The physics of strain localization in dynamic earthquake rupture simulations

Eric G. Daub

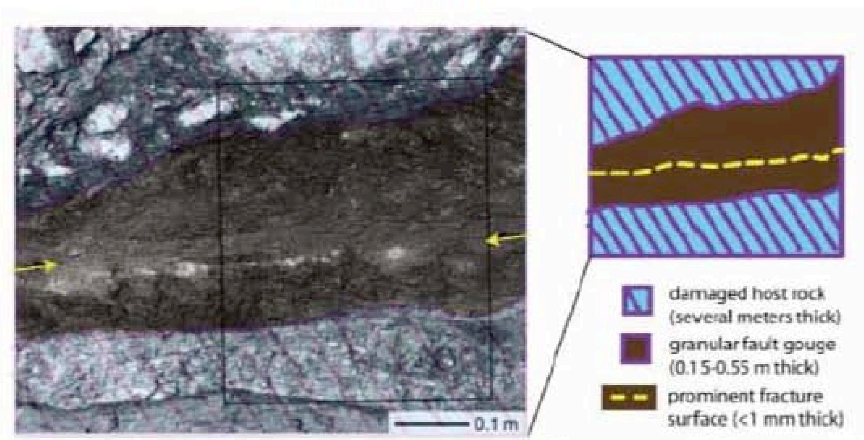
Geophysics Group/Center for Nonlinear Studies

Los Alamos National Laboratory

with M. Lisa Manning (Princeton) and Jean M. Carlson (UCSB)

How does grain-scale deformation affect fault-scale earthquake rupture?

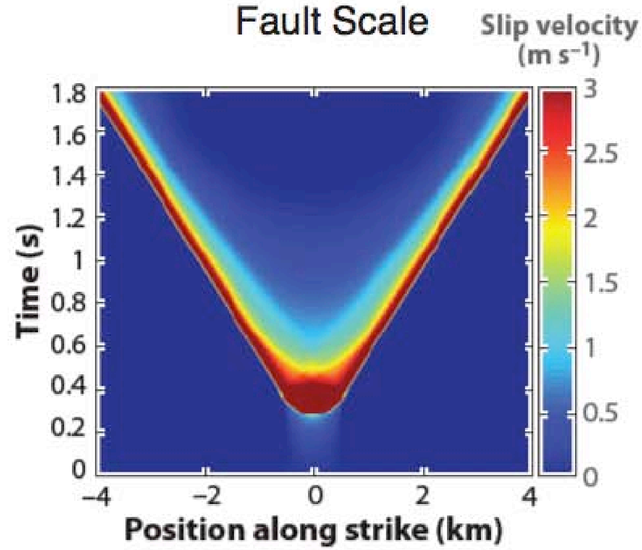
Grain Scale



Chester and Chester, 1998

?

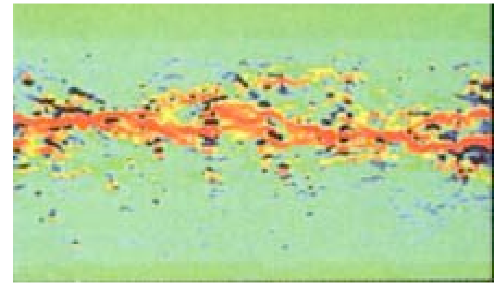
Fault Scale



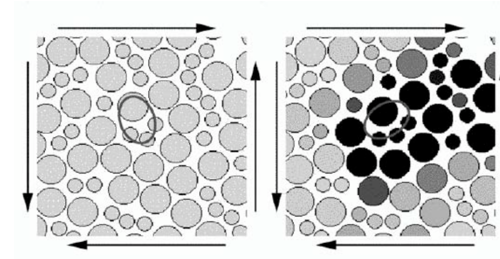
How do we develop physical friction models that capture the dynamics of strain localization?

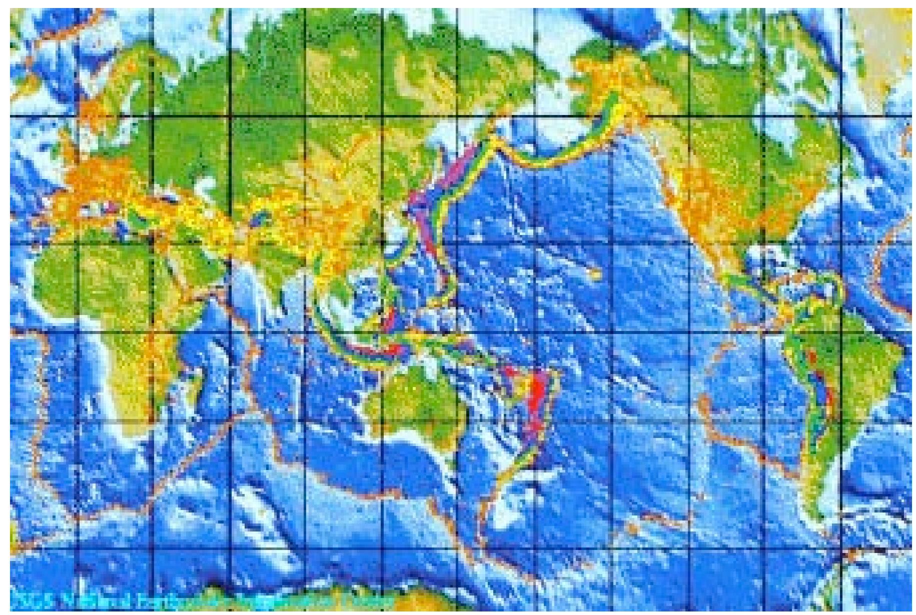
What are the implications for rupture dynamics?

Goal: improve our understanding of the basic physics of earthquake rupture



Interdisciplinary problem -- draws on physics, seismology, materials science, engineering, etc.

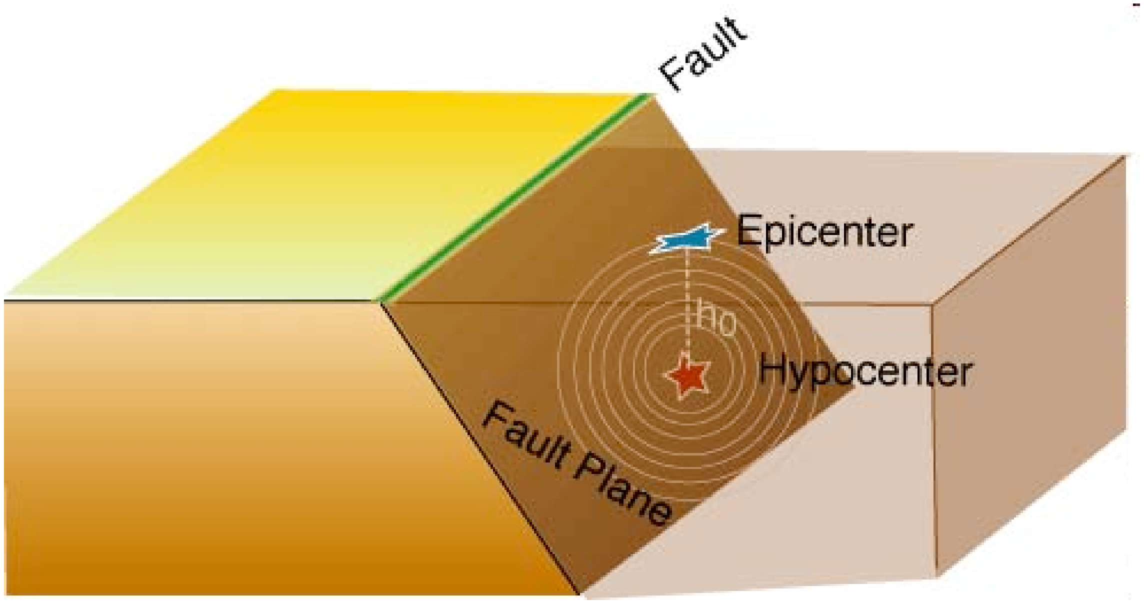


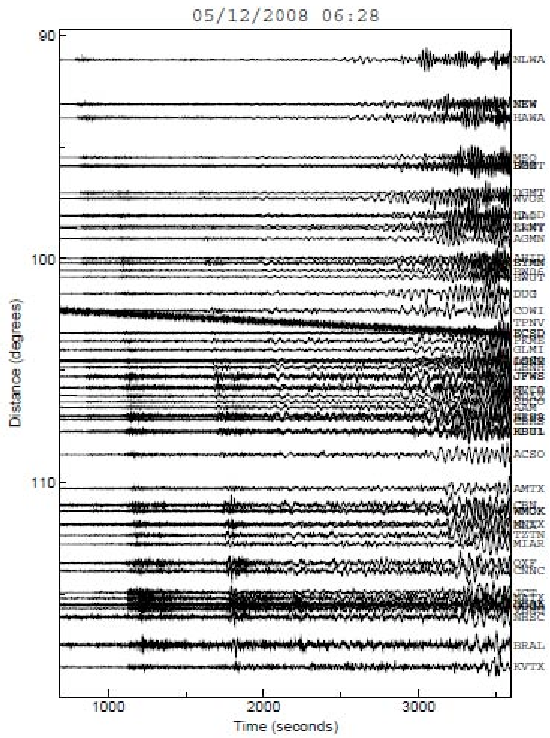


Physics of Earthquakes

Seismologists do not have a complete description of the physics governing earthquake rupture. Why?

1st Problem: Earthquakes happen deep in the earth's crust, and we can't observe them directly





Look at seismic waves instead.

Physics of Earthquakes

Seismologists do not have a complete description of the physics governing earthquake rupture. Why?

2nd Problem: Occur at extreme physical conditions (hard to replicate in lab experiments)

• Large slip velocities (~1 m/s), Large slip (up to 20 m)

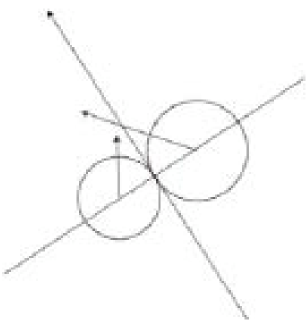
• Large confining pressures (~100 MPa), fluids present

• All current data compromises on at least one of these conditions

Physics of Earthquakes

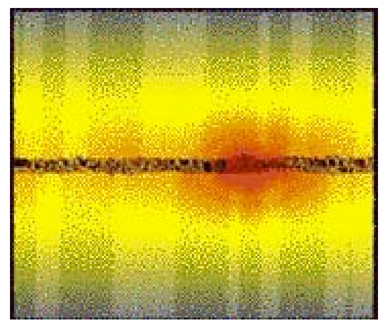
But even if we knew all the basic physics, we're still faced with the problem that earthquakes are complex systems, with a huge range of important length and time scales:

Contacts



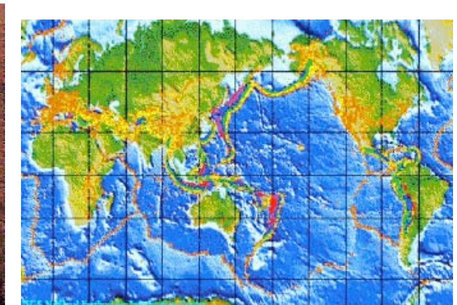
Grains

Friction



Faults

Networks

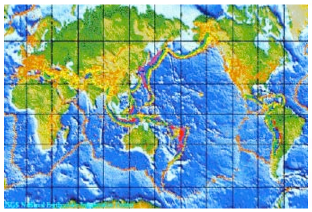


Increasing length scales

Increasing time scales

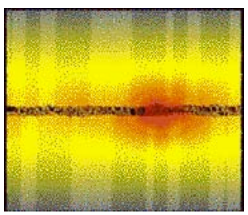
Multi-Scale Earthquake Problem

Time & Space

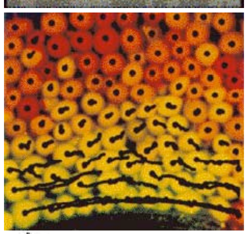


Networks

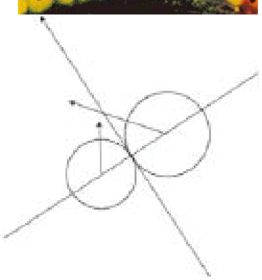
Faults



Friction



Grains



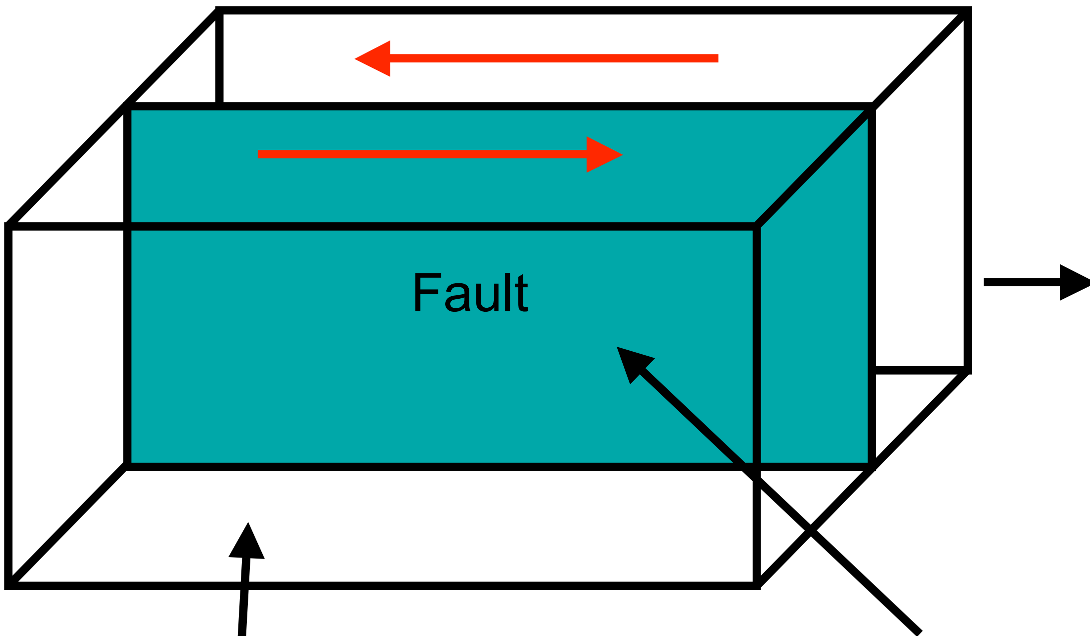
Contacts

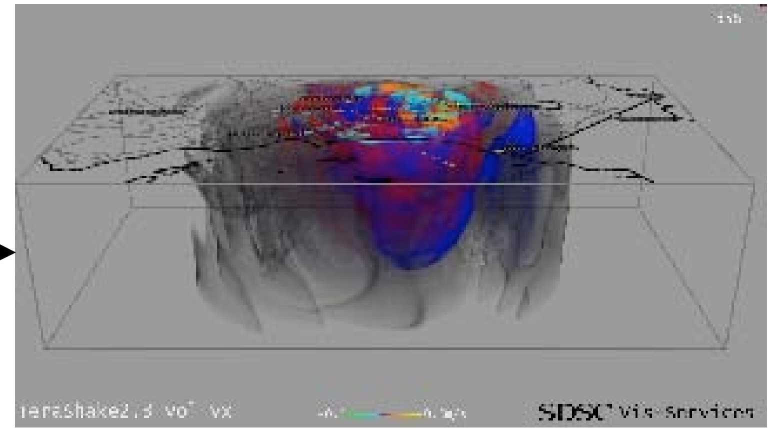
"Vertical:" connect different scales

"Horizontal:" each level is a complex, often heterogeneous, dynamical system, with rich behavior, and many unknowns

Our approach is "vertical": determine large scale impact of small scale physics

How to Model Earthquake Rupture?





(Terashake, SCEC and SDSC)

On Fault: Fault is a weak interface

Describe fault with a constitutive (friction) law – relation that tells you what the fault shear stress is as a function of slip, slip rate, etc.

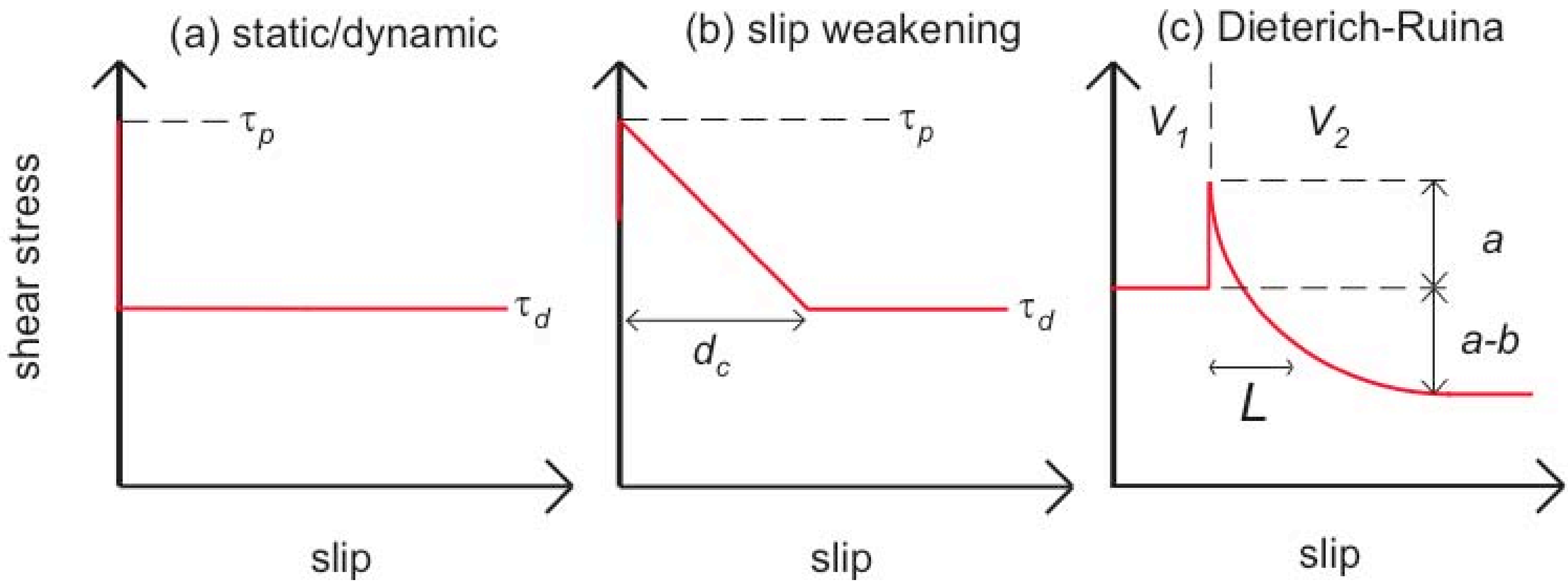
Where you might incorporate small scale physics!

Off Fault: Rocks in the earth's crust.

Important properties: elasticity, seismic velocity structure, plastic yielding/damage, etc.

Constitutive Laws

Common examples of friction laws:



Friction law from introductory physics

Adds a frictional length scale

Adds phenomenological slip rate dependence from lab experiments

However, these models do not tell us much about the underlying physical processes of earthquake rupture.

