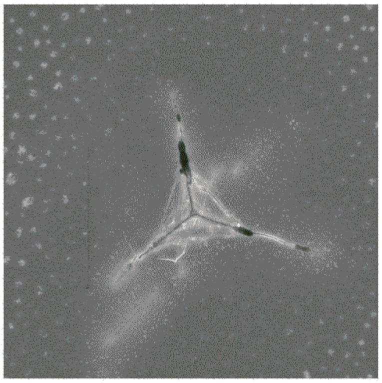
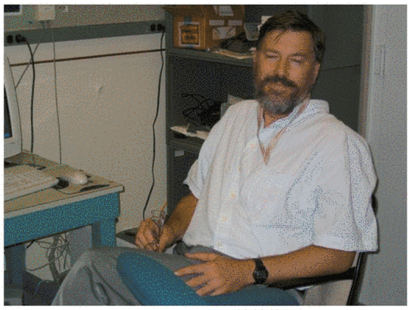
Creep and Friction of Microscopic Single Contacts in Minerals: Application to Earthquake Mechanics

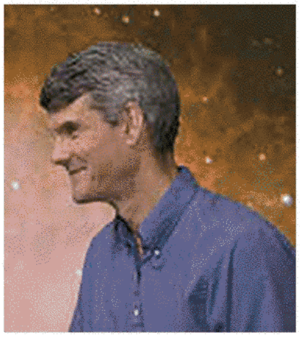
David L. Goldsby
Dept. of Geological Sciences
Brown University



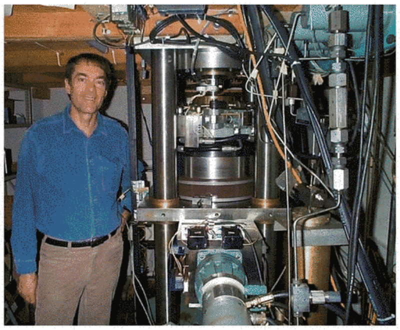
Acknowledgements



Andrei Rar-ORNL



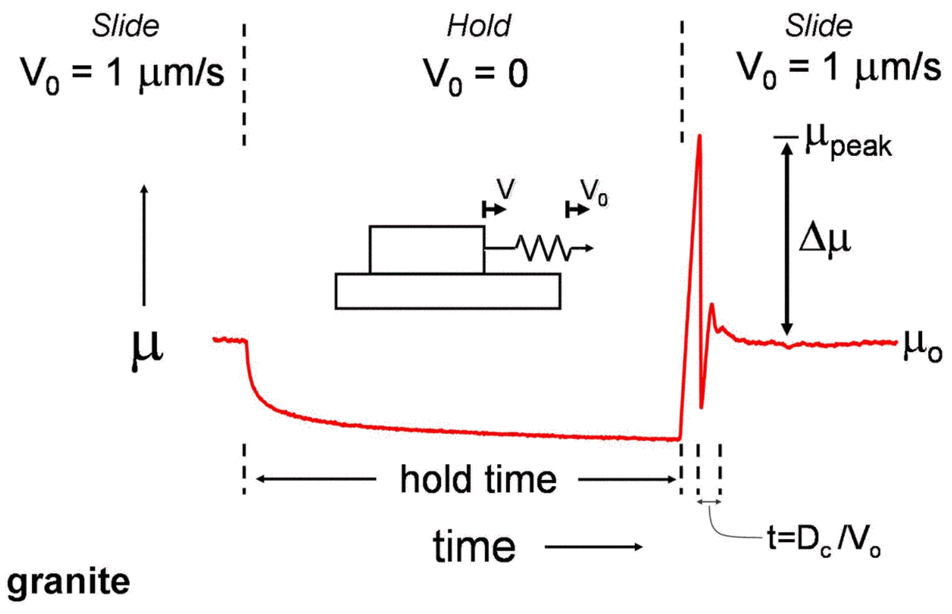
George Pharr-ORNL

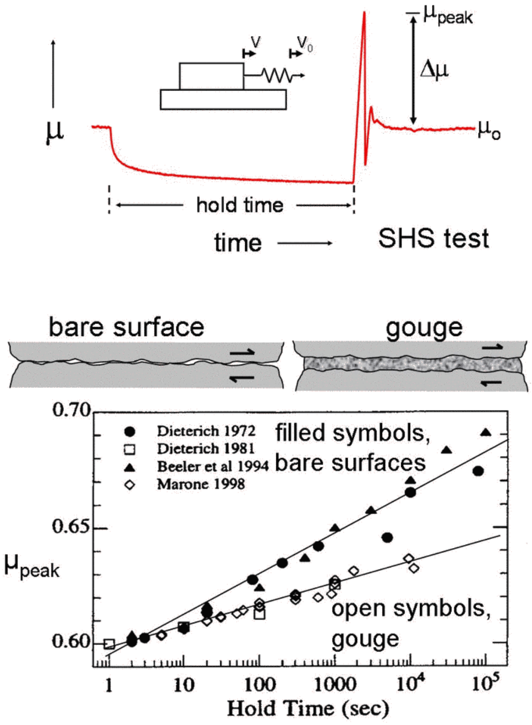


Terry Tullis - Brown

-SHaRE Program, Oak Ridge National Lab, Oak Ridge, TN

Time Dependence of Friction





James H. Dieterich (1972)

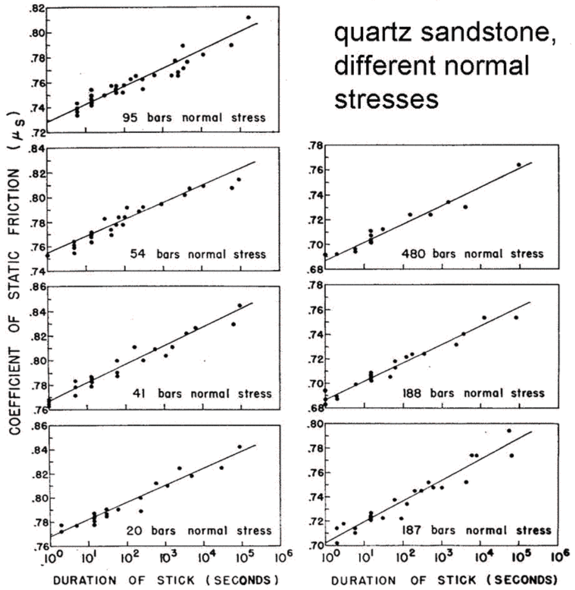
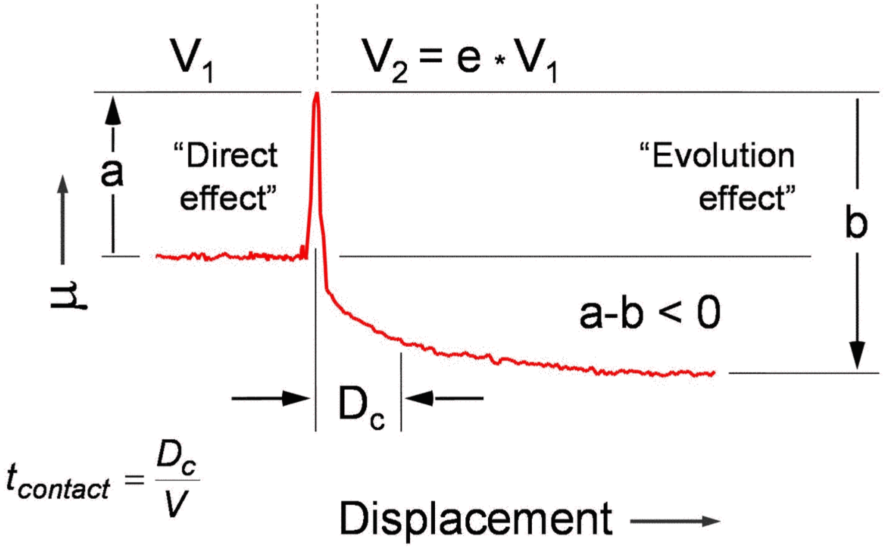


Fig. 2. Time dependence of the coefficient of static friction μ_s for sandstone.

quartz sandstone,
different normal
stresses

times up to 50,000 s

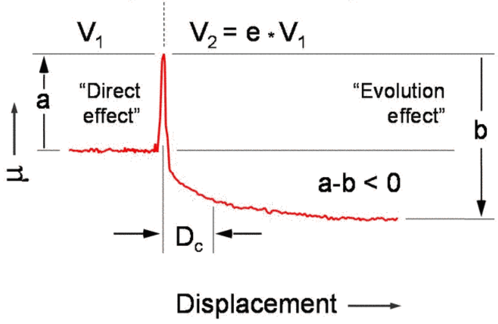
Velocity Dependence of Friction



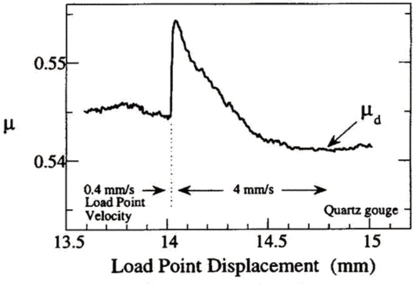
$$t_{contact} = \frac{D_c}{V}$$

Velocity Dependence of Friction

initially bare surfaces - granite



quartz 'gouge'



Marone (1998)

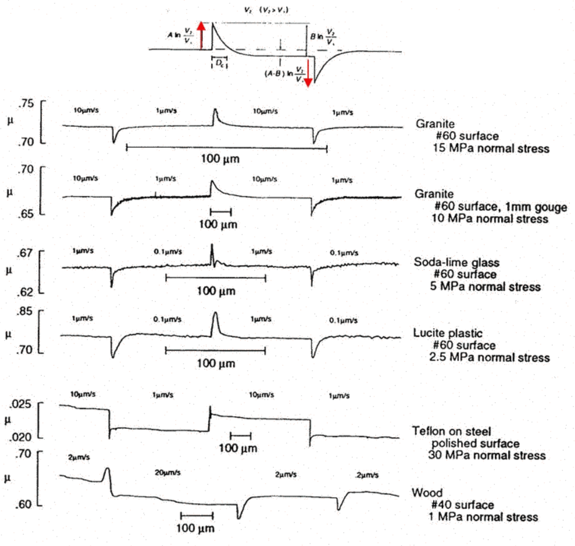


Figure 1

Effect of steps in slip speed on coefficient of friction μ in various materials. The top curve gives response predicted by constitutive equations (1) and (2). D_c is commonly represented as the e-folding distance for change of friction following a step in slip speed. D_c varies with surface roughness and characteristics of layers of comminuted material separating the surfaces (gouge).

after Dieterich and Kilgore (1994)

Rate and State Friction Laws

$$\mu = \mu_o + \mathbf{a} \ln\left(\frac{V}{V_o}\right) + \mathbf{b} \ln\left(\frac{\theta V_o}{D_c}\right)$$

Dieterich-Ruina

Direct effect

Evolution effect

Possible evolution laws

$$\frac{d\theta}{dt} = 1 - \frac{\theta V}{D_C}$$ *Slowness* law

$$\frac{d\theta}{dt} = -\frac{\theta V}{D_c} \ln\left(\frac{\theta V}{D_c}\right)$$ *Slip* law

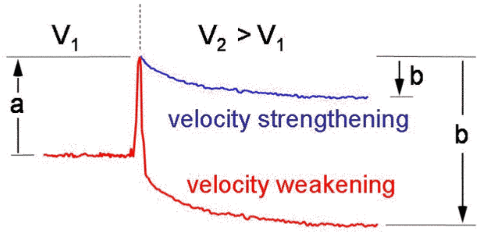
---

Stability of Sliding

$$\mu = \mu_o + \mathbf{a} \ln\left(\frac{V}{V_o}\right) + \mathbf{b} \ln\left(\frac{\theta V_o}{D_c}\right)$$

Direct

Evolution



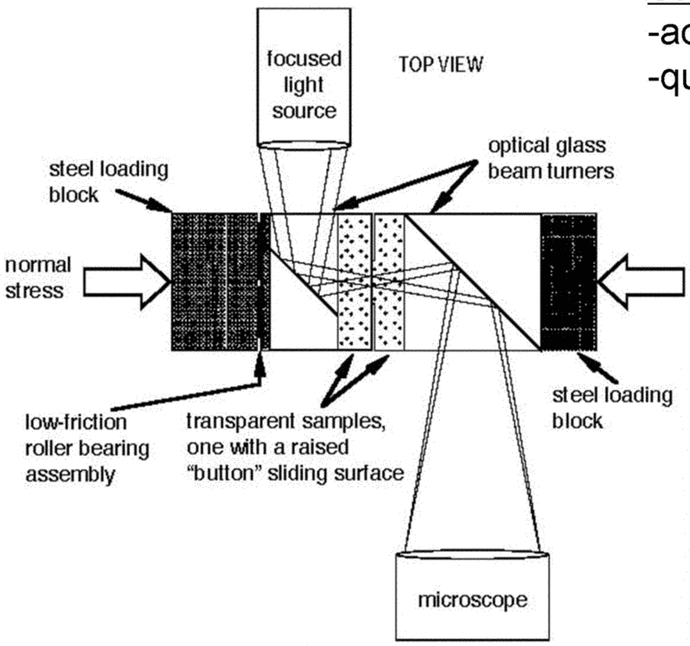
Stability analyses (*Rice and Ruina*, 1983; *Gu et al.*, 1984)

