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Ninth Workshop on Non-linear Dynamics and Earthquake Predictions

1 - 13 October 2007

Seismic Melts
and
Earthquake Mechanics
Part 2

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Seismic melts and earthquake mechanics
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International Centre for Theoretical Physics, Trieste, Italy

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Outline

1) A natural lab of a seismogenic source

2) Earthquake rupture dynamics

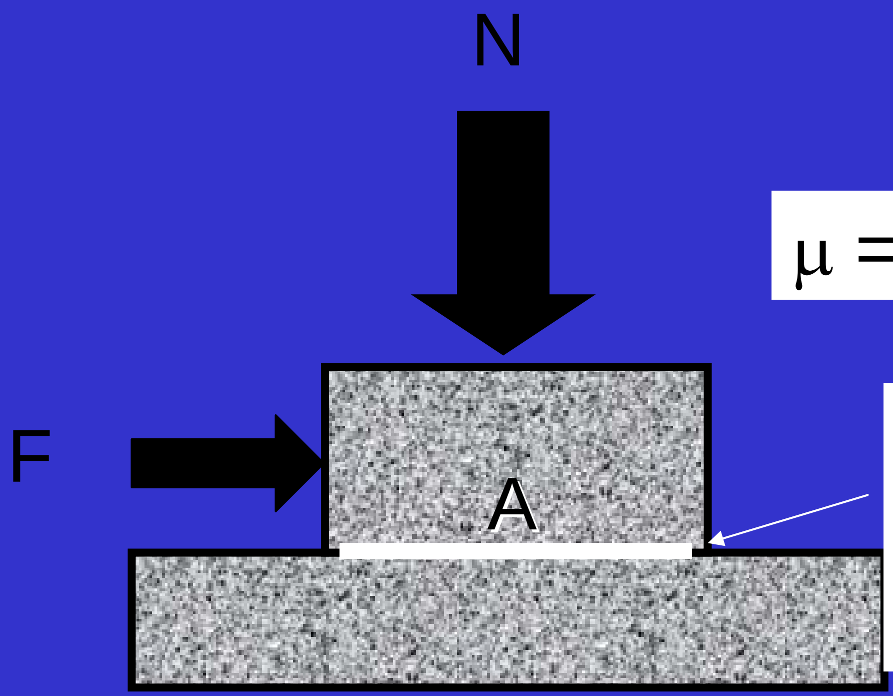
3) Fault strength during seismic slip

4) Earthquake energy budgets

Fault strength and rock friction

$\mu = F / N$

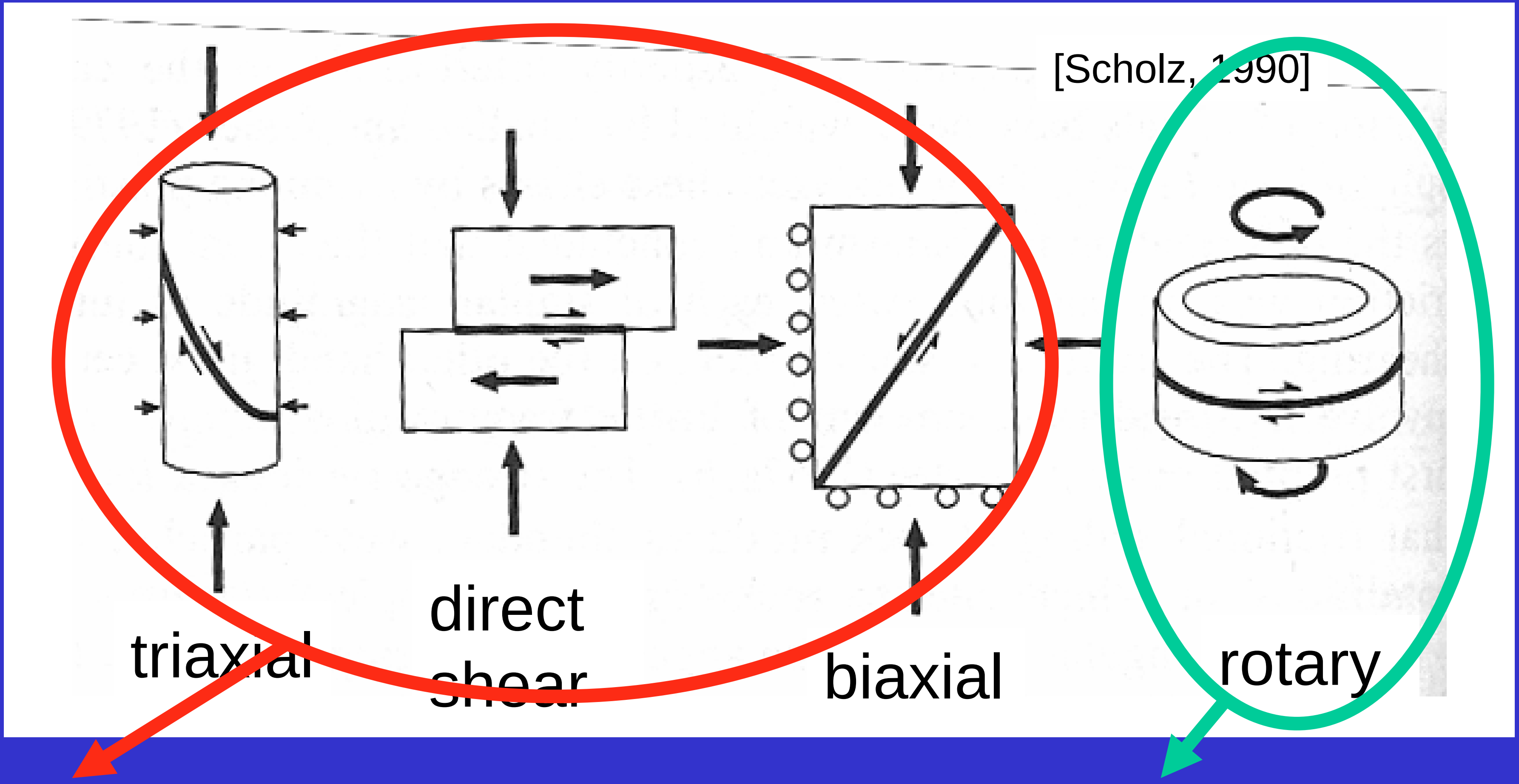
μ = friction coefficient



$\mu = (F/A) / (N/A) = \tau / \sigma_n$

A = Nominal Area of contact

Experimental configurations



Conventional exp.

Short displacements: < cm

Low slip rates: < mm/s

High normal stress: GPa

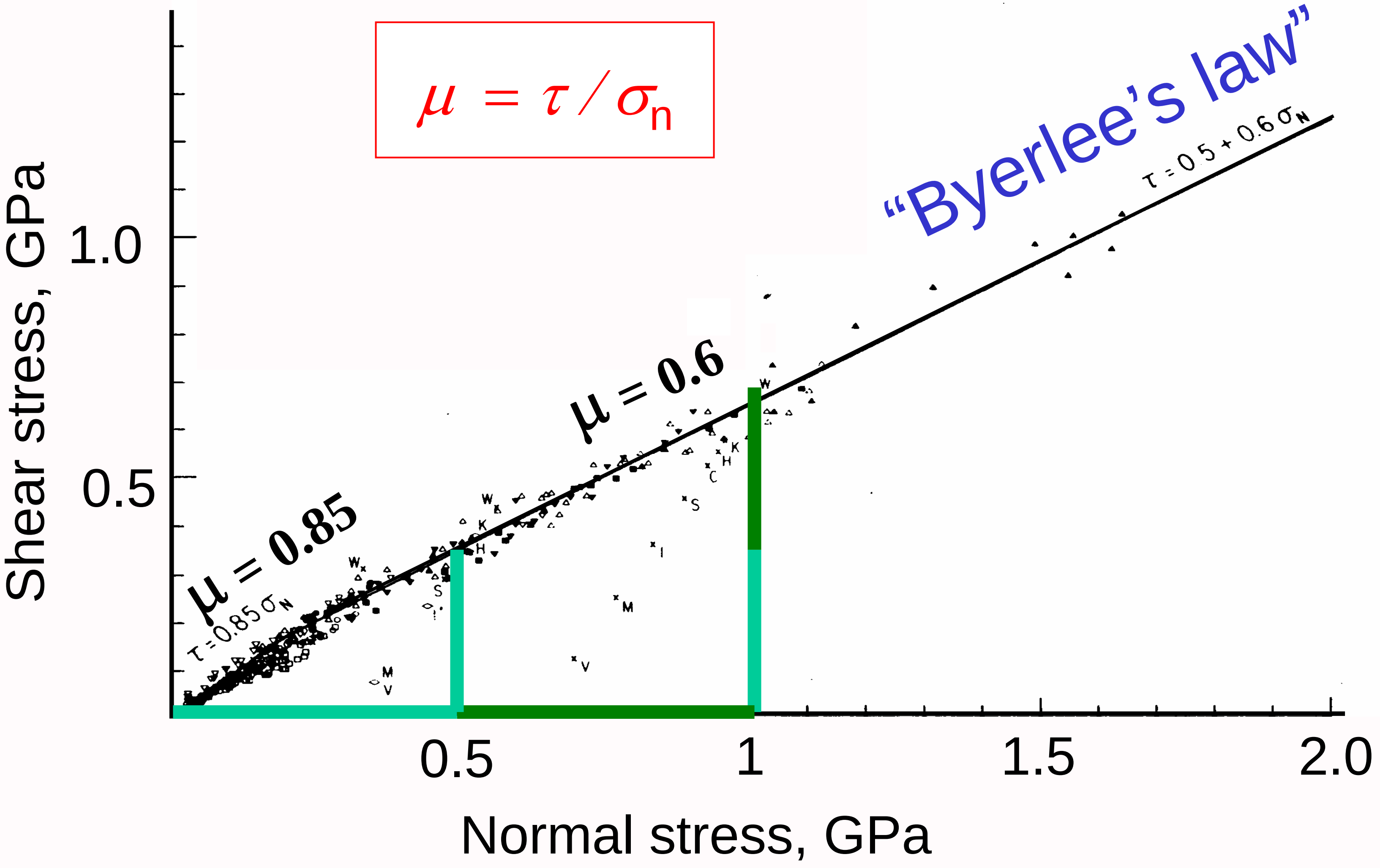
Non-Conventional exp.

Large displacements: m

High slip rates: m/s

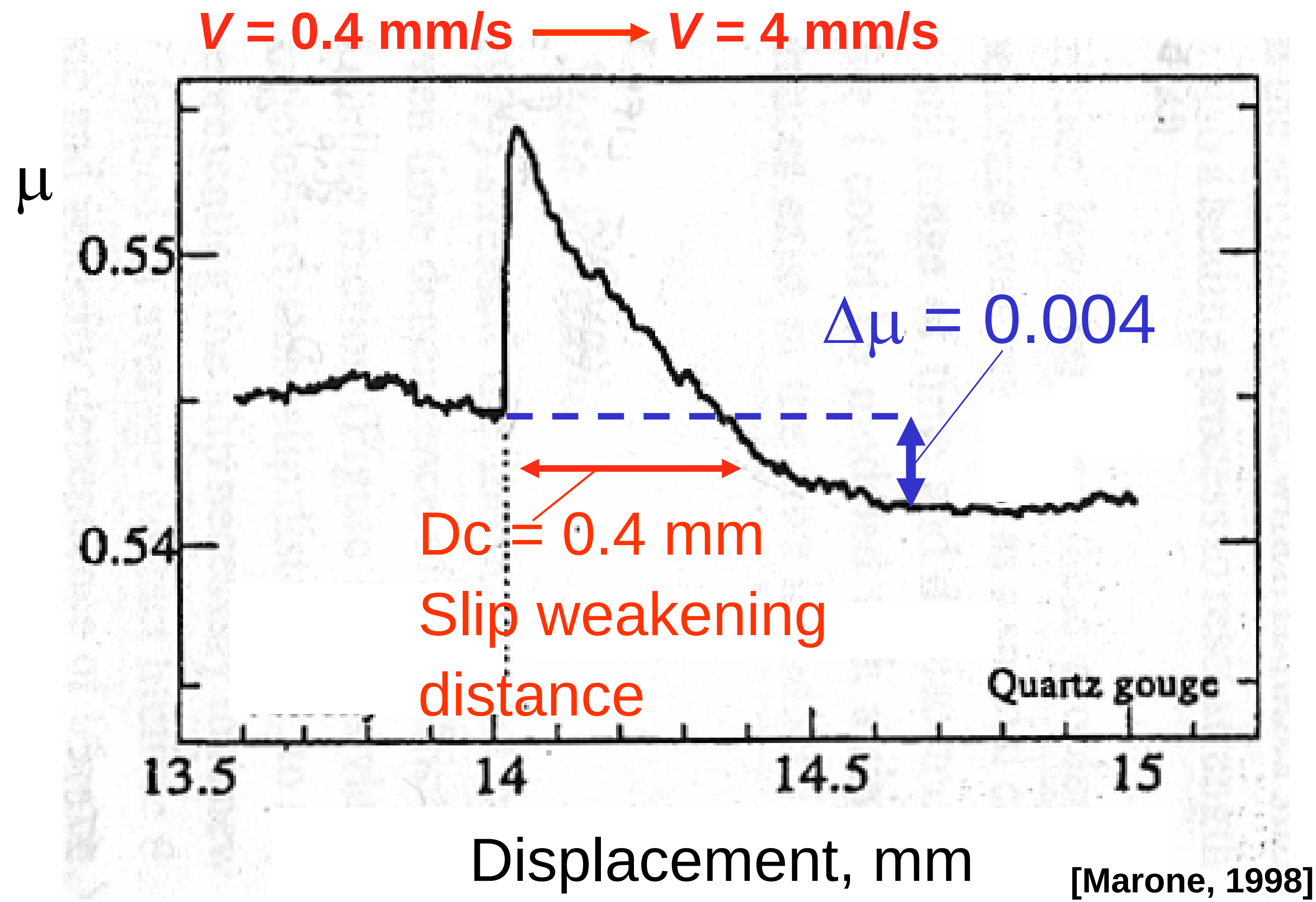
Low normal stress: MPa

"Friction produces double the amount of effort if the weight be doubled" [Leonardo da Vinci 1452-1519]



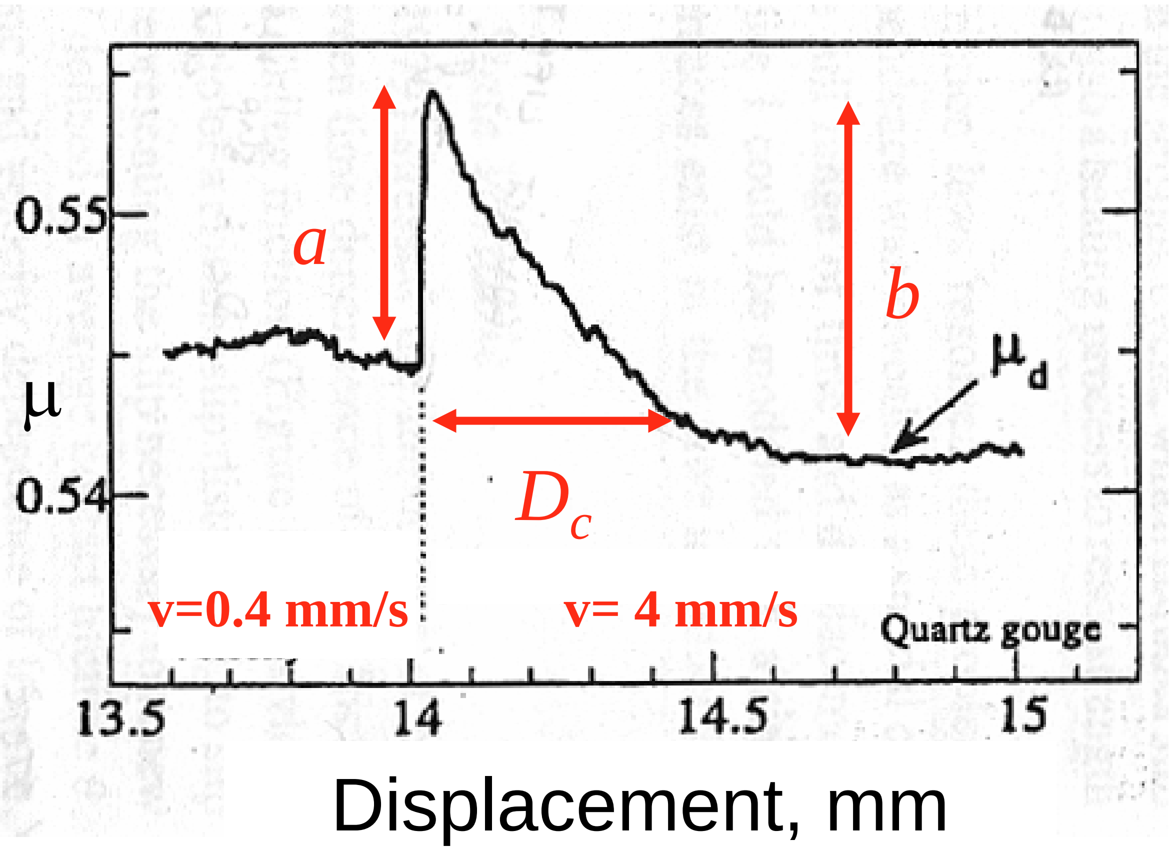
[Byerlee, PAGEOPH,1978]

For small changes in *V*, μ varies of few % and the slip weakening distance is few hundreds microns



[Marone, 1998]

Rate and State law (Dieterich-Ruina)



[Marone, 1998]

$$\mu = \mu_0 + a \ln\left(\frac{V}{V_0}\right) + b \ln\left(\frac{\theta V_0}{D_c}\right)$$

Direct Effect Evolution Effect

a & ***b***
empirical
constants

D_c
critical slip
distance
10^{-6}-10^{-4} m

θ
state
variable
with units
of time

These experimental results found broad application in EQ mechanics (EQ nucleation, aftershock dynamics, etc., *Scholz, Nature, 1998*).

But during earthquakes

- Slip rates of **0.1- 4 m/s (or ~ 1 m/s)**
- Displacements **up to 20 m**
- Dc (estimated to be) of **0.5 - 4 m**

Reduction in strength during EQ might determine:

1. Whether dynamic stress drop is larger than static stress drop *(e.g., Bouchon, JGR,1997).*
2. Rupture propagation mode: self-healing pulse vs. crack-like *(e.g., Heaton, PEPI 1990).*
3. Increase in the ratio of radiated energy vs. seismic moment with EQ size *(Mayeda & Walter, JGR 1996).*
4. Low heat production during coseismic slip *(e.g. Lachenbruch, JGR, 1980).*

Fault weak. mech. proposed till 2001

	μ
1. **Thermal pressurization of pore fluids** [*Sibson*, 1973]	**0.0?**
2. **Normal interface vibrations** [*Brune et al*., 1993]	**0.0?**
3. Acoustic fluidization [*Melosh*, 1996]	**0.0?**
4. Frictional melting (?) [*Spray*, 1993; *Tsutsumi and Shimamoto*, 1997]	**0.6-0.5**
5. Flash heating [*Rice*, 1999]	**0.0?**
6. Elastohydrodynamic lubrication [*Brodsky and Kanamori*, 2001]	**0.0?**

experimental data for rocks in yellow

Need for non-conventional rock friction experiments

These preliminary experiments revealed many “new” fault weakening mechanism activated at seismic slip rates

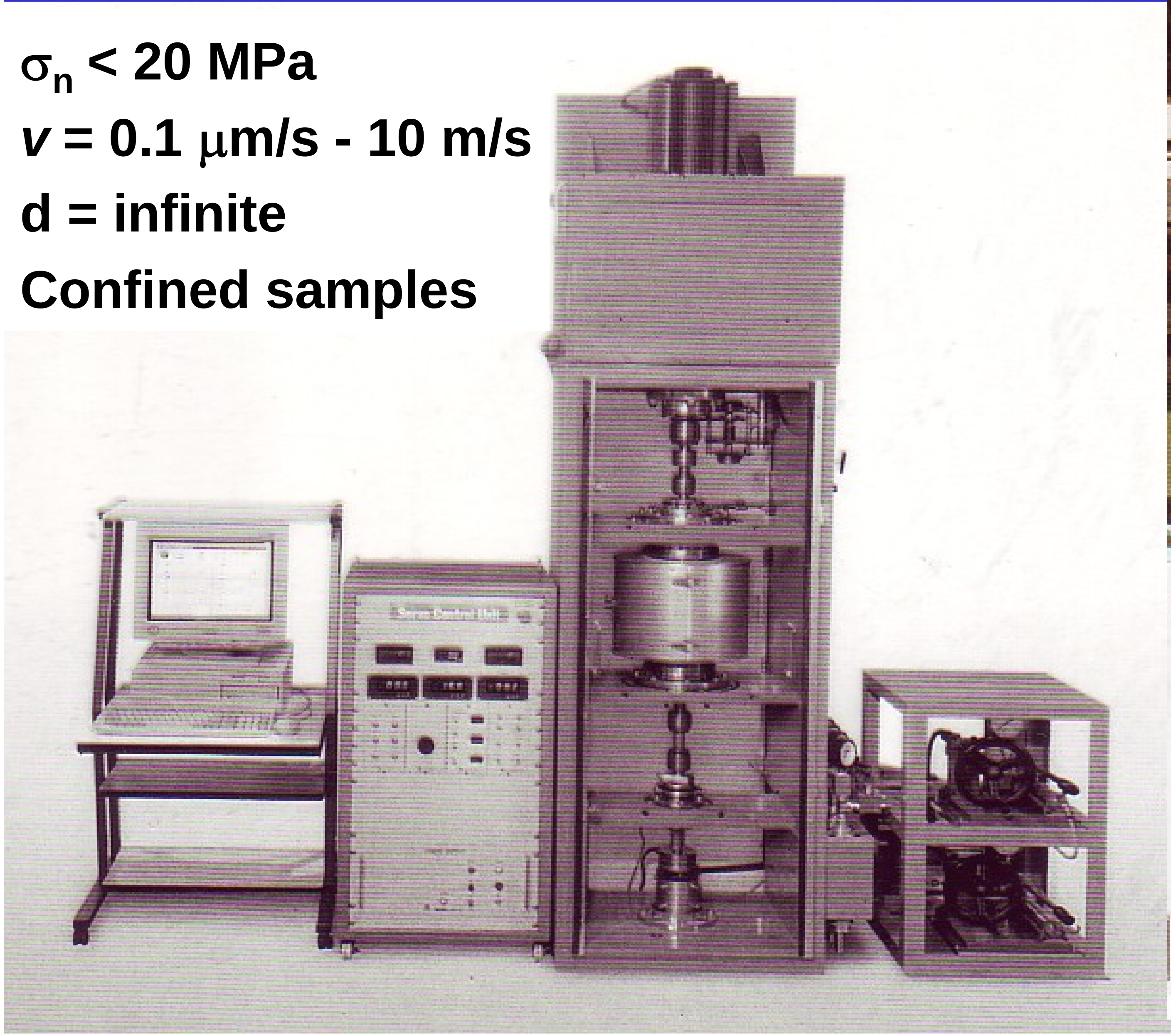
HV-Rock Friction Apparatus (2000-07) designed by Shimamoto (Hiroshima, JPN)

