Energetics of Strain Localization in a Model of Seismic Slip

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ABSTRACT

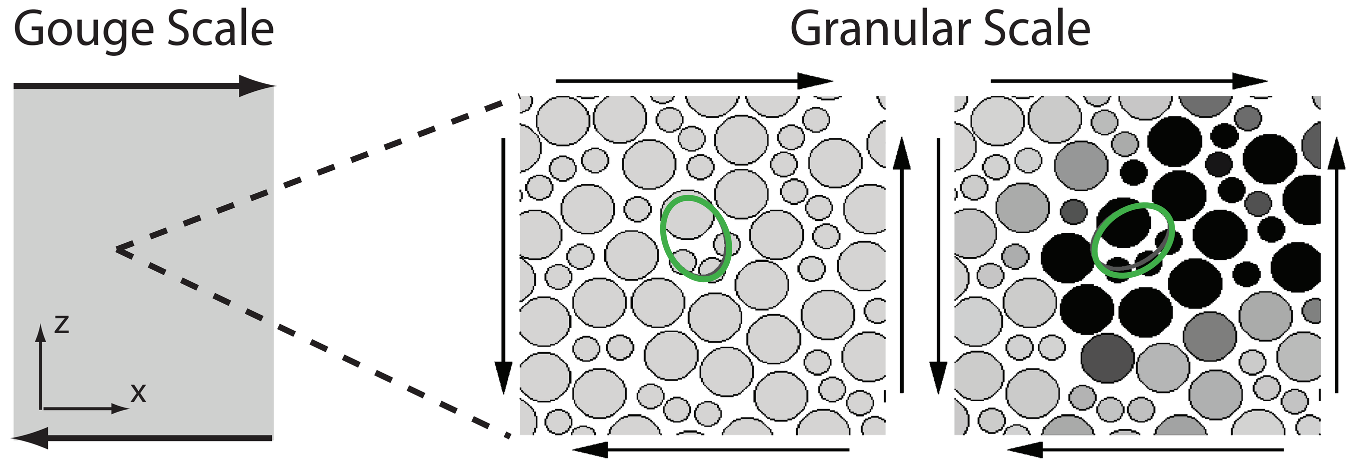
We quantify the energy dissipated to heat and to local disorder in a sheared layer of granular fault gouge. Local disorder is modeled using Shear Transformation Zone (STZ) Theory, a continuum approximation of plastic deformation in disordered solids that resolves spontaneous localization of strain. Strain localization decreases the total energy dissipated during slip. In addition, a fraction of this energy is dissipated to increasing local disorder as the material is sheared, thereby decreasing the amount of energy dissipated as thermal heat. We quantify the heat dissipated per unit area as a function of total slip and find that less heat is dissipated per unit area compared to results obtained using a traditional energy partition.

STZ FRICTION MODEL

- approximates plastic deformation in disordered solids (such as granular fault gouge)
- captures dynamics of spontaneous strain localization
- consequences for energy dissipation:

→ strain localization decreases total energy dissipated

→ a fraction of energy is dissipated to increasing local disorder, thereby decreasing the energy dissipated as thermal heat



[Falk and Langer, 1998]

- Localized "Shear Transformation Zones" (STZs) accommodate plastic strain under applied shear stress
- STZs flip orientations as the material is sheared
- Shear stress s determines rate at which STZs flip
- Effective temperature χ characterizes the density of STZs: higher χ ⟹ more disorder ⟹ more STZs

