Dramatic Reductions in Fault Friction at Earthquake Slip Rates

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Many thanks for providing data and slides go to:
David Goldsby, Giulio Di Toro,
Nick Beeler, Vikas Prakash, Toshi Shimamoto,
Jim Rice, Nadia Lapusta

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Main Point

- Friction of rock at slip velocities < 1 mm/s is relatively high, 0.6-0.8 (Byerlee's law)
- Most *in situ* stress measurements in the upper crust suggest tectonic stresses are relatively high, bounded by Byerlee's law
- As I will show, many potential high slip speed weakening mechanisms exist, all possibly giving low coseismic friction
- If dynamic friction at seismic slip rates (~1 m/s) is low, then either:
  1. Earthquake stress drops could be large, potentially creating extreme ground motion, or
  2. Tectonic stress is actually lower than the in situ measurements suggest

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Outline

- Proposed mechanisms for reduction in friction at high slip rates
- Where available, recent laboratory results on them
- Implications for earthquake stress drops and for tectonic stresses

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Difficult to Reproduce Earthquake Conditions in Lab

Simultaneously need to have:

- High slip rates (1-3 m/s)
- Large displacements (up to 20 m)
- High effective normal stresses (50-200 MPa)
- Elevated pore-fluid pressures (0.4-1 times σ_v)

Consequently present experimental data compromise on one or more of these

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Dynamic fault weakening mechanisms

1. Normal interface vibrations
2. Dynamic normal stress reduction from elastic mismatch
3. Acoustic fluidization
4. Elastohydrodynamic lubrication
5. Thermal pressurization of pore fluids
6. Local “Flash” weakening/melting at asperity contacts
7. Interfacial lubrication by frictional melt
8. Lubrication by thixotropic silica gel layer

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Normal Interface Vibrations

Proposed by *Brune et al*., 1993

Involves either opening of surface or dynamic reductions in normal stress during sliding

Thus shear resistance is much reduced

Is theoretically predicted only in cases where differences in elastic properties exist across the interface (bimaterials, i.e. next mechanism)

Has been seen in experiments using identical foam rubber blocks

Intuitively might be expected during sliding of surfaces with small-scale roughness – asperities bouncing off one another

Not well understood; could be important for earthquakes

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Dynamic Normal Stress Reduction From Elastic Mismatch

- Proposed by *Weertman*, 1963, 1980. Studied by many others including *Adams*, 1995, 1998, 2001; *Andrews and Ben Zion*, 1997; *Ben Zion* and *Andrews*, 1998; Cochard and Rice, 2000; Ranjith and Rice, 2001; *Shi and Ben Zion*, 2005.
- Involves dynamic reductions in normal stress near rupture tip during sliding on a bimaterial interface
- Can result in propagation of a wrinkle-like pulse
- Is theoretically predicted if differences in elastic properties exist across the interface
- Magnitude depends on amount of elastic mismatch & on difference between static and dynamic friction
- Observed elastic mismatches across San Andreas fault from 5 to 30% are sufficient
- Could be important for earthquakes

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Acoustic Fluidization

Proposed by *Melosh*, 1979, 1996

Involves acoustic waves bouncing around inside a shearing granular aggregate with sufficient intensity to partially hold the particles apart

Thus shear resistance is much reduced

Is an interesting idea, but whether it can actually occur is unclear

Experiments to investigate it have been proposed, but I know of no results

Not well understood; importance for earthquakes is questionable

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Elastohydrodynamic Lubrication

Proposed by *Brodsky and Kanamori*, 2001

Involves increases in pressure of a fluid separating two irregular sliding surfaces due to the viscous fluid being actively squeezed by closing gaps

Pressure would increase in closing gaps and decrease in opening gaps

In order to get a net increase in pressure, elastic distortion of the solids occurs in the pressurized gaps, making the geometry asymmetrical

Shear resistance is reduced due to the increase in fluid pressure (effective normal stress lowered)

Hydrodynamic lubrication is well-known in journal bearings, but the geometry is more favorable

No relevant experiments

Water insufficiently viscous. Not clear whether it can be important for more viscous fluids like melt or silica gel.

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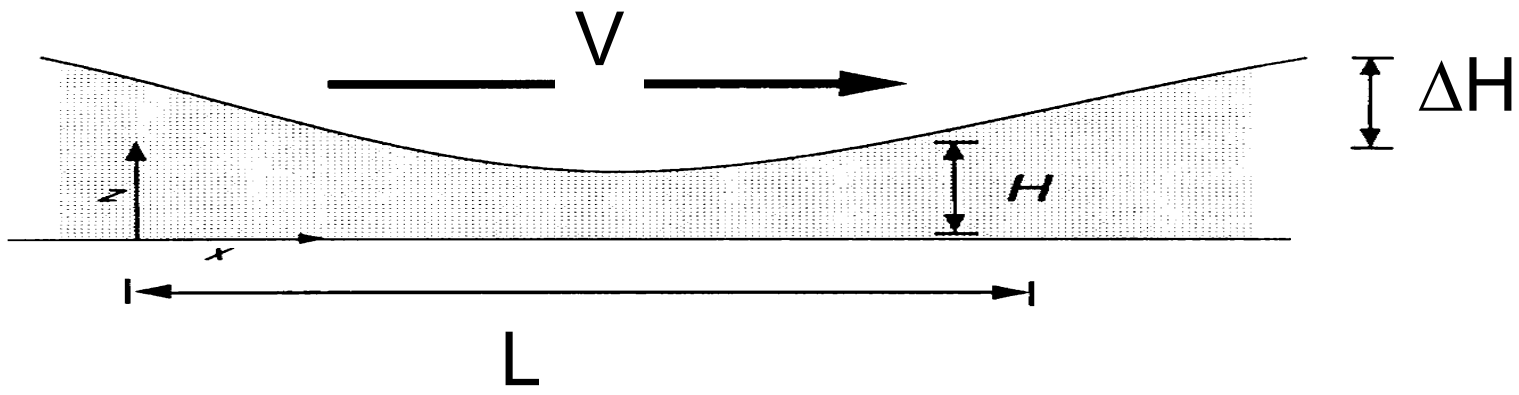
Elastohydrodynamic lubrication



$$P_L \approx \frac{6\,\eta\,\mathrm{V}\,\mathrm{L}\Delta\mathrm{H}}{H^3}$$

Fluid trapped in fault exerts a normal pressure tending to separate surfaces, reducing effective normal stress and thus weakening fault

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Thermal Pressurization of Pore Fluid

Proposed by *Sibson*, 1973. Studied by many including *Lachenbruch*, 1980; *Mase and Smith*,1985, 1987; *Andrews*, 2002; *Rice*, 2004.

Involves thermal expansion of pore fluid in a fault separating relatively impermeable rocks for sufficiently rapid and localized slip that elevated temperatures result

Could be overcome by dilatancy of the fault zone if this occurs and persists with slip

Experimental evidence lacking, but relevant lab experiments still remain to be conducted

Well understood theoretically; Applicability for faults still unclear; Could be important for earthquakes

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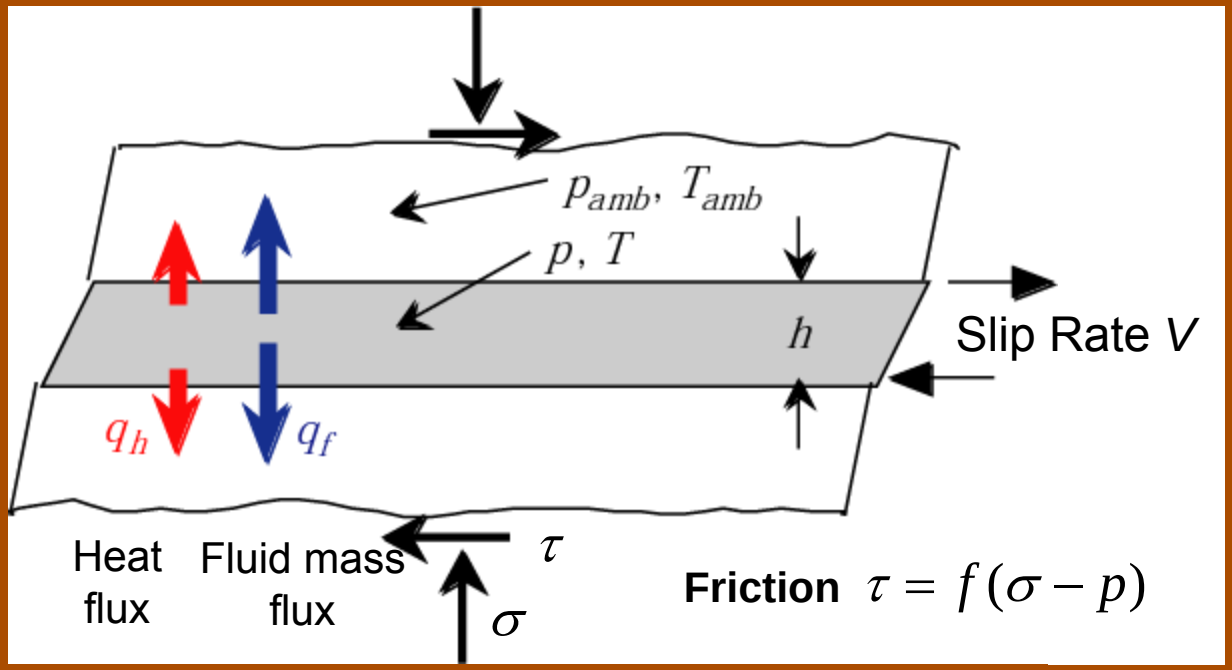
Thermal Pressurization of Pore Fluid



[Rice 2003,
building on Sibson (1973),
Lachenbruch (1980),
Mase & Smith (1985, 1987),
Rudnicki & Chen (1988),
Segall & Rice (1995a,b),
Andrews (2001),
Garagash & Rudnicki
(2003a,b)]

Energy conservation

$$\frac{\tau V}{h} = \rho^o c_{sp.ht.} \frac{dT}{dt} + 2\frac{q_h}{h}$$

Assume adiabatic conditions (q_h = 0).

Neglect dilatancy (dn^{pl} / dt = 0).

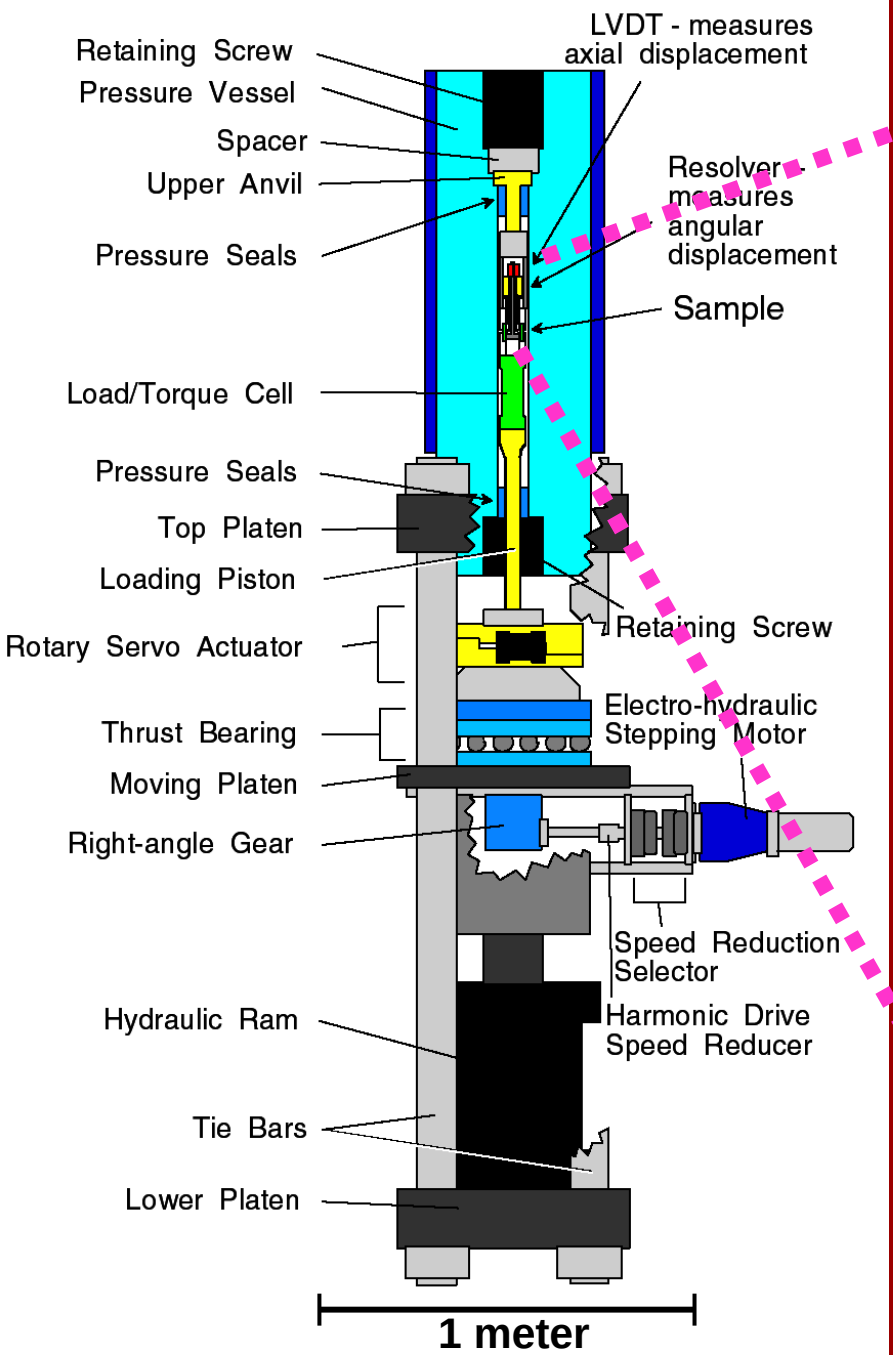
Fluid mass conservation

+ Some thermo-poro-elastic calculations

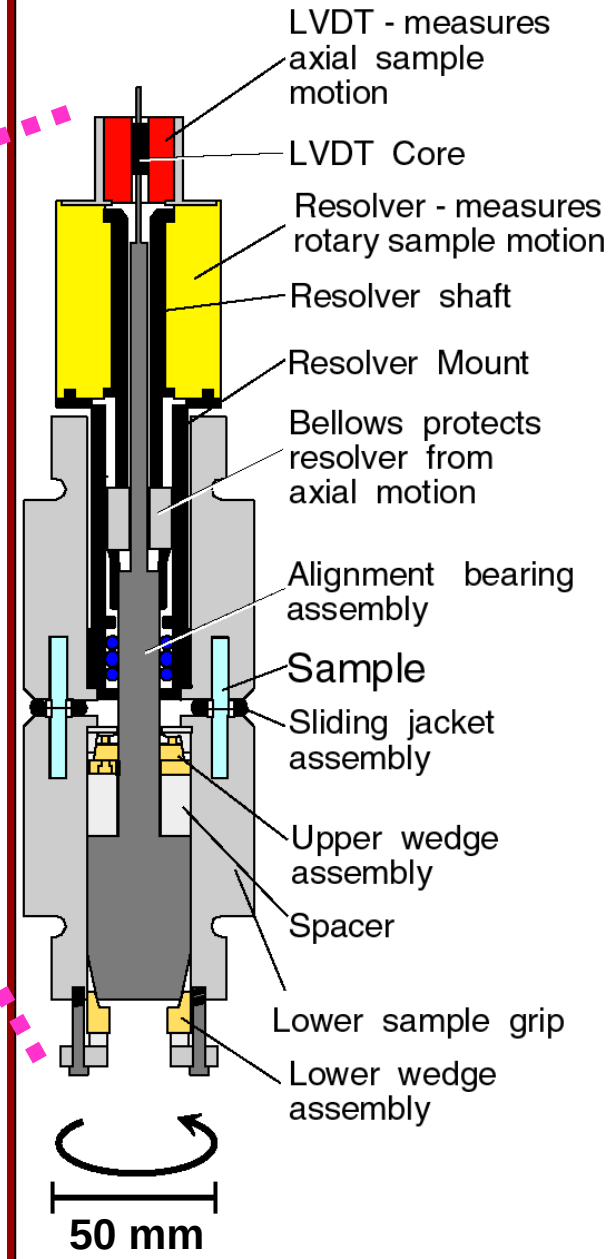
$$\frac{dp}{dt} - \Lambda \frac{dT}{dt} + \frac{1}{\beta}\frac{dn^{pl}}{dt} = -2\frac{q_f}{\rho_f \beta h} \; ; \; q_f = -\frac{\rho_f k}{\eta_f}\frac{\partial p}{\partial y}$$

[Lachenbruch: We can neglect q_h if $h > 3.5(c_{th}\delta/V_{avg})^{1/2}$

or $h > 3.5\ \mathrm{mm}\ (\delta/\mathrm{m})^{1/2}$ using $V_{avg} \approx 1\ \mathrm{m/s}$]

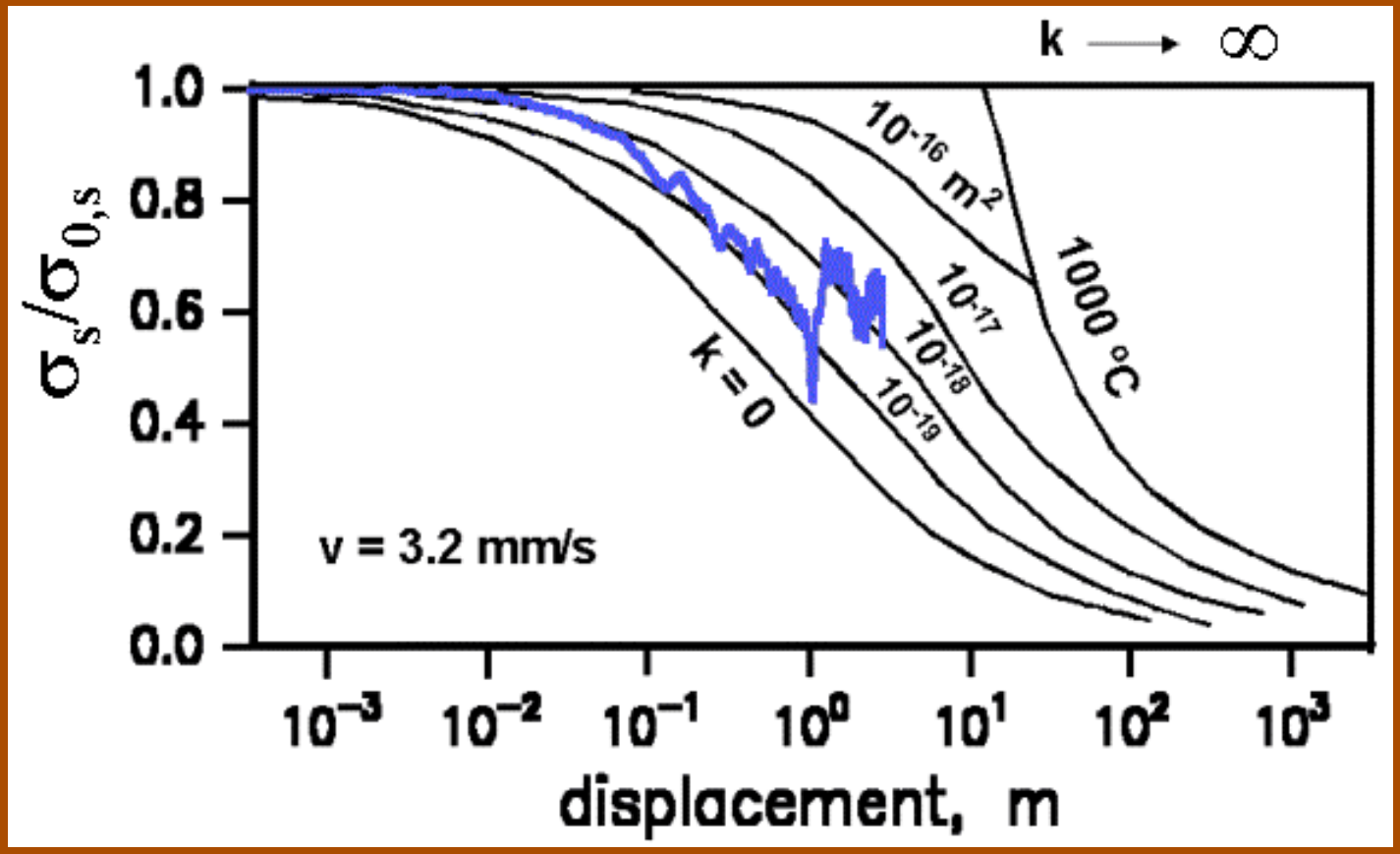


Overall Rotary Shear Apparatus



Sample Assembly with Internal Rotary and Axial Displacement Transducers

Comparison Between Quartzite Data (in blue) and Prediction from Thermal Pressurization of Pore Fluid



Quartzite was water saturated and had permeability of 10^{-19} m^2 *Goldsby and Tullis* (1997, 1998)

Theory of *Mase and Smith*, 1983

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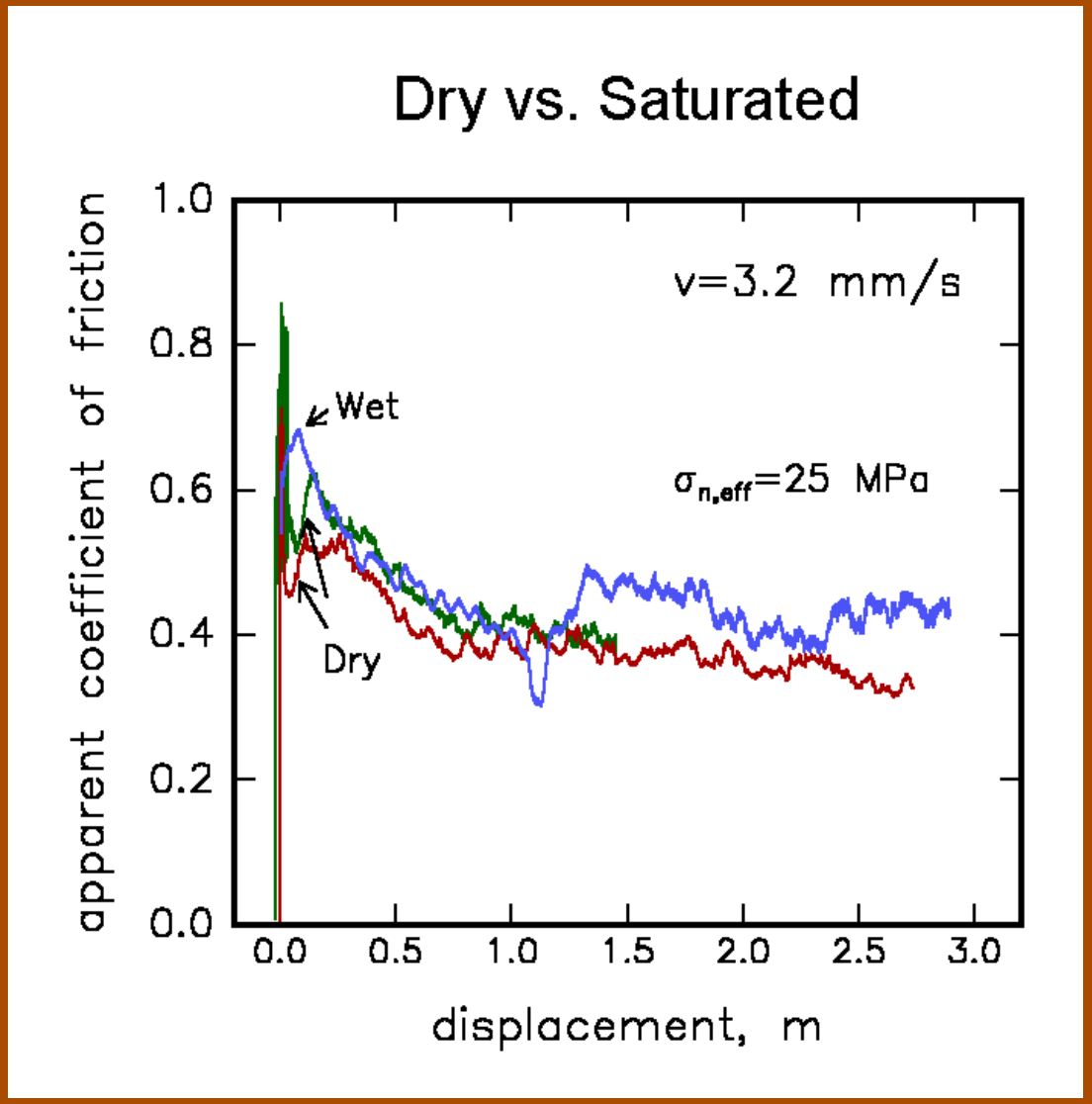
But with no water, behavior is the same!



