Microphysical modeling of fault friction: extension to high-velocity regime

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Recent experimental studies show that the value of friction varies over a wide range of sliding velocities (slow sliding exhibits high friction and rate-and-state behavior, and remarkable weakening occurs as velocity approaches seismic velocity). In this study, we extend a microphysically-based friction model for granular gouges (Chen and Spiers, 2016; Niemeijer and Spiers, 2007) to the high-velocity regime, by introducing additional creep mechanism(s) activated by frictional heating. The modeling results capture all of the main features and trends seen in the experiments, including both steady state and transient aspects of the observed behavior, with reasonable quantitative agreement.

1. Chen-Niemeijer-Spiers (CNS) Microphysical Model

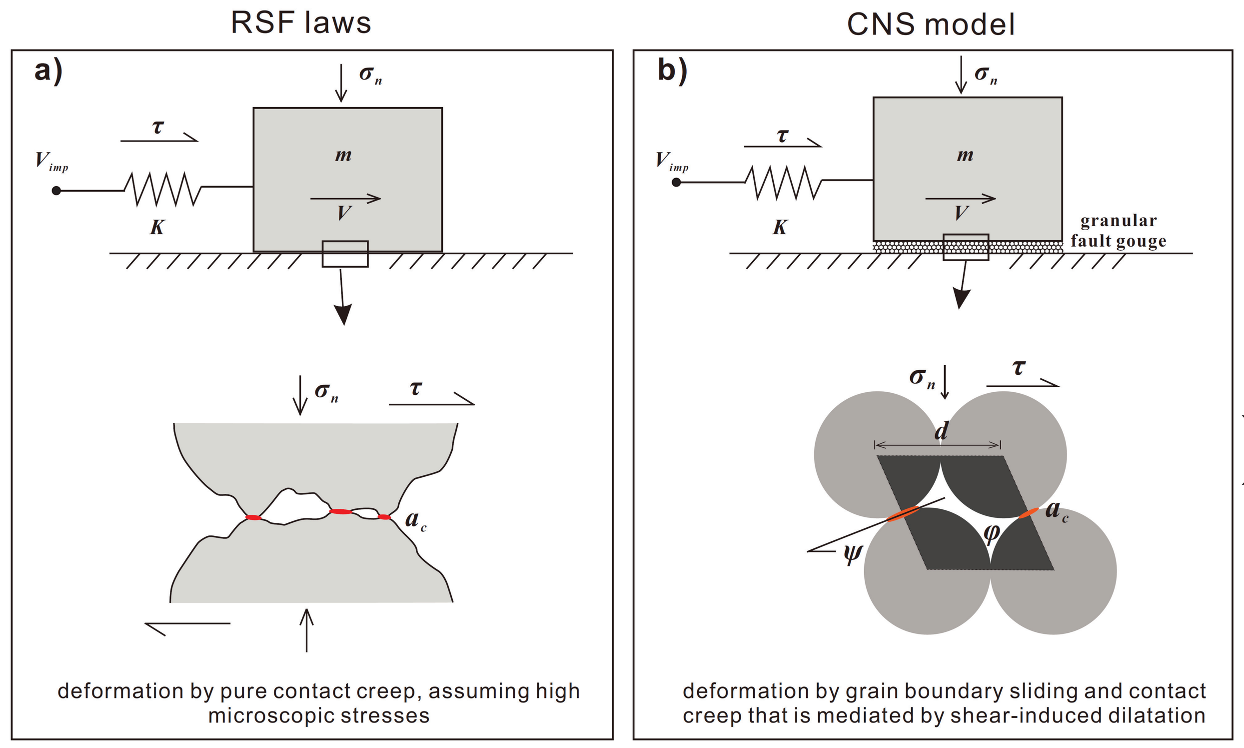


Fig. 1 Conceptual model of a) solid-solid frictional interface and b) granular friction, giving physical underpinnings for classic rate-and-state friction laws and a general microphysical friction model, respectively.

$$V = W\left(\dot{\gamma}_{pl} + \dot{\gamma}_{gr}\right) \quad (1)$$

State equation

$$\frac{\dot{\varphi}}{(1-\varphi)} = \dot{\gamma}_{gr}\tan\psi - \dot{\varepsilon}_{pl}$$

Friction "law"

$$\tau = \frac{\tilde{\mu} + \tan\psi}{1 - \tilde{\mu}\tan\psi}\sigma_n$$

$$\tilde{\mu} = \tilde{\mu}^* + a_{\tilde{\mu}}\ln\left(\dot{\gamma}_{gr}/\dot{\gamma}_{gr}^*\right)$$

$$\tan\psi = 2H(\varphi_c - \varphi)$$

- All the parameters fall into two categories. One is related to the **fault zone configuration**, such as shear zone thickness, particle size, temperature, and normal stress. The other category consists of the **kinetic constants of the deformation mechanism**(s), e.g. creep-related parameters.