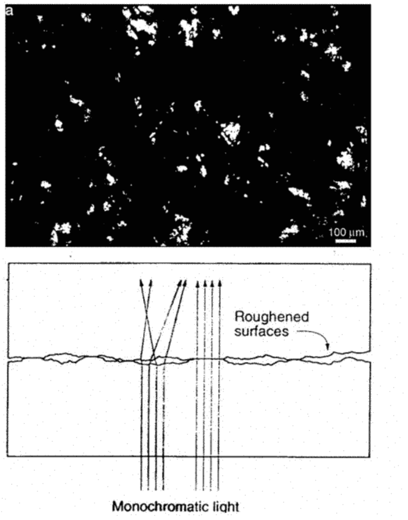
a - b > 0, Velocity strengthening *Sliding always stable*, EQ nucleation not possible

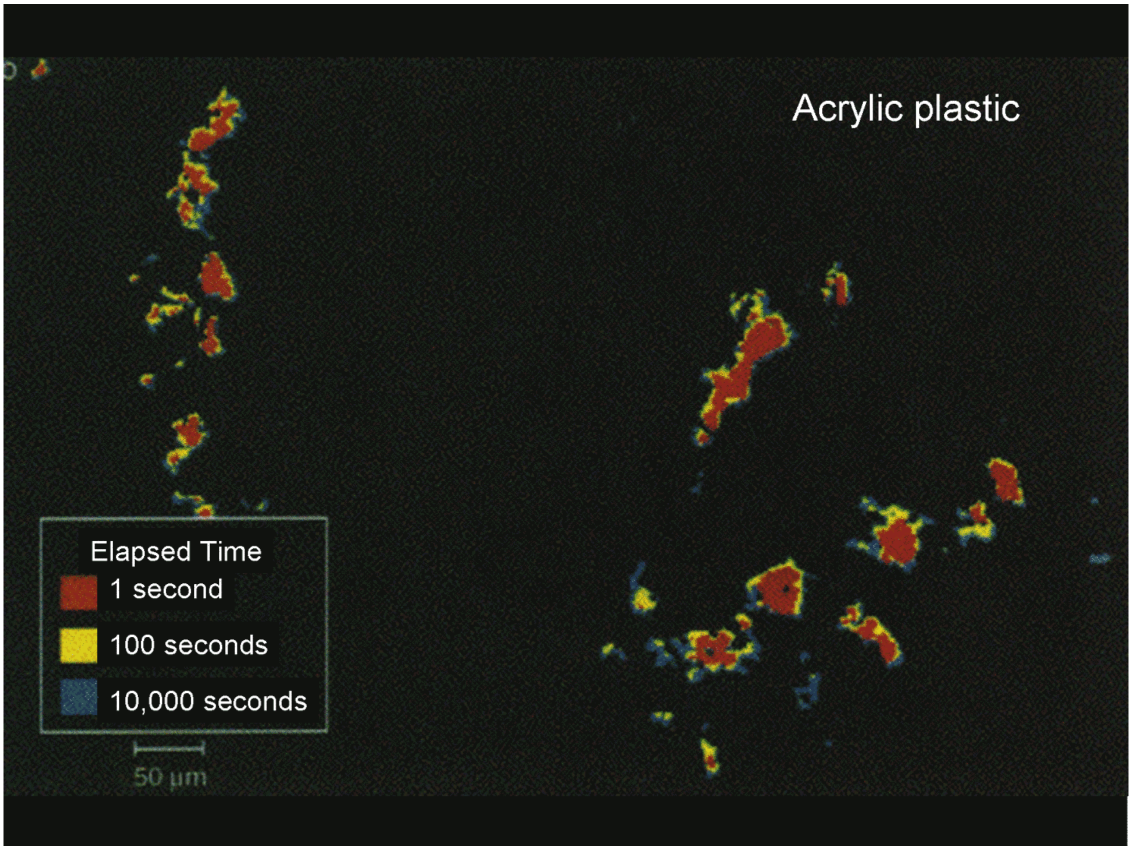
a - b < 0, Velocity weakening *Conditionally unstable*, EQ nucleation possible

'See-through apparatus' Dieterich and Kilgore (1994)

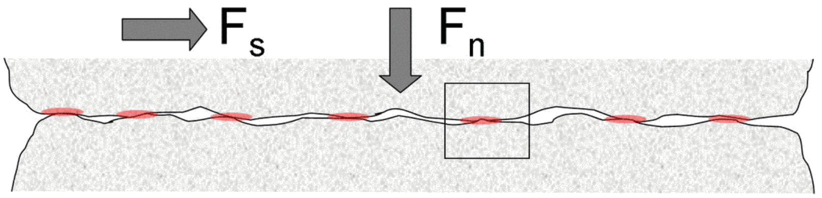
Samples
-acrylic plastic, glass
-quartz







Time Dependence of Rock Friction



$$F_S = \mu F_N$$

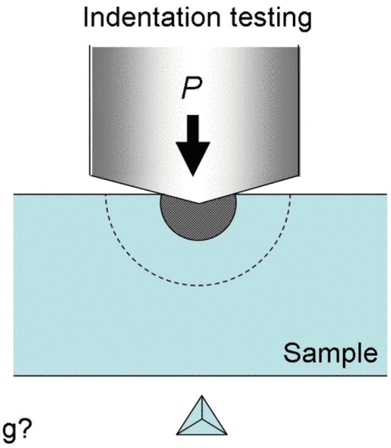
$$F_S = \tau_c \, \Sigma A_c$$

$$\tau_C = \tau_C(t) \qquad A = A(t)$$

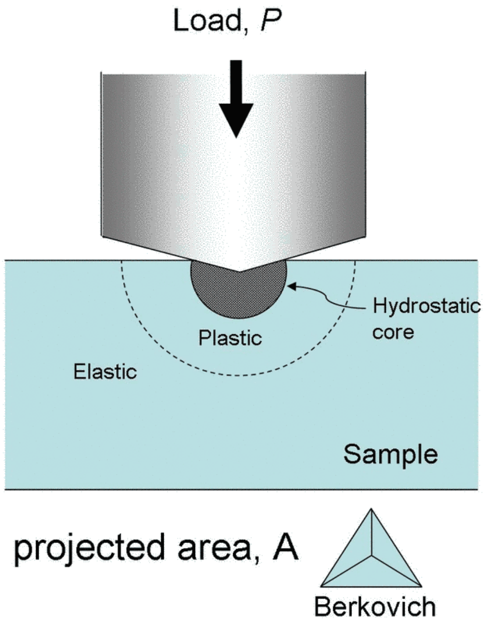
Contact ‘quality’

Contact ‘quantity’ (area)

Creep? Distributed cracking?



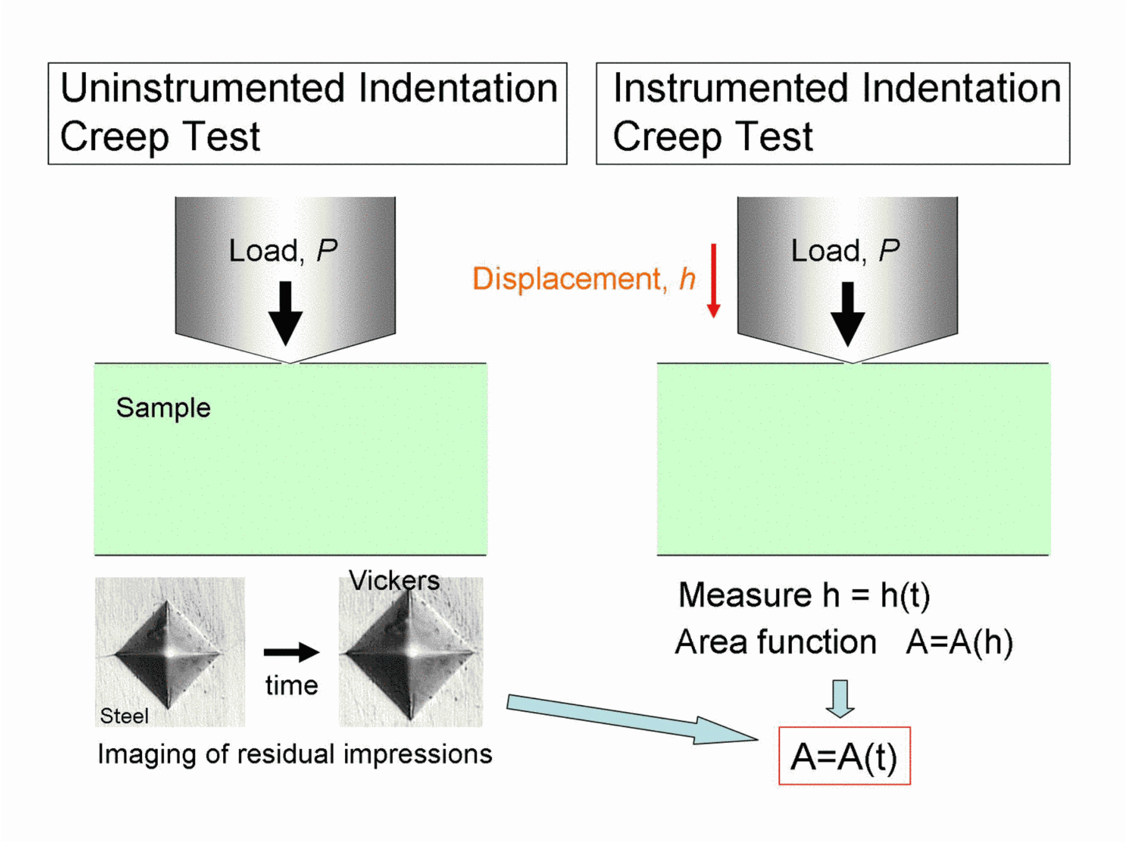
Indentation testing



Hardness, H

$$H = \frac{P}{A}$$

$$H(t) = \frac{P}{A(t)}$$



Uninstrumented Indentation Creep Test

Instrumented Indentation Creep Test

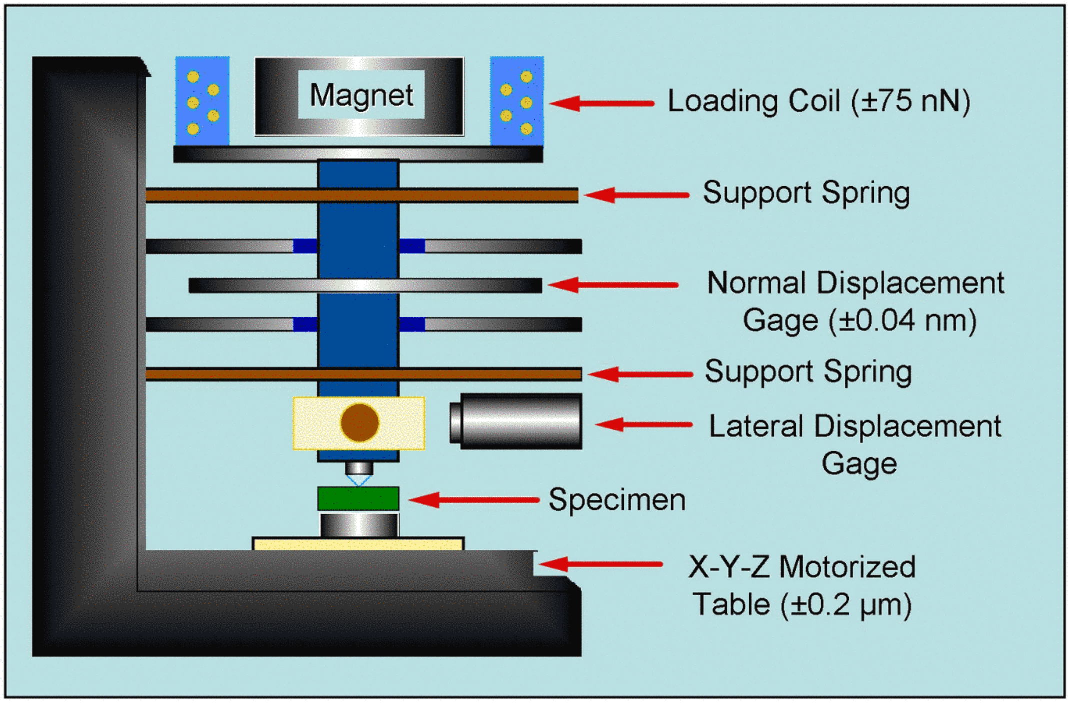
Imaging of residual impressions

Measure h = h(t)

