Discrete Element Simulations of Granular Shear Zones

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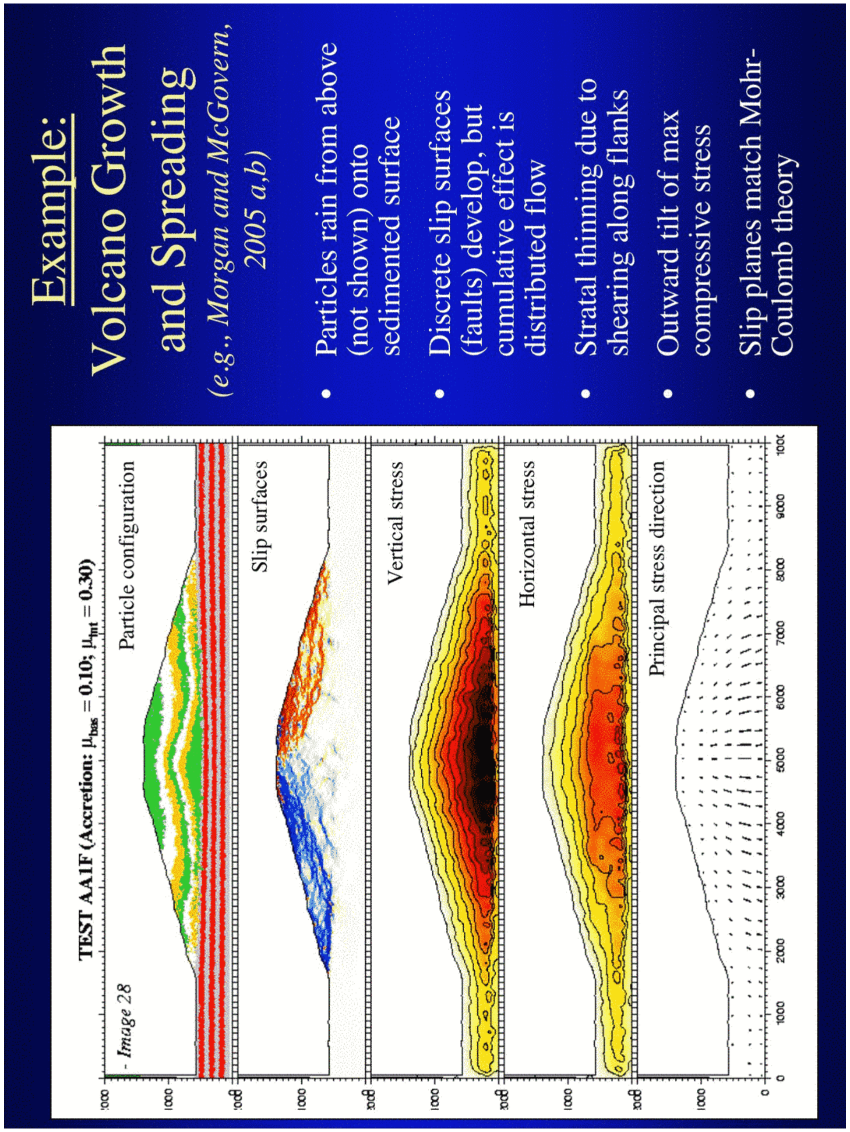
Granular Materials & Fault Zones

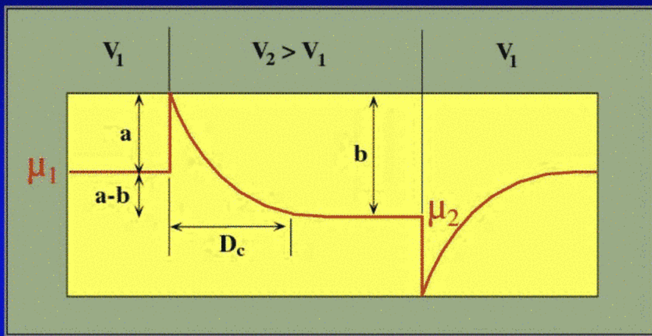
- Granular materials can exhibit distributed or localized deformation
- Persistent localizations are necessary for unstable, seismogenic sliding - under what conditions does this occur?
- And what happens within semi-localized granular gouge, i.e., rock fragments derived from the fault blocks?
- The intergranular contacts are probably subject to healing and weakening processes as in discrete rock surfaces.
- But in aggregate, granular materials show coordinated behavior that can affect the localization tendency.


Example:
Volcano Growth and Spreading
(e.g., Morgan and McGovern, 2005 a,b)
Particles rain from above (not shown) onto sedimented surface
Discrete slip surfaces (faults) develop, but cumulative effect is distributed flow
Stratal thinning due to shearing along flanks
Outward tilt of max compressive stress
Slip planes match Mohr-Coulomb theory
TEST AA1F (Accretion: μbas = 0.10; μint = 0.30)
Image 28
Particle configuration
Slip surfaces
Vertical stress
Horizontal stress
Principal stress direction


Frictional Sliding - Planar Surface
Lab experiments, on many different materials show: frictional strength varies with sliding velocity
Rate- & State-Dependent Friction
Stability depends on relative change in friction with velocity
– a: Direct effect
– b: Evolutionary effect
(Dieterich and Kilgore, 1994)

Rate- & State-Dependent Friction

(e.g., Dieterich, 1979)



$$\mu = \mu_0 + a\ln(V/V_0) + b\ln(V_0\theta/D_c)$$

$$d\theta/dt = 1 - (V_0\theta/D_c)$$

- **Stability of sliding:**

  If a-b > 0
  -> velocity strengthening

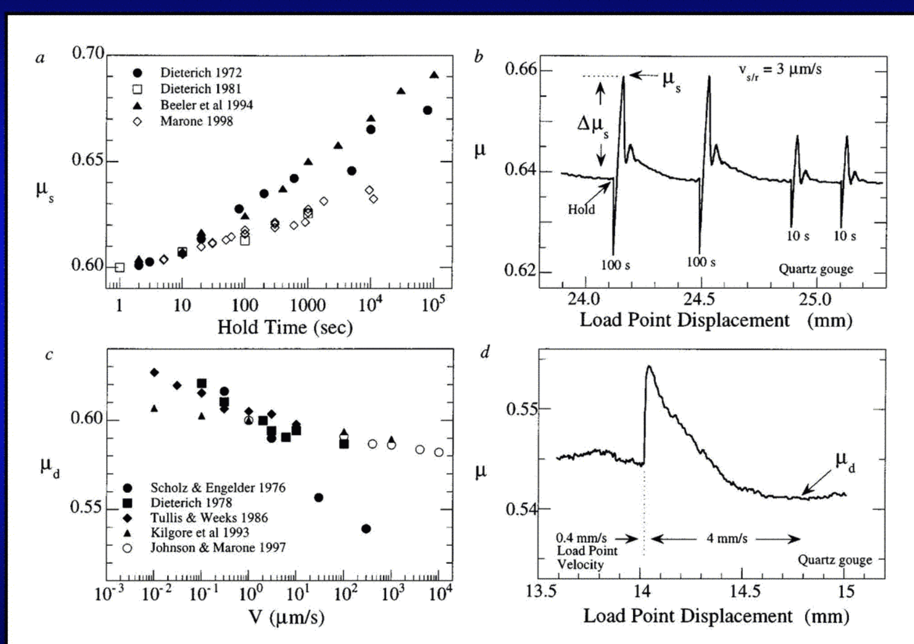
  a-b < 0
  -> velocity weakening

  --> unstable!!

Fault friction depends on sliding velocity, V, and system “state”, θ_i (t, D_c, σ_n).