We will return to the explanation for the weakening later: silca gel

More experiments needed on rocks that don't show gel weakening

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“Flash” Weakening/Melting at Asperity Contacts

- Discovered by *Bowden and Tabor*, 1942. Studied by *Archard*, 1958, 1959; *Rice*, 1999; *Beeler and Tullis*, 2003.
- Involves local transient heating of short-lived contacts by frictional sliding at very high asperity contact stresses
- Shear resistance is reduced ether due to thermal softening or to melting
- Theoretically is only effective above a velocity that depends on local strength and dimensions of asperities
- Originally observed experimentally by flashes of light seen in transparent materials
- Weakening has been observed in rocks that fits predictions of this mechanism (*Goldsby and Tullis*, 2003; *Prakash*, 2003). Direct proof still needed.
- Could be important for earthquakes

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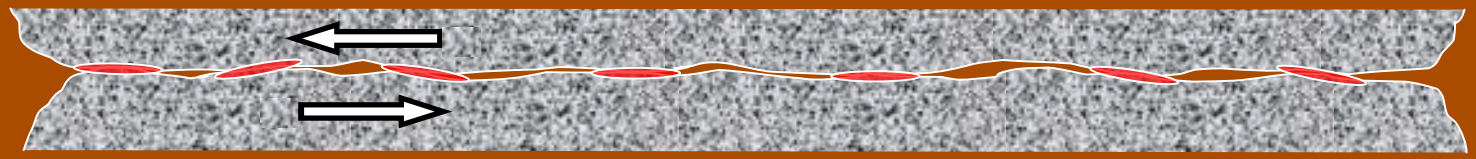
Calculations of Weakening Due to Flash Melting

- Flash heating is local heating at tips of contacting asperities
  - Bowden and Tabor saw small flashes of light when they looked at a sliding surface through a transparent plate



- *Jim Rice* developed simple model for strength as a function of velocity for asperities of one size
- Extension using a distribution of asperity sizes and assuming non-zero strength of melted contacts (*Nick Beeler*)

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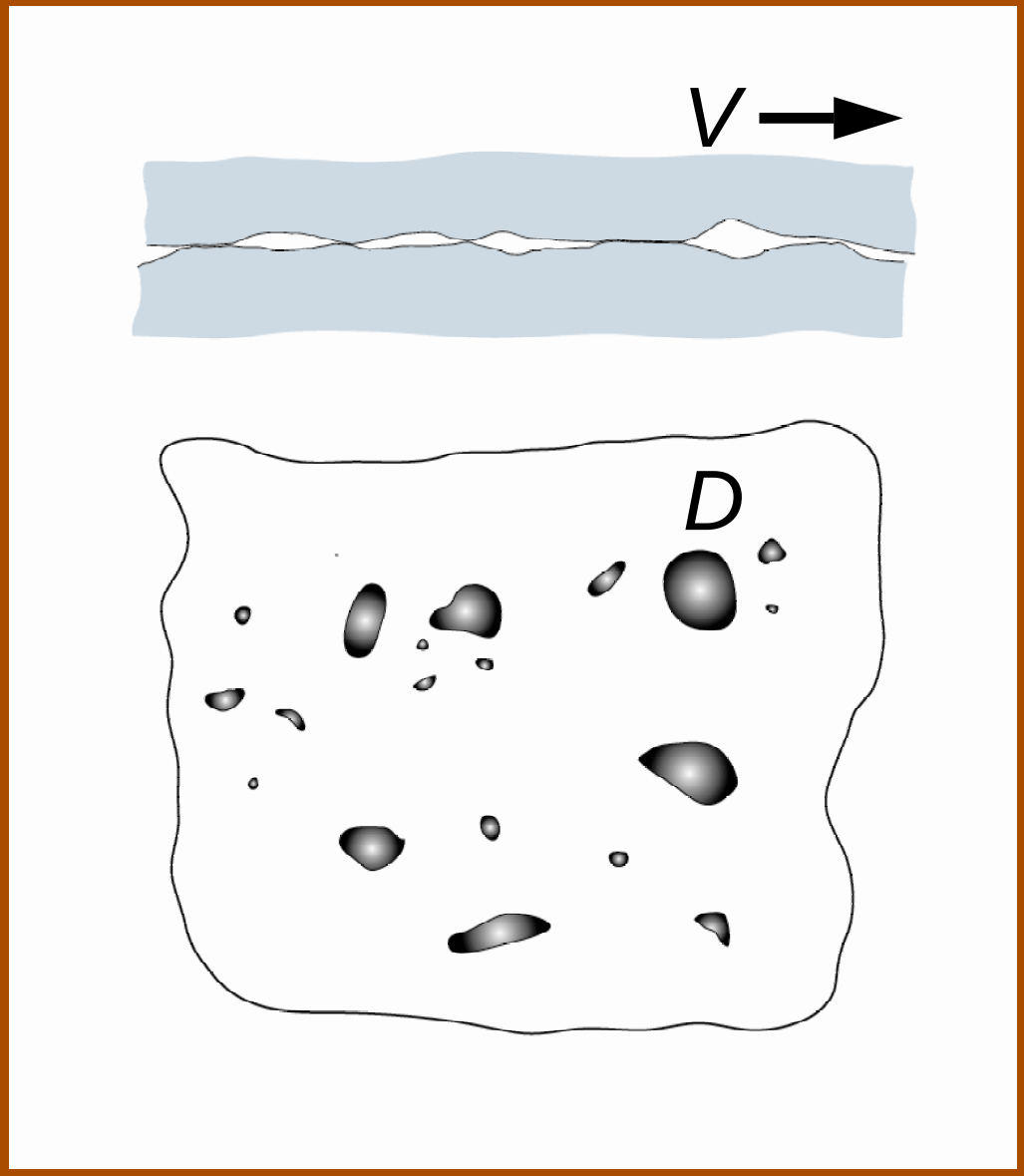
Flash Heating Analysis of *Rice* (1999)



D = contact size

V = slip rate

Contact lifetime

$\theta = D/V$

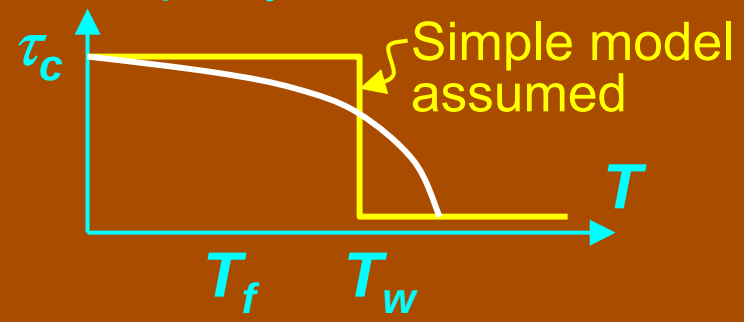
T_w is weakening T

T_f is ave. fault T

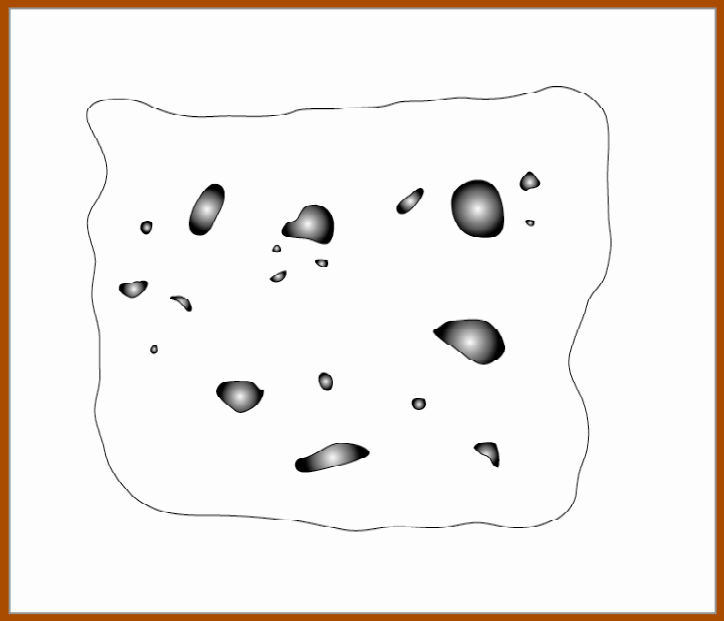
$T < T_w$: τ constant = τ_c

$T \geq T_w$: τ negligible

τ at asperity contact



Theory (*Rice*, 1999)



θ_w = time to weaken

Equate heat input $\tau_c V \theta_w$
to thermal energy storage $\rho c (T_w - T_f)$
over an effective distance $\sqrt{(\pi c_{th} \theta_w)}$

$$\theta_w = (\pi c_{th} / V^2) [\rho c (T_w - T_f) / \tau_c]^2$$

Will weaken if [time to weaken] is < [lifetime of asperity], or

$\theta_w < \theta$ when $V > V_w = (\pi c_{th} / D) [\rho c (T_w - T_f) / \tau_c]^2$

Representative values: c_{th} = 1 (mm)^2/s, ρc = 4 MJ/m^{3}K,
D = 5 μm, $T_w - T_f$ = 1000 K and τ_c = 7 GPa

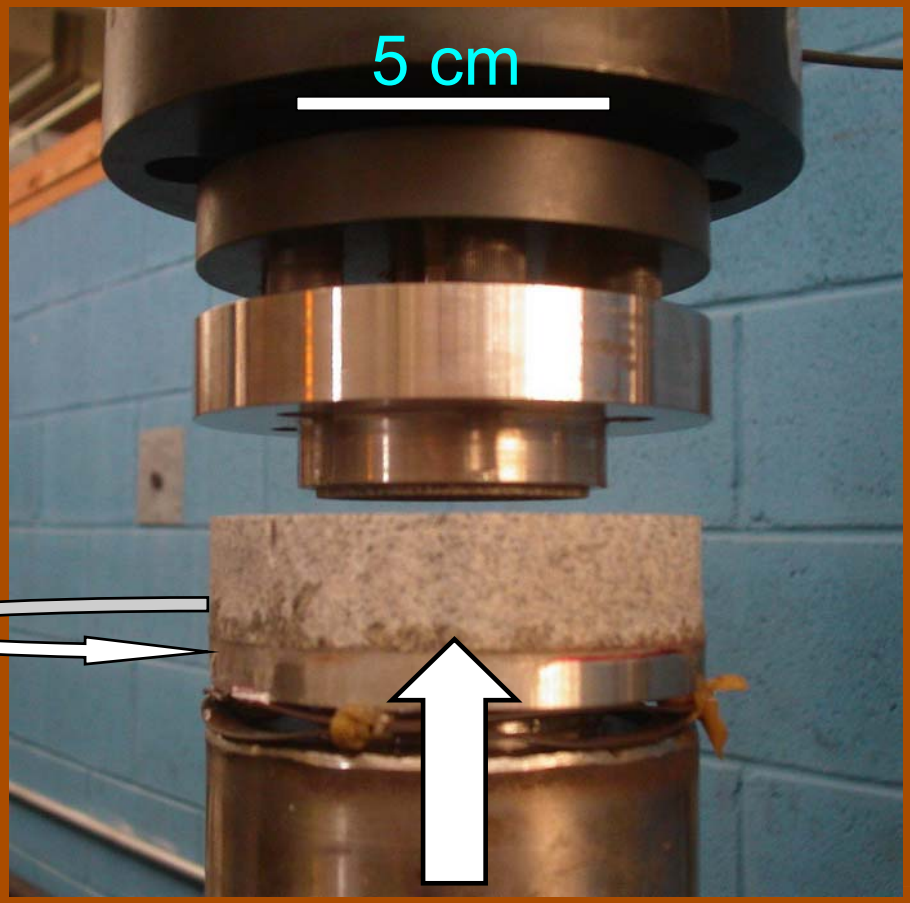
Gives V_w = 0.1 m/s for onset of severe thermal weakening

Also, $0 < V < V_w$: Friction = $\mu_0 \approx 0.6$, and

$V > V_w$: Friction = $\mu_0 (V_w / V) \approx 0.6 (V_w / V)$

Unconfined Rotary Shear Friction Experiment

Flash Weakening



High speed

$V \leq 0.38$ m/s

Small Displacement:
$\delta = 4$ cm

$\sigma_n = 5$ MPa

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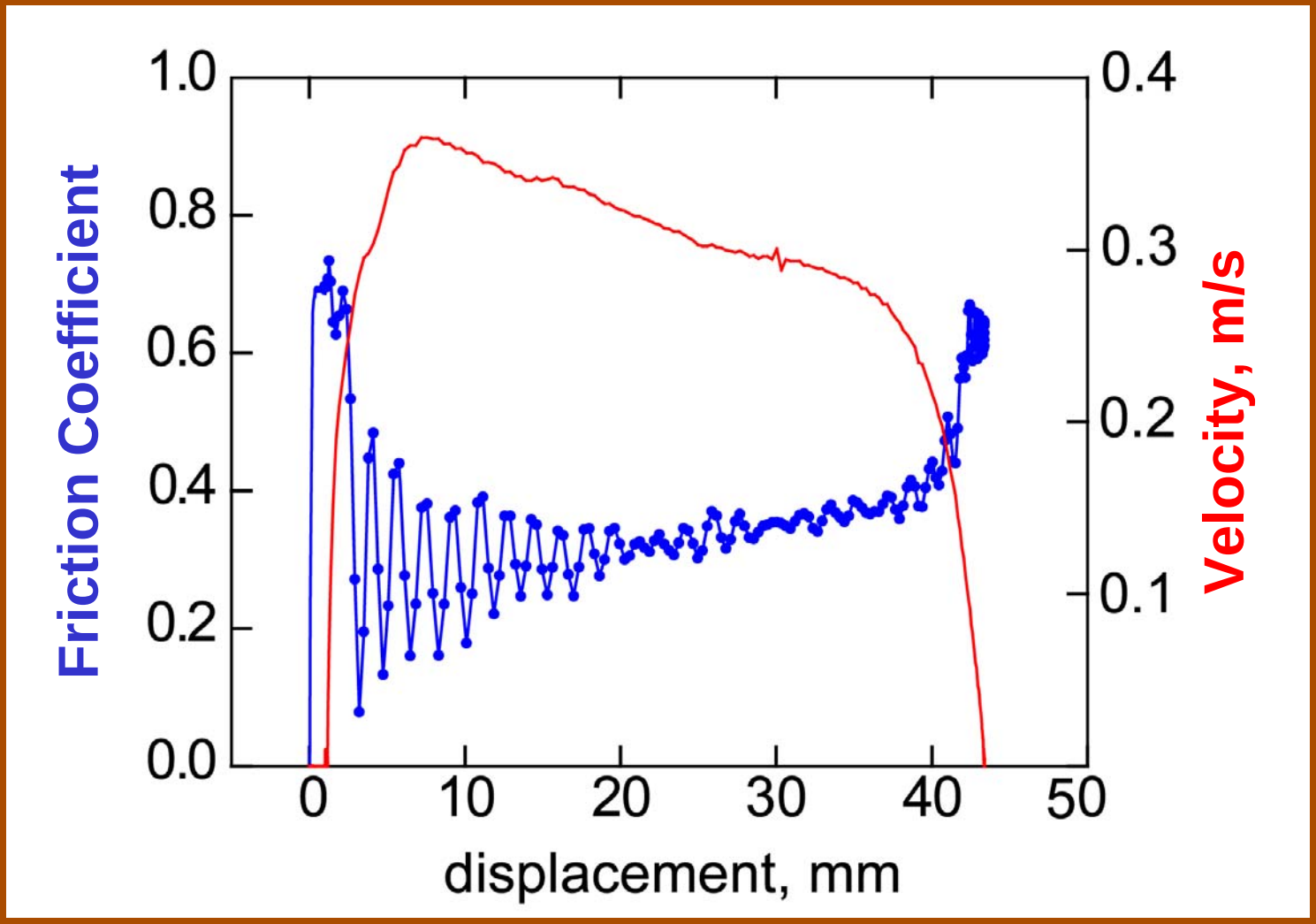
Quartz Velocity and Friction in one 90 deg. Rotation



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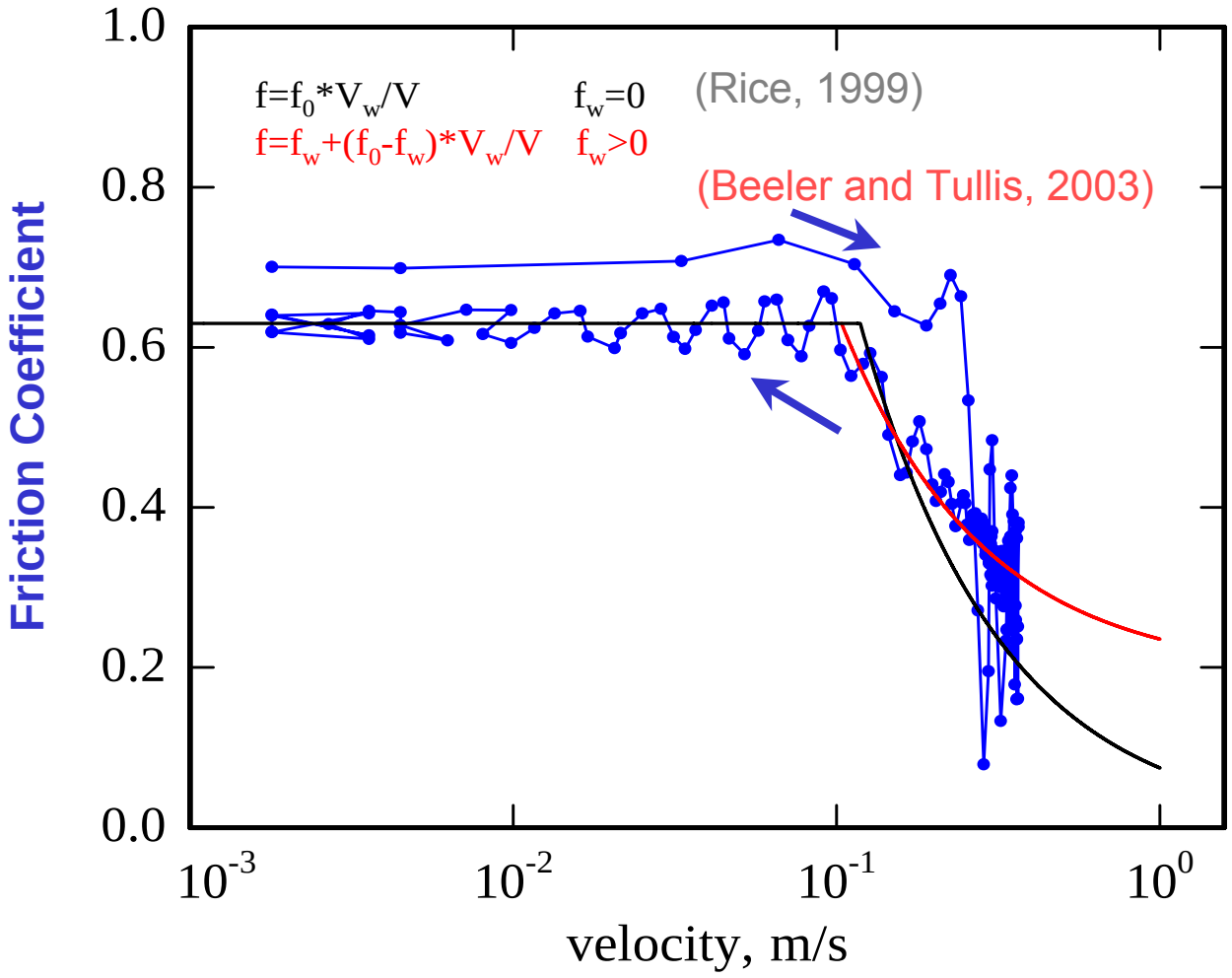
Same Quartz Data Plotting Friction vs. Velocity