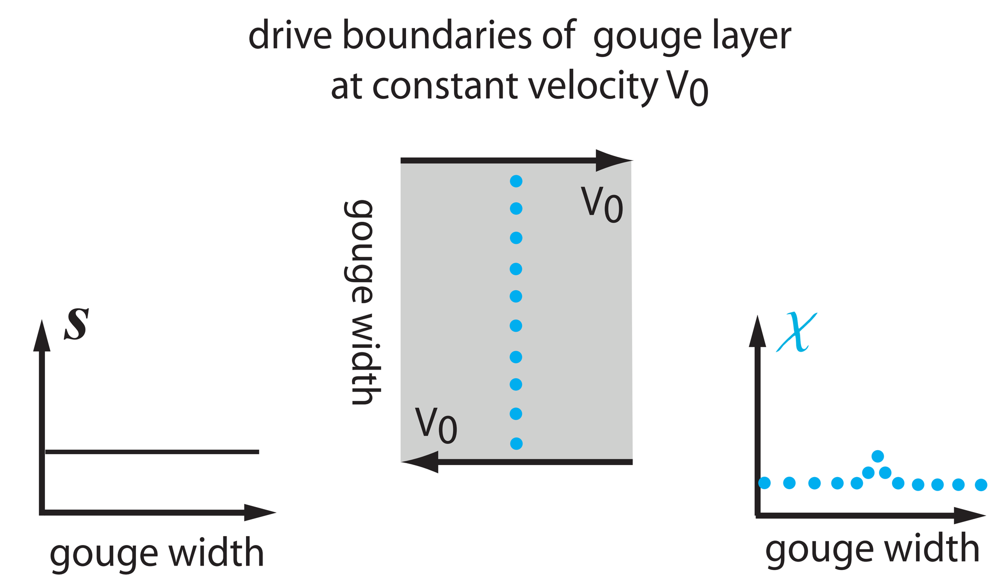
plastic strain rate:

$$\dot{\gamma}_{pl} = (\epsilon_0/\tau_0)\,\underbrace{R(s)}_{\text{rate at which STZs flip}}\,\underbrace{\exp(-1/\chi)}_{\text{density of STZs}}$$

time evolution of effective temperature:

$$\frac{\partial \chi}{\partial t} = \underbrace{\frac{\dot{\gamma}_{pl}\, s}{c_0\, s_y}\left(1-\frac{\chi}{\hat{\chi}(\dot{\gamma}_{pl})}\right)}_{\text{energy dissipated to increasing local disorder (increasing } \chi \text{ toward steady state value } \hat{\chi}(\dot{\gamma}_{pl}))} + \underbrace{\frac{\partial}{\partial z}\left(D\,\dot{\gamma}_{pl}\frac{\partial \chi}{\partial z}\right)}_{\text{diffusion across gouge width}}$$

SHEARED GOUGE MODEL



- assume shear stress is constant across gouge width
- resolve effective temperature on spatial grid that spans gouge width
- initial effective temperature determines type of deformation (homogeneous or strain-localized)

STRAIN LOCALIZATION

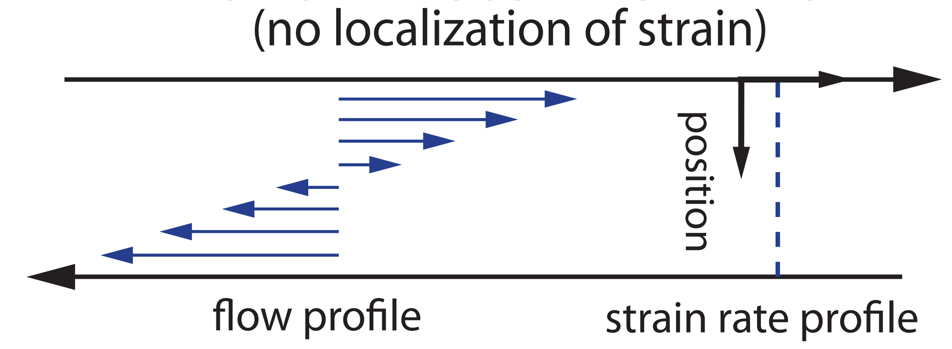
uniform initial effective temperature (completely homogeneous material)

↓

uniform strain

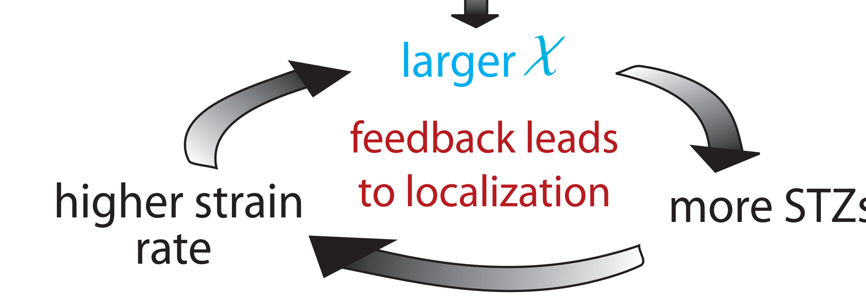
↓

HOMOGENEOUS DEFORMATION (no localization of strain)