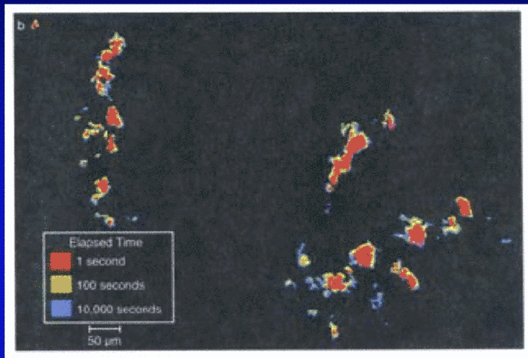
(More than one state variable can exist)

Frictional Sliding - Fault Gouge



(Marone, 1998)

What defines material "State"



(Dieterich & Kilgore, 1994)

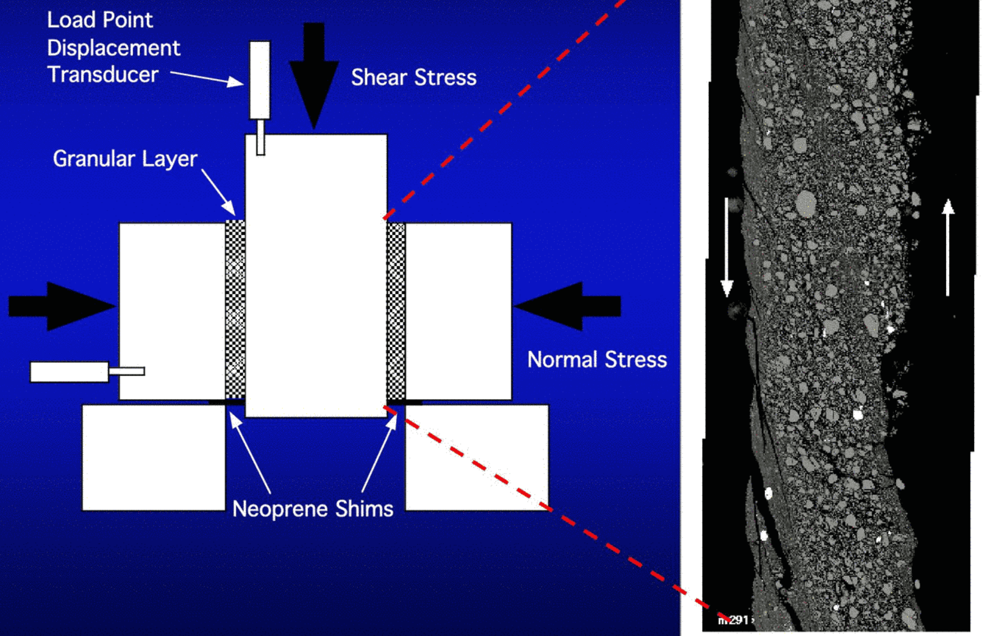
PLANAR FAULT

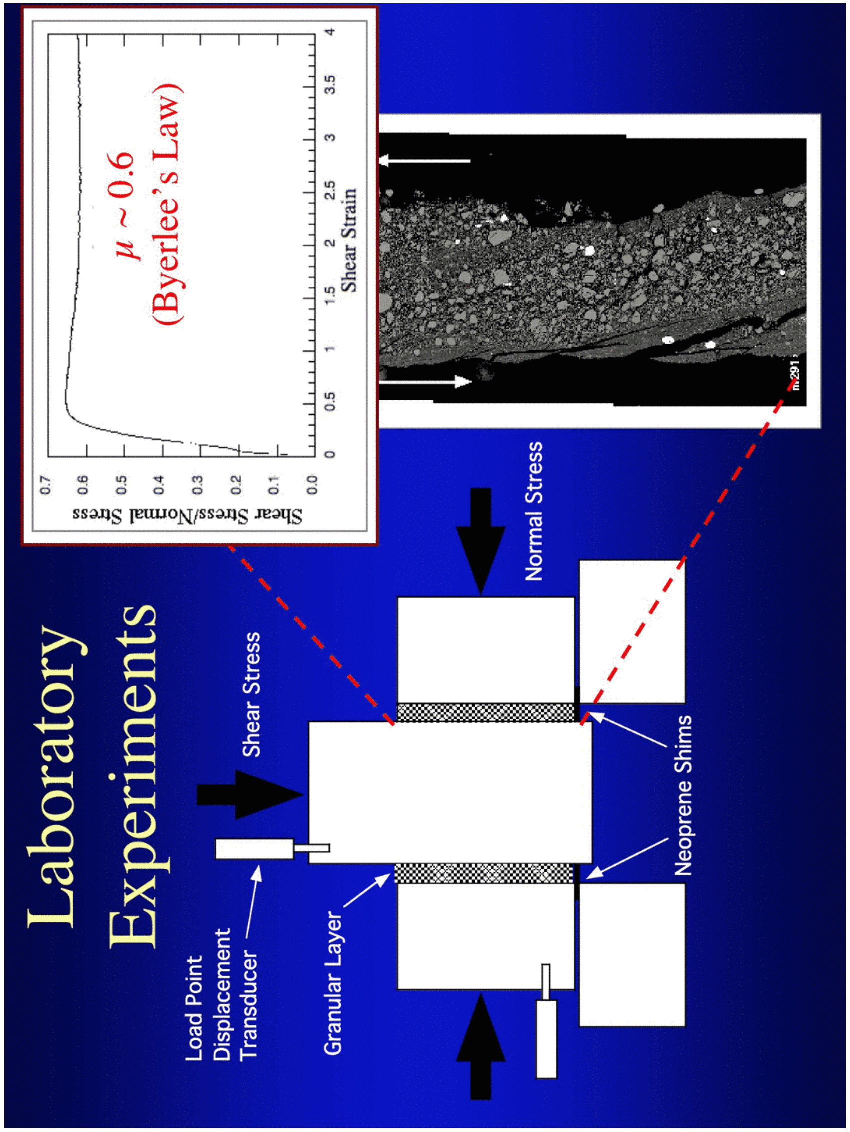
- Solid contact area increases w/ log(time), increases adhesion
- D_c is slip distance required to define new contact population