Dieterich-Ruina Friction

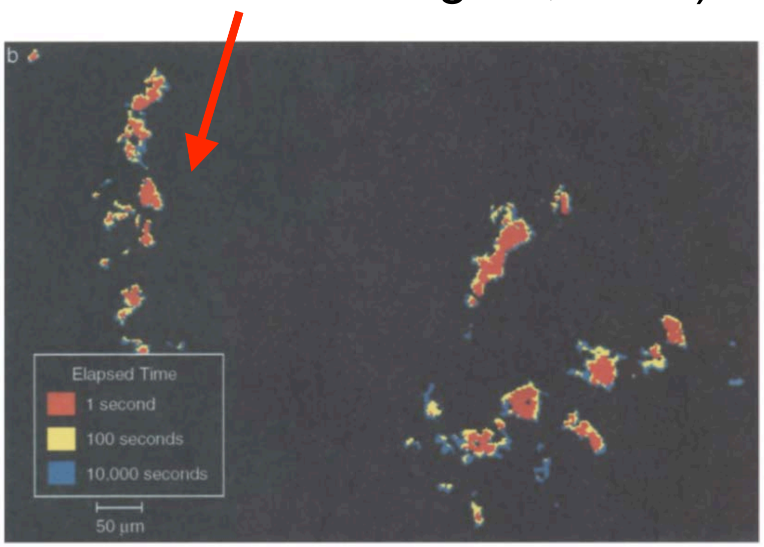
• Phenomenological fit to data from laboratory experiments

• Steady-state friction depends on log of the slip rate

• State variable has units of time, represents average surface asperity contact time (observed by Dieterich and Kilgore, 1994)

$$\tau = \sigma \left(f_0 + a \log \left(\frac{V}{V_0} \right) + b \log \left(\frac{\theta V_0}{L} \right) \right)$$

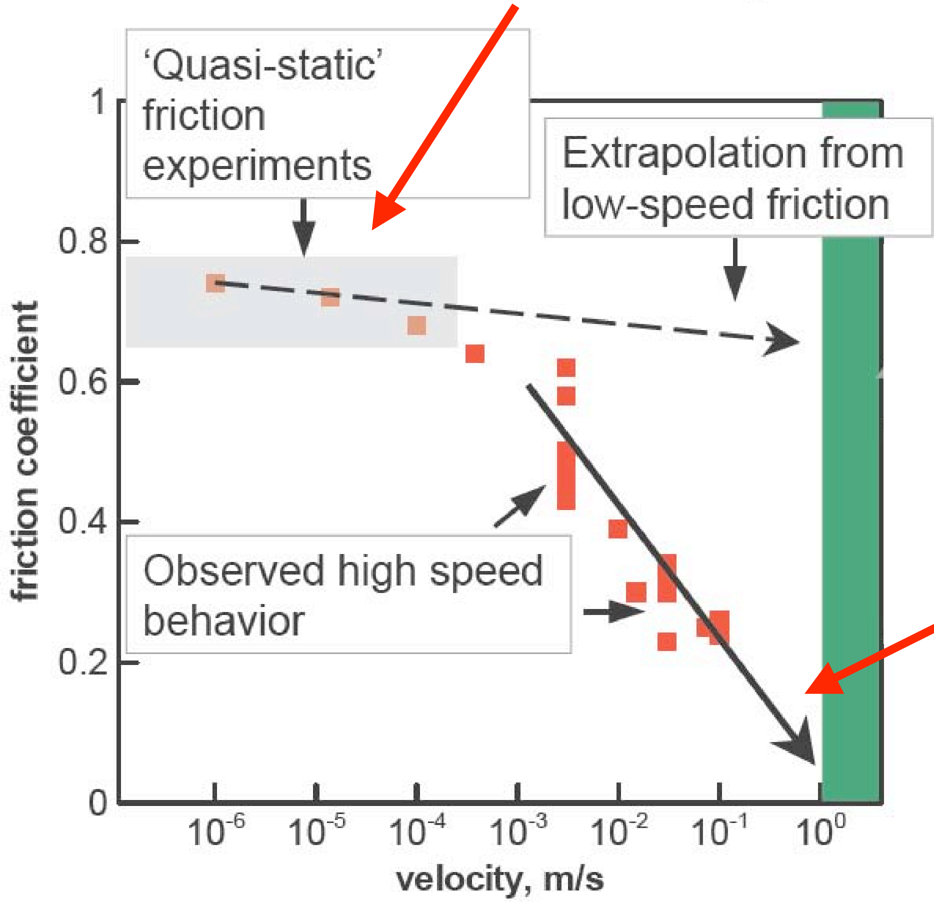
$$\frac{d\theta}{dt} = 1 - \frac{\theta V}{L}$$



Not derived from microscopic physics, but widely used in seismology.

Fits to Data Bad for Extrapolation

DR Law



Di Toro, Goldsby, Tullis, 2004

Earthquakes

- DR Law can fail in extreme cases
- Instead, base friction on microscopic physics.

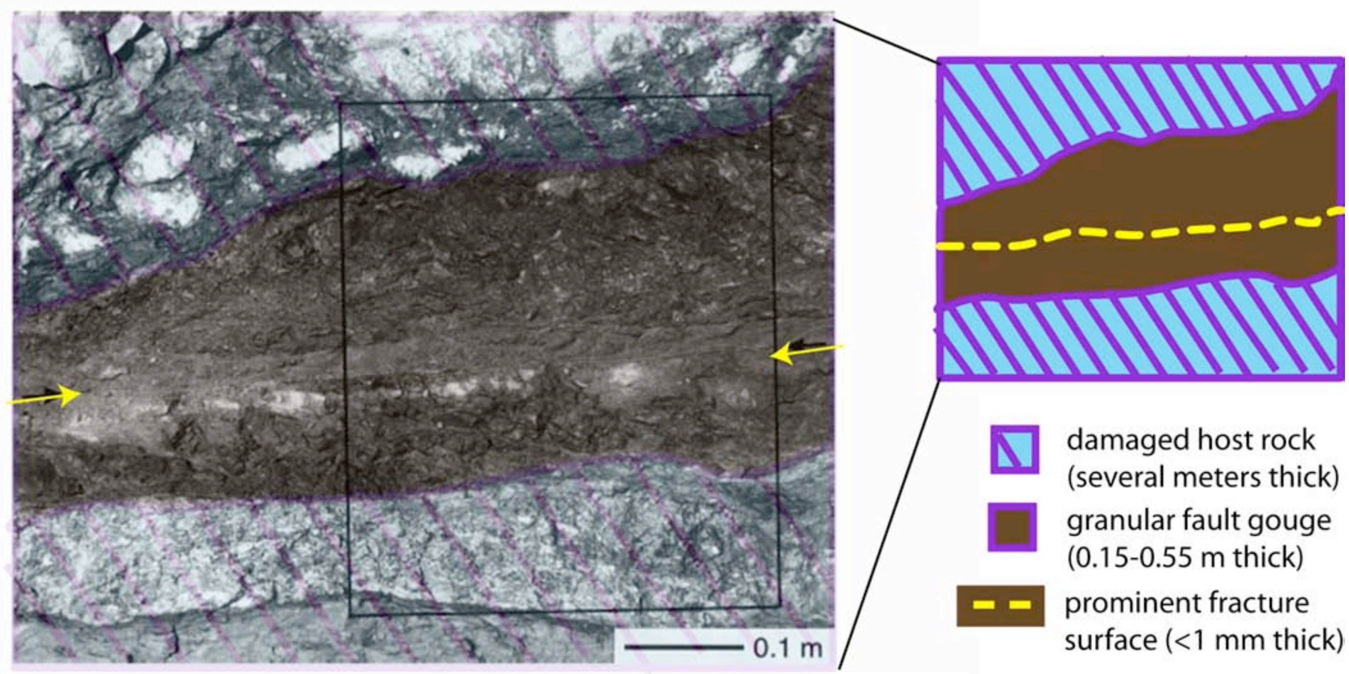
Better Constitutive Law?

Need to develop a friction law that gives more physical insight into fault slip. But basic physics of earthquake slip is poorly constrained…

Develop a model that captures robust common features of deformation in materials similar to faults:

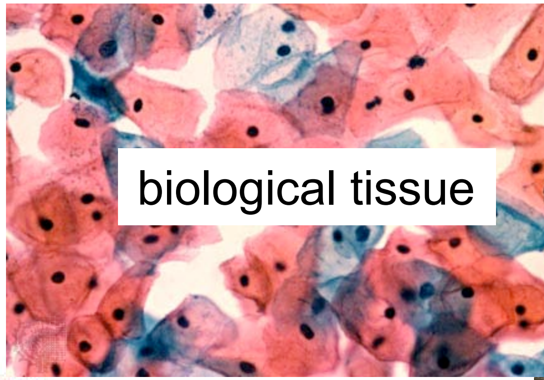
Faults contain granular material (gouge)

Very finely crushed, no crystal structure = amorphous material



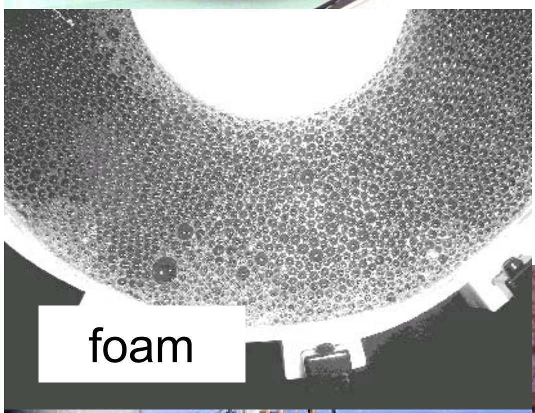
Examples:


Best Foods
BRING OUT THE BEST
REAL
MAYONNAISE
PRICE CLUB
dense
colloids/
emulsions


biological tissue


glass


silicon panels


foam

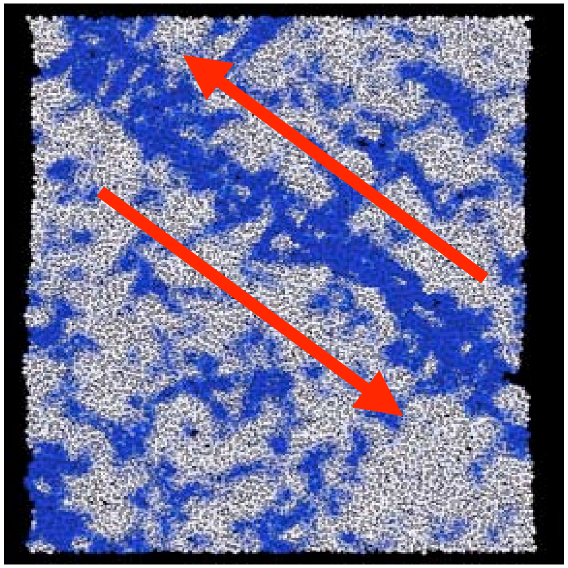

grain

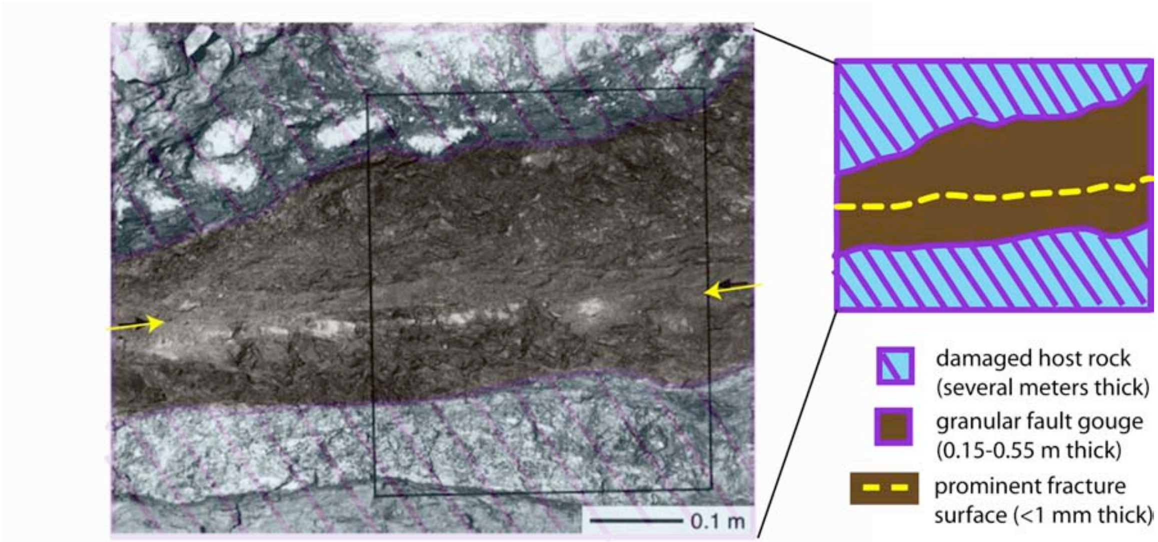

fault gouge


sand


bulk metallic glass

Constitutive Law





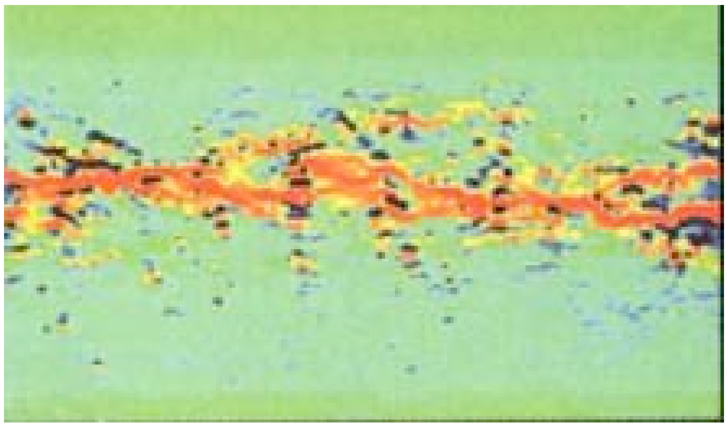
Develop a model that captures observations from experiments and simulations of how amorphous solids deform:

- Fluid flow described by continuum Navier-Stokes Equations. Want to develop a similar model for amorphous solids.
- dynamics are both solid-like and liquid-like:
    - creeps slowly or doesn't flow (jammed) under some conditions
    - flows easily under other conditions
- Amorphous materials exhibit strain localization

Strain Localization in Amorphous Materials

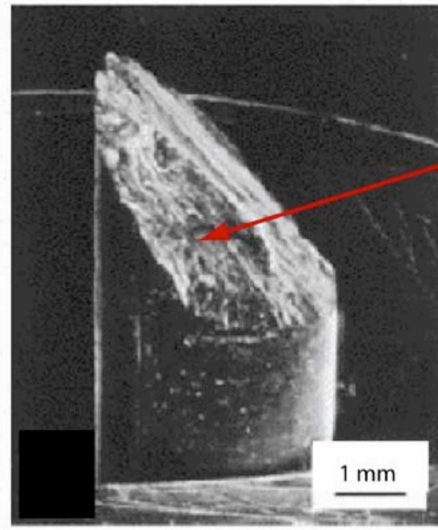
Simulations

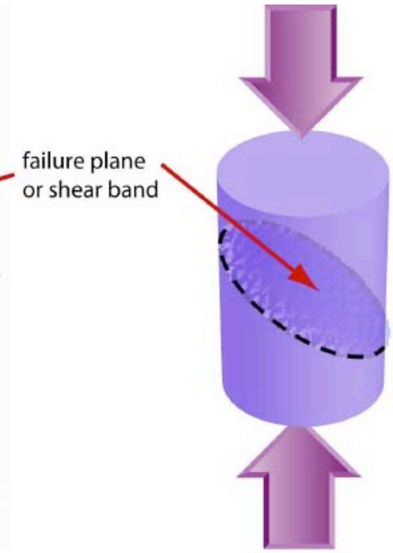
Morgan and Boettcher,
JGR 104(B2), 1999



Laboratory

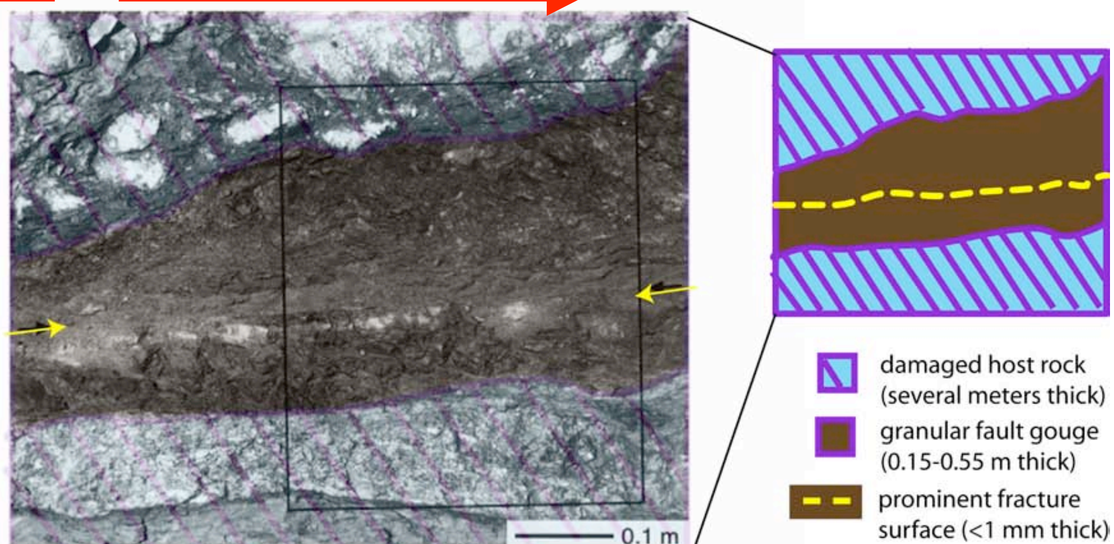
Lu et al., 2003





Field

Chester and Chester,
Tectonophys. 295, 1998.