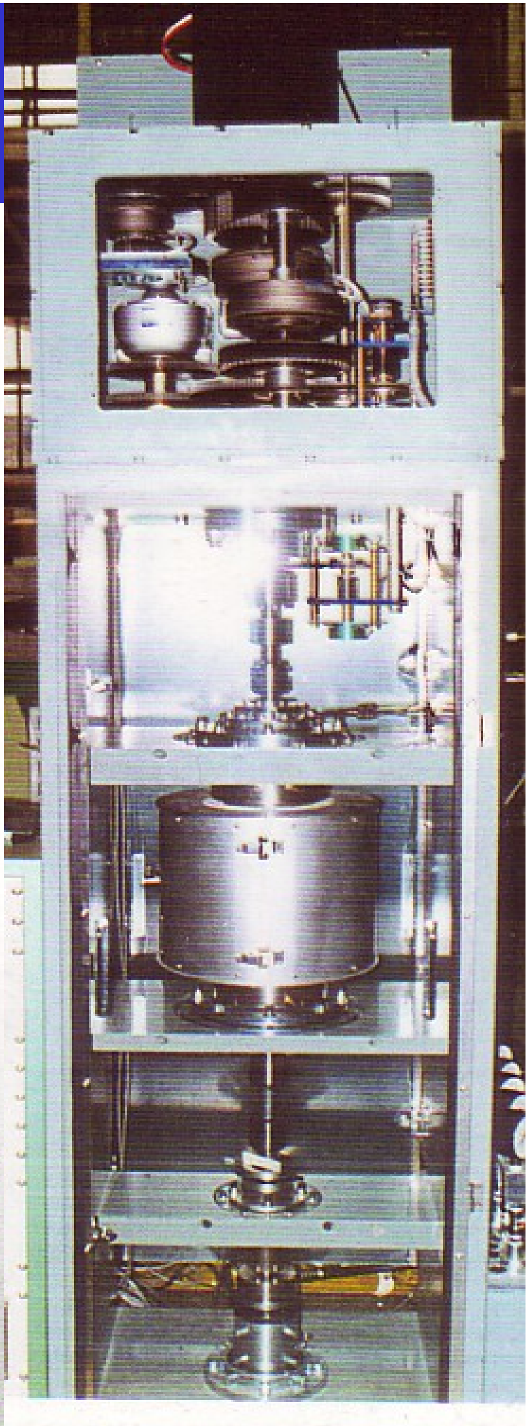
$\sigma_n < 20$ MPa

$v = 0.1\ \mu$m/s - 10 m/s

d = infinite

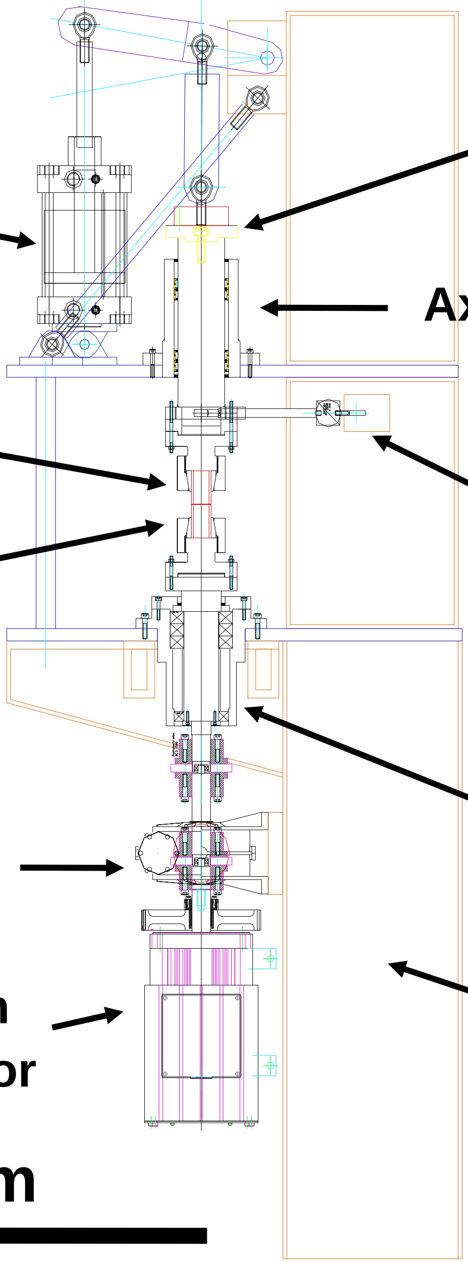
Confined samples





Soon in Italy?

Lateral view



Axial load actuator

Axial load cell

Axial column

Upper specimen

Torque cell

Lower specimen

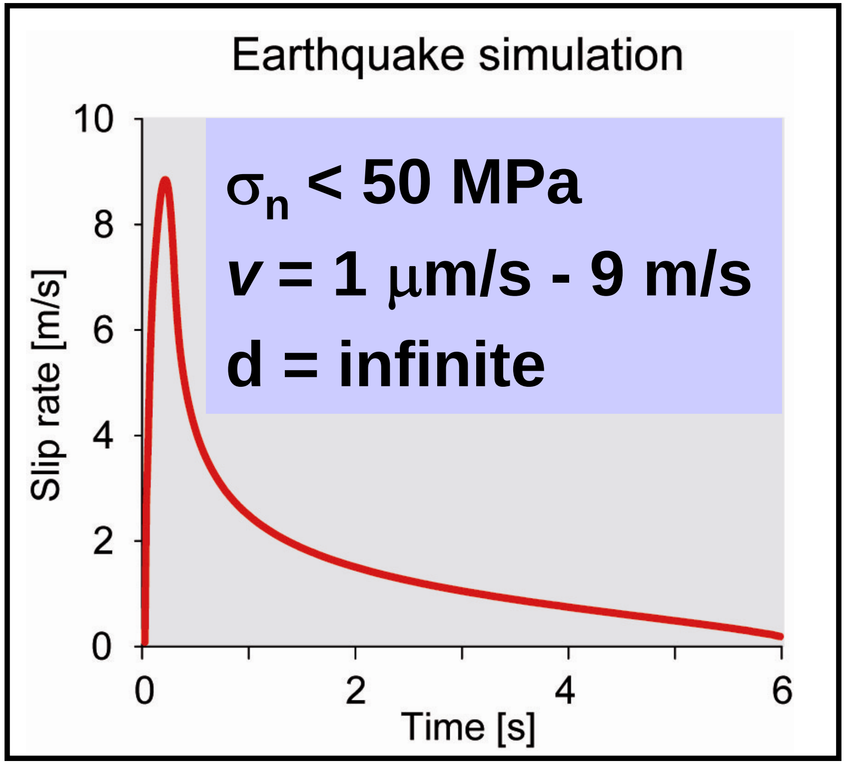
Secondary motor

Rotary column

Main motor

Frame

1 m

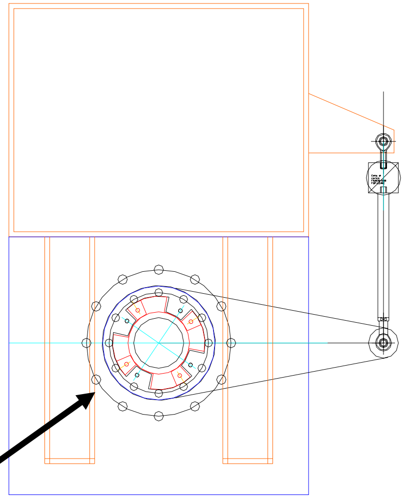


$\sigma_n < 50$ MPa

$v = 1\ \mu$m/s - 9 m/s

d = infinite

Top view



Frame

Torque cell

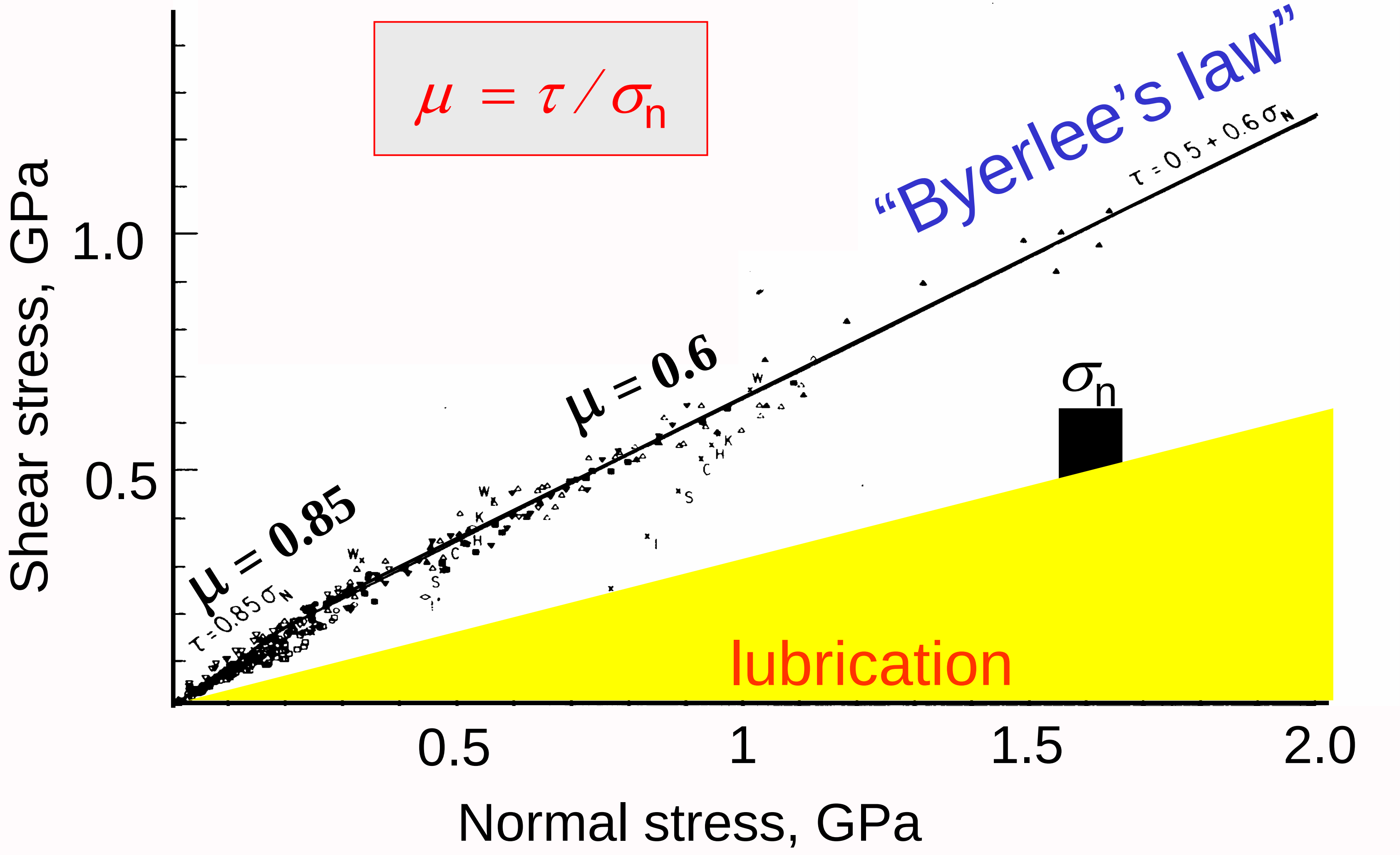
Stationary shaft

Fault weak. mech. proposed 2002-2007

	μ
1. Gouge-related weakening [*Chambon et al.*, 2002; *Mizoguchi et al.*, 2007]	**< 0.2**
2. Silica gel lubrication [*Goldsby and Tullis*, 2002; *Di Toro et al.*, 2004]	**0.2**
3. Melt lubrication [field & exper. evidence, *Di Toro et al.*, 2006]	**0.1**
4. Flash heating and dehydration weakening [*Hirose and Bystricky*, 2007]	**0.1**
5. Thermal decomposition weakening [*Han et al.*, 2007]	**0.1**

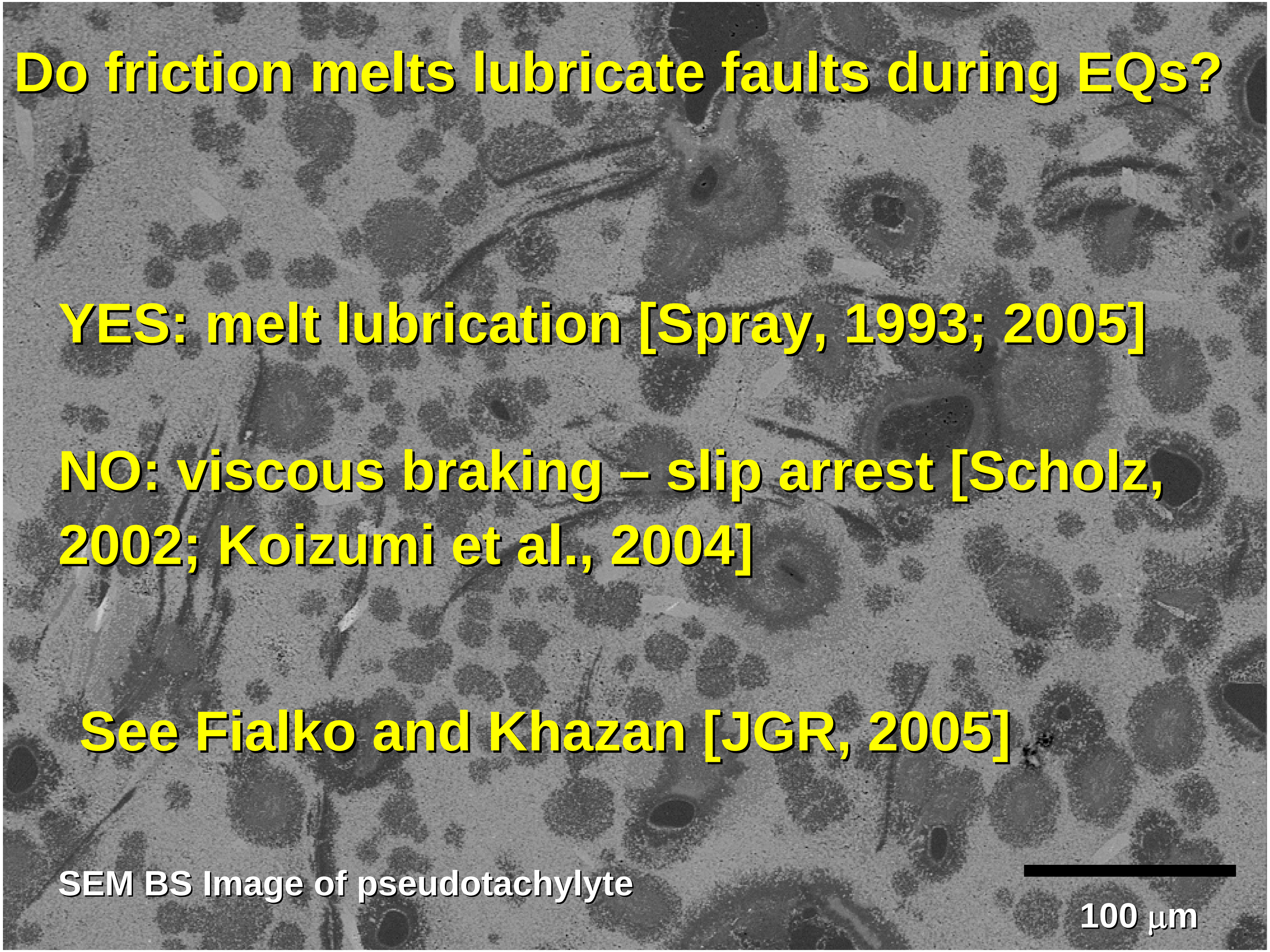
experimental data for rocks in yellow

Fault strength during an EQ **cannot be determined** from seismograms!!!



[Byerlee, PAGEOPH,1978]

Do friction melts lubricate faults during EQs?



YES: melt lubrication [Spray, 1993; 2005]

NO: viscous braking – slip arrest [Scholz, 2002; Koizumi et al., 2004]

See Fialko and Khazan [JGR, 2005]

SEM BS Image of pseudotachylyte

Three **independent** source of information suggest that **melt lubrication** occurs during EQs:

a- **Estimates** of fault strength from **field analysis**.

b- **Measures** of fault strength in the **laboratory**.

c- **Estimates** of fault strength from **theor. analys.**

a- Field analysis

Estimate of τ_{av} from PT-bearing faults:

$$\boxed{\tau_{av} \approx (t / d)\, E^{*} \rho \qquad \text{in Pa}}$$

[mod. from *Sibson*, 1975]

τ_{av}	average dynamic shear stress in Pa
t	average pseudotachylyte thickness in m
d	coseismic fault displacement in m
E^{*}	energy to heat and melt 1 kg of rock (J kg^{-1})
ρ	rock density in kg m^{-3}

Main assumption... maybe not an assumption:

<u>All work done in faulting is converted to heat</u>

[Pittarello et al., submitted, see last section of the seminar]

How was this Equation obtained?

(see Di Toro et al., Tectonophysics, 2005)

W_f	work done in faulting on a point of a fault (Scholz, 1990)
Q	heat
U_s	surface energy

$$\boxed{W_f = Q + U_s}$$

Energy exchanged in gouge formation is negligible and the process is adiabatic [*Lockner and Okubo*, JGR, 1983; *Di Toro et al.,* AGU Monograph, 2006]

$$\boxed{W_f \sim Q}$$

$$\boxed{W_f = \tau d A = \mu\ \sigma_n^{eff}\ d\ A}$$

τ	average dynamic shear stress
d	displacement
μ	friction coefficient (velocity dependent)
σ_n^{eff}	effective stress normal to the fault surface
$\boldsymbol{A}$	fault area

Energy E to heat and melt a volume of rock

$$E^* = E_{\mathrm{melt}} + E_{\mathrm{heat}}$$

$$E^* = [c_{\mathrm{pm}}\,(T)\,\Delta T + H\,]\; v_{\mathrm{m}} / v_{\mathrm{pt}} + [c_{\mathrm{pcl}}\,(T)\,\Delta T\,]\;(v_{\mathrm{pt}} - v_{\mathrm{m}}) / v_{\mathrm{pt}}$$

H	latent heat of fusion (J kg^{-1})
$\Delta T = T_{\mathrm{melt}} - T_{\mathrm{hr}}$	temperature difference between host rock and PST (K)
c_{pm}	specific heat for friction-induced melt (kJ K^{-1} mol^{-1})
c_{pcl}	specific heat for clasts (kJ K^{-1} mol^{-1})
$\gamma = v_{\mathrm{m}} / v_{\mathrm{pt}}$	matrix content
$(v_{\mathrm{pt}} - v_{\mathrm{m}}) / v_{\mathrm{pt}}$	clast content

if: $c_{\mathrm{pm}}\,(T) \approx c_{\mathrm{pcl}}\,(T)$

$$E^* = [\,\gamma\, H + c_{\mathrm{p}}\,(T)\,\Delta T\,] \quad \text{in J/kg}$$

Melted rock mass
$M = \rho\, A\, t$

$$Q = E\, M = [\gamma\, H + c_{\mathrm{p}}\,(T)\,\Delta T\,]\,\rho\, A\, t \quad \text{in J}$$

