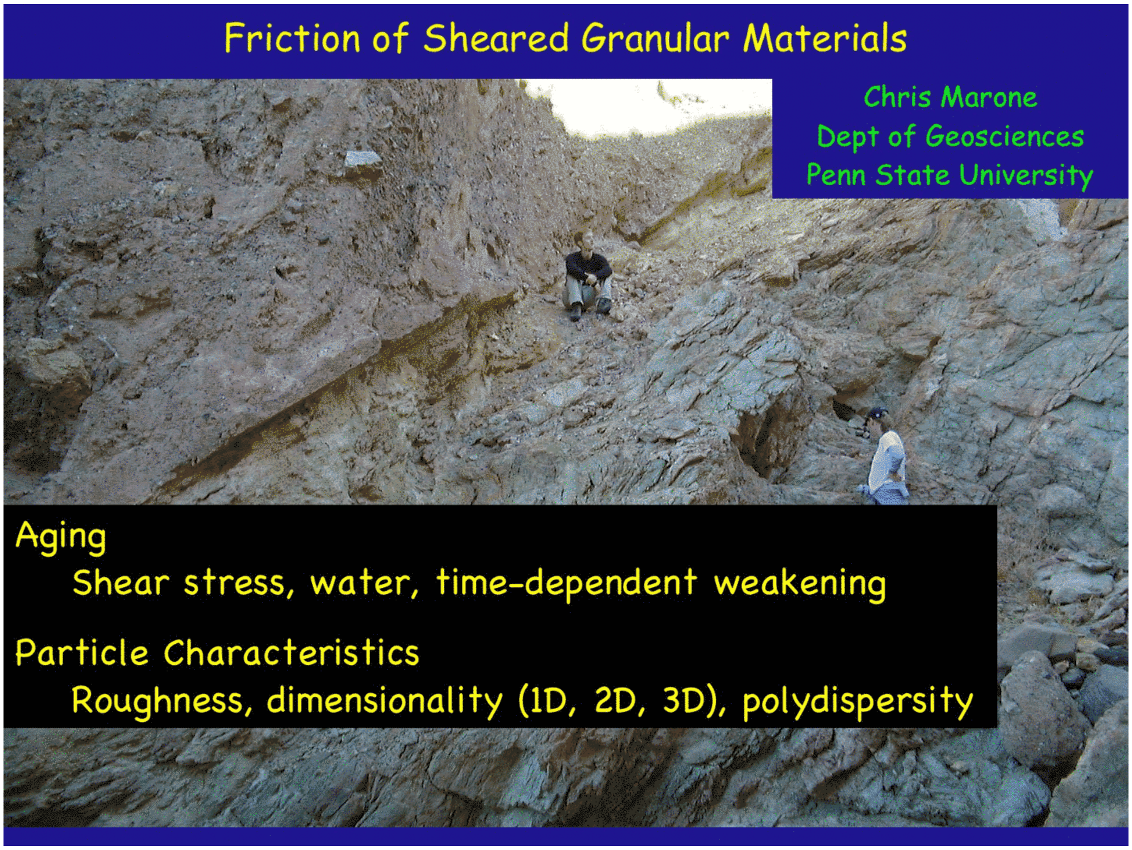
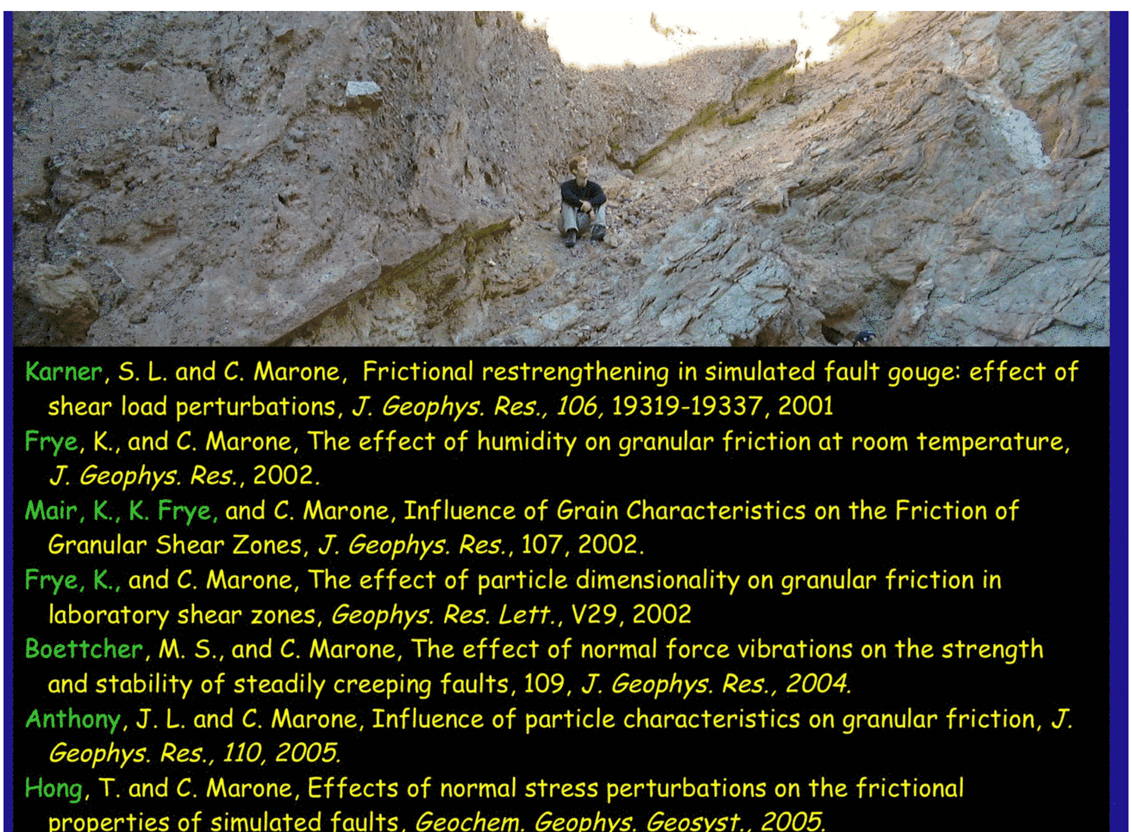

Friction of Sheared Granular Materials
Chris Marone
Dept of Geosciences
Penn State University
Aging
Shear stress, water, time-dependent weakening
Particle Characteristics
Roughness, dimensionality (1D, 2D, 3D), polydispersity


Karner, S. L. and C. Marone, Frictional restrengthening in simulated fault gouge: effect of shear load perturbations, J. Geophys. Res., 106, 19319-19337, 2001
Frye, K., and C. Marone, The effect of humidity on granular friction at room temperature, J. Geophys. Res., 2002.
Mair, K., K. Frye, and C. Marone, Influence of Grain Characteristics on the Friction of Granular Shear Zones, J. Geophys. Res., 107, 2002.
Frye, K., and C. Marone, The effect of particle dimensionality on granular friction in laboratory shear zones, Geophys. Res. Lett., V29, 2002
Boettcher, M. S., and C. Marone, The effect of normal force vibrations on the strength and stability of steadily creeping faults, 109, J. Geophys. Res., 2004.
Anthony, J. L. and C. Marone, Influence of particle characteristics on granular friction, J. Geophys. Res., 110, 2005.
Hong, T. and C. Marone, Effects of normal stress perturbations on the frictional properties of simulated faults, Geochem. Geophys. Geosyst., 2005.

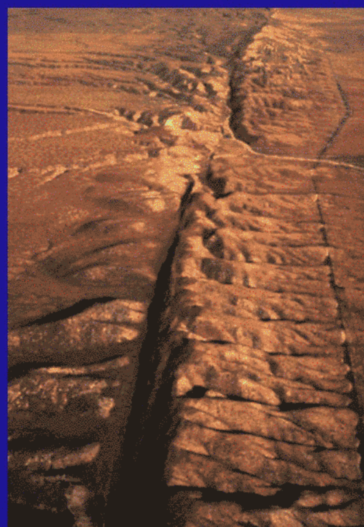
Seismogenic Faults:

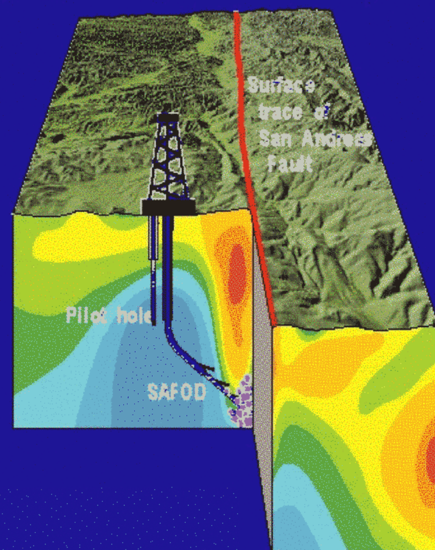
Effective Normal Stress of order 10 to 100 MPa

Fault Gouge is wear material, Fault Zone is 1-1000 m wide

Earthquake stress drop is ≈ 10% of total shear strength.

Therefore (probably) *stressed* aging during the seismic cycle

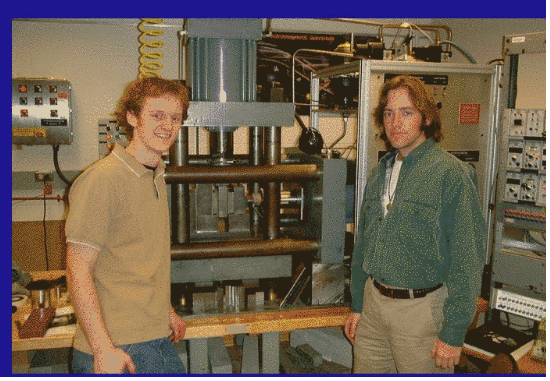


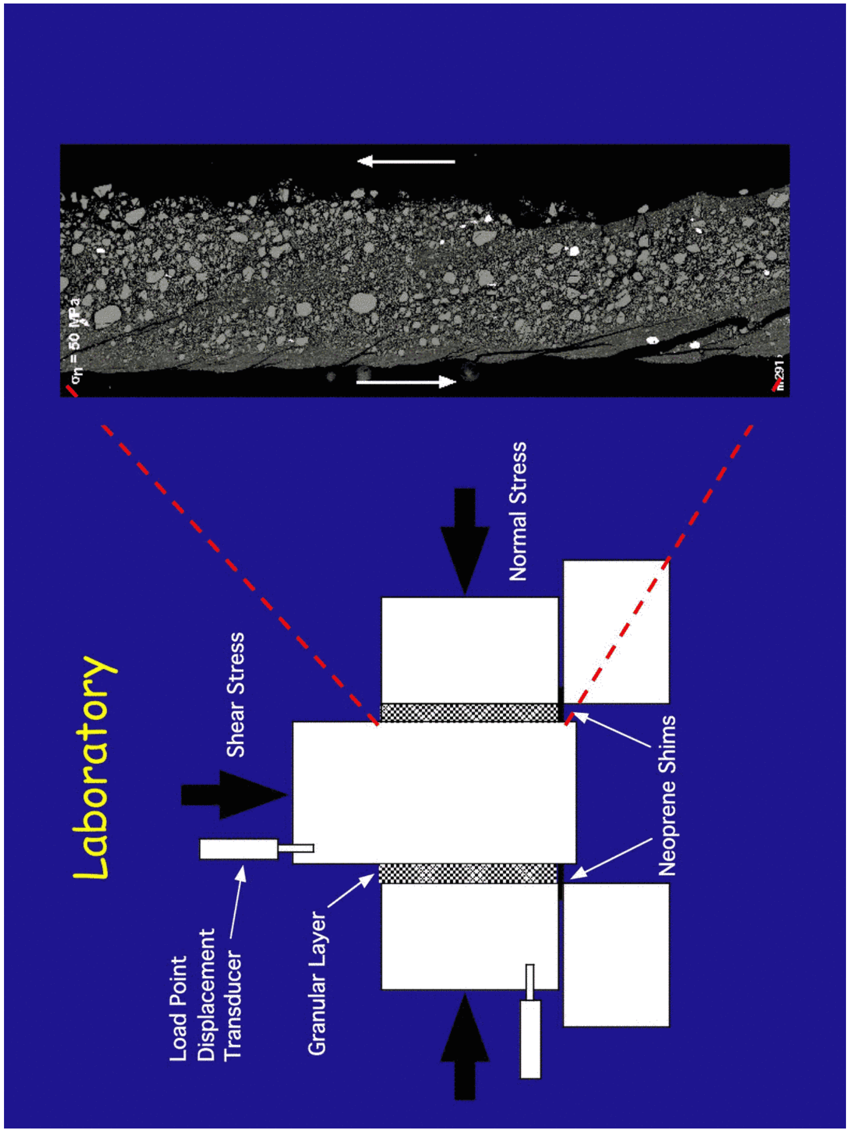


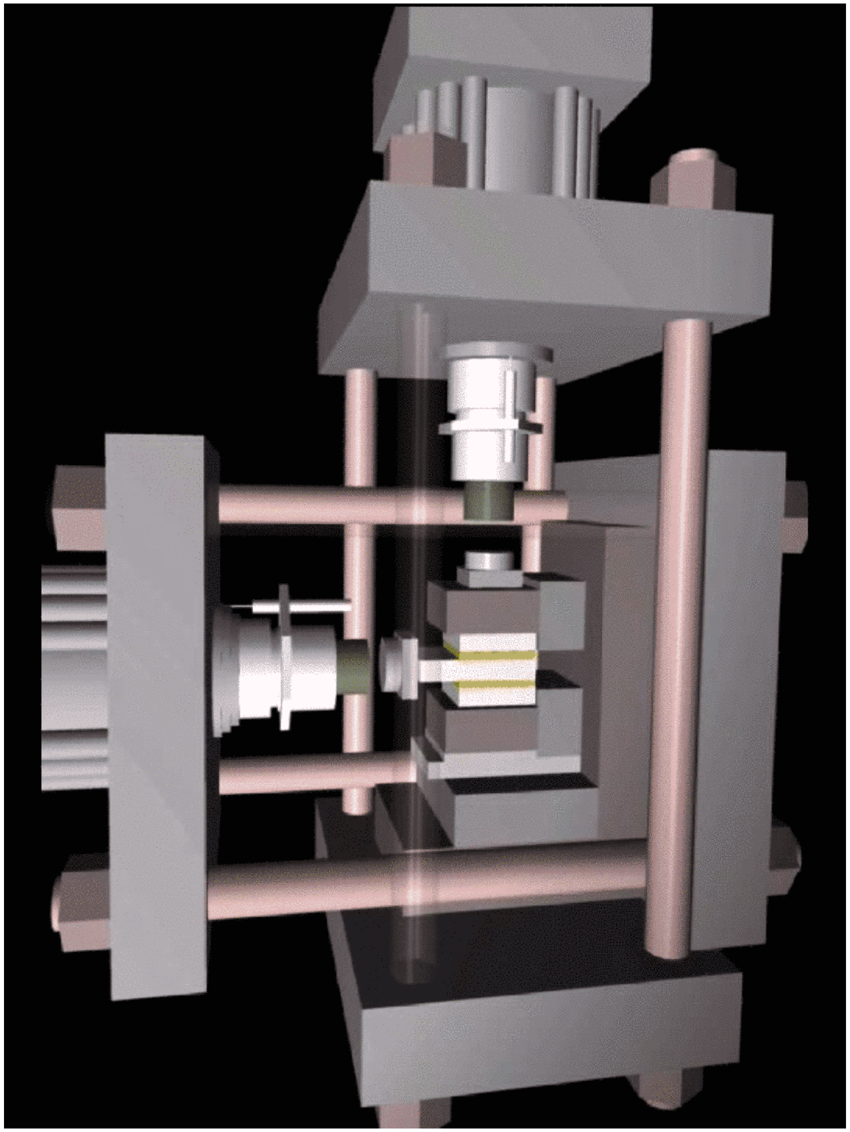
SAFOD The San Andreas Fault Observatory at Depth

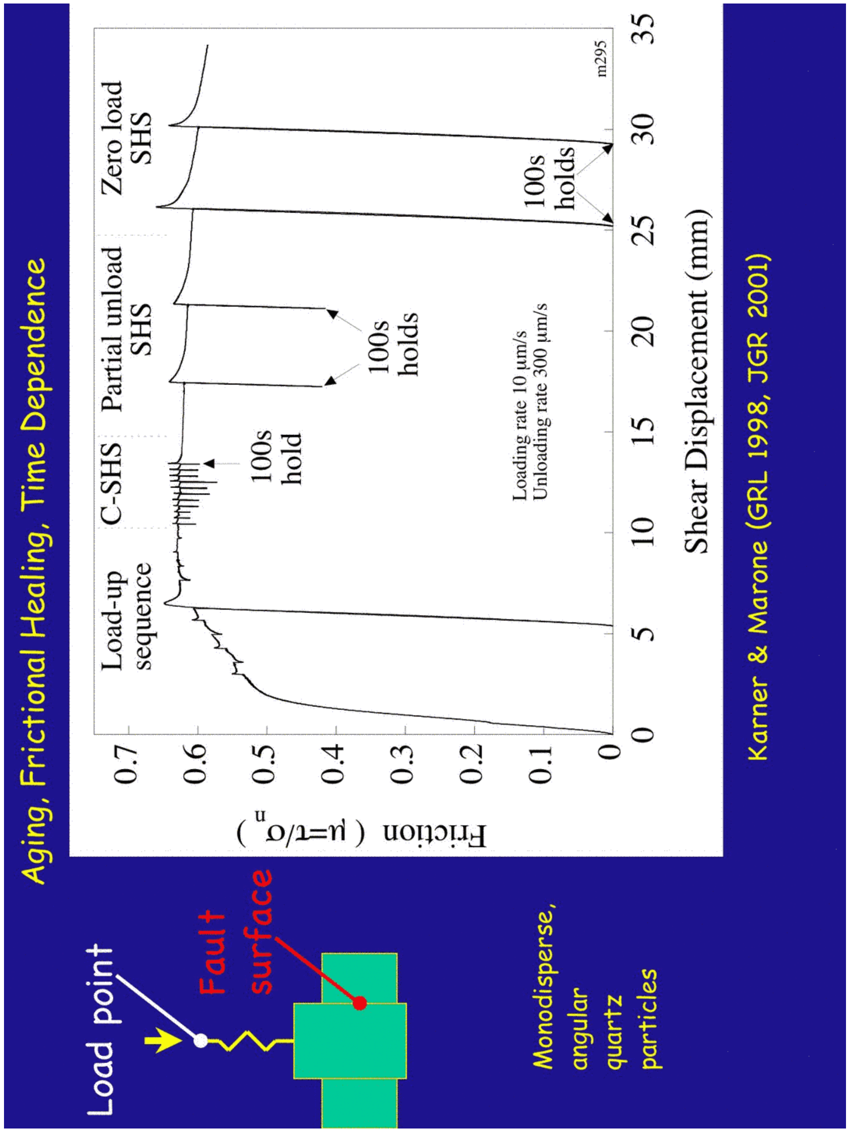
Geophysical laboratory studies of friction sheared granular layers