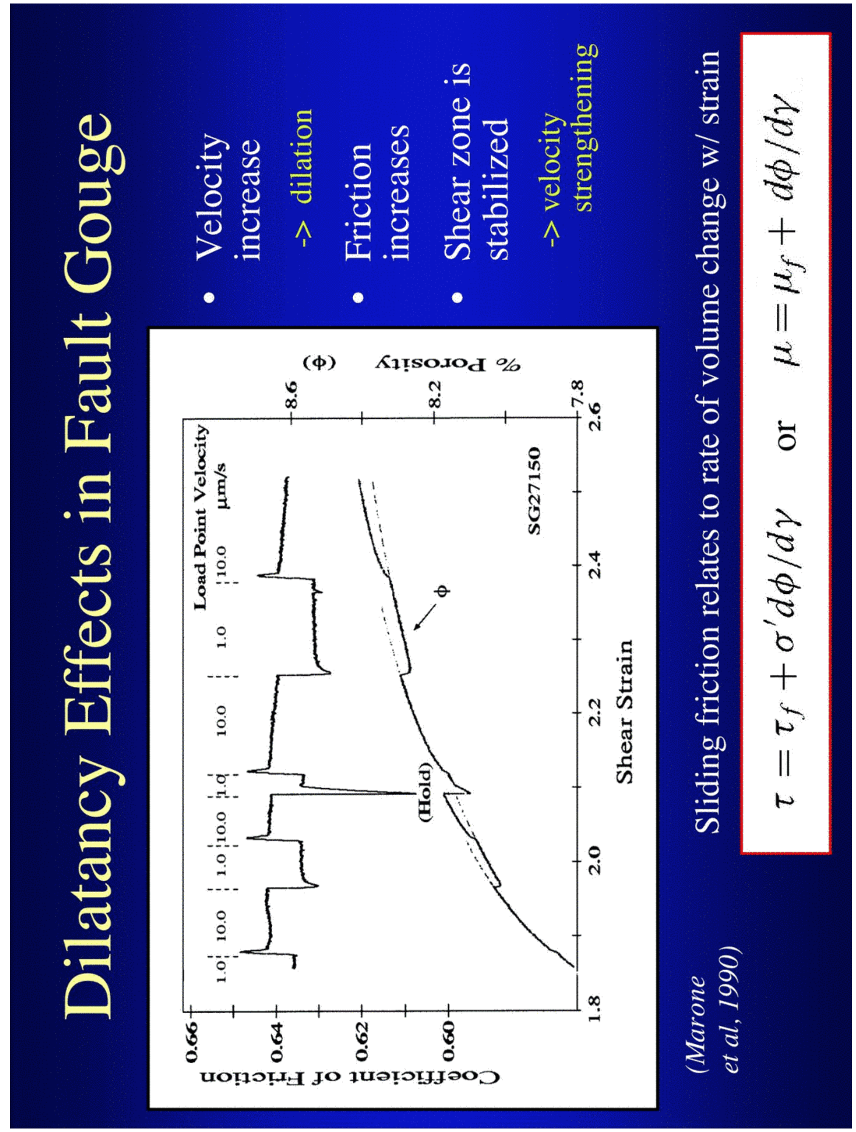
GRANULAR GOUGE

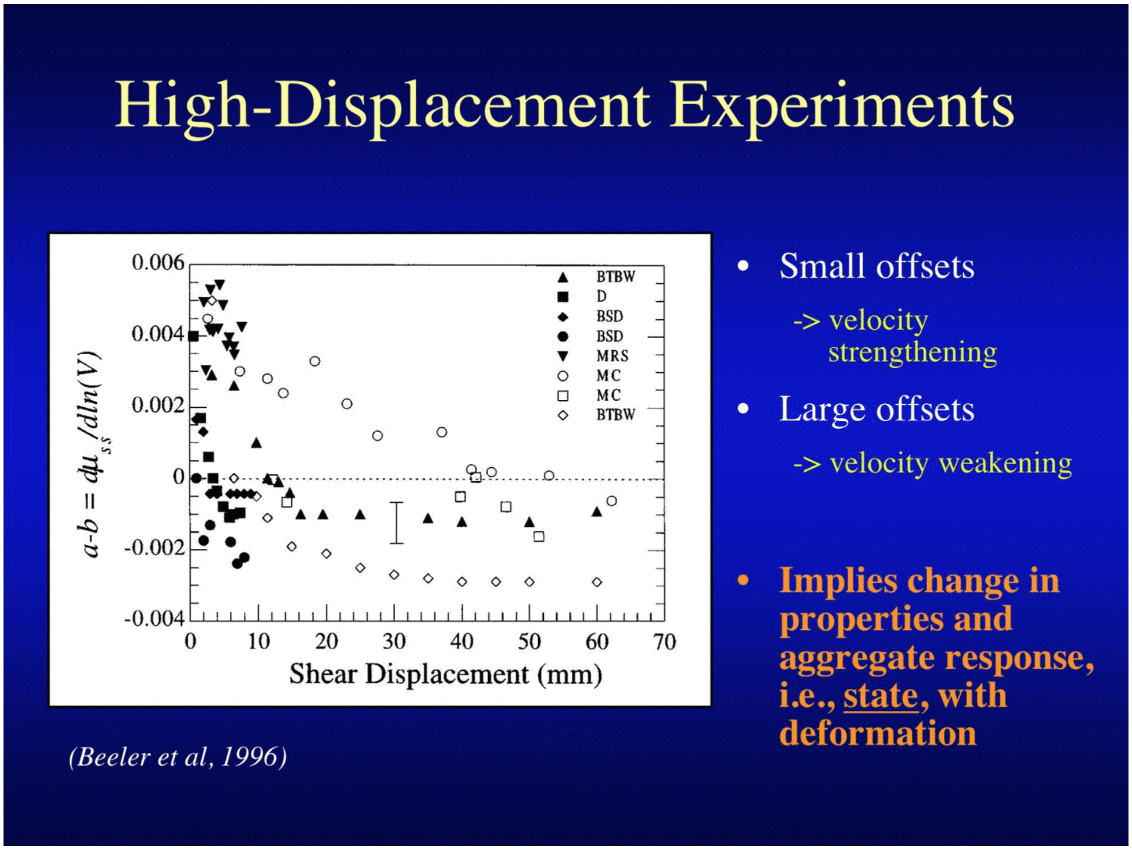
- Similar contact effects are likely at interparticle contacts
- But what else controls:
  - Magnitude of contact force
  - Force distribution (fabric)
  - Number of contacts (grain size, and distribution, porosity)
- Dilatancy also important; requires work against σ_n, adding to friction

