - But roughness and wear, progressive increase in average surface temperature with slip, can affect critical slip distance and transient μ

Example multi-scale effects for flash weakening

- Double-direct shear of Westerly granite blocks, 75 cm^2 area
- 9 MPa normal stress, step to 0.9 m/s, 35 mm displacement
- IR imaging of surface temperature (color shading) to determine local normal stress, σ_L (contours in multiples of macroscopic normal stress)
  - Illuminates mm scale contacts
  - mm-scale contacts formed by plowing and wear accumulation



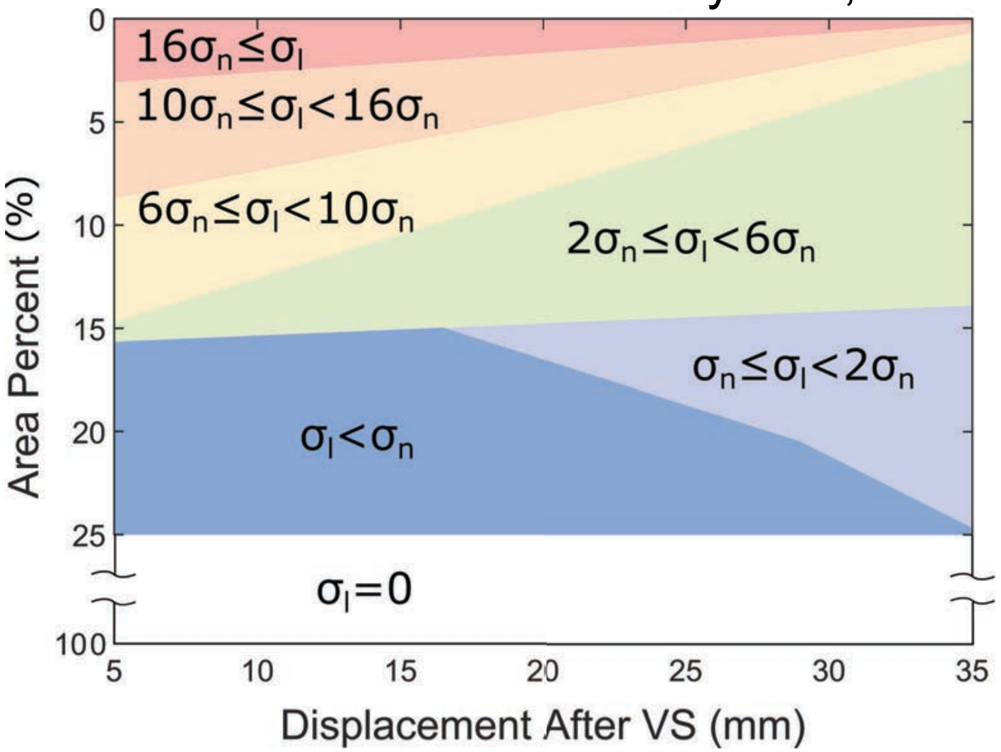
Barbery et al, 2019

Example multi-scale effects for flash weakening

High-speed DDS (continued)

- Contact development at mm-scale sets surface temperature for micrometer-scale contacts.
- Scaling of normal stress at contacts:

Contact size (dia.)	Area	Normal stress
~1 decimeter (sample)	100%	9 MPa
1 millimeter	10%	100 MPa
10 micrometer	1%	~1 GPa


Barbery et al, 2019

Lockner et al. (2017) Triaxial shear friction and melting during stick-slip

- High-pressure, lapped surfaces with micron-scale roughness only
- Very thin, continuous melt layer (<10 μm thick) within a few mm slip

Contact size (dia.)	Area	Normal stress
3 cm (sample)	100%	200 - 400 MPa
10 micrometer	~ 20 - 50%	~1 GPa

Concluding thoughts (for discussion)

- Ability to identify seismic slip in rock record, though takes much work, tends to confirm most faults studied have slipped seismically.
- The recognition of pseudotachylytes in rock record may suffer from preservation, but also could represent common operation of other weakening processes such as thermal pressurization to reduce effective stress, flash weakening to reduce friction, or production of melting to produce viscous lubricant.
- The adhesion theory of friction is robust, continues to explain many phenomena including rate & state friction and flash weakening on engineered surfaces, or layers, with only small scale roughness.
- The adhesion theory based on intragranular, low-T plasticity can qualitatively capture major transitions in friction and flow behavior over the range of temperature and strain rates of seismic faults, but is likely incomplete without considerations of surface chemistry, reactions and diffusion, particularly involving water and silicates.

Concluding thoughts (continued)

- Studies of large, natural polished slip surfaces with self-affine and direction-dependent roughness support theory that macroscopic friction originates at the nanometer and micrometer scales, but also suggests scale dependent processes and failure strength that impact fault mechanics.
- Although small polished surfaces are common in brittle fault zones operating at shallow to moderate depths, large surfaces are about as common as classic exposures of pseudotachylytes. As important as it is to understand these surfaces, and extremely localized slip in thin ultracataclasite zones, it is similarly important to understand sections of faults where such localization is not long lived.
- Seismic slip on mated self-affine surfaces produces strong stress inhomogeneity at length sales up to slip magnitude, moderated by wear and off surface failure, and post-seismic time-dependent deformation in damage zones. These likely contributes to a macroscopic, slip-weakening behavior.
- Thermal weakening during seismic slip also is sensitive to fault processes operating over a range of length scales, and thus critical displacements for weakening much greater than expected for rate and state friction.
- High-speed, laboratory friction experiments at different pressures may be thought of as different patches of a rough fault under the same far-field stress.