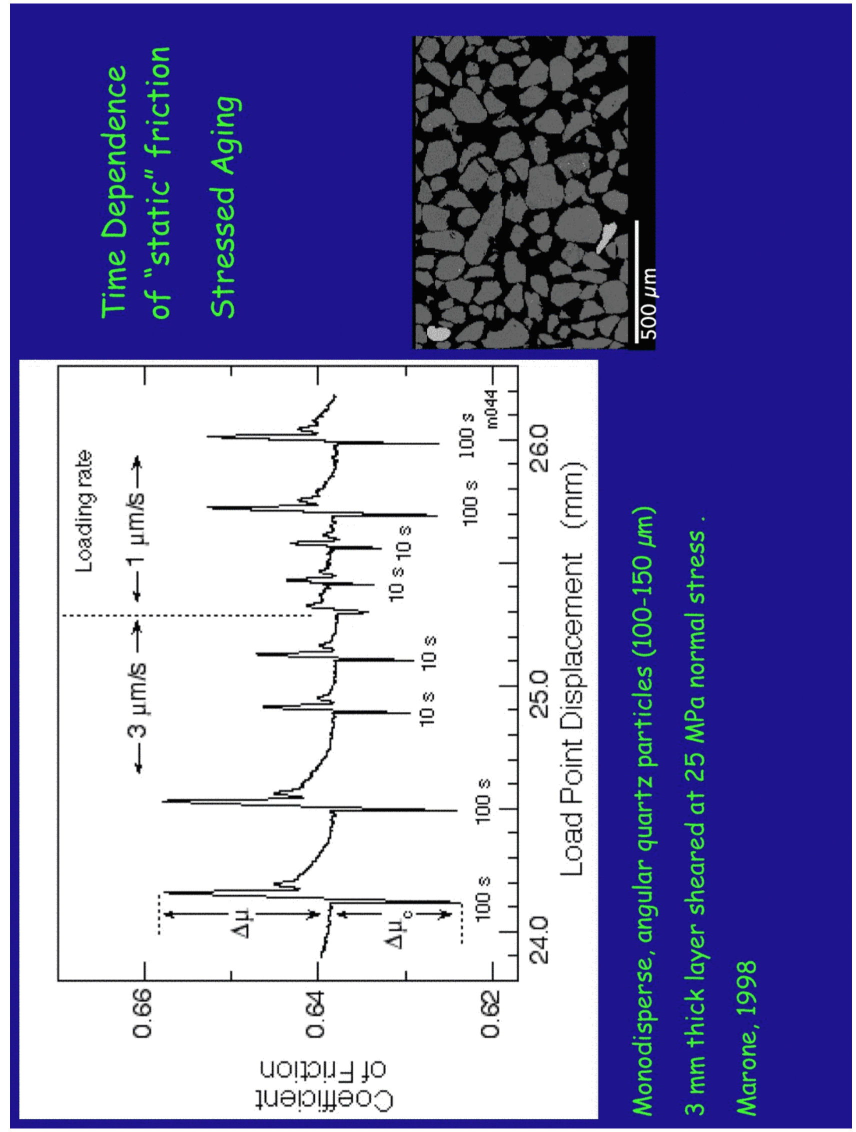
- Double-direct shear configuration
  - rock surfaces, natural or synthetic fault gouge.
- Study the effect of gouge properties: particle size distribution, particle shape, fracture, material (granular v. clay-rich).
- Room temperature and (controlled) humidity
- Slip velocities in the range 1 μm/s to 1 mm/s.
- Fracture or Non-fracture loading regime (σ_n 10- 200 MPa)
- Sheared layers, thickness >> particle size

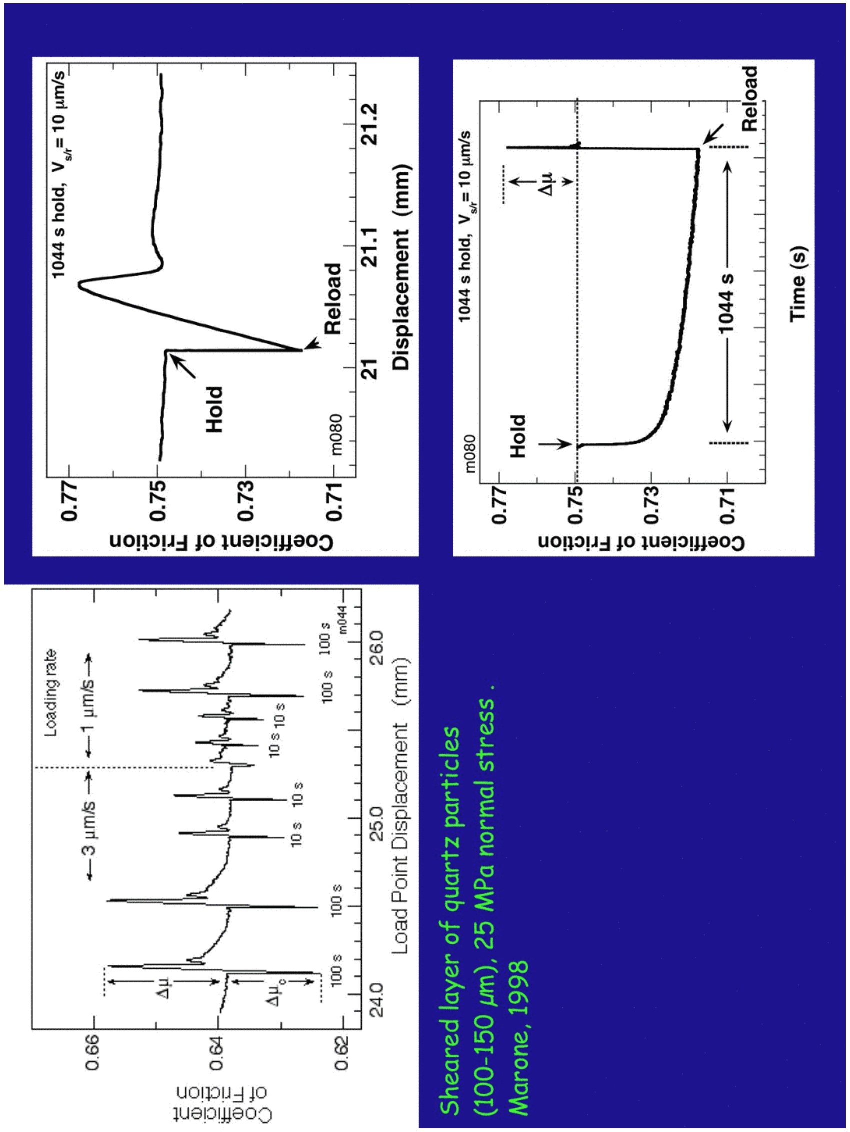


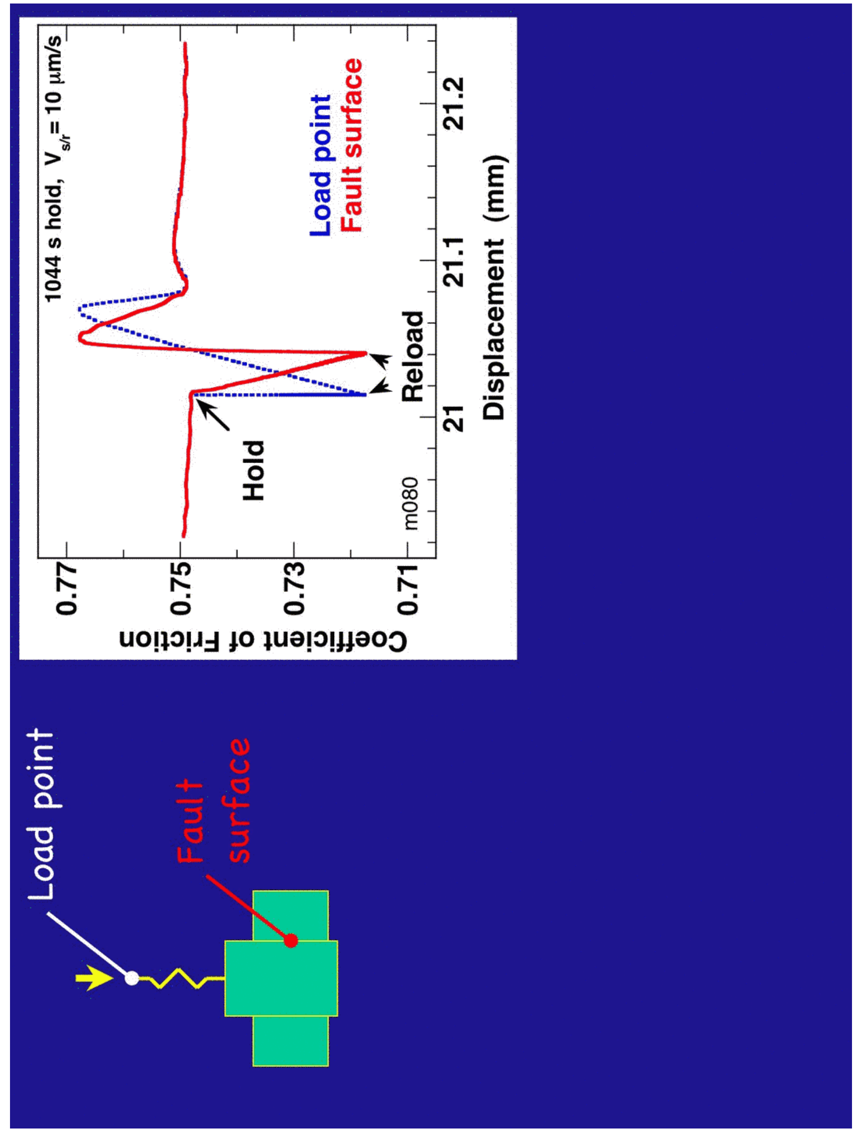

Laboratory
Shear Stress
Normal Stress
Load Point
Displacement
Transducer
Granular Layer
Neoprene Shims

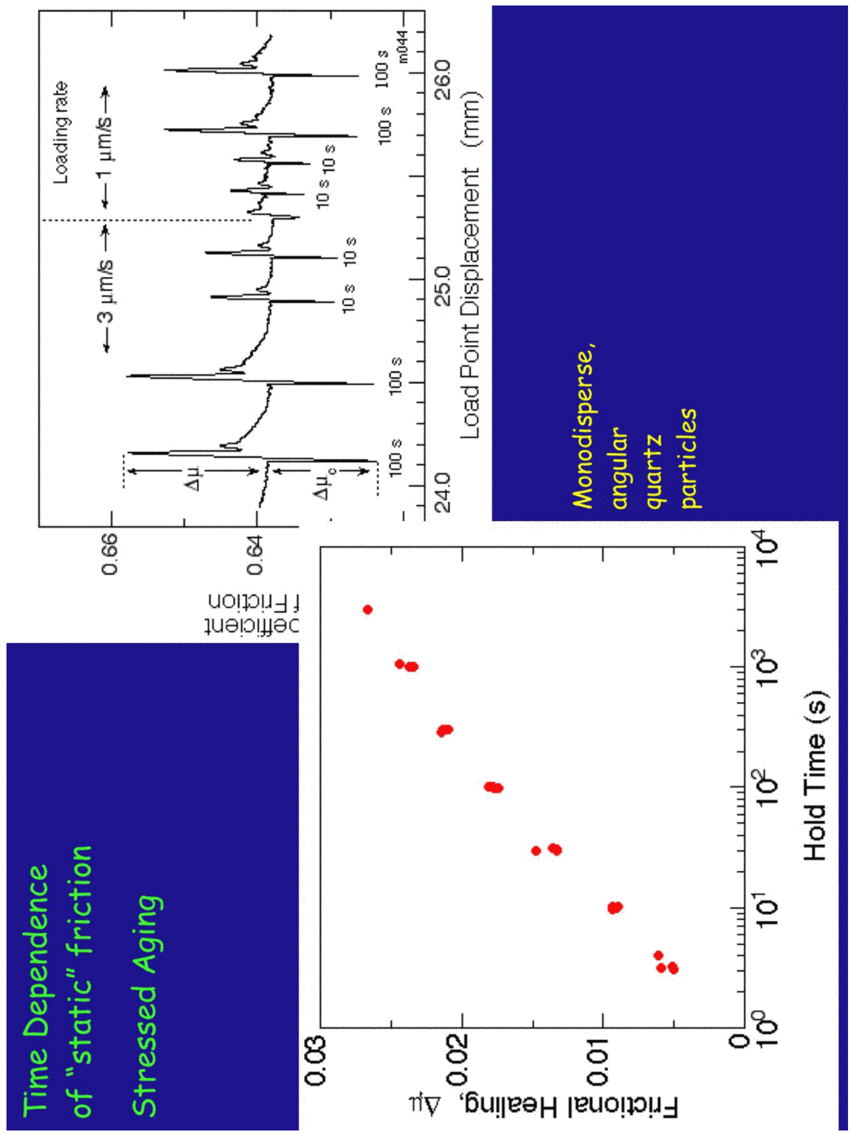


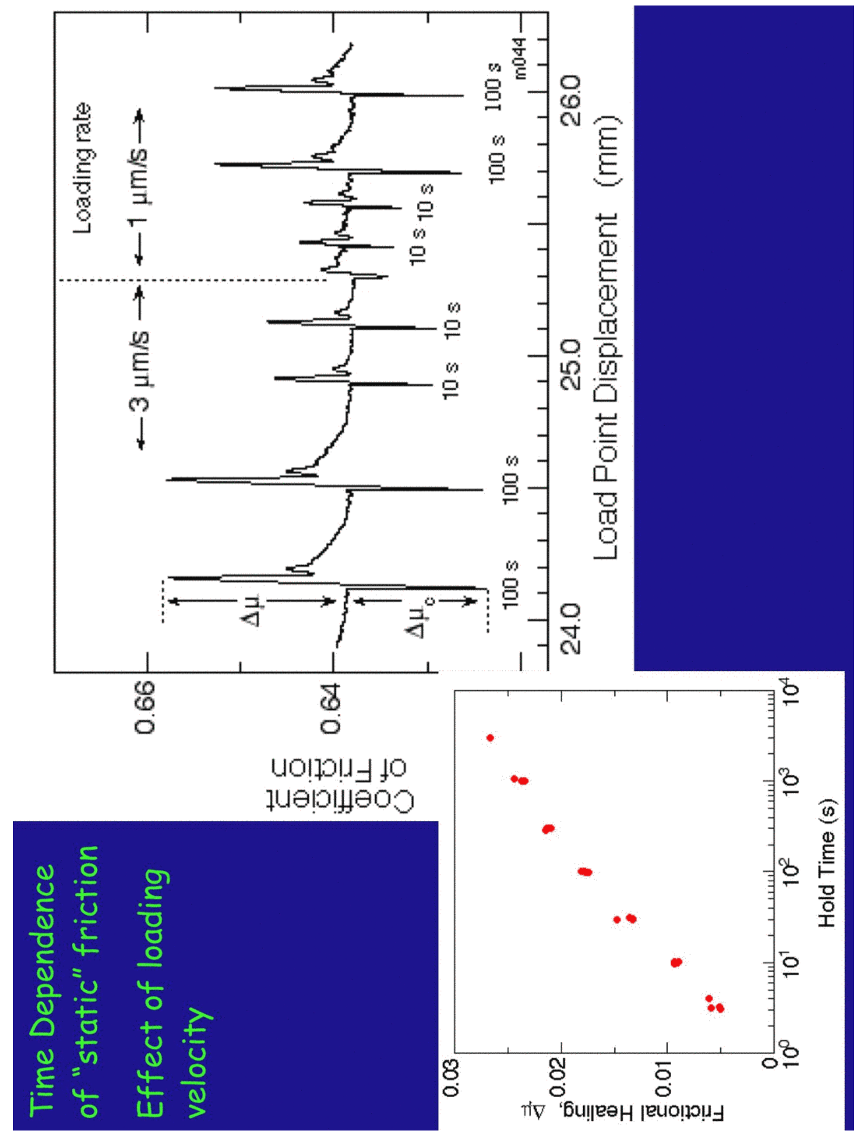

Aging, Frictional Healing, Time Dependence
Load point
Fault surface
Monodisperse, angular quartz particles
Load-up sequence
C-SHS
Partial unload SHS
Zero load SHS
100s hold
100s holds
100s holds
Loading rate 10 µm/s
Unloading rate 300 µm/s
m295
Friction (µ=τ/σn)
Shear Displacement (mm)
Karner & Marone (GRL 1998, JGR 2001)

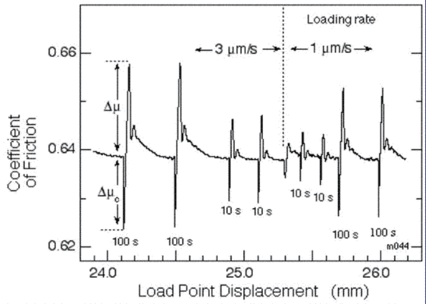

Time Dependence of "static" friction
Stressed Aging
500 µm
Loading rate
3 µm/s
1 µm/s
Δµ
Δµc
100 s
10 s
m044
Coefficient of Friction
Load Point Displacement (mm)
Monodisperse, angular quartz particles (100-150 µm)
3 mm thick layer sheared at 25 MPa normal stress.
Marone, 1998

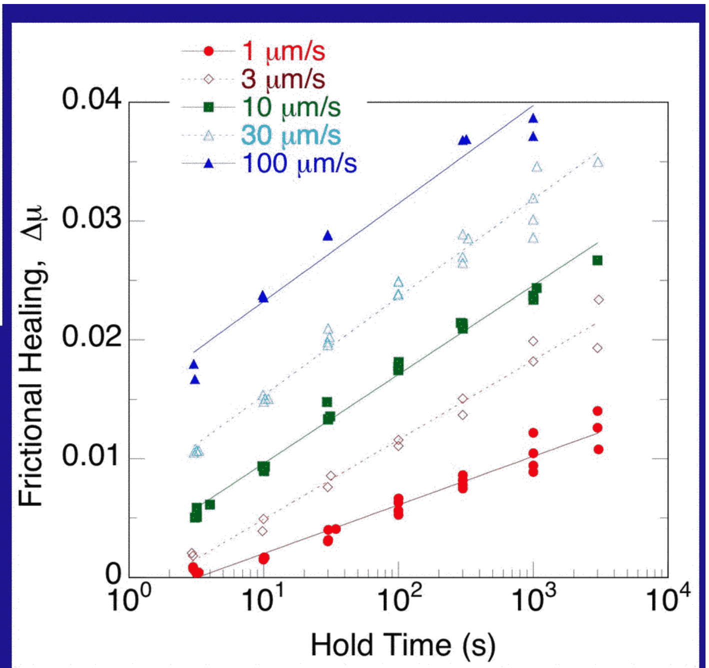

1044 s hold, $V_{s/r}$ = 10 µm/s
Coefficient of Friction
Displacement (mm)
Hold
Reload
m080
1044 s hold, $V_{s/r}$ = 10 µm/s
Δμ
1044 s
Time (s)
Loading rate
3 µm/s
1 µm/s
Δμ
$Δμ_c$
100 s
10 s
m044
Coefficient of Friction
Load Point Displacement (mm)
Sheared layer of quartz particles
(100-150 µm), 25 MPa normal stress .
Marone, 1998