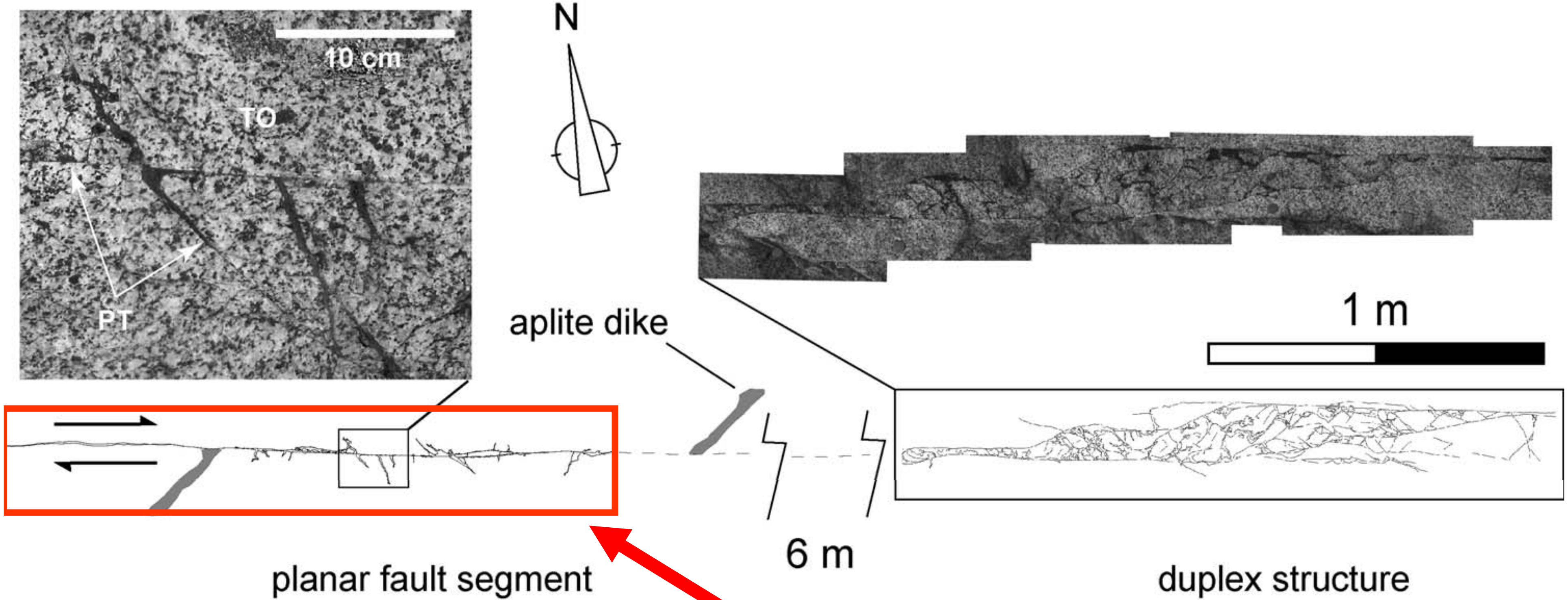
$W_f = \tau\; d\, A = Q$

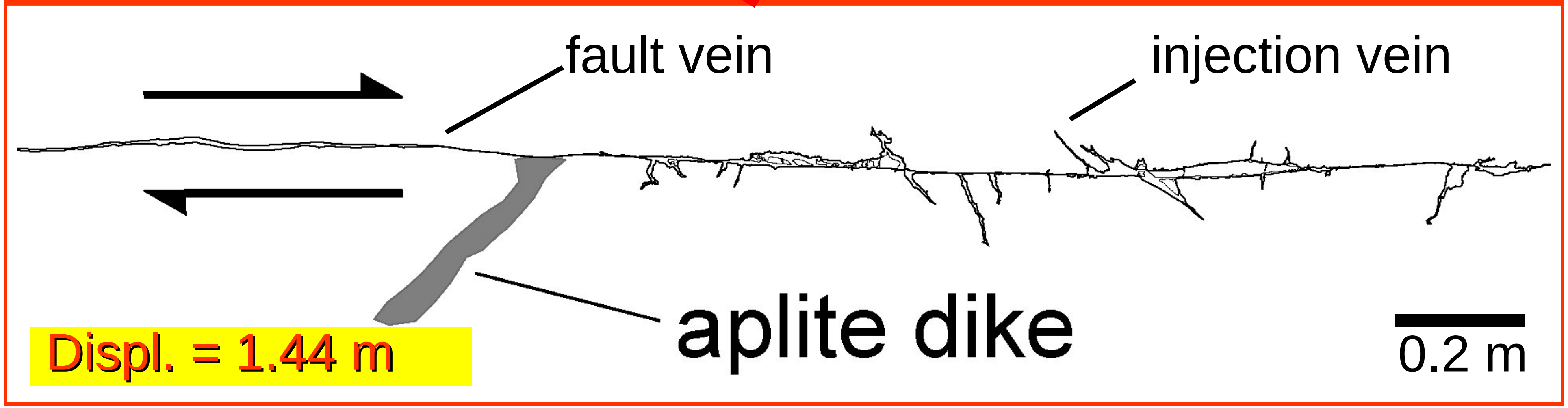
$$\tau\;\; d\, A = [\gamma\, H + c_{\mathrm{p}}\,(T)\,\Delta T\,]\,\rho\, A\, t$$

t = PST thickness
d = displacement

$$\tau = \rho\;\; E^*\;\; (t\, /\, d) \quad \text{in Pa}$$

Some fault segments have one PST layer



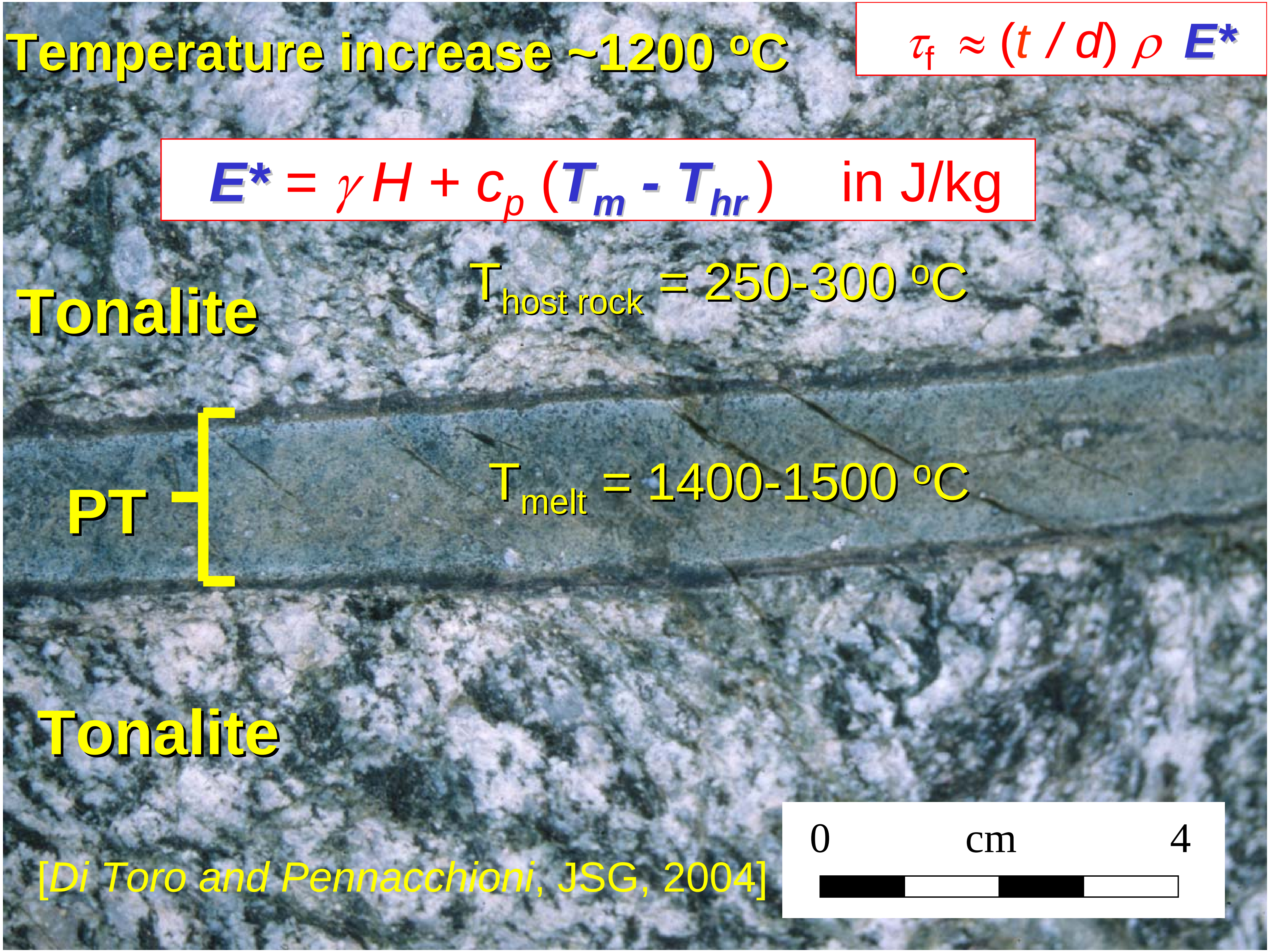


Displ. = 1.44 m

Temperature increase ~1200 °C

$$\tau_f \approx (t / d)\, \rho\, E^*$$

$$E^* = \gamma H + c_p\,(T_m - T_{hr}) \quad \text{in J/kg}$$



$T_{host\ rock}$ = 250-300 °C

T_{melt} = 1400-1500 °C

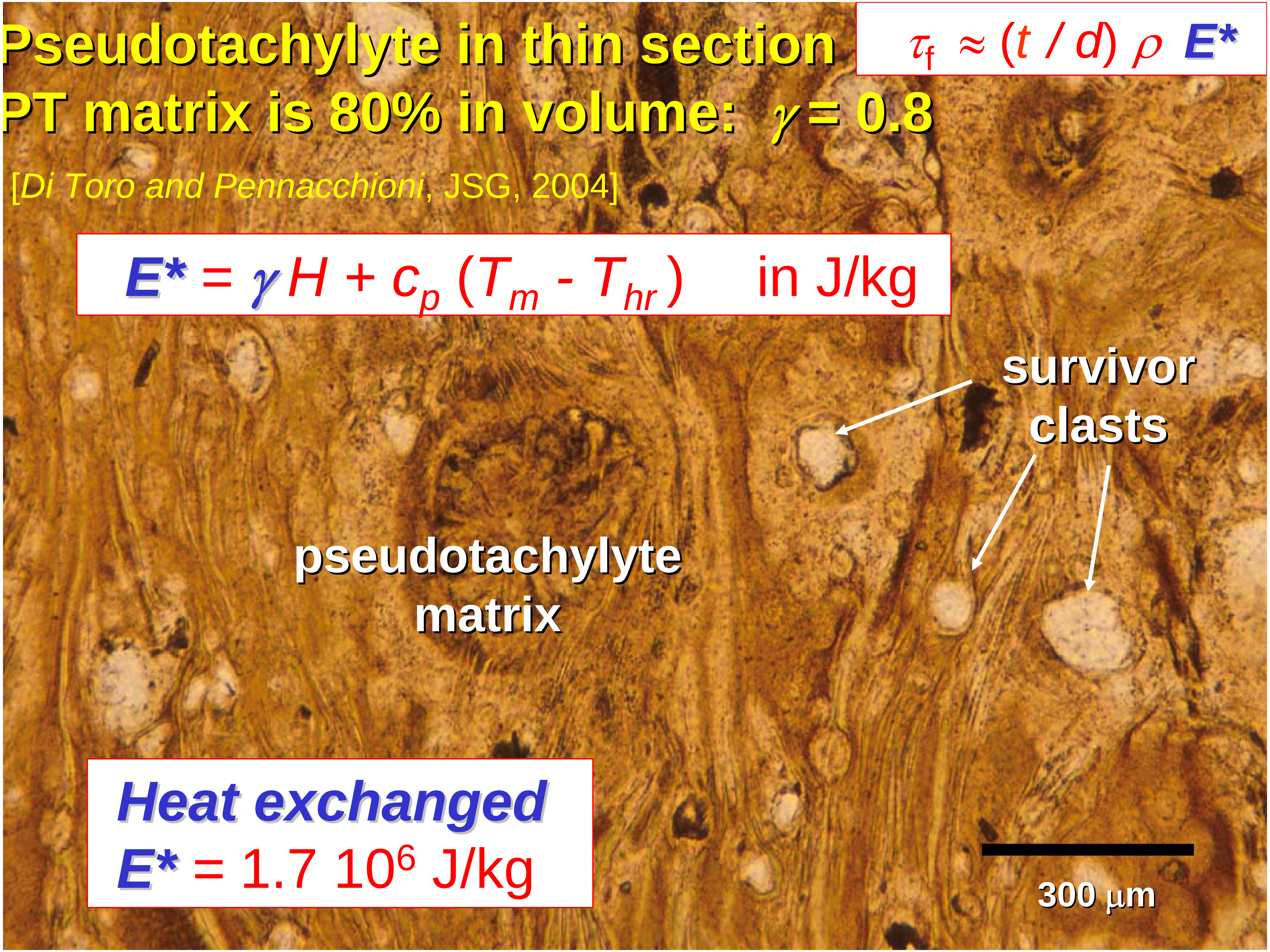
[*Di Toro and Pennacchioni*, JSG, 2004]

Pseudotachylyte in thin section

PT matrix is 80% in volume: $\gamma = 0.8$

$$\tau_f \approx (t / d)\, \rho\, E^*$$

[*Di Toro and Pennacchioni*, JSG, 2004]

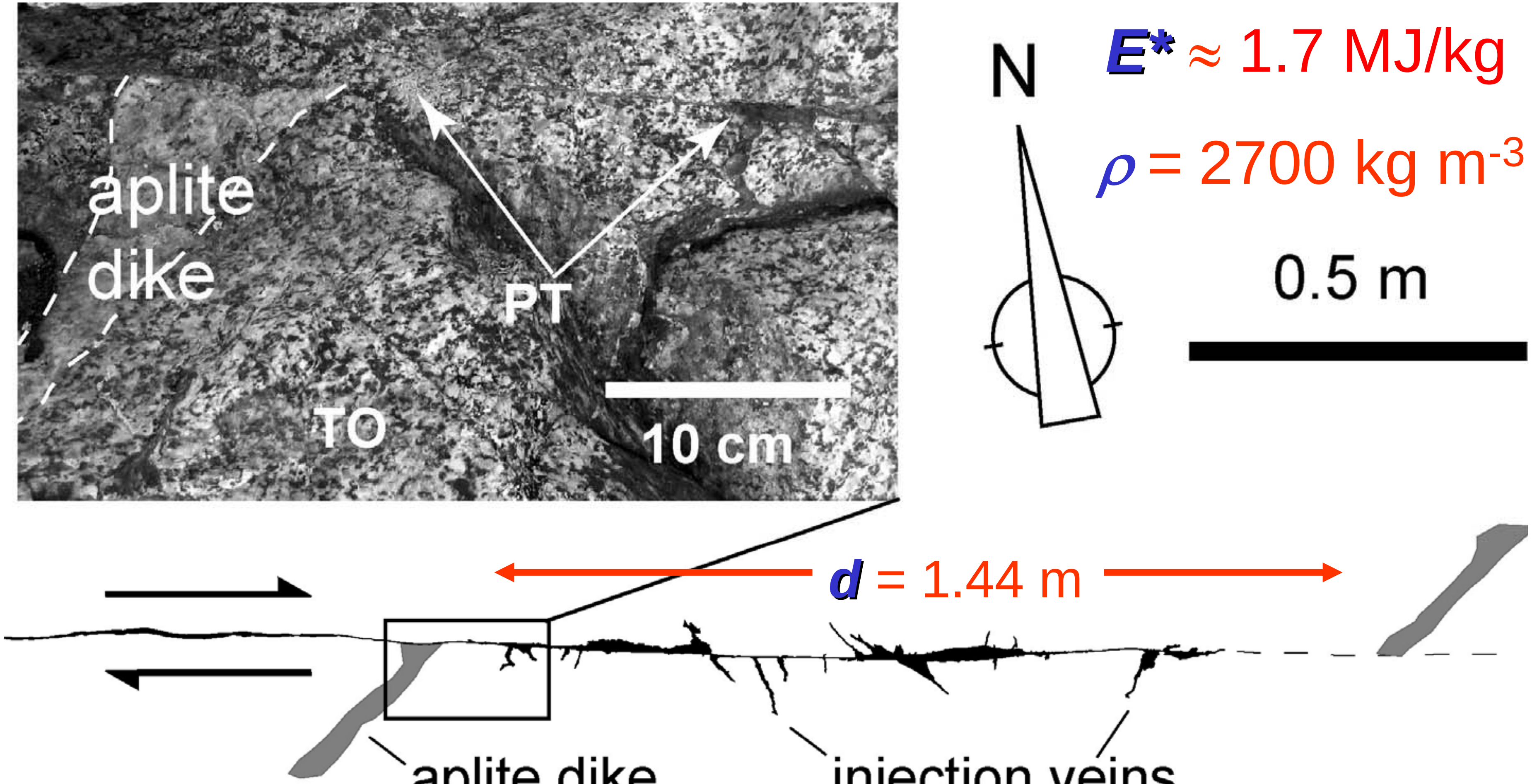


$$E^* = \gamma H + c_p\,(T_m - T_{hr}) \quad \text{in J/kg}$$

Heat exchanged

$E^* = 1.7\ 10^6$ J/kg

Determination of average dynamic shear stress



$E^* \approx$ 1.7 MJ/kg

ρ = 2700 kg m^{-3}

d = 1.44 m

t = area (PT) / fault length segment = 5.9 mm

$$\tau_{av} \approx (t / d)\, E^* \rho = 18.4 \quad \text{MPa}$$

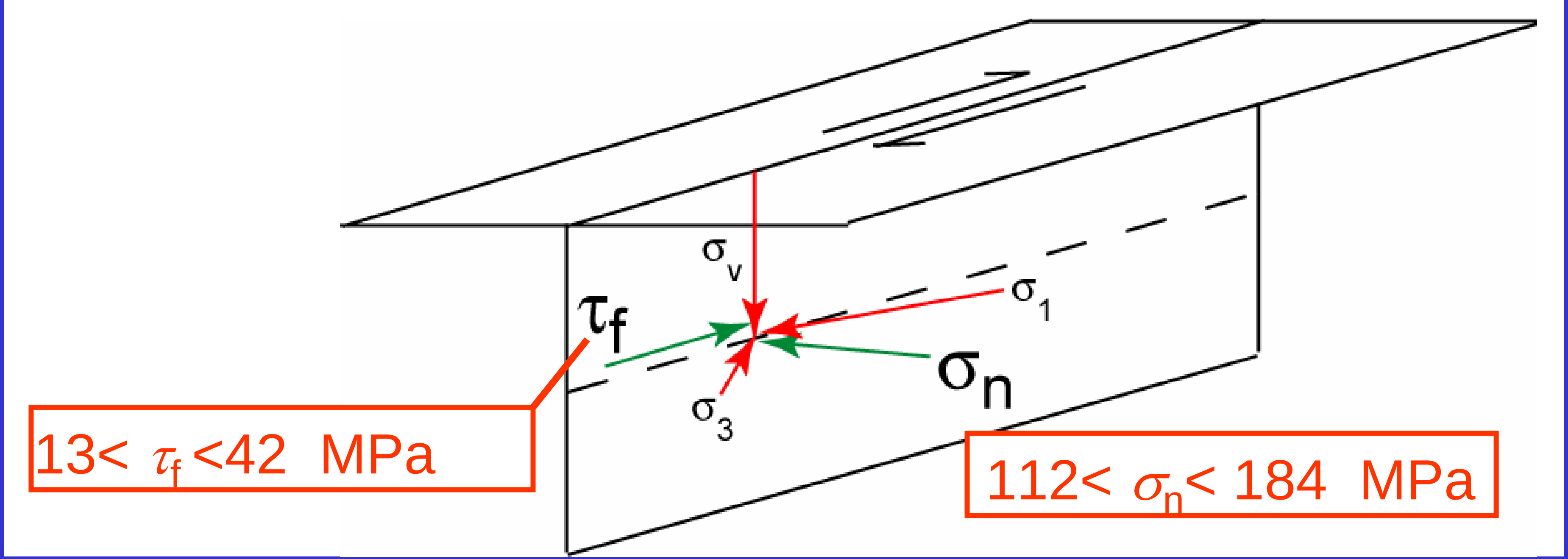
We did the same for many faults (determ. displ. from separations):

$13 < \tau_{av} < 42$ MPa

Estimate of the stress normal to the fault

Depth 10 km; σ_1 at 37° from fault and $\mu = 0.75$; lithostatic vertical stress ($\sigma_v = \sigma_2 = \rho g z$); pore pressure **(from zero to hydr. or $0 < \lambda < 0.4$)**; Andersonian faulting: **$\sigma_v = (\sigma_1 + \sigma_3) / 2$**

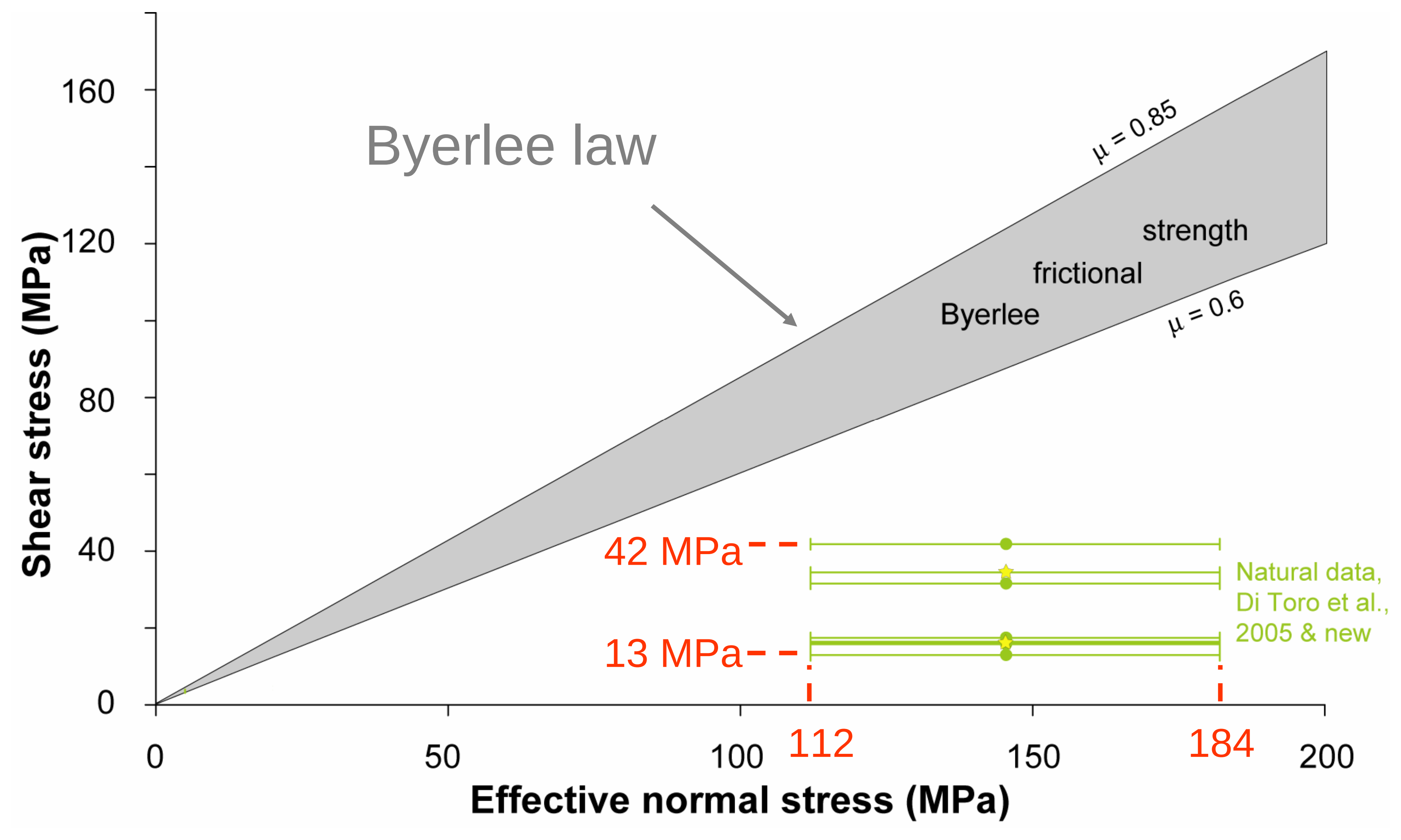
Eff. stress normal to f.: $112 < \sigma_n^{eff} < 184$ MPa