Multi-Scale Earthquake Problem

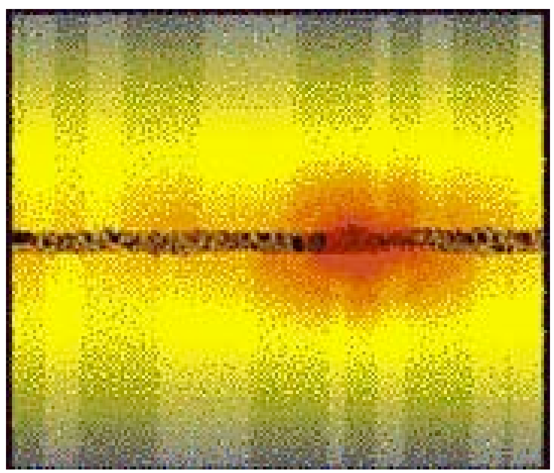
Plan: study the large scale impact of strain localization in amorphous materials and earthquake rupture

Think about many different scales in this talk, so I use the images below to indicate the current scale (move from small scales to large scales as the talk progresses)

Collective Grain Motion

→

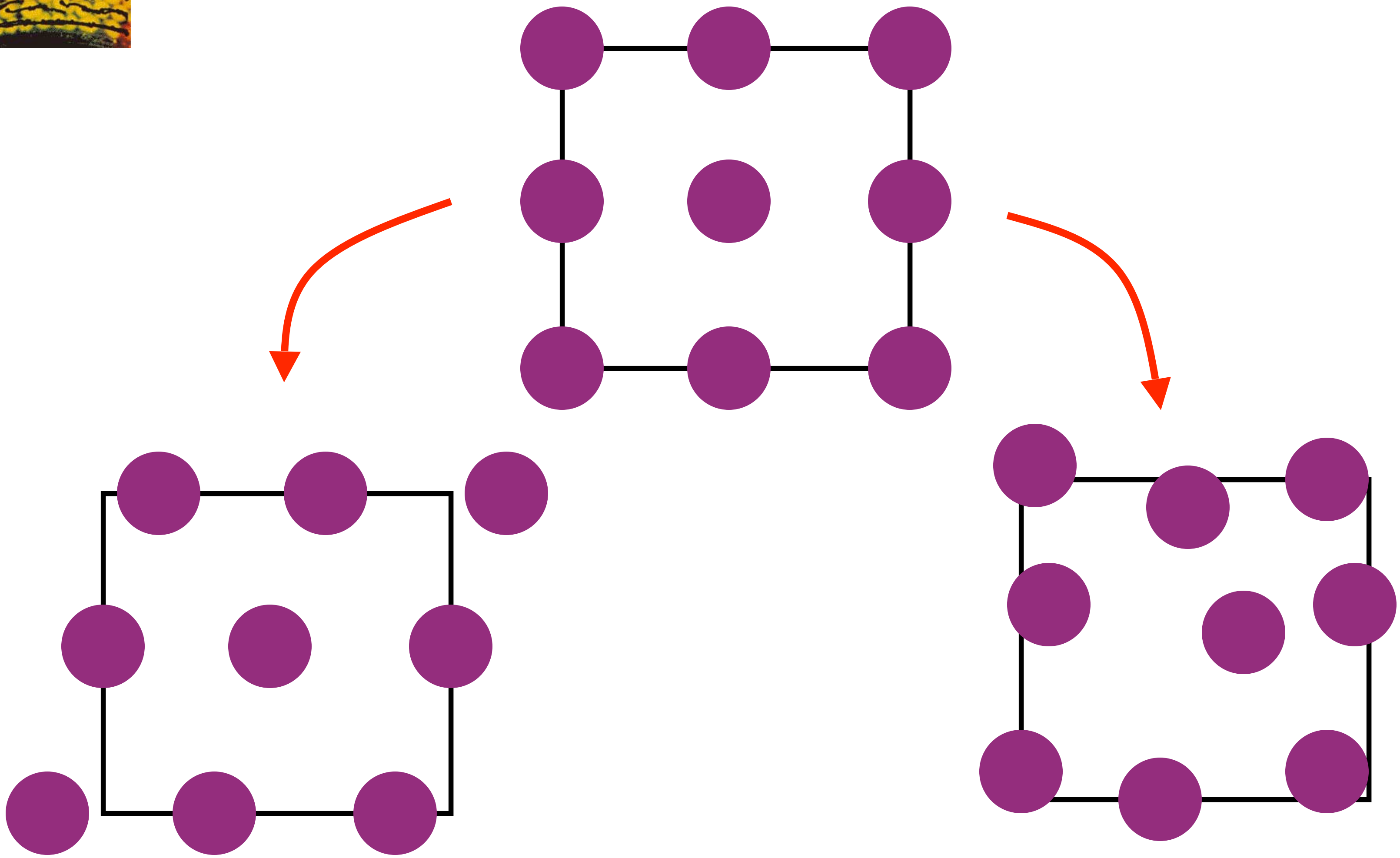
Interfacial Friction



→

Fault Dynamics

Types of Deformation

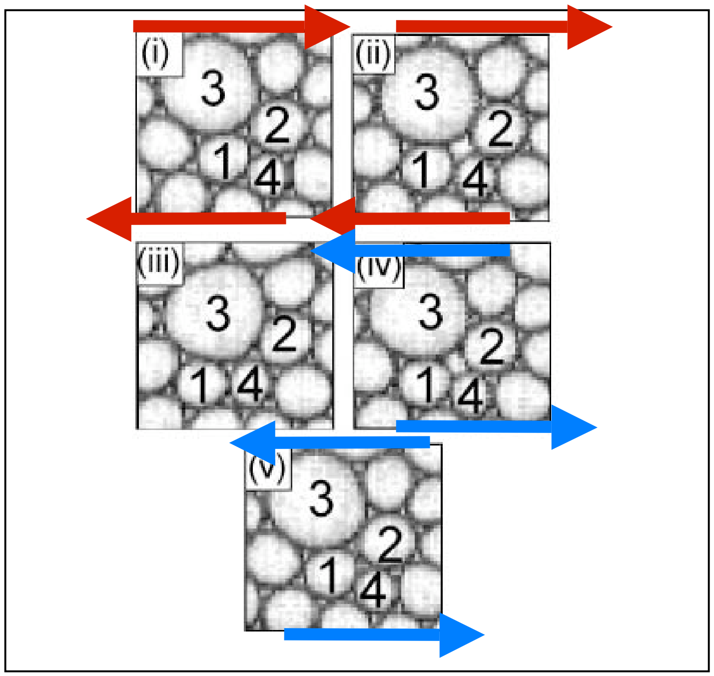


Elastic = Affine

Plastic = Non-Affine

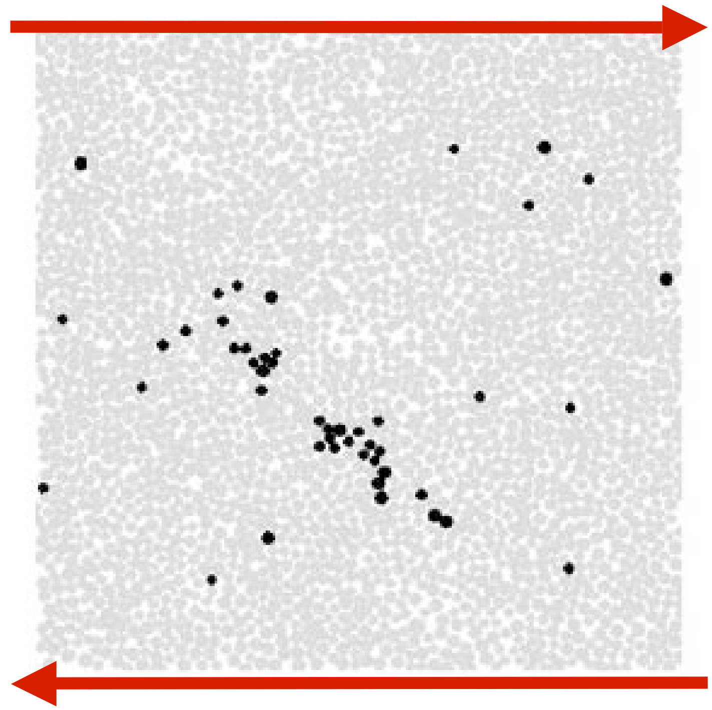
Non-Affine Deformation

Experimental Foams (Lundberg *et al, 2007*)



Images of plastic events in a foam

Simulated granular materials (Lois, Lemaitre and Carlson, *2005*)

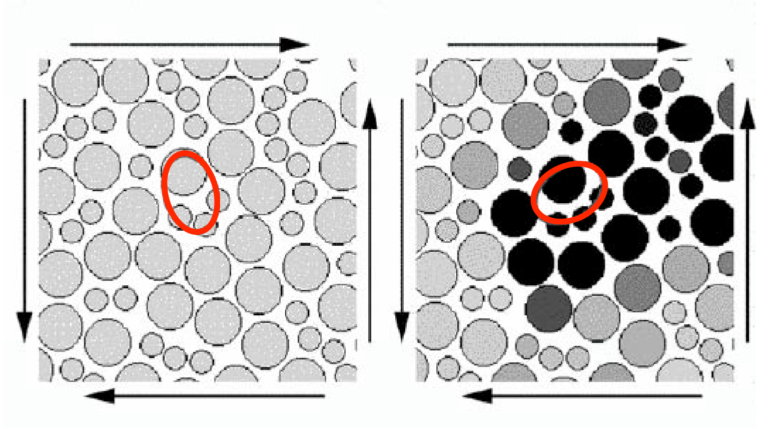


Black spots are regions of plastic deformation after 5% strain

Big Idea: plastic strain occurs in localized regions.

Shear Transformation Zone Model

Plastic strain occurs in local regions. Number of regions governed by effective disorder temperature χ.



$$\dot{\gamma} = \frac{\epsilon}{t_0} f(\tau) \exp(-1/\chi)$$

Stress determines rate at which STZs flip

Effective temperature determines how many STZs there are

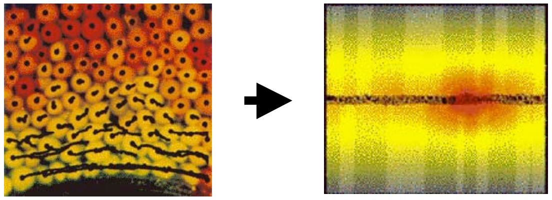
$$\frac{\partial \chi}{\partial t} = \frac{\dot{\gamma}\tau}{c_0 \tau_y}\left(1 - \frac{\chi}{\hat{\chi}(\dot{\gamma})}\right) + \frac{\partial}{\partial z}\left(\dot{\gamma} D \frac{\partial \chi}{\partial z}\right) + R\left(1 - \frac{\chi}{\chi_0}\right)\exp(-\beta/\chi)$$

Energy dissipation increases eff. temp.

Diffusion

Time-dependent relaxation (healing)

(Falk and Langer, PRE 1998; Langer and Manning, PRE 2007; Langer, PRE 2008)



STZ Friction

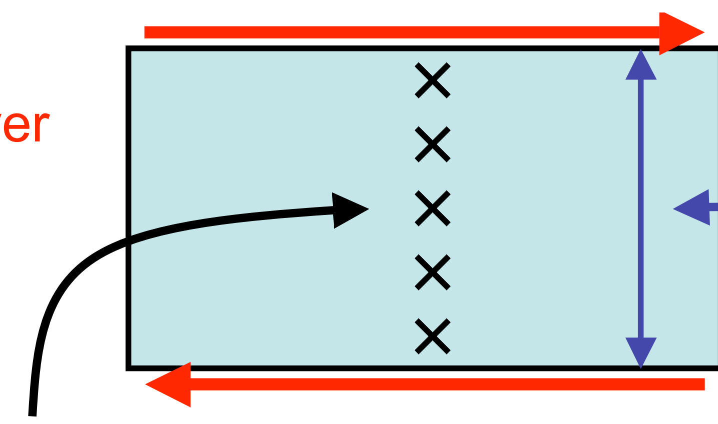
$$\dot{\gamma} = \frac{\epsilon}{t_0} f(\tau) \exp(-1/\chi)$$

Stress determines rate at which STZs flip

Effective temperature determines how many STZs there are

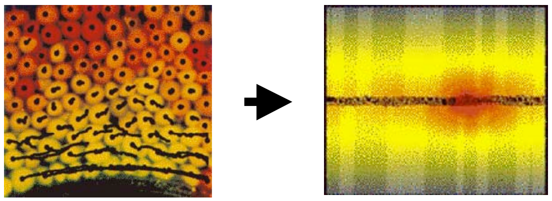
$$\frac{\partial \chi}{\partial t} = \frac{\dot{\gamma}\tau}{c_0 \tau_y}\left(1 - \frac{\chi}{\hat{\chi}(\dot{\gamma})}\right) + \frac{\partial}{\partial z}\left(\dot{\gamma} D \frac{\partial \chi}{\partial z}\right) + R\left(1 - \frac{\chi}{\chi_0}\right)\exp(-\beta/\chi)$$

Sheared gouge layer

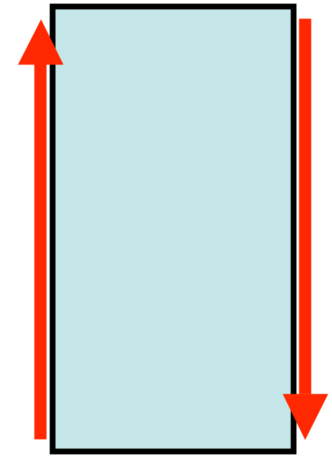


Solve for effective temperature on a spatial grid

Assume stress is constant across width of gouge (solution to static problem); timescale for stress equilibration faster than effective temperature evolution



Friction Dynamics

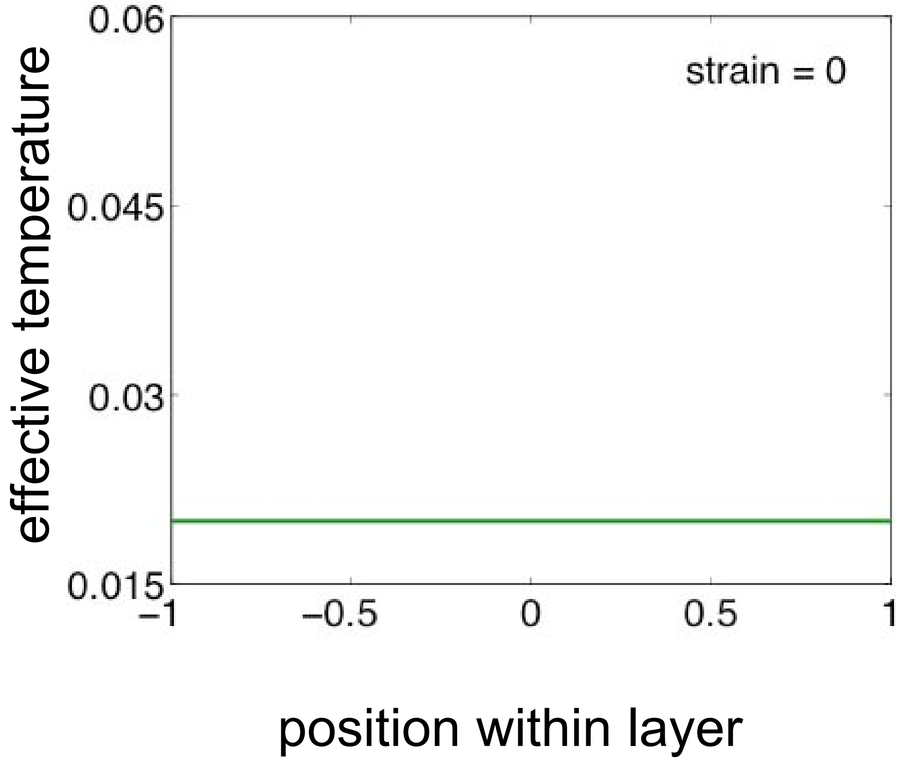


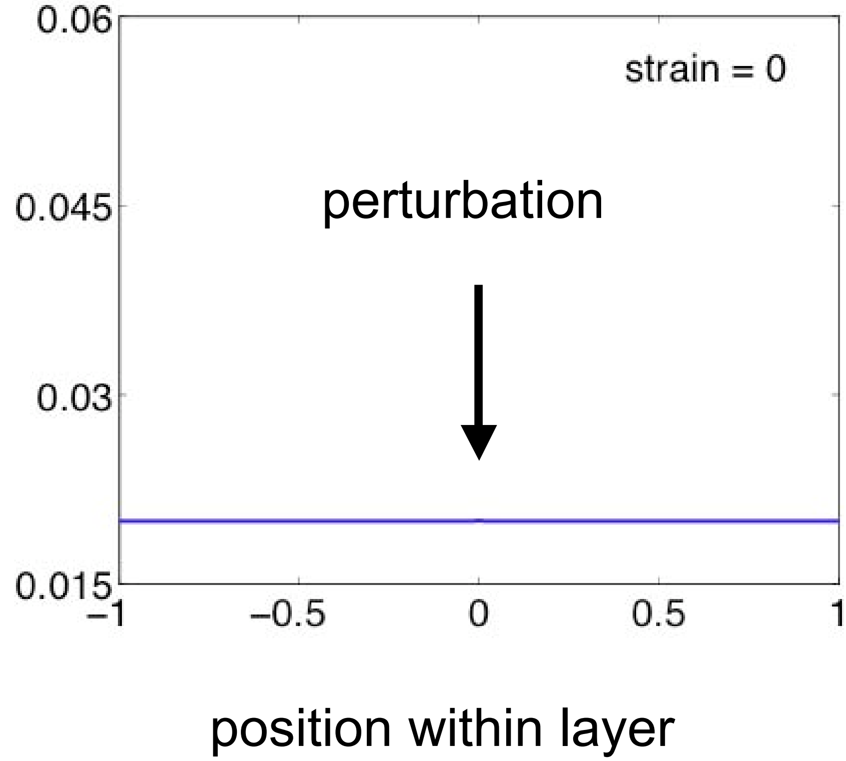
Shear an amorphous material governed by STZ law. How does effective temperature evolve?

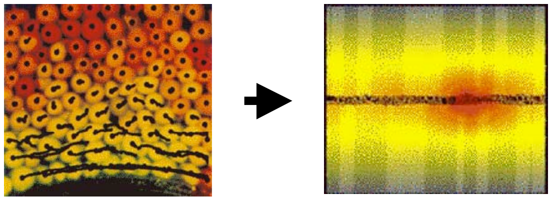
Initial Conditions

Homogeneous

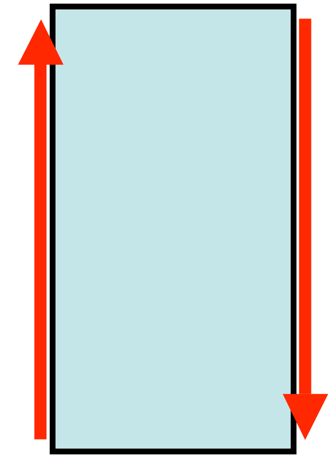
Homogeneous + small pert.







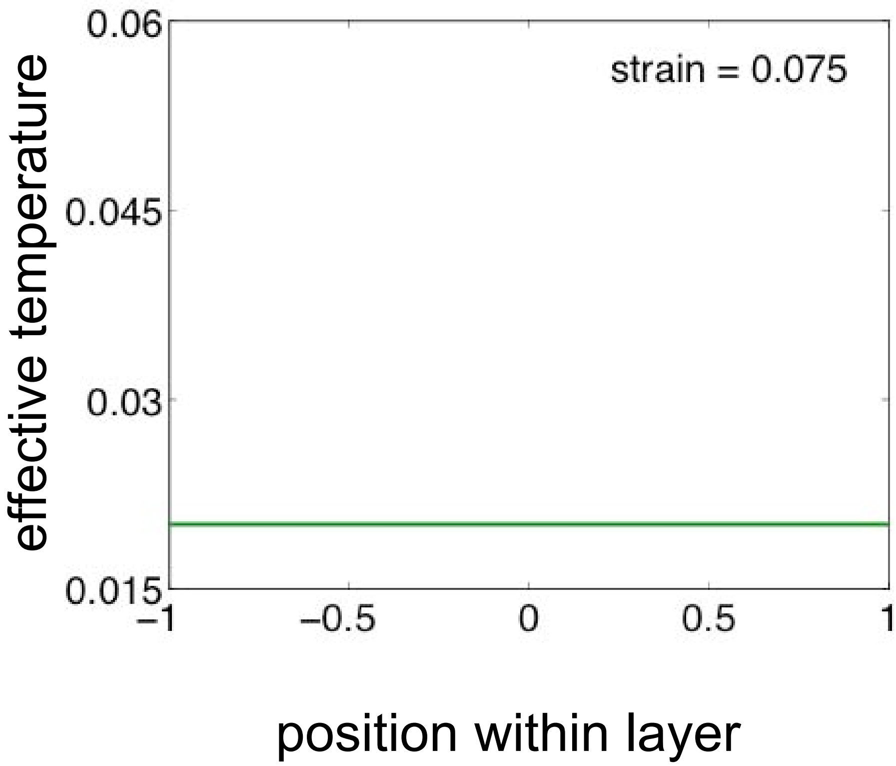
Friction Dynamics



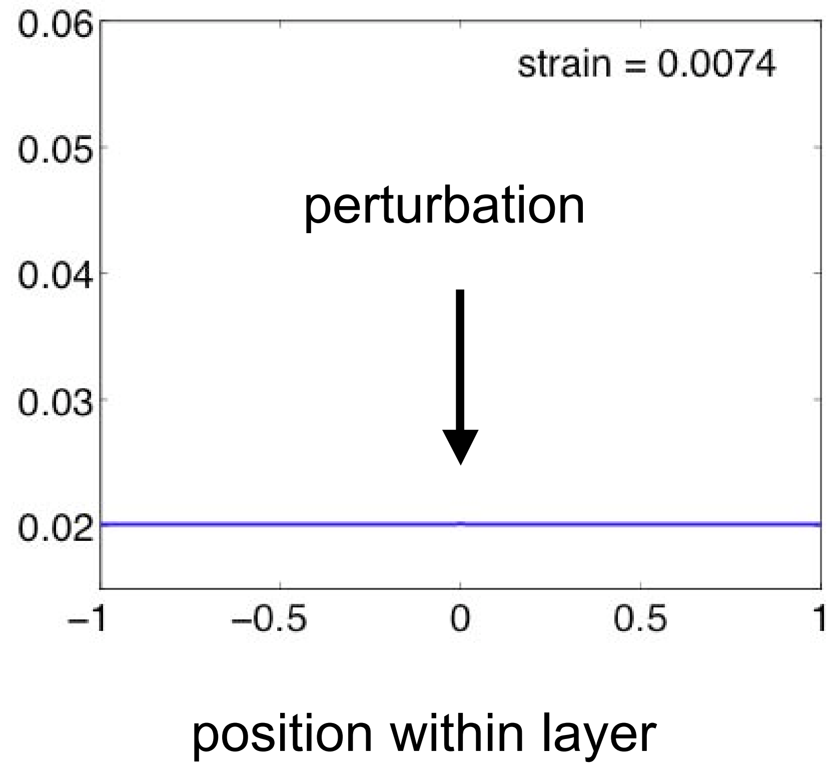
Shear a layer of gouge governed by STZ law.
How does effective temperature evolve?