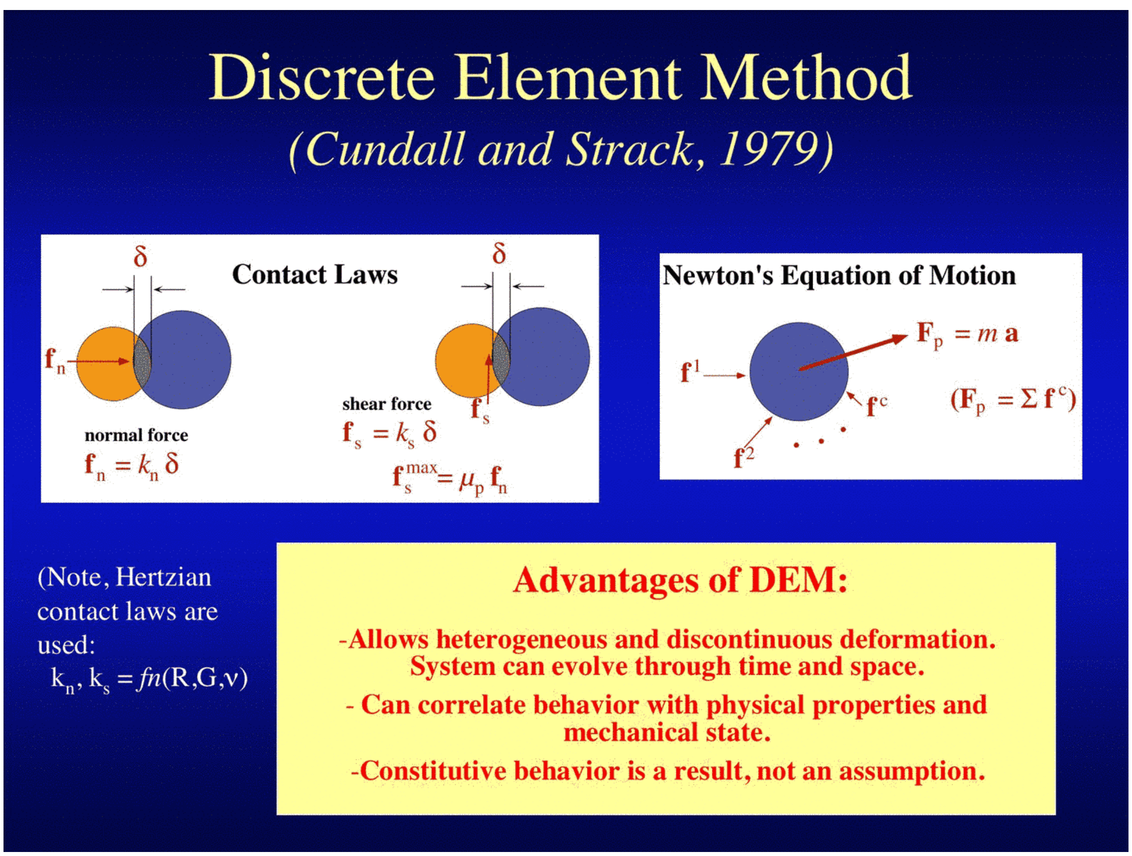
Laboratory Experiments

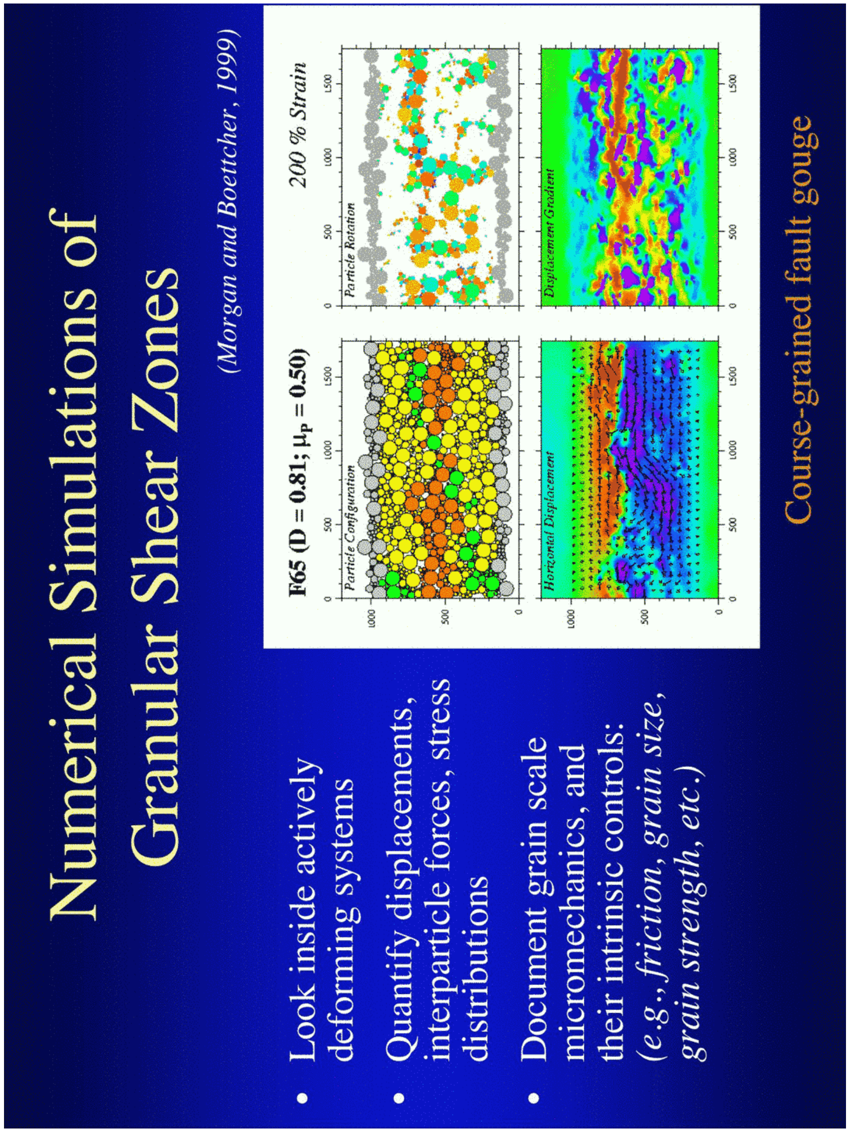


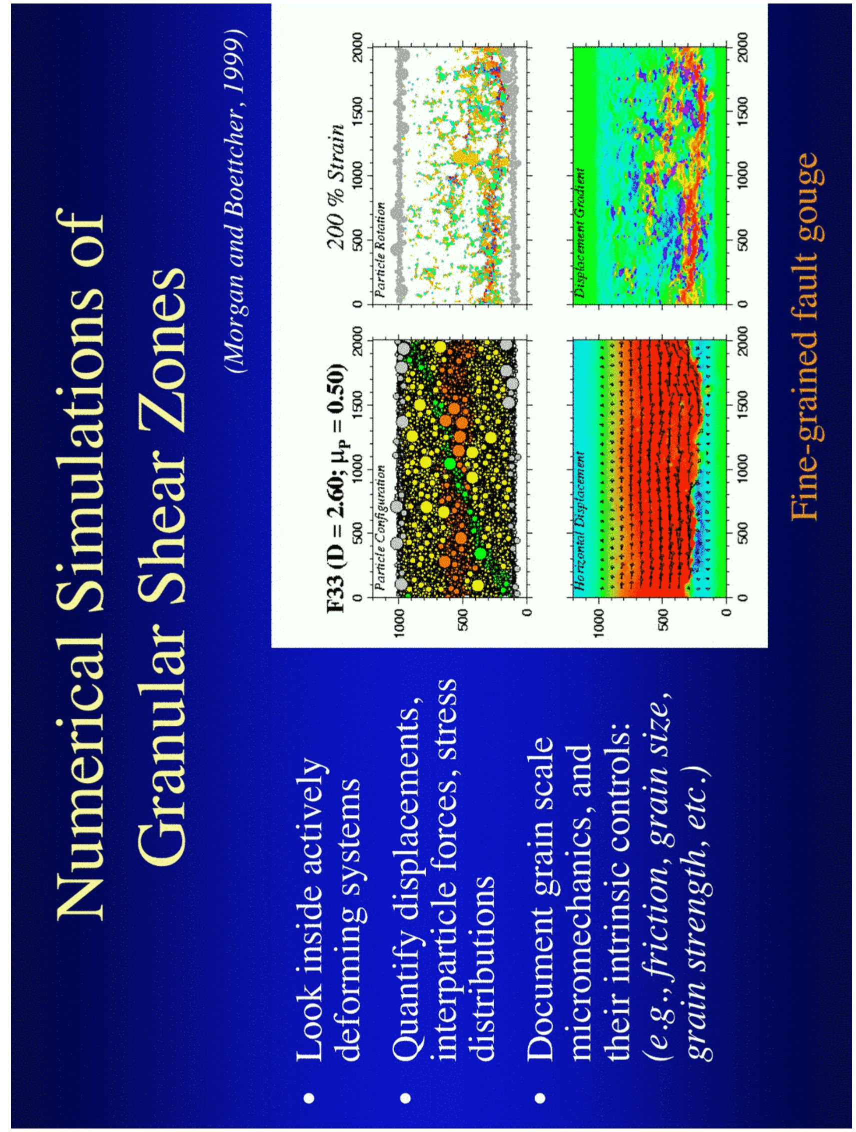

Laboratory Experiments
μ ~ 0.6
(Byerlee's Law)
Shear Stress/Normal Stress
Shear Strain
Shear Stress
Normal Stress
Load Point Displacement Transducer
Granular Layer
Neoprene Shims


Dilatancy Effects in Fault Gouge
• Velocity increase
-> dilation
• Friction increases
• Shear zone is stabilized
-> velocity strengthening
Coefficient of Friction
Shear Strain
% Porosity (φ)
Load Point Velocity μm/s
(Hold)
SG27150
(Marone et al, 1990)
Sliding friction relates to rate of volume change w/ strain
$\tau = \tau_f + \sigma' d\phi/d\gamma$ or $\mu = \mu_f + d\phi/d\gamma$


High-Displacement Experiments
a-b = dμss /dln(V)
Shear Displacement (mm)
BTBW
D
BSD
BSD
MRS
MC
MC
BTBW
(Beeler et al, 1996)
• Small offsets
-> velocity strengthening
• Large offsets
-> velocity weakening
• Implies change in properties and aggregate response, i.e., state, with deformation


Discrete Element Method
(Cundall and Strack, 1979)
Contact Laws
normal force
fn = kn δ
shear force
fs = ks δ
fsmax = μp fn
Newton's Equation of Motion
Fp = m a
(Fp = Σ fc)
(Note, Hertzian contact laws are used:
kn, ks = fn(R,G,ν)
Advantages of DEM:
-Allows heterogeneous and discontinuous deformation. System can evolve through time and space.
- Can correlate behavior with physical properties and mechanical state.
-Constitutive behavior is a result, not an assumption.