$13 < \tau_f < 42$ MPa

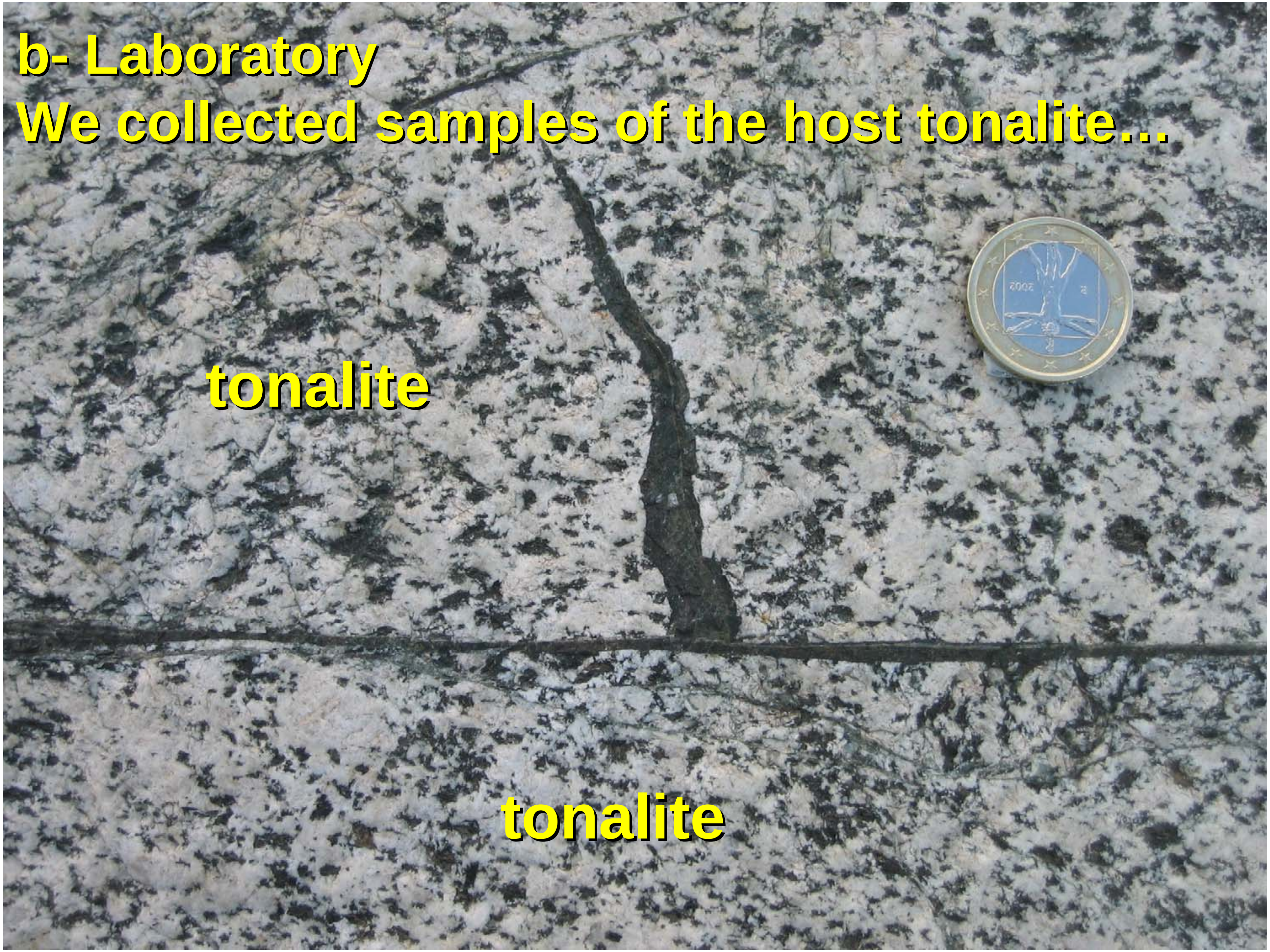
$112 < \sigma_n < 184$ MPa

Field data: **low strength** in the presence of melt (melts **lubricate** faults)



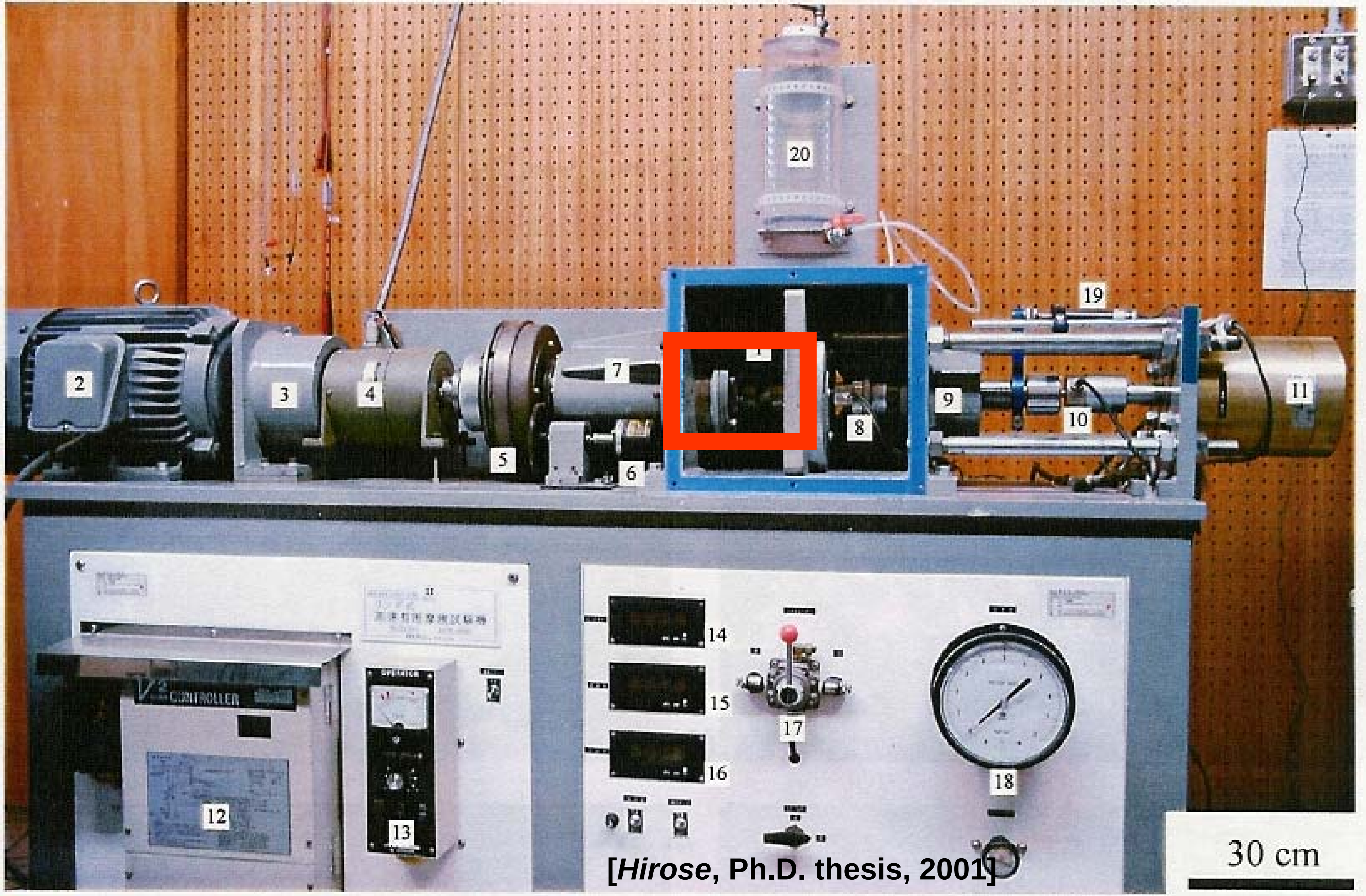
b- Laboratory

We collected samples of the host tonalite…



worked cylinders and slid them in the…

High-velocity rotary shear in Kyoto (JPN)



[*Hirose*, Ph.D. thesis, 2001]

Tonalite, v = 1.3 m/s, σ_n = 20 MPa

20 mm

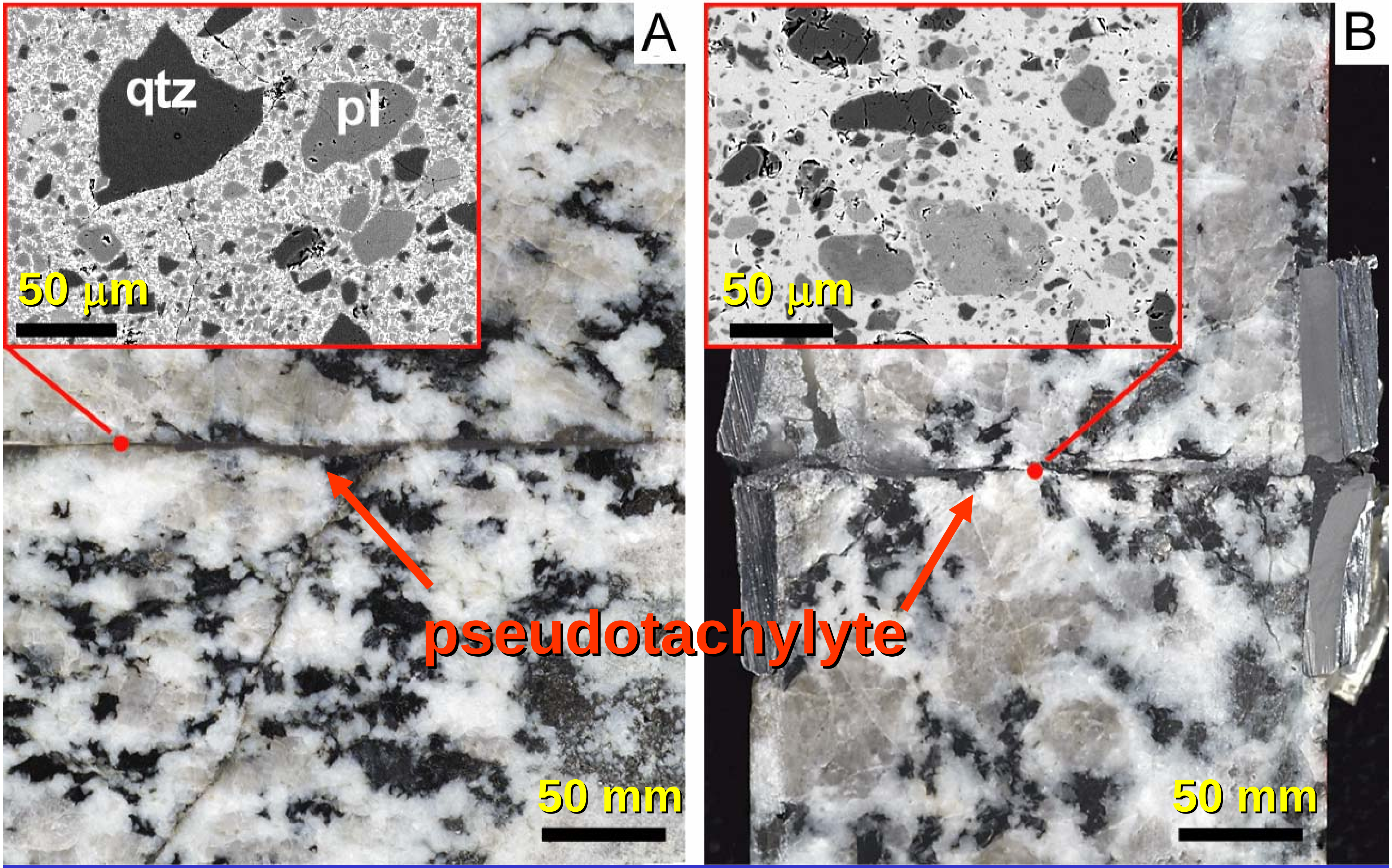
“The very rapid friction of two bodies produces fire”

[Leonardo da Vinci]

Novaculite, v = 1.4 m/s, σ_n = 9.8 MPa

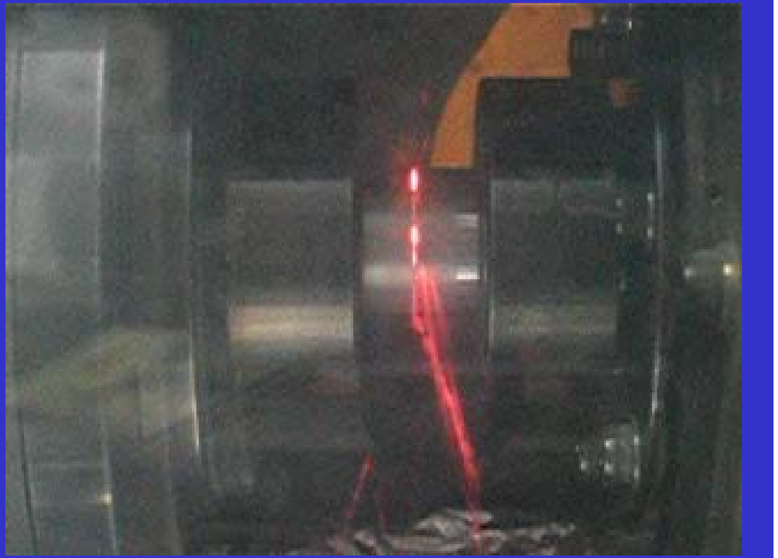
20 mm

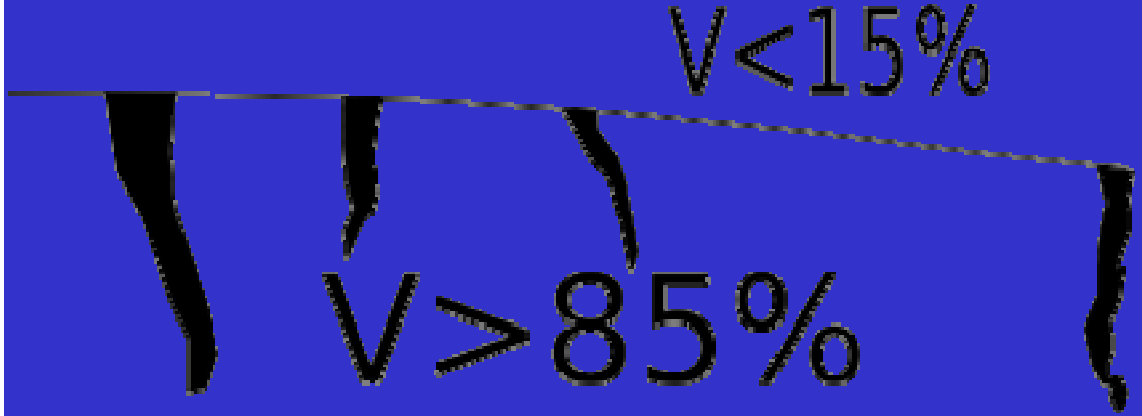
Fabric is very similar (also under SEM)



Nature **Experiment**

Melt extrusion in nature and experiments

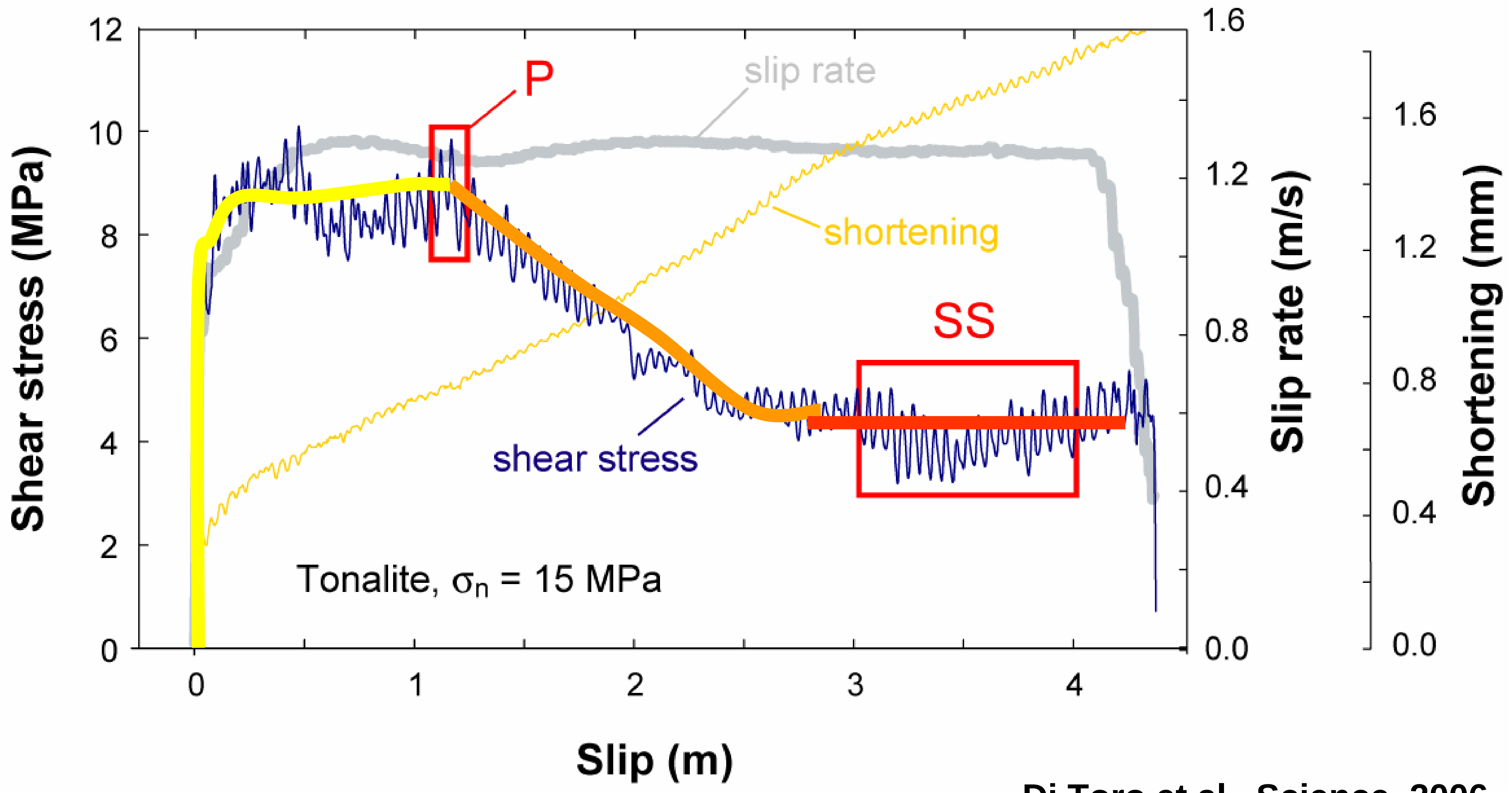




Nature

Experiment

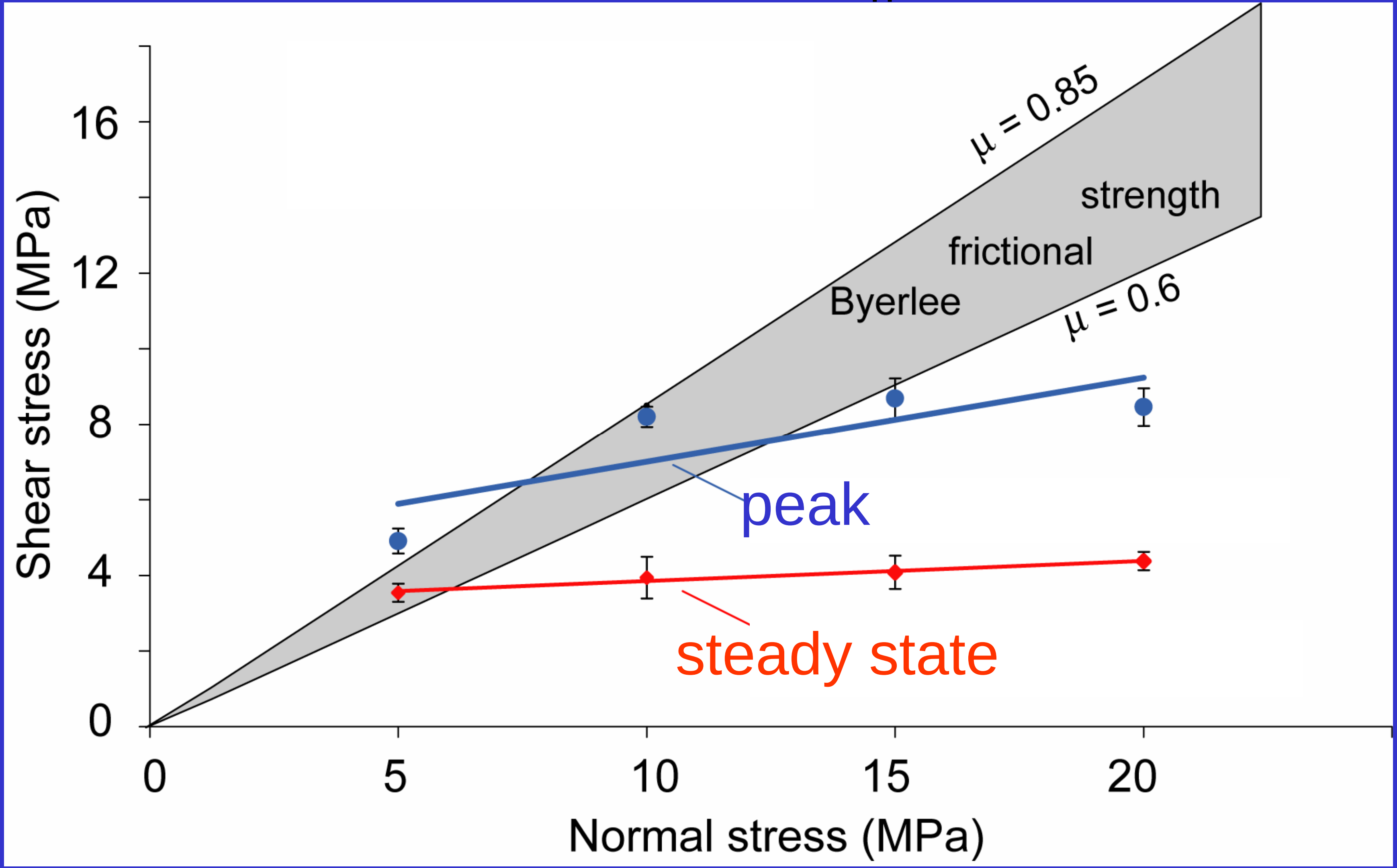
Traction evolution:
1. strengthening stage
2. transient stage
3. steady state stage