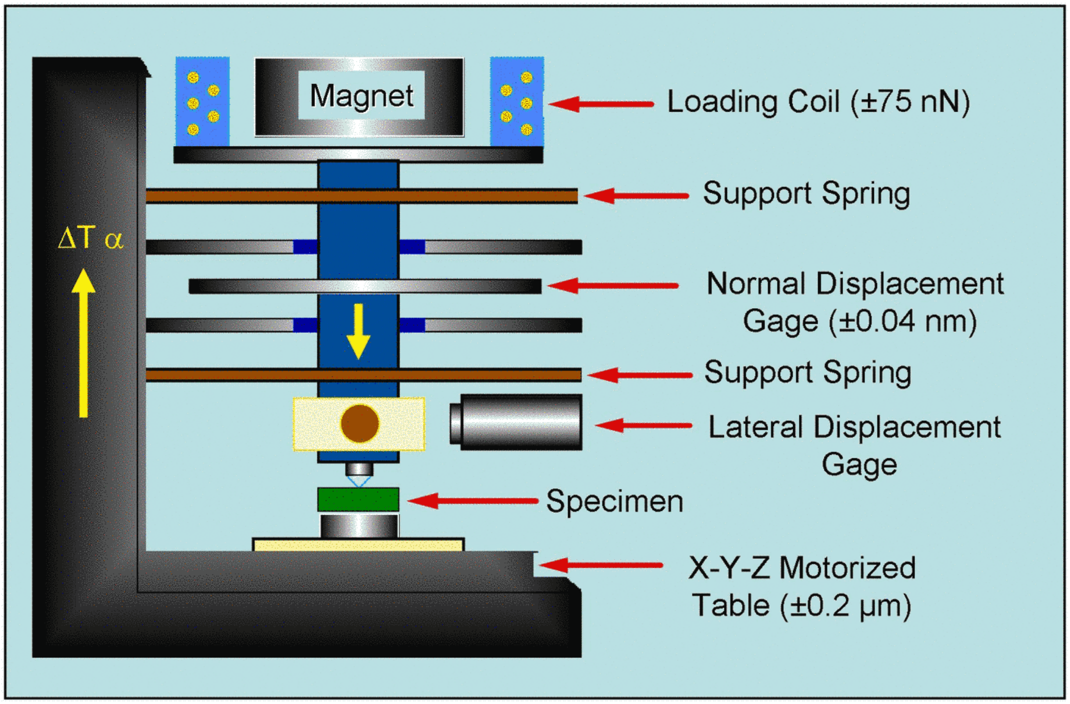
Area function A=A(h)

A=A(t)

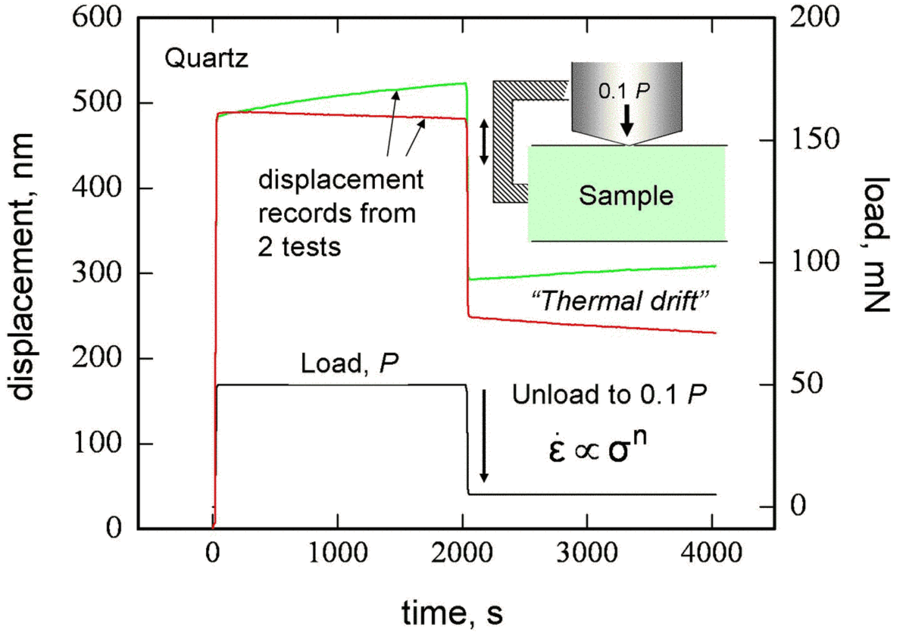
NANOINDENTER



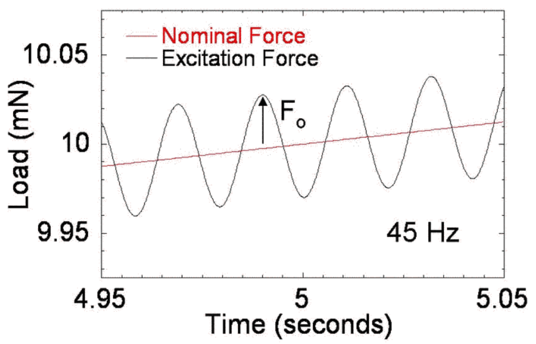
Thermal Drift

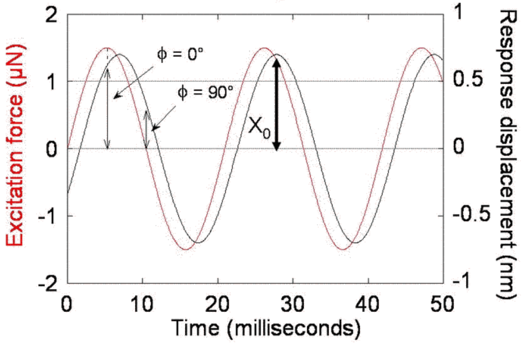


‘Conventional’ Nanoindentation Creep Tests



Continuous Stiffness Technique





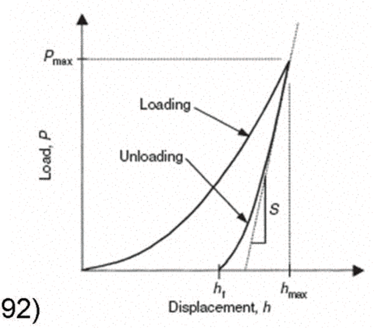
$$X_0 = \frac{F_o}{\sqrt{(k - m\omega^2)^2 + [(C_i + C_s)\omega]^2}}$$

$$\phi = \tan^{-1}\frac{(C_i + C_s)\omega}{k - m\omega^2} \qquad k = K_s + K_i$$

$$S = K_s = \frac{dP}{dh} = \frac{2}{\sqrt{\pi}} E_R \sqrt{A}$$

Oliver and Pharr (1992)

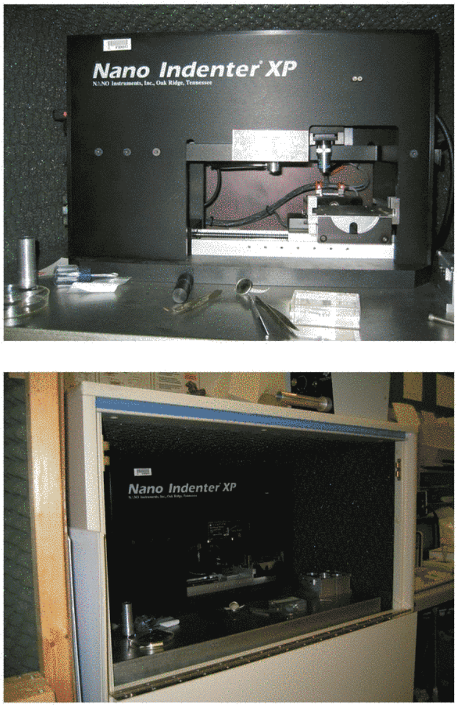
Pethica and Oliver (1986)



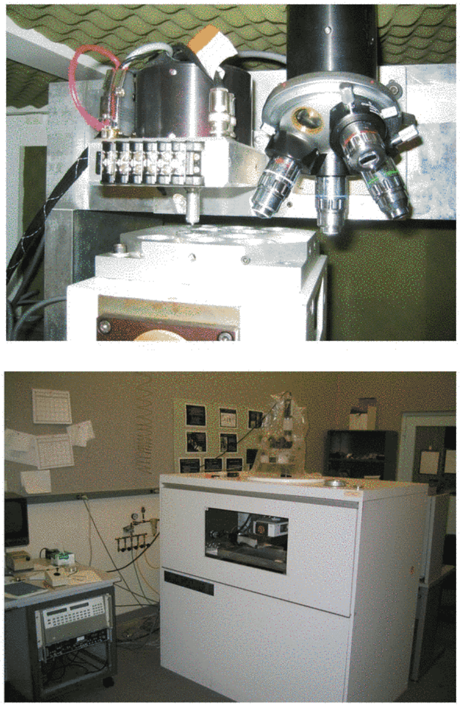
Indentation Creep Experiments

- Ambient T, humidity
- Polished minerals (0.03 μm grit)
- Indenter tips - diamond Berkovich, ruby ball
- Load P = 50 to 700 mN
- ***Continuous stiffness*** techniques
- Times up to 50,000 s (SHS rock friction tests)

Nanoindenter XP



Nanoindenter II



Samples

Minerals

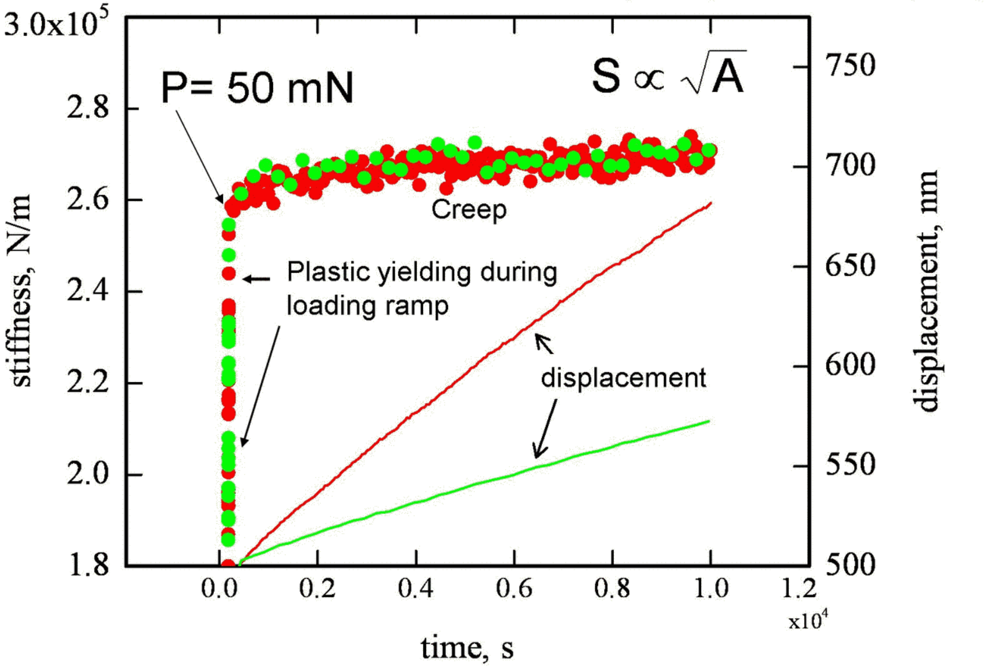
• Quartz	SiO_2
• Olivine	$(Mg,Fe)_2SiO_4$
• Calcite	$CaCO_3$
• Feldspar	$(Ca,Na)(Si, Al)_4O_8$
• Pyroxene	$(Ca,Na)(Mg,Fe,Al)(SiAl)_2O_6$
• Garnet	$Mg_3Al_2Si_3O_{12}$

Non-minerals

- Fused Quartz
- Aluminum
- Diamond
- Sapphire

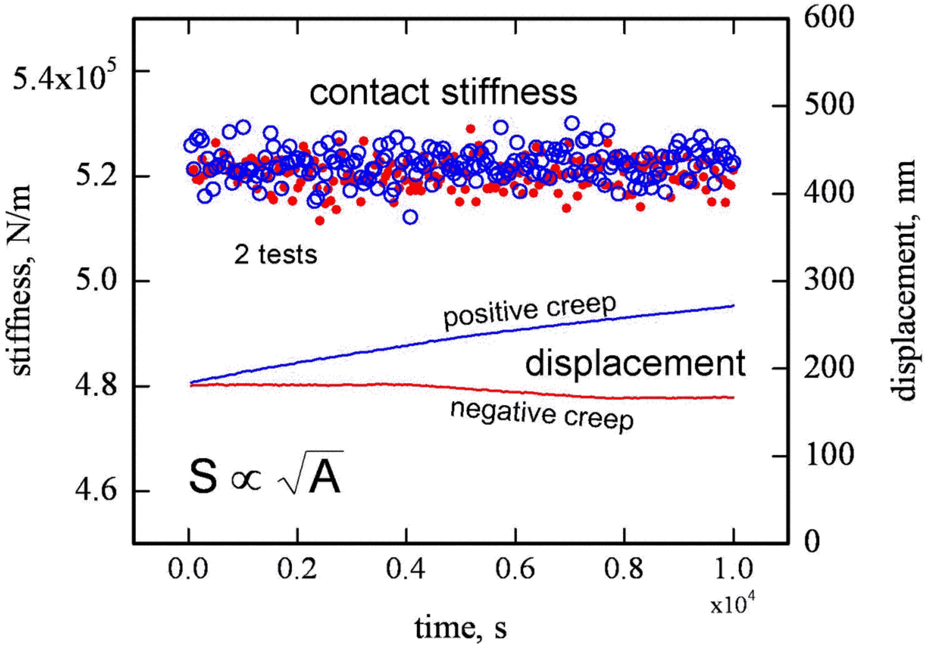
Berkovich on Quartz

Goldsby et al., J. Mater. Res. (2004)