1044 s hold, $V_{s/r}$ = 10 µm/s
Load point
Fault surface
Hold
Reload
m080
Coefficient of Friction
Displacement (mm)
Load point
Fault surface


Time Dependence
of "static" friction
Stressed Aging
Monodisperse,
angular
quartz
particles
Loading rate
3 μm/s
1 μm/s
Load Point Displacement (mm)
Hold Time (s)
Frictional Healing, Δμ


Time Dependence
of "static" friction
Effect of loading
velocity
Loading rate
3 μm/s
1 μm/s
Coefficient
of Friction
Load Point Displacement (mm)
Hold Time (s)
Frictional Healing, Δμ

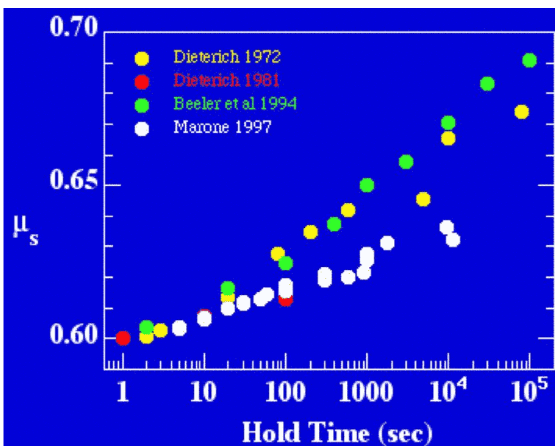




Stressed Aging

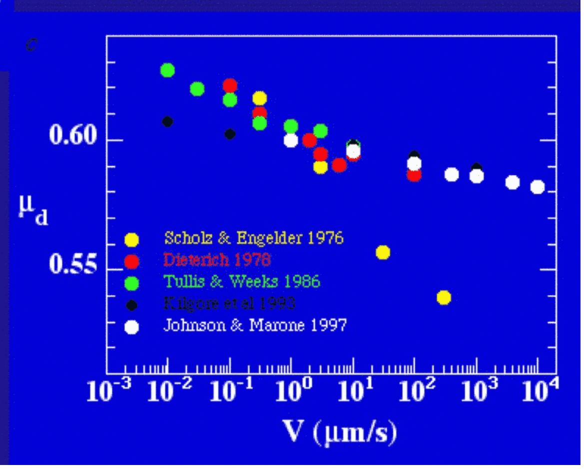
Aging rate depends on the rate of shearing

(Marone, 1998, *Nature*)



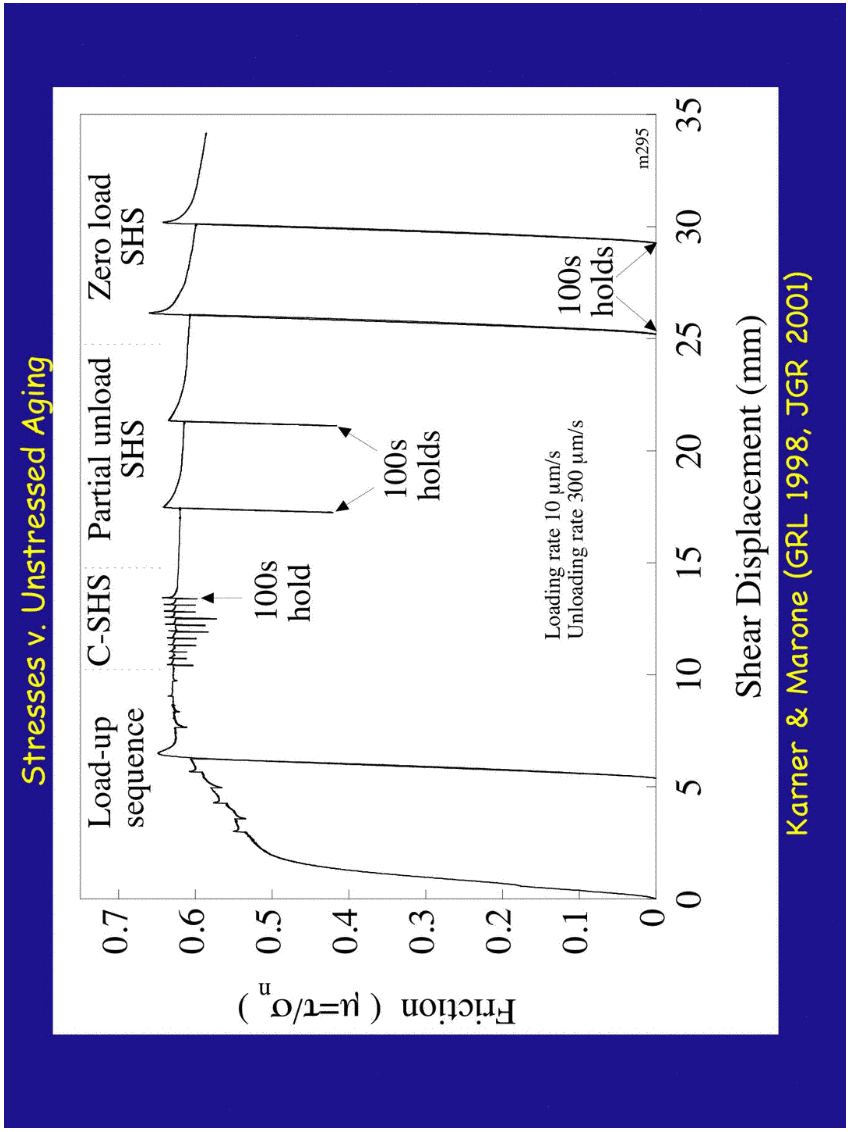
Time dependence of friction
Aging

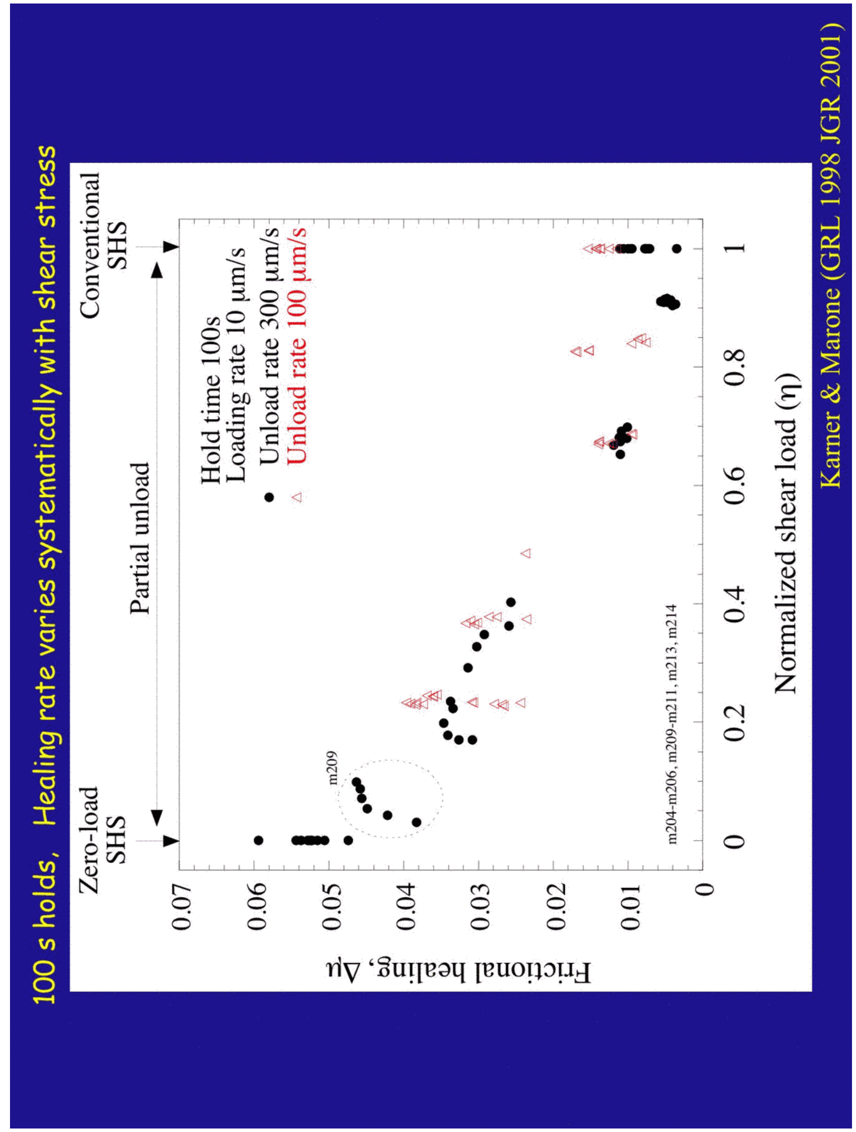
Velocity (rate) dependence of friction.

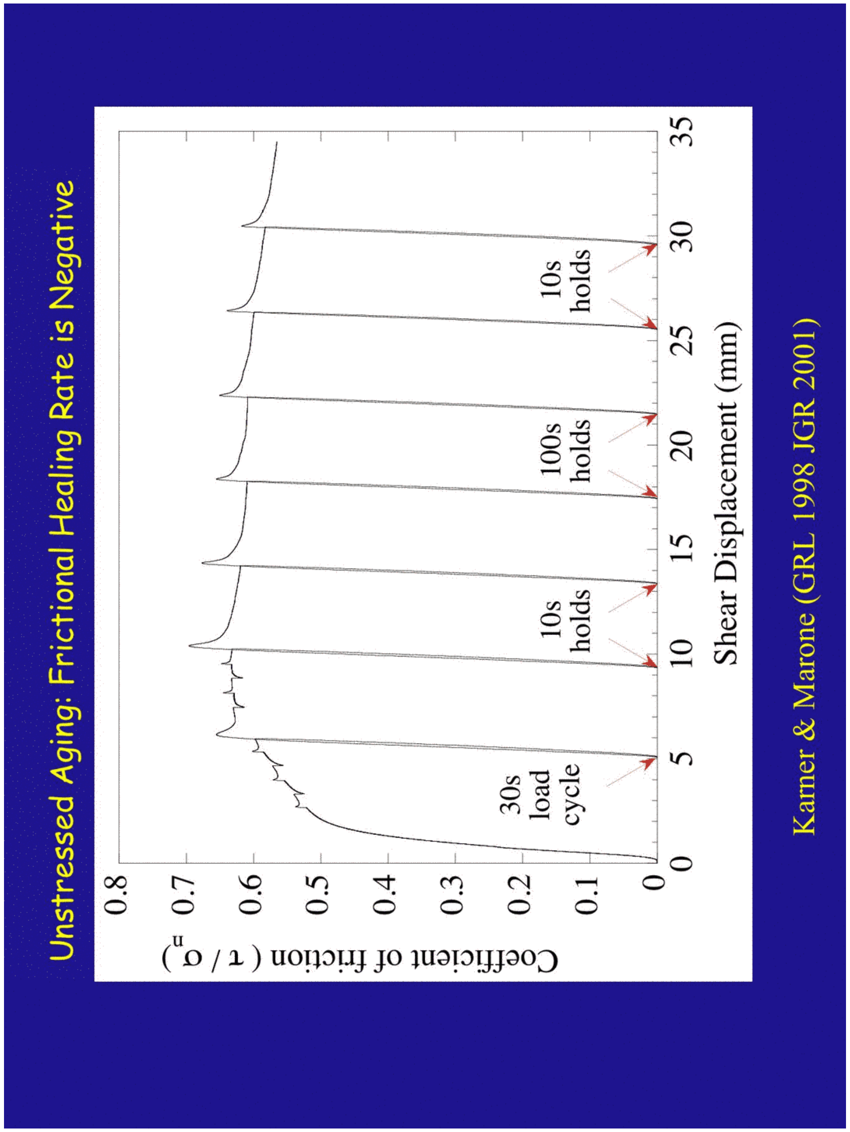


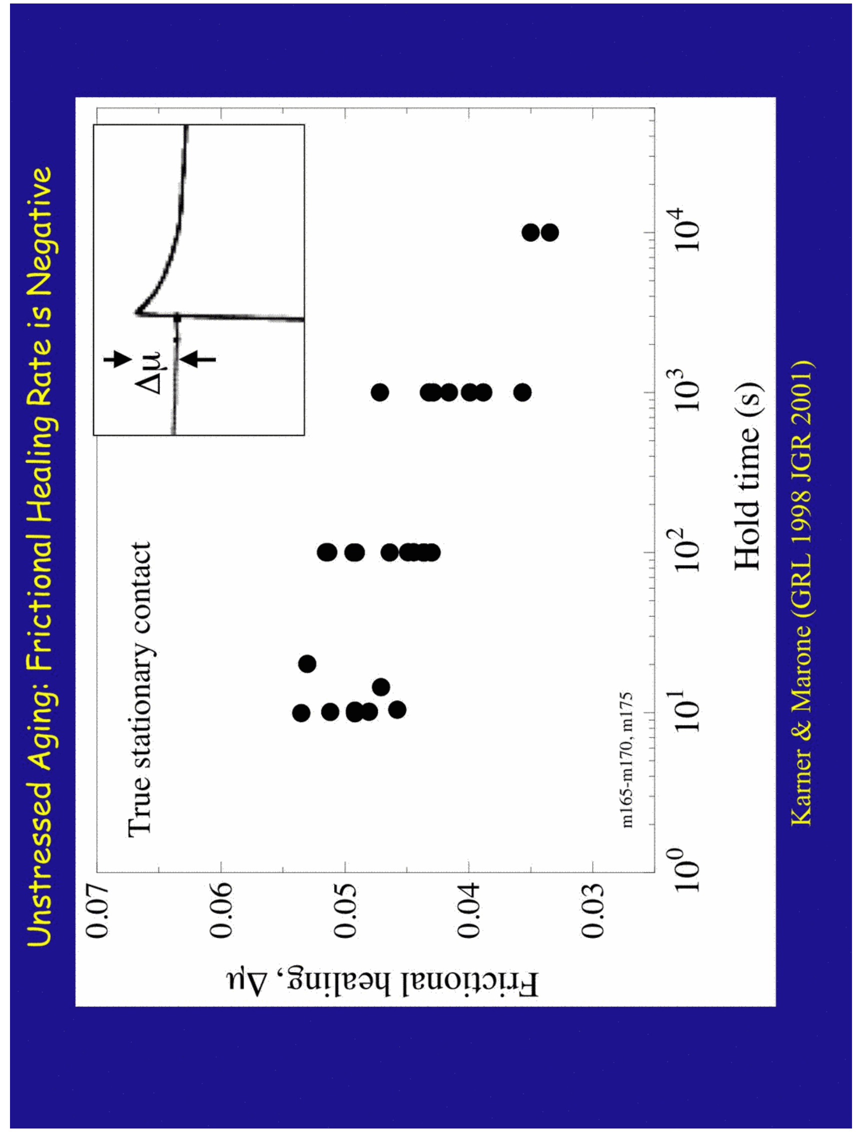
Duality of time and displacement dependence of friction.

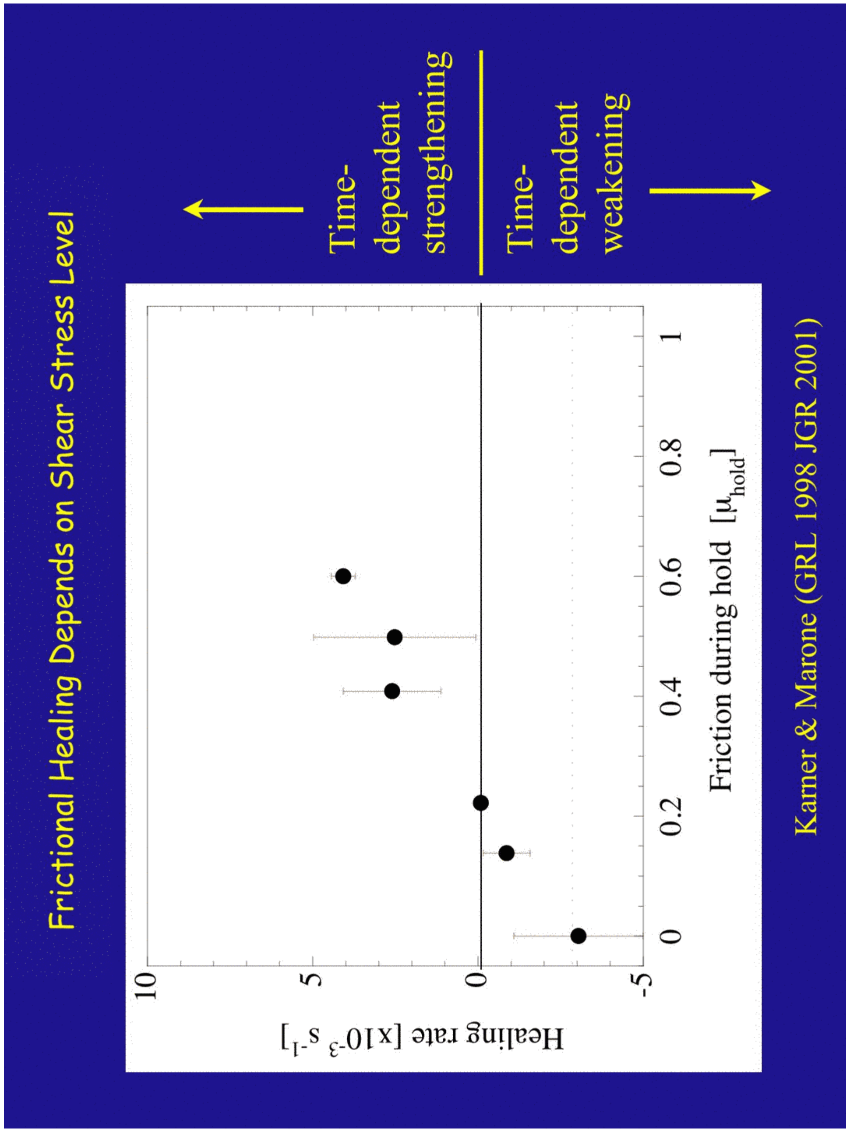
Static and *dynamic* friction are special cases of a more general behavior