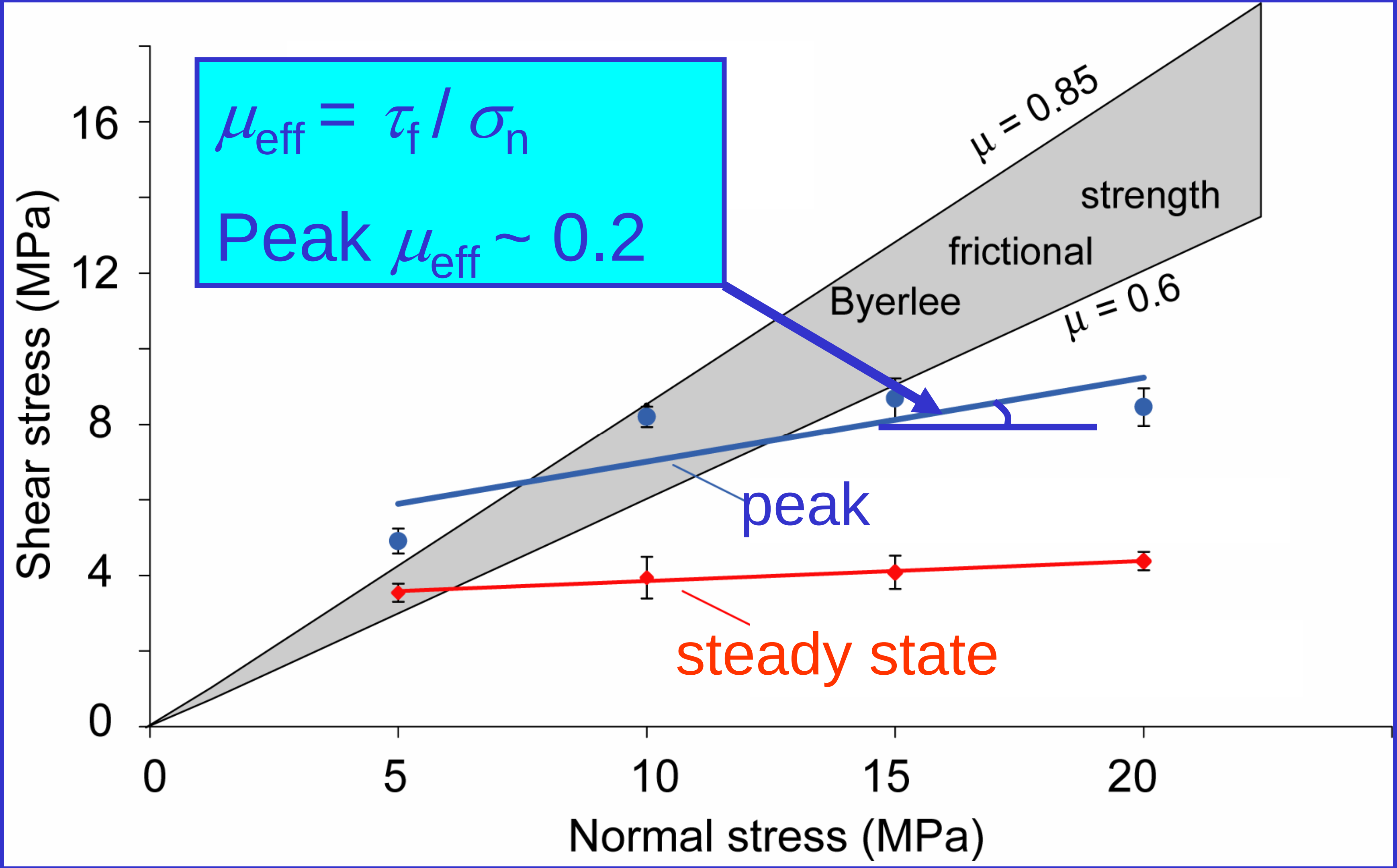
Di Toro et al., Science, 2006

By performing several exp. with increasing σ_n

- **low strength** in the presence of melt
- slight dependence of τ with σ_n (**melt lubrication**)



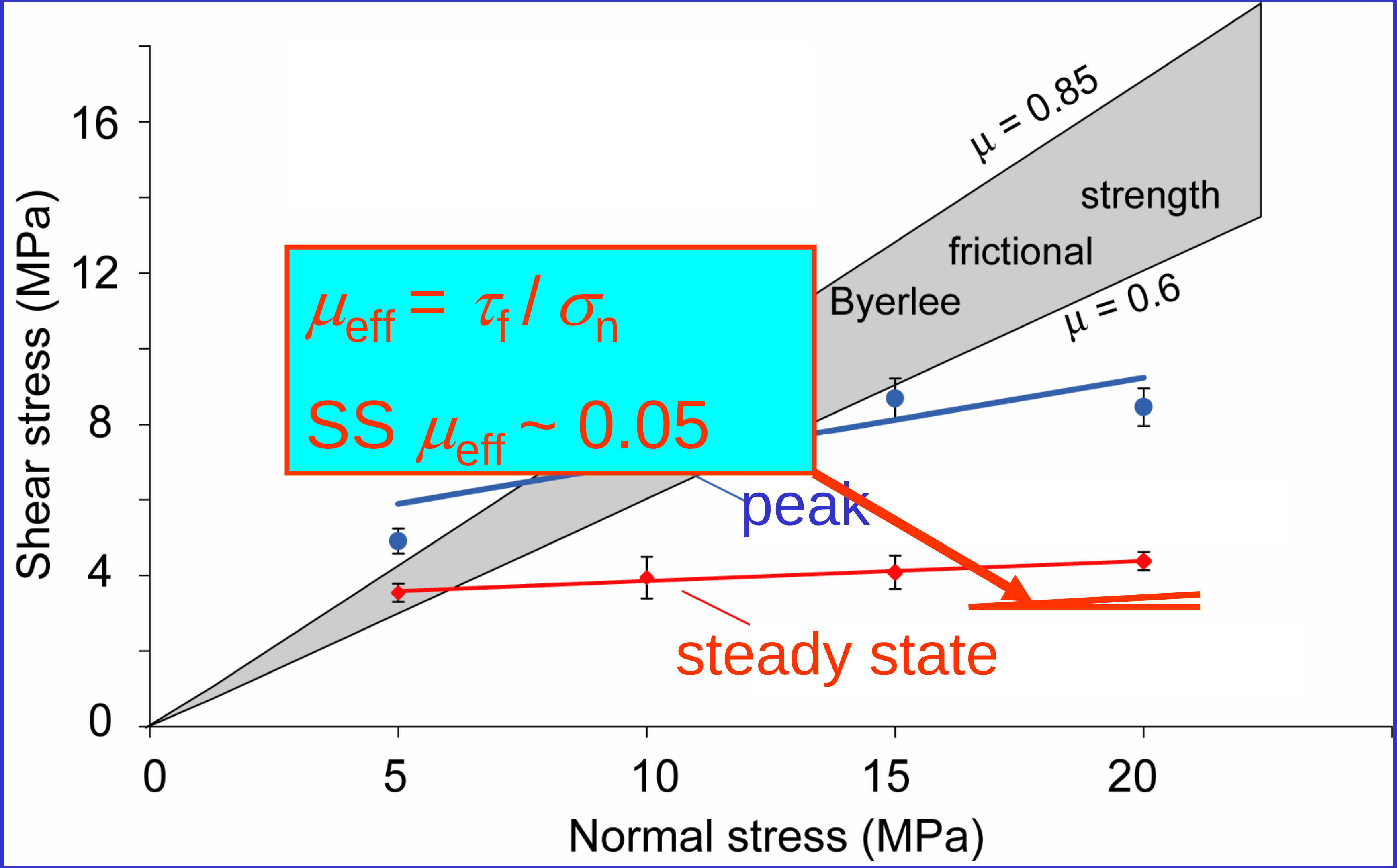
A rough approx.: **effective friction coeff.**



$\mu_{eff} = \tau_f / \sigma_n$

Peak μ_{eff} ~ 0.2

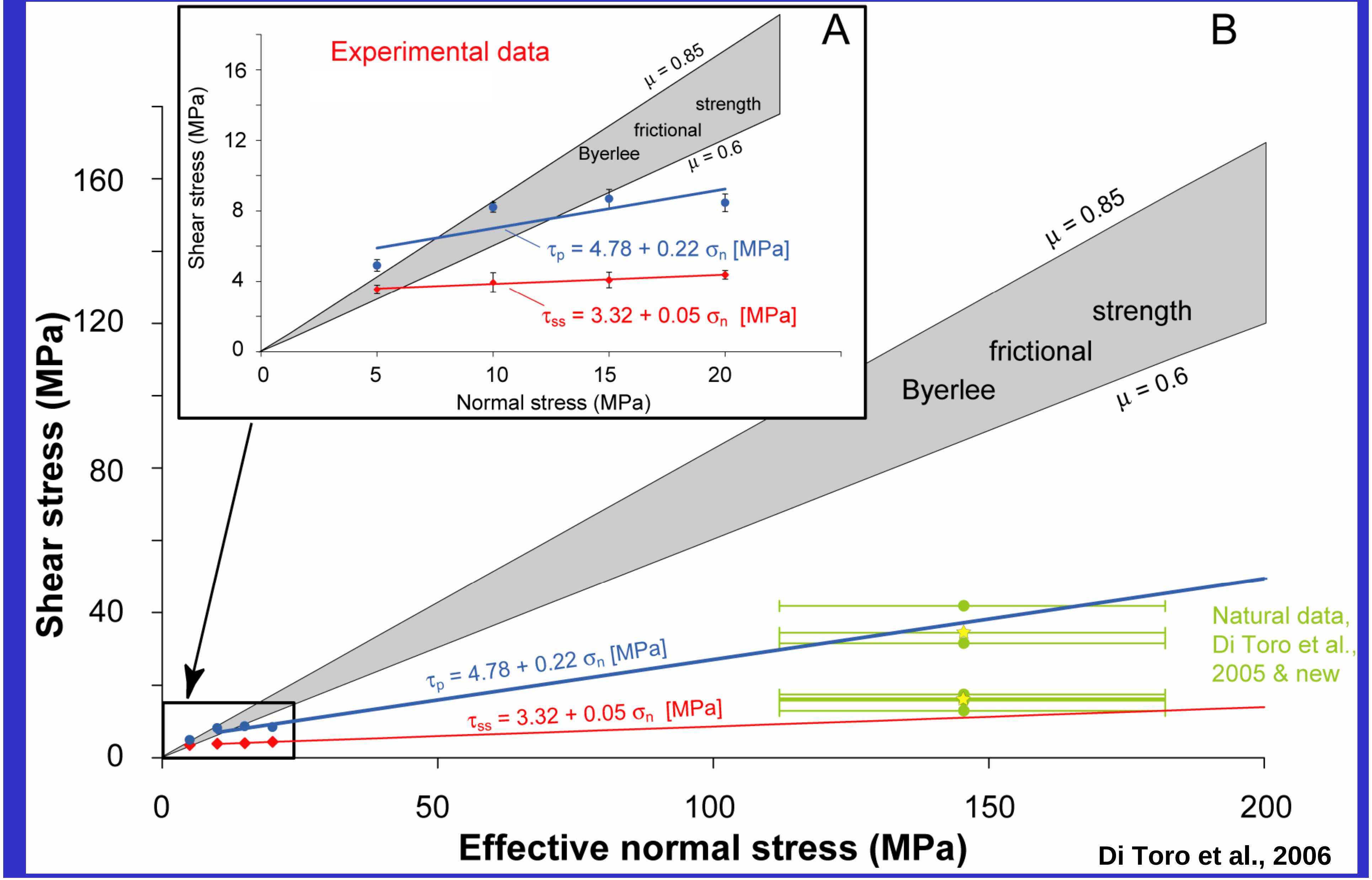
A rough approx.: **effective friction coeff.**



$\mu_{eff} = \tau_f / \sigma_n$

SS $\mu_{eff} \sim 0.05$

Melt lubrication in nature and experiments… **BUT**

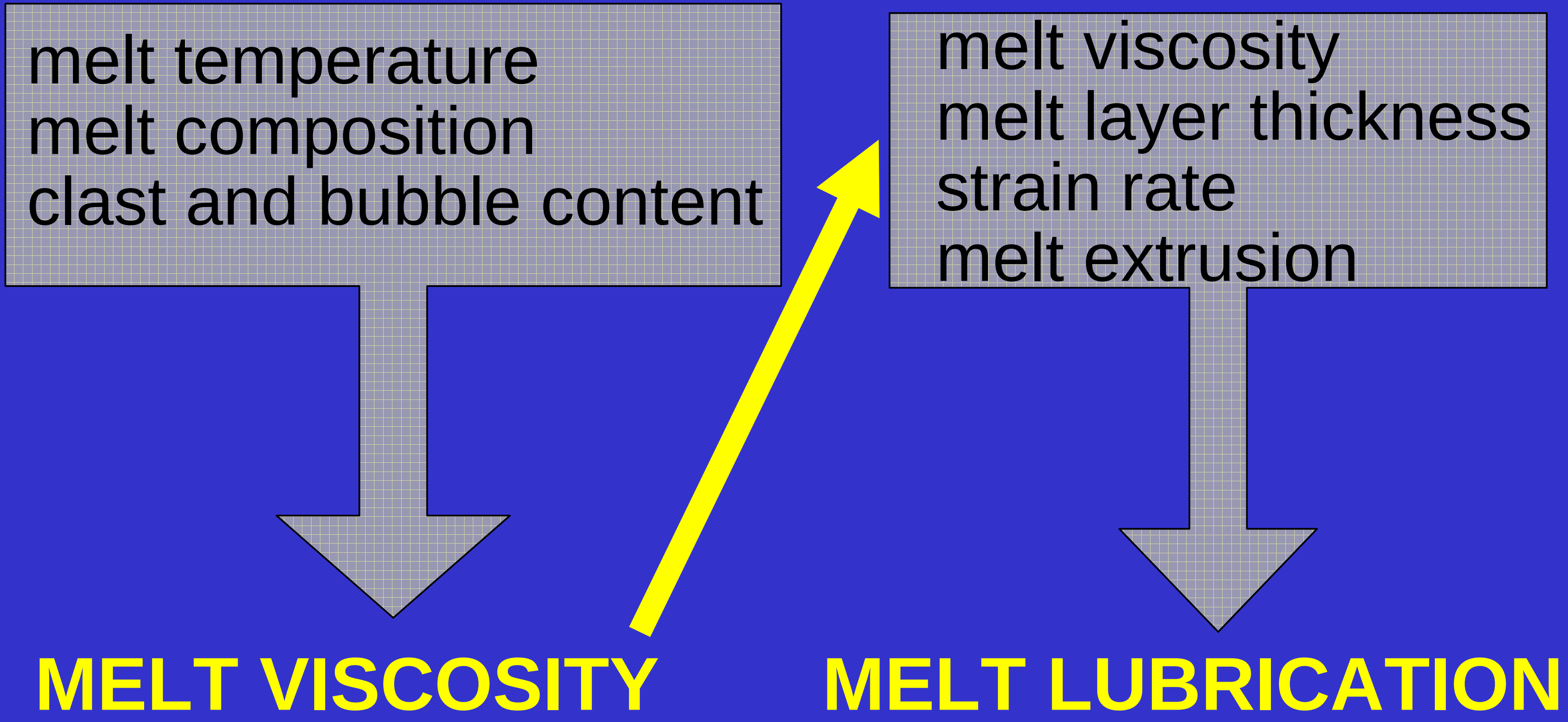


Di Toro et al., 2006

This is a poor extrapolation

The **effective friction coefficient** does not fit the “physics”: no solid friction here.

Melt lubrication is the result of



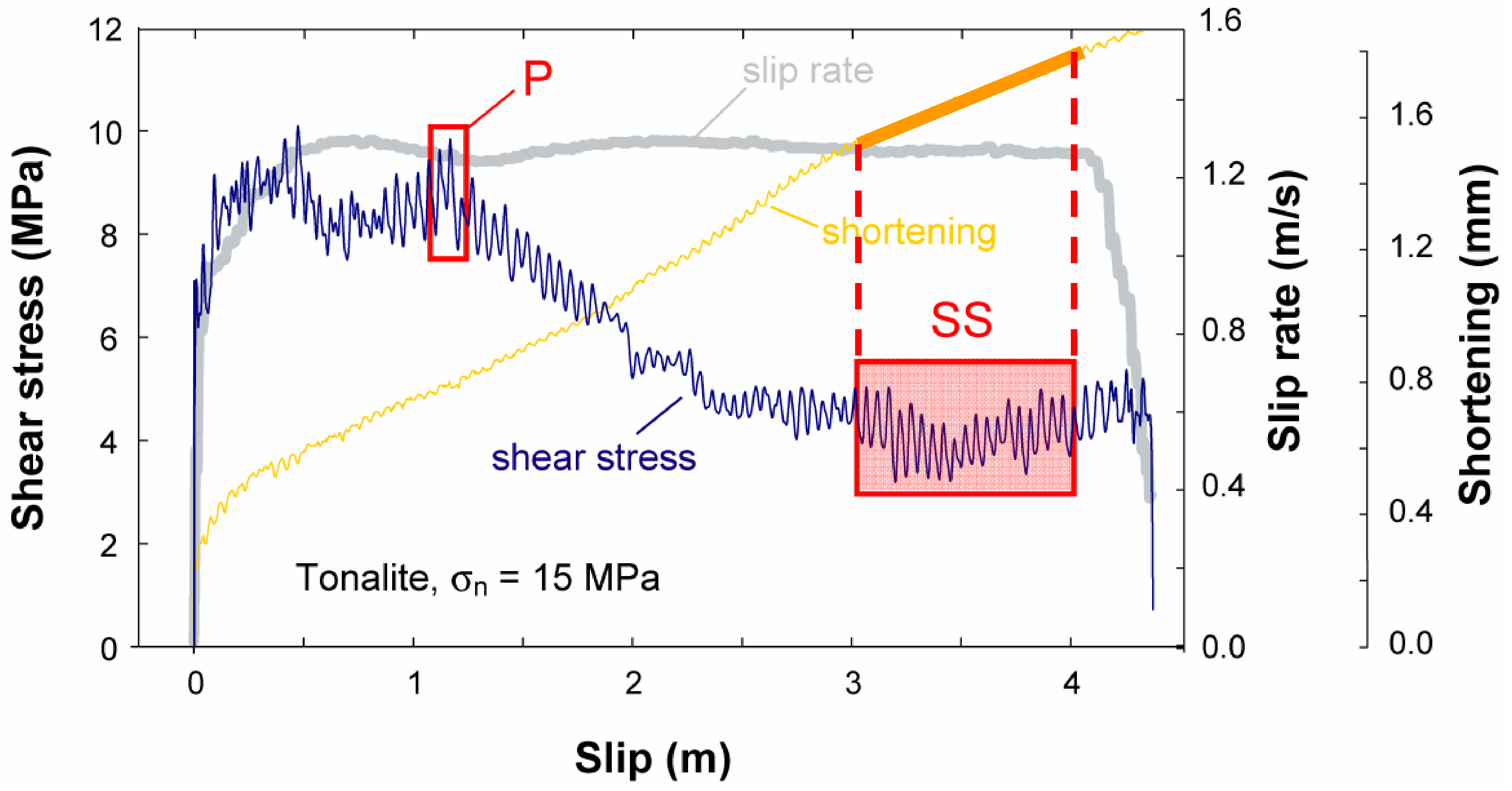
melt temperature
melt composition
clast and bubble content