Diamond Berkovich on Diamond

no increase in stiffness (area) with time



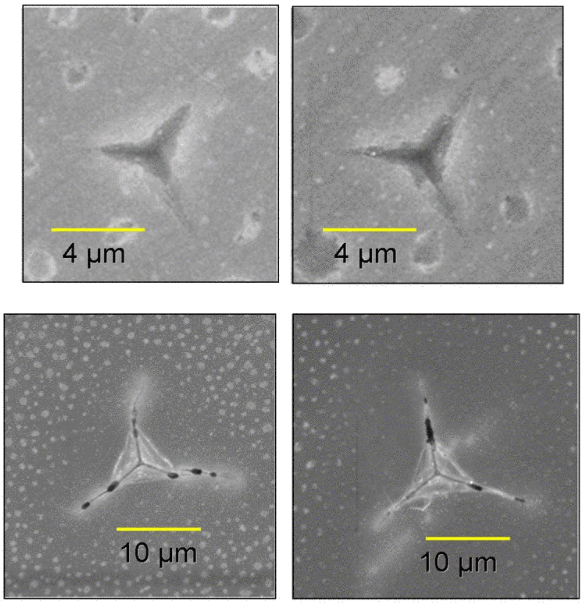
FEGSEM Micrographs

Quartz

100 s creep 10,000 s (10% larger)

P= 50 mN

P=700 mN



Increase in size consistent with change in area determined from stiffness measurements

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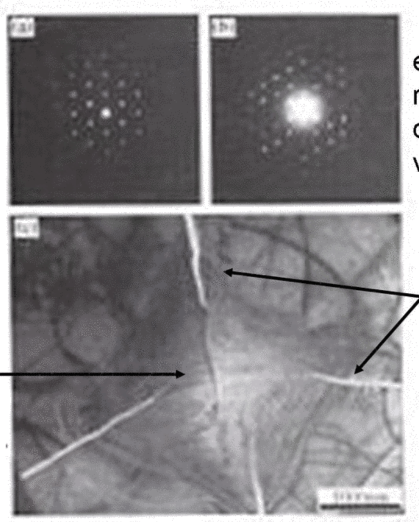
Deformation Mechanisms - Quartz

"Lattice creasing"- Masuda et al. (2000)

Vickers indent,
P=98 mN

'normal' diffraction pattern from outside indented volume



electron diffraction pattern reveals regions of lattice distortion within indented volume

No dislocations observed within the indented volume

cracks induced by thinning of TEM foil (not indentation)

TEM Micrograph

Deformation Mechanisms - Quartz

Shear faulting - Lawn et al.

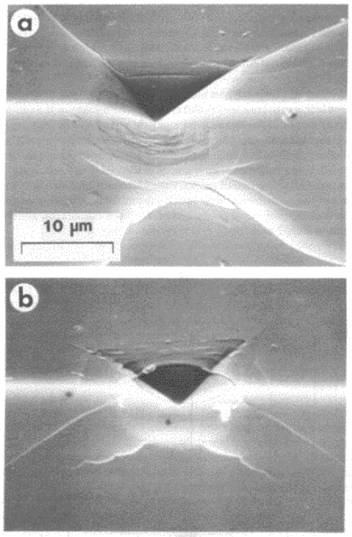
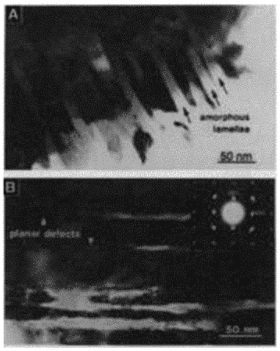


FIG. 1—*Scanning electron micrographs of Vickers indentations in* (a) *soda lime and* (b) *fused silica glasses, showing half-surface and section views.*

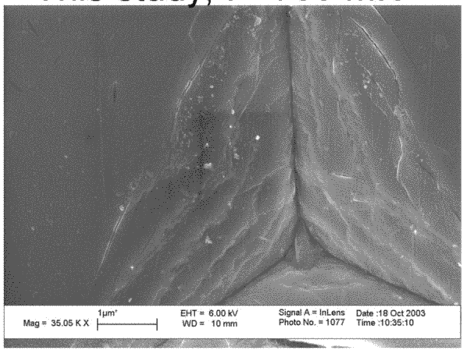


Diamond anvil cell (DAC) experiments on quartz

TEM micrographs

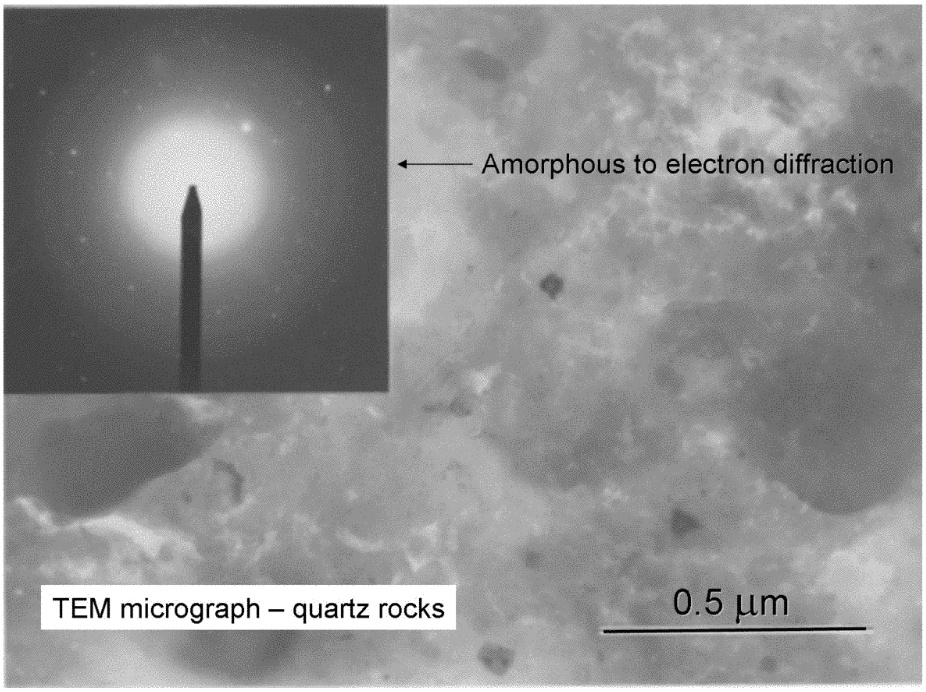
Kingma et al. (1993)

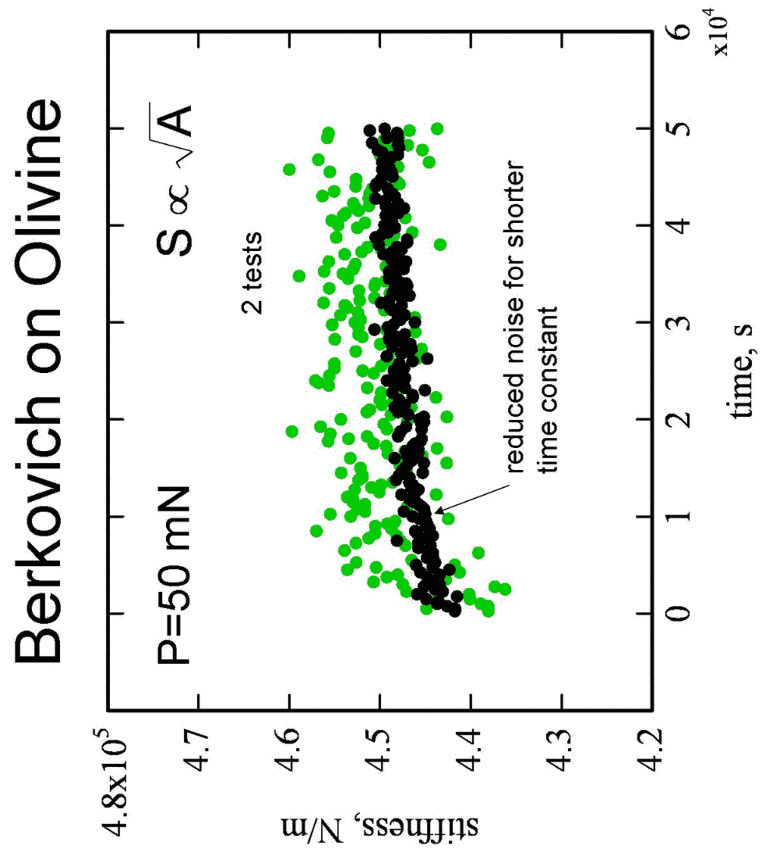
This study, P=700 mN

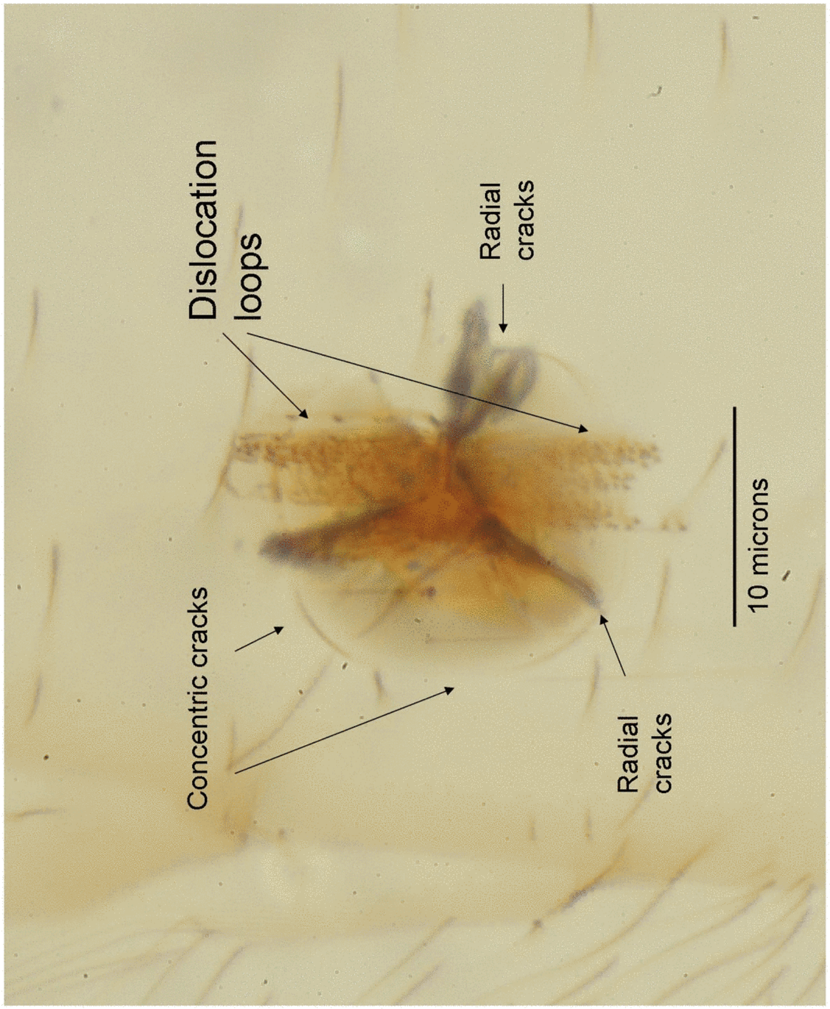


Amorphous wear debris (gouge) in rock friction tests

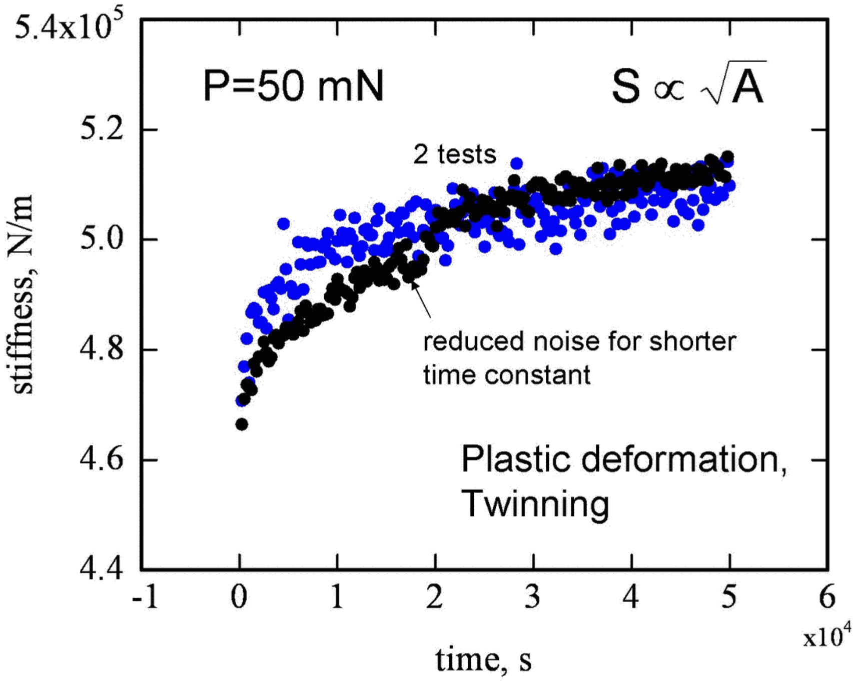
Yund et al. (1990)