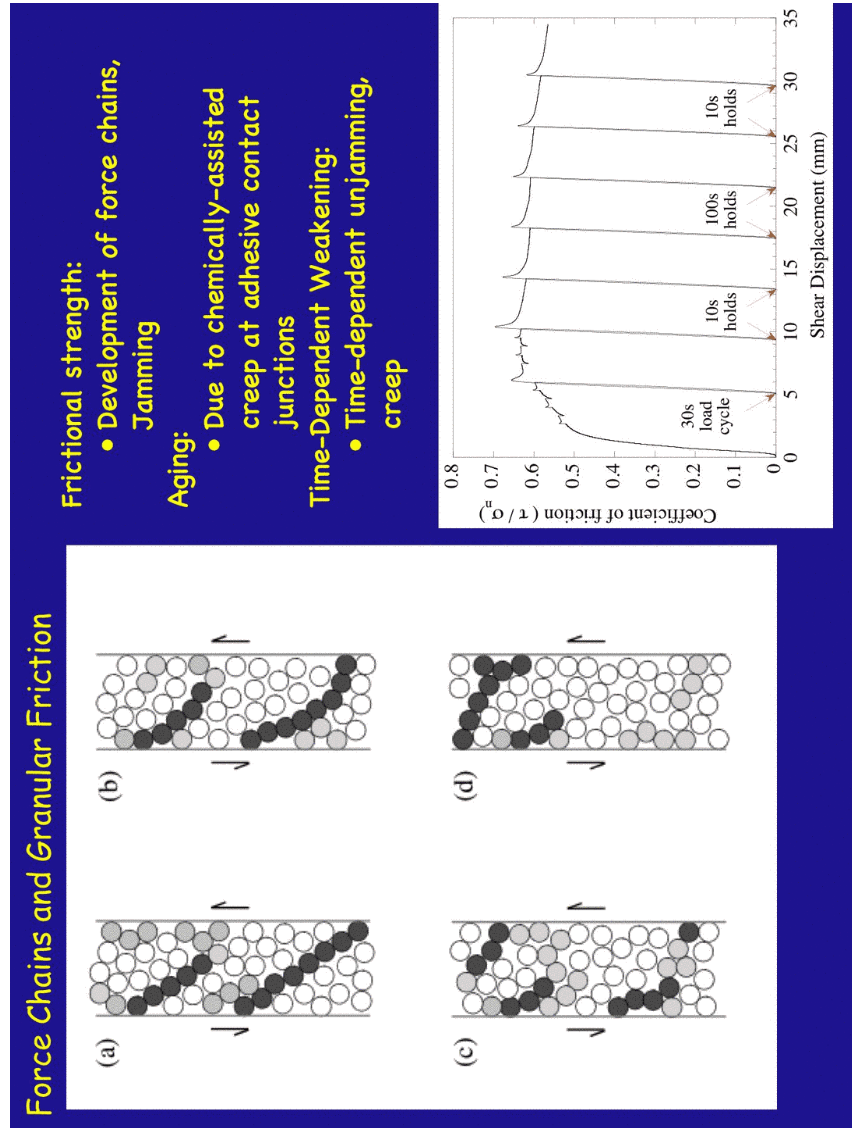

Stresses v. Unstressed Aging
Load-up sequence
C-SHS
Partial unload SHS
Zero load SHS
100s hold
100s holds
100s holds
Loading rate 10 µm/s
Unloading rate 300 µm/s
m295
Friction (µ=τ/σn)
Shear Displacement (mm)
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7
0 5 10 15 20 25 30 35
Karner & Marone (GRL 1998, JGR 2001)

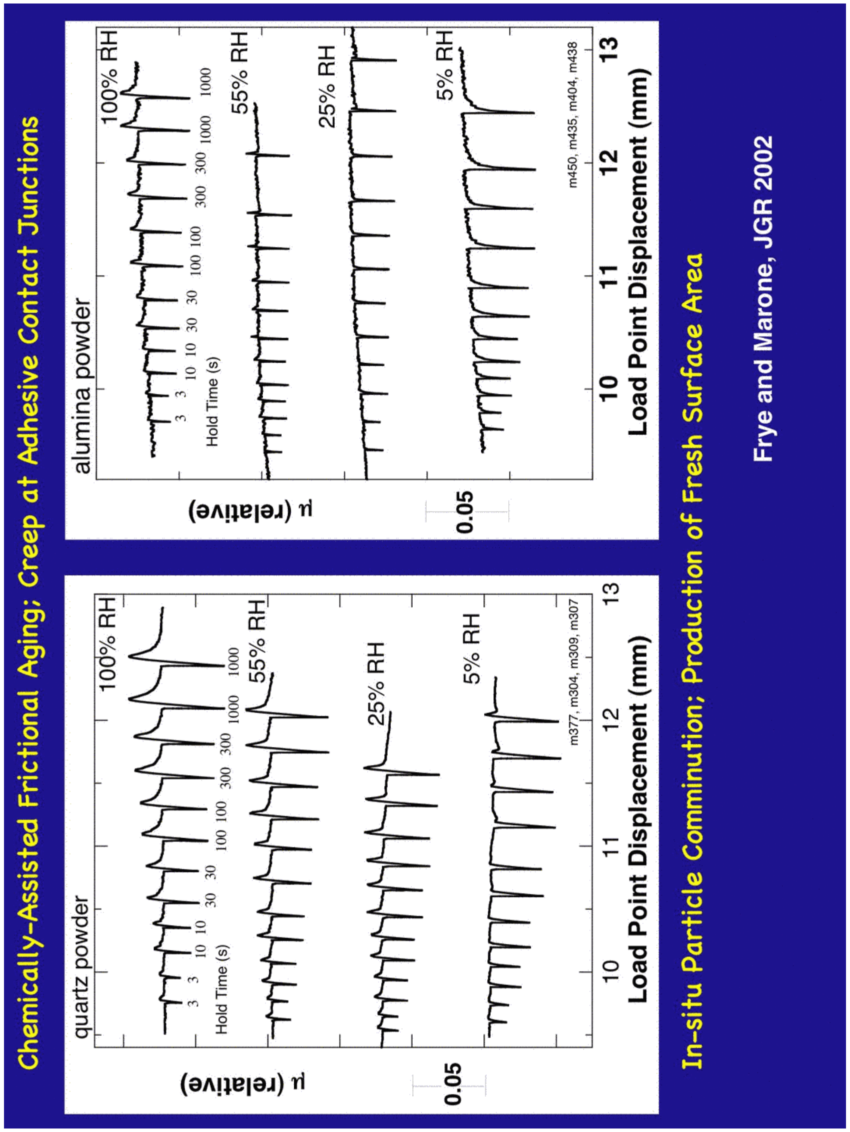

100 s holds, Healing rate varies systematically with shear stress
Zero-load SHS
Partial unload
Conventional SHS
Hold time 100s
Loading rate 10 µm/s
Unload rate 300 µm/s
Unload rate 100 µm/s
m209
m204-m206, m209-m211, m213, m214
Frictional healing, Δµ
Normalized shear load (η)
0 0.01 0.02 0.03 0.04 0.05 0.06 0.07
0 0.2 0.4 0.6 0.8 1
Karner & Marone (GRL 1998 JGR 2001)

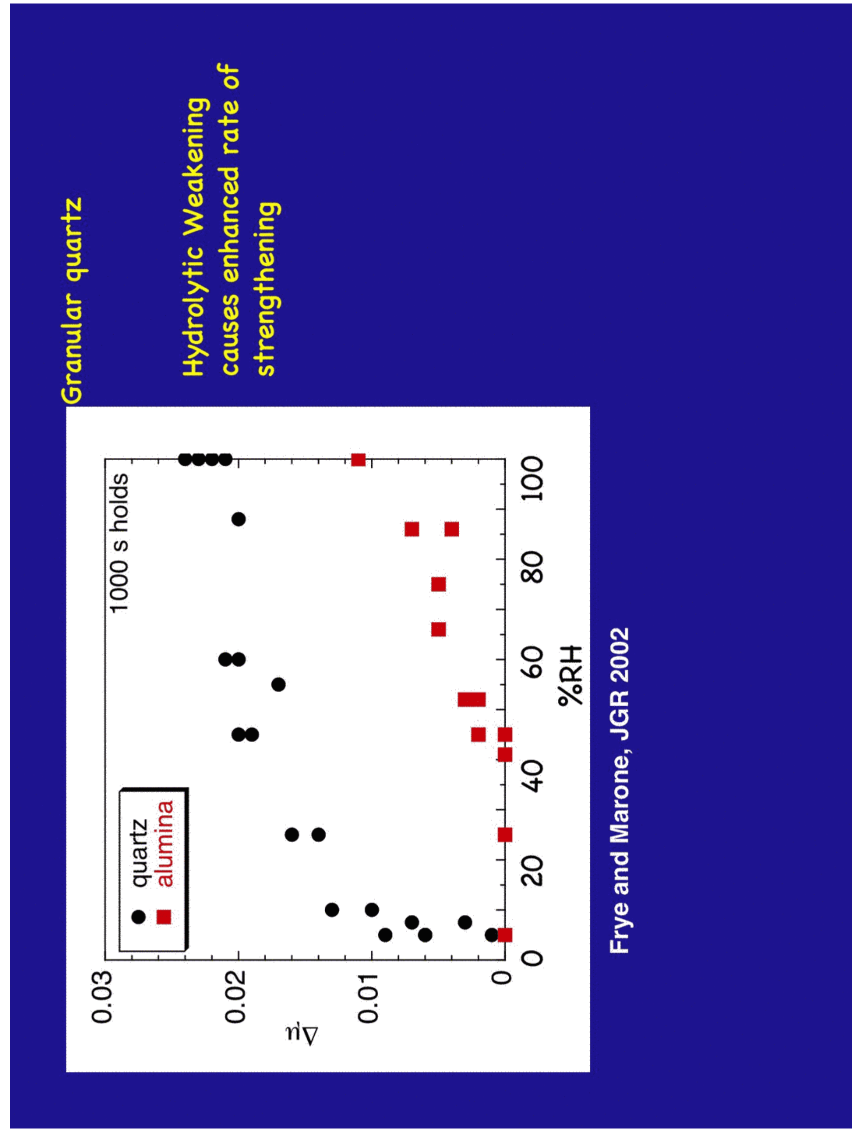

Unstressed Aging: Frictional Healing Rate is Negative
Coefficient of friction (τ / σn)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
30s load cycle
10s holds
100s holds
10s holds
0
5
10
15
20
25
30
35
Shear Displacement (mm)
Karner & Marone (GRL 1998 JGR 2001)


Unstressed Aging: Frictional Healing Rate is Negative
Frictional healing, Δμ
0.07
0.06
0.05
0.04
0.03
True stationary contact
Δμ
m165-m170, m175
10^0
10^1
10^2
10^3
10^4
Hold time (s)
Karner & Marone (GRL 1998 JGR 2001)

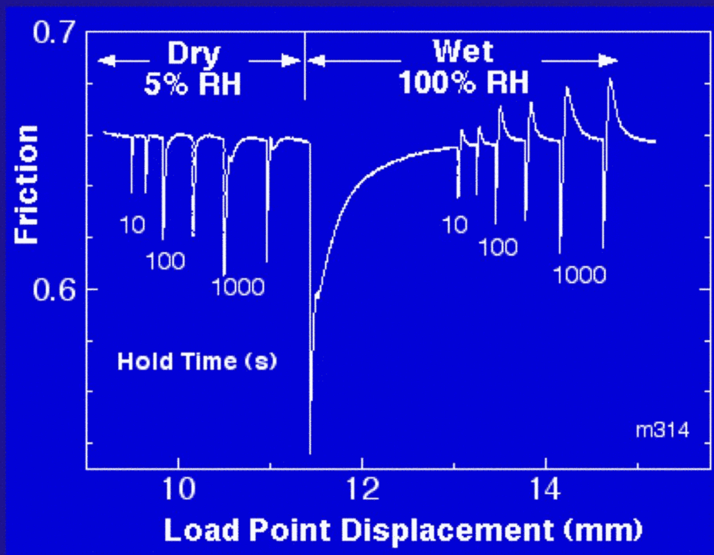

Frictional Healing Depends on Shear Stress Level
Time-dependent strengthening
Time-dependent weakening
Healing rate [x10-3 s-1]
Friction during hold [μhold]
Karner & Marone (GRL 1998 JGR 2001)


Force Chains and Granular Friction
(a)
(b)
(c)
(d)
Frictional strength:
• Development of force chains, Jamming
Aging:
• Due to chemically-assisted creep at adhesive contact junctions
Time-Dependent Weakening:
• Time-dependent unjamming, creep
Coefficient of friction (τ / σn)
Shear Displacement (mm)
30s load cycle
10s holds
100s holds
10s holds


Chemically-Assisted Frictional Aging; Creep at Adhesive Contact Junctions
quartz powder
alumina powder
100% RH
55% RH
25% RH
5% RH
Hold Time (s)
3 3 10 10 30 30 100 100 300 300 1000 1000
μ (relative)
0.05
m377, m304, m309, m307
m450, m435, m404, m438
10 11 12 13
Load Point Displacement (mm)
In-situ Particle Comminution; Production of Fresh Surface Area
Frye and Marone, JGR 2002


Granular quartz
Hydrolytic Weakening causes enhanced rate of strengthening
1000 s holds
quartz
alumina
Δμ
0 0.01 0.02 0.03
0 20 40 60 80 100
%RH
Frye and Marone, JGR 2002

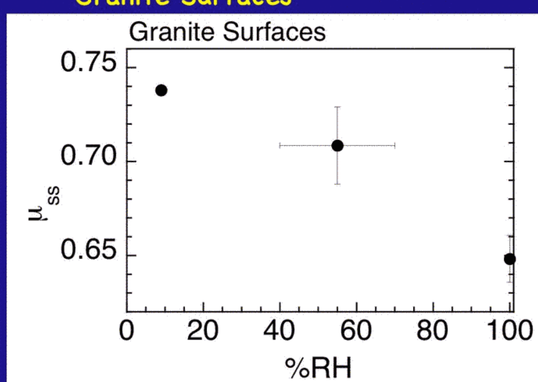
Chemically-Assisted Frictional Aging; Creep at Adhesive Contact Junctions



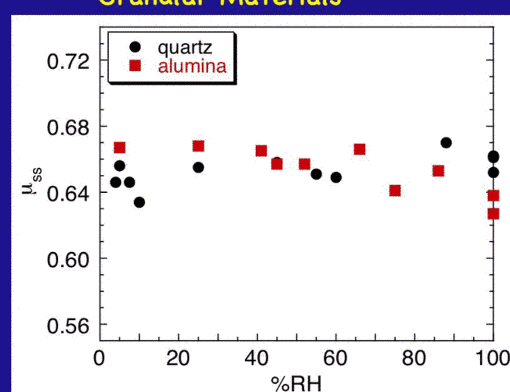
Hydrolytic Weakening causes enhanced rate of strengthening, but base level frictional strength is unchanged

Frye and Marone, JGR 2002

Granite Surfaces



Granular Materials

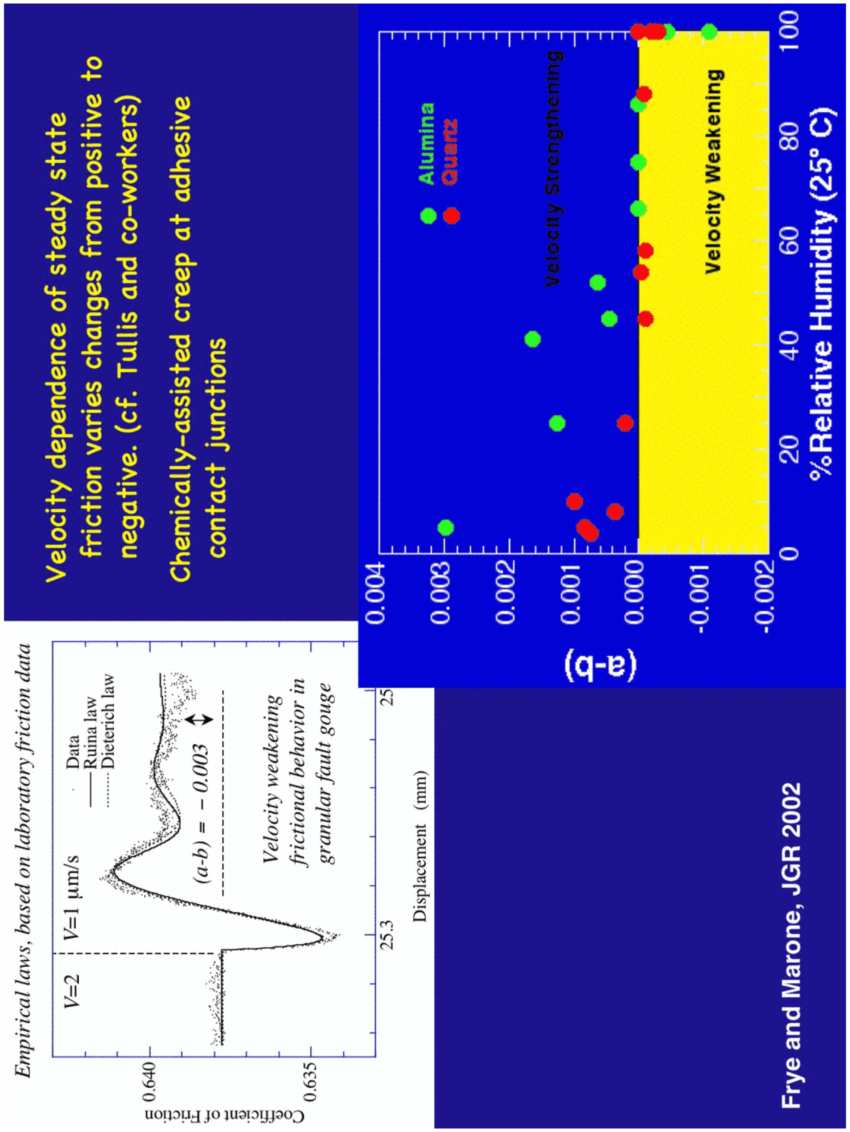


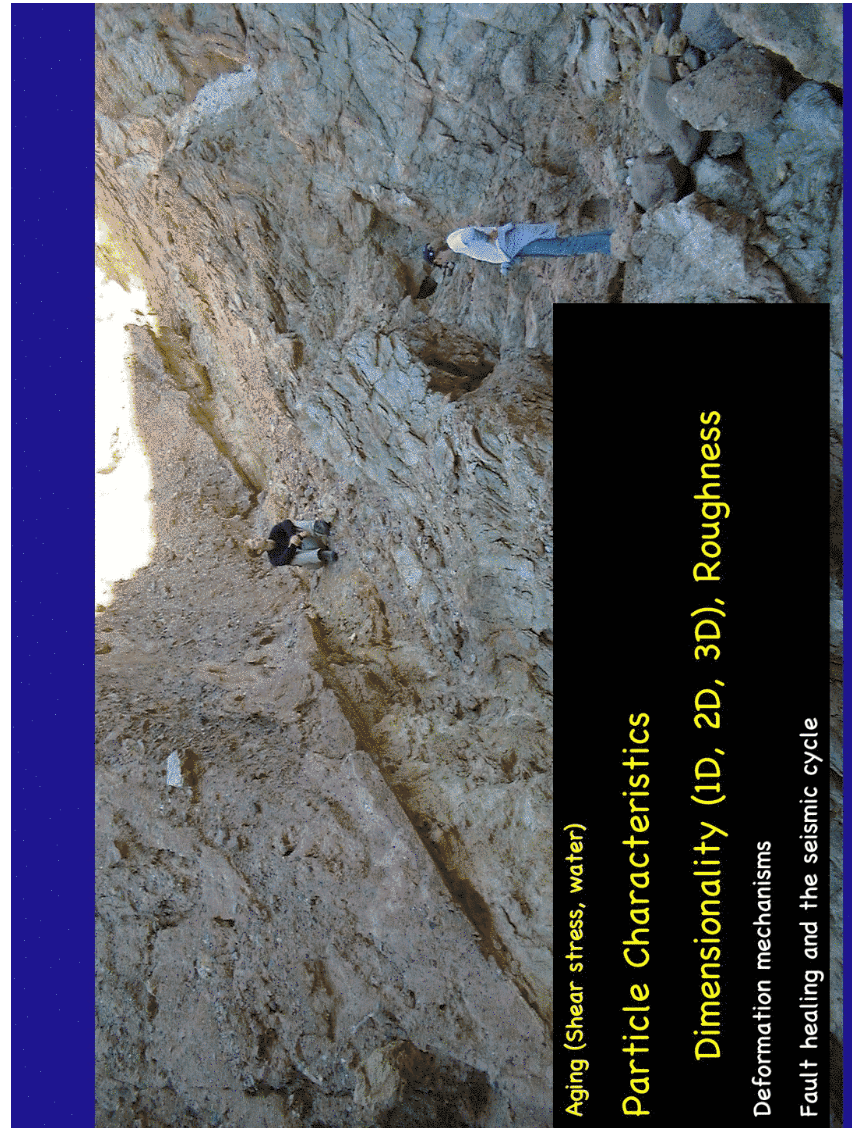
Solid Surfaces: Base level of frictional strength decreases with increasing water content (cf. Dieterich & Conrad, 1984)