At lower speeds this rapid weakening is not seen

Is reversible with no time delay – Namely healing is instantaneous

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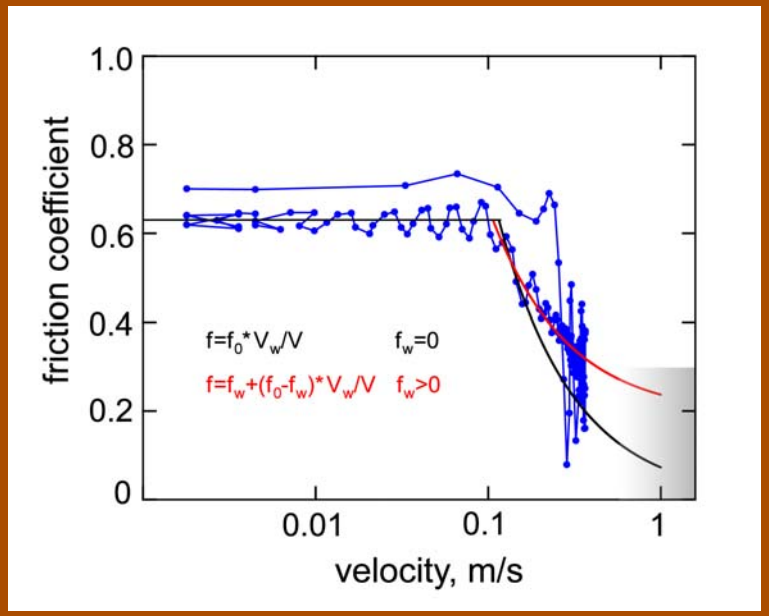
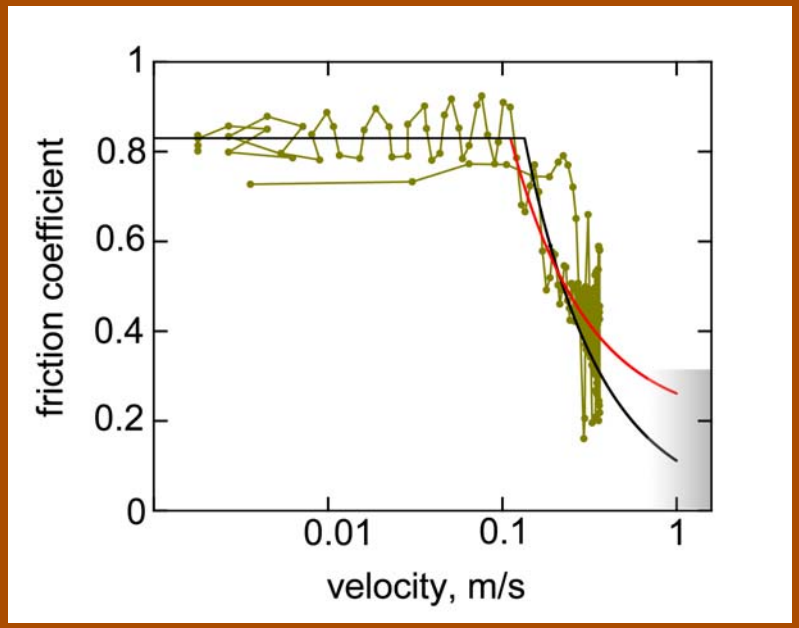
Similar Behavior is Seen for Several Rock Types:

Friction coefficient is 0.2 at seismic slip rates

Quartz:



Granite:



Gabbro:

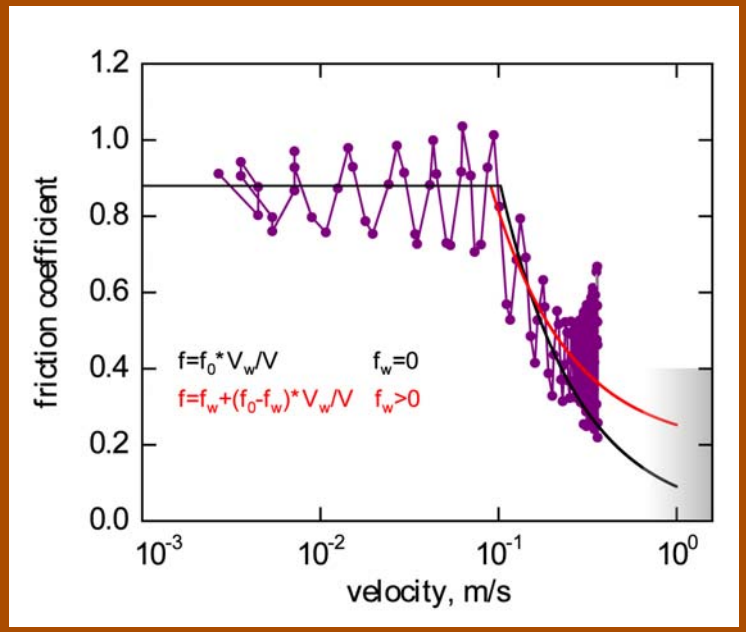


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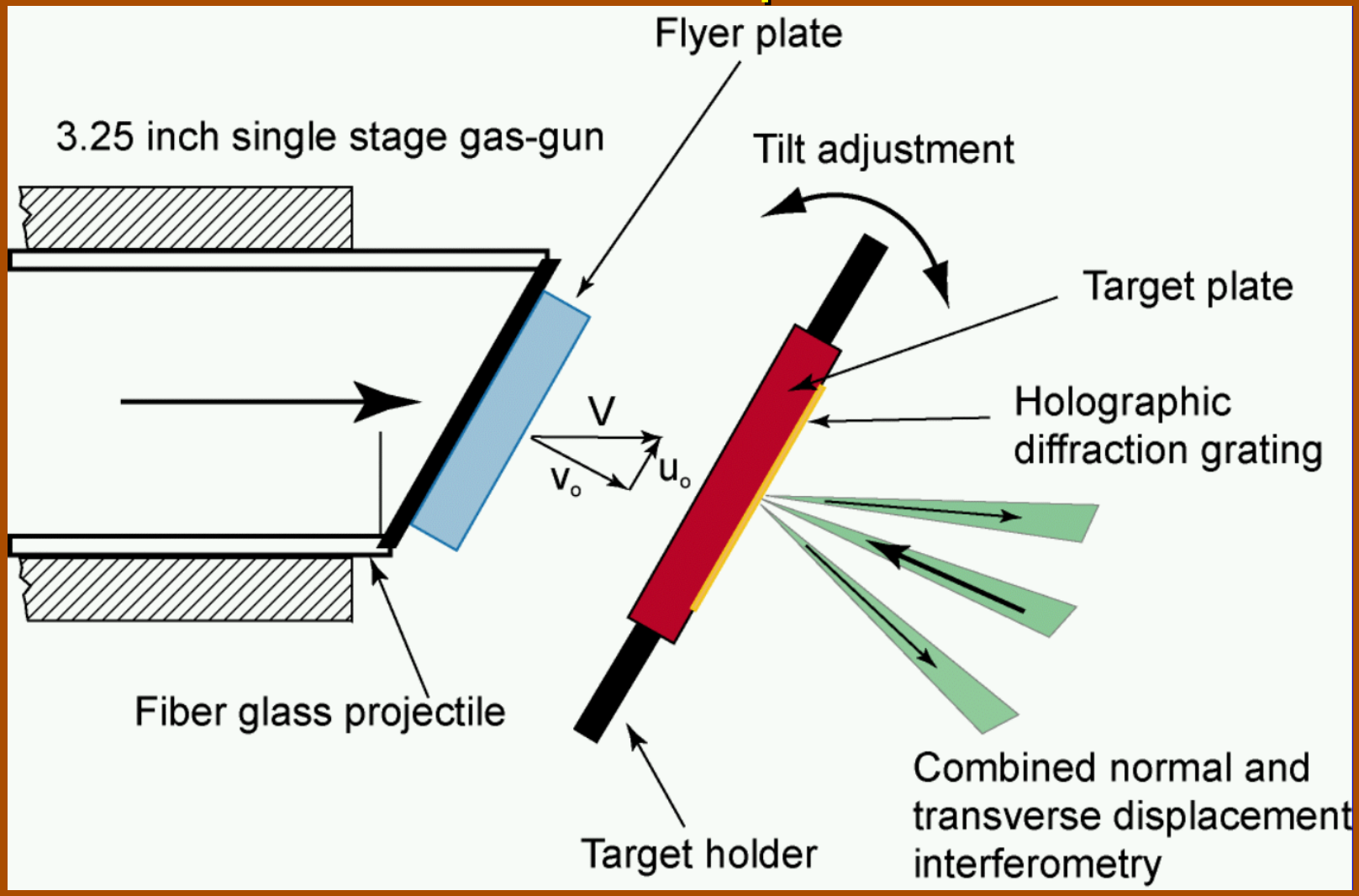
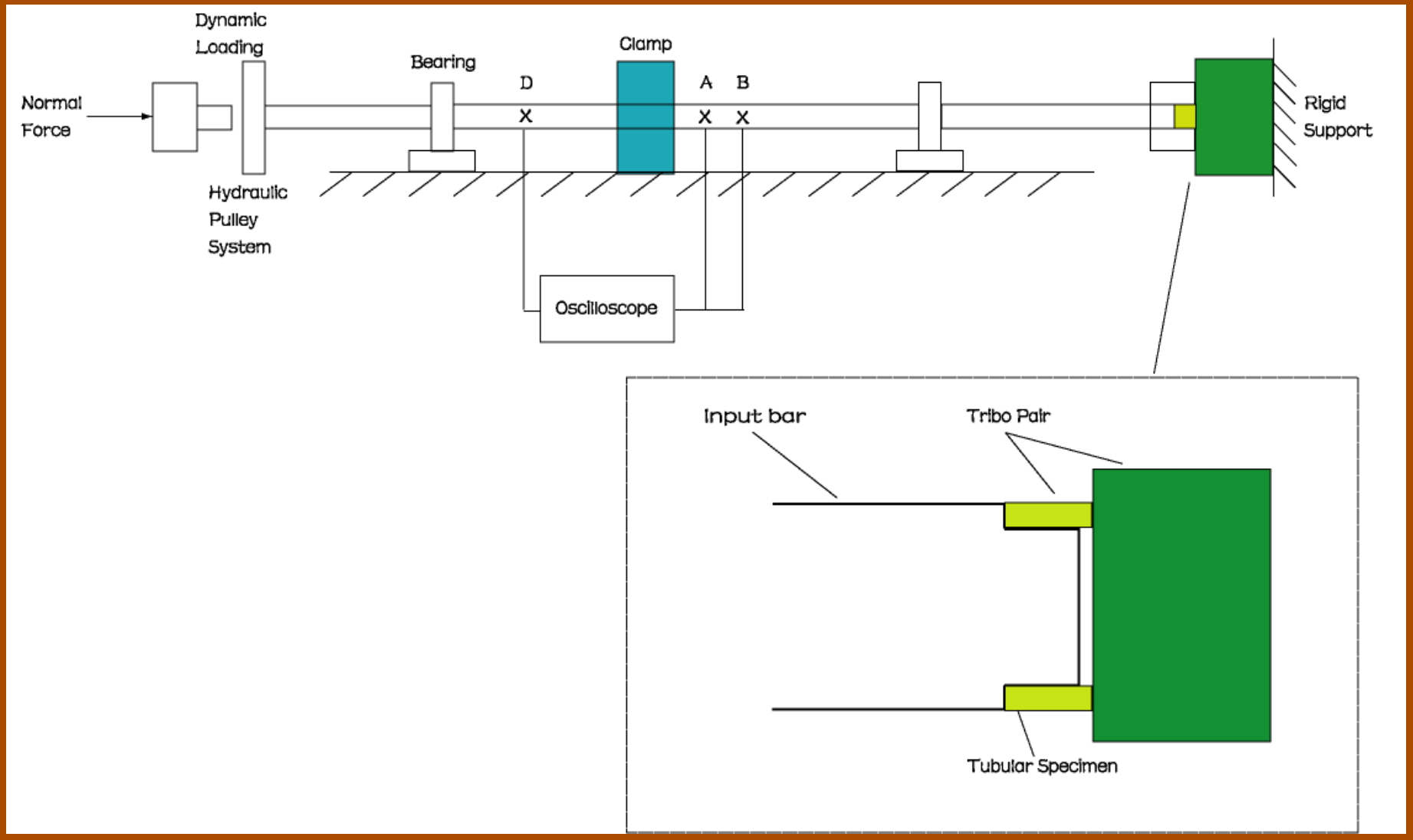
Plate Impact Pressure-Shear Friction Experiment



Vikas Prakash

Torsional Kolsky bar apparatus



Vikas Prakash

Conditions Assessable Using Non-conventional Experimental Techniques to Measure Sliding Resistance at Seismic Slip Rates

	Pressure Shear Friction Experiment	Kolsky-bar Friction Experiment
Normal pressure	100 MPa to 2 GPa	1-100 MPa
Slip speed	1-50 m/s	1-10 m/s
Slip distance	< 0.5 mm	10 mm

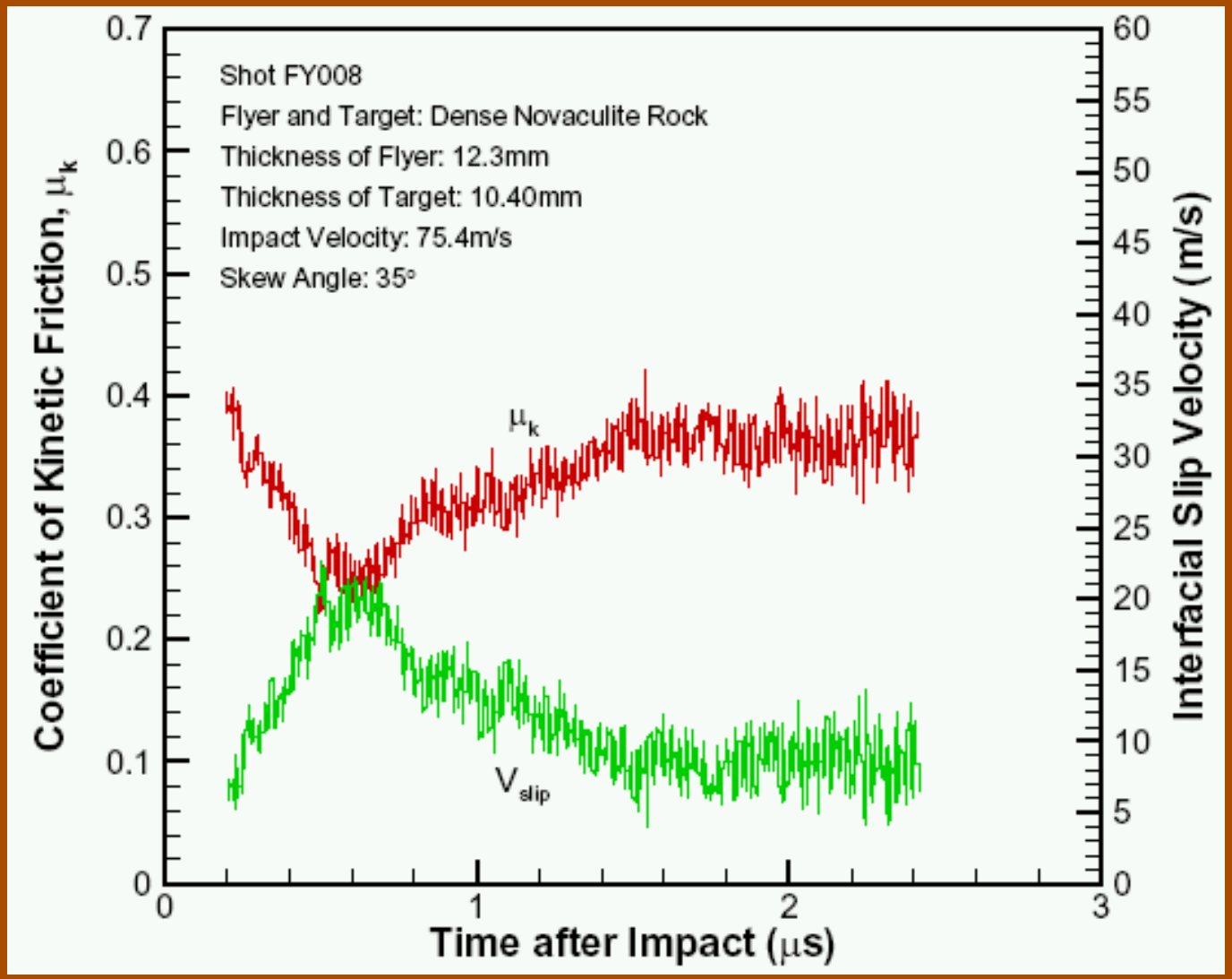
The Kolsky-bar friction experiment can access more interesting ranges of normal pressures and slip distances than the pressure shear friction experiment, but also at high slip speeds

Vikas Prakash

Results from Plate Impact Pressure-Shear Pilot Experiments

Results on a dense Arkansas novaculite:

Could be compatible with flash melting and enlargement of viscous melt layer



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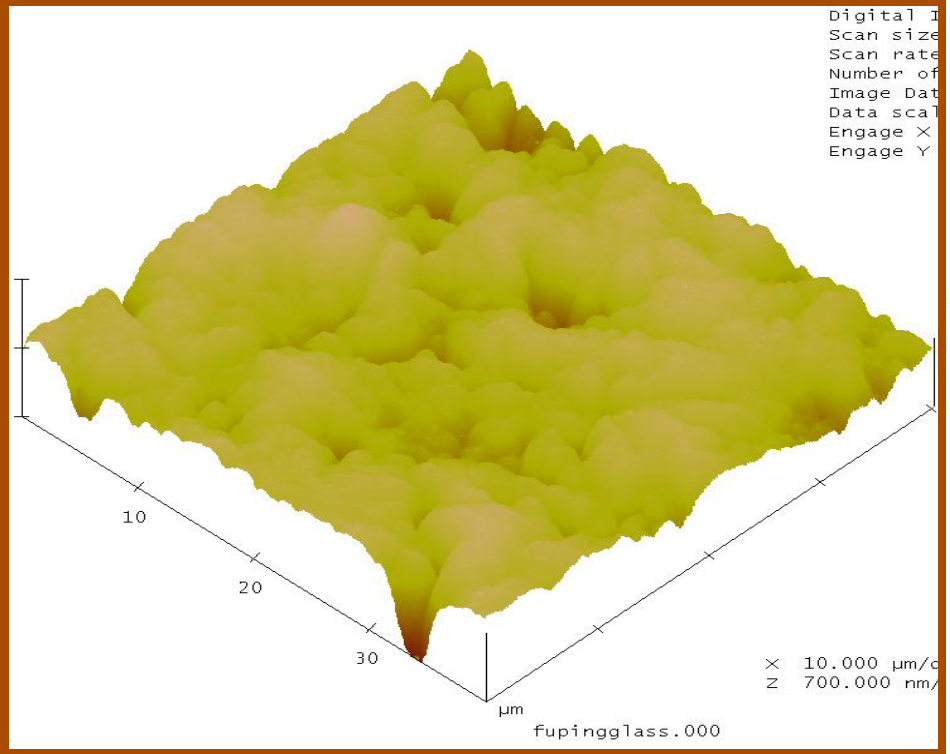
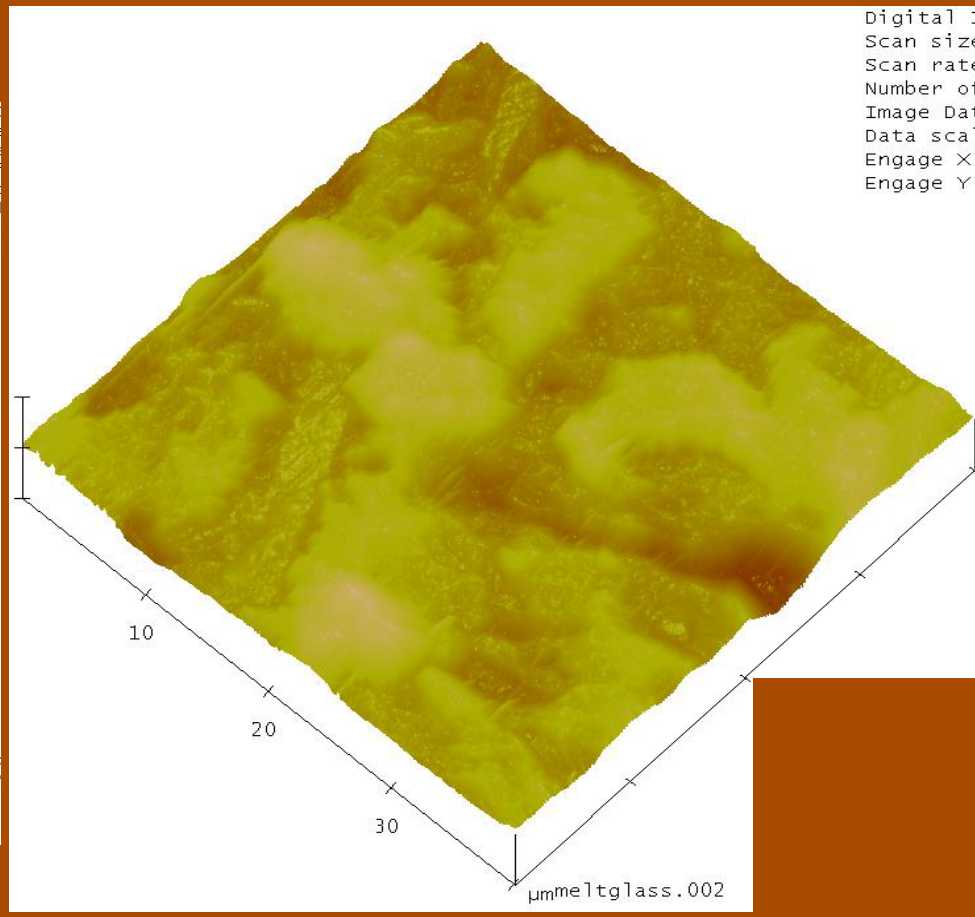
Topography of Surfaces