Berkovich on Olivine
P=50 mN
$S \propto \sqrt{A}$
2 tests
reduced noise for shorter time constant
stiffness, N/m
4.8×10^5
4.7
4.6
4.5
4.4
4.3
4.2
time, s
0
1
2
3
4
5
6
$\times10^4$


Dislocation loops
Radial cracks
Concentric cracks
Radial cracks
10 microns

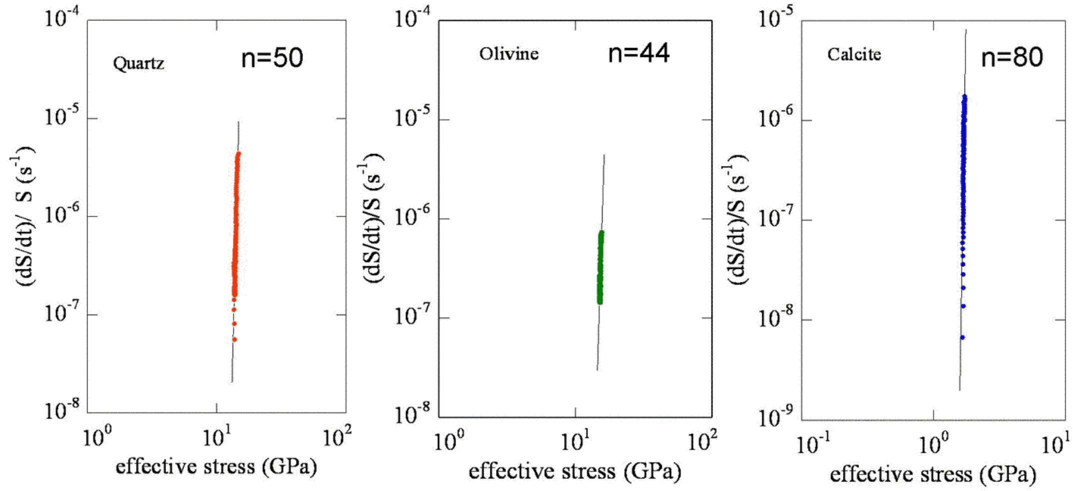
Berkovich on Calcite



Deformation Mechanisms

Effective stress $\sigma_{eff} = \frac{P}{A}$ Effective strain rate $\dot{\varepsilon}_{eff} = \frac{\dot{S}}{S}$

Weihs and Pethica (1991)



Data shown for:

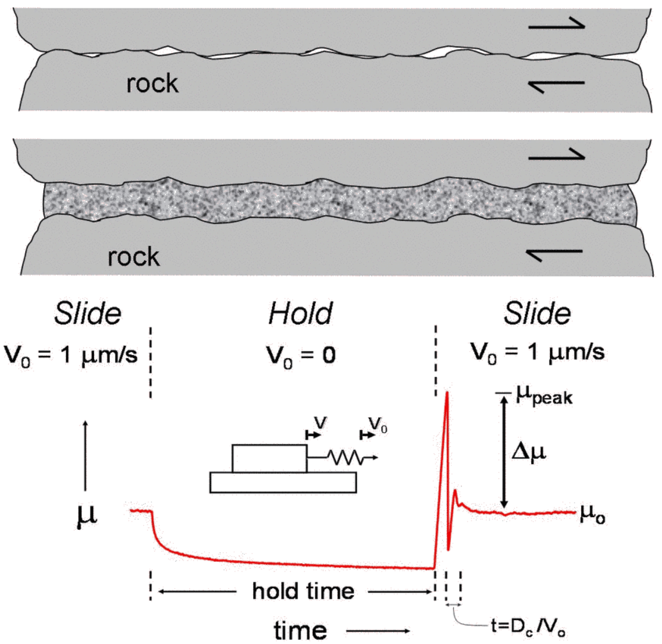
- Quartz SiO_2
- Olivine $(Mg,Fe)_2SiO_4$
- Calcite $CaCO_3$

Similar results for:

- Feldspar $(Ca,Na)(Si, Al)_4O_8$
- Pyroxene $(Ca,Na)(Mg,Fe,Al)(SiAl)_2O_6$
- Garnet $Mg_3Al_2Si_3O_{12}$

All undergo indentation creep
at room T!

Comparison of Indentation Data with SHS Rock Friction Data



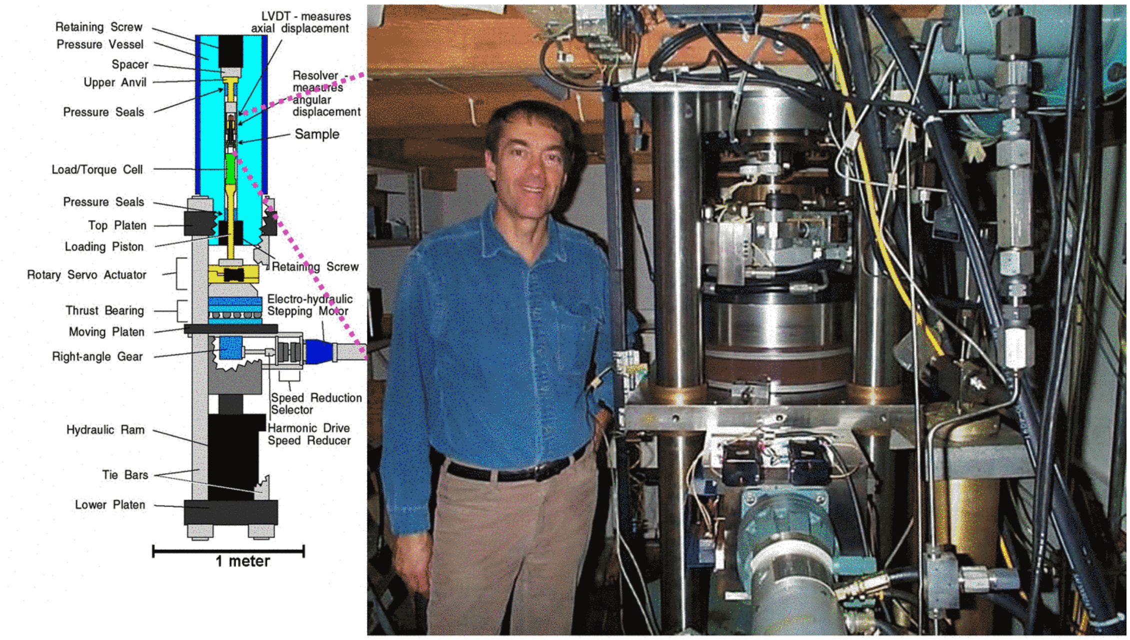
Initially bare
sliding surface

Simulated fault
gouge

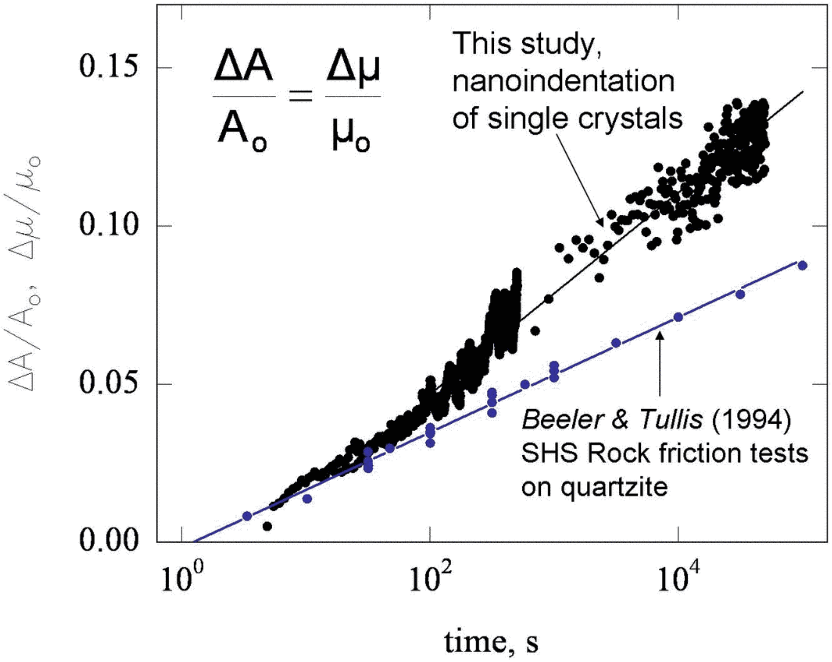
Changes in friction result
from changes in contact
area

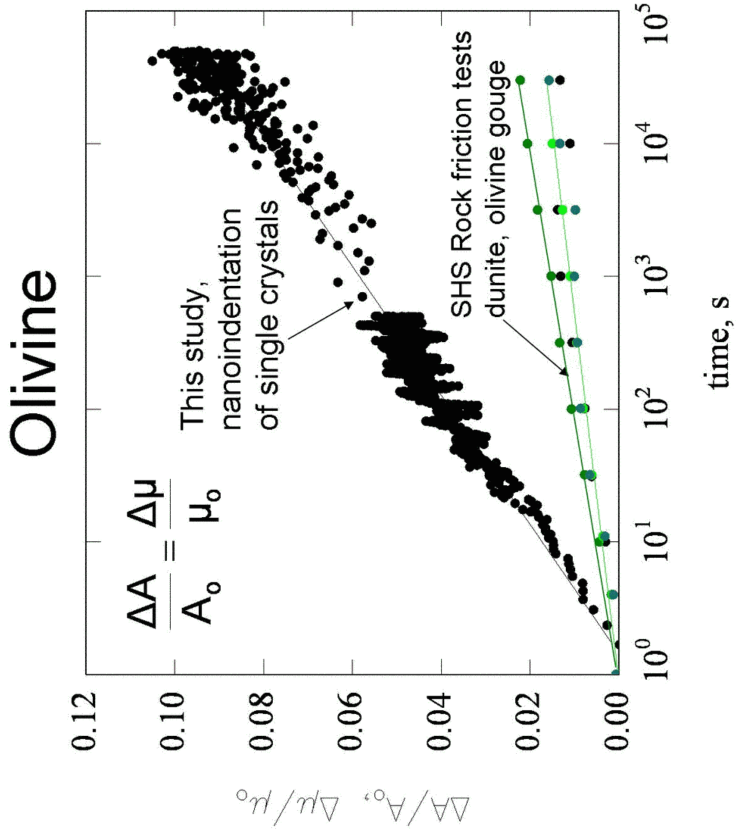
$$\frac{\Delta A}{A_o} = \frac{\Delta \mu}{\mu_o}$$