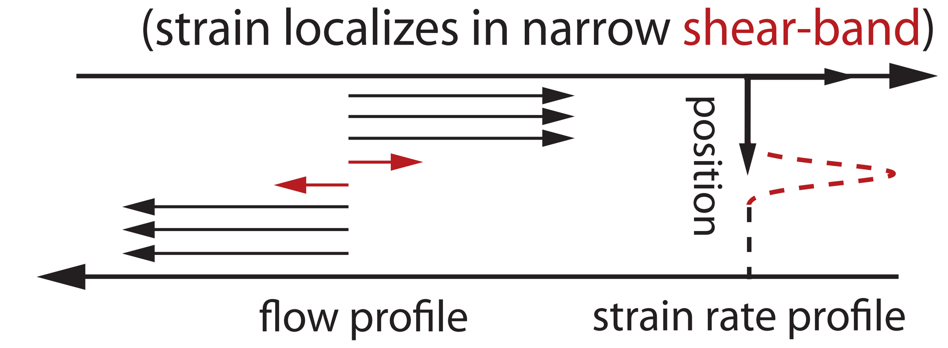


uniform initial effective temperature with perturbation

↓

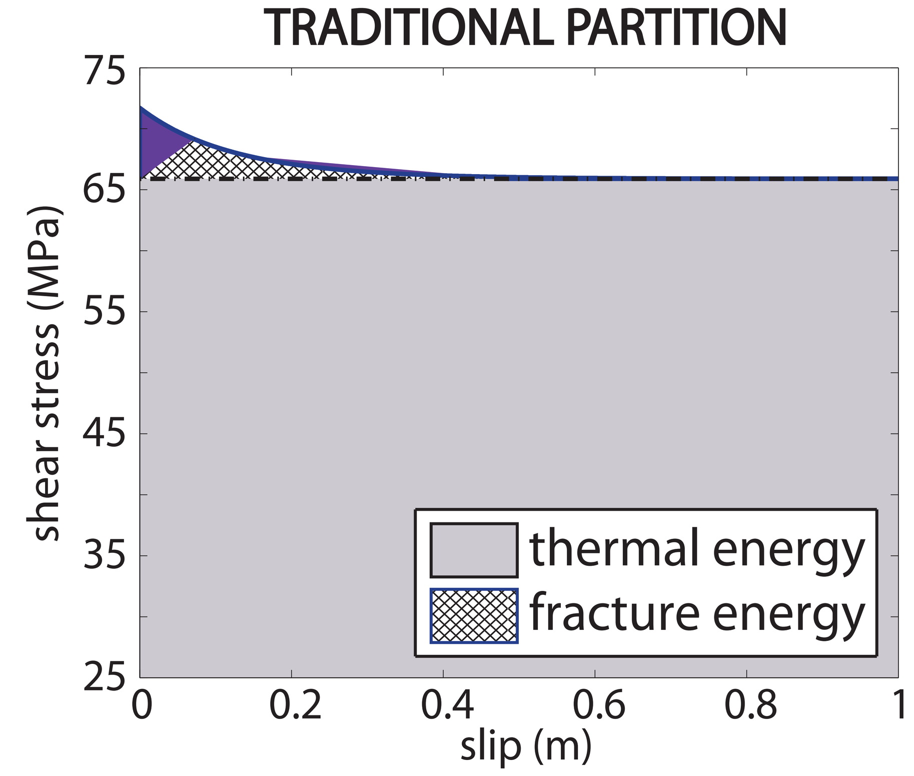


LOCALIZED DEFORMATION (strain localizes in narrow shear-band)