Before sliding



After Sliding – crests smoothed off



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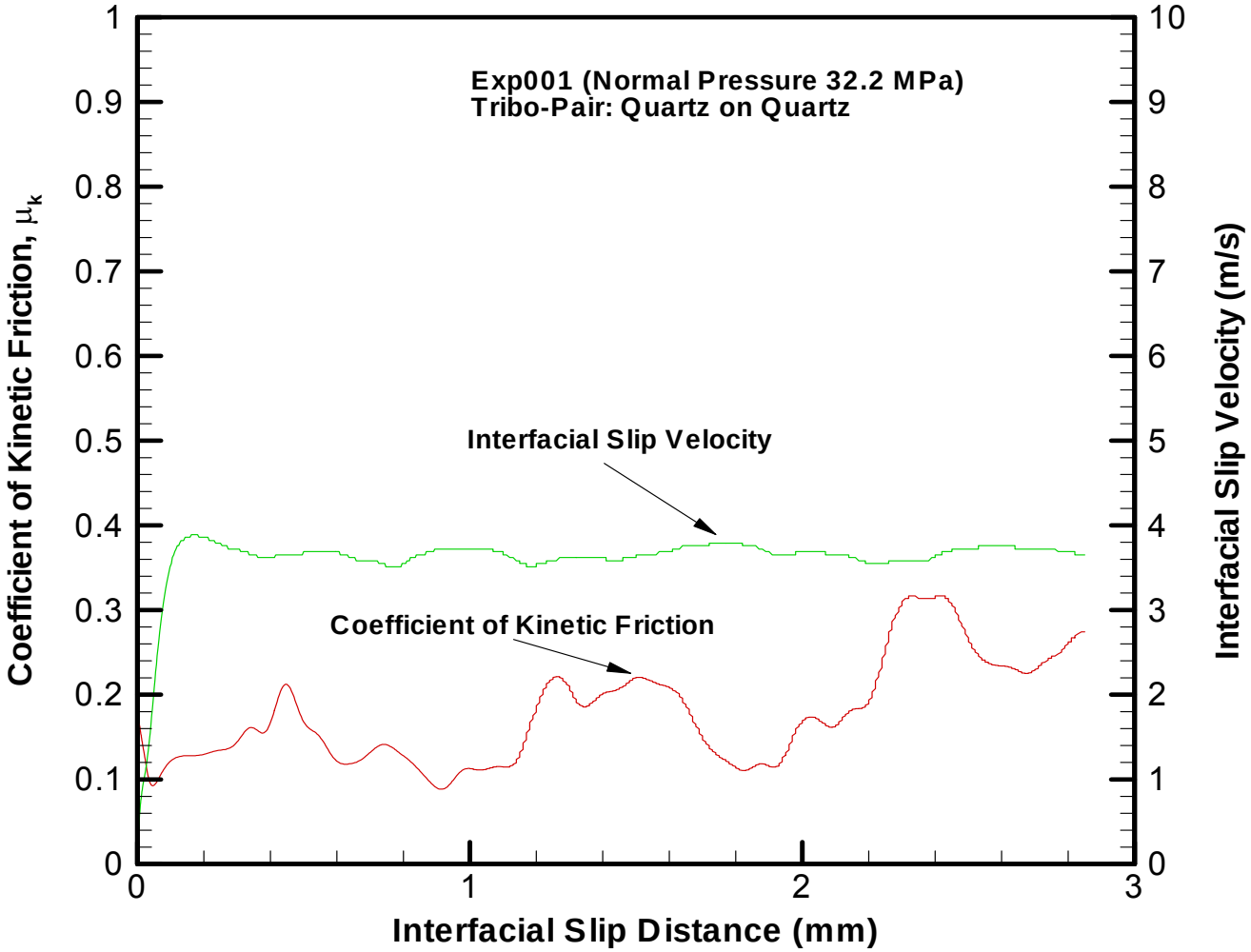
Torsional Kolsky Bar Results (Exp001)



Vikas Prakash

What Might Be Done to Verify The Weakening Is Due to Flash Weakening/Melting?

Theory says: $V_w = (\pi c_{th} / D) [\rho c (T_w - T_f) / \tau_c]^2$

Thus as T_f increases V_w will decrease, so changing ambient Temperature T_f will make predictable changes in V_w

Also as D increases V_w increases, so changing surface roughness should change D and so V_w

Attempts to observe small amounts of melt at asperities also should be made, but it is difficult

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Interfacial Lubrication by Frictional Melt

- Proposed by *Jeffreys*, 1942; *McKenzie and Brune*, 1972
- Involves enough frictional heating to create a layer of melt separating the adjoining blocks
- Shear resistance would seem to be reduced, but viscous coupling can be a factor
- Theory is complex due to negative feedback between weakening and heating
- Has been seen in experiments at low normal stresses, but strength is a complex function of slip (*Tsutsumi and Shimamoto*, 1997; *Hirose and Shimamoto*, 2005)
- Occurs during some earthquakes, generating pseudotachylytes, but not clear how frequently

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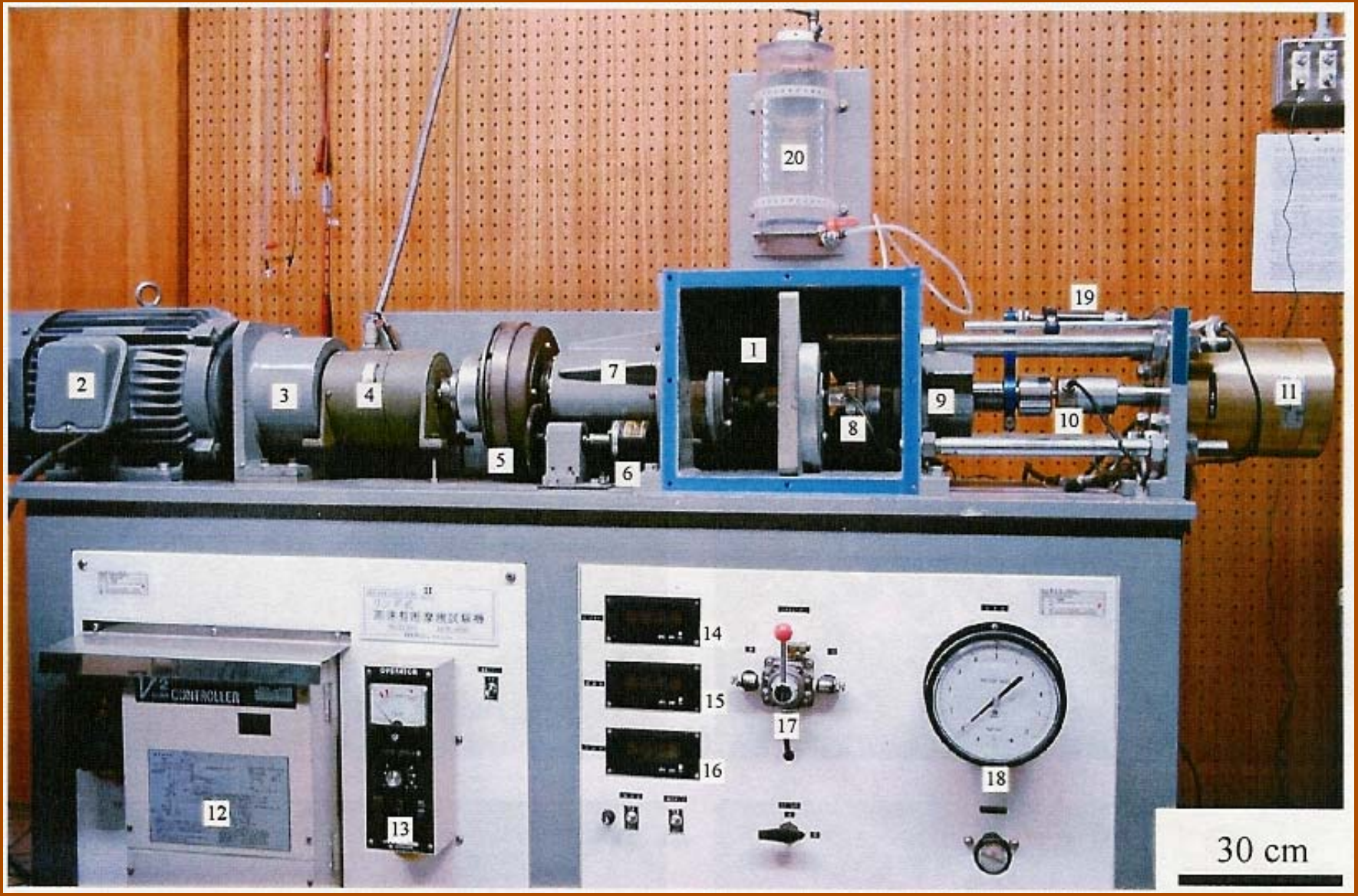
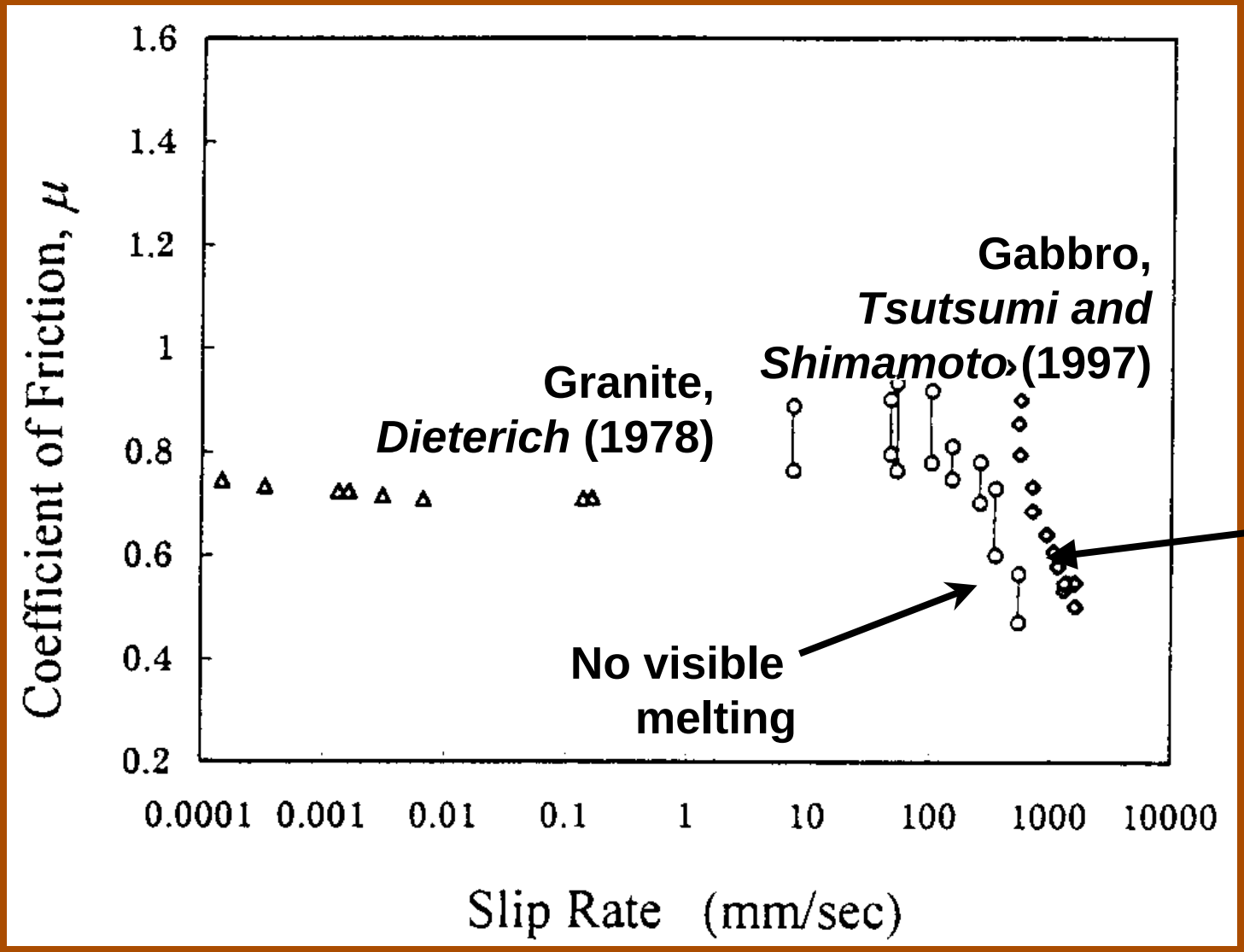
High-velocity Rotary Shear in Kyoto



Apparatus of *Toshi Shimamoto* [*Hirose*, Ph.D. thesis, 2001]

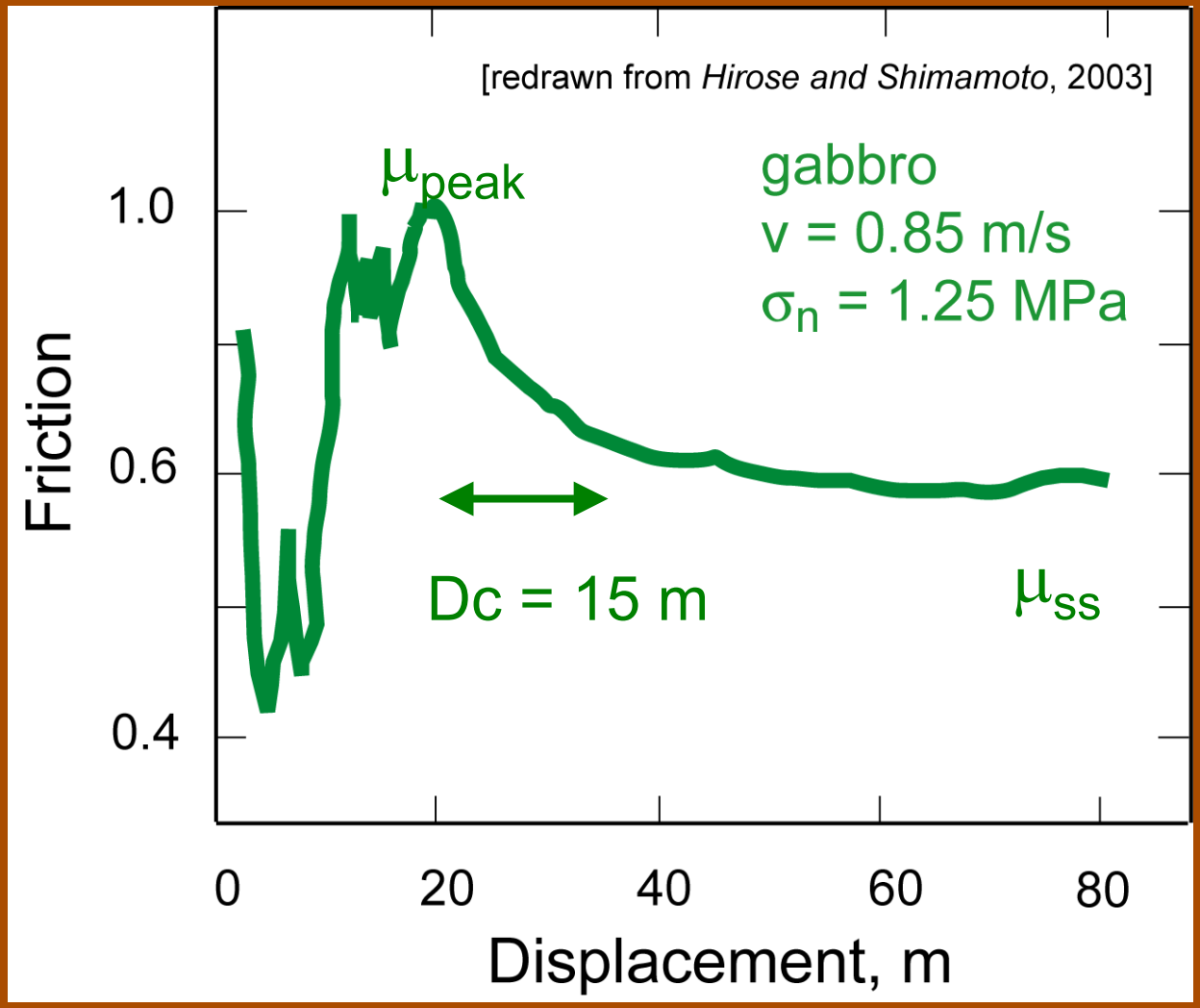
Friction in the presence of melt at low normal stress



Tsutsumi & Shimamoto, 1997

Weakening-strengthening-weakening behavior

σ_n = 1.25 MPa, μ_{ss} = 0.6, D_c = 15 m and slip up to 80 m



Hirose & Shimamoto, 2003

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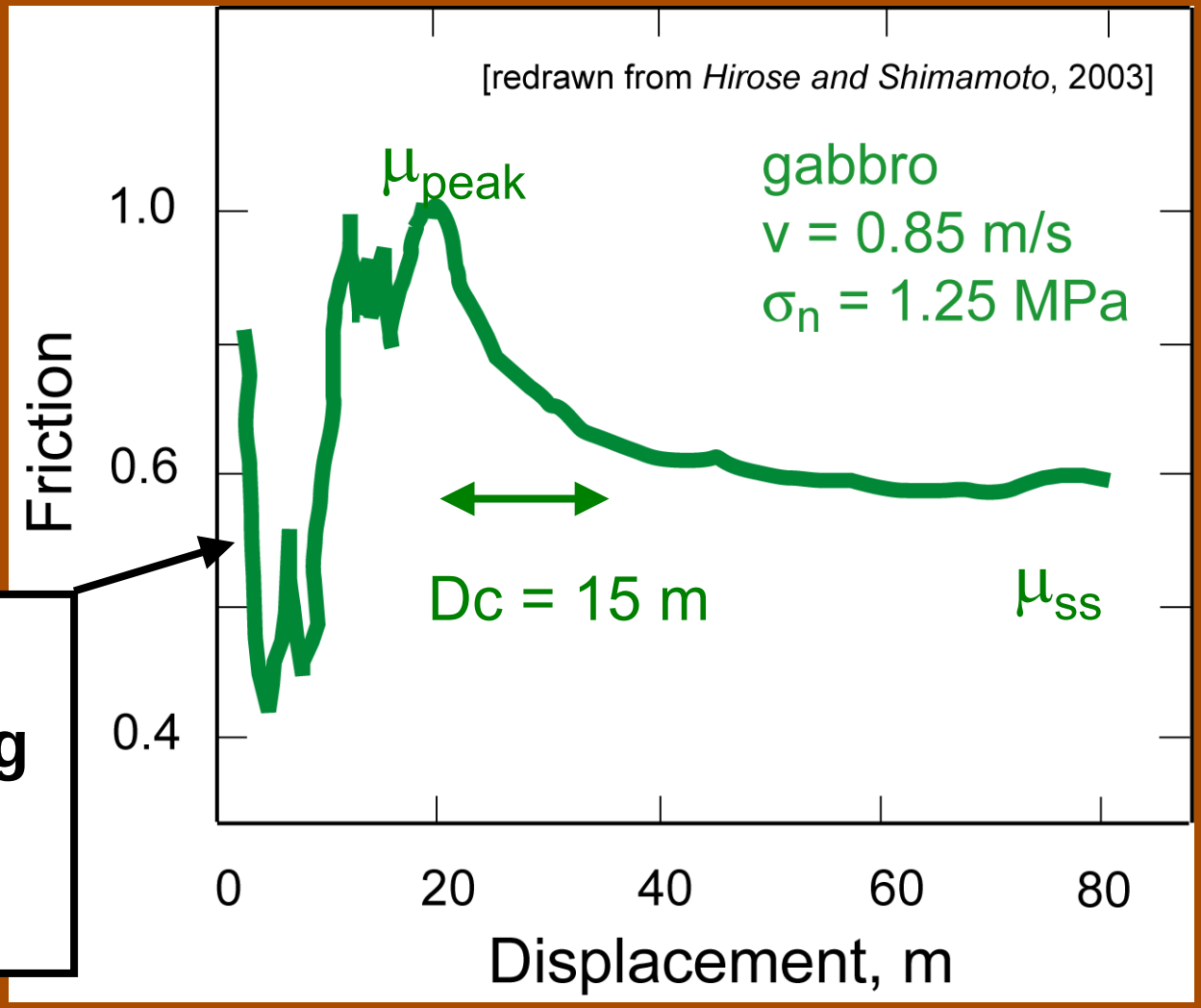

Hirose & Shimamoto, 2003

First weakening = flash melting

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Weakening-strengthening-weakening behavior