2. Extension to high velocity regime: frictional heating actives new creep mechanism(s)

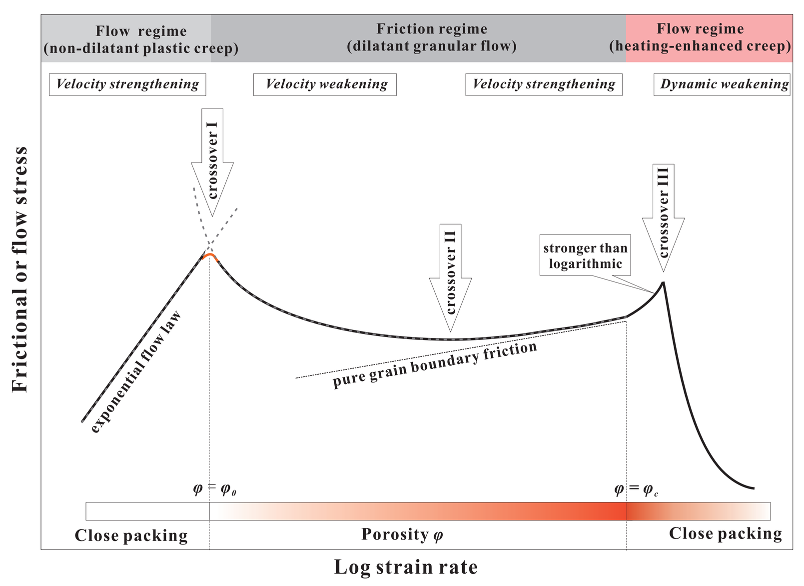
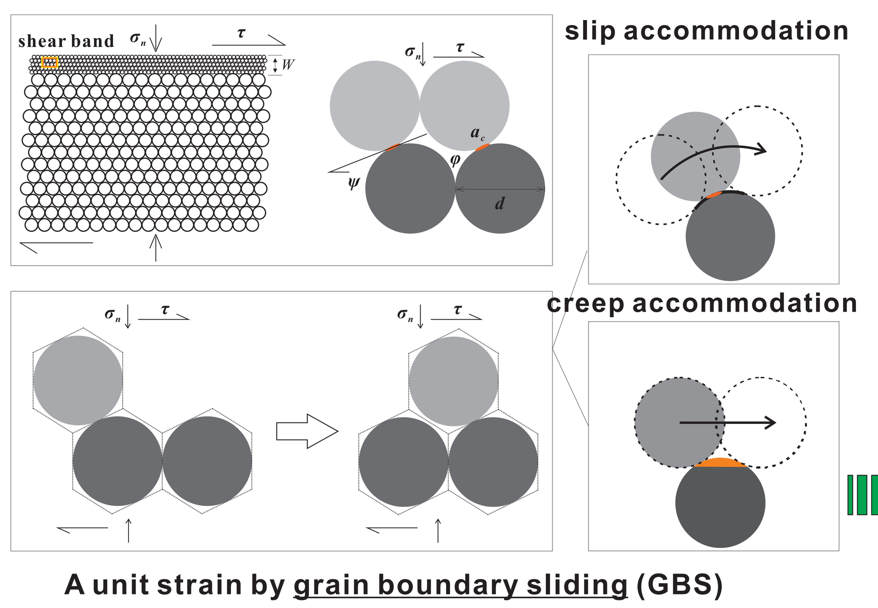


Fig. 2 Schematic model of steady-state friction as a function of log(strain rate) for granular fault.

1) **At low velocities**, it shows velocity strengthening behavior with deformation accommodated by non-dilatant plastic creep.

2) **At intermediate velocities**, as the velocity increases, the friction behavior will be first controlled by dilatant granular slip that is mediated by compactional contact creep, giving rise to a velocity weakening behavior; as the velocity increases further, the frictional behavior will be controlled by GBS which is inherently rate-strengthening.