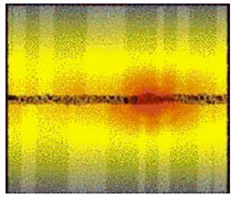
Initial Conditions

Homogeneous

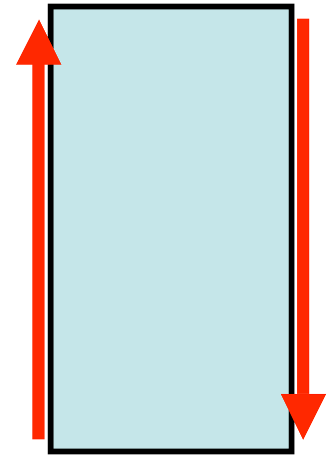


Homogeneous + small pert.





Friction Dynamics

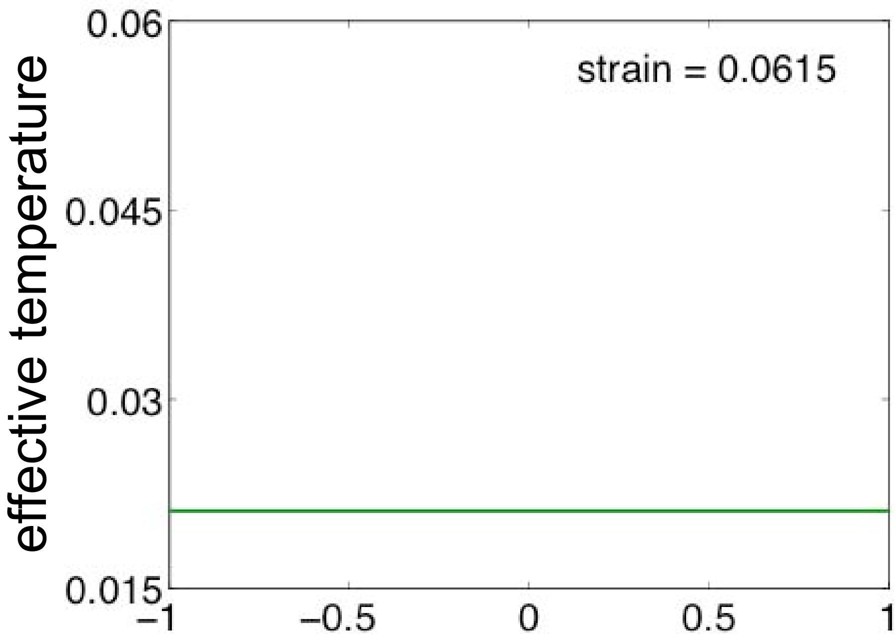


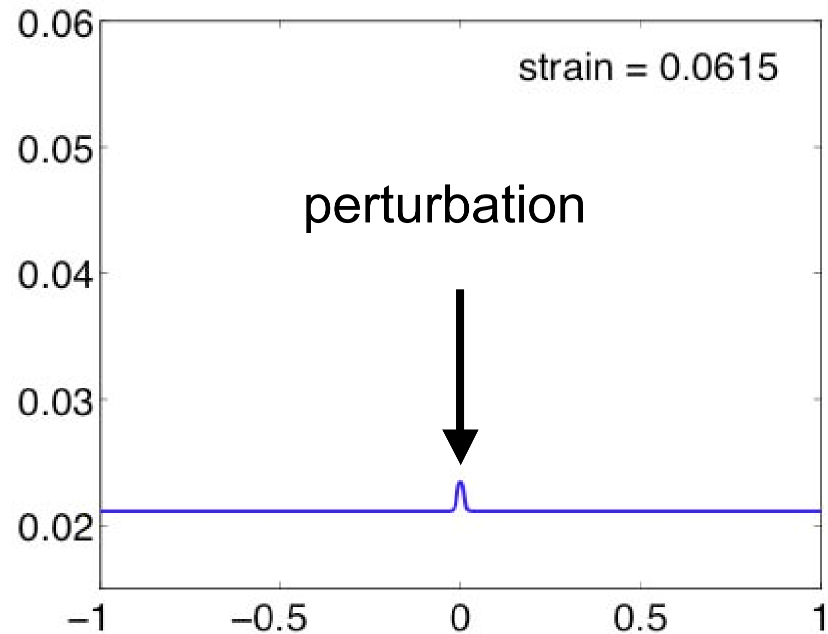
Shear a layer of gouge governed by STZ law.
How does effective temperature evolve?

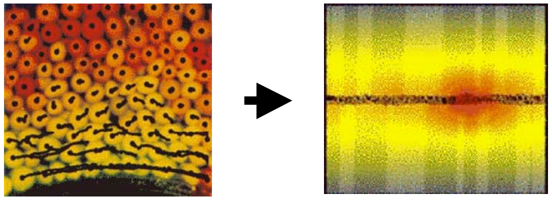
Initial Conditions

Homogeneous

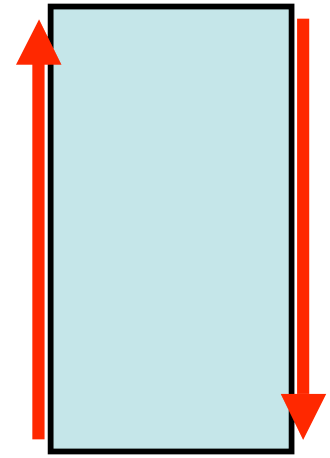
Homogeneous + small pert.







Friction Dynamics

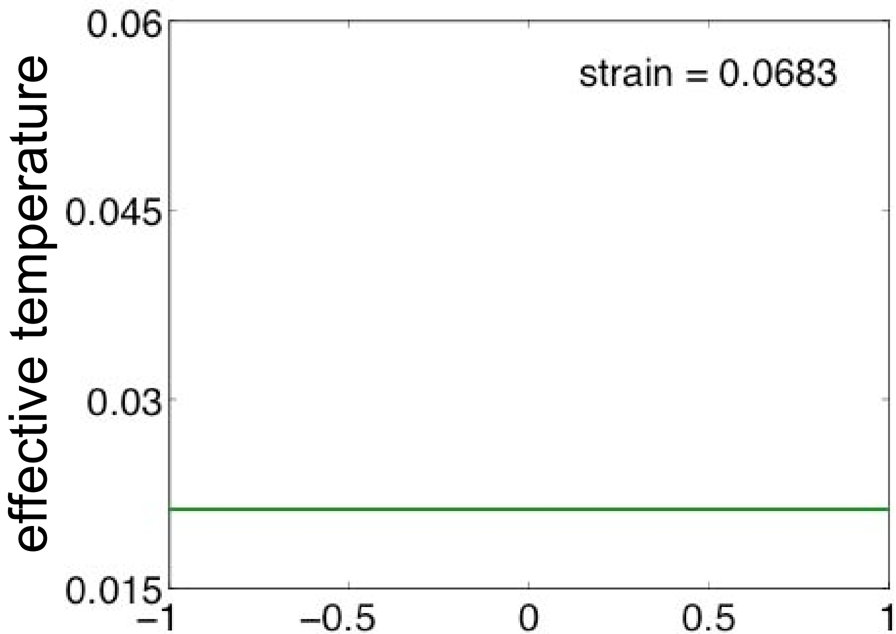


Shear a layer of gouge governed by STZ law.
How does effective temperature evolve?

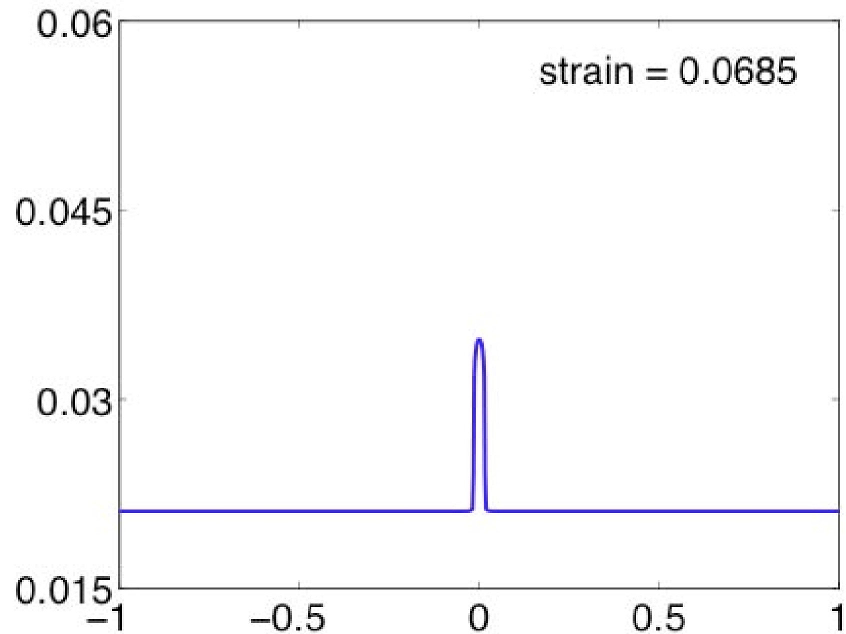
Initial Conditions

Homogeneous

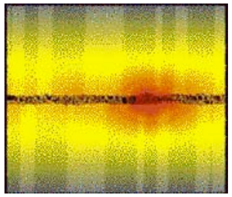
Homogeneous + small pert.



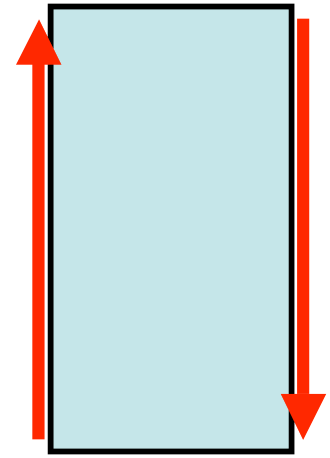
position within layer



position within layer



Friction Dynamics

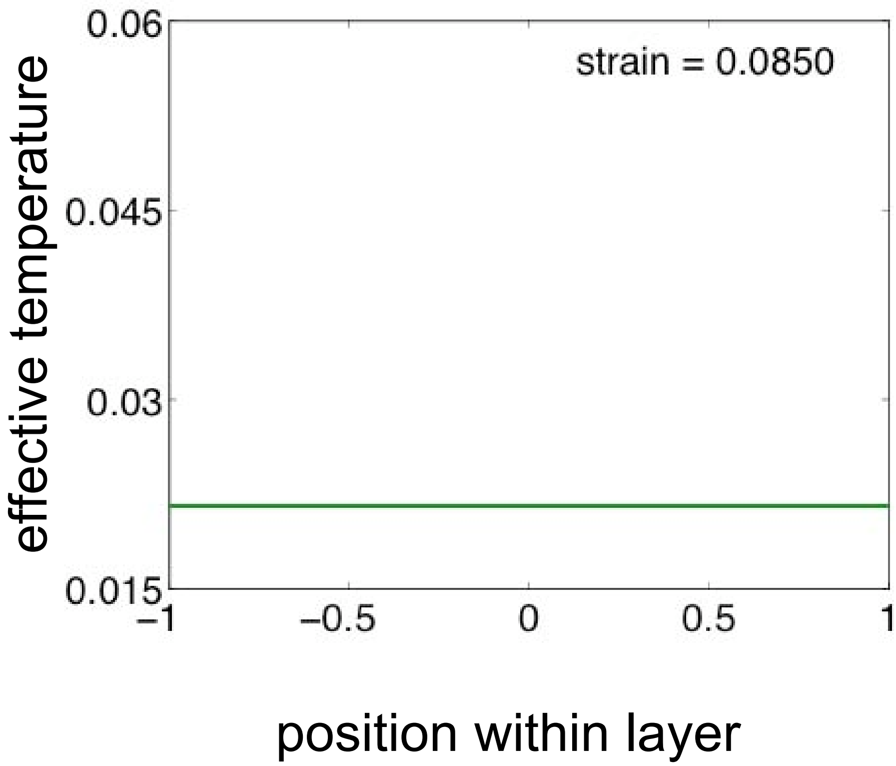


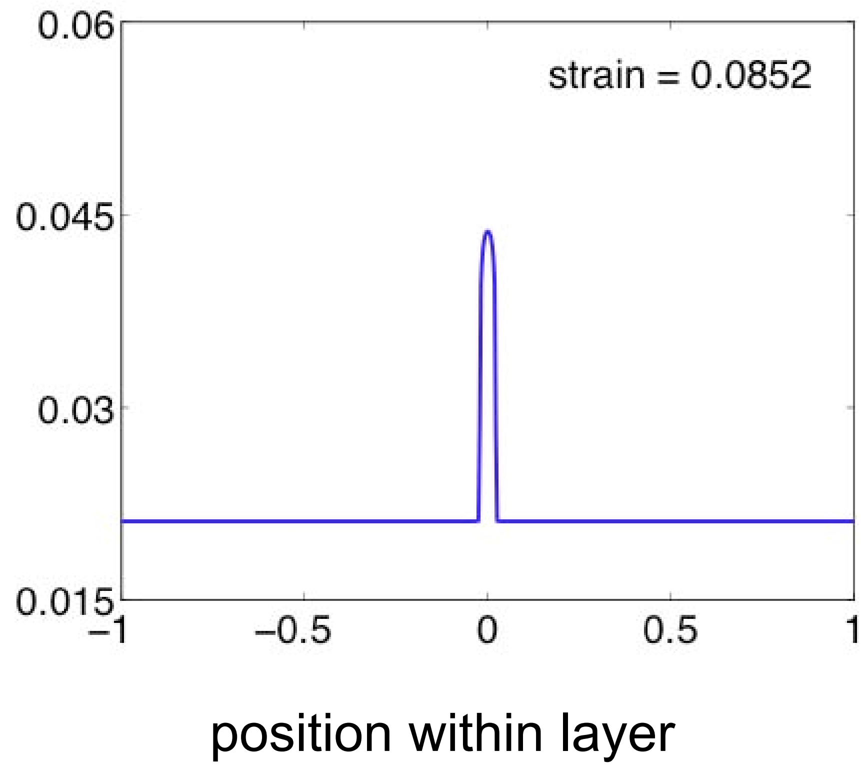
Shear a layer of gouge governed by STZ law.
How does effective temperature evolve?

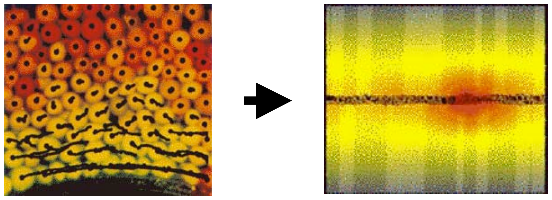
Initial Conditions

Homogeneous

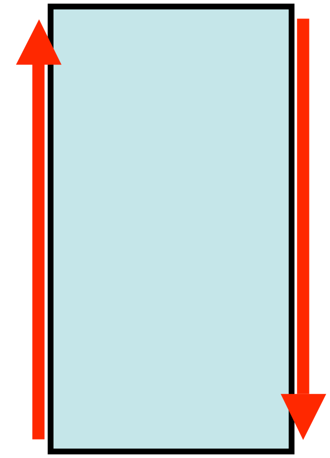
Homogeneous + small pert.







Friction Dynamics

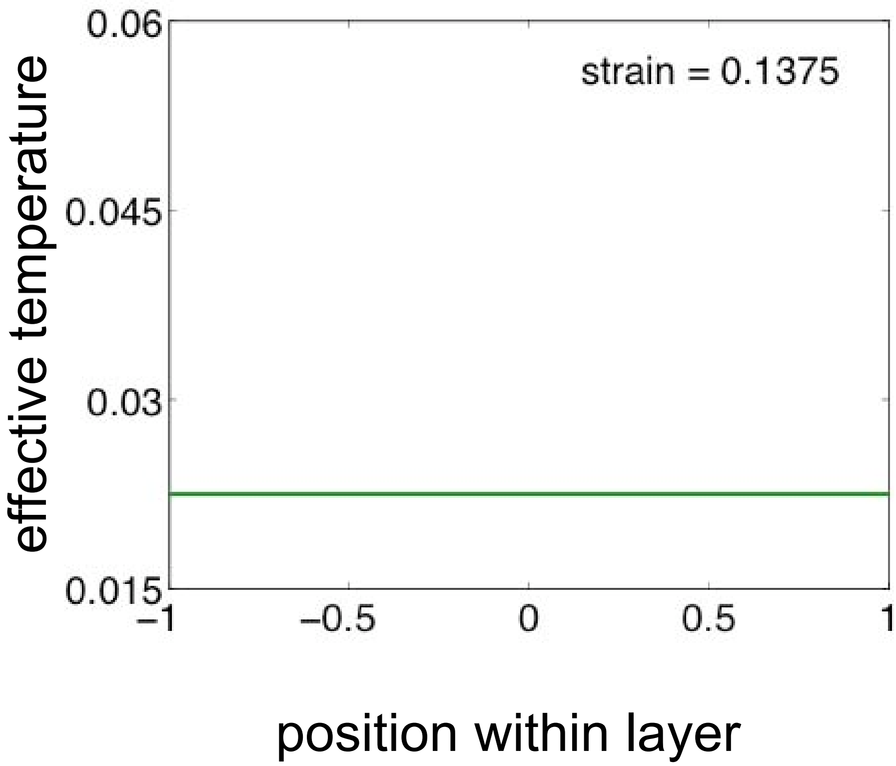


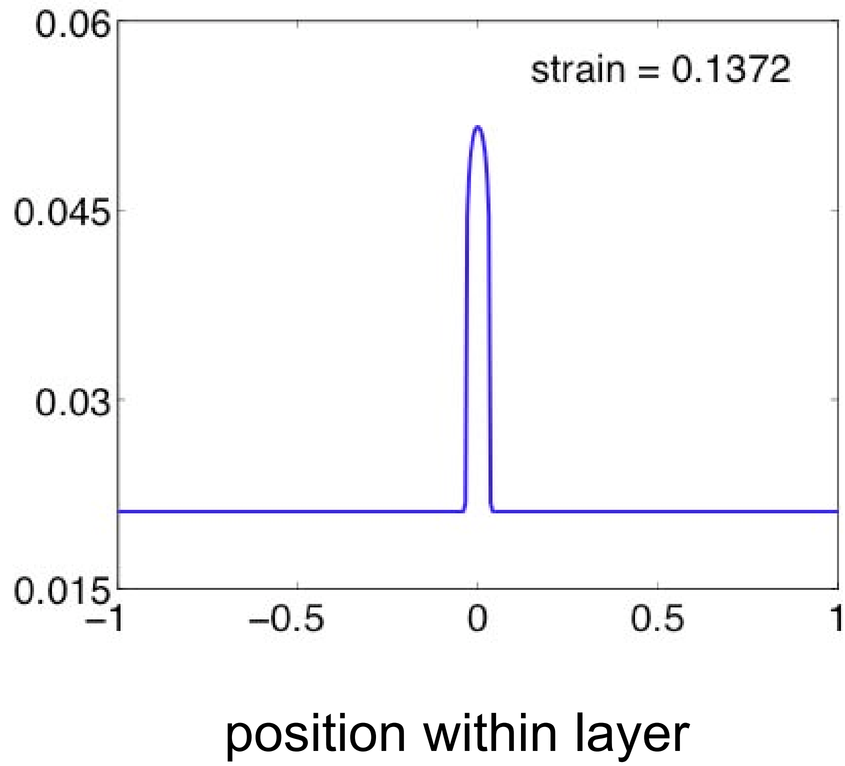
Shear a layer of gouge governed by STZ law.
How does effective temperature evolve?