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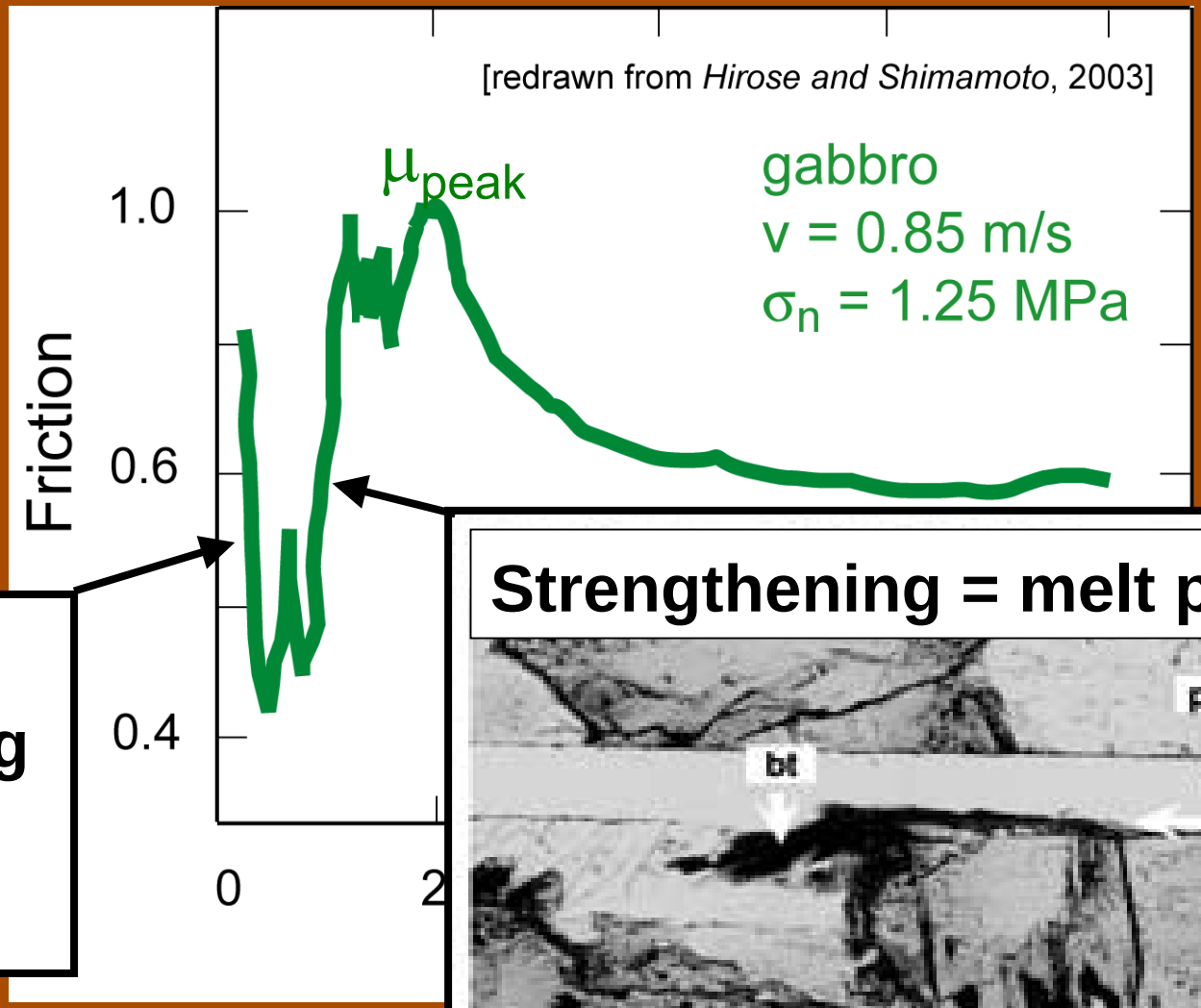
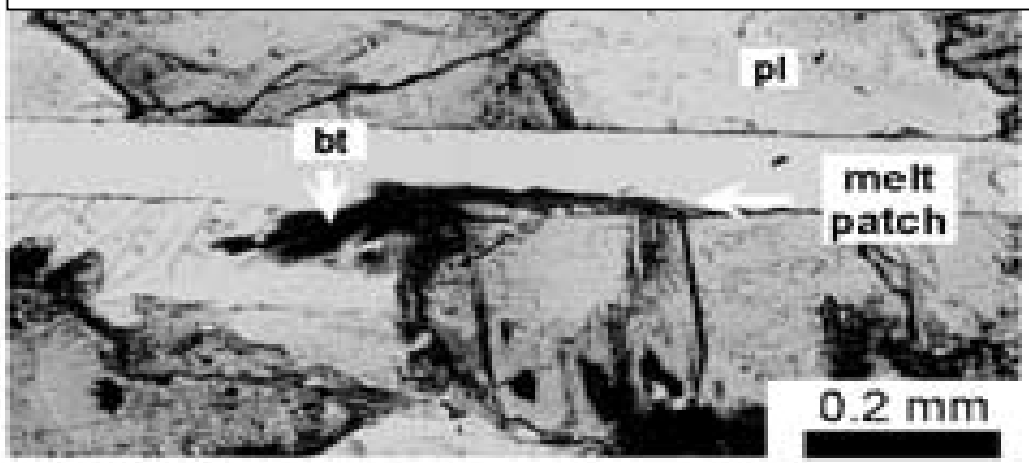


Hirose & Shimamoto, 2003

First weakening = flash melting

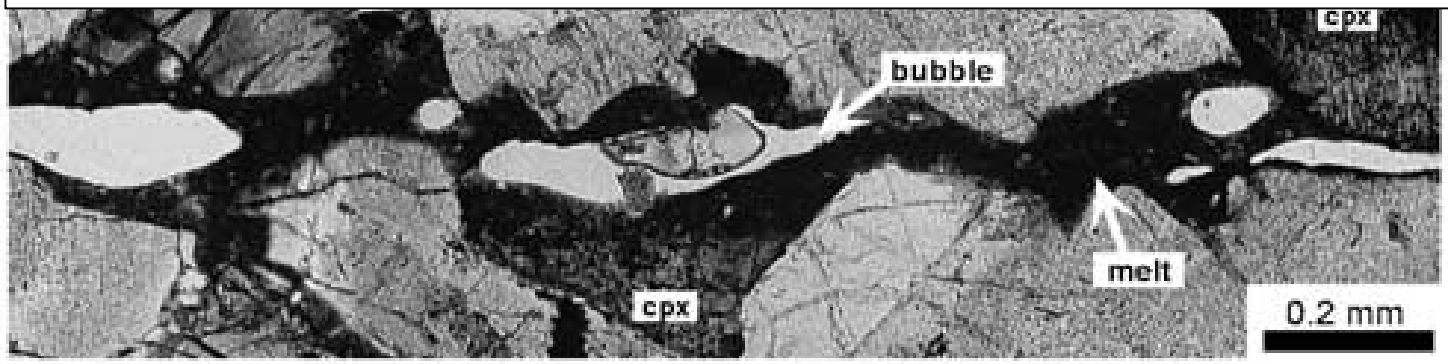
Strengthening = melt patches

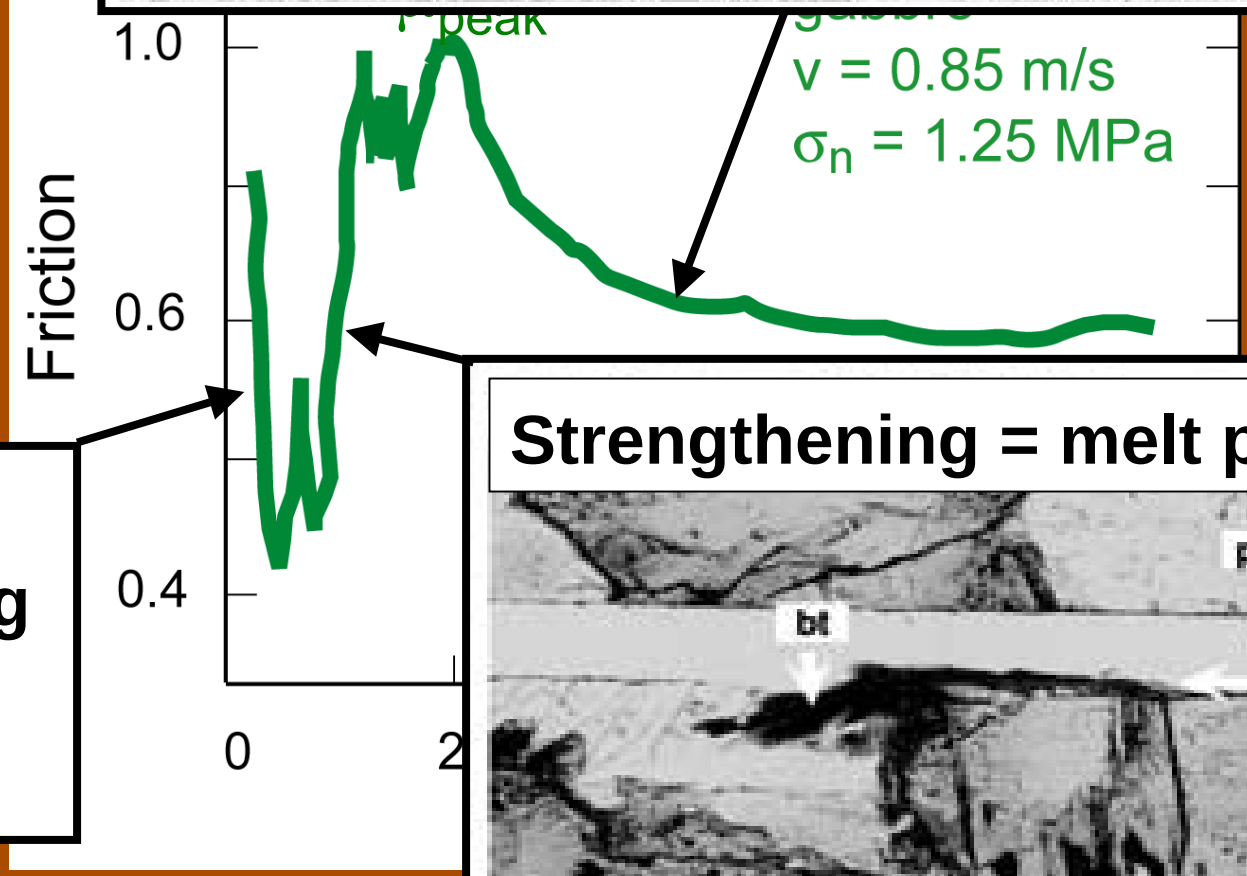


Weakenin

σ_n = 1.25 MPa, μ_{ss} = 0.6, D_c = 15 m and slip up to 80 m

Second weakening = melt layer

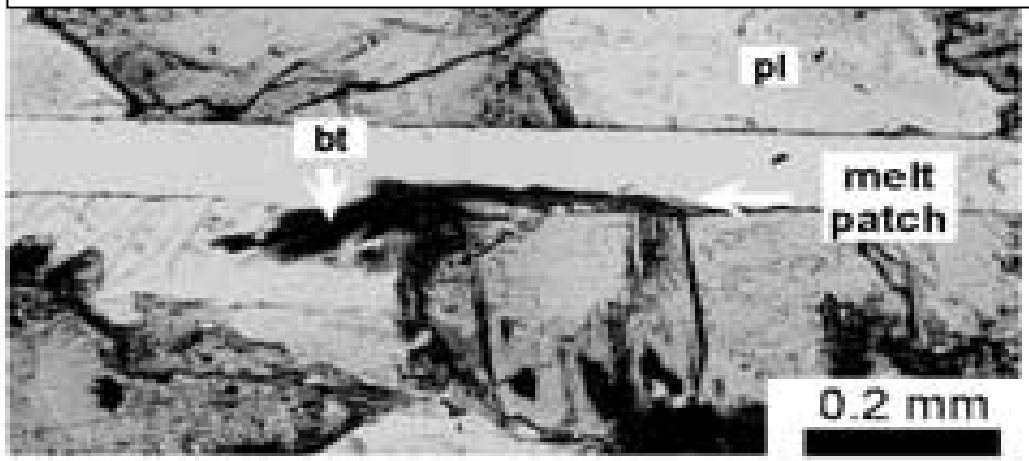


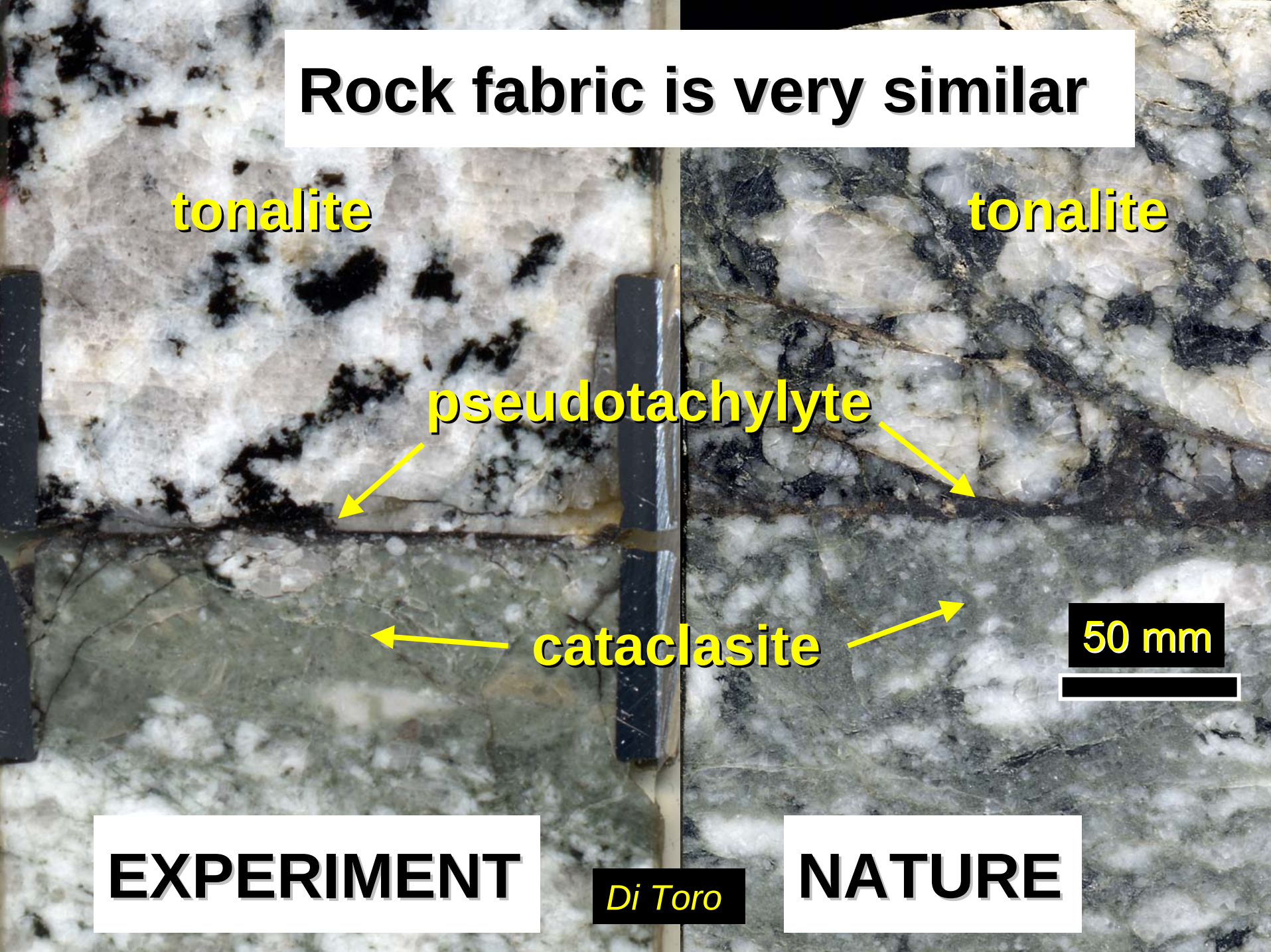


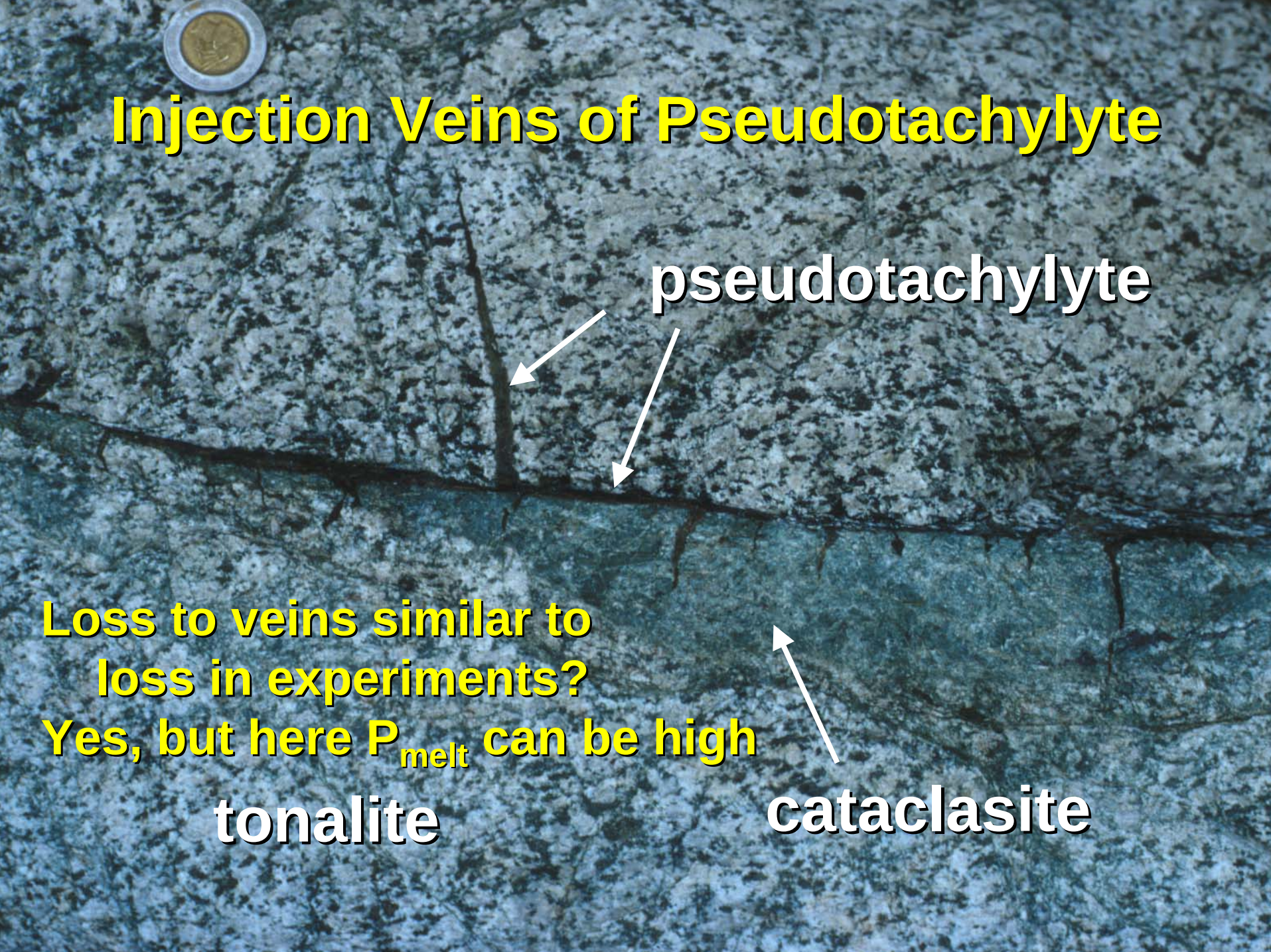
Hirose & Shimamoto, 2003

First weakening = flash melting

Strengthening = melt patches




Rock fabric is very similar
tonalite
tonalite
pseudotachylyte
cataclasite
50 mm
EXPERIMENT
Di Toro
NATURE


Injection Veins of Pseudotachylyte
pseudotachylyte
Loss to veins similar to
loss in experiments?
Yes, but here P_{melt} can be high
tonalite
cataclasite

What Are Implications of Doing Unconfined Experiments Where Melt is Lost?

- Melt loss occurs in both, either to exterior or to melt veins
- However, melt pressure may be quite different
- If resistance is due to viscosity, then the viscosity and so the shear resistance will not be very pressure dependence
- However, the apparent friction will be much lower if the normal stress is much higher
- Experiments are needed at elevated normal stress where the fluid is either retained or at least the melt pressure stays high

BROWN GEOLOGY

Dynamic fault weakening mechanisms

1. Normal interface vibrations
2. Dynamic normal stress reduction from elastic mismatch
3. Acoustic fluidization
4. Elastohydrodynamic lubrication
5. Thermal pressurization of pore fluids
6. Local “Flash” weakening/melting at asperity contacts
7. Interfacial lubrication by frictional melt
8. Lubrication by thixotropic silica gel layer

BROWN GEOLOGY

Lubrication by Thixotropic Silica Gel Layer

Discovered by *Goldsby and Tullis*, 2003; Studied by *Di Toro, Goldsby, and Tullis*, 2004.

Involves generation of a layer of silica gel by interaction of water with SiO_2

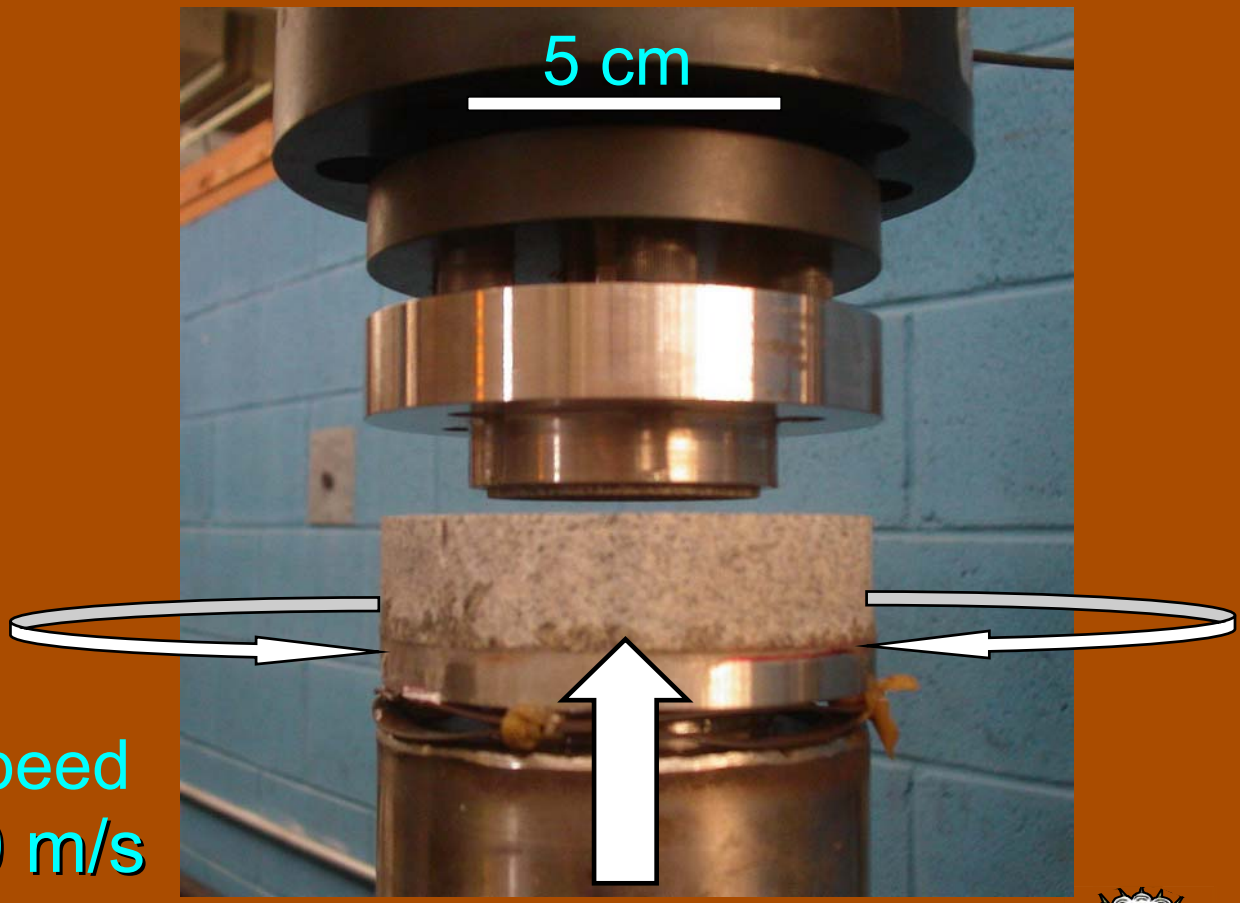
Shear strength of gel is lowered by fast slip and large slip – thixotropic – strength depends on competition between time dependent strengthening and strain dependent weakening

Was discovered in experiments on quartz, but occurs in rocks with over 50 percent SiO_2

Could be important for earthquakes. Field evidence for its operation may be hard to find.