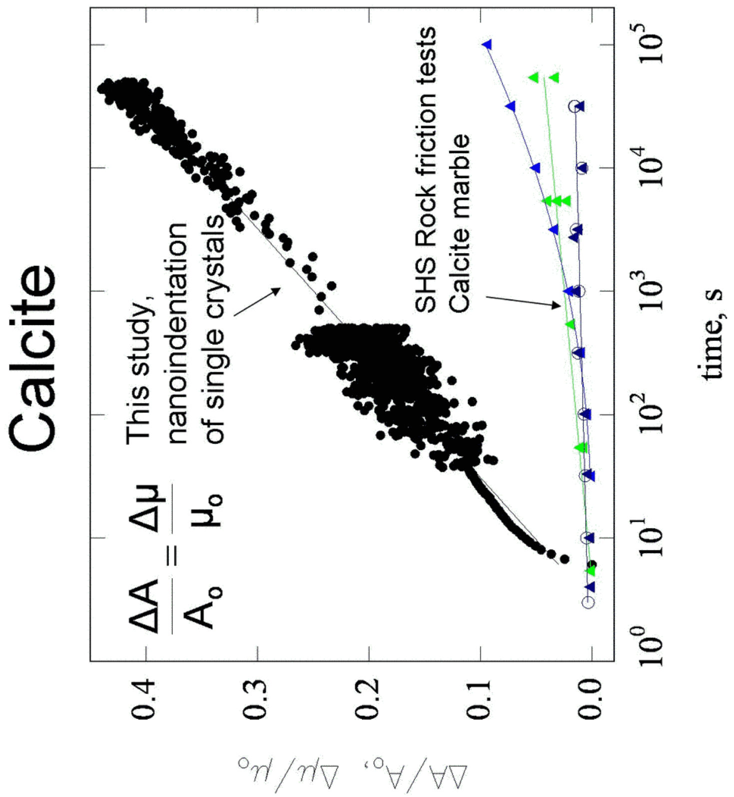
Hi-P Rotary Shear Friction Apparatus



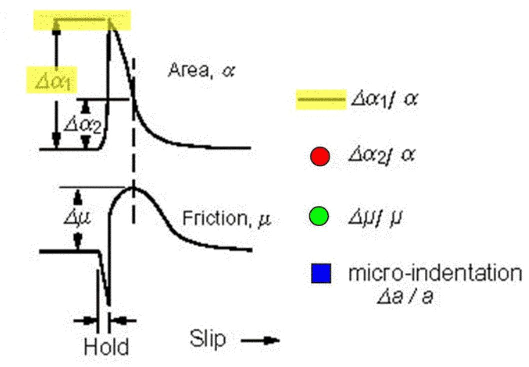
Quartz

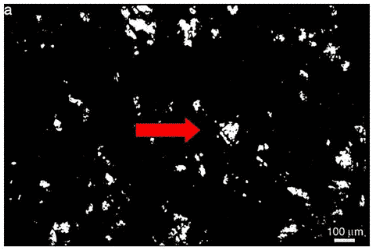


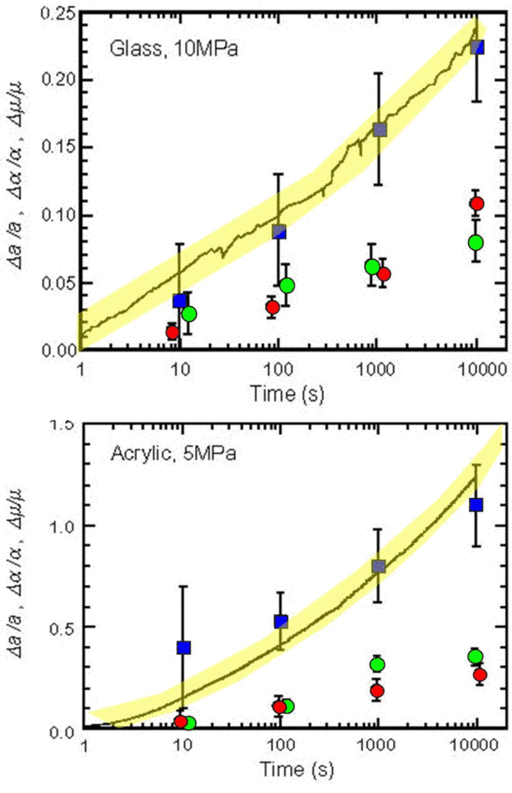

Olivine
$\frac{\Delta A}{A_o} = \frac{\Delta \mu}{\mu_o}$
This study, nanoindentation of single crystals
SHS Rock friction tests dunite, olivine gouge
time, s
10^0
10^1
10^2
10^3
10^4
10^5
0.00
0.02
0.04
0.06
0.08
0.10
0.12
$\Delta A/A_o$, $\Delta\mu/\mu_o$


Calcite
$\frac{\Delta A}{A_o} = \frac{\Delta \mu}{\mu_o}$
This study, nanoindentation of single crystals
SHS Rock friction tests Calcite marble
time, s
10^0
10^1
10^2
10^3
10^4
10^5
0.0
0.1
0.2
0.3
0.4
$\Delta A/A_o$, $\Delta\mu/\mu_o$

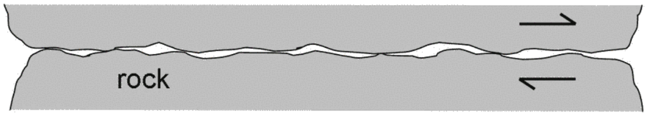
Slide-Hold-Slide Tests



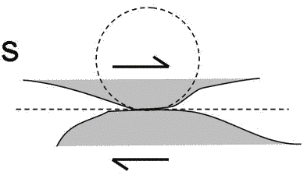




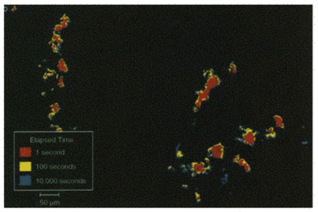
Lower contact stresses in SHS rock friction experiments than in nanoindentation tests



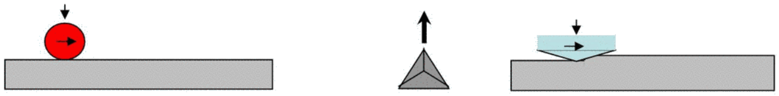
- Elastic contacts – due to asperity geometries
  - Plasticity index (plastic contact density)
    - Greenwood and Williamson (1966)
    - McCool (1986)



- Emergence of new contacts, decreasing average contact stress

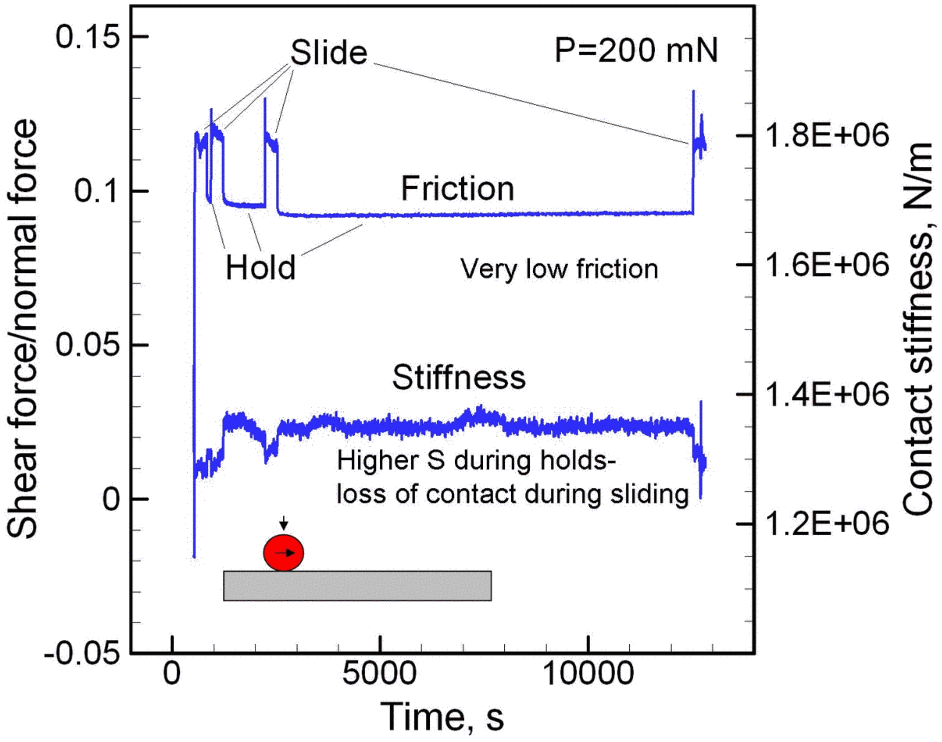


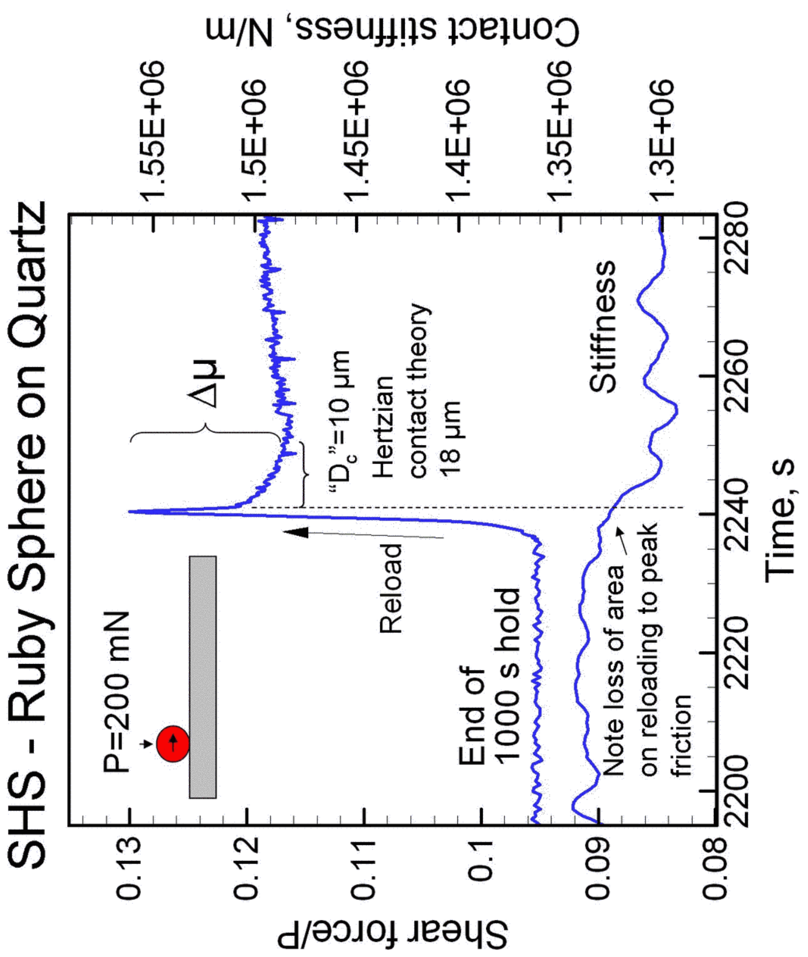
Nanoindentation Friction Tests

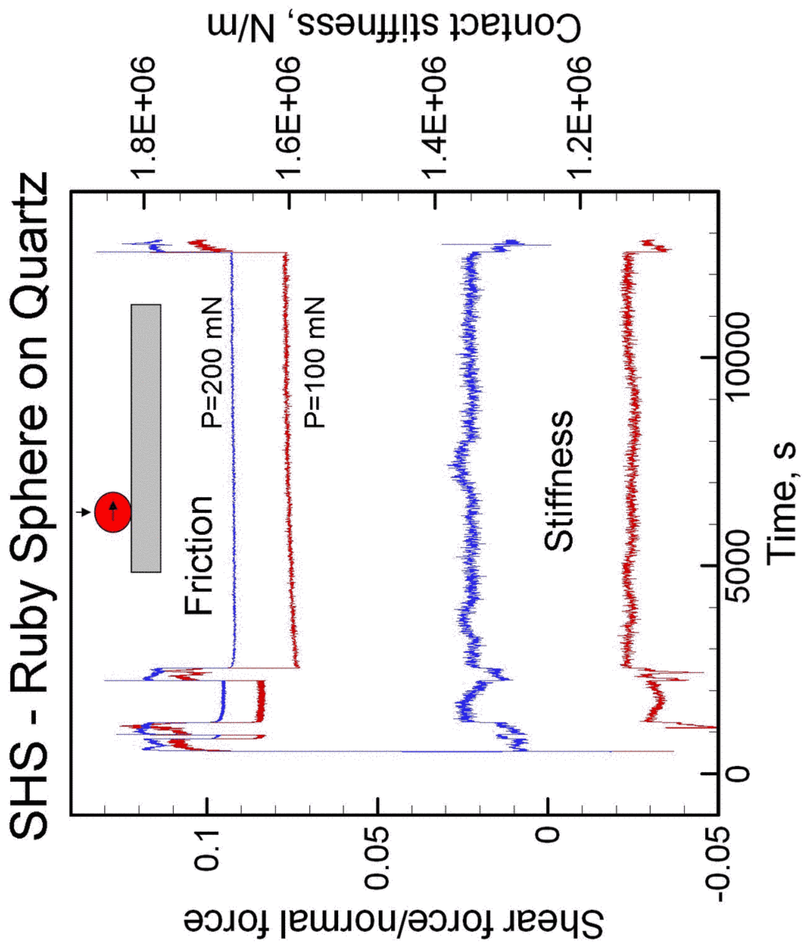


- Ambient T, humidity
- Polished single crystals of various crustal rock-forming minerals
- Ruby sphere (500 μm), diamond Berkovich
- Load P = 50 to 300 mN
- **Continuous stiffness** methods

SHS - Ruby Sphere on Quartz

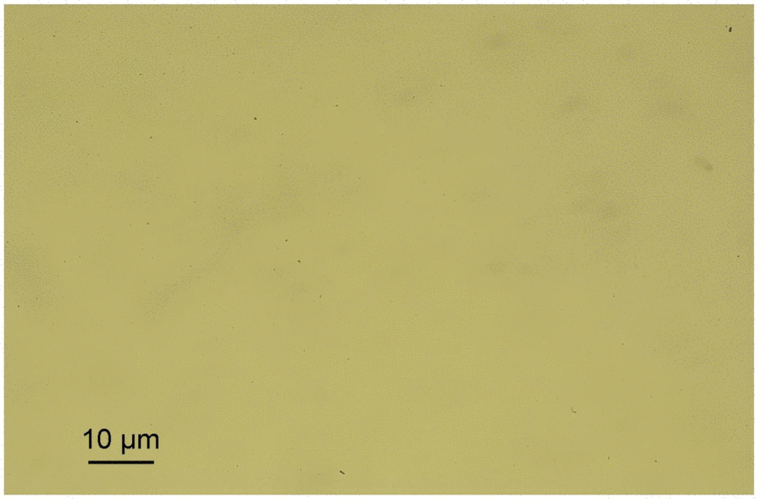



SHS - Ruby Sphere on Quartz
Shear force/P
0.13
0.12
0.11
0.1
0.09
0.08
Time, s
2200
2220
2240
2260
2280
Contact stiffness, N/m
1.55E+06
1.5E+06
1.45E+06
1.4E+06
1.35E+06
1.3E+06
P=200 mN
Reload
End of 1000 s hold
Note loss of area on reloading to peak friction
Stiffness
Δμ
"D_c"=10 μm
Hertzian contact theory 18 μm