3) **At high velocities**, dynamic friction decreases substantially due to thermal weakening effects (e.g. thermal pressurization, flash heating, superplasticity).



Key

Fig 3. Schematic model illustrating the deformation by GBS for both intermediate- and high-velocity regimes. In the intermediate regime, GBS is accommodated by (frictional) slip, while in the high-velocity regime, by a (plastic) creep mechanism.

Leading to continuous transition from friction to flow behavior from dilatant to compacted gouge

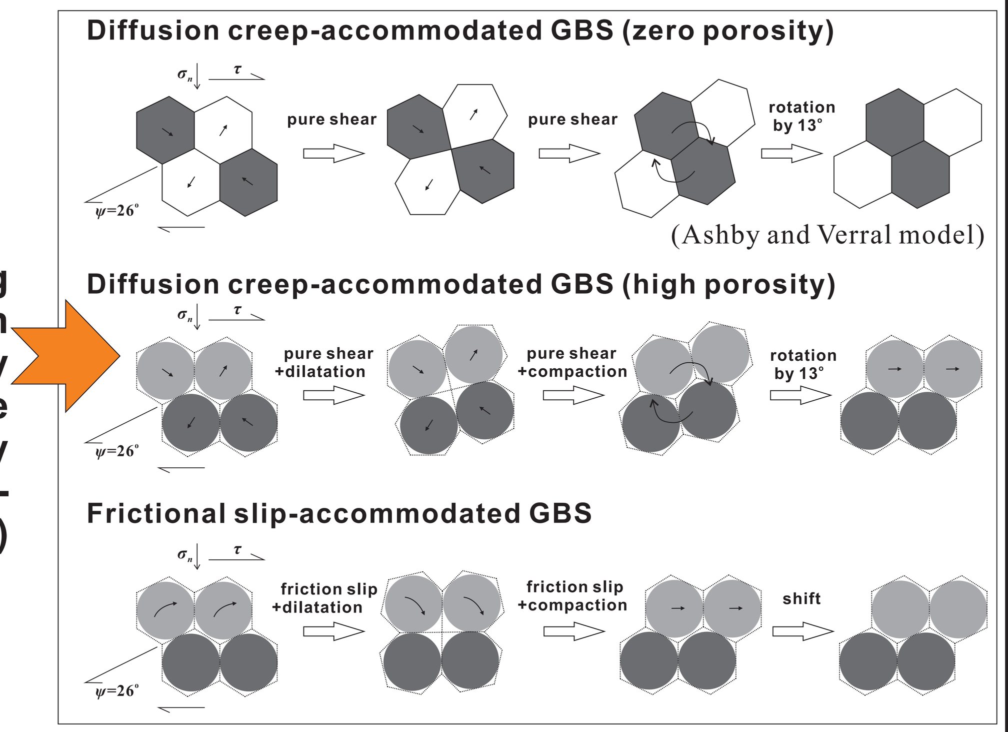


Fig 4. Deformation steps of a unit strain by two end-member and the intermediate GBS processes.

Multi-creep mechanisms:

$$\dot{\gamma}_{pl} = \sum \dot{\gamma}_{pl}^i$$

$$\dot{\gamma}_{pl} = A_t \exp\left(-\frac{H}{RT}\right)\frac{[\tau f_t(\varphi)]^n}{d^m}$$

$$f_t(\varphi) = \left(1 - \frac{\varphi}{\varphi_c}\right)^{-p}$$

For carbonate gouges

pressure solution
+
diffusion-accommodated grain boundary sliding (GBS)
Schmid et al.(1977)
+
dislocation creep (grain size-insensitive)
Schmid et al.(1980)

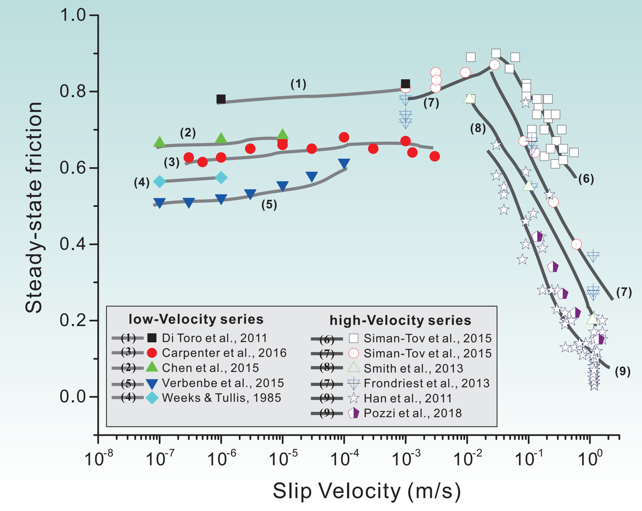
Numerical method:

Assuming a spring-slider fault system and incorporating realistic across-fault structure, the governing (ordinary) equations are solved in combination with a FE model for calculating **temperature** and **grain size** evolution over the fault thickness. Evolution of **PSZ thickness** is prescribed based on laboratory microstructural observations.