Numerical Simulations of
Granular Shear Zones
(Morgan and Boettcher, 1999)
• Look inside actively deforming systems
• Quantify displacements, interparticle forces, stress distributions
• Document grain scale micromechanics, and their intrinsic controls: (e.g., friction, grain size, grain strength, etc.)
F65 (D = 0.81; μP = 0.50)
200 % Strain
Particle Configuration
Particle Rotation
Horizontal Displacement
Displacement Gradient
Course-grained fault gouge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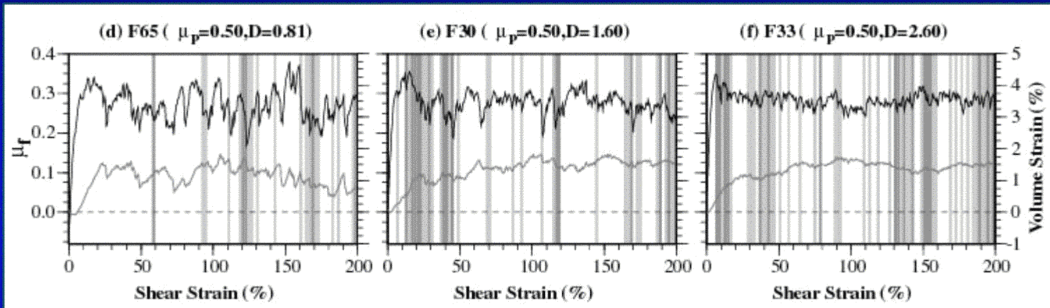
• Quantify displacements, interparticle forces, stress distributions
• Document grain scale micromechanics, and their intrinsic controls: (e.g., friction, grain size, grain strength, etc.)
F33 (D = 2.60; μP = 0.50)
200 % Strain
Particle Configuration
Particle Rotation
Horizontal Displacement
Displacement Gradient
Fine-grained fault gouge

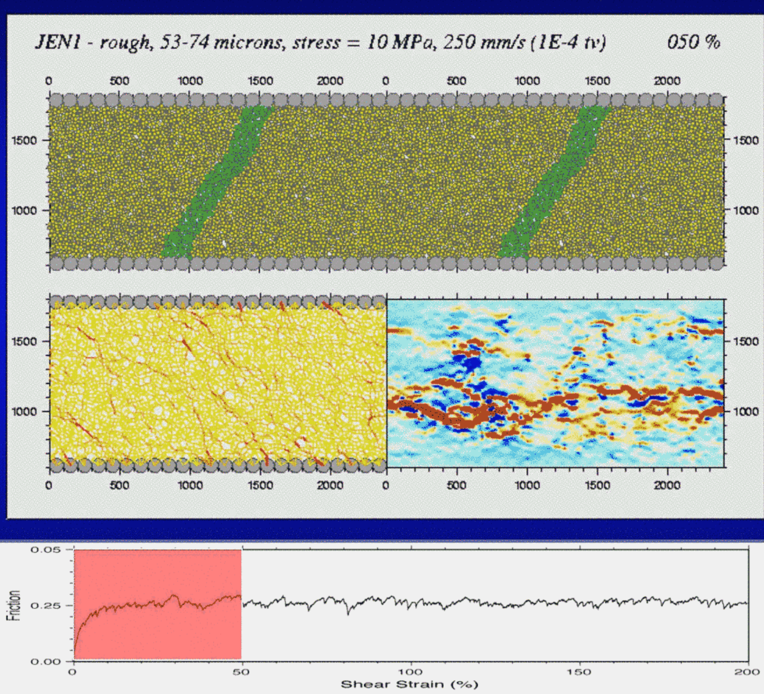
DEM Simulations of Granular Friction



Increasing abundance of small particles ---> *(Morgan, 1999)*

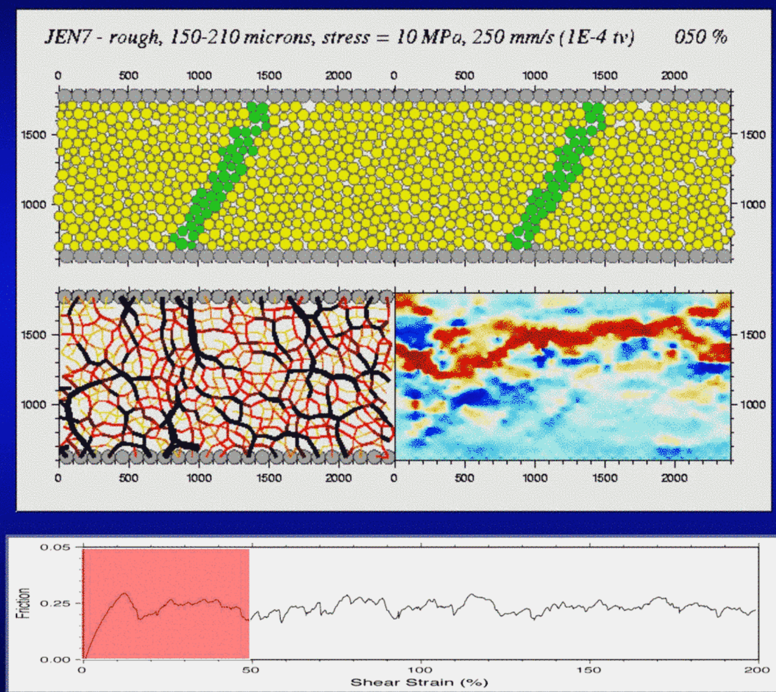
- Low sliding friction, $\mu \sim 0.3$.
- Stick slip and strain localization (gray bars).
- Strength and stress drop depend on particle size and size distribution.

Fine Grained Gouge



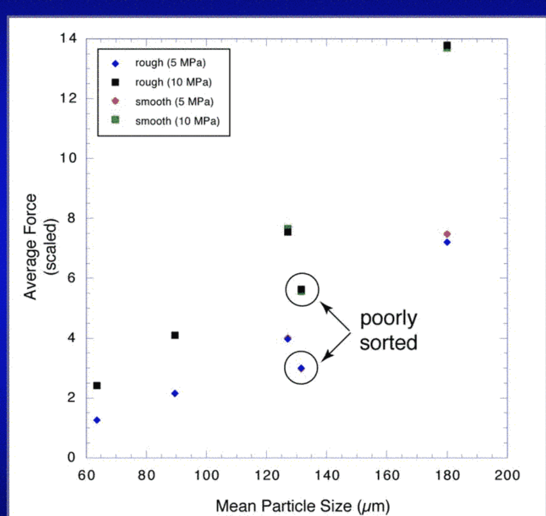
- Force chain network spans shear zone.
- Low contact forces evolve rapidly.
- Distributed deformation
- Uniform strength, low stress drops.

Coarse Grained Gouge



- Force chain network spans shear zone.
- High contact forces.
- Paired force chains.
- Irregular strength, high stress drops.

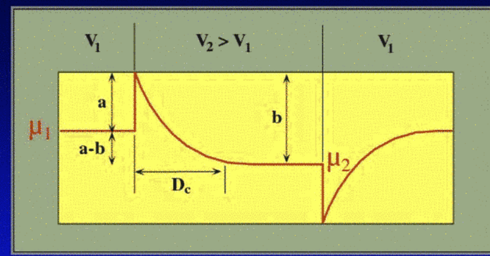
Force Chains - Results



- Complicated, evolving networks of contact forces, dependent on grain size and distribution.
- Generally, contact force magnitudes scale up with particle size.
- Force chain distributions and evolution control shear zone friction and stress fluctuations.

Rate- and State Friction

Contact Healing



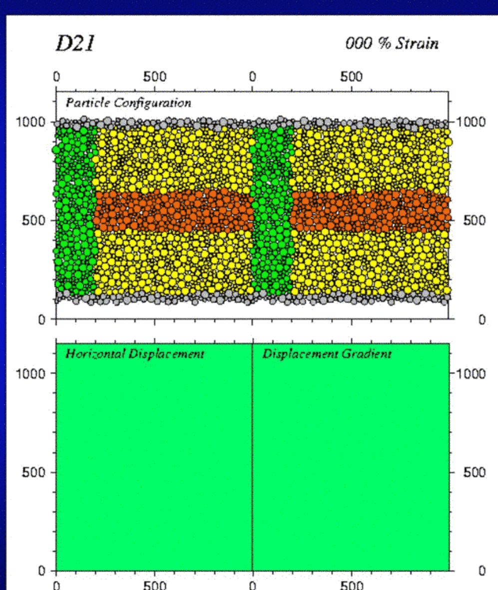
- Implement time-dependent healing at contacts.