melt viscosity
melt layer thickness
strain rate
melt extrusion

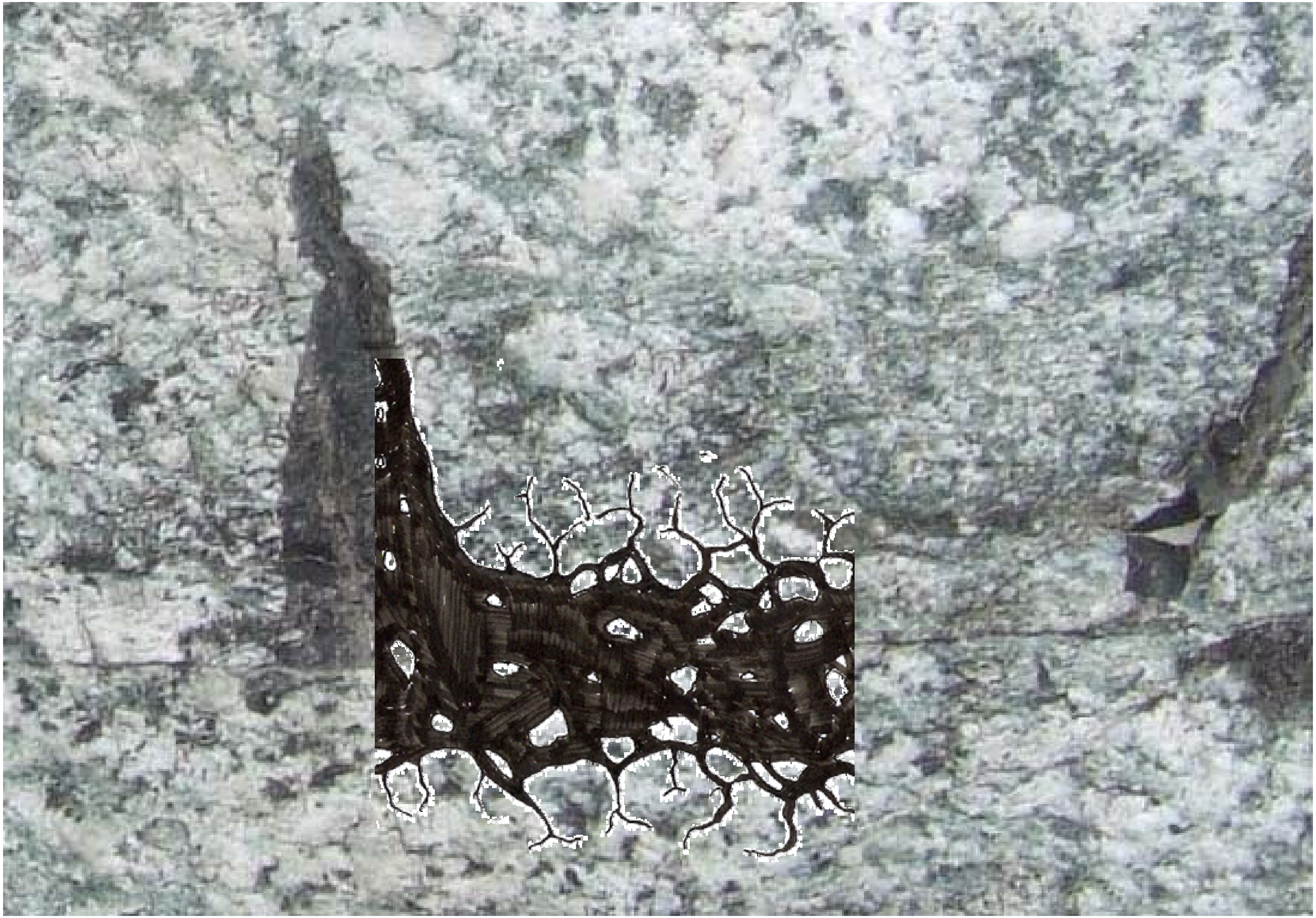
MELT VISCOSITY

MELT LUBRICATION

A **constitutive equation** for melt lubrication. Let’s focus on the **steady state** stage. Here the **shortening rate** is constant.

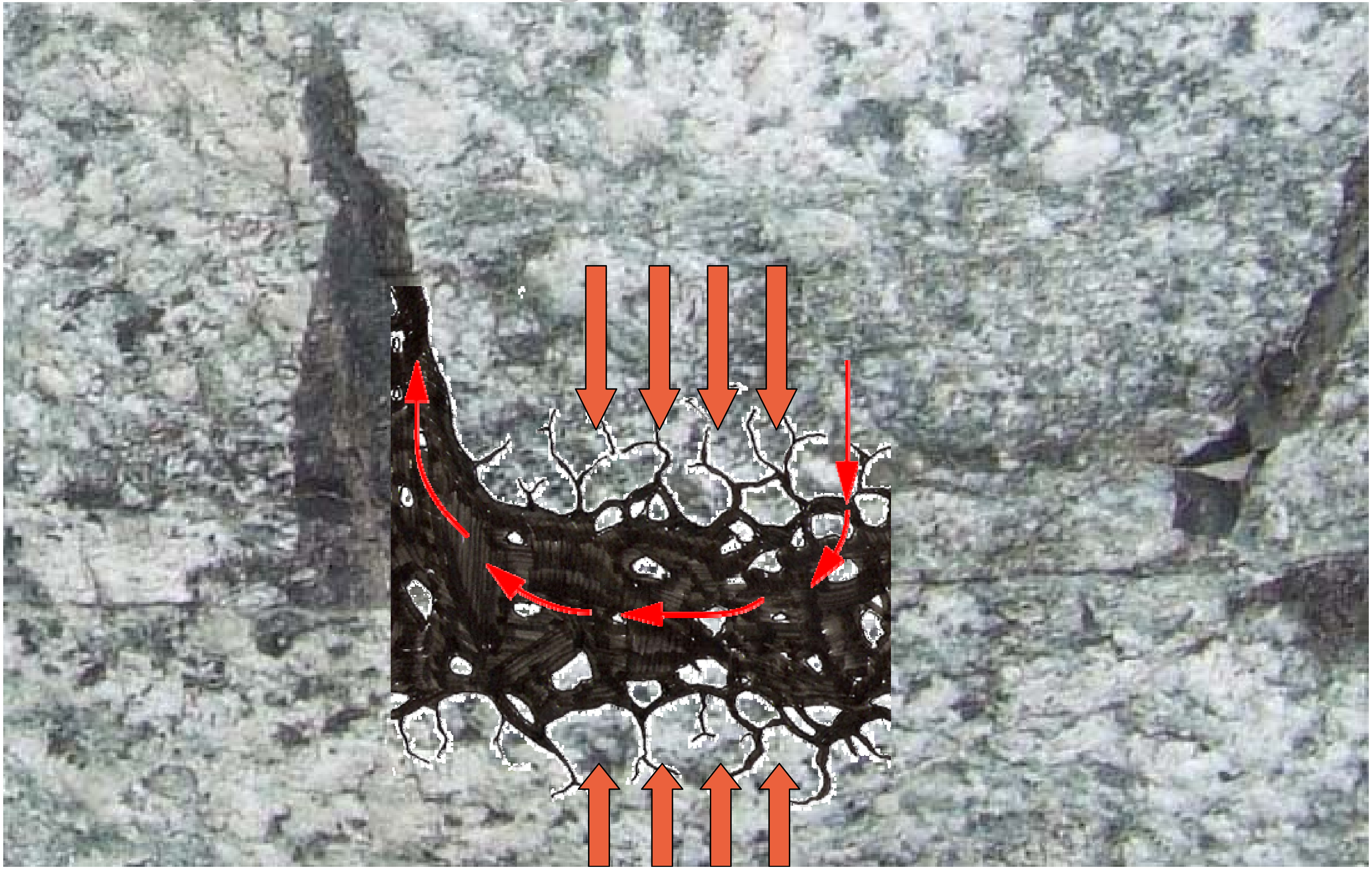


Modelling steady-state: a complex world



melt thickness is constant (Hirose and Shimamoto, 2005)

melting-, shortening-, melt extrusion-rate = cst

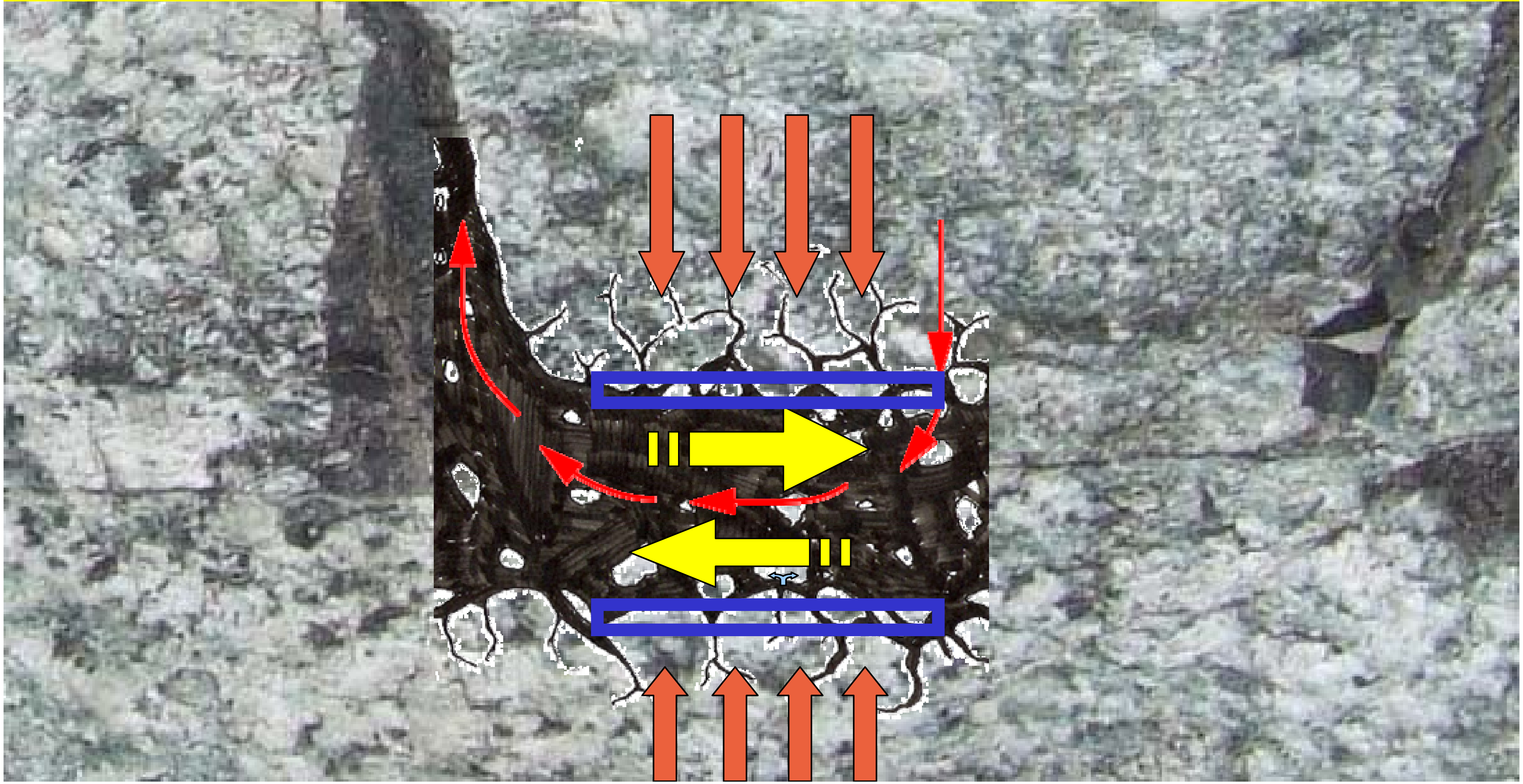


melt thickness is constant (Hirose and Shimamoto, 2005)

melting-, shortening-, melt extrusion rate = cst.

heat produced by viscous flow & shear heating

latent heat of fusion = heat loss by melt extr.



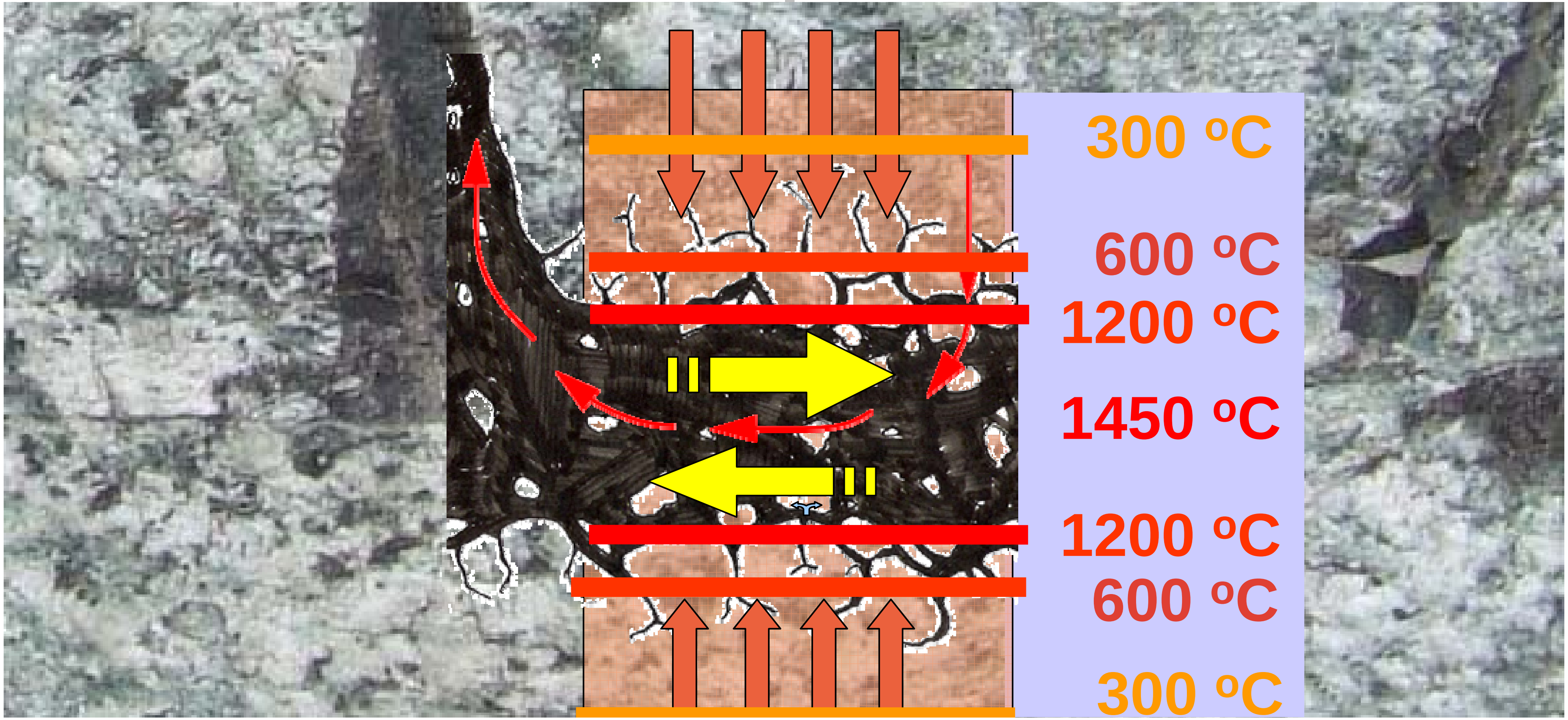
melt thickness is constant (Hirose and Shimamoto, 2005)

Melting-, shortening-, melt extrusion-rate = cst

heat produced by viscous flow & shear heating

latent heat of fusion = heat loss by melt extr.

isotherms are fixed in space and time



System of **five coupled equations**:

1) Melt/solid interface: Stefan problem
2) Solid host rock: heat diffusion
3) Melt layer: shear heating
4) Extrusion: viscous flow and cooling
5) Hydrodynamic pressure

The solution is:

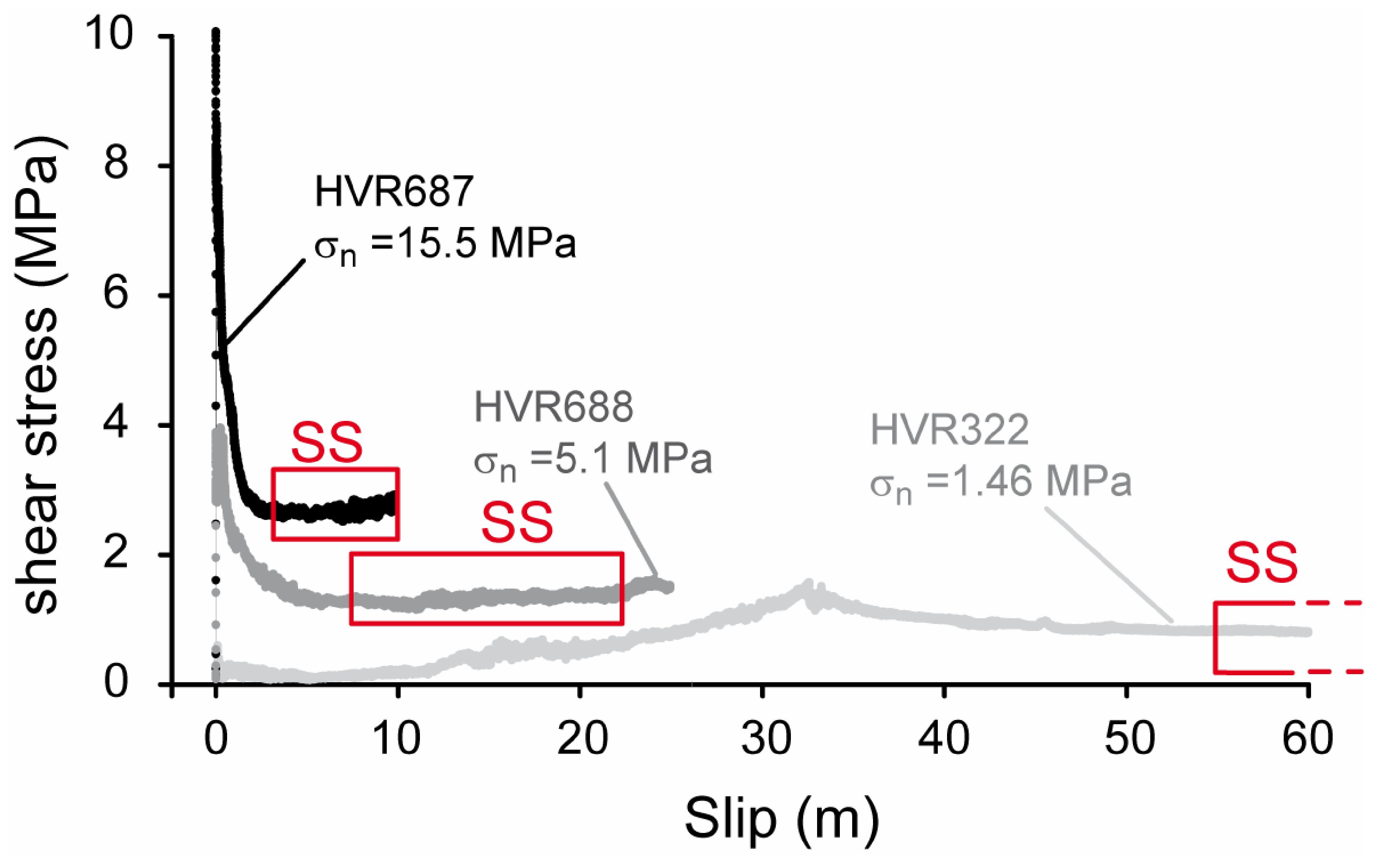
$$\tau_{ss} = \Theta^{3/4} \, \sigma_n^{1/4} \sqrt{\frac{\kappa}{R\,V}}$$

Θ	normalizing factor with stress units
κ	thermal diffusivity
R	melt escaping distance
V	slip rate

It should work for lubrication in rock, ice, etc.

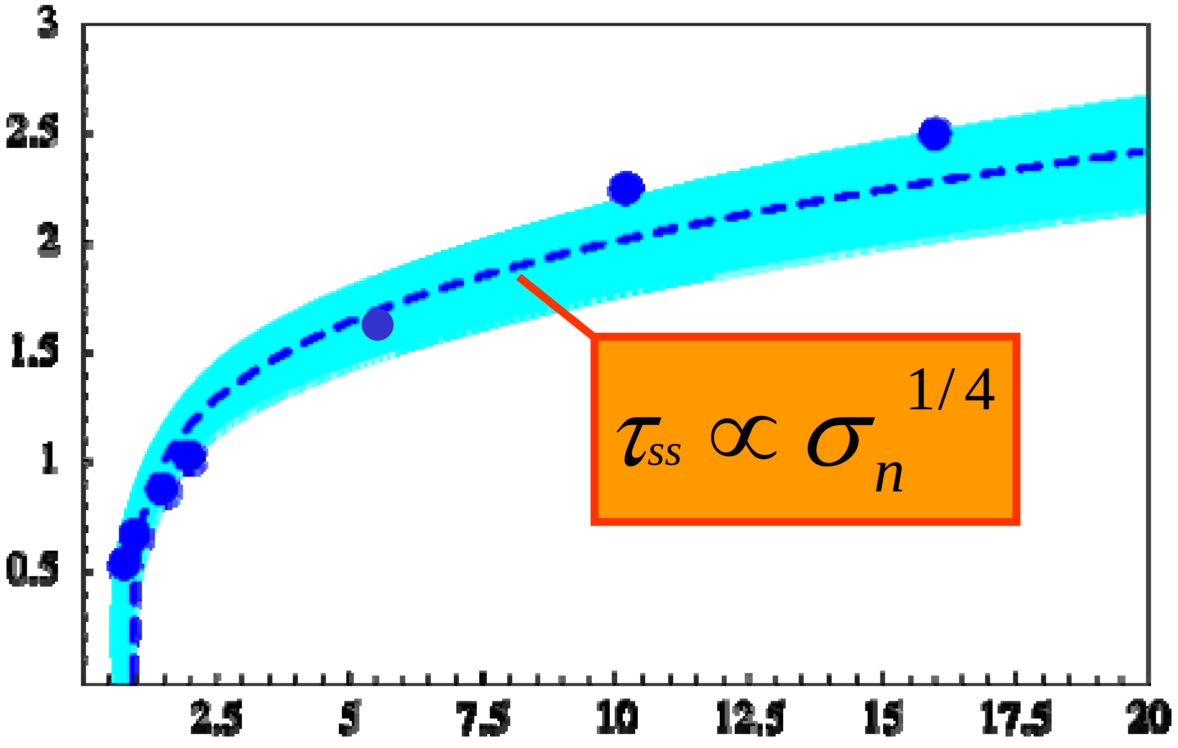
We performed experiments to test the equation (Nielsen et al., JGR, accept.)