BROWN GEOLOGY

Unconfined Rotary Shear Friction Experiment



High speed
$V \leq 0.20$ m/s

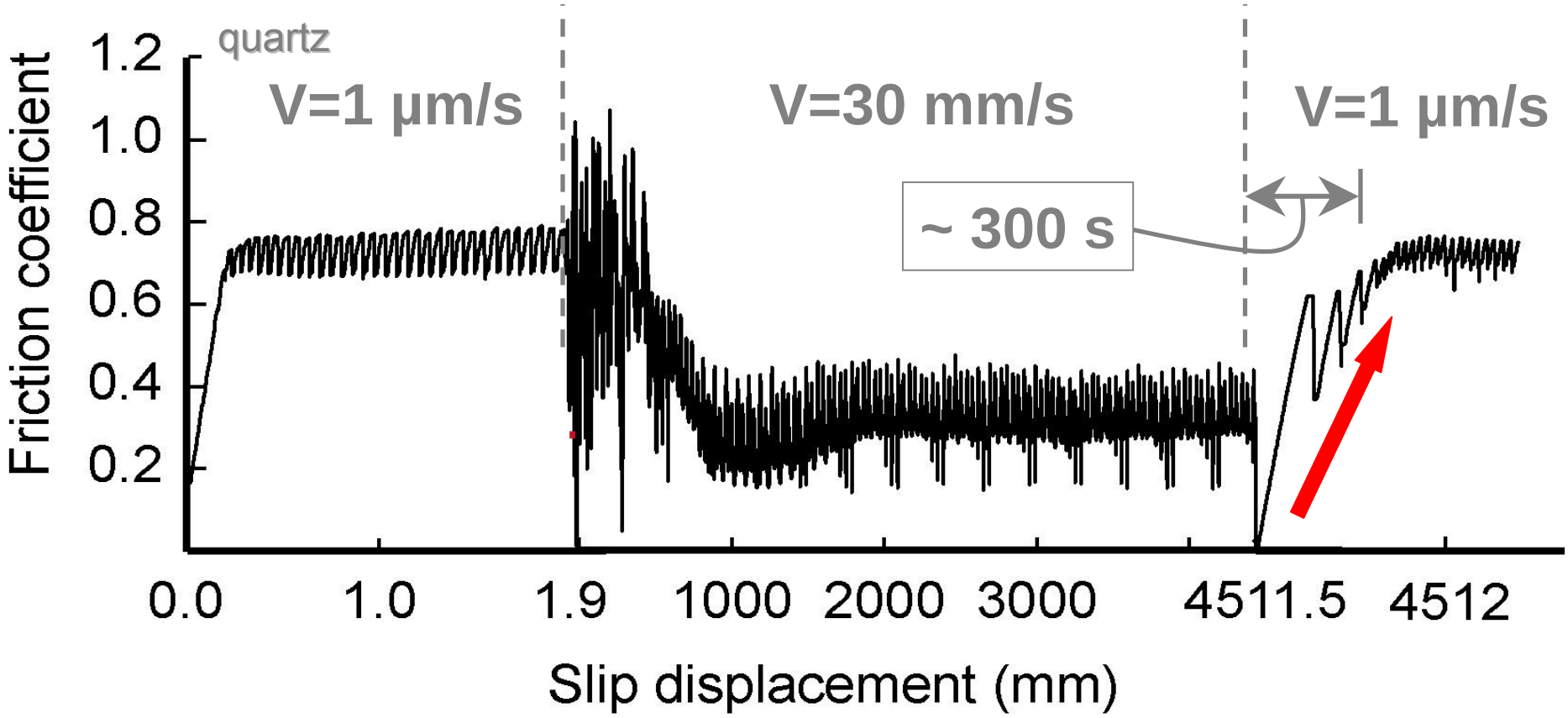
Large Cumulative Displacement:
$\delta = 4.5$ m

$\sigma_n = 5$ MPa

David Goldsby

BROWN GEOLOGY

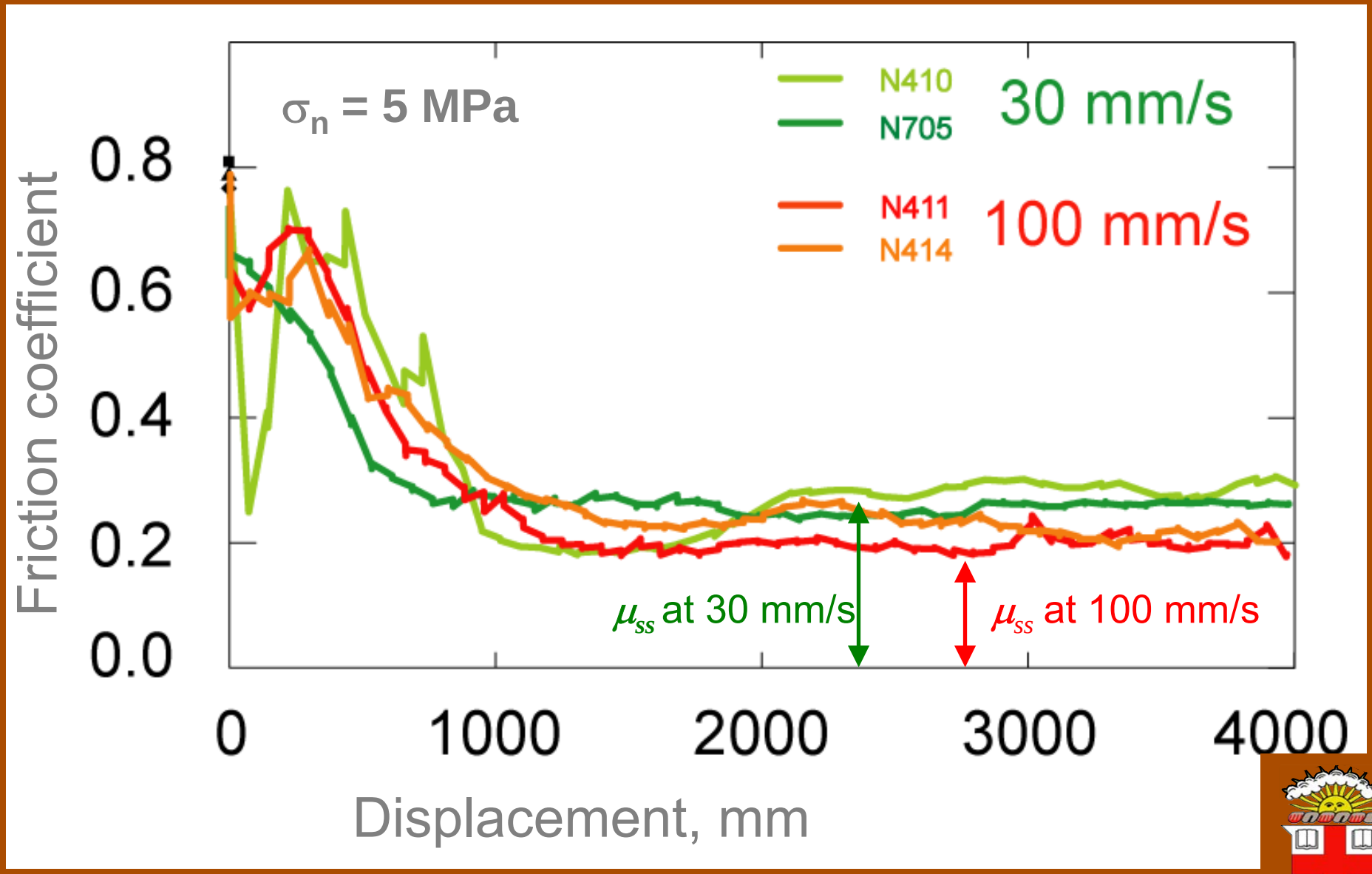
Friction Drops at High Speed, Slowly Recovers at Low Speed



Di Toro, Goldsby, & Tullis, 2004

BROWN GEOLOGY

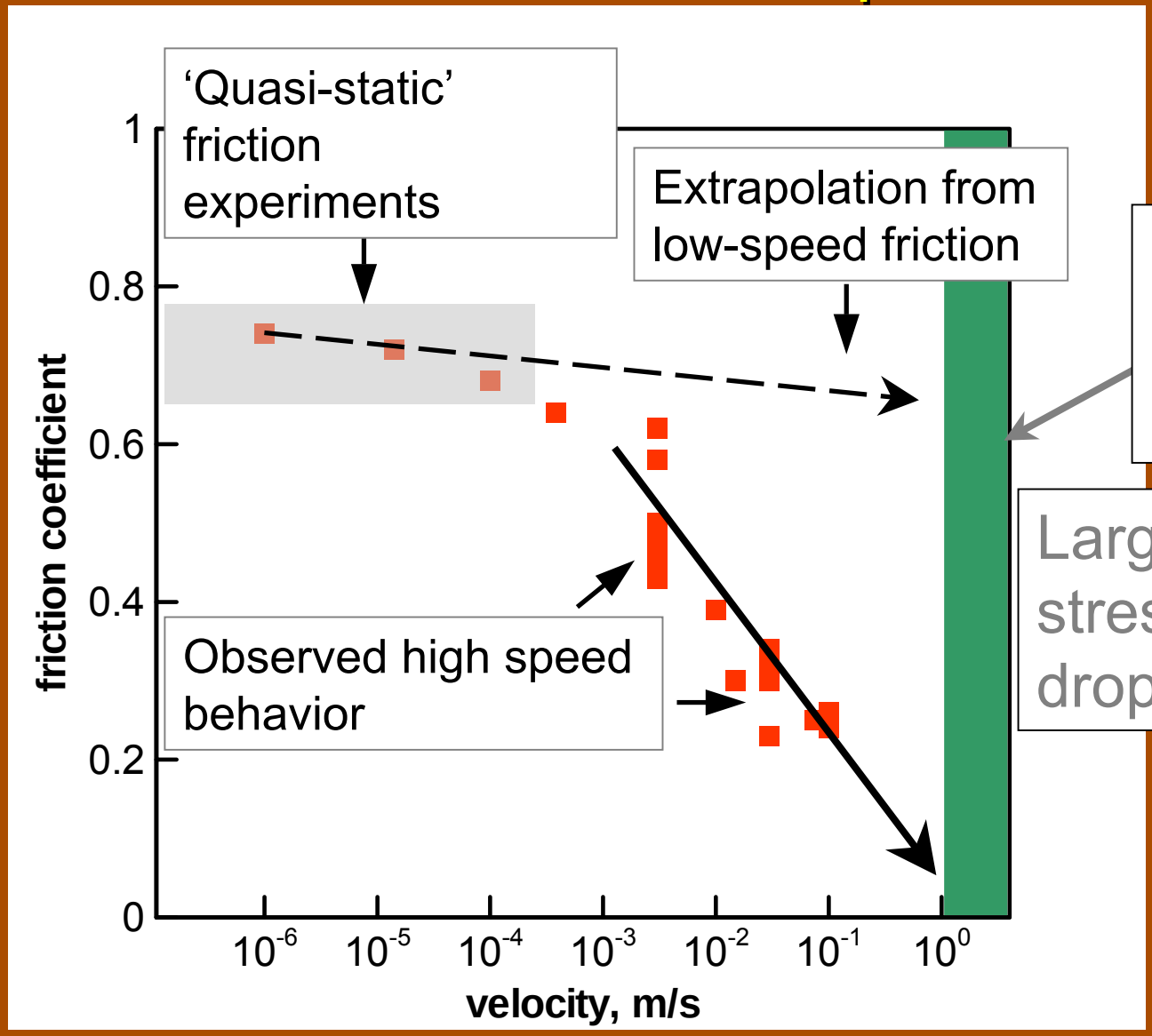
Slip Dependence for Gel Weakening



Di Toro, Goldsby, Tullis, 2004

BROWN GEOLOGY

Friction for Quartz Rocks Extrapolates to Zero at Seismic Slip Rates



Di Toro, Goldsby, & Tullis, 2004

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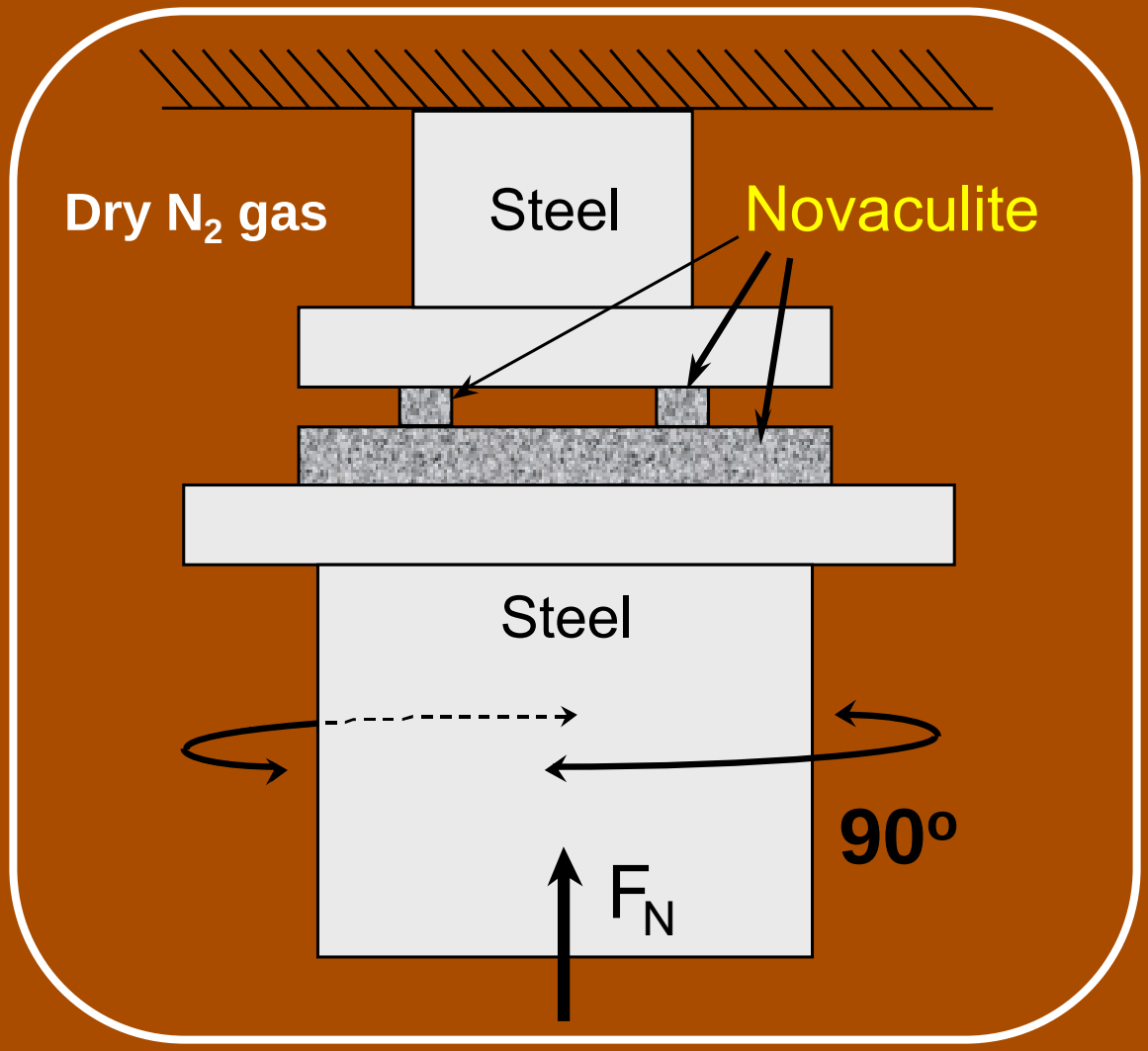
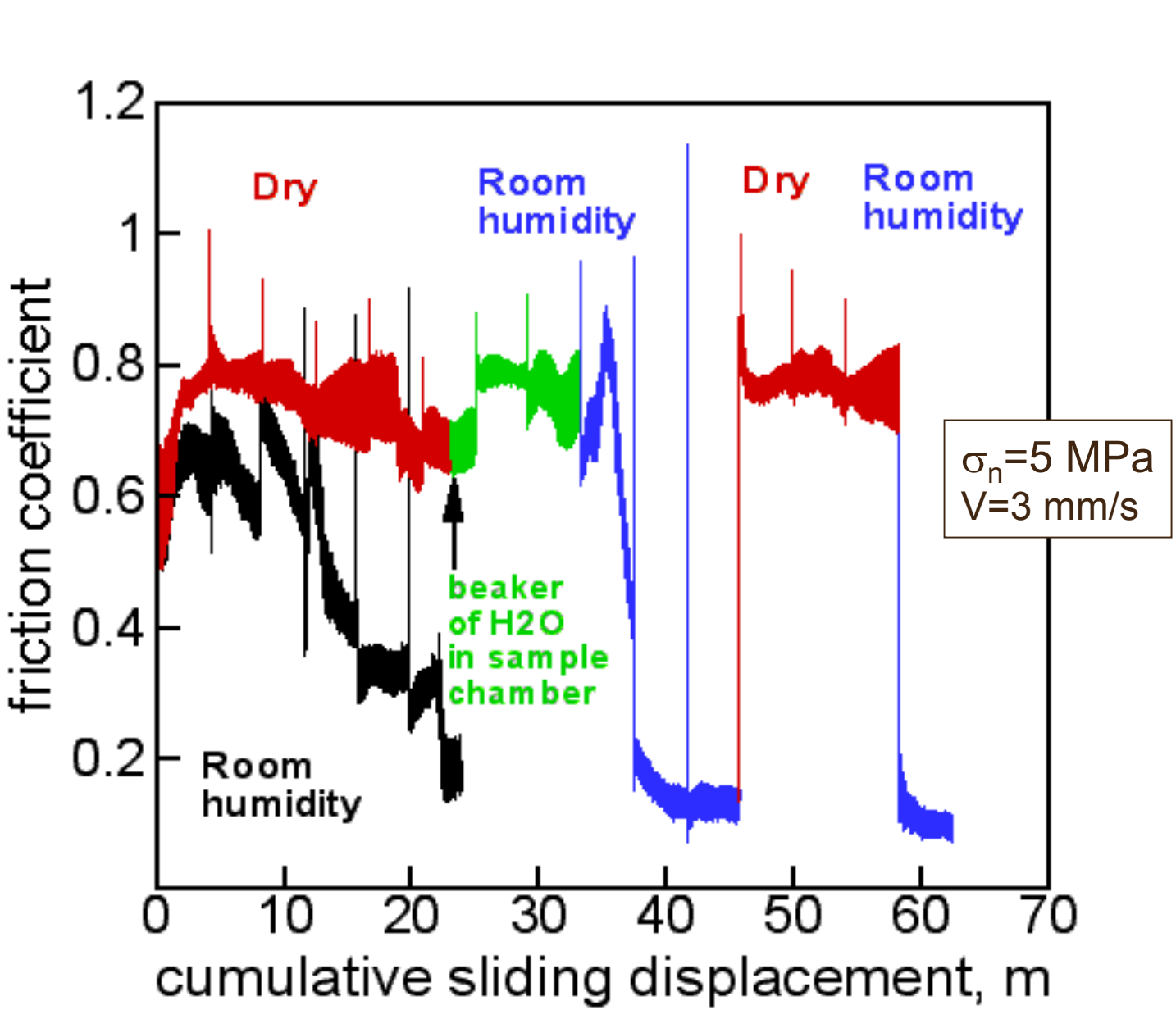
Controlled Humidity Test in 1-atm Apparatus