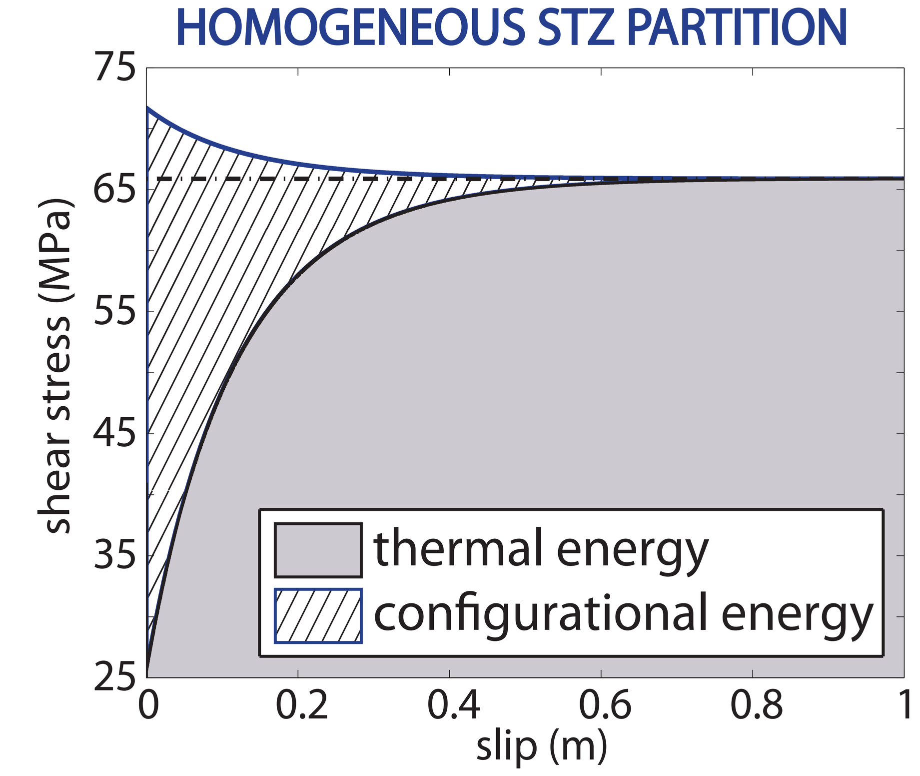
ENERGY PARTITIONING

TRADITIONAL PARTITION



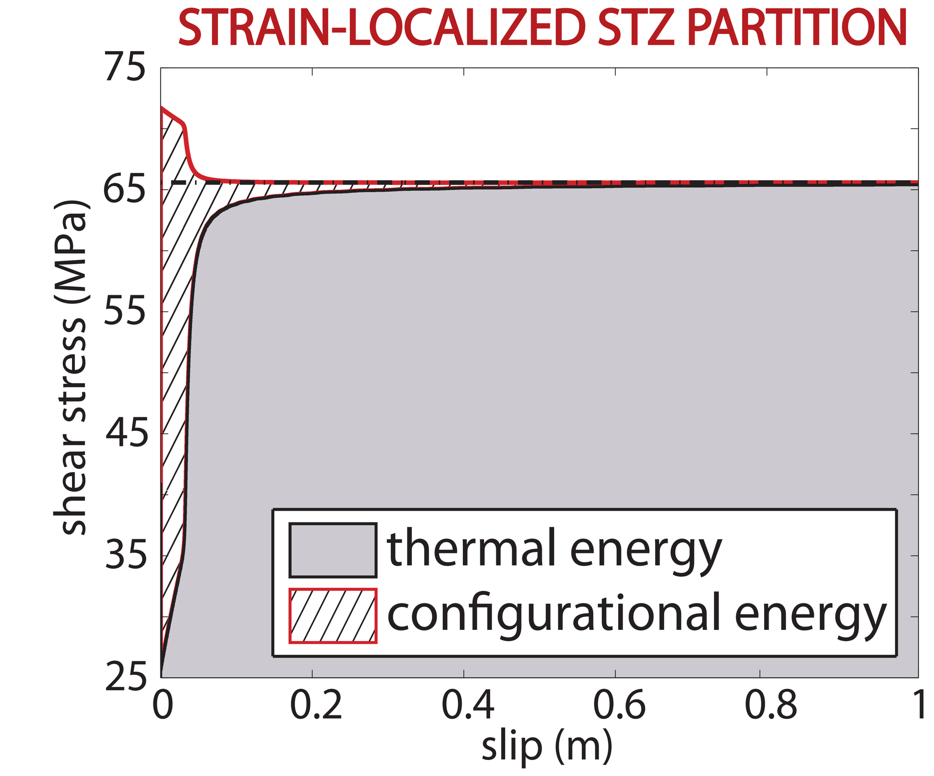
- coarse approximation of thermal energy
- remaining energy is attributed to rock fracture

HOMOGENEOUS STZ PARTITION



- a fraction of the total energy is dissipated to increasing the effective temperature
- remaining energy is attributed to thermal heat
- once the effective temperature reaches steady state, all energy is dissipated as heat