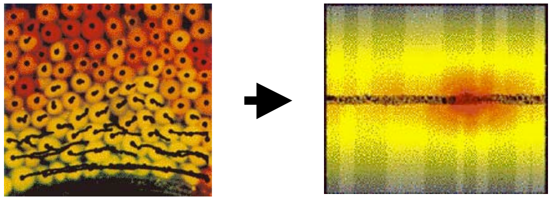
Initial Conditions

Homogeneous

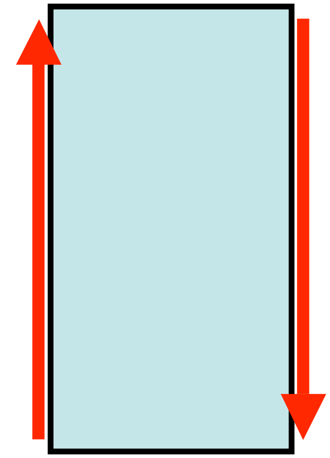
Homogeneous + small pert.







Friction Dynamics

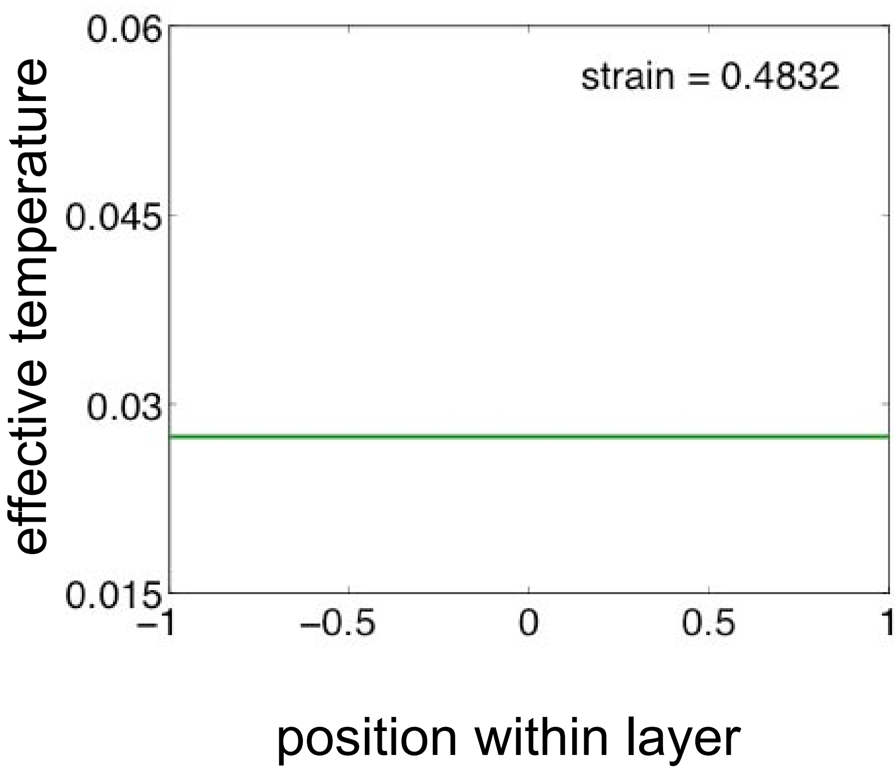


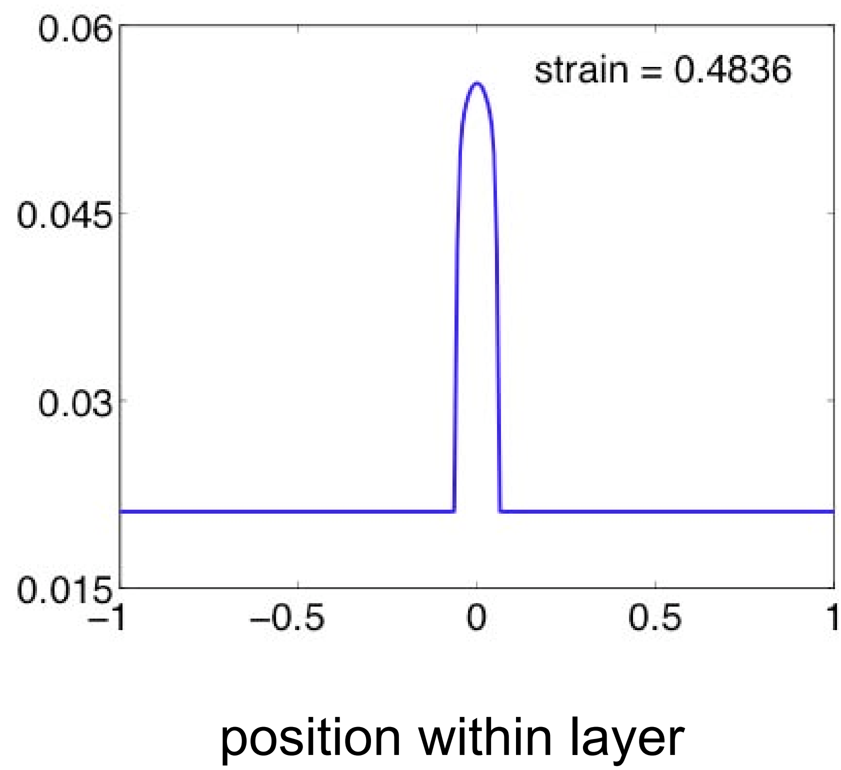
Shear a layer of gouge governed by STZ law.
How does effective temperature evolve?

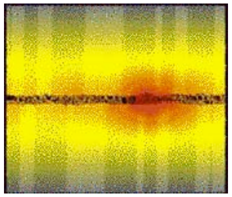
Initial Conditions

Homogeneous

Homogeneous + small pert.



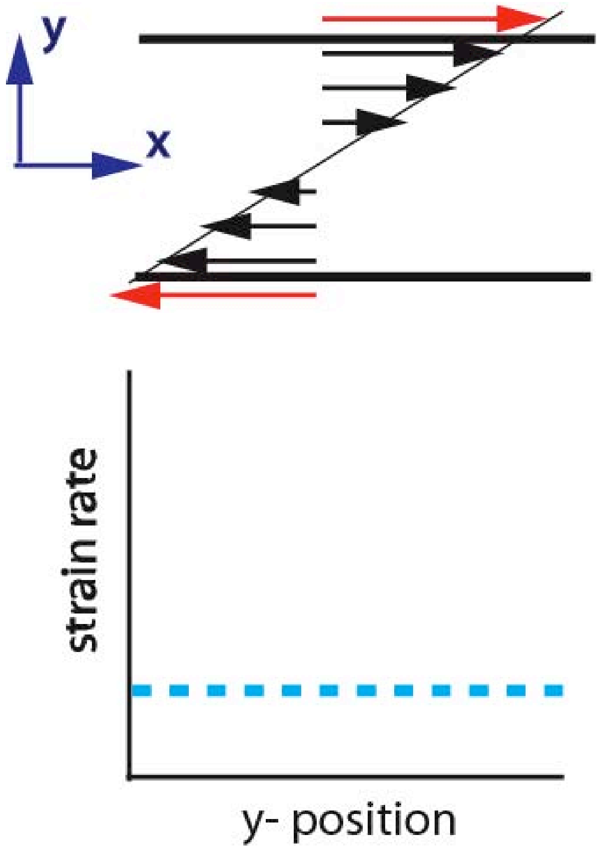




Localization in STZ Friction Law

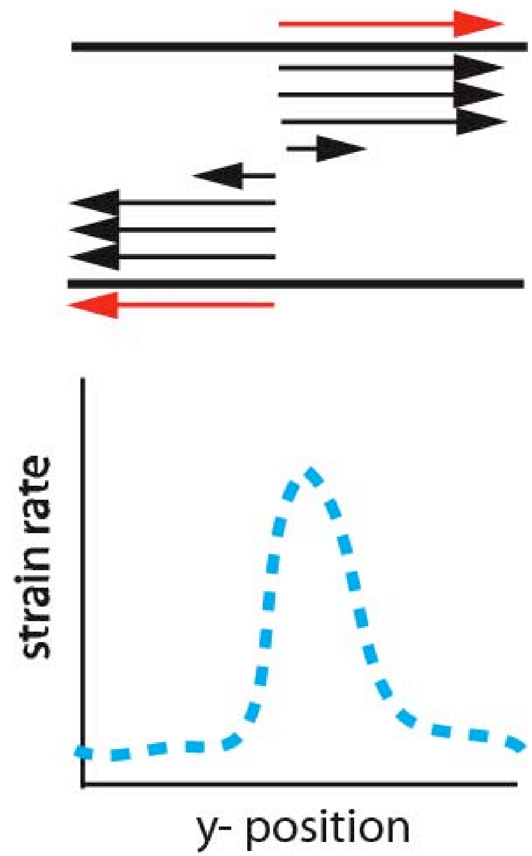
Homogeneous initial effective temperature (no perturbation)

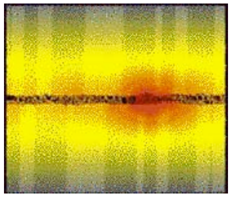
Homogeneous strain



Perturbation to homogeneous effective temperature

Localized strain

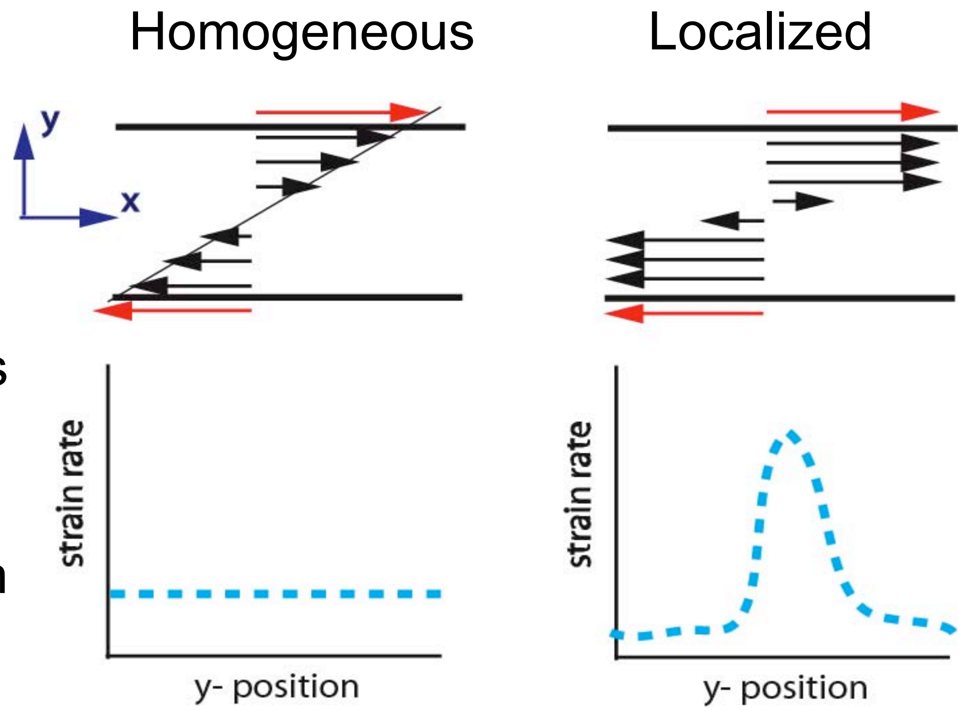




Localization in STZ Friction Law

Shear bands form spontaneously in STZ law. Feedback in effective temperature dynamics:

Larger Effective Temperature → More STZs → Higher Strain Rate → Increased Energy Dissipation → Larger Effective Temperature

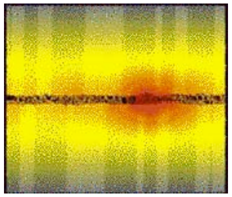


Linear Stability Analysis:

Rate Weakening → Steady sliding unstable, shear bands form

Rate Strengthening → Steady sliding stable, but shear bands can still form due to transient effects

(Manning, Daub, Langer, and Carlson, PRE, 2009)

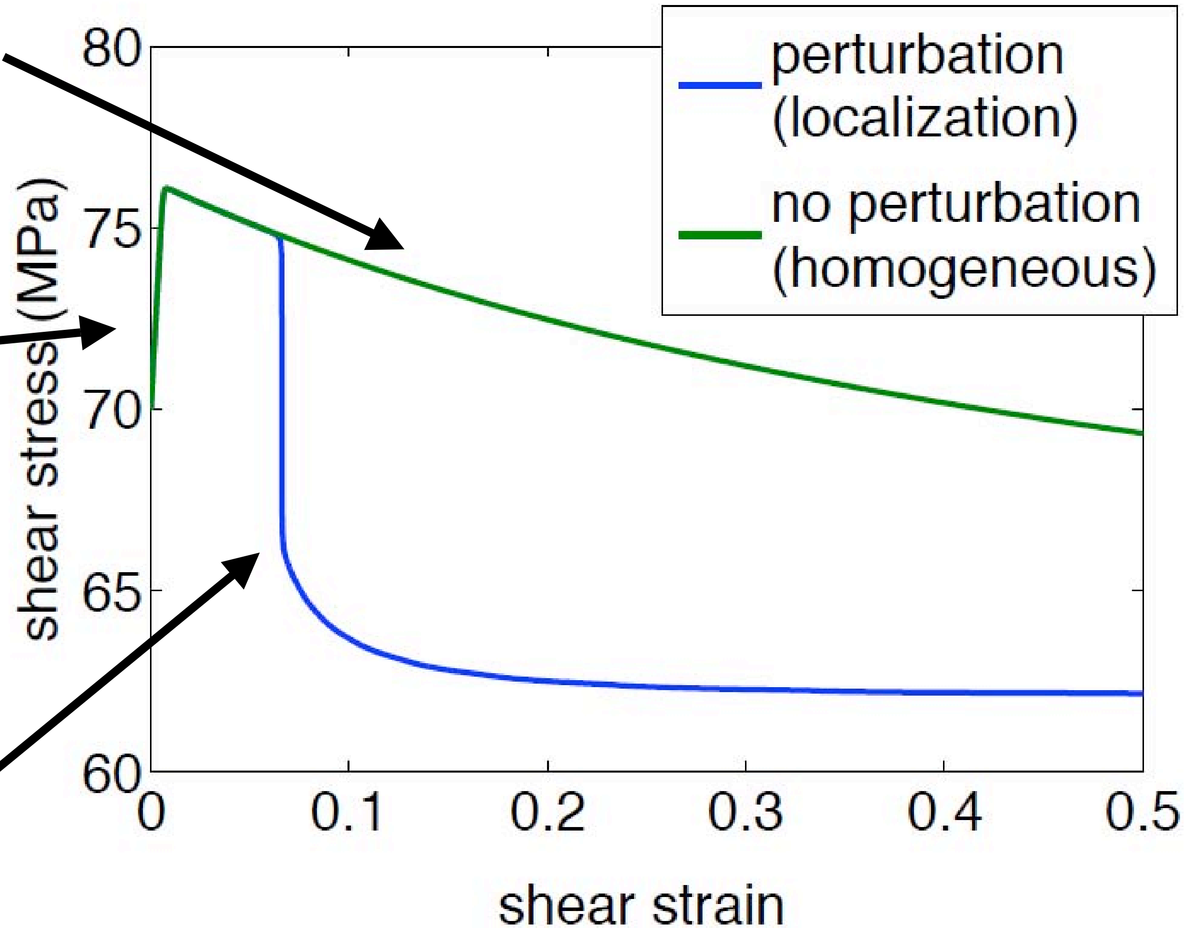


Stress-Strain Behavior

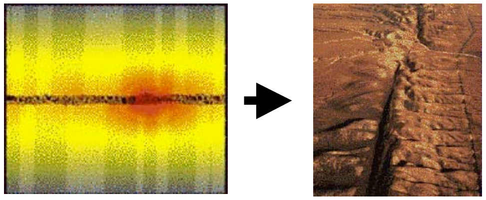
Homogeneous is very similar to DR friction

Brief elastic response (solid-like)

Shear band formation produces dynamic weakening

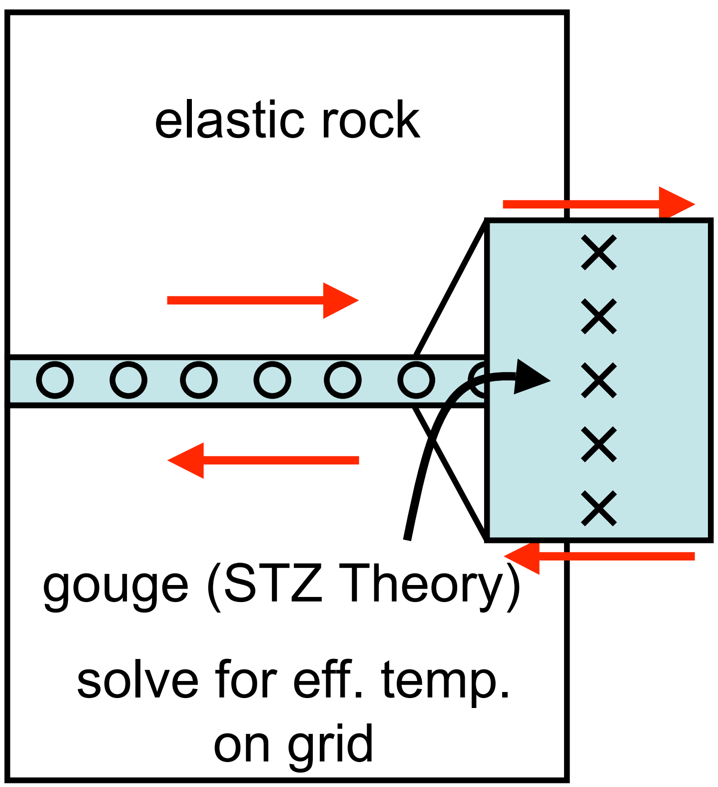


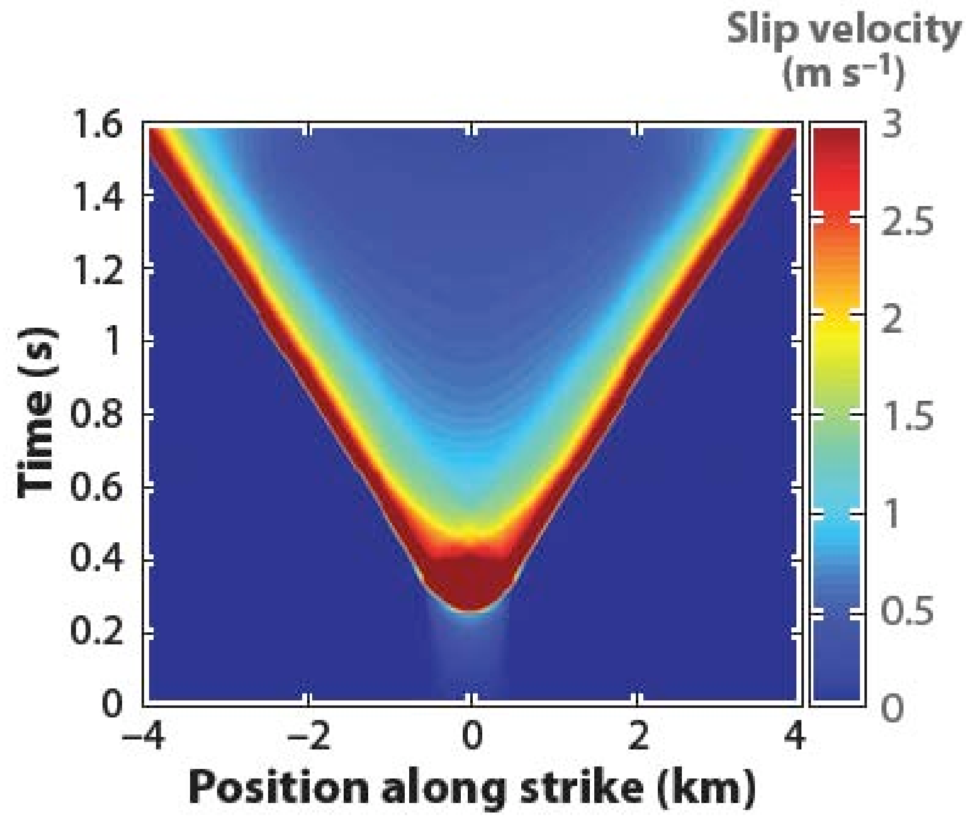
Can’t match all features of localization with a homogeneous (single state variable) law.