By varying the normal stress….



…the solution fits the shear stress dependence with normal stress.

$$\tau_{ss} = \Theta^{3/4}\,\boxed{\sigma_n^{1/4}}\sqrt{\frac{\kappa}{R\,V}}$$

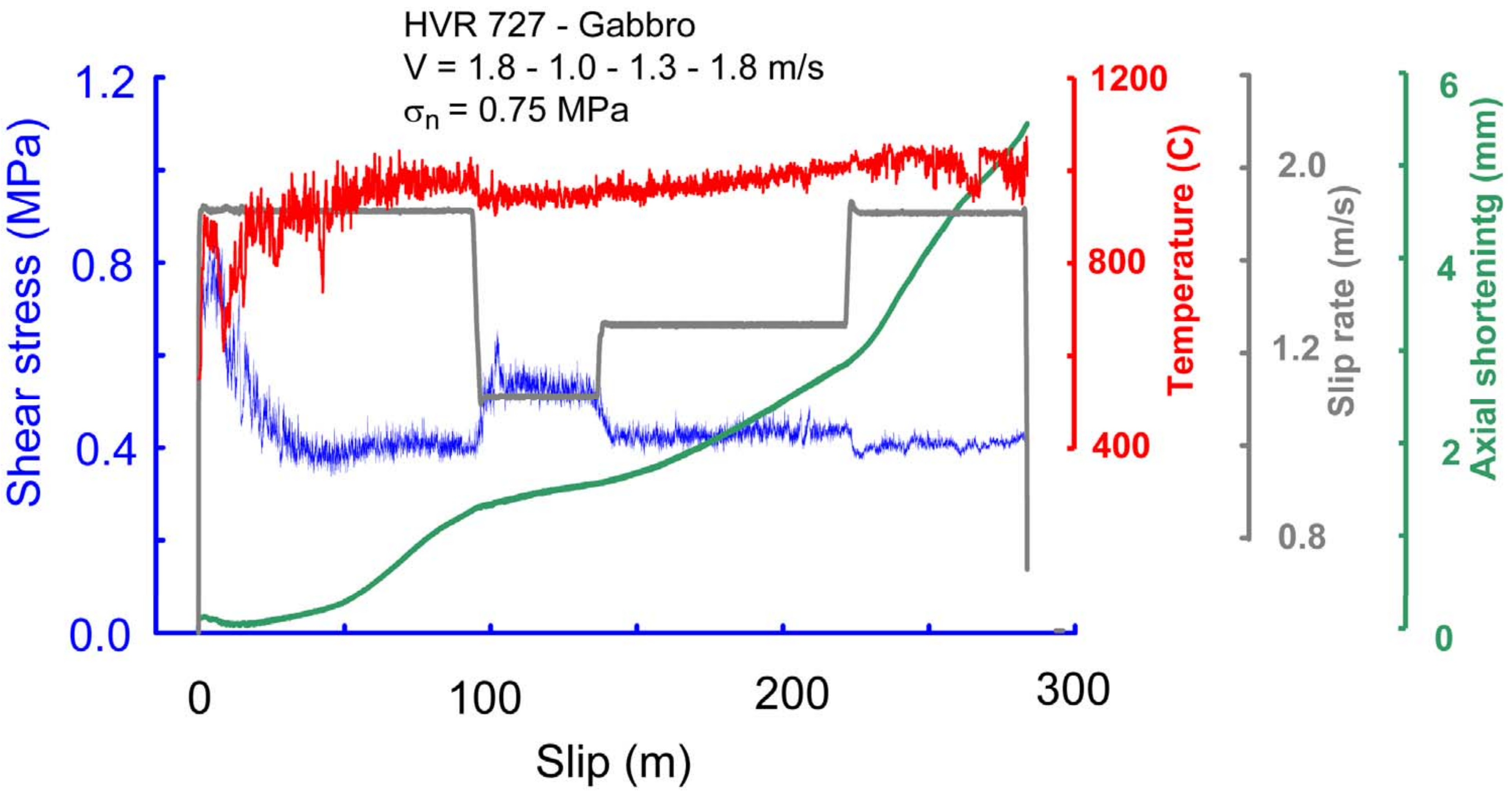


$\tau_{ss} \propto \sigma_n^{1/4}$

Steady state shear stress (MPa)

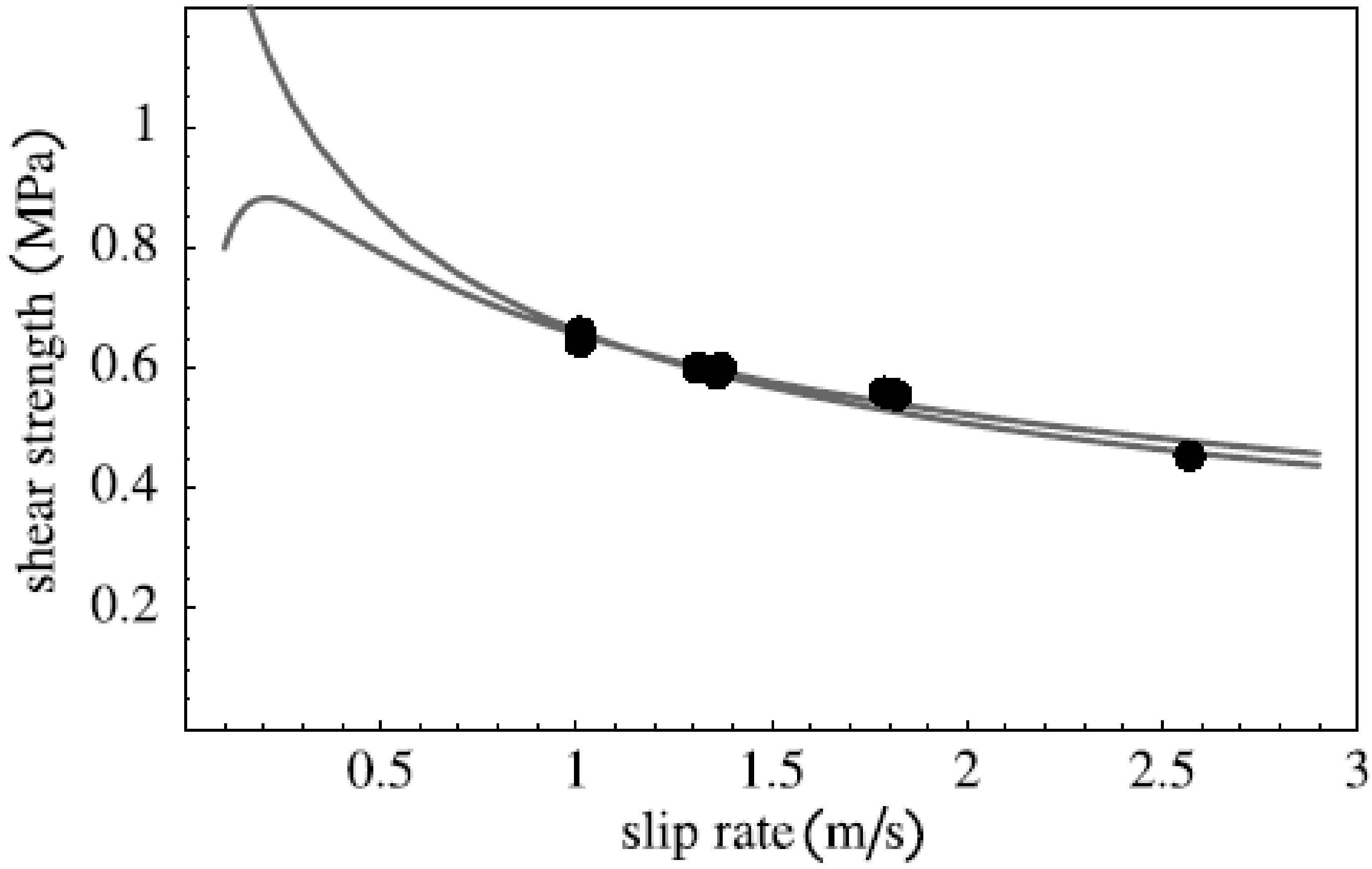
Normal stress (MPa)

By varying the slip rate V….



..the solution fits the shear stress dependence with slip rate.

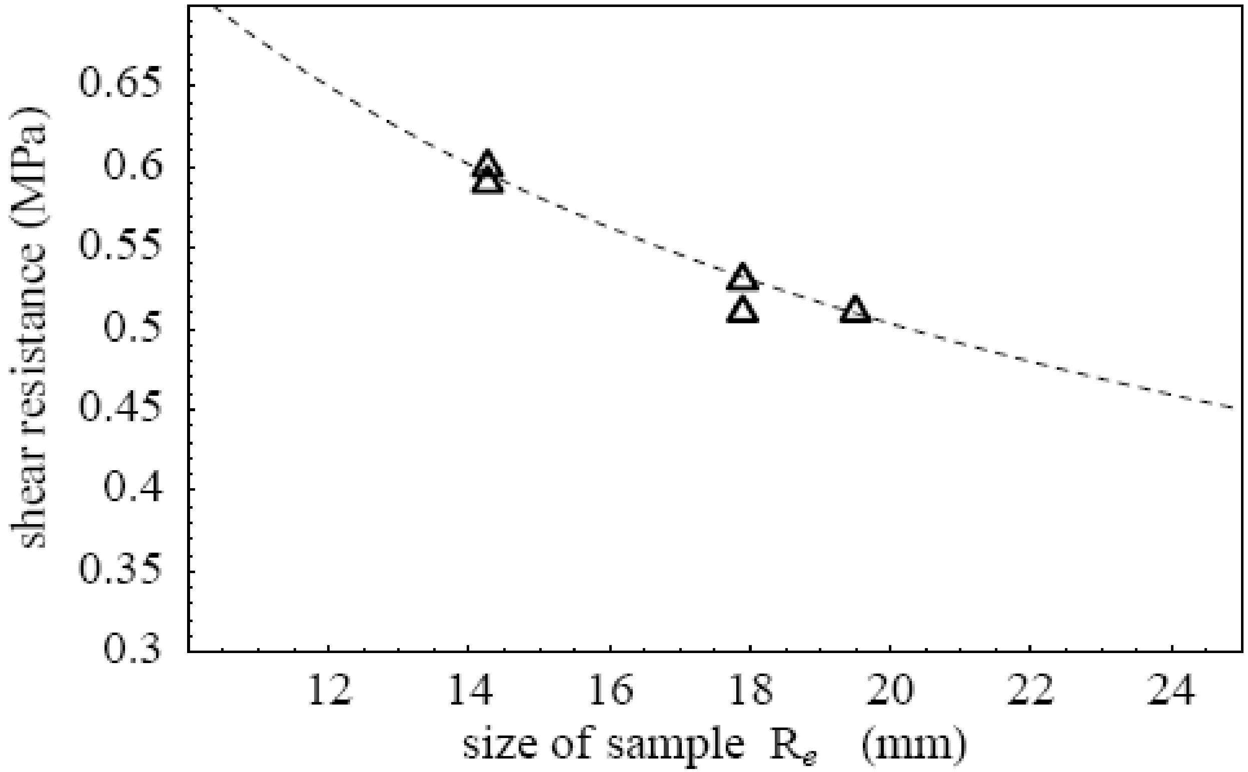
$$\tau_{ss} = \Theta^{3/4}\ \sigma_n^{1/4}\ \sqrt{\frac{\kappa}{R\,V}}$$



By varying the sample size (i.e., melt escaping dist.)

… the solution fits the shear stress dependence with the melt escaping distance.

$$\tau_{ss} = \Theta^{3/4}\ \sigma_n^{1/4}\ \sqrt{\frac{\kappa}{RV}}$$



$$\tau_{ss} = \Theta^{3/4}\ \sigma_n^{1/4}\ \sqrt{\frac{\kappa}{R\,V}}$$

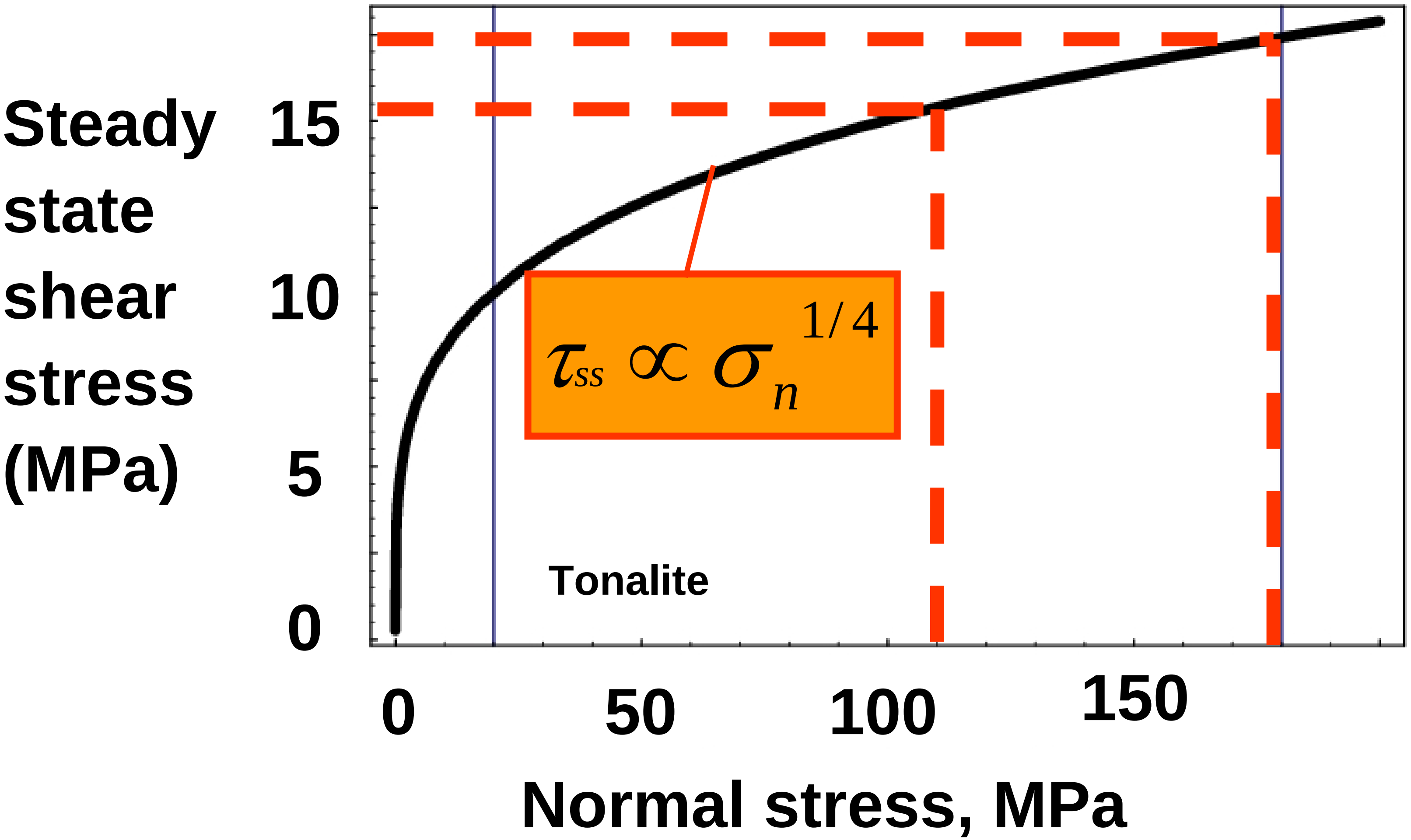
It seems that the solution for melt lubrication works.

Let’s apply the Eq. to natural conditions

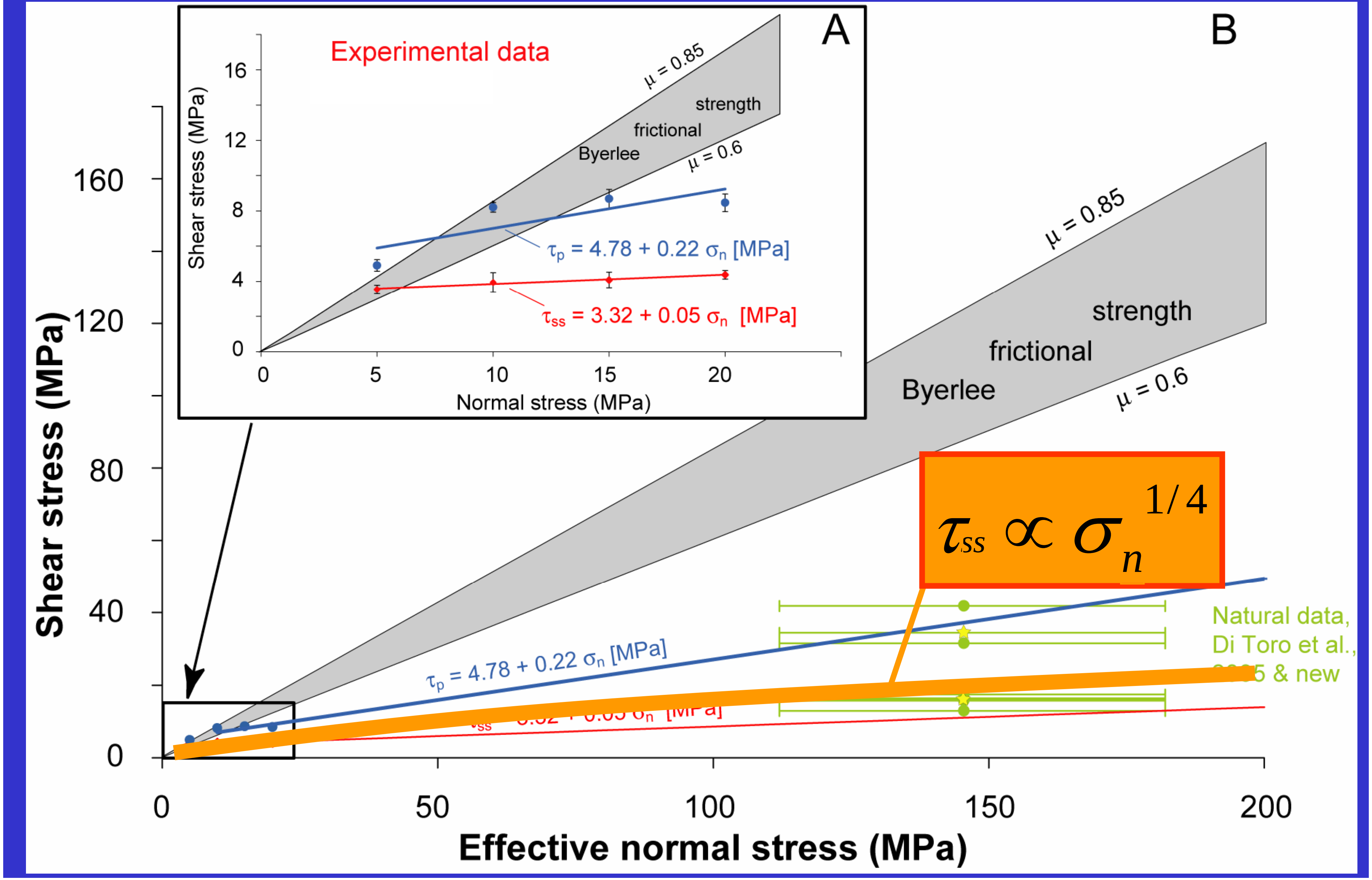
Estimate for τ_{ss} for the 30 Ma GLF EQs ~ **16 MPa**

τ_{ss} ~ 15-17.5 MPa

For σ_n ~150 MPa and *V* = 1 m/s



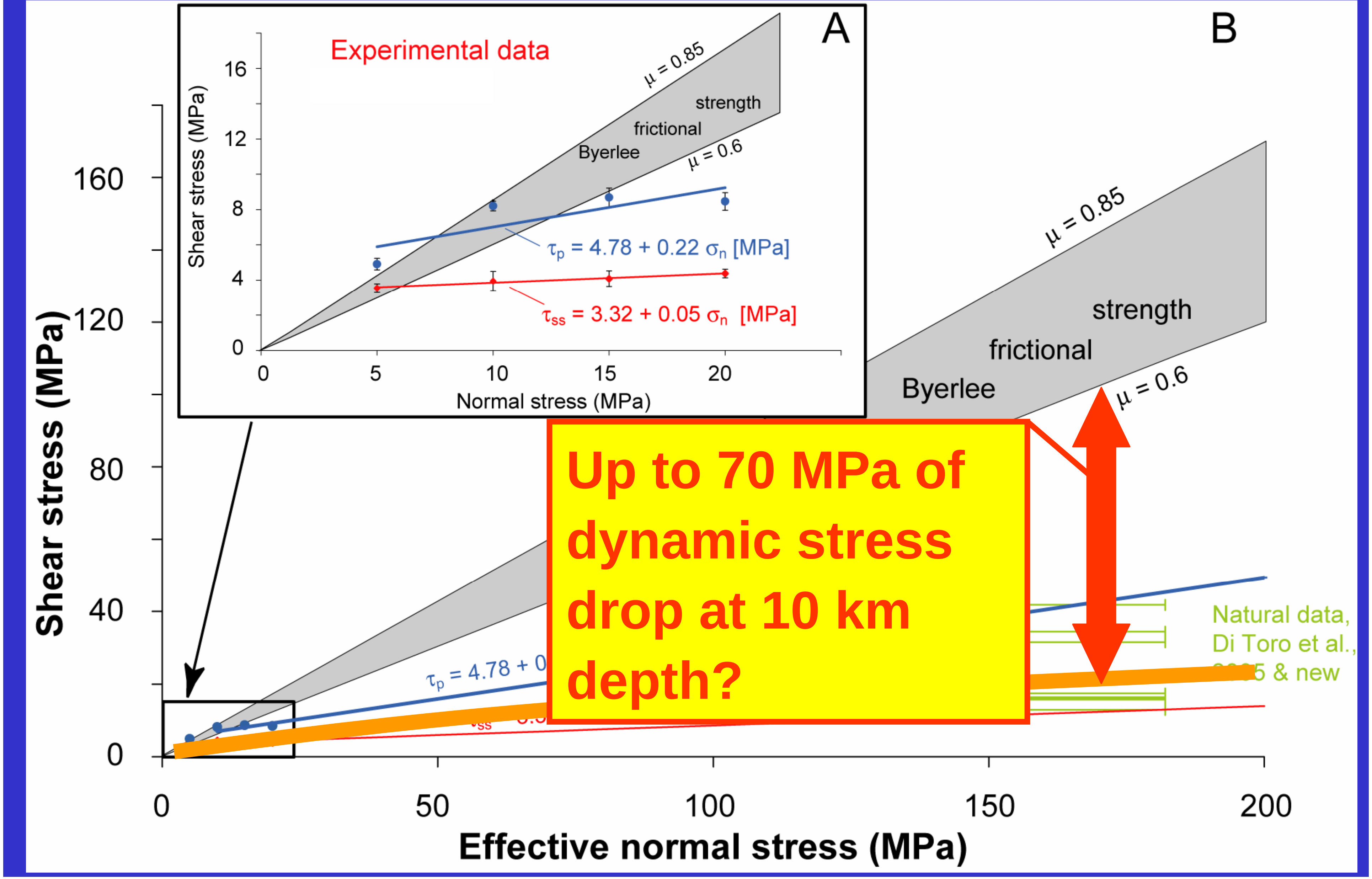
Melt lubrication in experiments, nature and theory



$$\tau_{ss} \propto \sigma_n^{1/4}$$

…..problems….