Equation (1) rewrites as: $V = W_{sb}\dot{\gamma}_{gr} + \int_0^W \dot{\gamma}_{pl}dx$

These are implemented in the FE package Comsol.

3. Steaty-state behavior



Prescribed nominal grain size within the shear zone following laboratory studies (De Paola et al., 2015)

$$d_{sb} = d_1 + \frac{(d_0 - d_1)}{2}*\left[1 - erf\left(\frac{logV + 1}{0.25}\right)\right]$$

low velocity: d_0 = 1 um
high velocity: d_1 = 10-100 nm

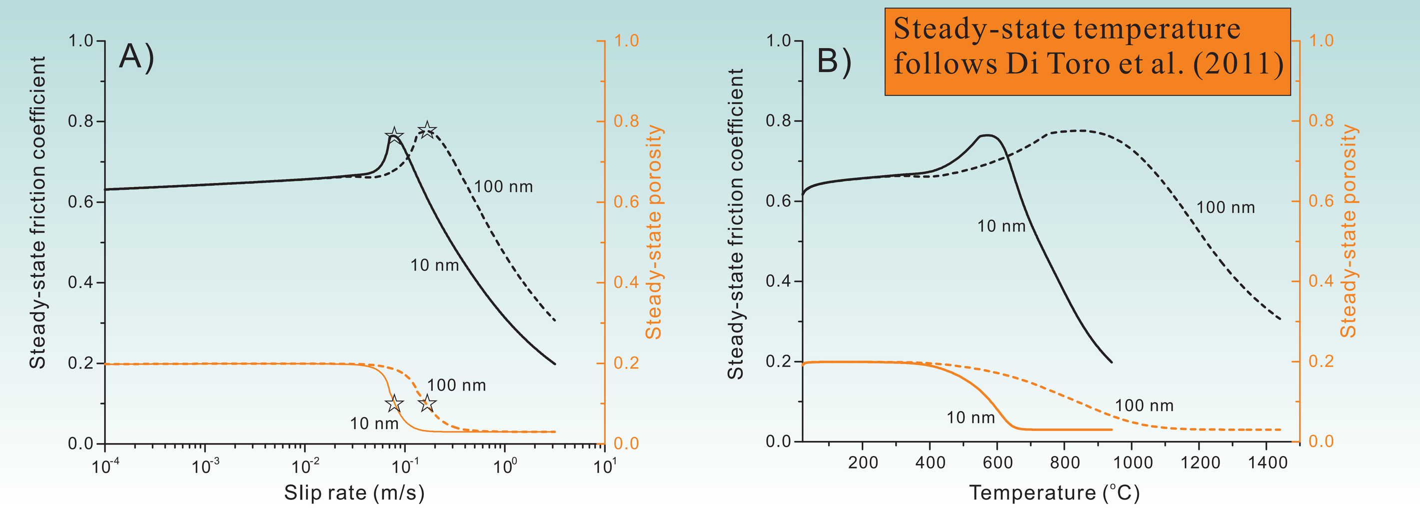
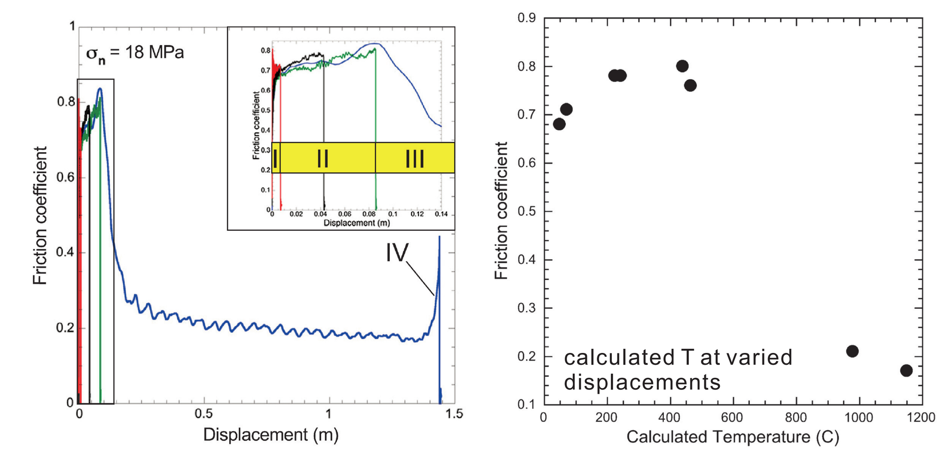