Dynamic Ruptures

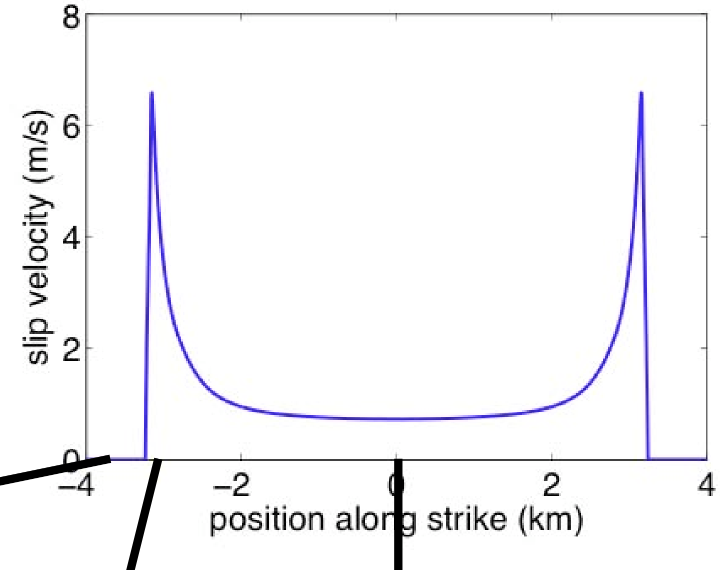
Implement STZ law into spontaneous elastodynamic rupture simulations. 2D ruptures (slip doesn't vary with depth), uniform initial shear stress and friction parameters (simple ruptures to make understanding the effects of localization easier).

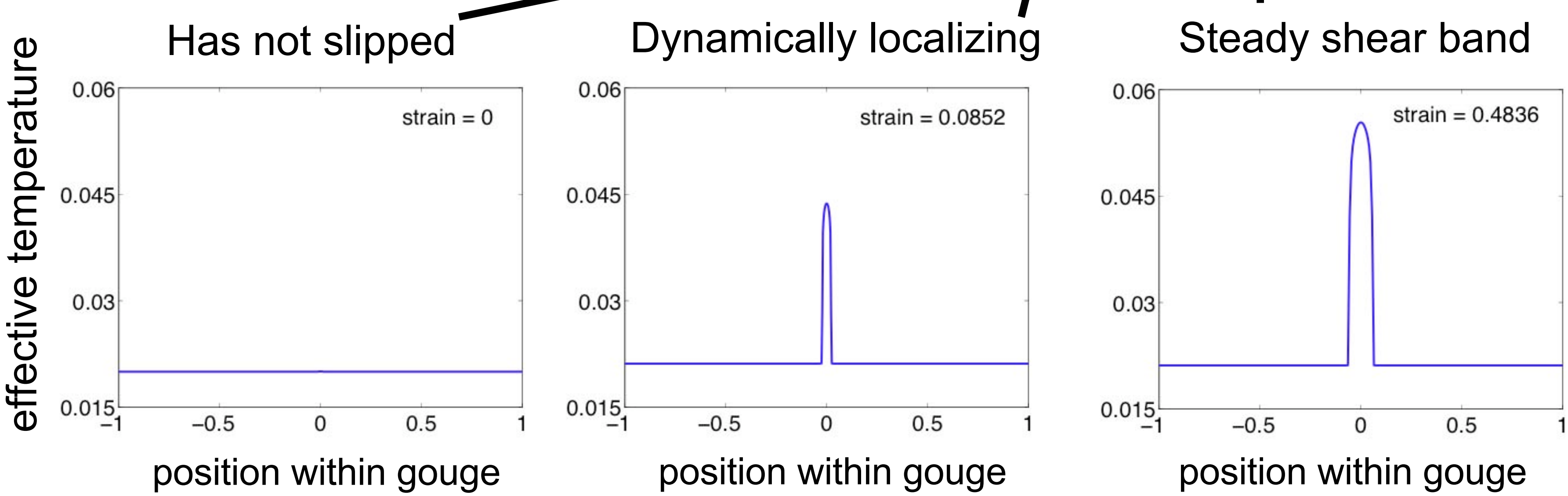




Localization in Dynamic Ruptures

At any given time, shear band is different at different points along strike, and is evolving due to slip on the fault.

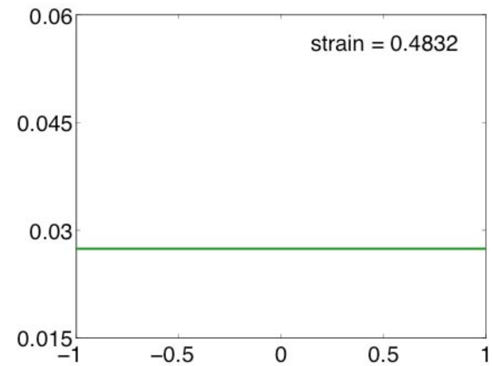




Localization in Dynamic Ruptures

Possible steady shear band profiles (after rupture front passes):

"Homogeneous" → No localization (homogeneous initial conditions) →

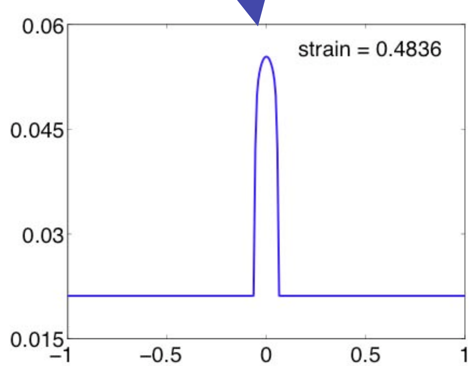


position within gouge

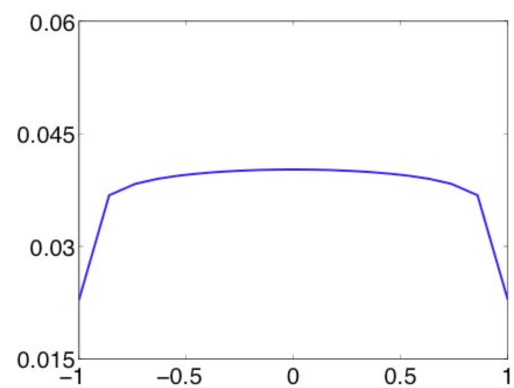
"Localized" → Effective temperature dynamics dictate strain localization

Large diffusion length scale ("Broad Shear Band")

Small diffusion length scale ("Narrow Shear Band")



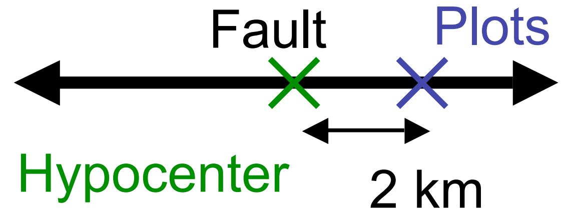
position within gouge

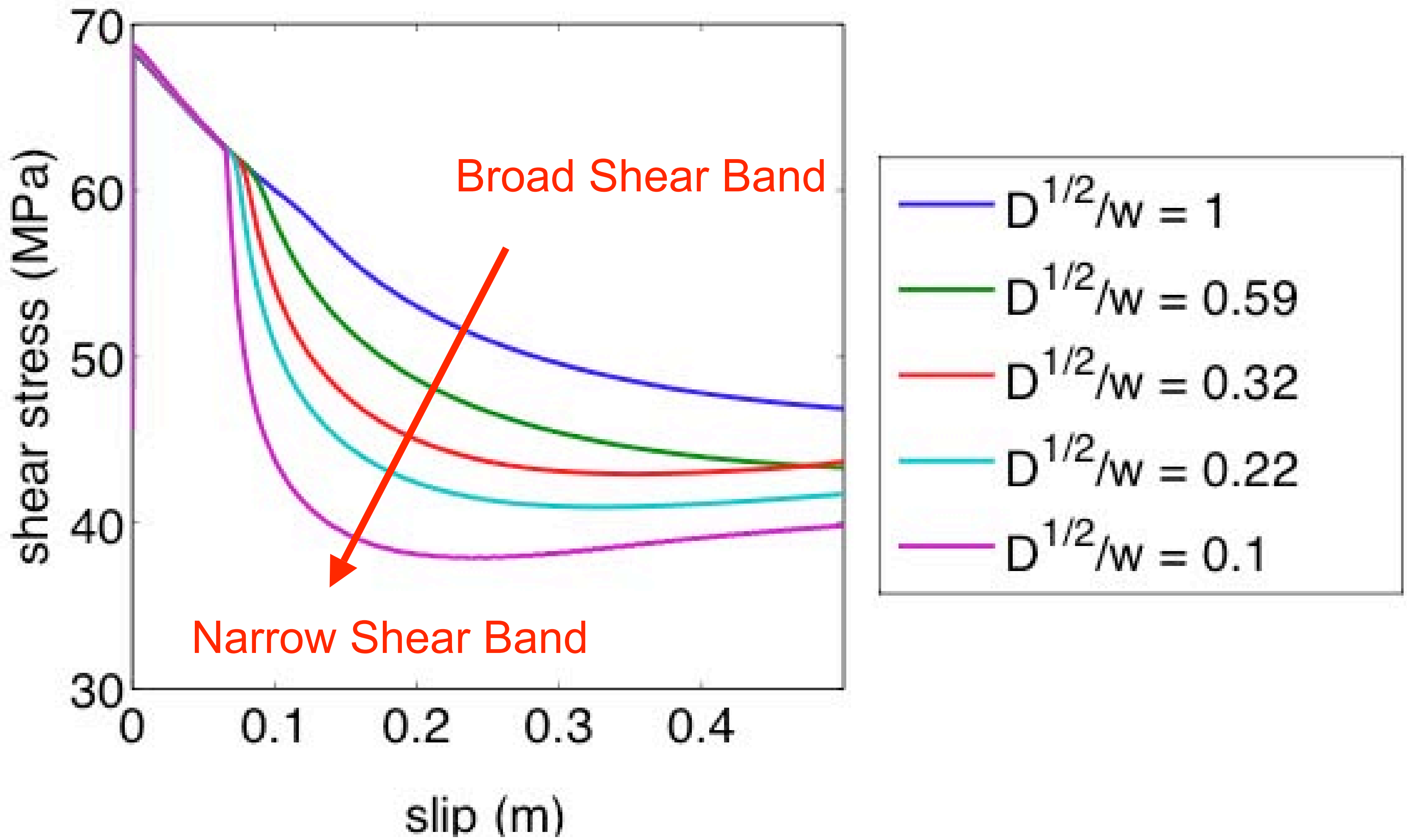


position within gouge

Localization = Dynamic Weakening

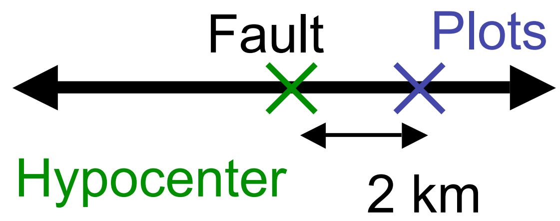
Shear stress drops rapidly due to formation of shear band. Narrower = weaker. Larger stress drop, less frictional dissipation.

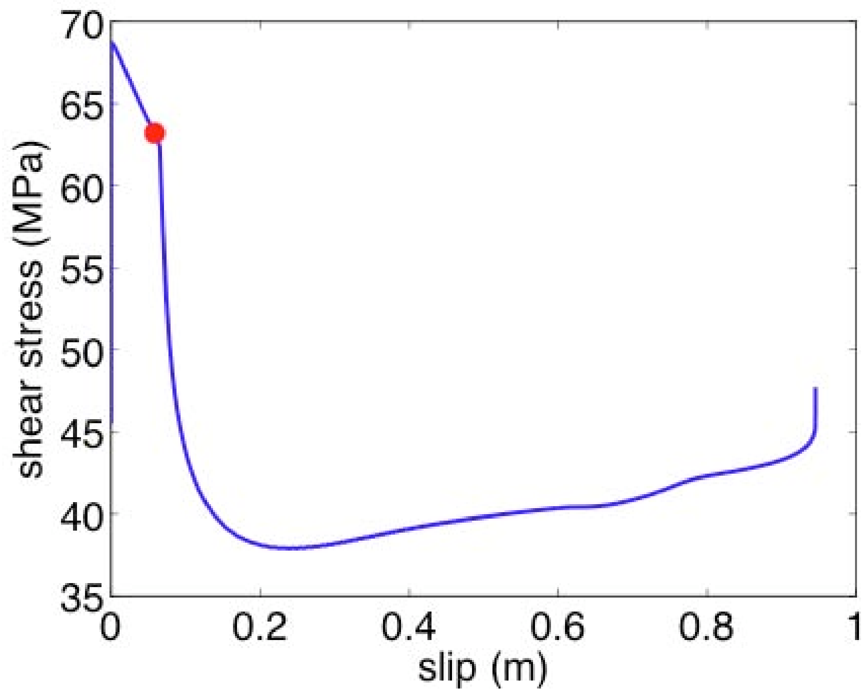


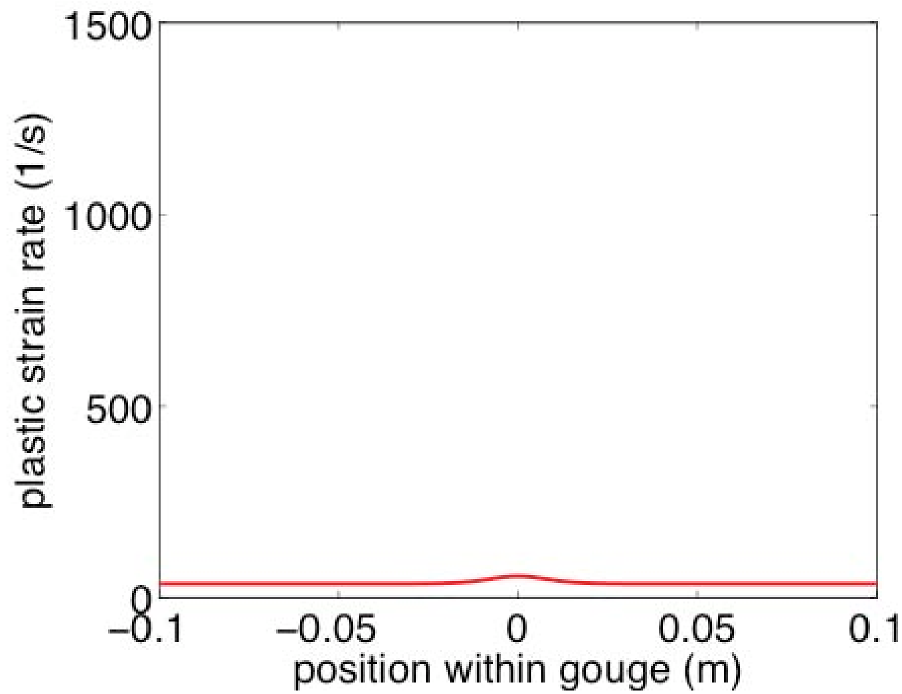


Dynamics of Localization

Plot snapshots of plastic strain rate during shear band formation at a point on the fault