V = 3 mm/s

BROWN GEOLOGY

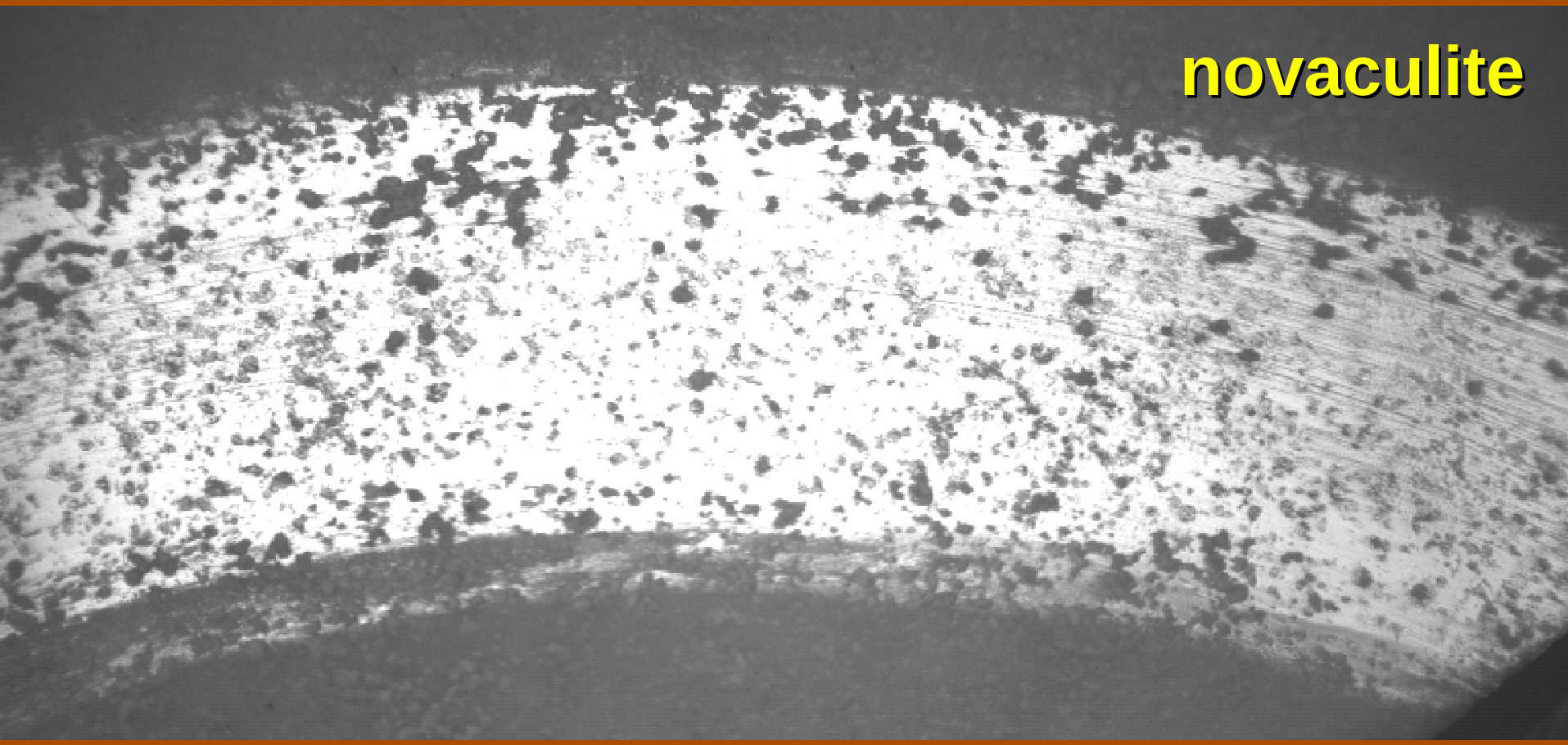
Controlled Humidity Tests



Water is needed for the weakening

BROWN GEOLOGY

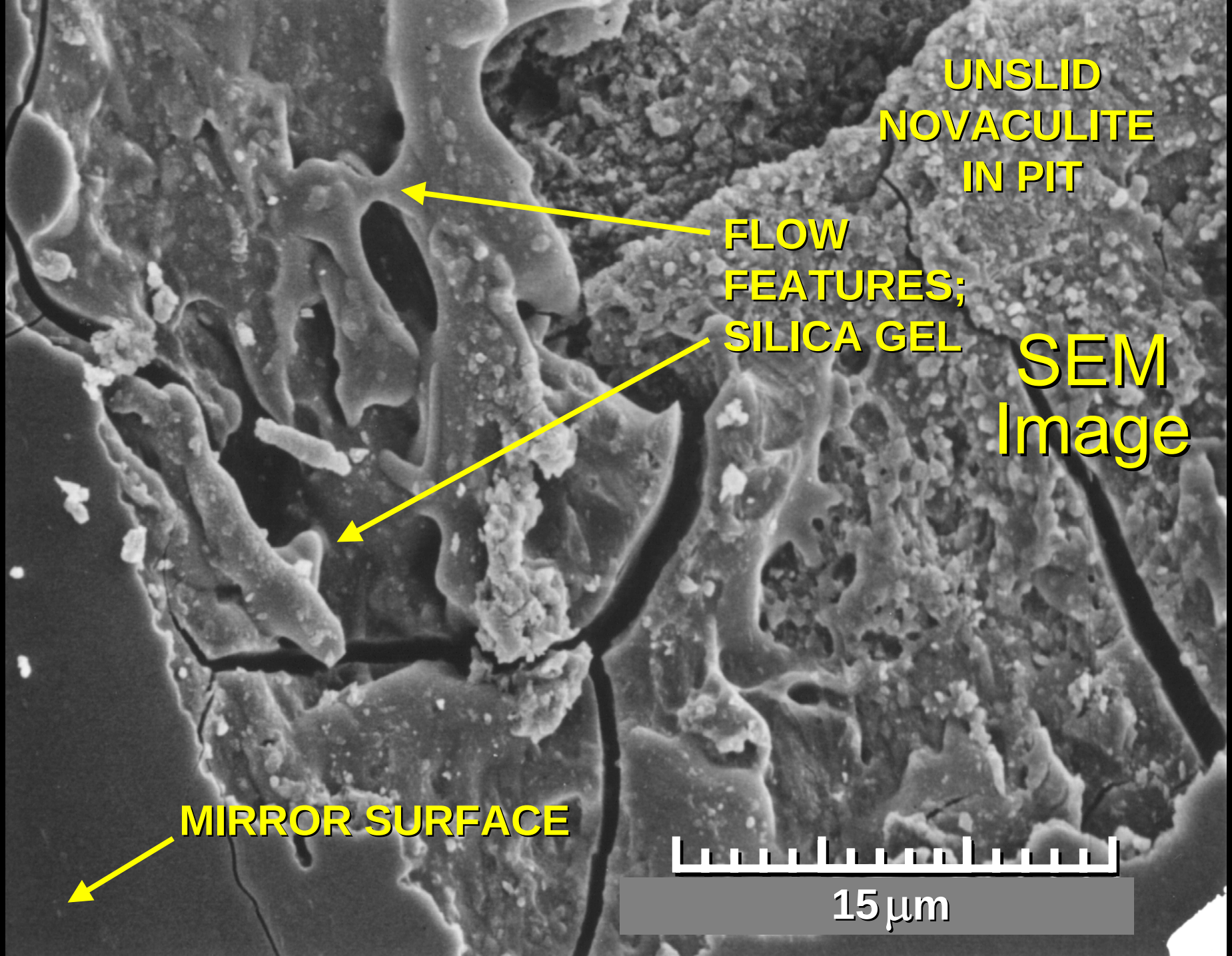
Reflected Light Image of Mirror Surface

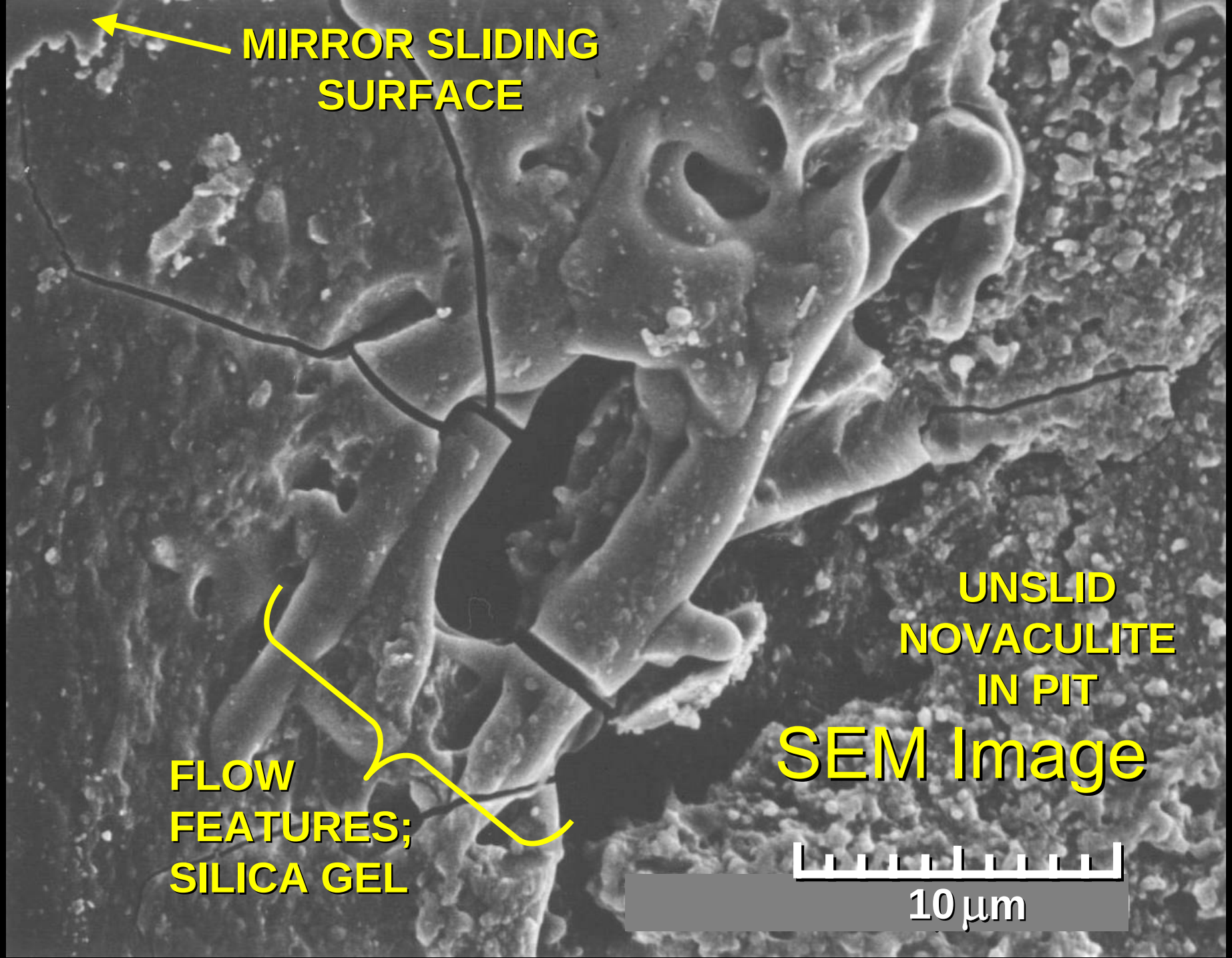


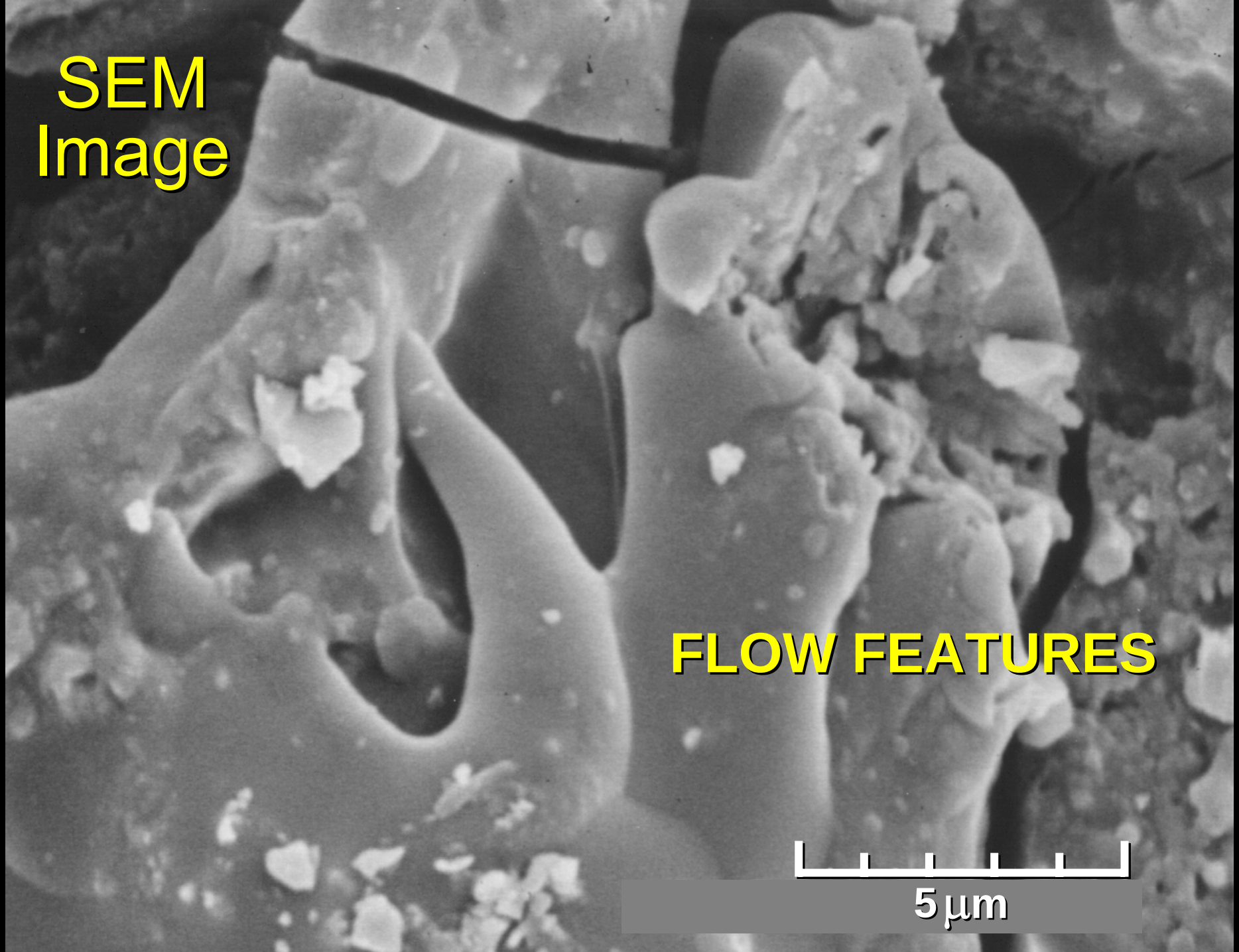
Dark spots = porosity-caused pits in surface

δ = 62 m, V= 3 mm/s, σ_n = 5 MPa

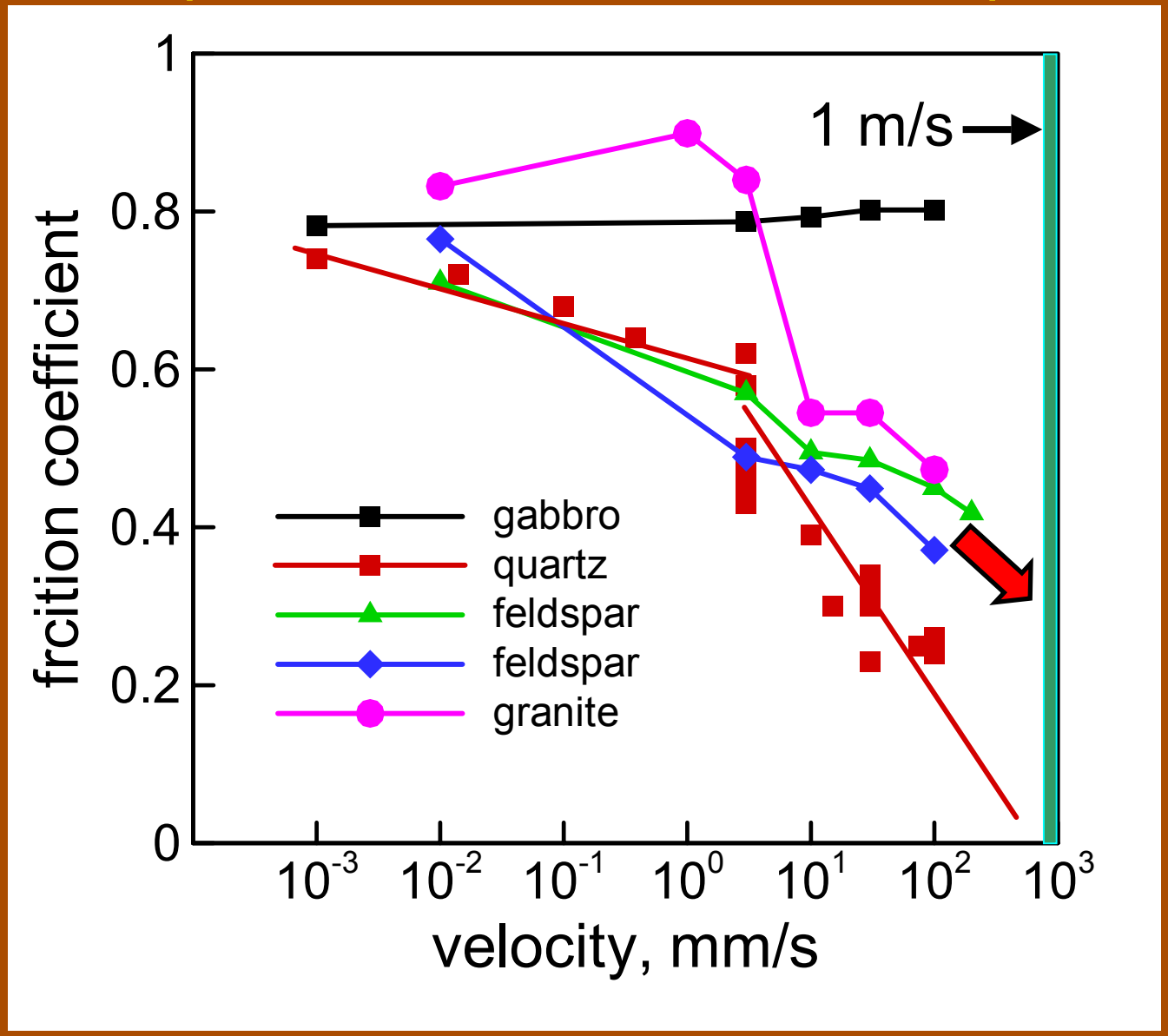
BROWN GEOLOGY


UNSLID
NOVACULITE
IN PIT
FLOW
FEATURES;
SILICA GEL
SEM
Image
MIRROR SURFACE
15 µm


MIRROR SLIDING SURFACE
UNSLID NOVACULITE IN PIT
SEM Image
FLOW FEATURES; SILICA GEL
10 μm


SEM
Image
FLOW FEATURES
5 µm

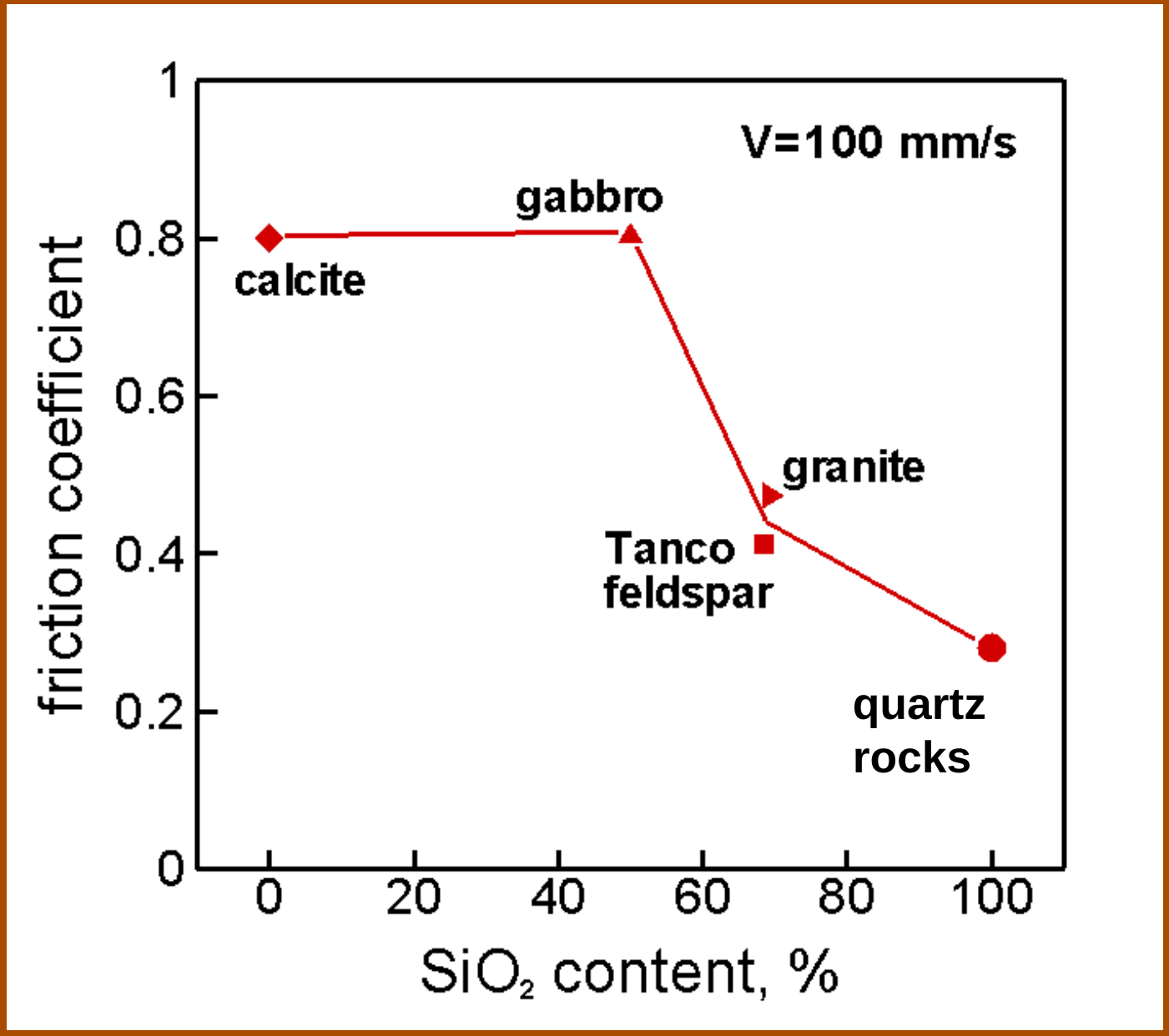
Friction Coefficients for Granite, Feldspar and Quartz Extrapolate to <0.4 at Seismic Slip Rates



Roig Silva et al., 2004

BROWN GEOLOGY

μ_{ss} decreases with SiO_2 content above 50 wt.%



Roig Silva et al., 2004

BROWN GEOLOGY

Thixotropic Behavior of Silica Gels

Characterized by particles with bonds between them that can be disrupted by strain – many paints and clays are thixotropic

Often called shear thinning, since the viscosity gets lower as strain increases

After strain, bonds become stronger with time

This means that the strength results from competition between strain-induced weakening and time-induced strengthening

Thus expect:

- Weaker at higher velocity
- Time-dependent healing with low or zero velocity
- This is what we observe!