Fig 5. Left: compilation of carbonate friction data at sub- to co-seismic slip rate & room-T conditions. Right: Predicted steady-state friction and porosity with respect to A) slip rate and B) slip zone temperature.

4a. De Paola et al. (2015): general fearture



$$\frac{\partial T}{\partial t} = \frac{K}{\rho c}\frac{\partial^2 T}{\partial x^2} + \frac{\tau\dot{\gamma}}{\rho c}$$

$$T_{PSZ} = \int_0^{W_{PSZ}} T\,dx / W_{PSZ}$$

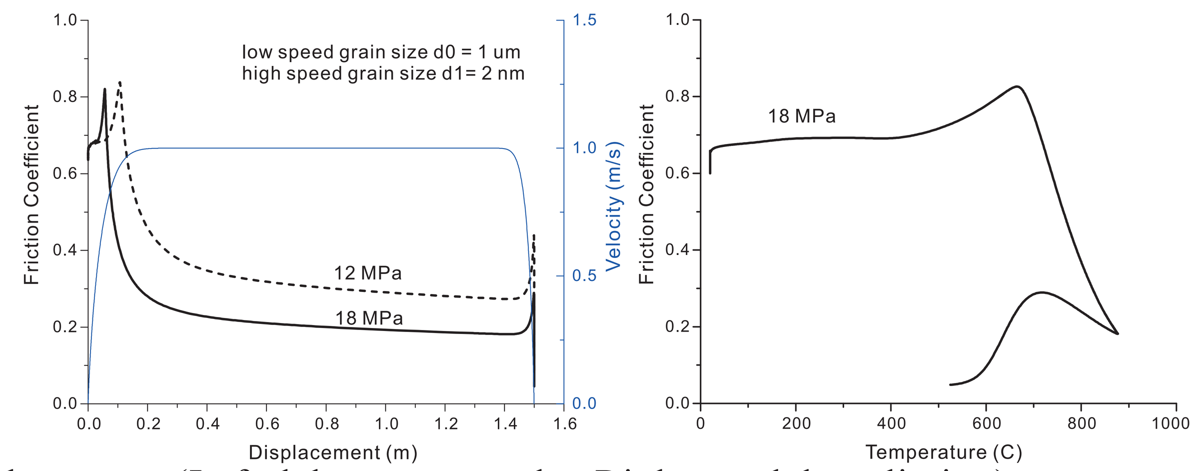
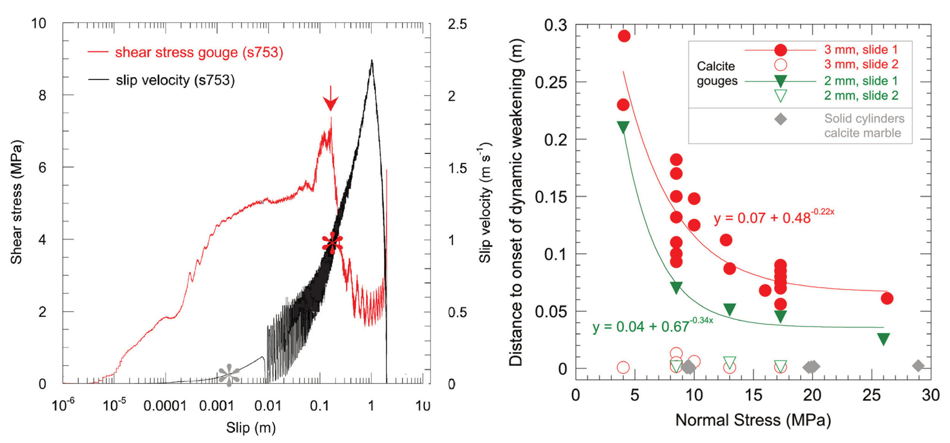