STRAIN-LOCALIZED STZ PARTITION



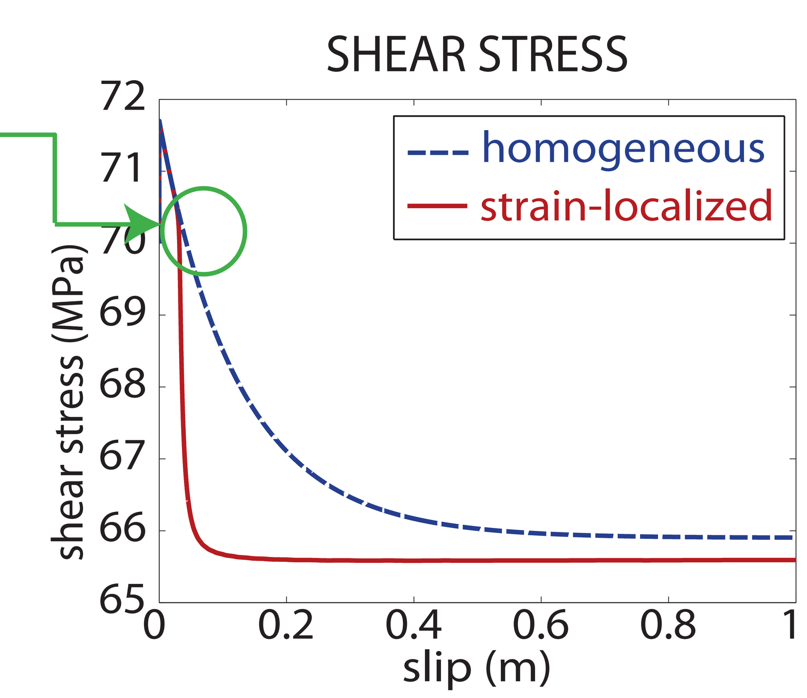
- strain localization decreases the total energy dissipated
- less configurational energy is required to drive the effective temperature to steady state

HEAT DISSIPATION

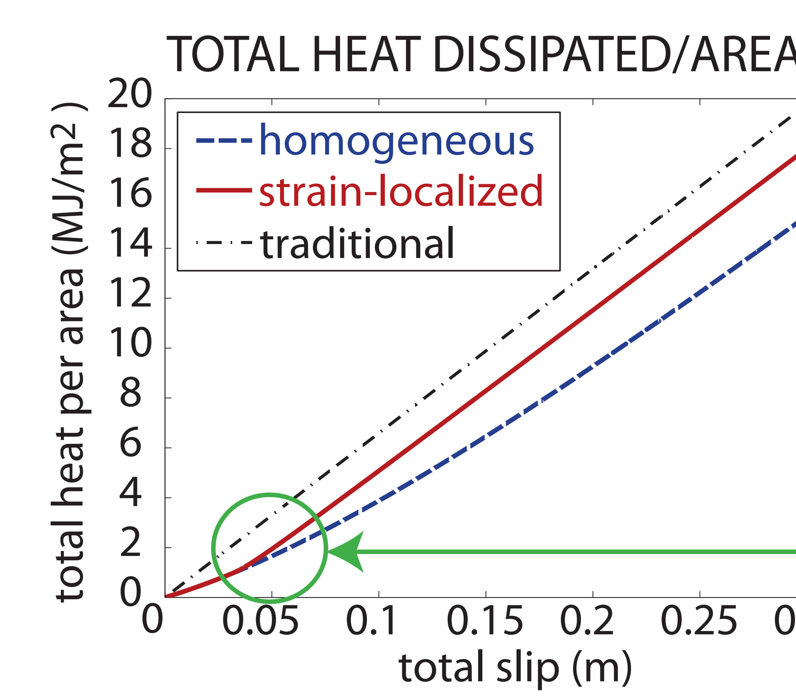
shear-band formation:

- rapid weakening: both stress and effective temperature stabilize more rapidly
- lower dynamic sliding stress

SHEAR STRESS



TOTAL HEAT DISSIPATED/AREA



shear-band formation:

- increases short-term rate of heat production
- decreases long-term rate of heat production

heat/area dissipated in both systems is less than predicted by traditional partition