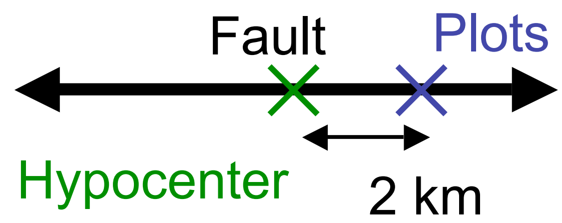


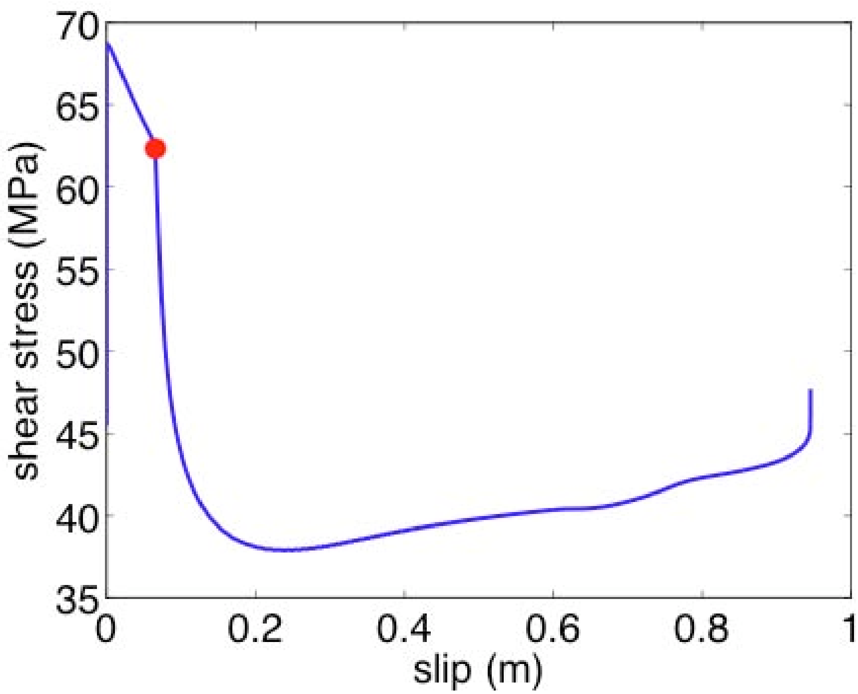


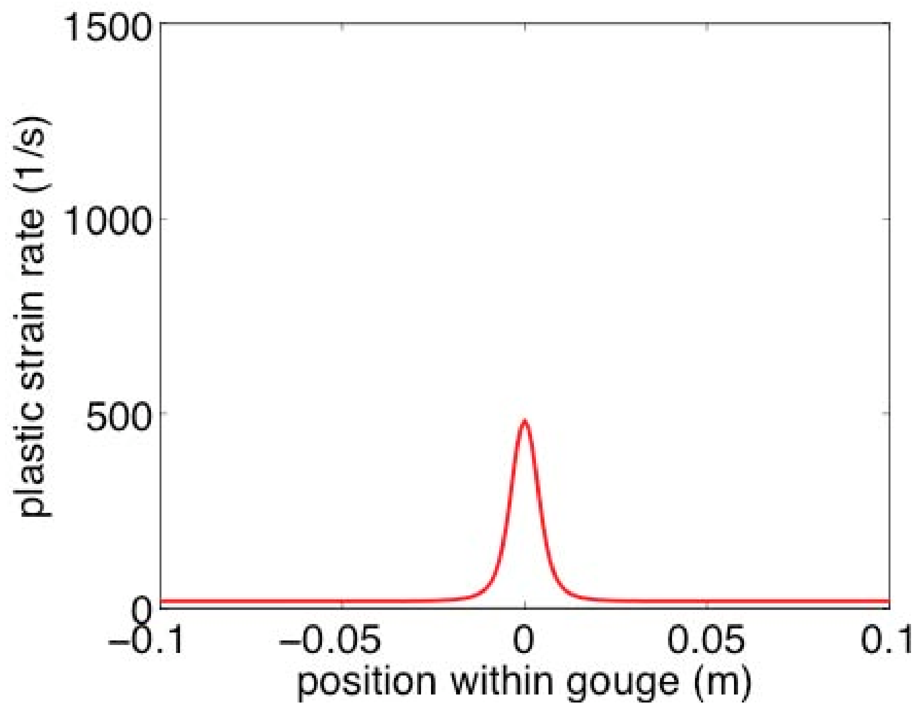
Peak strain rate (and slip rate) is largest when shear band first forms and stress is dropping most rapidly

Dynamics of Localization

Plot snapshots of plastic strain rate during shear band formation at a point on the fault



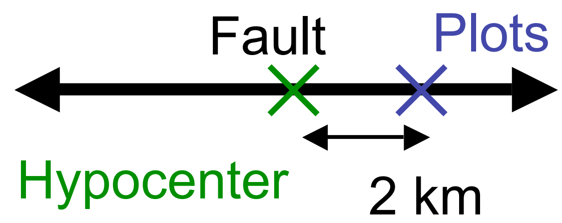


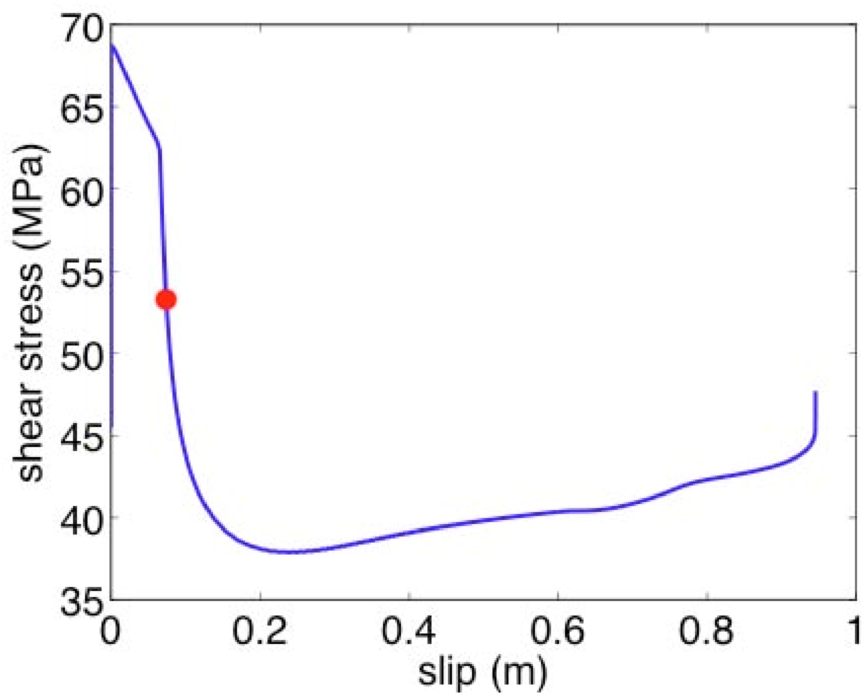


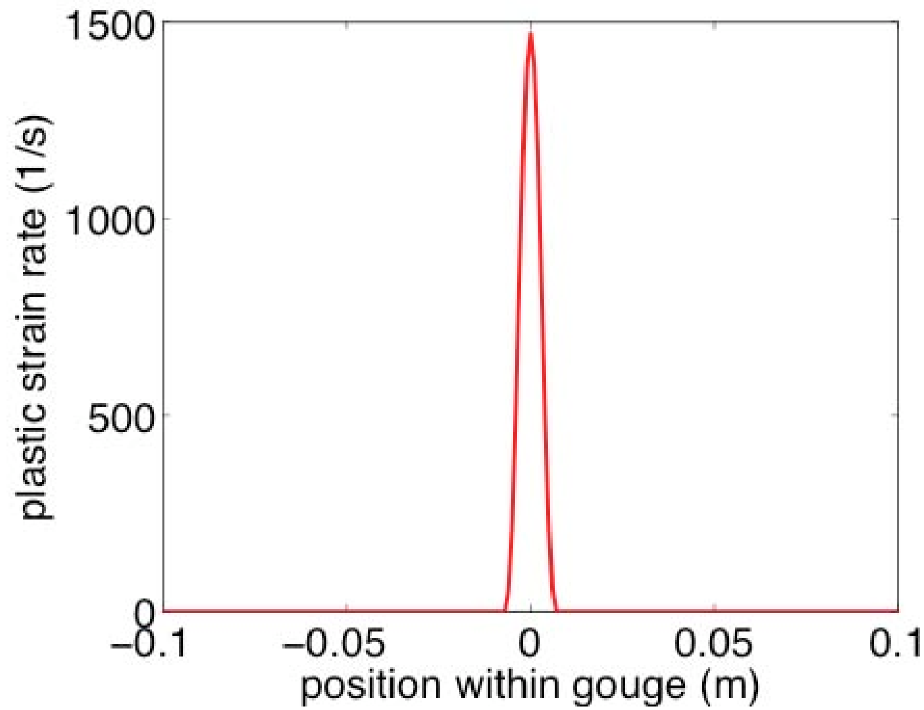
Peak strain rate (and slip rate) is largest when shear band first forms and stress is dropping most rapidly

Dynamics of Localization

Plot snapshots of plastic strain rate during shear band formation at a point on the fault



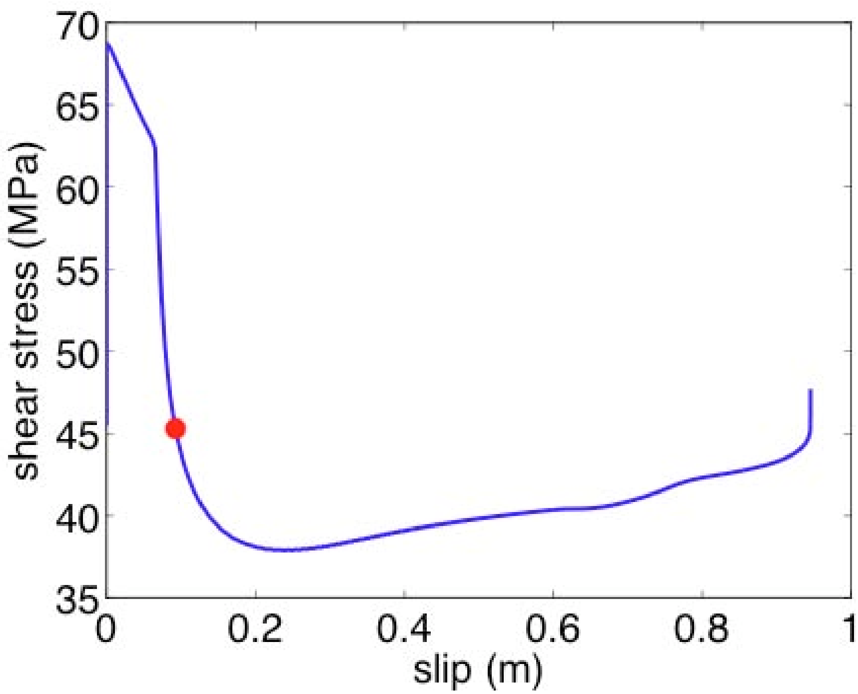


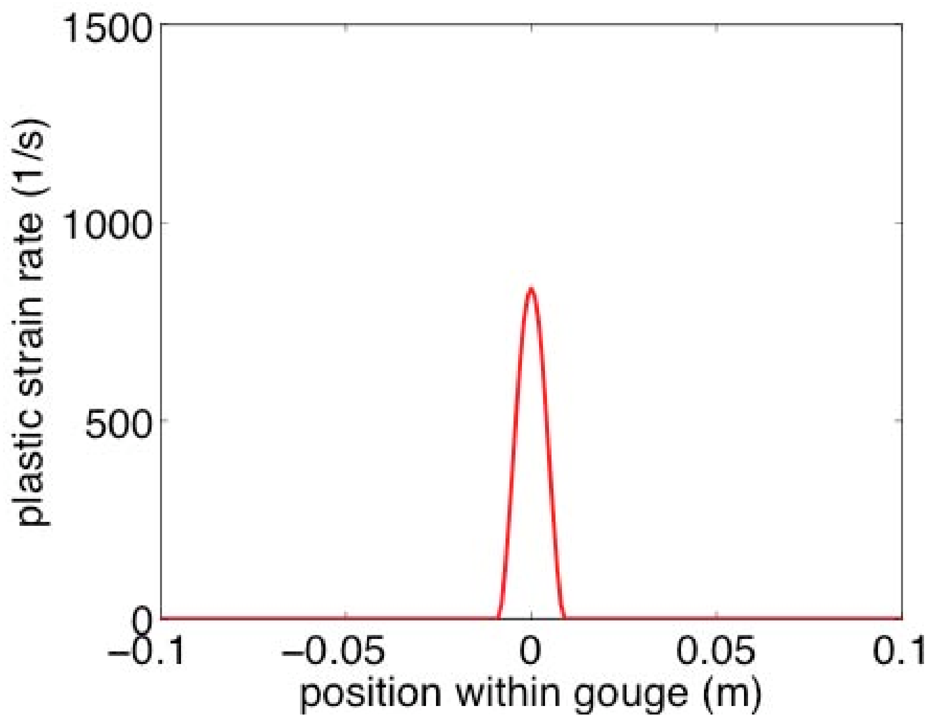


Peak strain rate (and slip rate) is largest when shear band first forms and stress is dropping most rapidly

Dynamics of Localization

Plot snapshots of plastic strain rate during shear band formation at a point on the fault

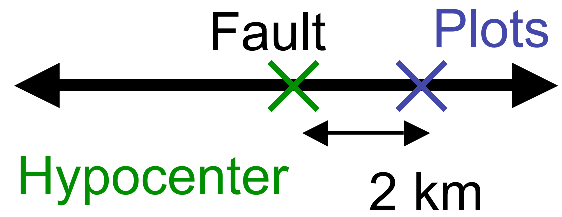


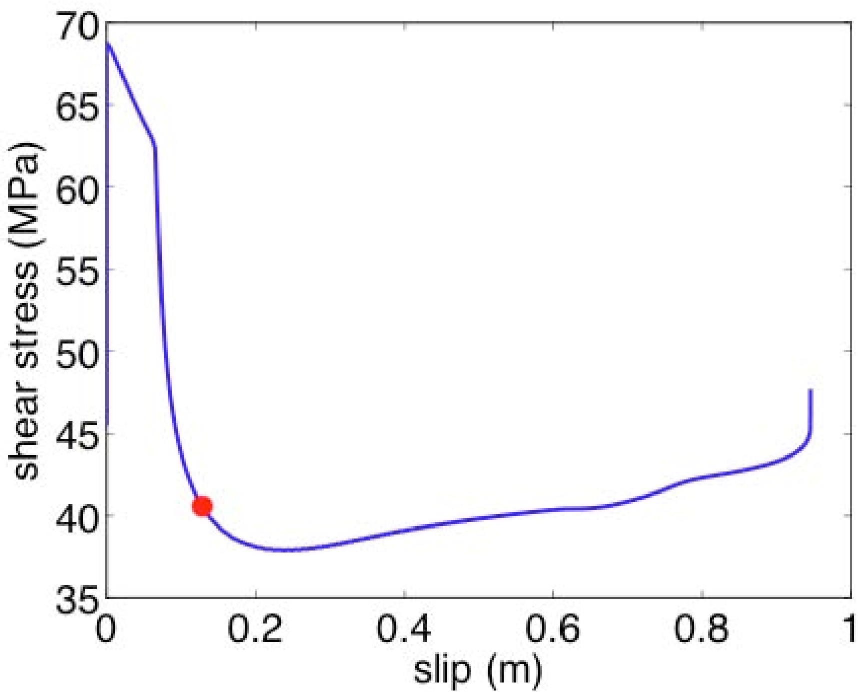


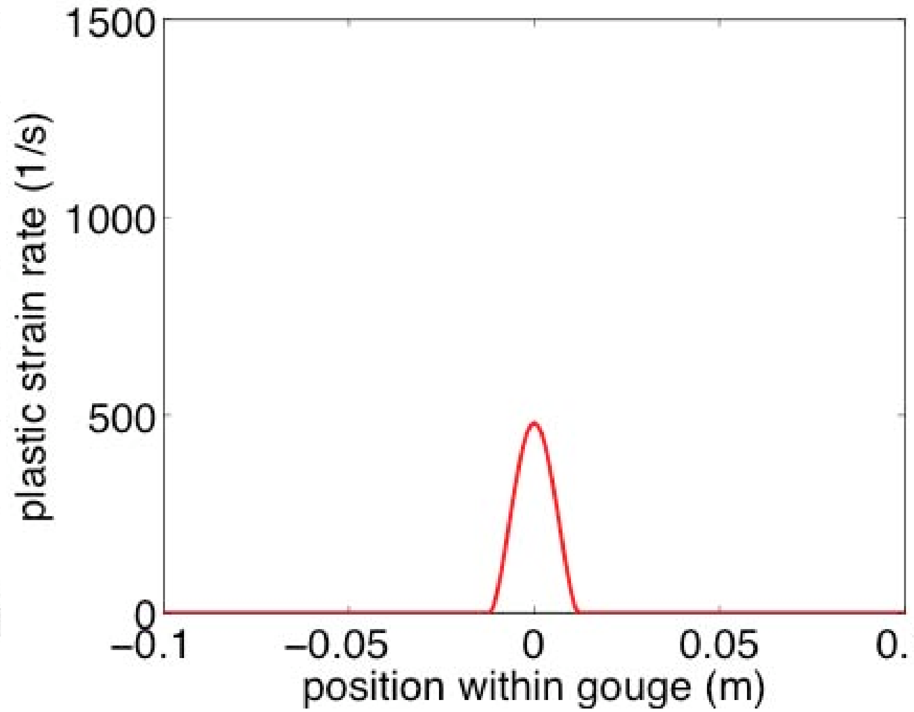
Peak strain rate (and slip rate) is largest when shear band first forms and stress is dropping most rapidly

Dynamics of Localization

Plot snapshots of plastic strain rate during shear band formation at a point on the fault

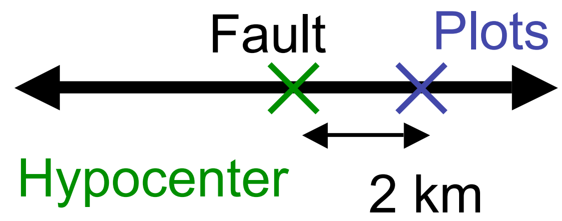




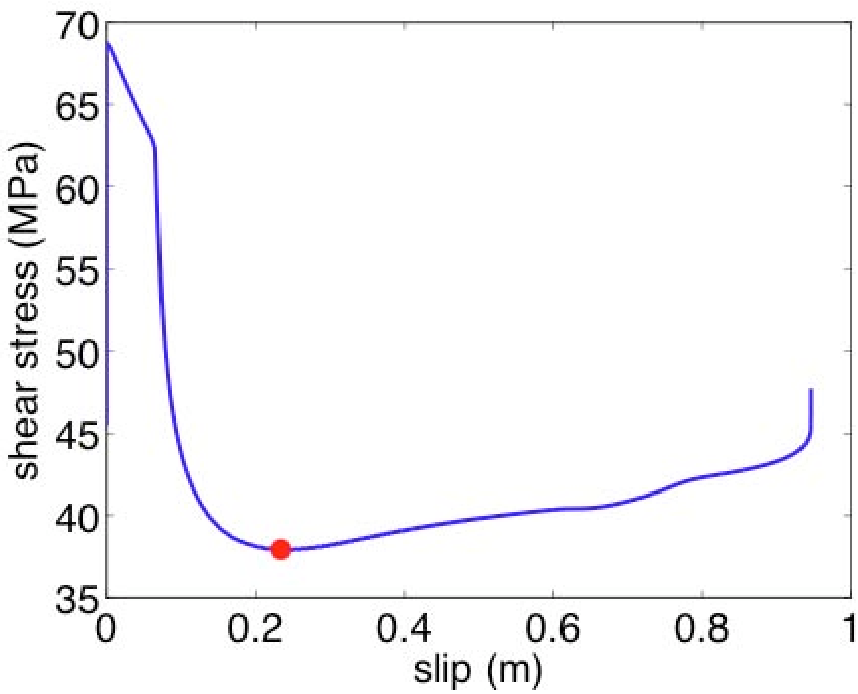


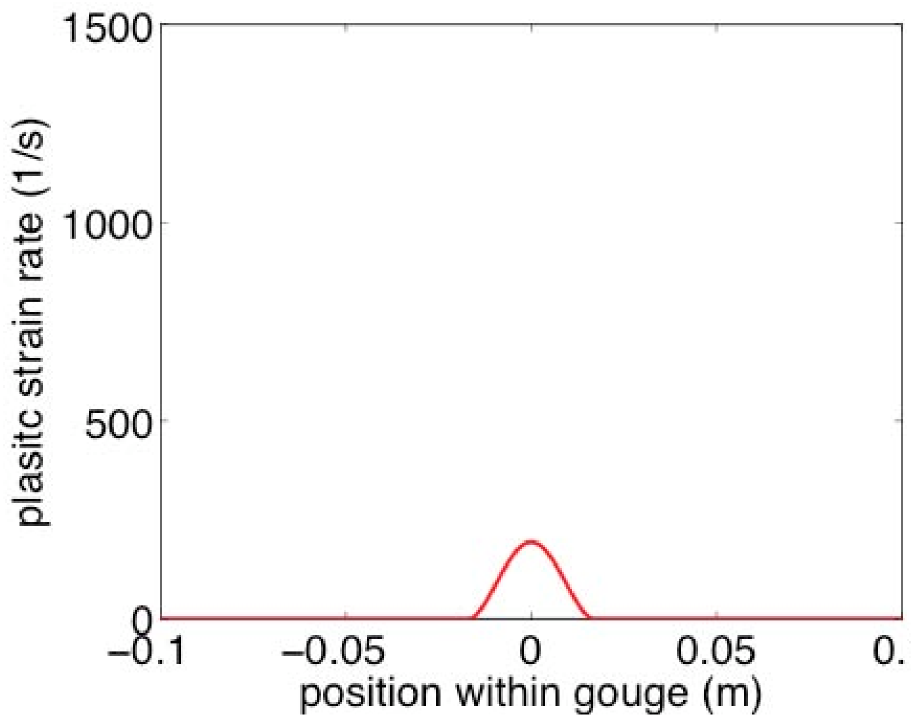
Peak strain rate (and slip rate) is largest when shear band first forms and stress is dropping most rapidly