Fig 6. Evolution of friction with displacement and calculated temperature of the shear zone (Left: laboratory results, Right: model prediction)

4b. Smith et al. (2015): "strengthening phase" and slip localization



Prescribed evolution of shear band thickness as guided by microstructural observations

$$W_{sb} = W_1 + \frac{(W_0 - W_1)}{2}*\left[1 - erf\left(\frac{logV + 1}{0.5}\right)\right]$$

low speed: W_0 = 50 um
high speed: W_0 = 10 um

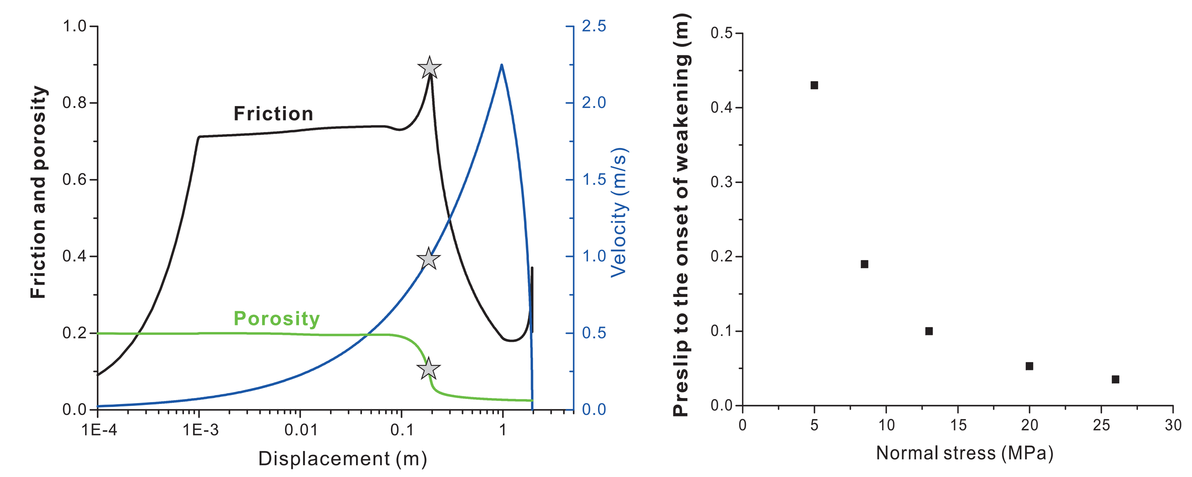


Fig 7. Predicted evolution of friction with the logarithm of displacement and the pre-weakening strengthening phase with normal stress (Left: laboratory results, Right: model prediction)

4c. Pozzi et al. (2018) : recystallization and microstructure evolution

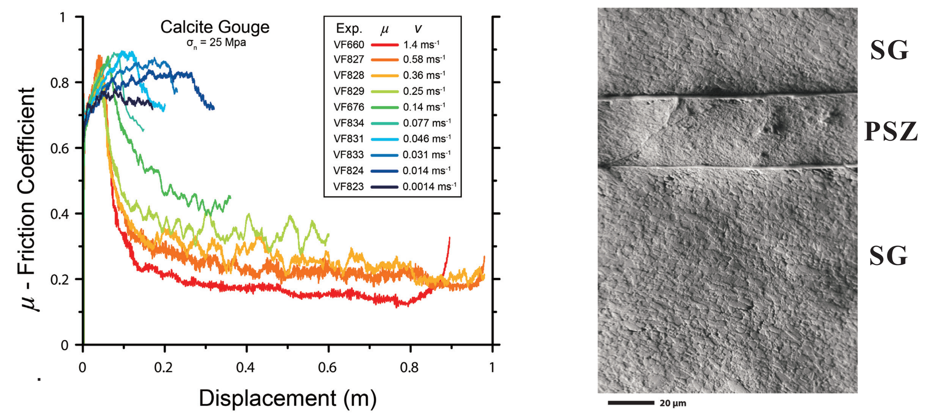


Fig 8. Friction and typical microstructures of calcite gouge sheared at 25 MPa, with Ti-alloy as host rocks.

Grain size growth: $d^{\frac{1}{n}} - d_0^{\frac{1}{n}} = ktexp\left(\frac{-H}{RT}\right)$

PSZ is pre-scribed following exp., but allowed to evolve as slip decelerates.