  (e.g., Dieterich, 1972; Beeler et al., 1994; Marone, 1998)

$$V = 0, \quad \mu = \mu_k + b\ln(t/t_0 + 1)$$
$$V > 0, \quad \mu = \mu_k,$$

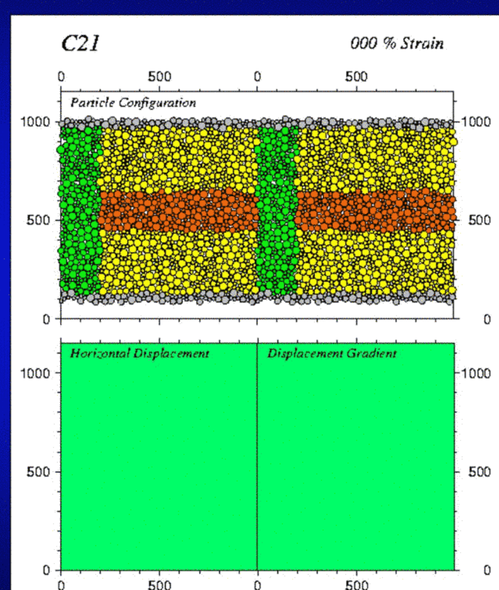
- Advantages:
  - Fundamental property of system.
  - Particle configuration defines "state".
  - Simple to implement.

No Healing
V = 1E-2 μm/s



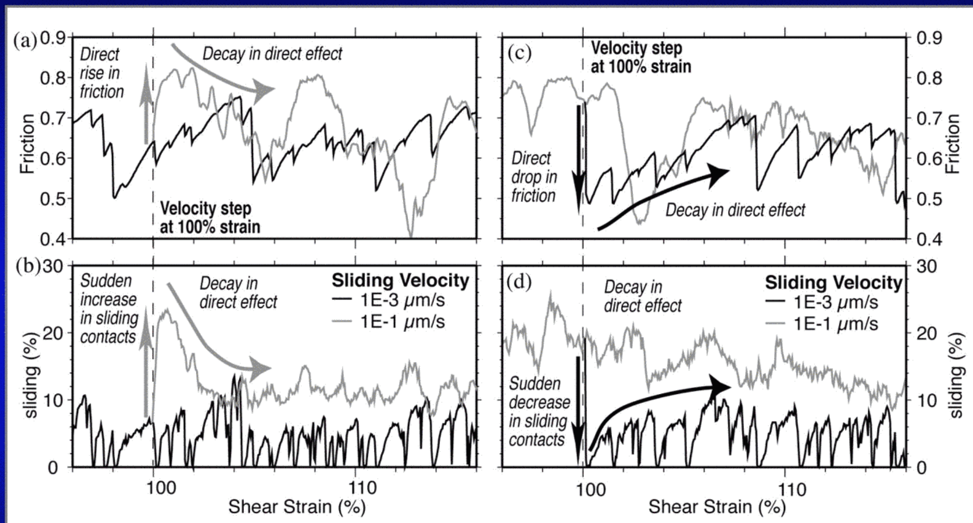
Cumulative strain is homogeneous.
- Distributed

Healing
V = 1E-2 μm/s



Cumulative strain is heterogeneous.
- Highly localized

Velocity Steps: 1E-1<-->1E-3 μm/s

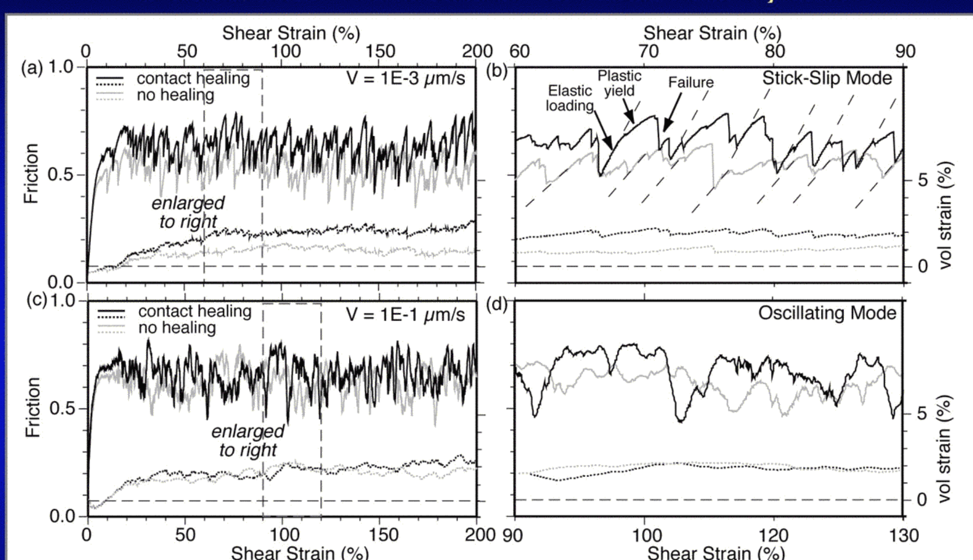


(Morgan, 2004)

- Velocity steps produce both direct and evolutionary changes on sliding friction, as inferred from laboratory experiments.

>>> Velocity Strengthening <<<

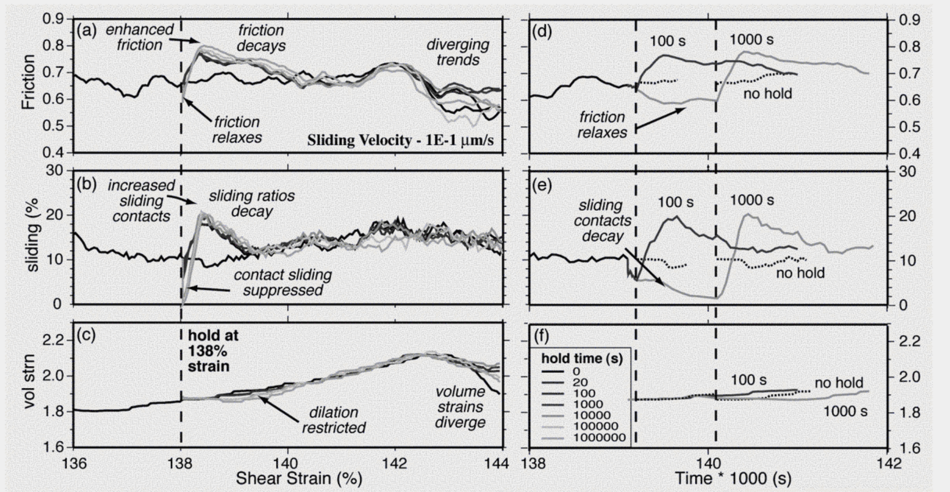
Friction - Strain: 1E-3 and 1E-1 μm/s



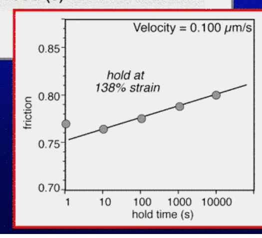
(Morgan, 2004)

- Irregular stick-slip events:
  - 1E-3 μm/s -> elastic-plastic loading and sudden failure
  - 1E-1 μm/s -> symmetric loading and unloading

Slide-Hold-Slide Tests: 1E-1 μm/s



(Morgan, 2004)

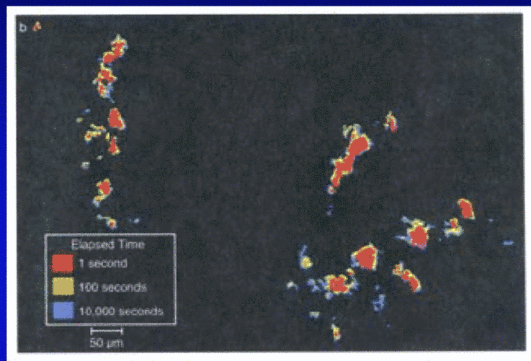


- Increased hold times results in logarithmic increase in yield strength, and suppressed dilation.