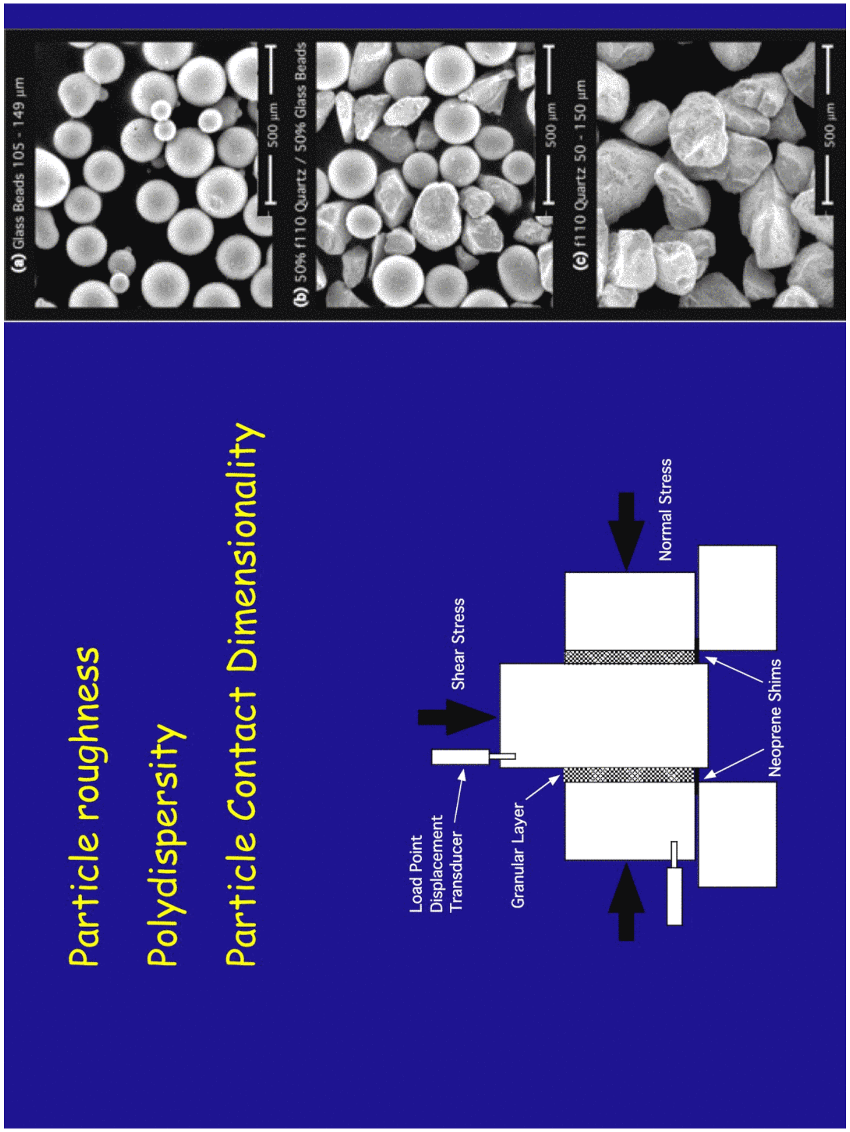
Granular Materials: Frictional strength is independent of water content

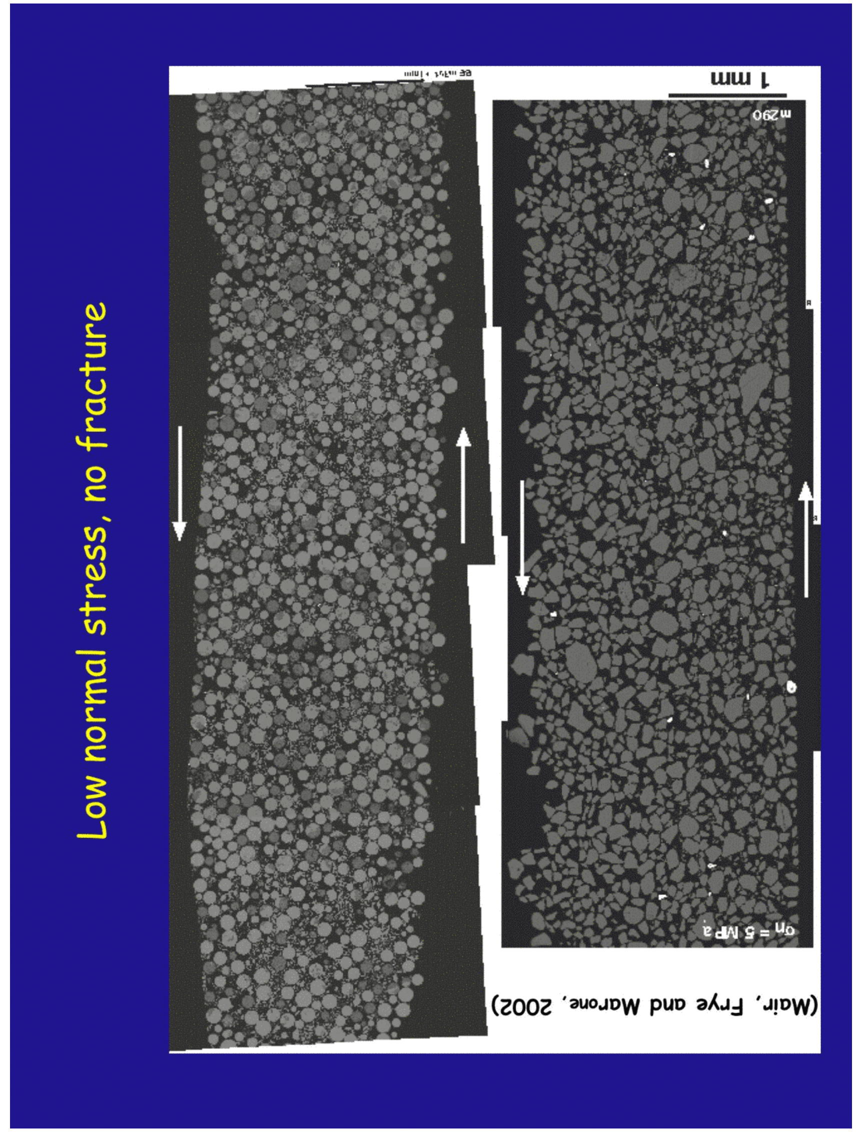
Interpretation: Contact junctions subject to time dependent strengthening or growth, which inhibits sliding, but particle rolling is not affected by these factors.

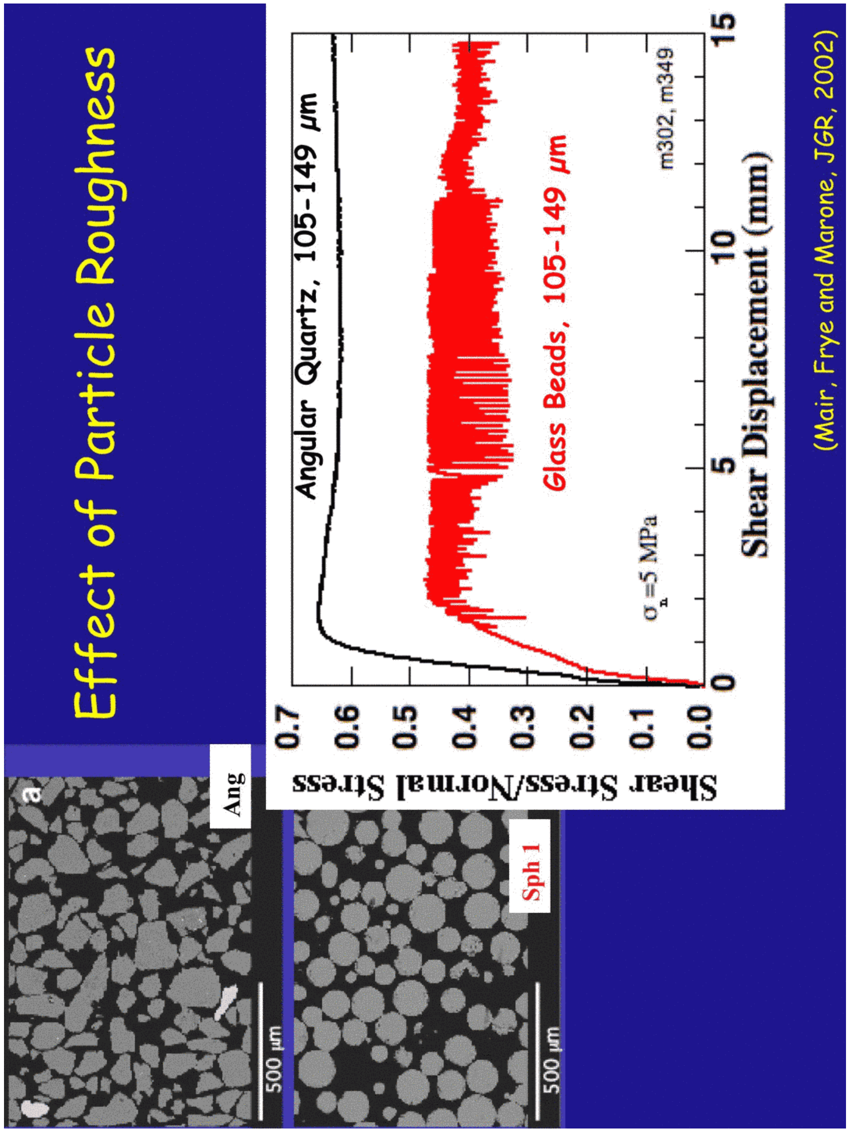
Frye and Marone, JGR 2002


Velocity dependence of steady state friction varies changes from positive to negative. (cf. Tullis and co-workers)
Chemically-assisted creep at adhesive contact junctions
Empirical laws, based on laboratory friction data
V=2
V=1 µm/s
Data
Ruina law
Dieterich law
(a-b) = − 0.003
Velocity weakening frictional behavior in granular fault gouge
Coefficient of Friction
0.640
0.635
25.3
Displacement (mm)
Alumina
Quartz
Velocity Strengthening
Velocity Weakening
(a-b)
0.004
0.003
0.002
0.001
0.000
-0.001
-0.002
0
20
40
60
80
100
%Relative Humidity (25° C)
Frye and Marone, JGR 2002

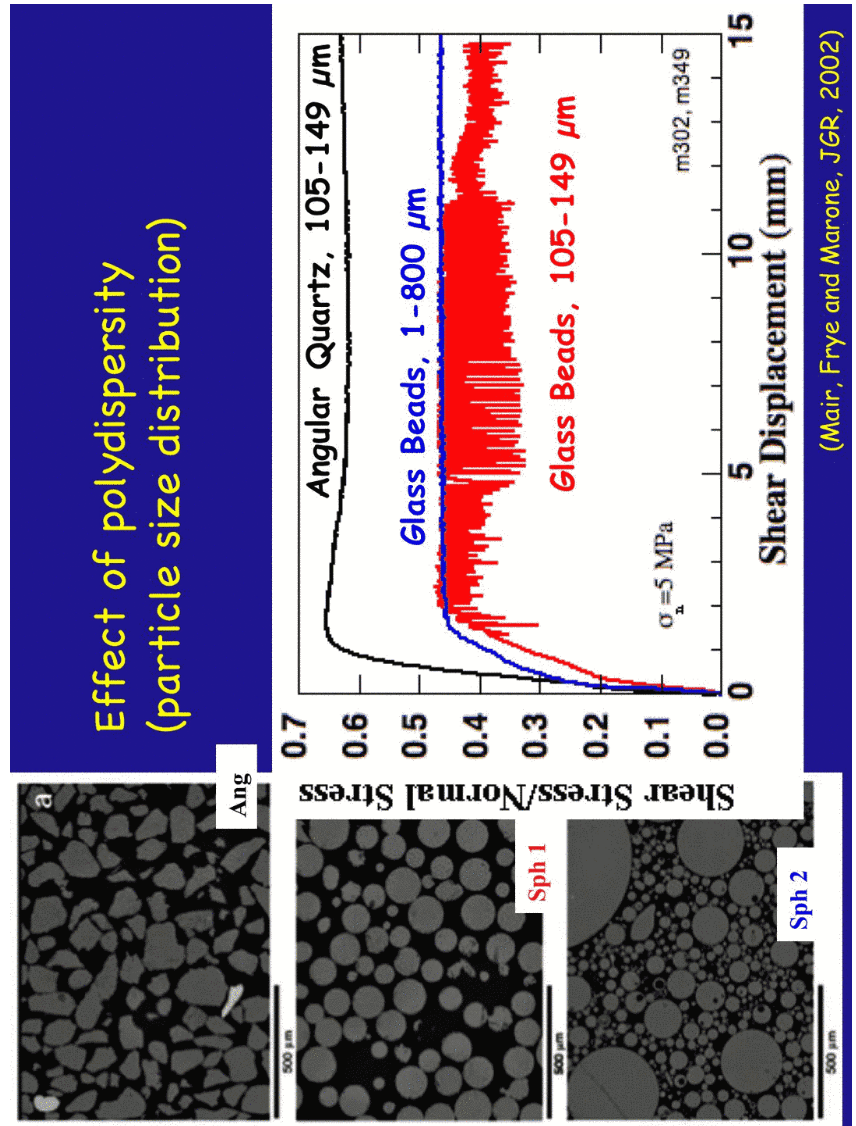

Aging (Shear stress, water)
Particle Characteristics
Dimensionality (1D, 2D, 3D), Roughness
Deformation mechanisms
Fault healing and the seismic cycle


(a) Glass Beads 105 - 149 µm
500 µm
(b) 50% f110 Quartz / 50% Glass Beads
500 µm
(c) f110 Quartz 50 - 150 µm
500 µm
Particle roughness
Polydispersity
Particle Contact Dimensionality
Normal Stress
Shear Stress
Neoprene Shims
Load Point Displacement Transducer
Granular Layer

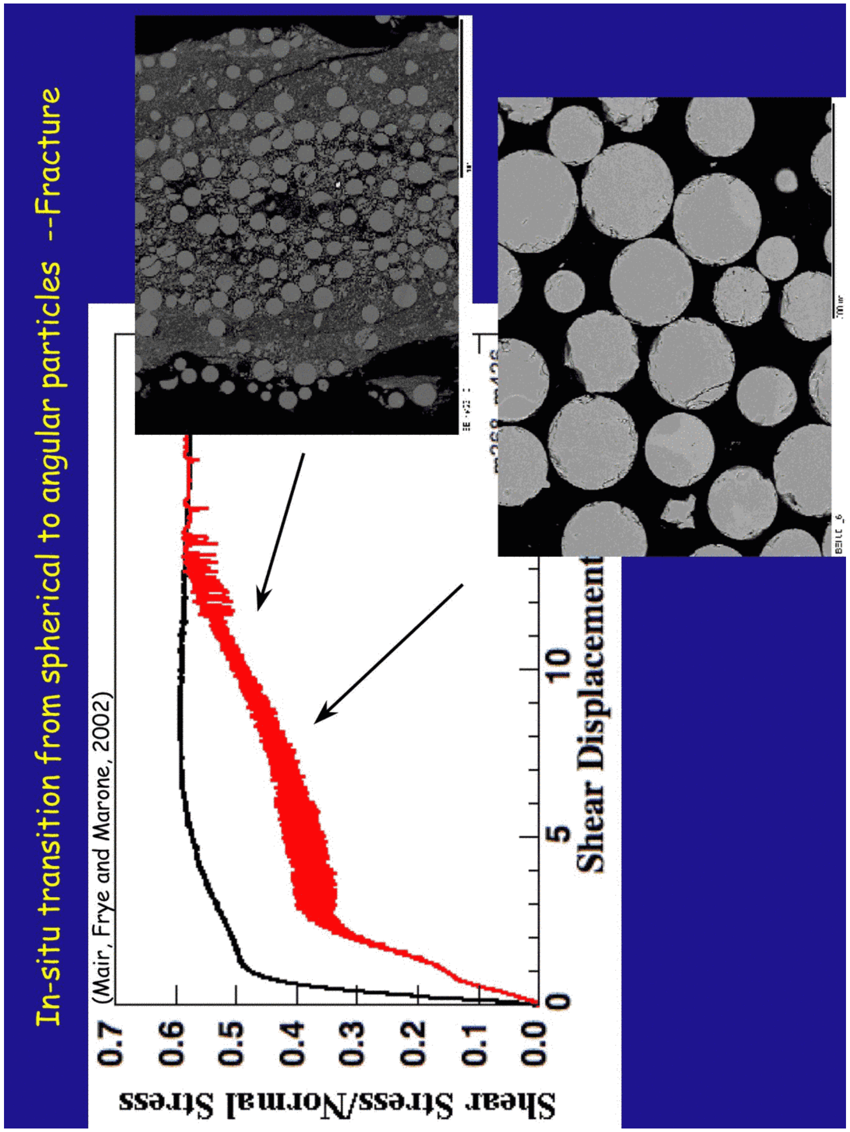

Low normal stress, no fracture
1 mm
σn = 5 MPa
(Mair, Frye and Marone, 2002)