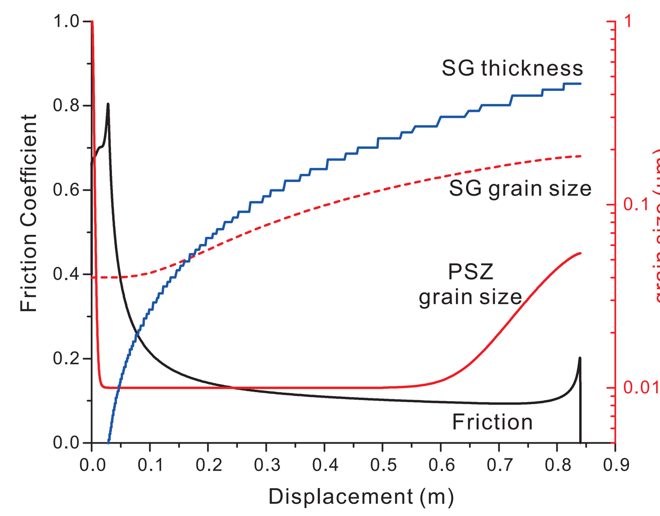


Fig 9. Predicted friction and microstructural parameters with displacement.

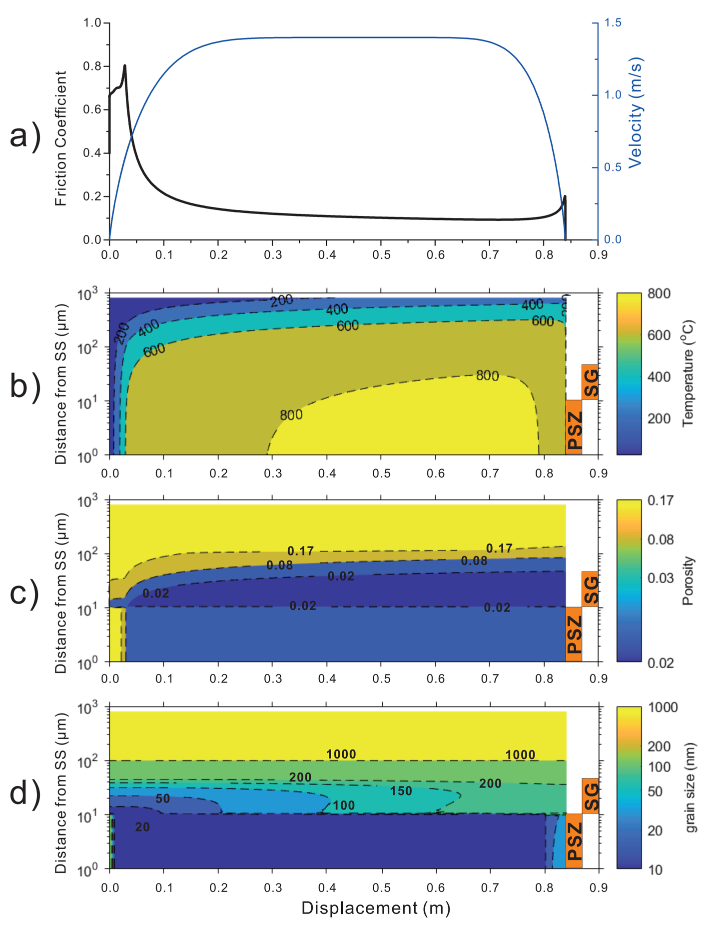


Fig 10. Evolution of a) friction, b) temperature, c) porosity and d) grain size over log(gouge thickness).

5. Discussion and future work

(1) Extended CNS model predicts a **steady-state frictional strength profile** over a wide velocity range (Fig. 5).
(2) The model reproduces typical laboratory experiments (friction and compaction/dilation, Fig. 6).
(3) Dynamic weakening occurs after a **"prolonged strengthening phase"** which shortens with increasing normal stress (Fig. 7) and increasing slip rate (not shown).
(4) The model predicts a "**Sintering Gradient**" zone, extending beyond the PSZ, characterized by low-porosity and nearly-uniform grain size, whose grain size and thickness increase with shear displacement (Fig. 9 and 10). As grain size increases, **dislocation creep** will become increasingly important (c.f. creep-accommodated GBS).

Limitation: prescribed slip localization.
Future work: (1) stability analysis; (2) earthquake cycle simulations with the extended model.