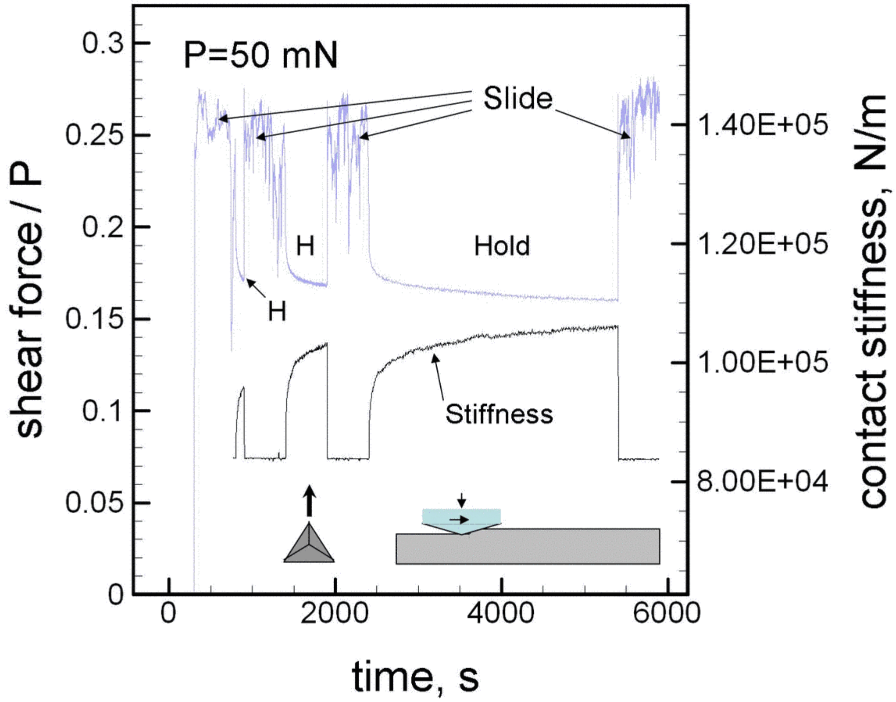

SHS - Ruby Sphere on Quartz
Shear force/normal force
0.1
0.05
0
-0.05
Time, s
0
5000
10000
Contact stiffness, N/m
1.8E+06
1.6E+06
1.4E+06
1.2E+06
Friction
P=200 mN
P=100 mN
Stiffness