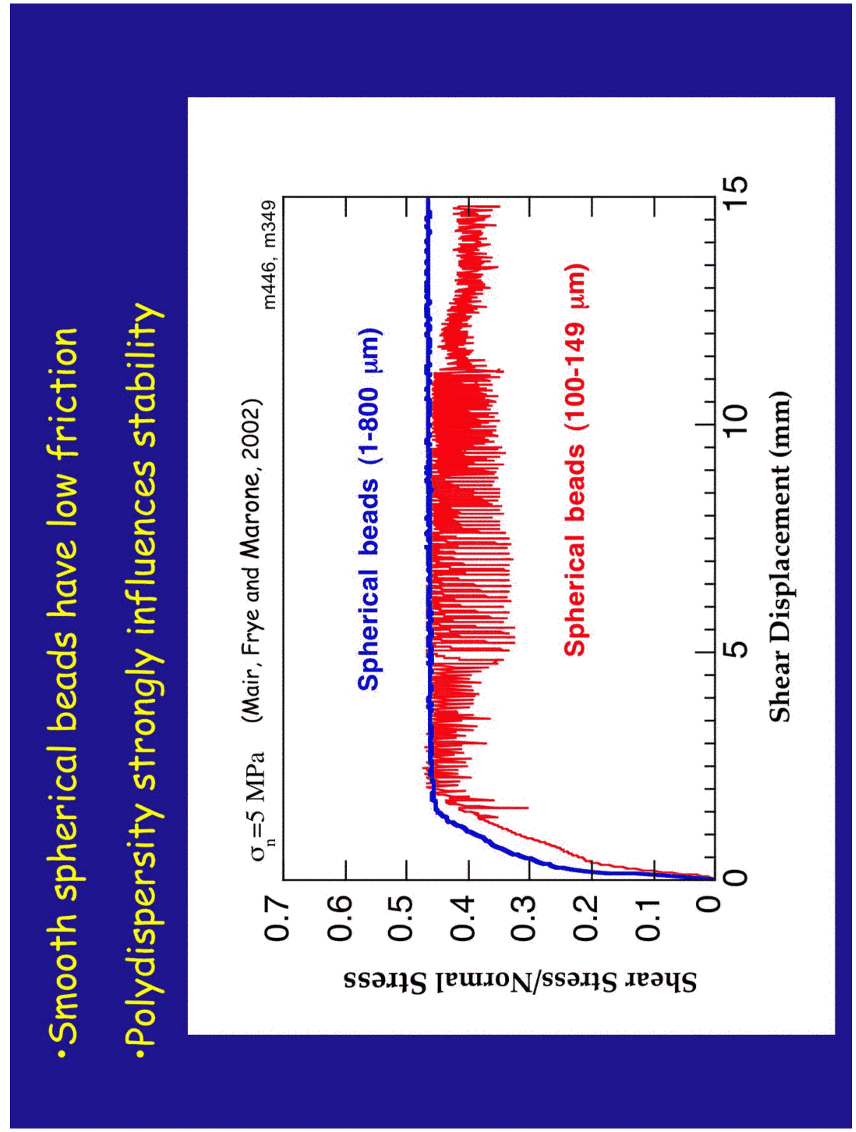


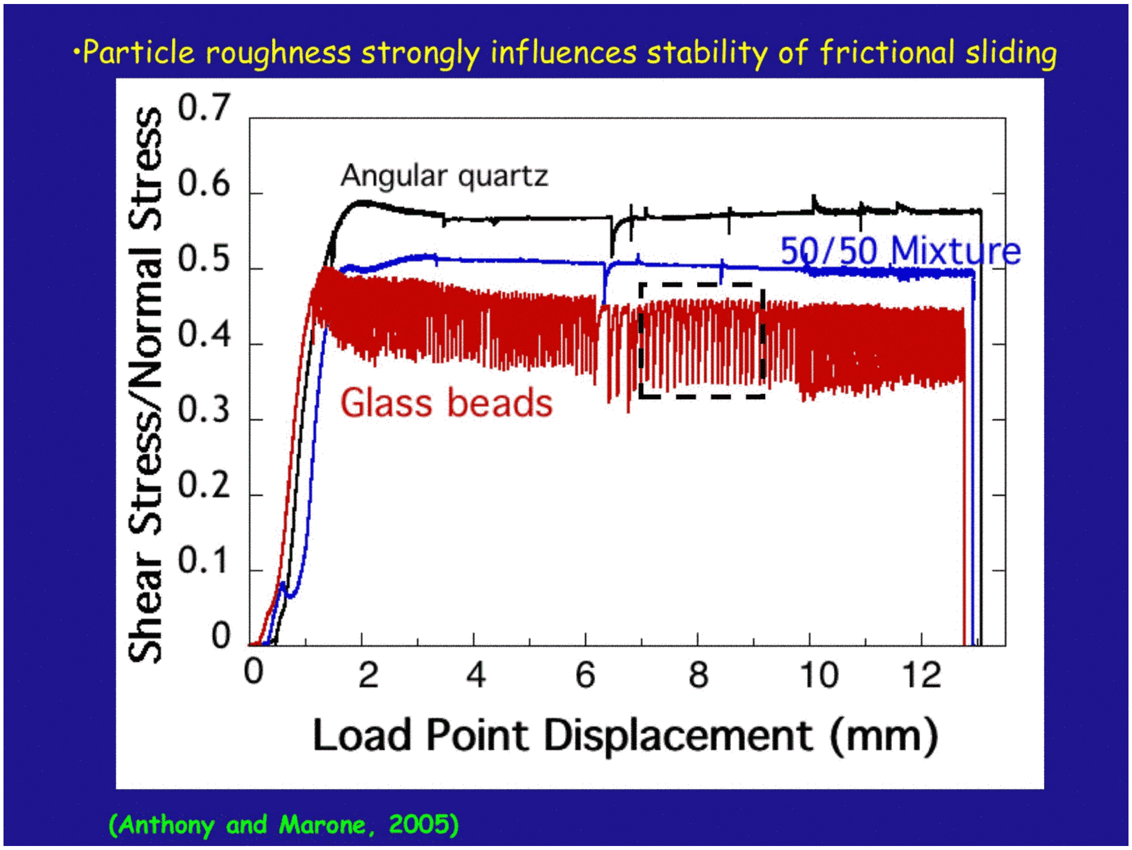
Effect of Particle Roughness
Angular Quartz, 105-149 μm
Glass Beads, 105-149 μm
σn=5 MPa
m302, m349
Shear Displacement (mm)
Shear Stress/Normal Stress
(Mair, Frye and Marone, JGR, 2002)
Ang
Sph 1
500 μm

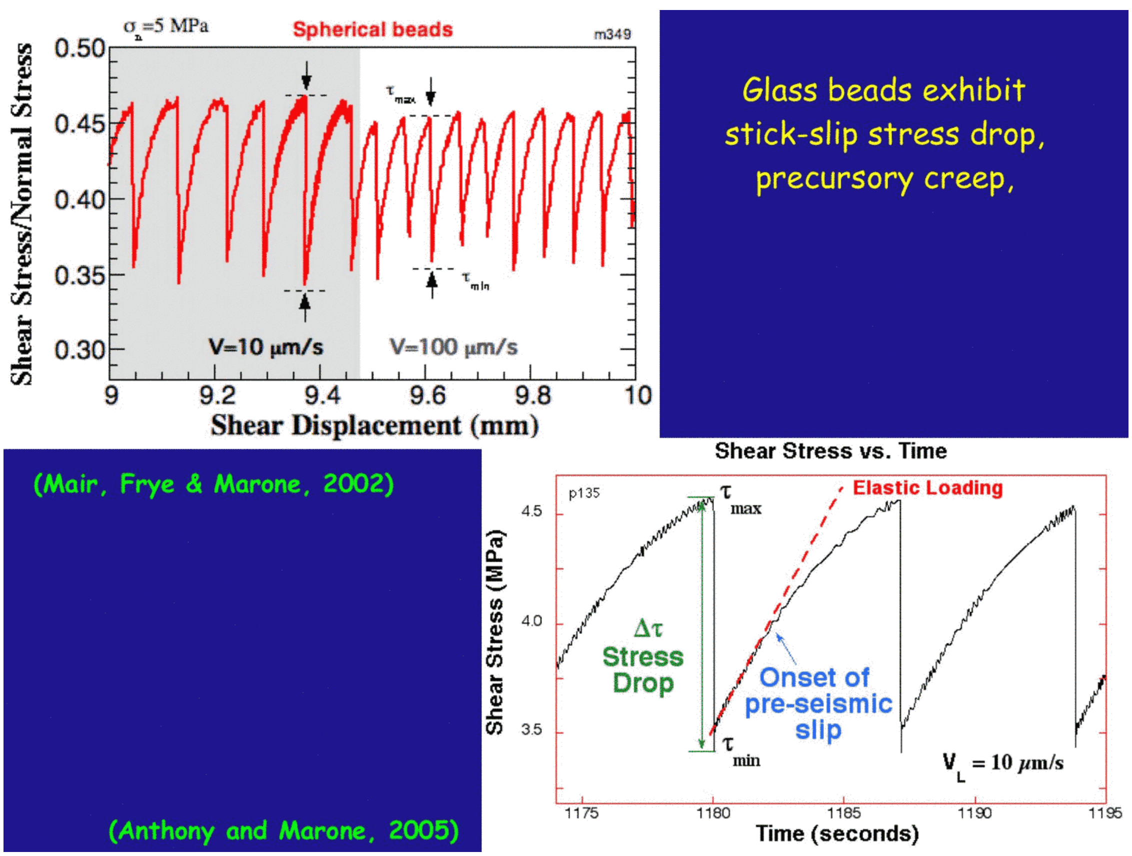


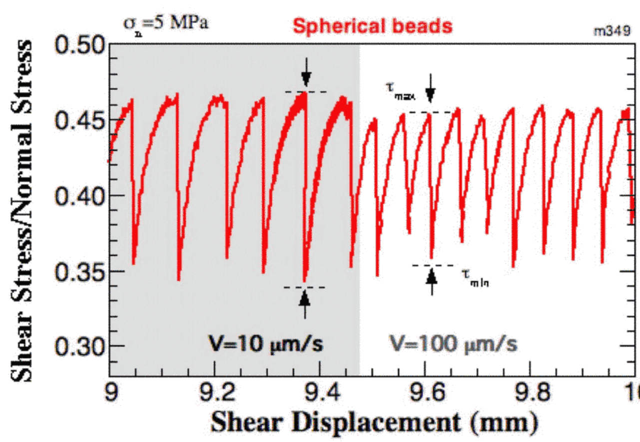
Effect of polydispersity
(particle size distribution)
Angular Quartz, 105-149 μm
Glass Beads, 1-800 μm
Glass Beads, 105-149 μm
σn=5 MPa
m302, m349
Shear Displacement (mm)
Shear Stress/Normal Stress
(Mair, Frye and Marone, JGR, 2002)
Ang
Sph 1
Sph 2


In-situ transition from spherical to angular particles --Fracture
(Mair, Frye and Marone, 2002)
Shear Stress/Normal Stress
Shear Displacement
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0
5
10


•Smooth spherical beads have low friction
•Polydispersity strongly influences stability
σ_n=5 MPa
(Mair, Frye and Marone, 2002)
m446, m349
Spherical beads (1-800 µm)
Spherical beads (100-149 µm)
Shear Stress/Normal Stress
Shear Displacement (mm)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0
5
10
15


•Particle roughness strongly influences stability of frictional sliding
Shear Stress/Normal Stress
Angular quartz
50/50 Mixture
Glass beads
Load Point Displacement (mm)
(Anthony and Marone, 2005)


Glass beads exhibit stick-slip stress drop, precursory creep,
σn=5 MPa
Spherical beads
m349
V=10 µm/s
V=100 µm/s
Shear Stress/Normal Stress
Shear Displacement (mm)
(Mair, Frye & Marone, 2002)
Shear Stress vs. Time
Elastic Loading
Onset of pre-seismic slip
Δτ Stress Drop
p135
VL = 10 µm/s
Shear Stress (MPa)
Time (seconds)
(Anthony and Marone, 2005)



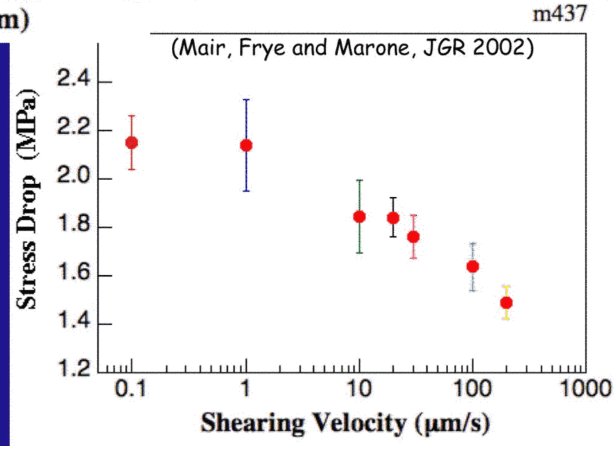
Glass beads exhibit stick-slip stress drop, precursory creep,

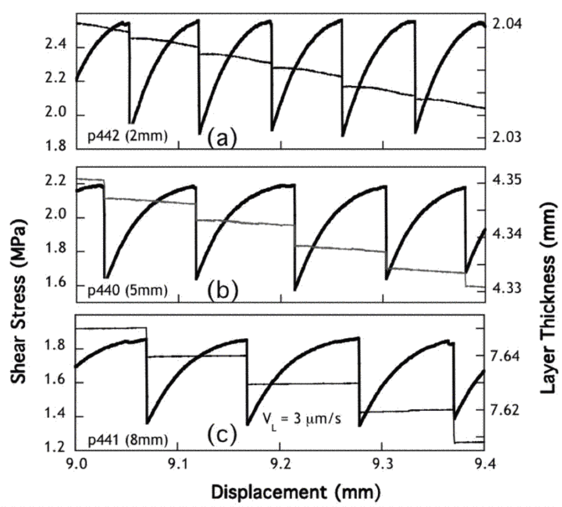
and larger stress drop for longer recurrence interval

(Mair, Frye & Marone, 2002)

Aging & Contact physics:

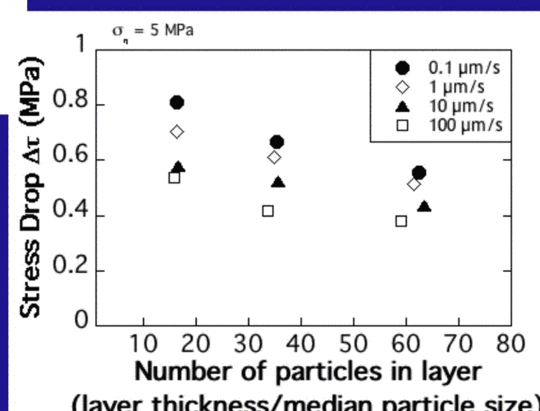
- Nothing different.
- Same mechanisms for spherical and angular particles.

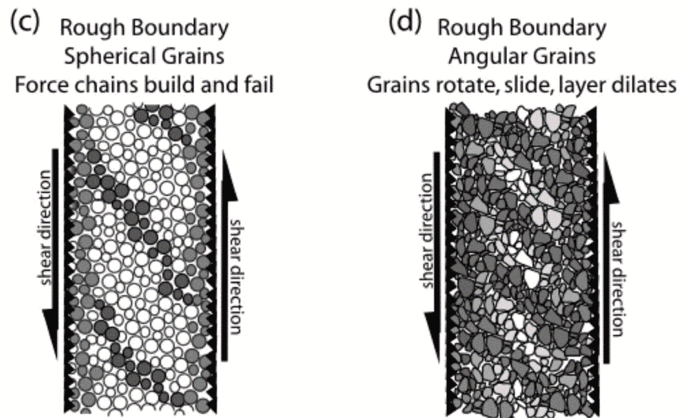




Magnitude of stick-slip stress drop scales inversely with layer thickness (decreases with increasing number of particles in a force chain)

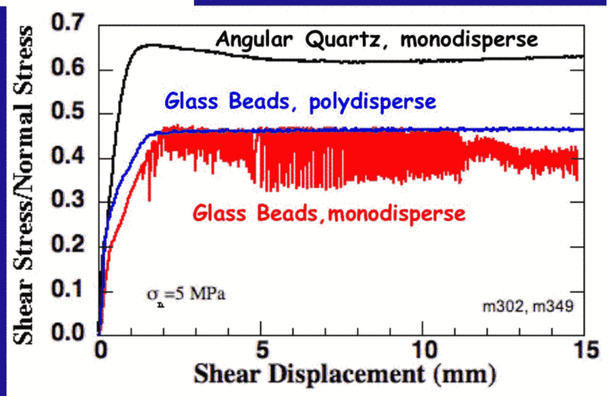
(Anthony and Marone, 2005)

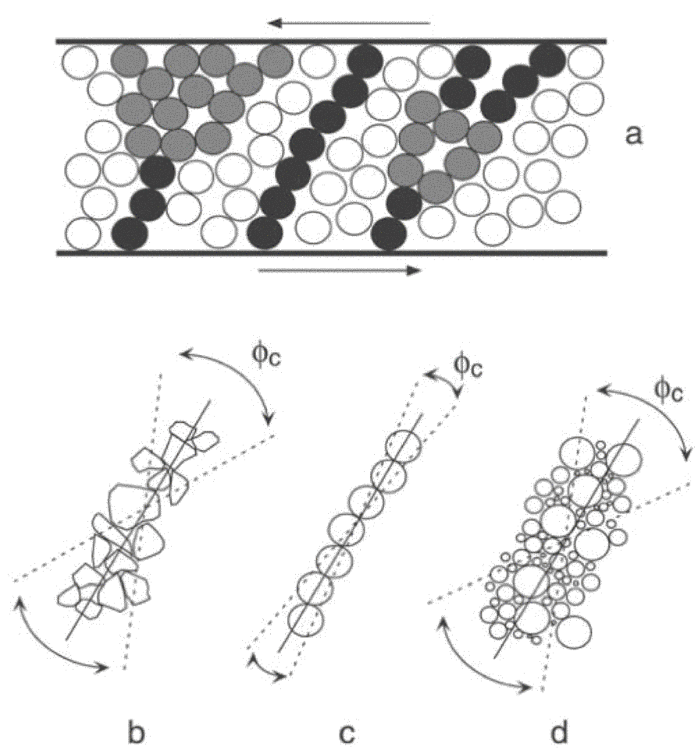




(Anthony and Marone, 2005)