Summary

- Numerical experiments capture many of the processes of laboratory experiments, and natural gouge deformation (in non-fracturing regime).
- Rate- and state-dependent frictional effects are also reproduced, with simplest of contact laws
  - Both direct and evolutionary change in friction.
  - Fault strengthening during holds
  - Velocity strengthening throughout
- Velocity dependent friction fluctuations
  - Low-velocities -> stick-slip mode (w/ elastic & plastic)
  - Higher-velocities -> oscillating mode

What defines material "State"



(Dieterich & Kilgore, 1994)

PLANAR FAULT

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- D_c is slip distance required to define new contact population

GRANULAR GOUGE

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- But what else controls:
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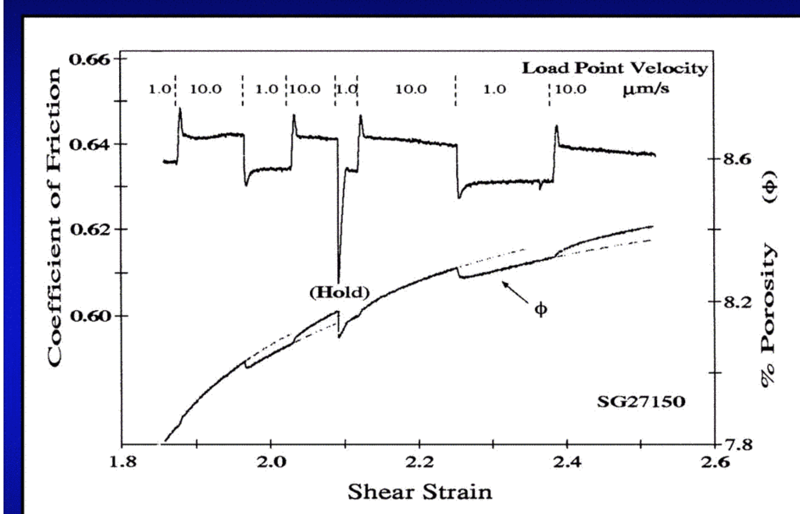
Dilatancy Effects in Fault Gouge

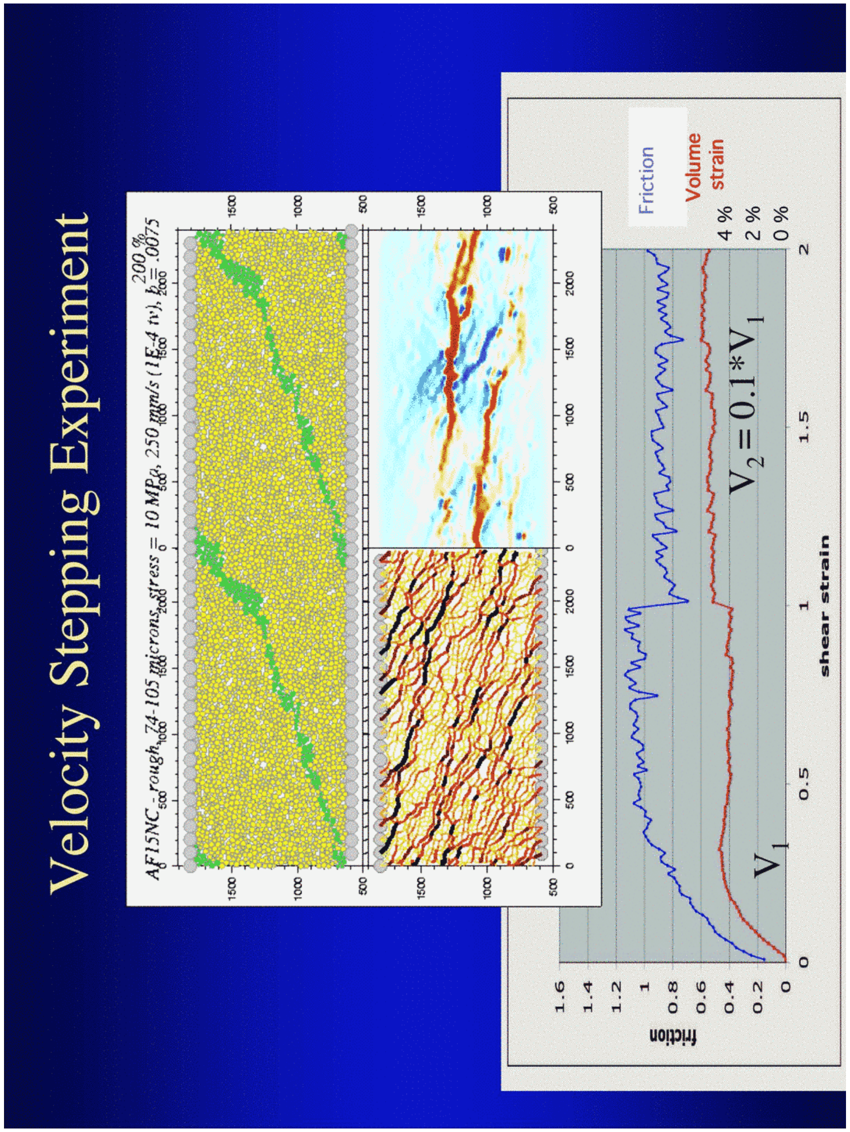


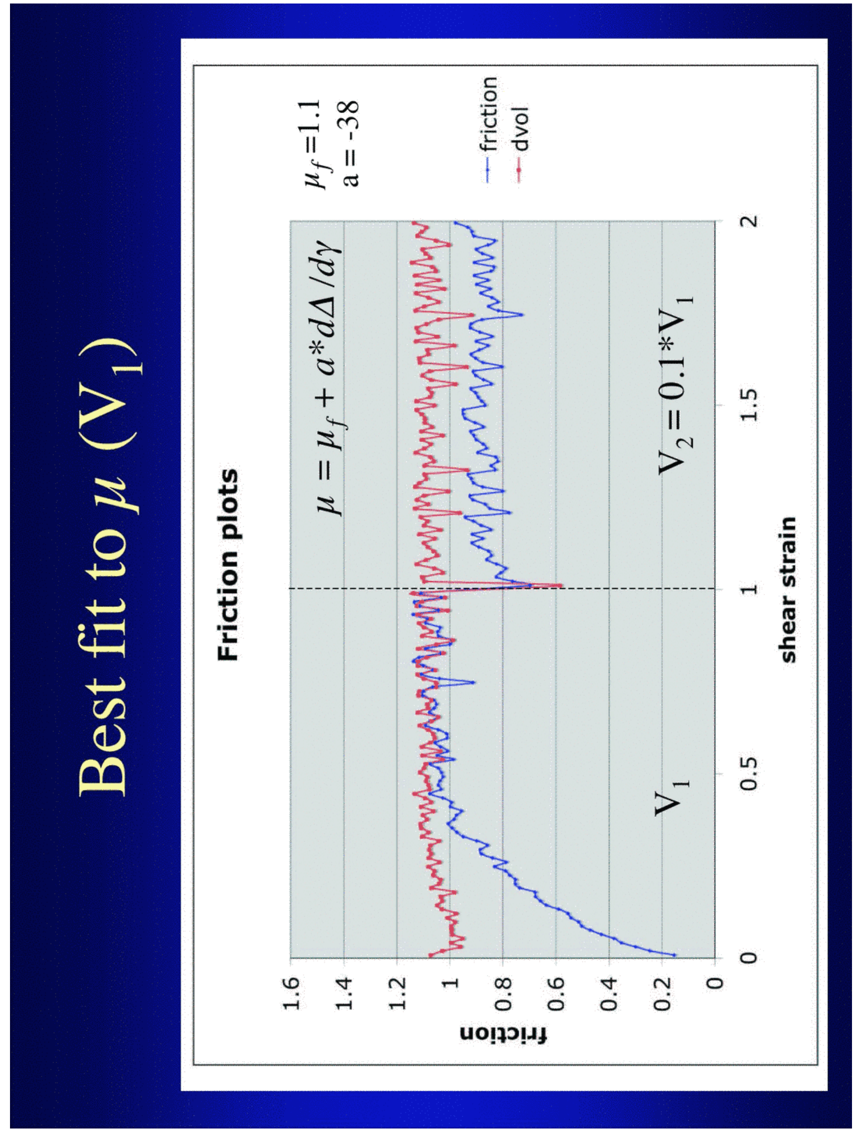
(Marone et al, 1990)