Dynamics of Localization



Plot snapshots of plastic strain rate during shear band formation at a point on the fault





Peak strain rate (and slip rate) is largest when shear band first forms and stress is dropping most rapidly

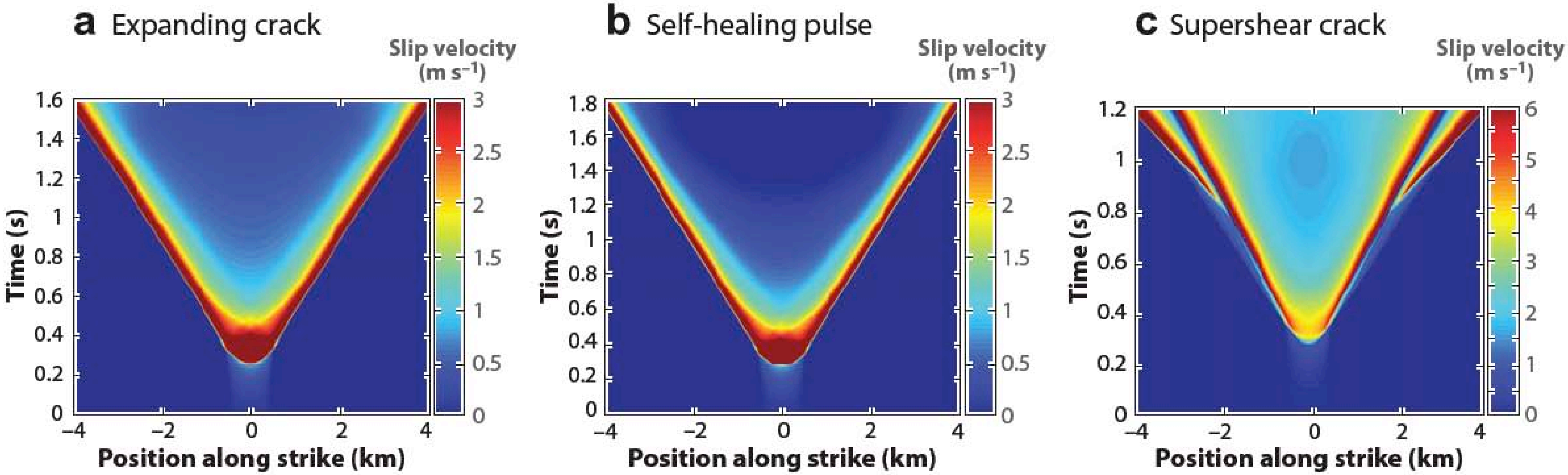
Spatio-temporal Rupture Propagation

What are the different ways that slip can propagate on a fault?

Slips during the entire duration of the rupture

Slips and then heals shortly afterwards

Rupture velocity faster than the shear wave speed

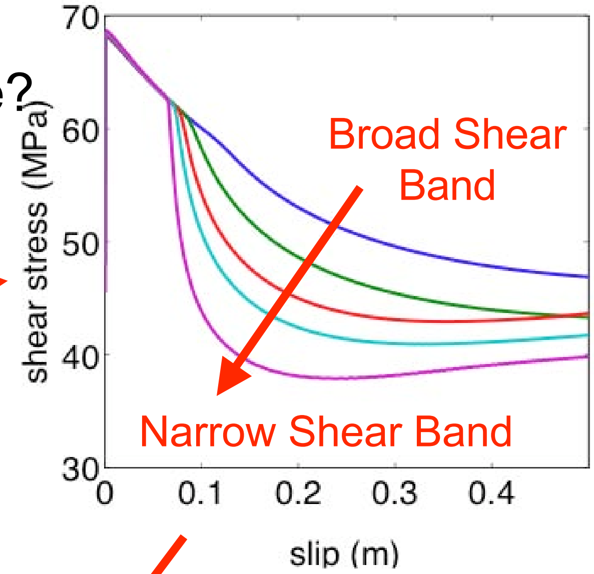


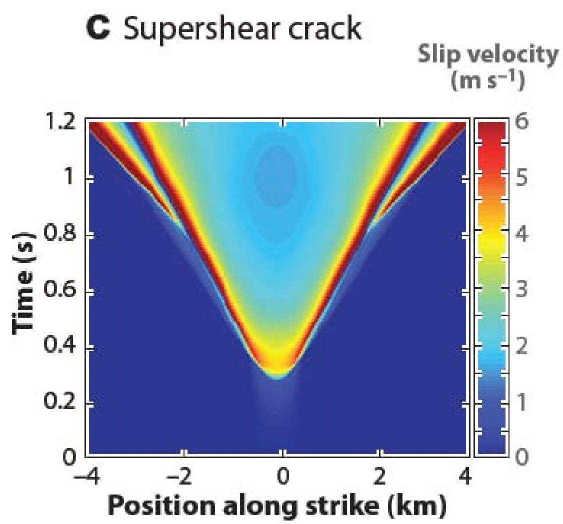
How does strain localization affect how ruptures propagate in space and time?

Effect of Localization

Why does localization affect fault scale rupture?

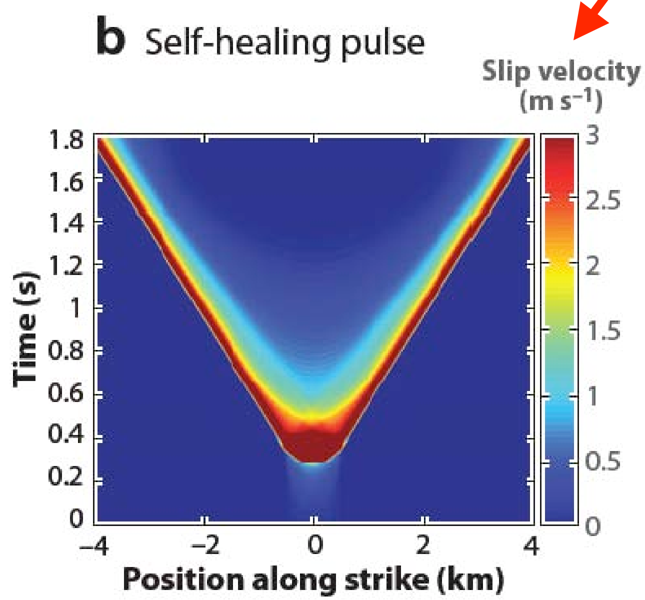
Localization is a mechanism for dynamic weakening





Supershear rupture triggered by seismic waves.

Dynamic weakening increases seismic radiation

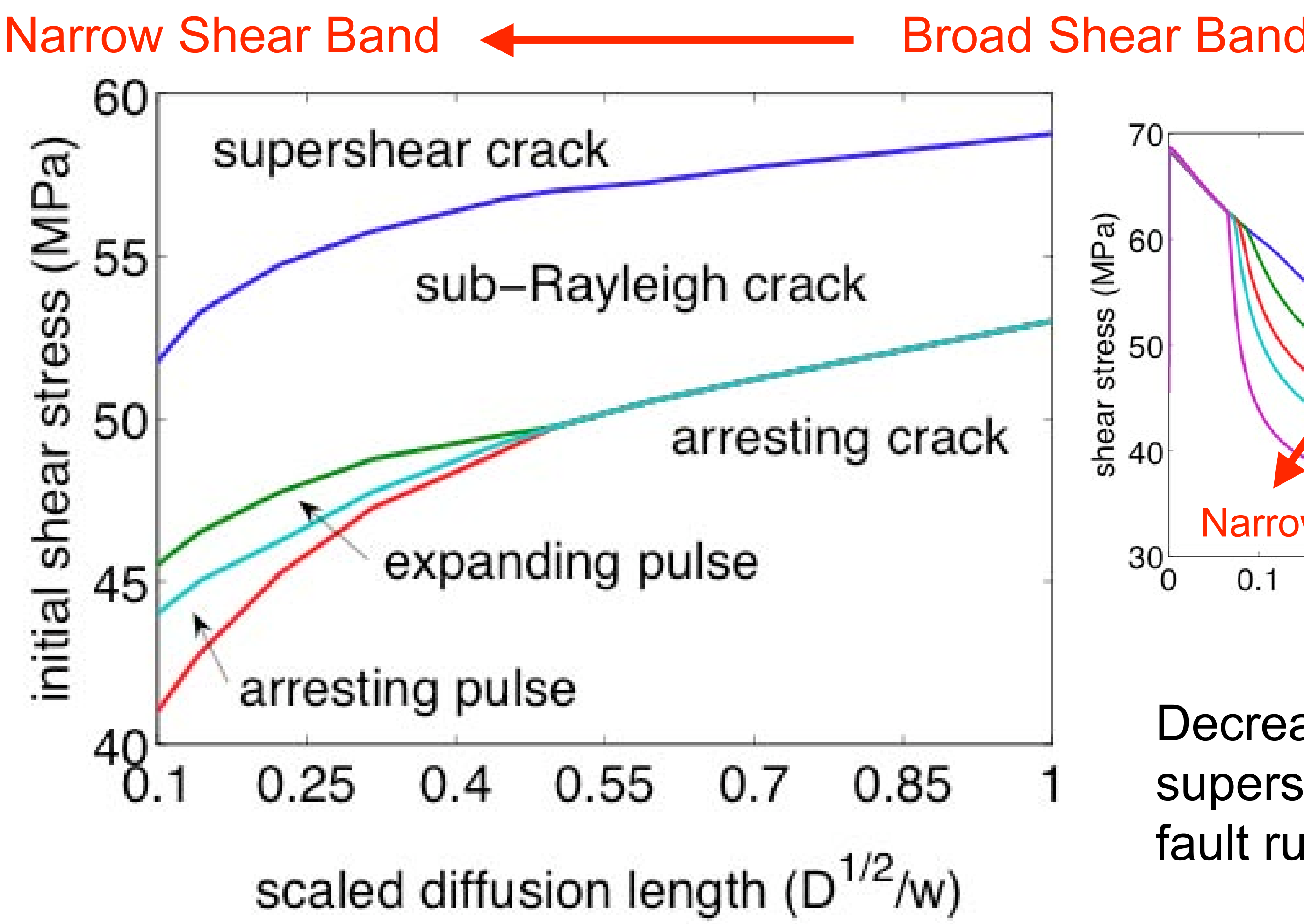


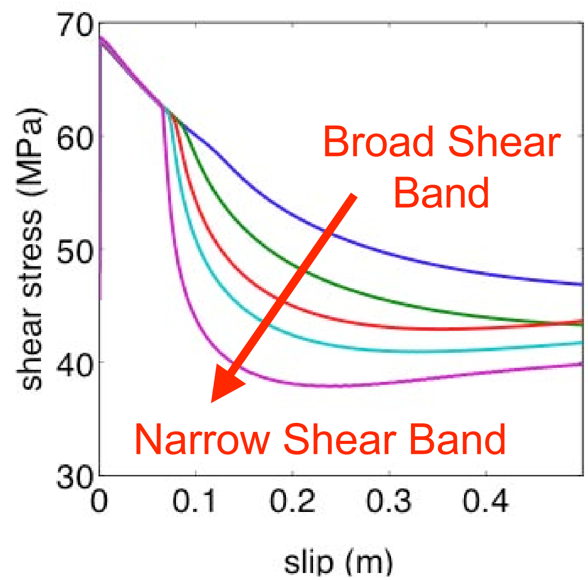
Pulse-like rupture due to increased frictional weakening.

Localization provides this weakening.

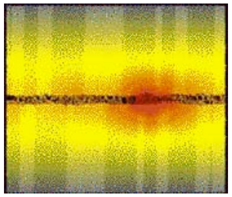
Dynamic Ruptures

Vary initial stress and shear band width (diffusion length scale) to generate a rupture characterization diagram.



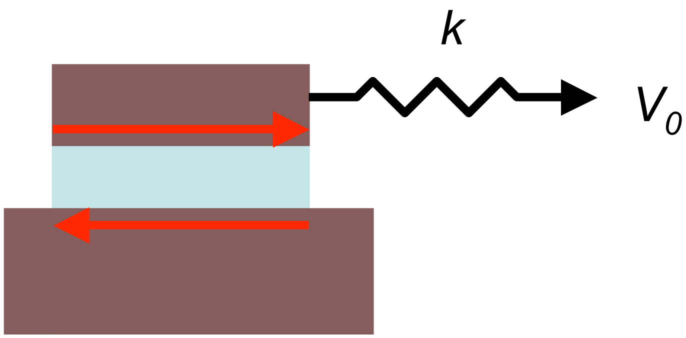


Decreases stress for supershear and full-fault rupture



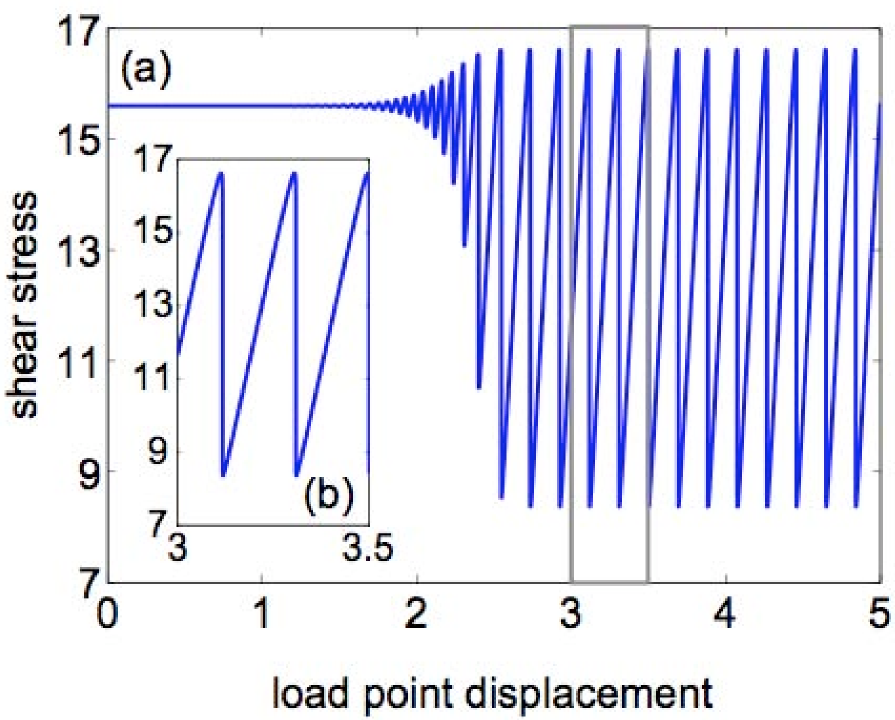
Other Applications

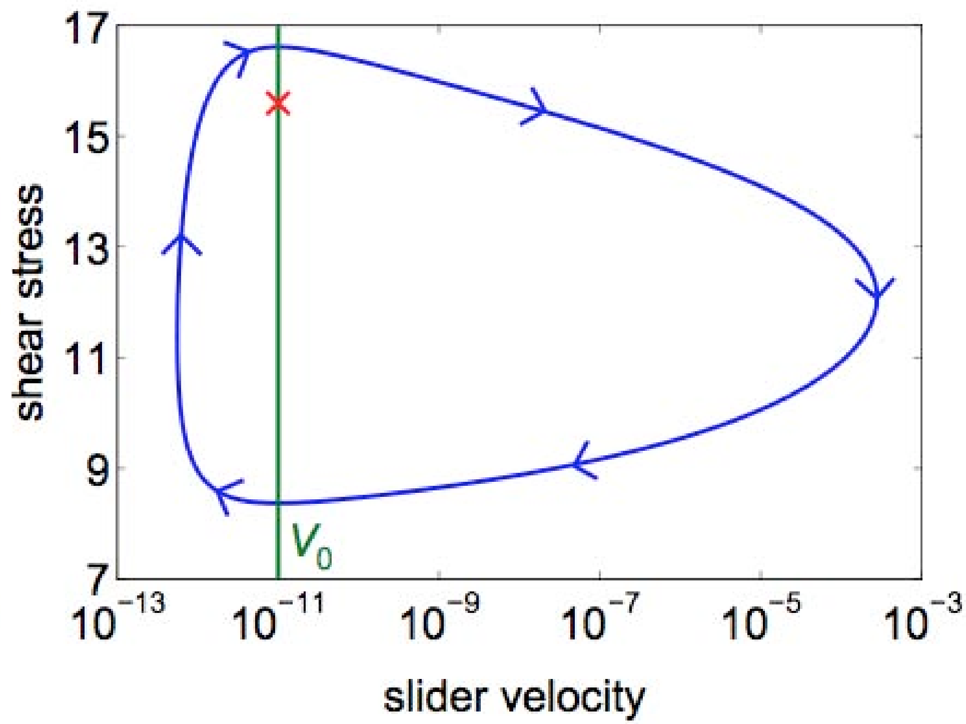
How do small scale physics affect the stability of frictional sliding?



Localization has a significant impact on macroscopic friction dynamics -- connects microscopic scale to large scale friction

(Daub and Carlson, PRE, 2009)



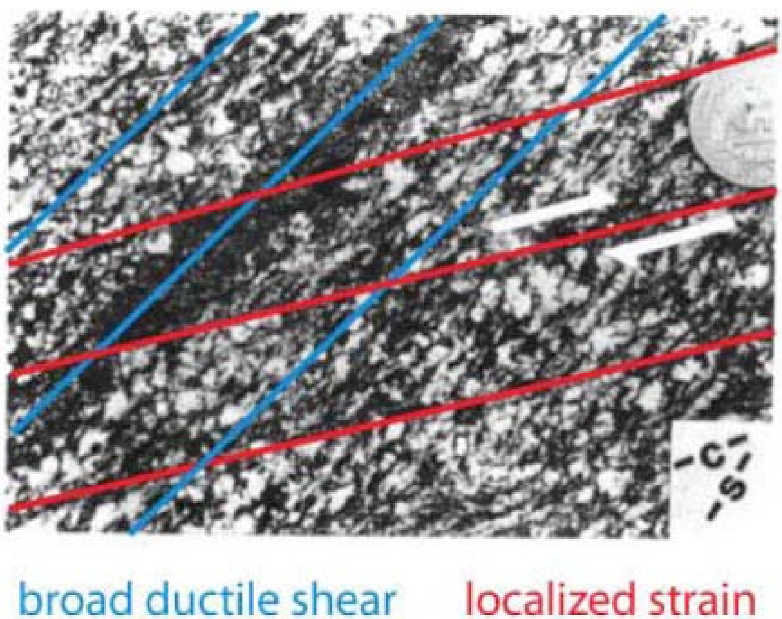


Other Applications

Shear bands form spontaneously in STZ friction model, and provide a mechansim for dynamic weakening. Other implications for earthquakes?

• Shear bands can form for rate strengthening materials when driven from steady state due to a transient instability

Field Observations (Simpson, 1984)



Snapshots of plastic strain rate at 15.75 km depth (rate strengthening)