Force chain geometry: width, length; Role of lateral stress

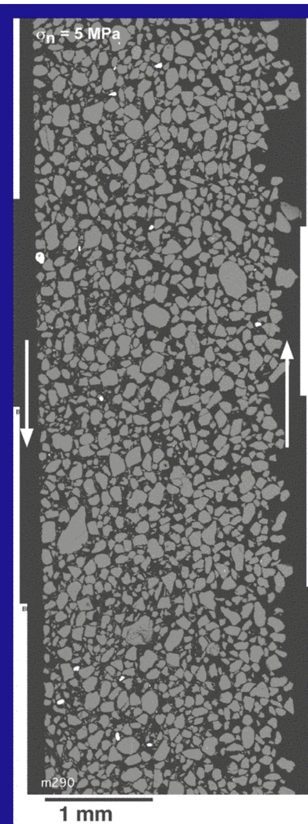




- Force chain geometry: width, length;
- Role of lateral stress
- Critical angle related to particle roughness

(Mair, Frye, & Marone, 2002)

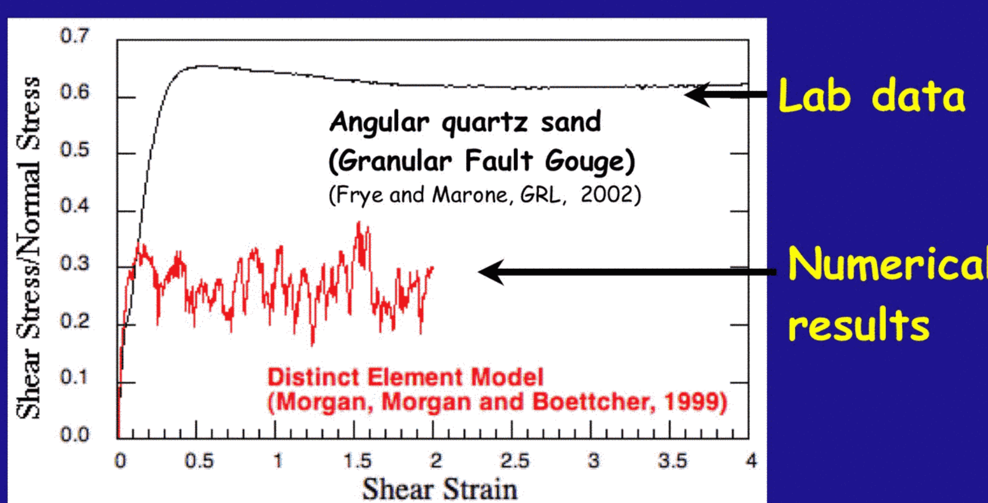
Granular friction: effect of particle dimensionality



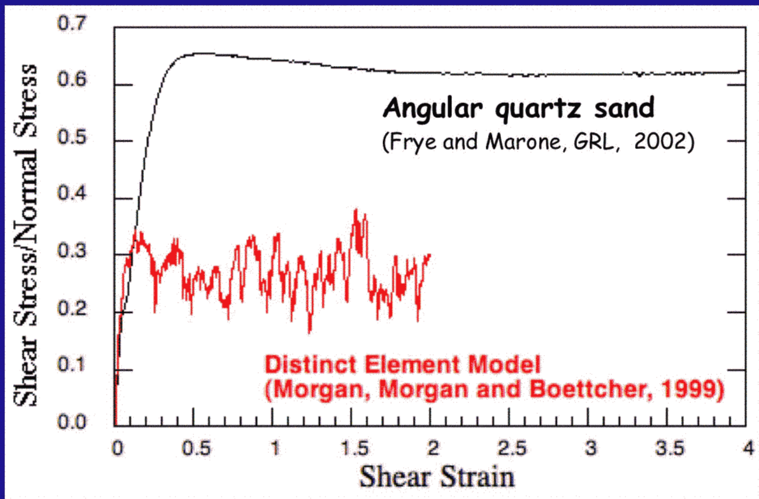
Mechanisms of Granular Shear

- Rolling
- Grain boundary sliding
- Dilation/compaction
- Fracture

- Comparison between numerical and laboratory studies of granular friction.
- 2D numerical models show lower friction coefficient and a different character of the strength curve.



2D Numerical models of granular friction typically find that sliding friction is ≤ 0.3, in contrast to lab results.



(Also Mora and co-workers)

Differences

- 2-D vs. 3-D particles
- Particle roughness
- Particle-size distribution
- Fracture