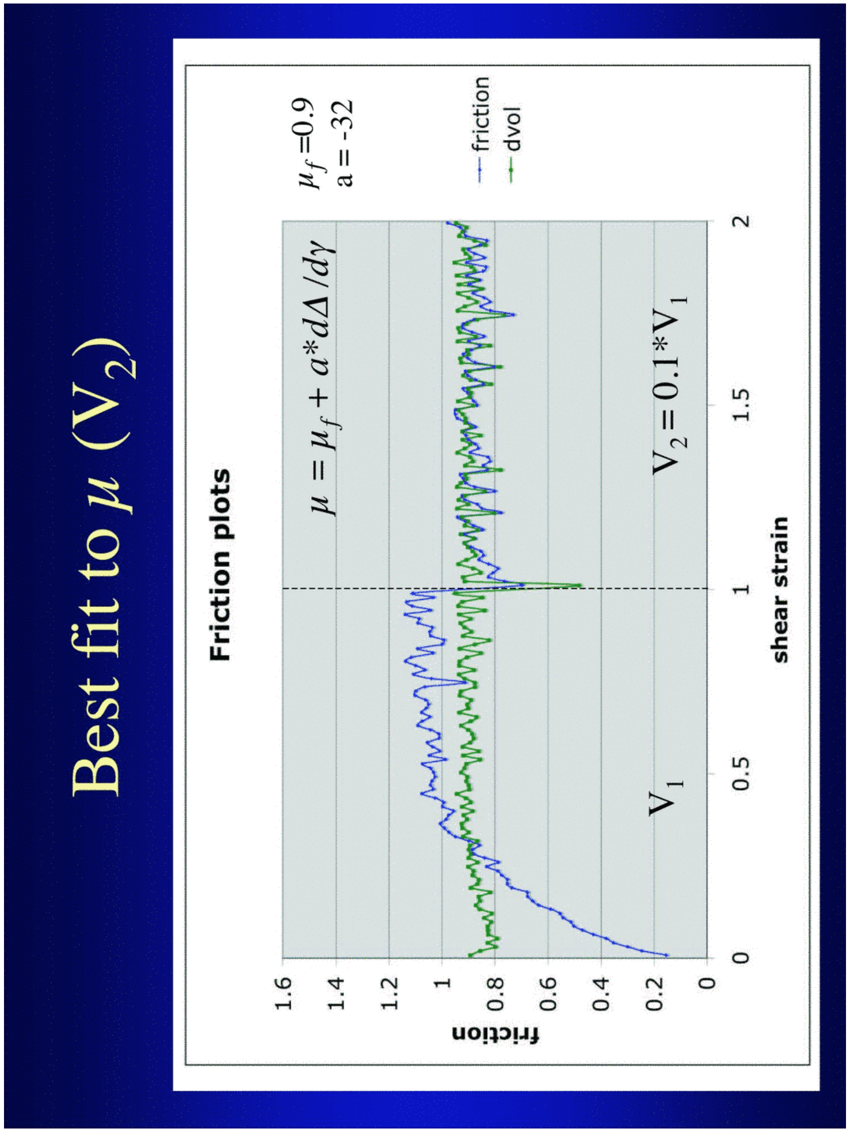
- Velocity increase
  - -> dilation
- Friction increases
- Shear zone is stabilized
  - -> velocity strengthening

Try to fit friction data to relationship below:

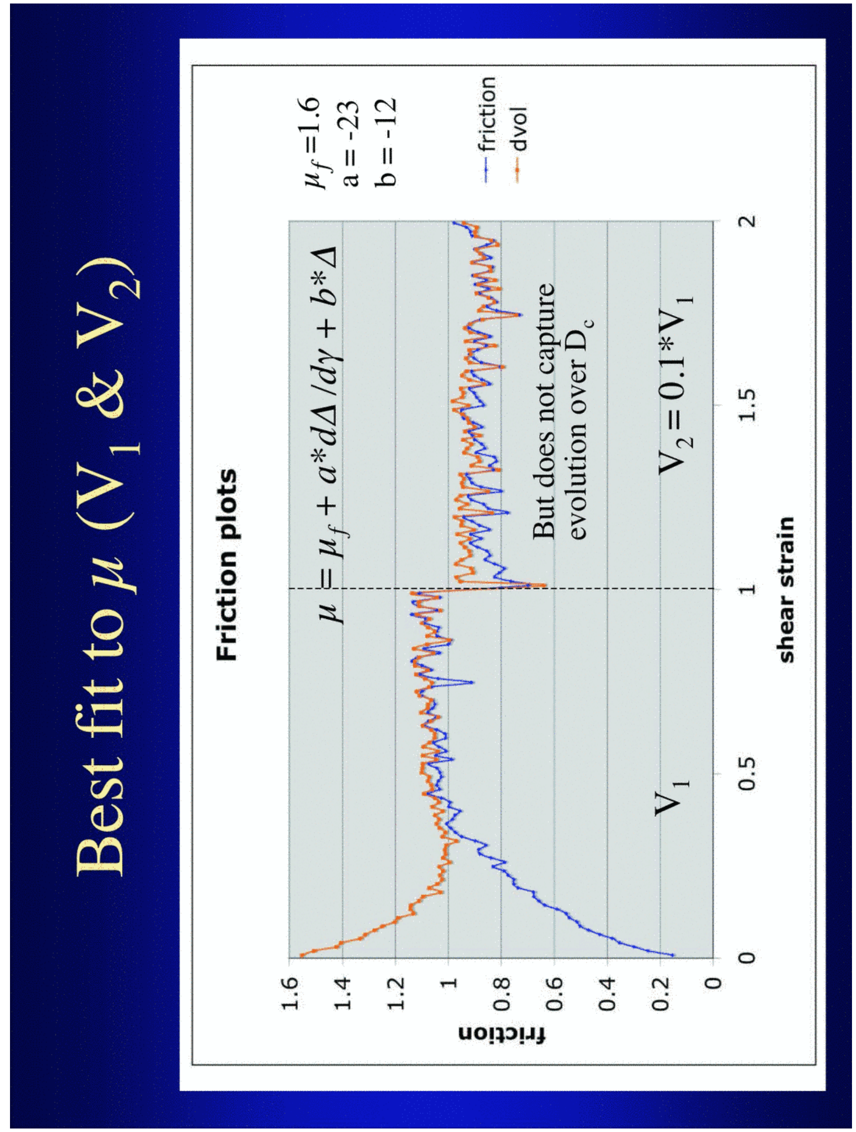
$$\tau = \tau_f + \sigma' d\phi/d\gamma \quad \text{or} \quad \mu = \mu_f + d\phi/d\gamma$$


Velocity Stepping Experiment
Friction
Volume strain
4 %
2 %
0 %
V_1
$V_2 = 0.1*V_1$
shear strain
friction


Best fit to μ (V_1)
Friction plots
$\mu = \mu_f + a*d\Delta/d\gamma$
μ_f=1.1
a = -38
friction
dvol
V_1
$V_2 = 0.1*V_1$
shear strain
friction



Best fit to μ (V2)
Friction plots
μ = μf + a*dΔ/dγ
μf =0.9
a = -32
friction
dvol
V1
V2 = 0.1*V1
friction
shear strain
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
0.5
1.5
2



Best fit to μ (V1 & V2)
Friction plots
μ = μf + a*dΔ/dγ + b*Δ
μf =1.6
a = -23
b = -12
friction
dvol
But does not capture
evolution over Dc
V1
V2 = 0.1*V1
friction
shear strain
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
0.5
1.5
2

Definition of "State"

- Friction in granular gouge friction depends on many parameters:
  - Intrinsic friction - elasticity of assemblage
  - Dilation rate (w/ shear strain), to do work against σ_n
  - And some internal property, relating to contact area…
- Is volume strain really the correct state variable defining contact area?? It does not capture D_c evolution.
- Likely, volume strain is a proxy for other properties, which also vary with velocity and strain:
  - Interparticle force magnitudes, networks, fabrics
  - Contacts per particle (coordination number)
  - Proportion of sliding contacts,
  - Etc….

For Example….