BROWN GEOLOGY

Friction From These Weakening Mechanisms

1. Normal interface vibrations ?
2. Dynamic normal stress reduction from elastic mismatch ?
3. Acoustic fluidization ?
4. Elastohydrodynamic lubrication ?
5. Thermal pressurization of pore fluids 0.0-0.6
6. Local “Flash” weakening at asperities ~0.2
7. Interfacial lubrication by frictional melt <0.5-0.6
8. Lubrication by thixotropic silica gel layer <0.2

BROWN GEOLOGY

Implications of Low Dynamic Strength for Earthquake Stress Drops and/or for Tectonic Stress Magnitudes

A dilemma exists if dynamic stresses are low:

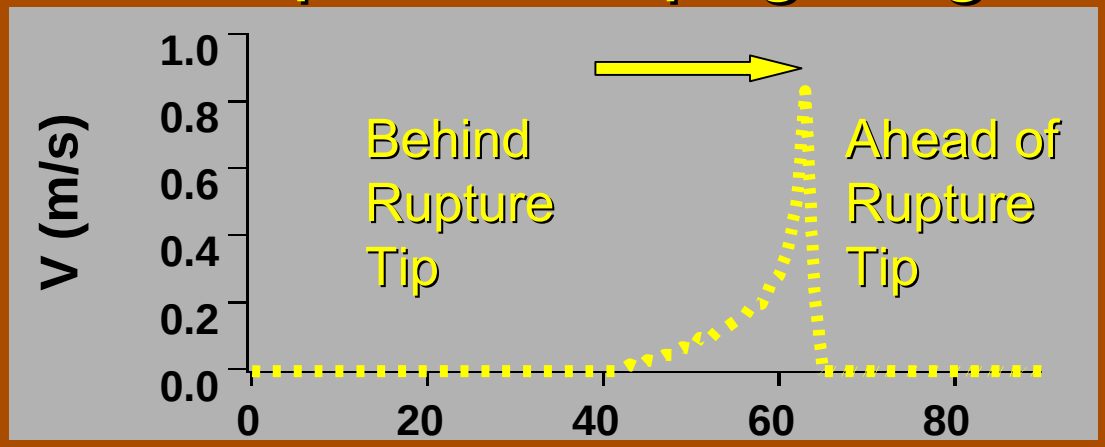
If tectonic stresses are close to static frictional strength, then one would expect larger stress drops and accelerations than are typically observed

A model with low tectonic stresses can overcome static friction and be compatible with low stress drops, but then one would expect to find low measured *in situ* stress values, rather that those that typically seem bounded by static frictional strength

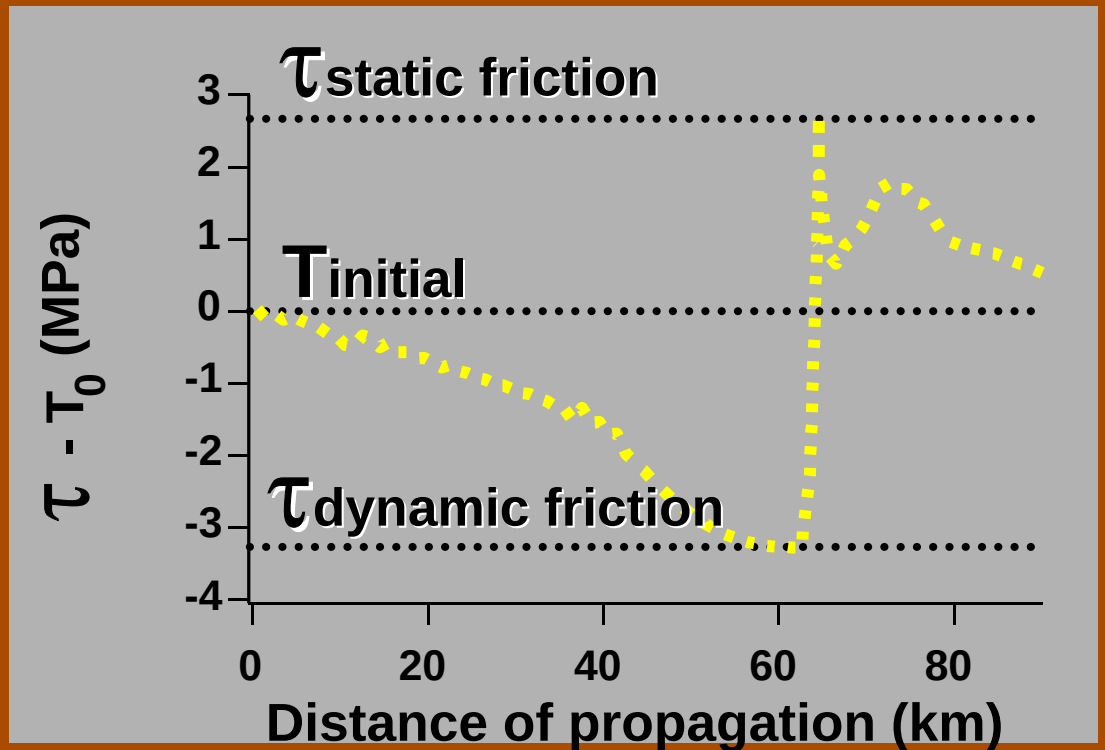
BROWN GEOLOGY

Slip Velocity and Shear Stress at the Tip of a Propagating Rupture

Slip Velocity



Shear Stress

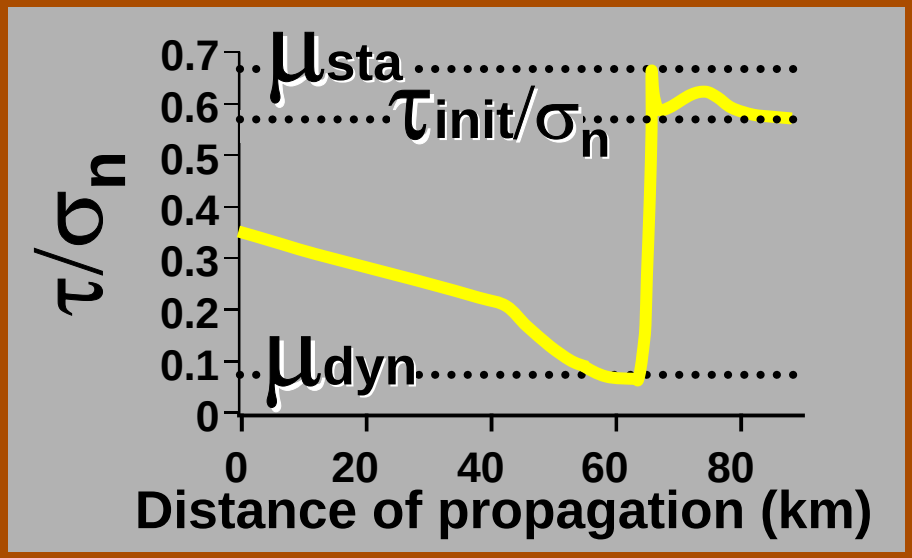


From *Beeler and Tullis* (1996)

An example for rate and state friction parameters that give a self-healing rupture; Propagation time = 25.00 s

BROWN GEOLOGY

One Possibility for Initial Stress Compared to Static and Dynamic Friction



High Stress Model:

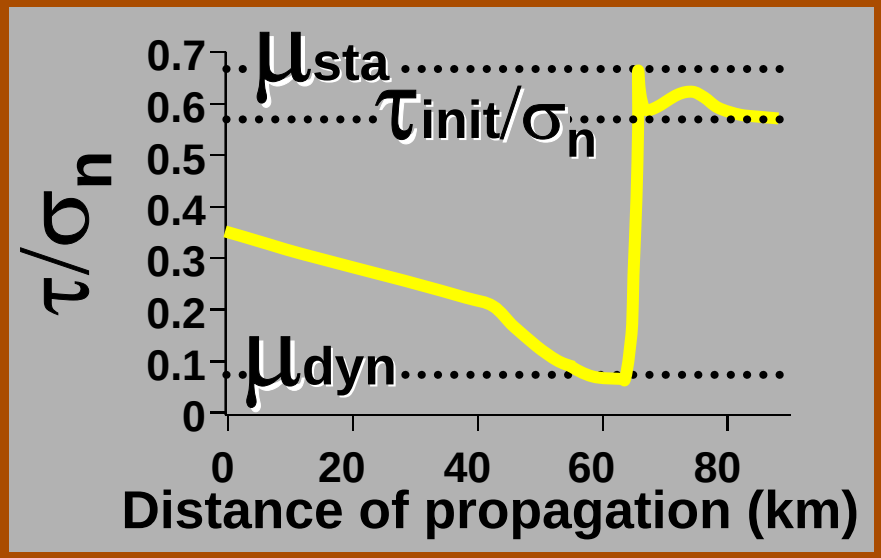
Large stress drop

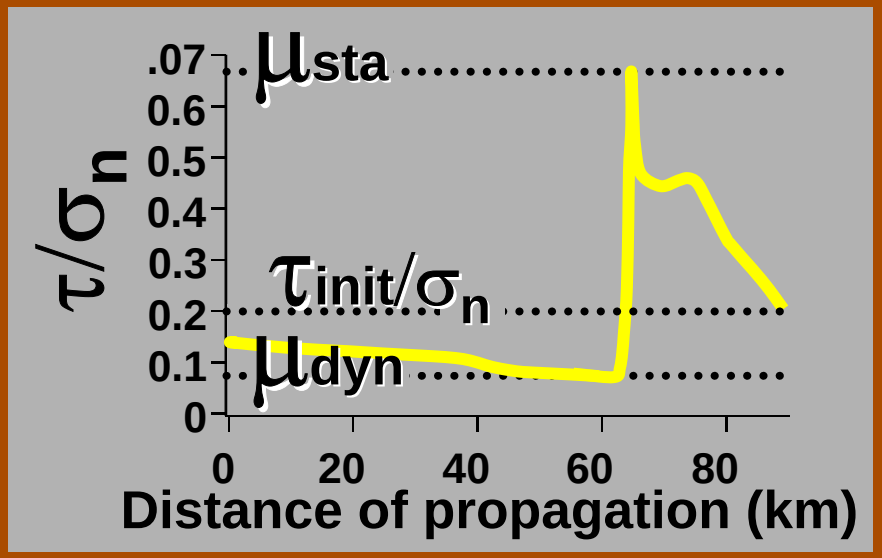
Static friction overcome mostly by initial stress.

LARGE ACCELERATION

BROWN GEOLOGY

Alternate Possibilities for Initial Stress Compared to Static and Dynamic Friction





High Stress Model:
- Large stress drop
- Static friction overcome mostly by initial stress.

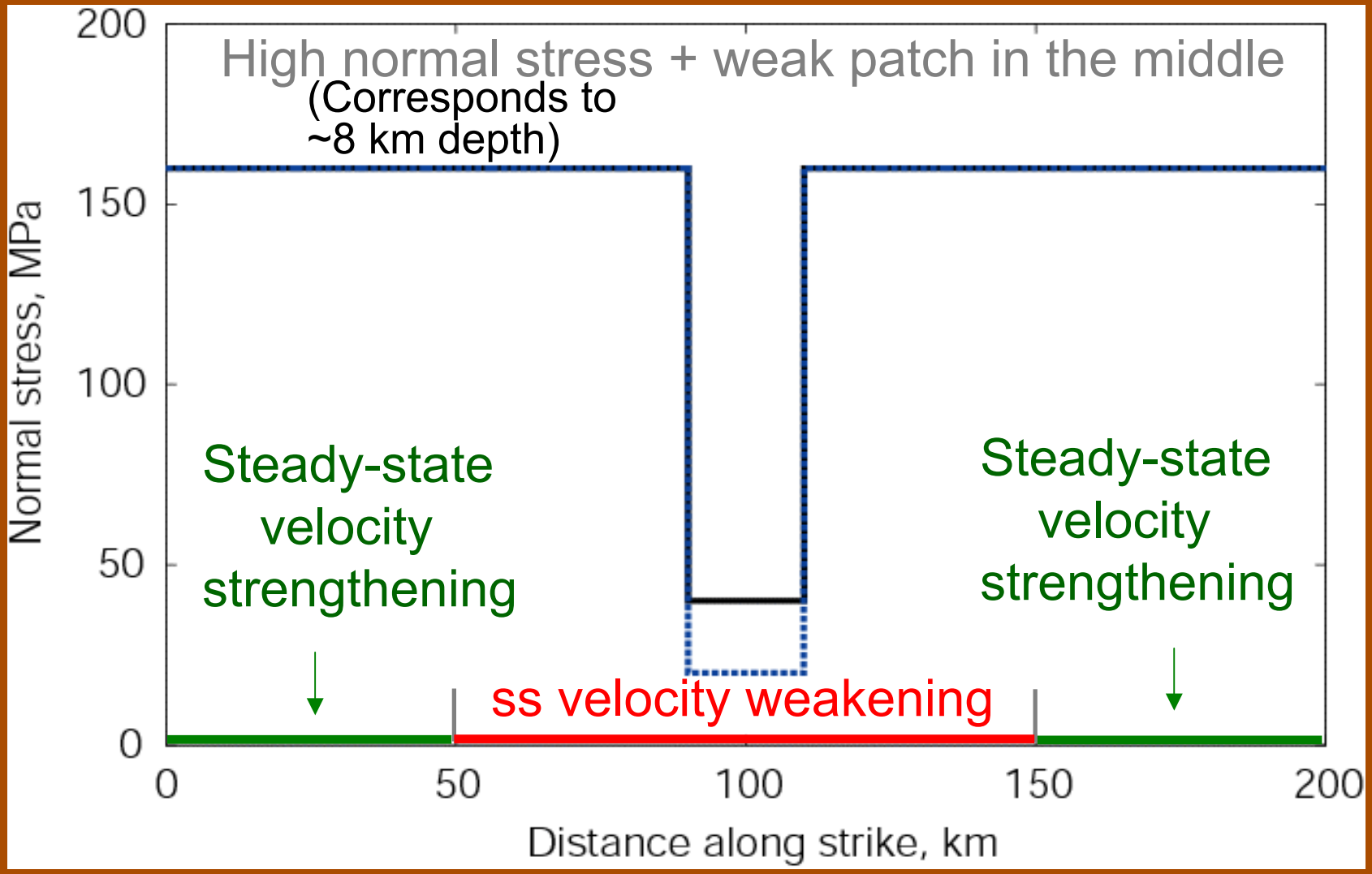
LARGE ACCELERATION

Brittle, Low Stress Model:
- Small stress drop
- Static friction overcome by large dynamic stress concentration.

SMALL ACCELERATION

Dynamic Rupture Models with Extreme High Speed Weakening

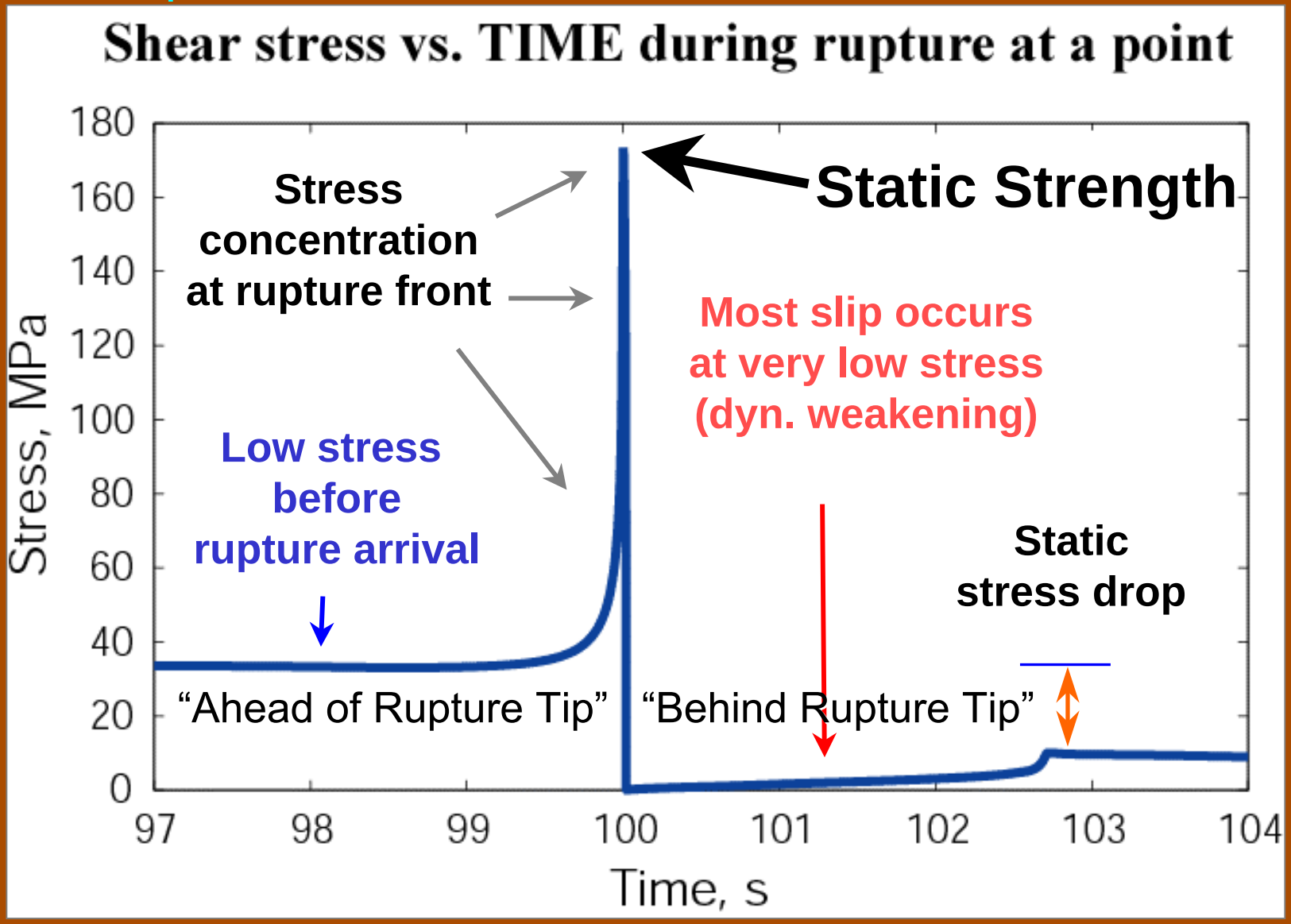
Uses Thermal Pressurization and Flash Weakening



Nadia Lapusta

Example with Low Initial Shear Stress

Rupture overcomes static friction via stress concentration

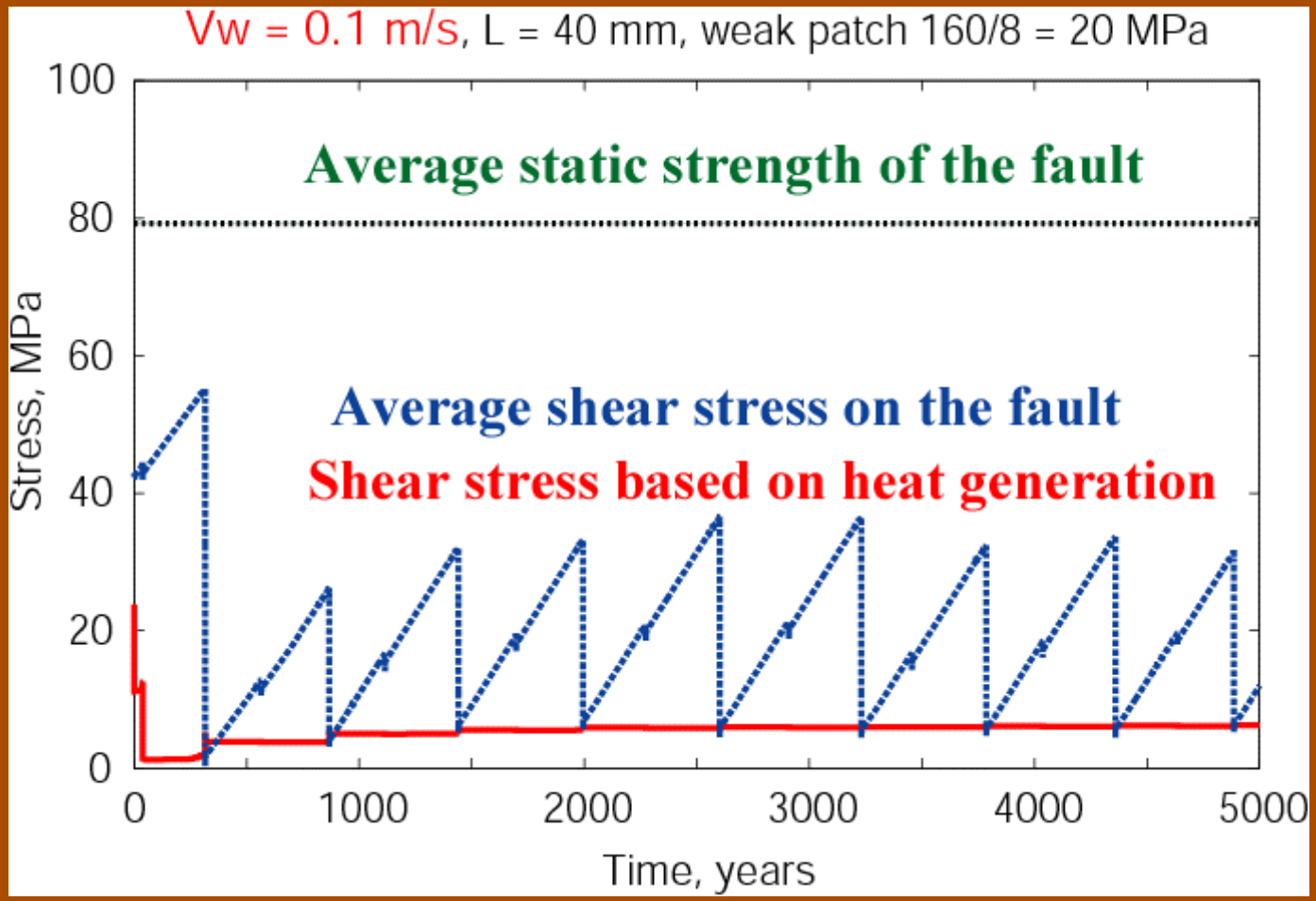


Static stress drop is *much smaller* than what one would expect *because* shear stress before the earthquake is much smaller than static strength.

Nadia Lapusta

Fault models with strong dynamic weakening based on Thermal Pressurization and Flash Weakening satisfy several observational constraints

Operates with low stress, low heat production!



Nadia Lapusta

Conclusions

1. Many high-slip-velocity weakening mechanisms potentially exist
2. Much remains to be understood about them
3. From what we know, the shear resistance from many of them is quite low
4. If shear resistance during earthquakes is low then either:
   A. The stress drops during earthquakes could be large, apparently larger than is typically observed, *or*
   B. The initial tectonic stress is low, so the stress drops are acceptably low. The static friction is overcome by dynamic stresses at the tip of the propagating rupture

BROWN GEOLOGY