Granular friction: effect of particle dimensionality

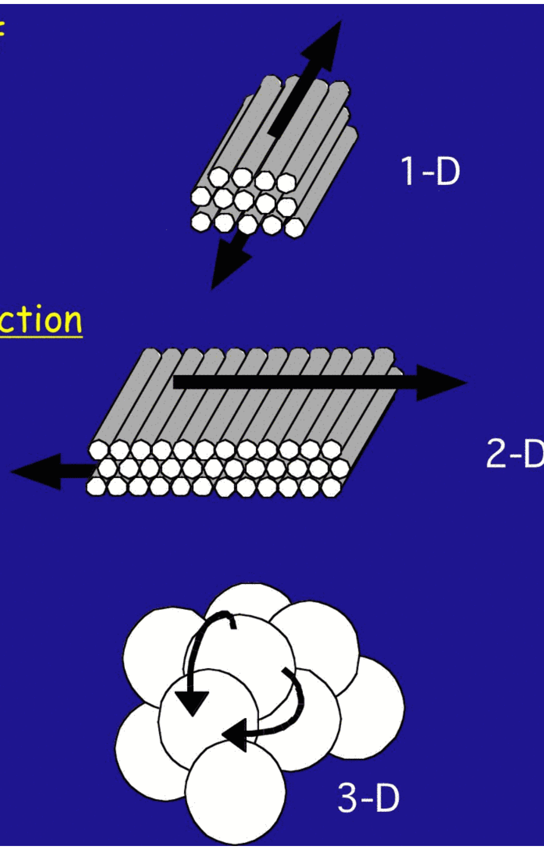
<u>Mechanisms of Granular Fiction</u>

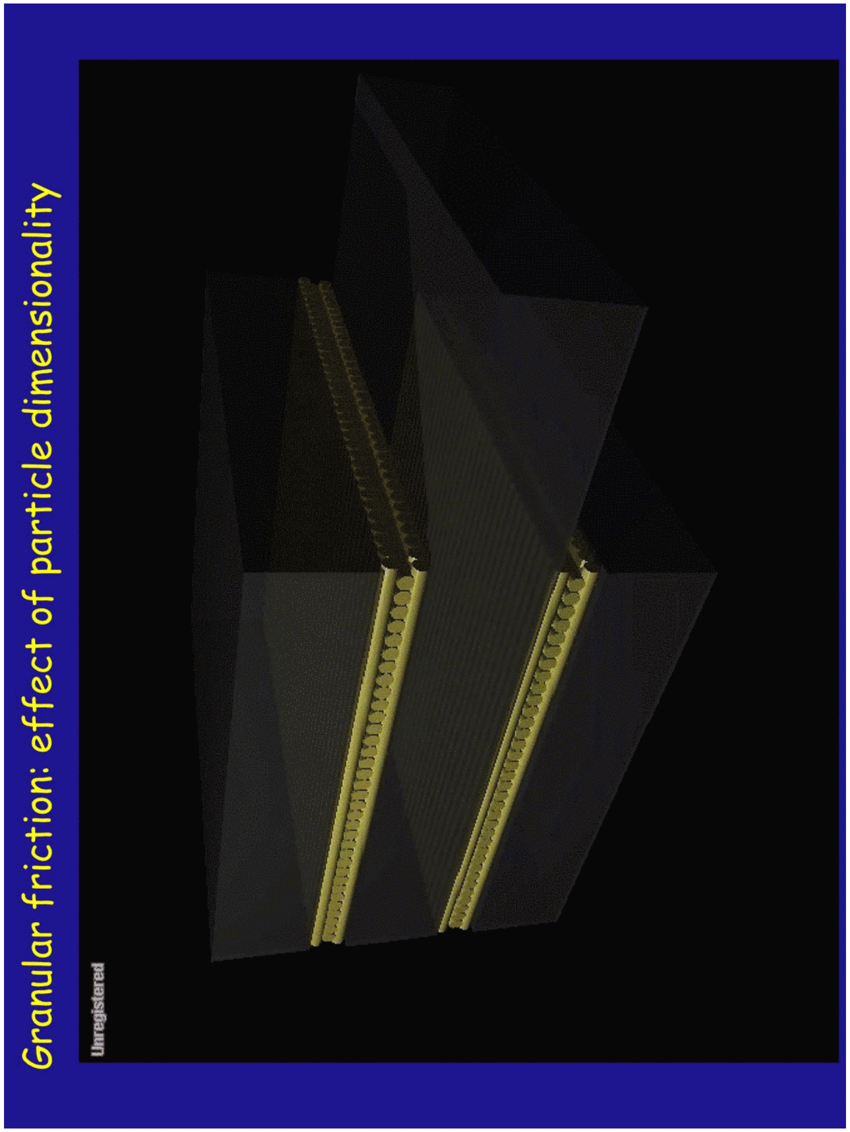
•Rolling

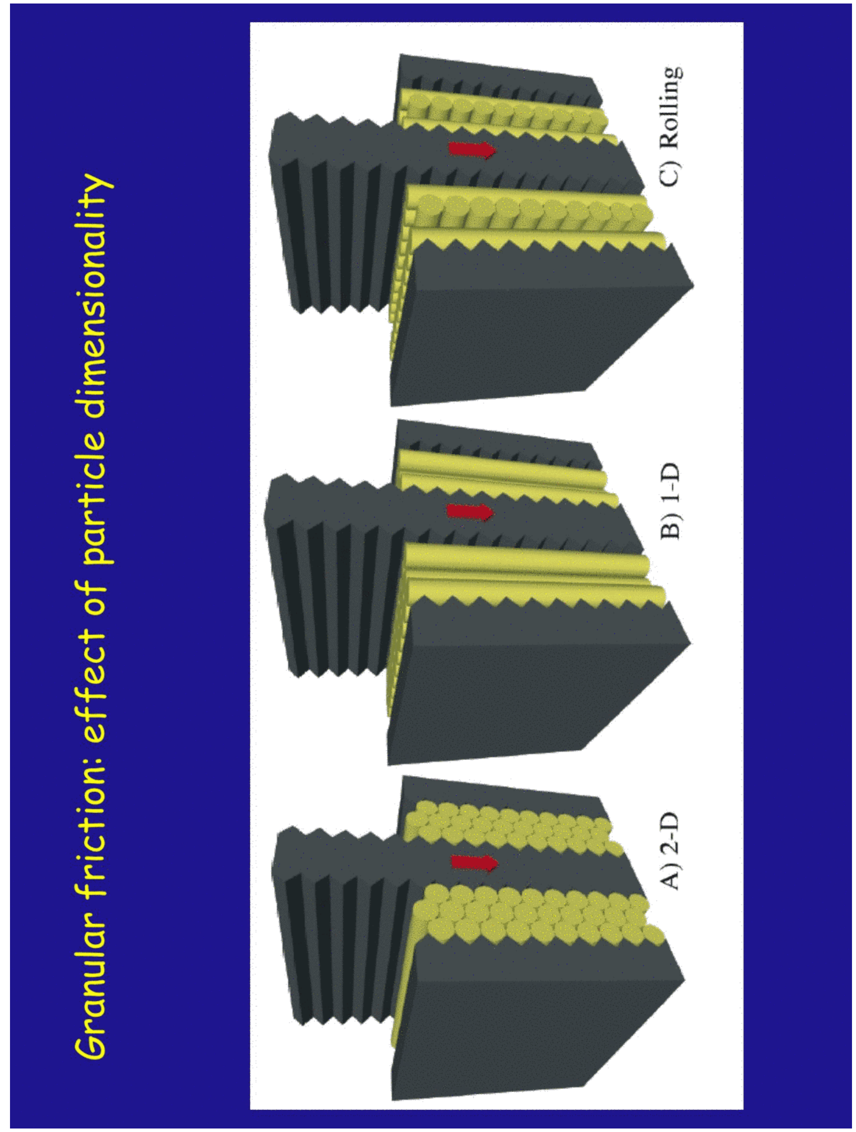
•Grain boundary sliding

•Dilation/compaction

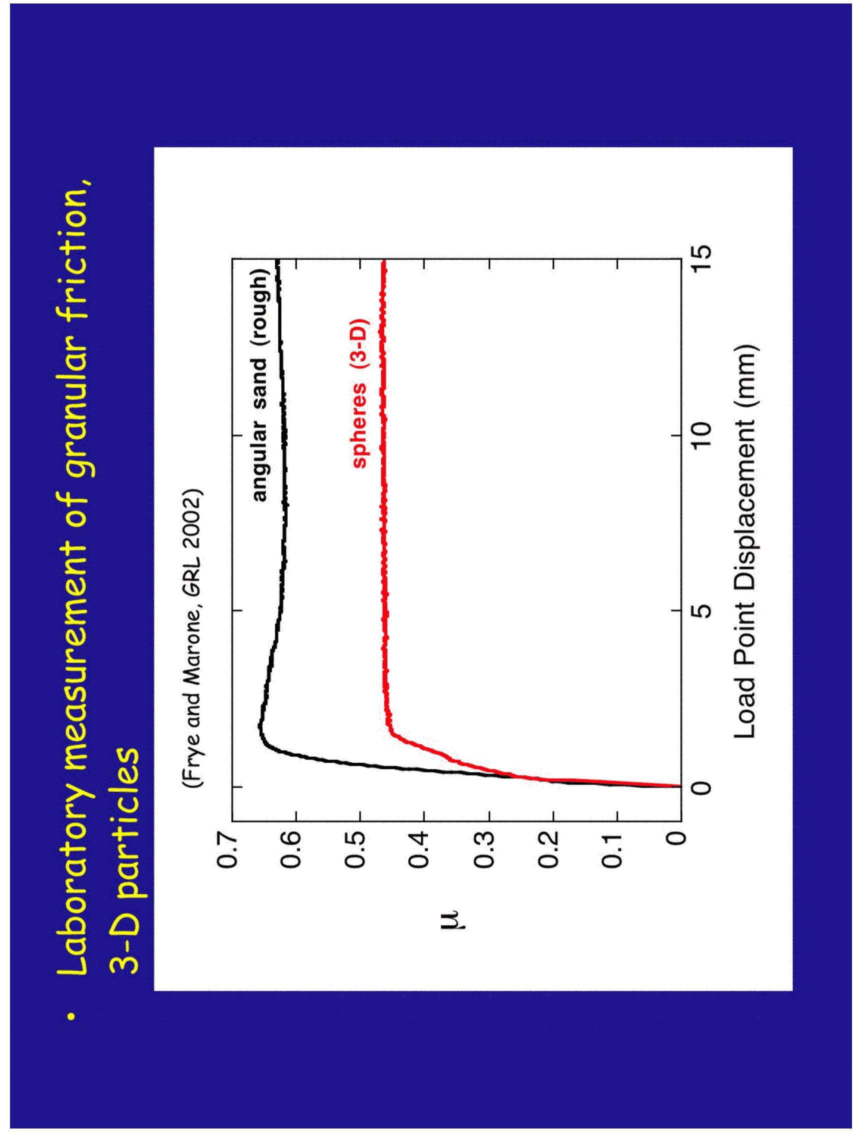
•Fracture

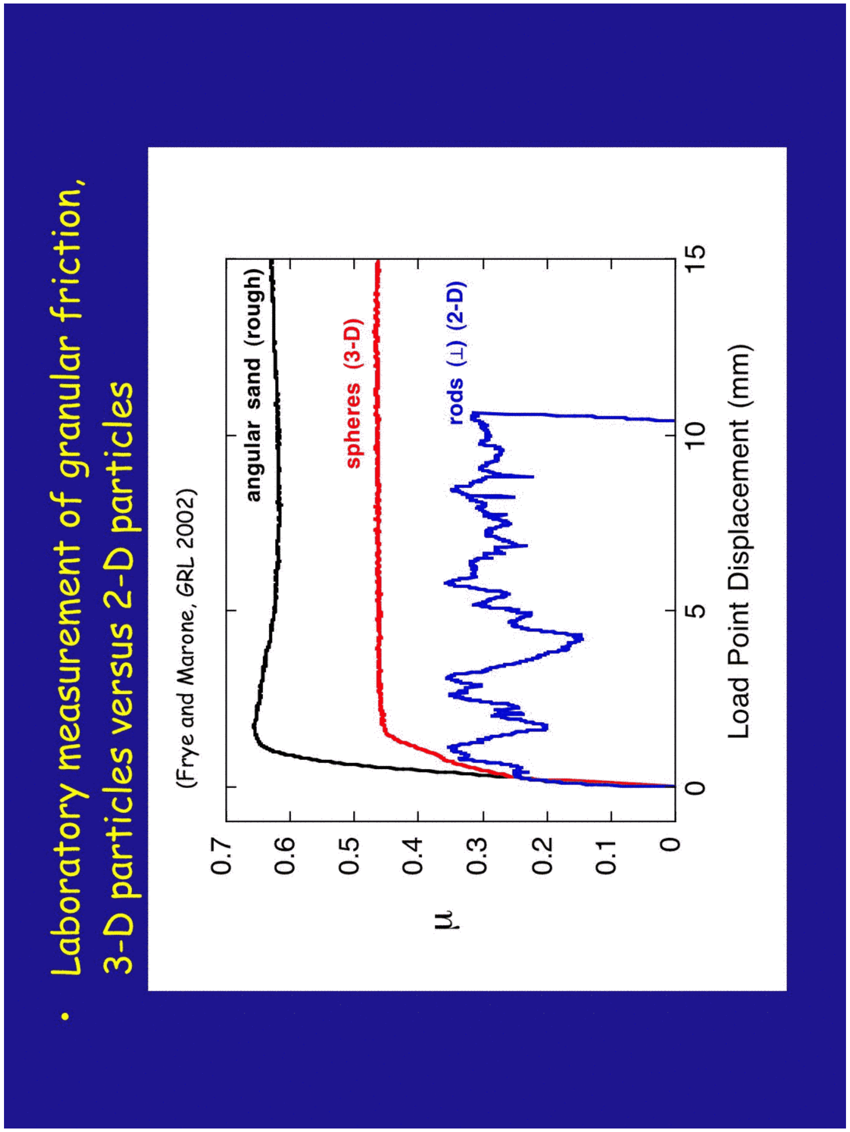



Granular friction: effect of particle dimensionality
Unregistered

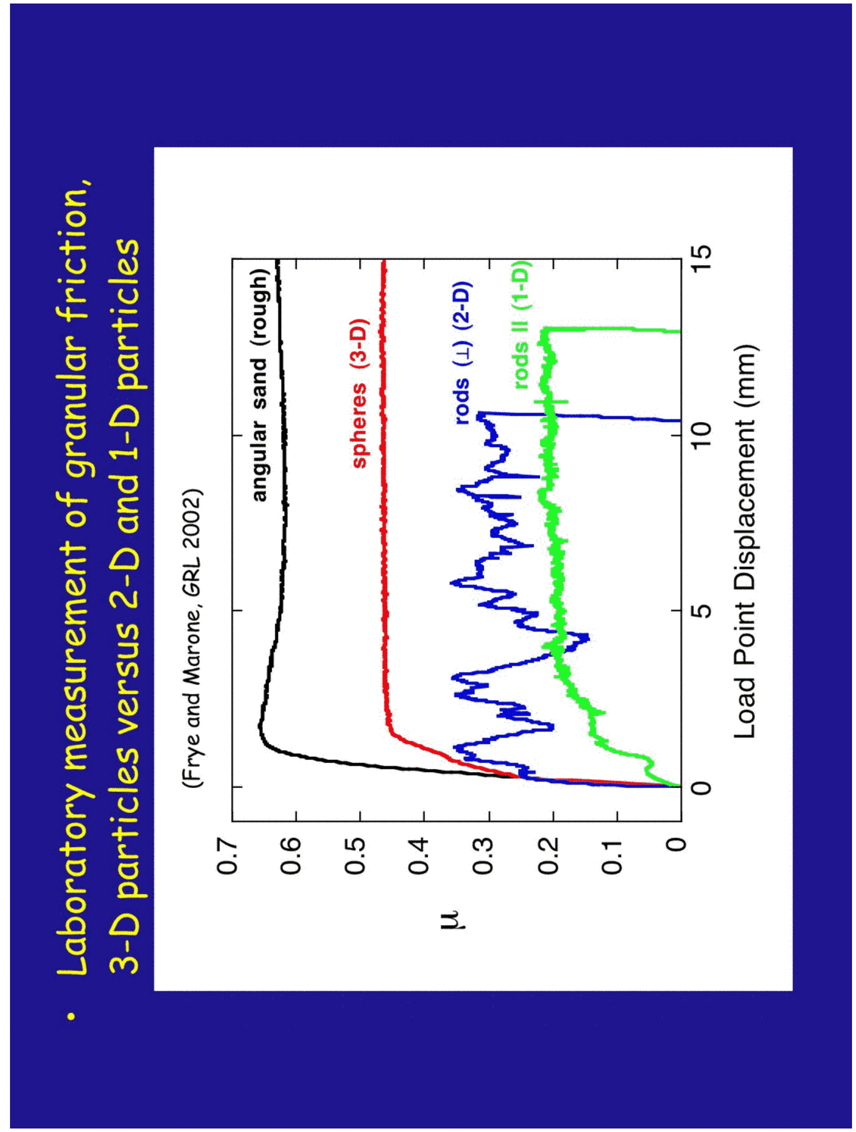

Granular friction: effect of particle dimensionality
A) 2-D
B) 1-D
C) Rolling


Rods:
Fused quartz rods (1 mm diameter)
Ronzoni pasta (#12 Angel hair, 0.91 mm, #11 Capellini 1.08 mm, #10 Vermicelli 1.32mm, #9 Thin spaghetti 1.58 mm, #8 Spaghetti, 1.86 mm)
Hardwood dowels (2.06 mm)
Brass Rods (1.59 mm)
SPAGHETTI · 8

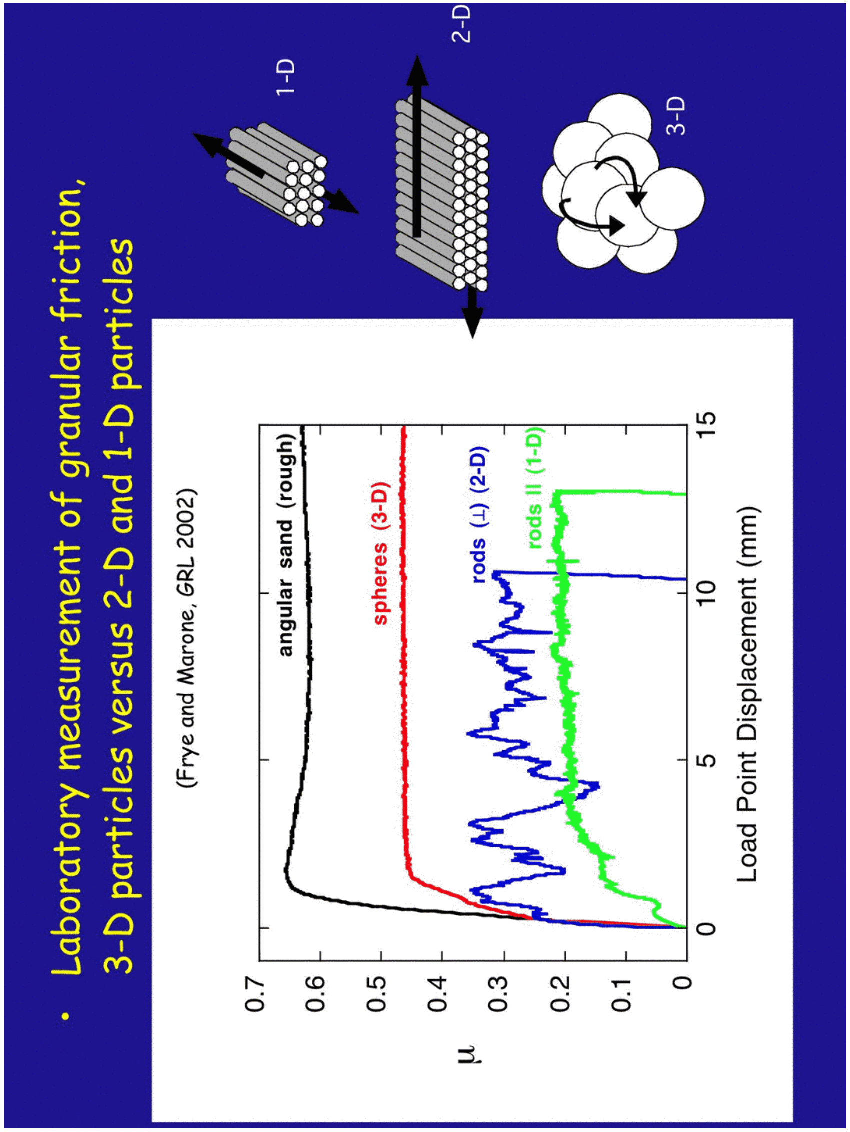

Laboratory measurement of granular friction, 3-D particles
(Frye and Marone, GRL 2002)
angular sand (rough)
spheres (3-D)
μ
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0
5
10
15
Load Point Displacement (mm)

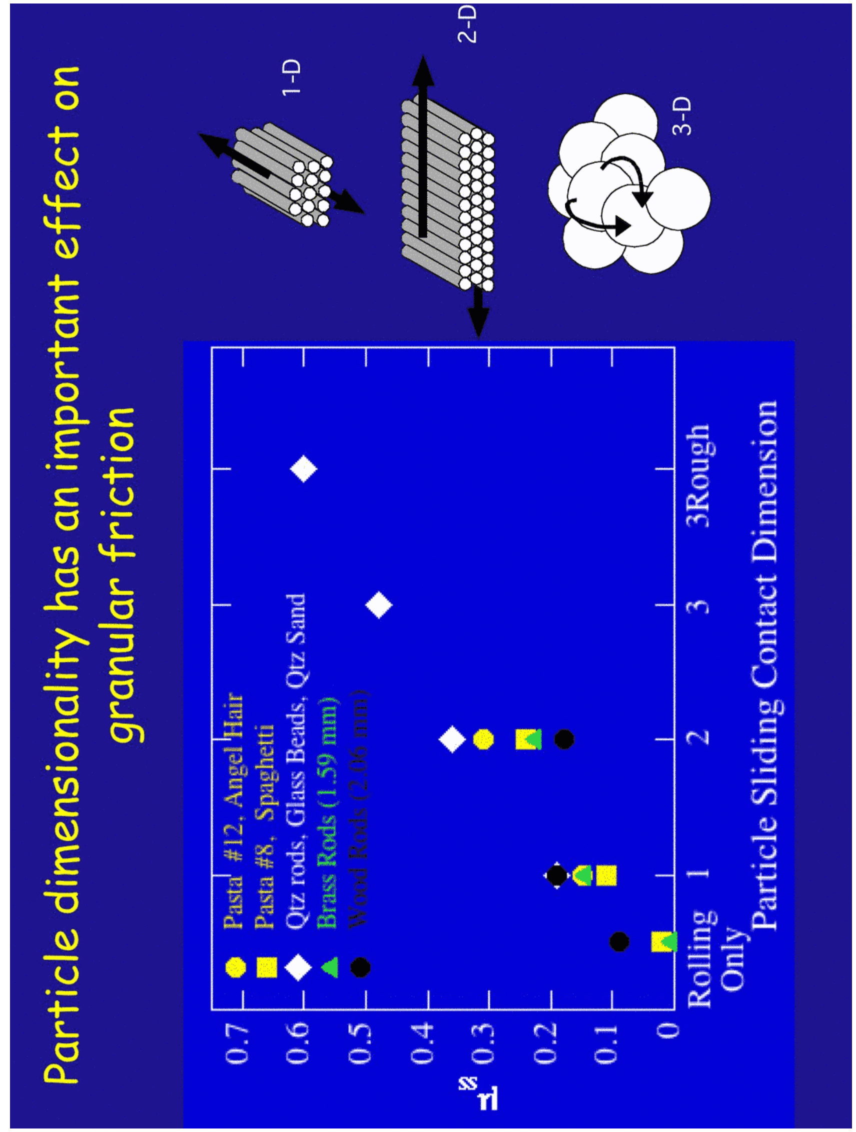


• Laboratory measurement of granular friction, 3-D particles versus 2-D particles
(Frye and Marone, GRL 2002)
angular sand (rough)
spheres (3-D)
rods (⊥) (2-D)
μ
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
Load Point Displacement (mm)

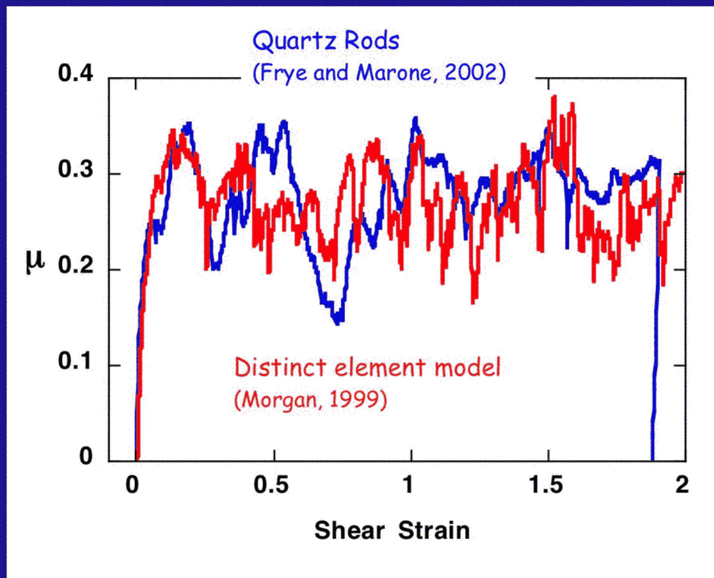


• Laboratory measurement of granular friction, 3-D particles versus 2-D and 1-D particles
(Frye and Marone, GRL 2002)
angular sand (rough)
spheres (3-D)
rods (⊥) (2-D)
rods II (1-D)
μ
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
Load Point Displacement (mm)


• Laboratory measurement of granular friction, 3-D particles versus 2-D and 1-D particles
1-D
2-D
3-D
(Frye and Marone, GRL 2002)
angular sand (rough)
spheres (3-D)
rods (⊥) (2-D)
rods II (1-D)
μ
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
Load Point Displacement (mm)

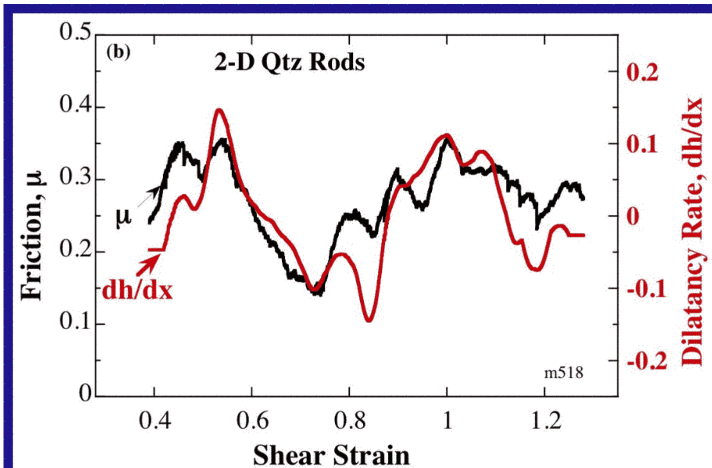

Particle dimensionality has an important effect on granular friction
1-D
2-D
3-D
Pasta #12, Angel Hair
Pasta #8, Spaghetti
Qtz rods, Glass Beads, Qtz Sand
Brass Rods (1.59 mm)
μ_{ss}
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Rolling Only
1
2
3
3Rough
Particle Sliding Contact Dimension

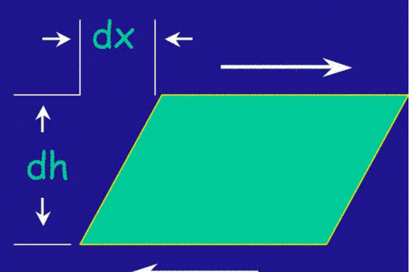
- Friction mechanics of 2-D particles, Comparison of laboratory and numerical results



- Character and mean value of laboratory data are very similar to numerical results

Friction mechanics of 2-D particles





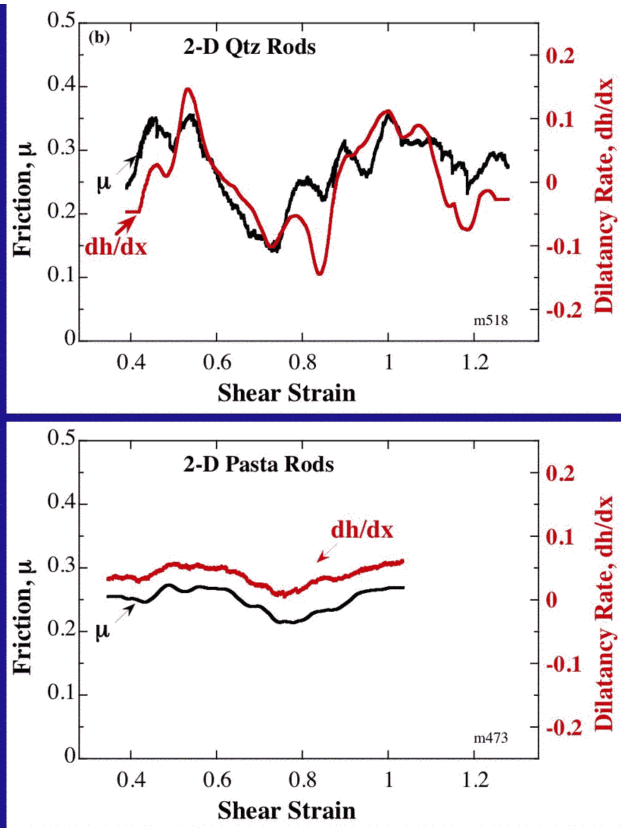
$$W = \tau_p \, d\gamma + \sigma \, d\theta$$

$$\tau = \sigma\left(\mu_p + d\theta / d\gamma\right)$$

$$\tau = \sigma\left(\mu_p + dh / dx\right)$$

$$\mu = \mu_p + dh/dx$$

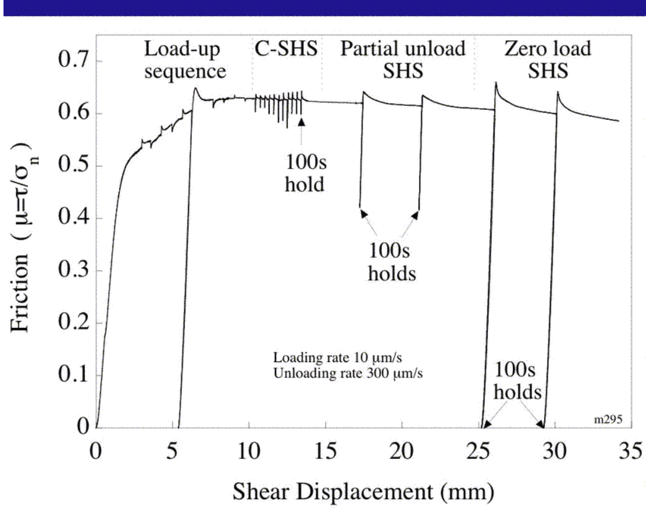
Dilatancy rate is a key factor for bulk frictional strength



2D Granular Shear

- Macroscopic variations in friction are due to variations in dilatancy rate.
- Smaller amplitude fluctuations in dilatancy rate produce smaller amplitude friction fluctuations.

Summary



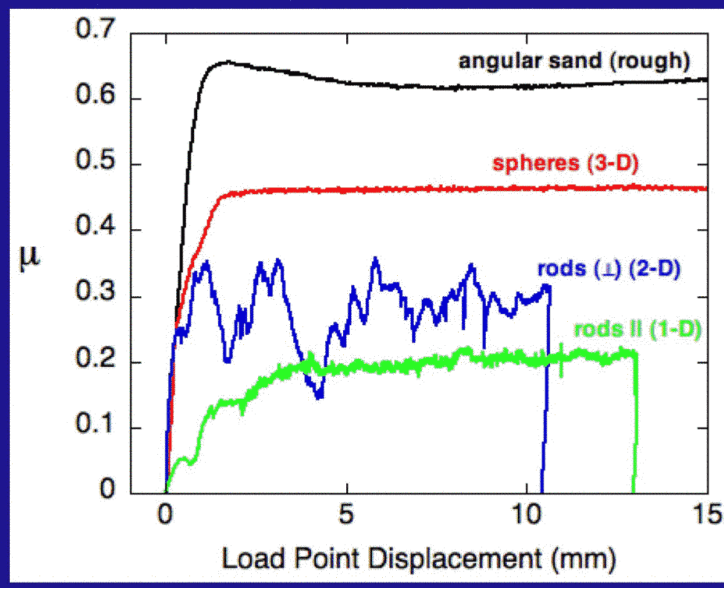
1) Aging

- Stressed vs. unstressed aging. Peak strength scales inversely with shear stress level. Aging rate scales directly with shear stress.
- Time dependent weakening for unstressed aging. Creep induced unjamming (?)
- Effect of water indicates a chemically-assisted low temperature plasticity mechanism.
- Base level of friction for granular materials is not influenced by the presence of water.

Summary

2) **Particle dimensionality**

- Frictional strength of sheared granular layers varies systematically with contact dimension.
- Friction is lowest for 1-D particles and higher for 2-D and 3-D configurations.



Summary

3) **Particle roughness and polydispersity**

- Stability of frictional sliding varies strongly with particle roughness and polydispersity.
- Implications for force chain geometry: width, length; Role of lateral stress