Ruby Sphere on Quartz

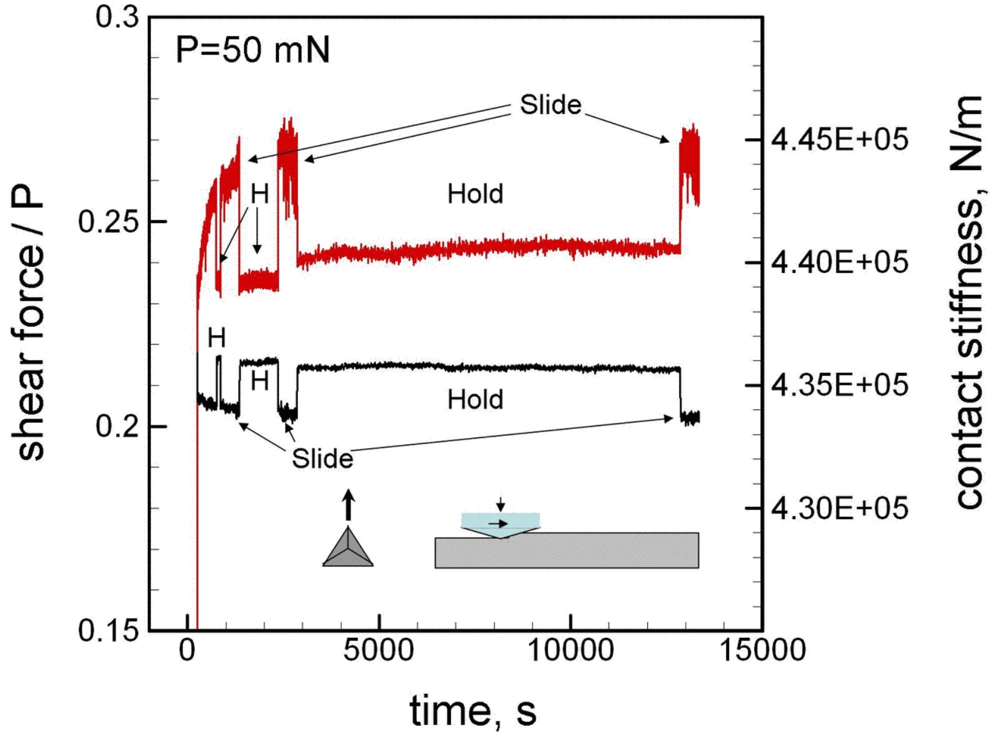
Invisible scratch tracks



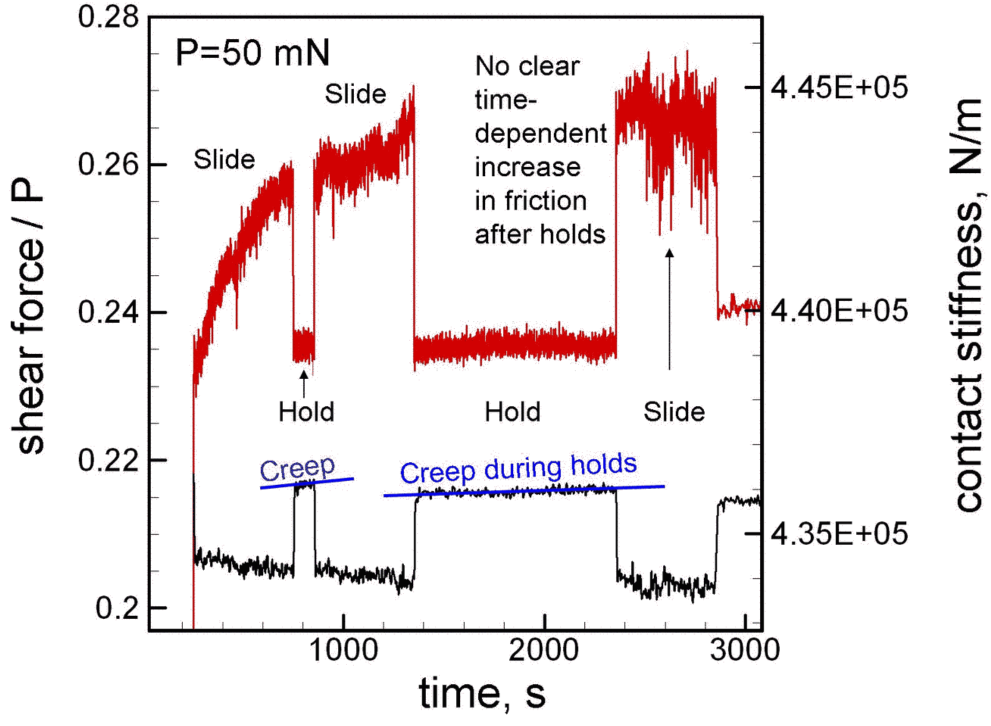
SHS - Diamond Berkovich on Aluminum



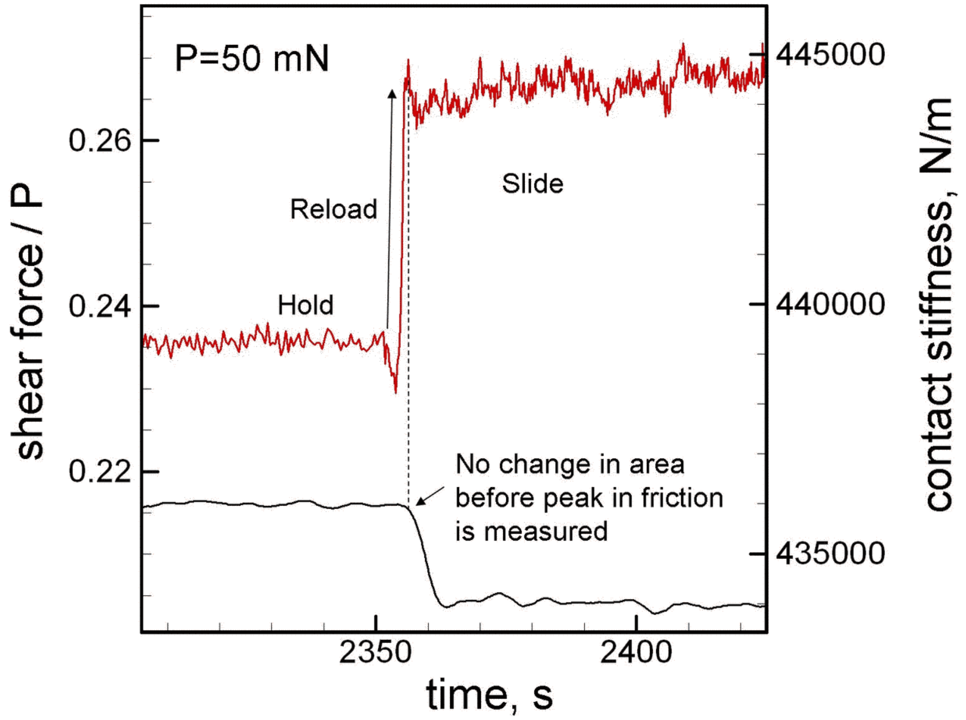
SHS - Diamond Berkovich on Quartz



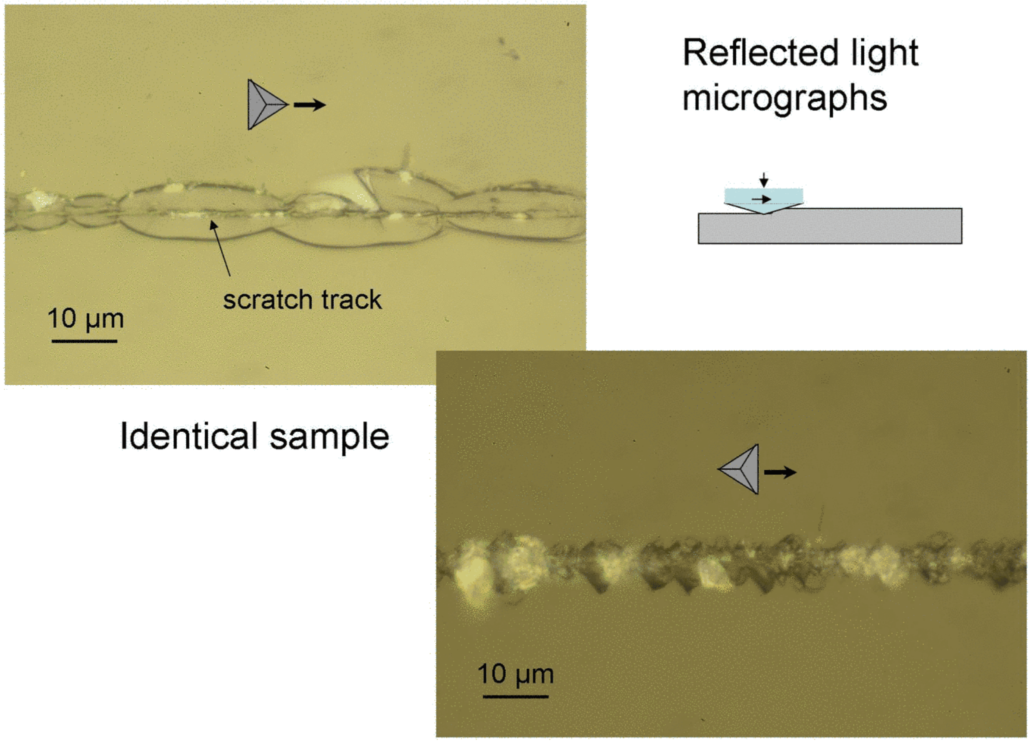
SHS - Diamond Berkovich on Quartz



SHS - Diamond Berkovich on Quartz

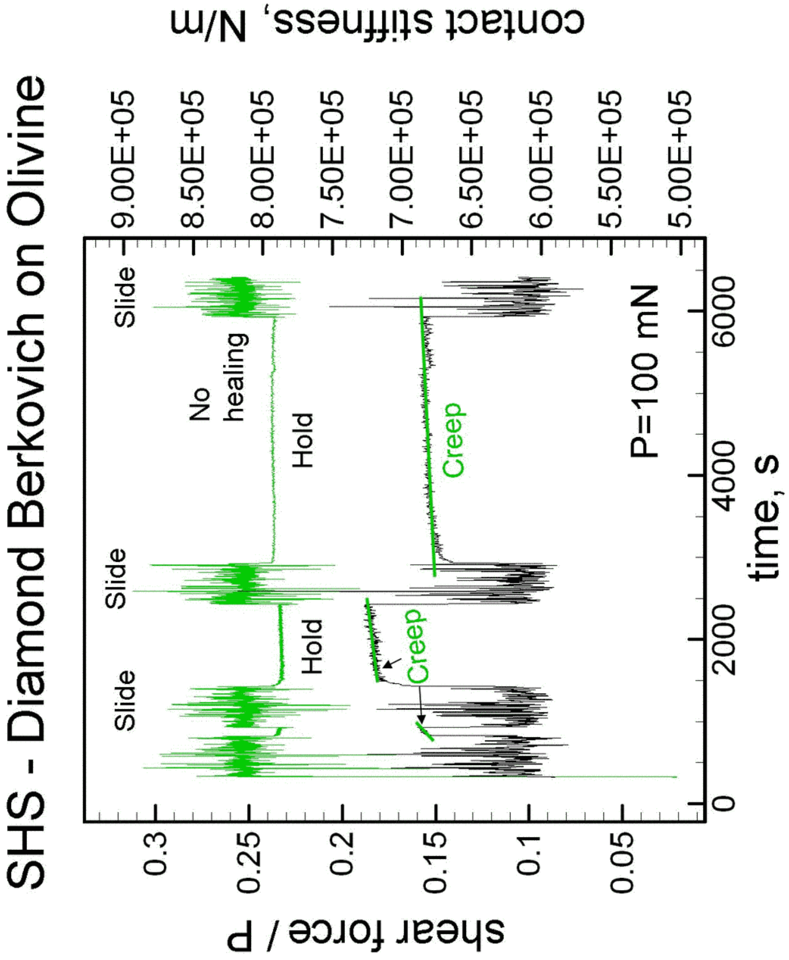


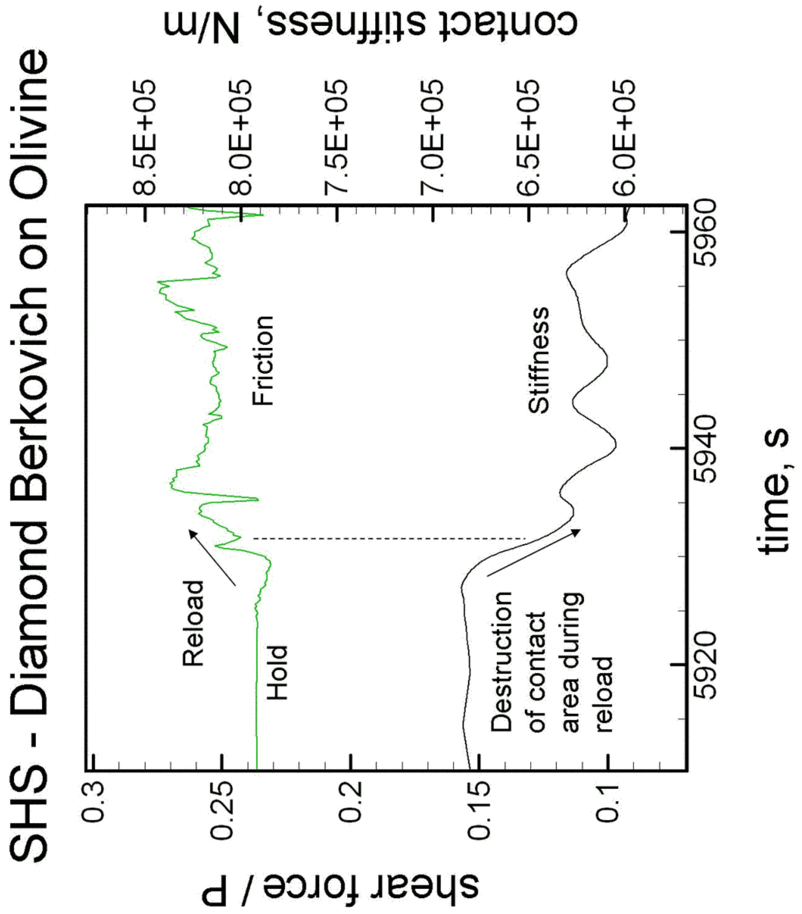
Diamond Berkovich Scratches on Quartz



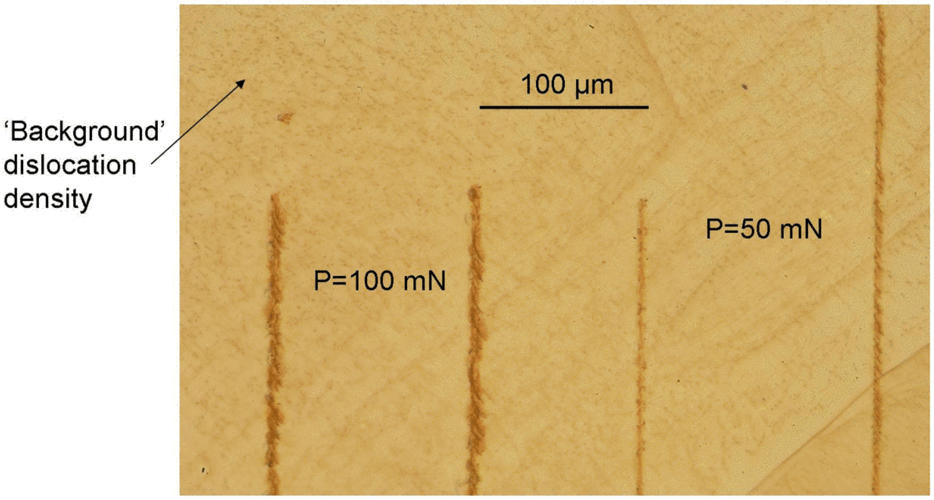
Reflected light micrographs

Identical sample


SHS - Diamond Berkovich on Olivine
shear force / P
0.3
0.25
0.2
0.15
0.1
0.05
contact stiffness, N/m
9.00E+05
8.50E+05
8.00E+05
7.50E+05
7.00E+05
6.50E+05
6.00E+05
5.50E+05
5.00E+05
time, s
0
2000
4000
6000
Slide
Slide
Slide
Hold
Hold
No healing
Creep
Creep
P=100 mN


SHS - Diamond Berkovich on Olivine
shear force / P
0.3
0.25
0.2
0.15
0.1
contact stiffness, N/m
8.5E+05
8.0E+05
7.5E+05
7.0E+05
6.5E+05
6.0E+05
time, s
5920
5940
5960
Hold
Reload
Friction
Stiffness
Destruction of contact area during reload

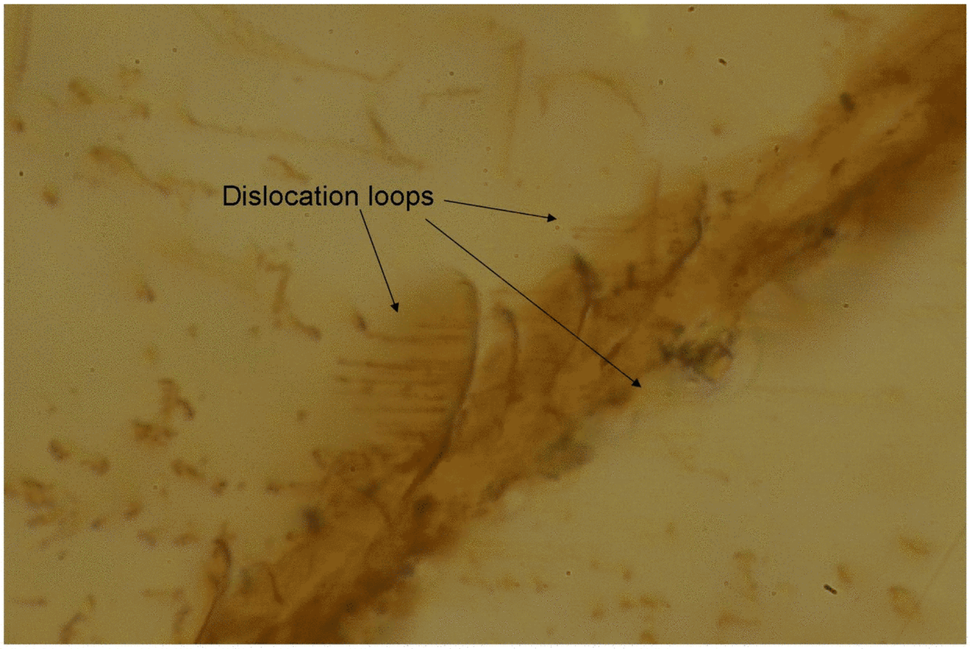
Diamond Berkovich Scratches on Olivine



Transmitted light micrograph

Sample oxidized in air @800 °C for 2 hours

Diamond Berkovich Scratches on Olivine



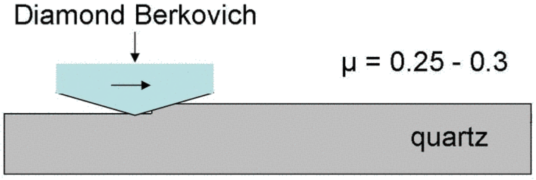
Summary - Quartz

Very low friction
Elastic contact (Hertz theory)
Invisible scratch track
'Large' contact area

Hertz theory A=172 – 356 μm^2
load range 100-300 mN

shear stress ~100 MPa

Adhesion



Low friction
Plastic contact (load-unload tests,S)
Prominent scratch track, abundant fracture
Smaller contact area than ruby tests

Stiffness ⟶ A=3.5 – 7 μm^2
load range 50 – 100 mN

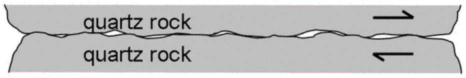
shear stress ~4 GPa

Ploughing, fracture

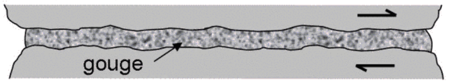
Rock Friction Tests

rough-on-rough
rock friction test

μ = 0.6 - 0.85

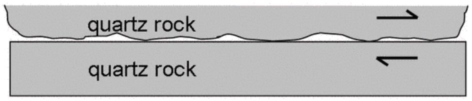


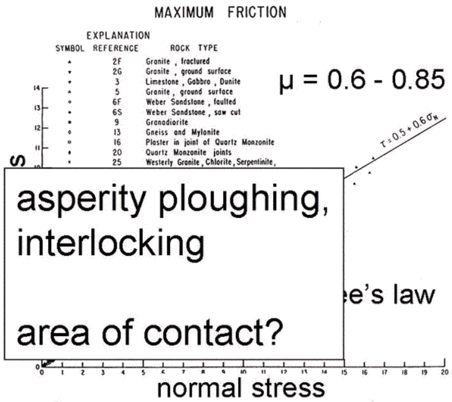
gouge experiments



rough-on-smooth
rock friction tests

μ = 0.25





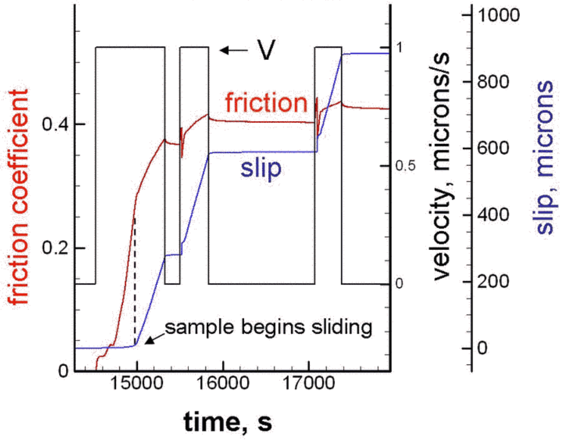
μ = 0.6 - 0.85

asperity ploughing,
interlocking

area of contact?

ee's law

normal stress



Conclusions - Indentation

1) All geologic materials undergo indentation creep at room T
    - A. quartz – solid-state amorphization
    - B. olivine – dislocation glide
2) Area of indentation increases linearly with log time up to 5☞10^4 s.
3) The change in fractional area with time in nanoindentation creep tests is larger than the change in fractional area inferred to occur in SHS rock friction tests.
    - A. Loss of contact during reloading
    - B. Smaller contact stresses in rock friction tests

Conclusions - Friction Tests

1) Friction in ruby ball tests on minerals is controlled by the adhesive strength of the contact junction

    -Adhesion increases with time of stationary contact

2) Friction in diamond Berkovich tests is higher than in ruby ball tests, reflecting significant contributions from ploughing/ interlocking, fracture in Berkovich tests

Conclusions- Friction Tests

3) Friction in Berkovich and ball experiments is smaller (by factors of at least 3 and 6, respectively) than in typical rock friction experiments

   - -Larger contributions of ploughing, interlocking in rock friction tests
   - -Larger area of contact in rock friction tests