Large dynamic stress drops



Up to 70 MPa of dynamic stress drop at 10 km depth?

But seismic stress drops are expected to be low (< 30 MPa) in the upper crust.

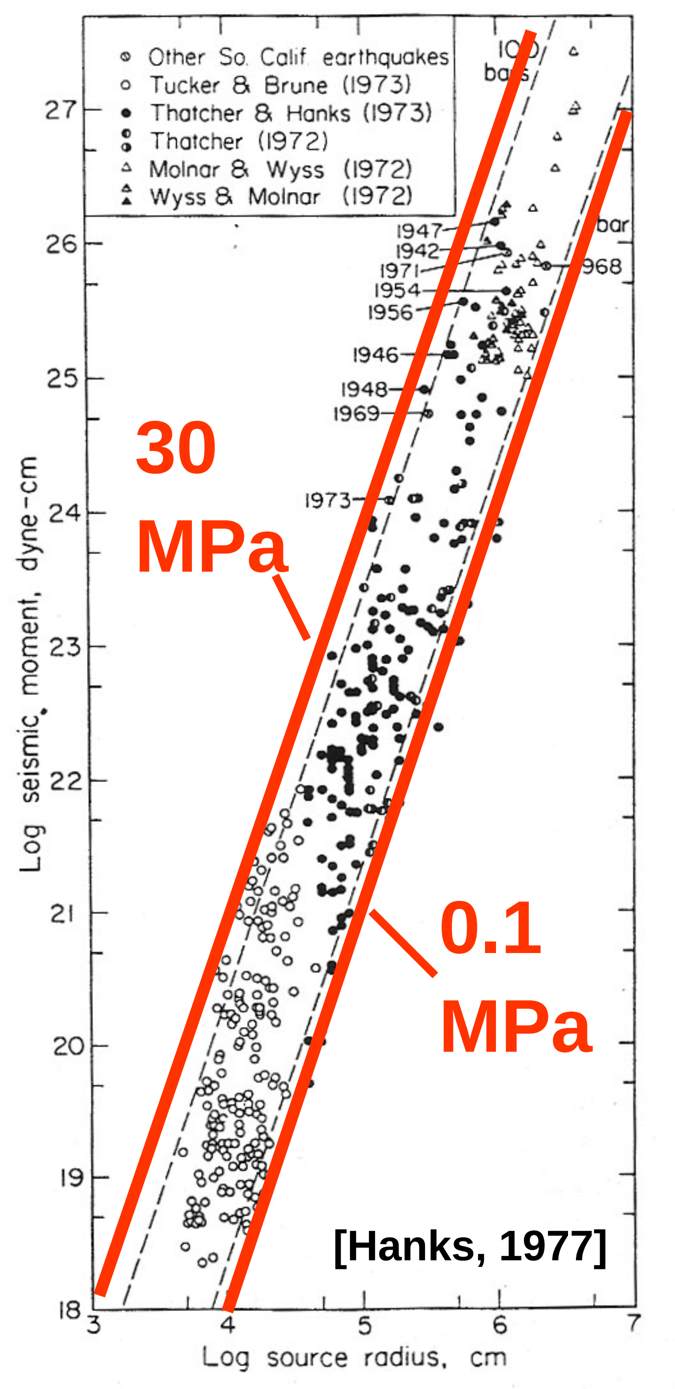
Possible answers:

~~a) Someone is wrong.~~

b) Dynamic stress drops ≠ static stress drops.

c) Fault roughness

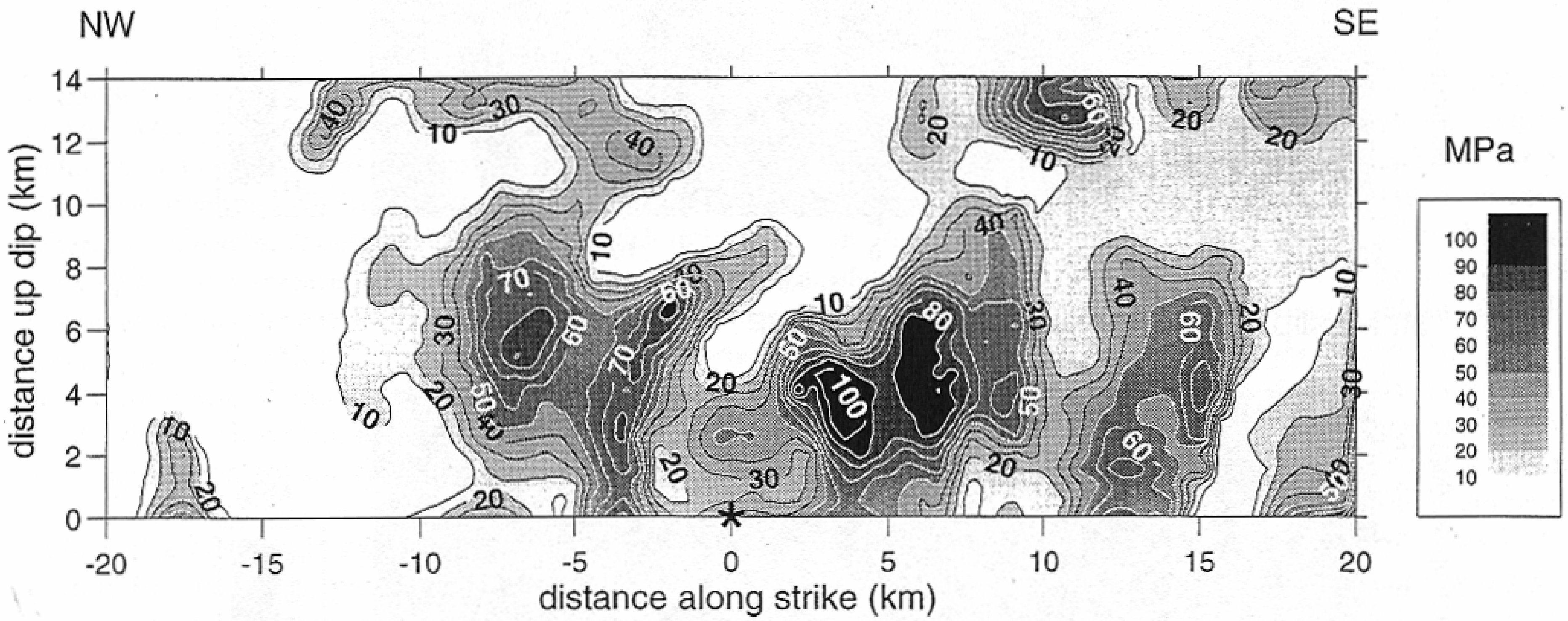
d) Shear stress dependence with slip rate.



[Hanks, 1977]

b) Dynamic stress drops ≠ static stress drops.

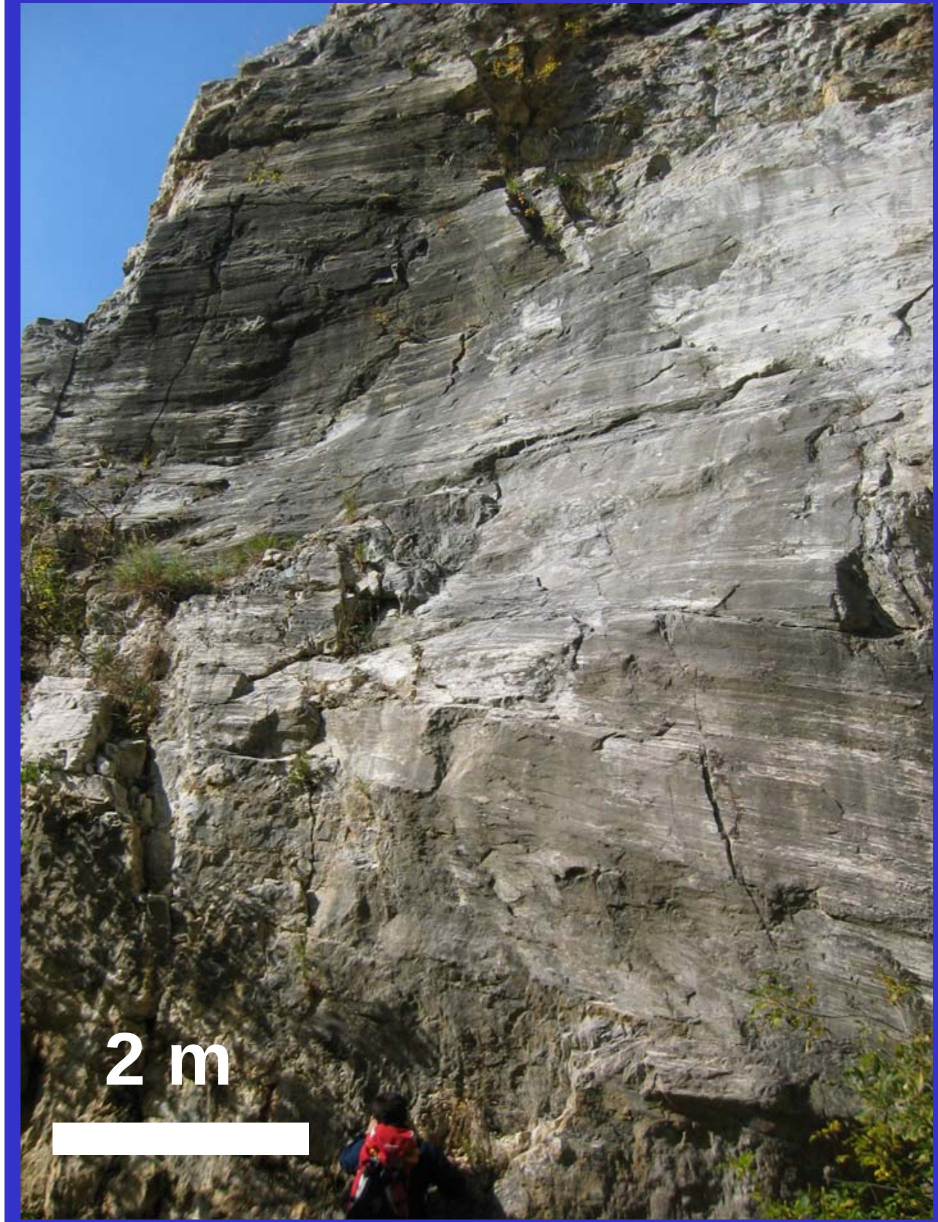
Bouchon (1997) estimated local dynamic stress drop as large as 100 MPa during the Loma Prieta (SAF) earthquake 1989, $M_L = 6.9$



dynamic stress drop

[Bouchon, JGR, 1997]

c) Fault roughness

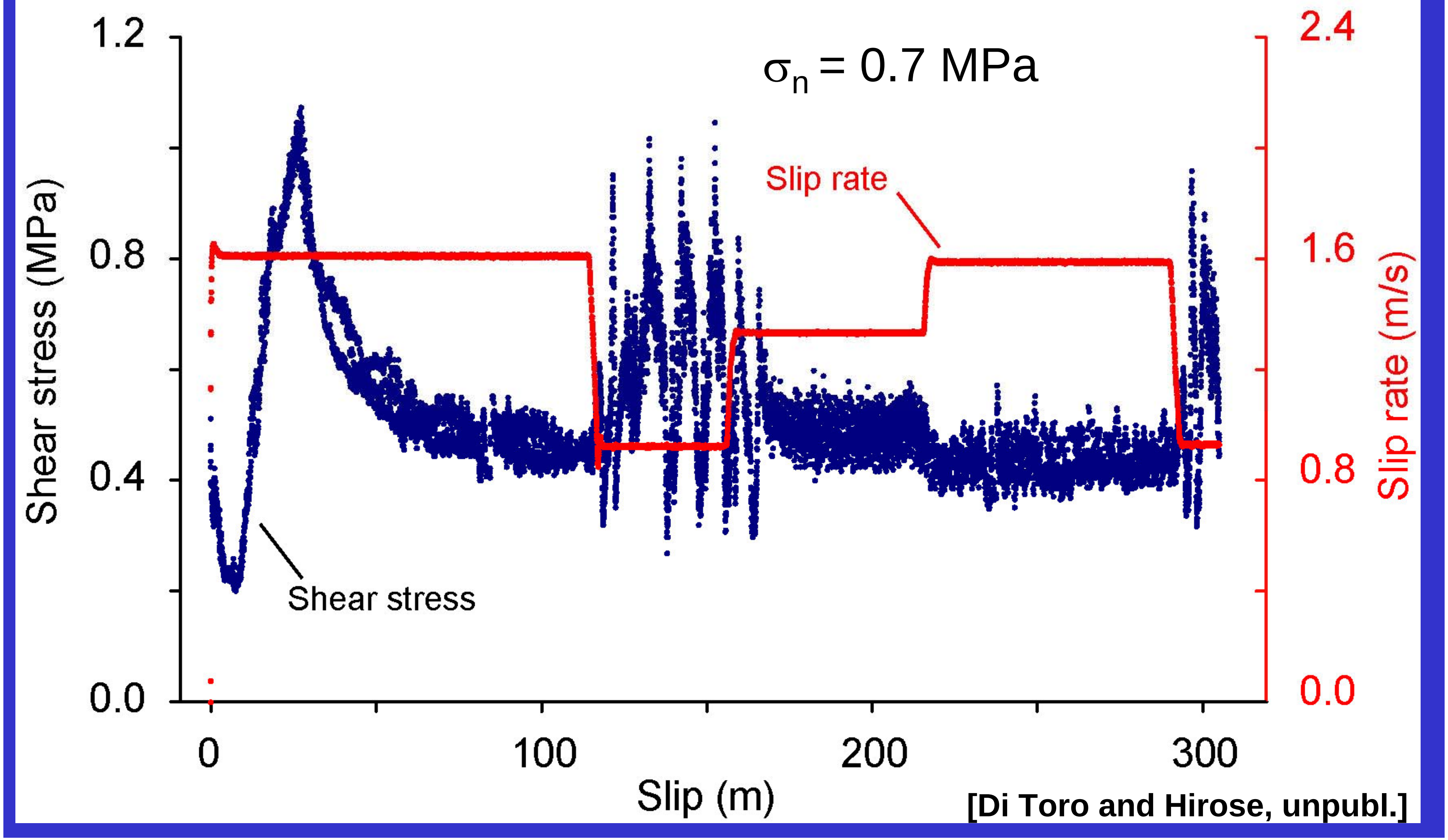


Natural faults are not as smooth as experimental sliding surfaces.

Bumps impede the smooth sliding typical of HVRFE

d) Shear stress dependence for critical *v*

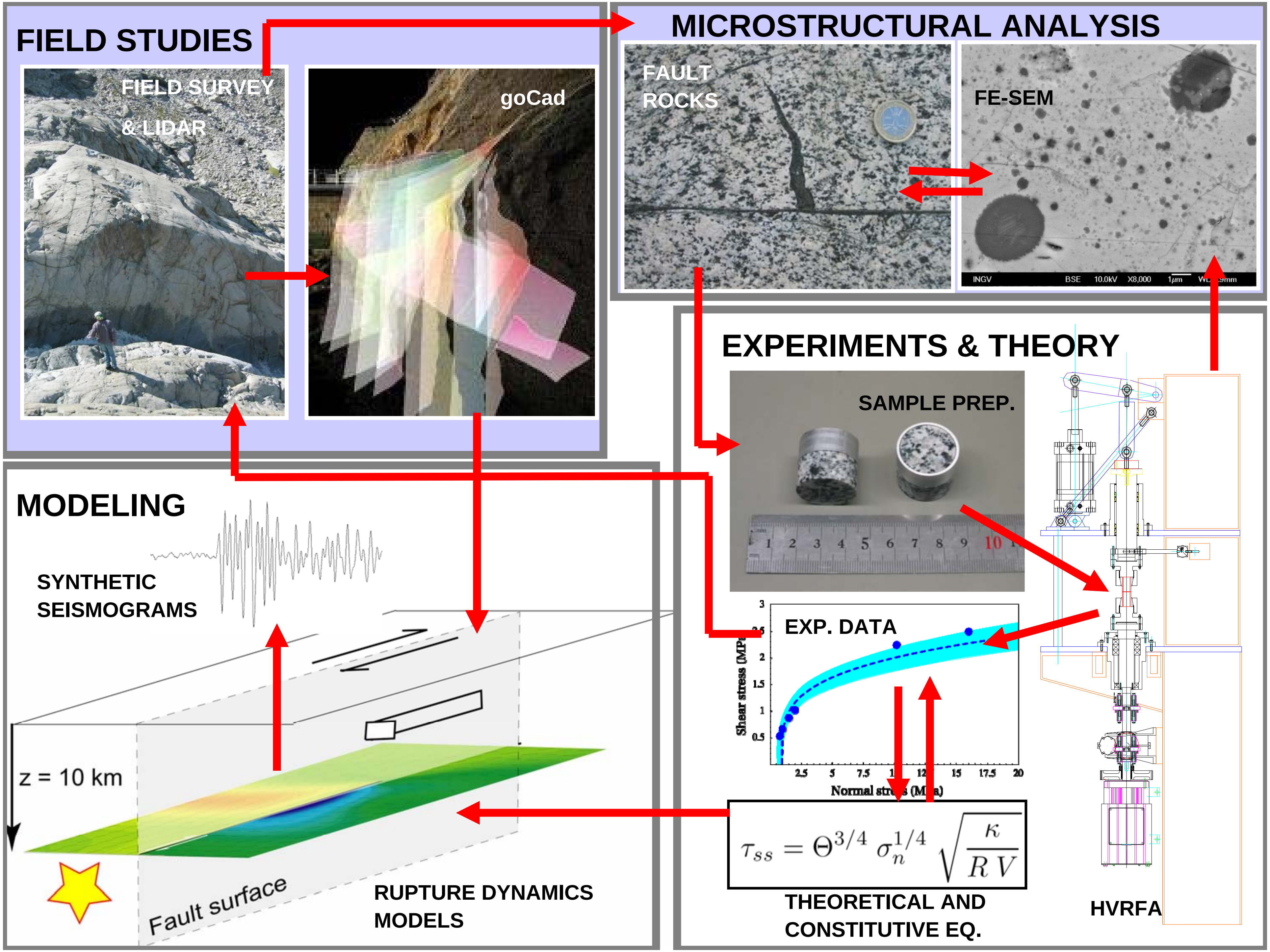
Example for melt lubrication (gabbro)



[Di Toro and Hirose, unpubl.]

To extrapolate experimental results to natural conditions,

maybe we should link….



FIELD STUDIES

FIELD SURVEY & LIDAR

goCad

MICROSTRUCTURAL ANALYSIS

FAULT ROCKS

FE-SEM

EXPERIMENTS & THEORY

SAMPLE PREP.

EXP. DATA

$$\tau_{ss} = \Theta^{3/4}\,\sigma_n^{1/4}\sqrt{\frac{\kappa}{R\,V}}$$

THEORETICAL AND CONSTITUTIVE EQ.

HVRFA

MODELING

SYNTHETIC SEISMOGRAMS

RUPTURE DYNAMICS MODELS

Conclusion

1) Melt lubrication may occur in nature.

2) Experiments allow the determination of new rock friction constitutive equations to apply to EQ mechanics.

3) Extrapolation of experimentally-derived results to dynamic rupture models is not trivial.

Outline

1) A natural lab of a seismogenic source

2) Earthquake rupture dynamics

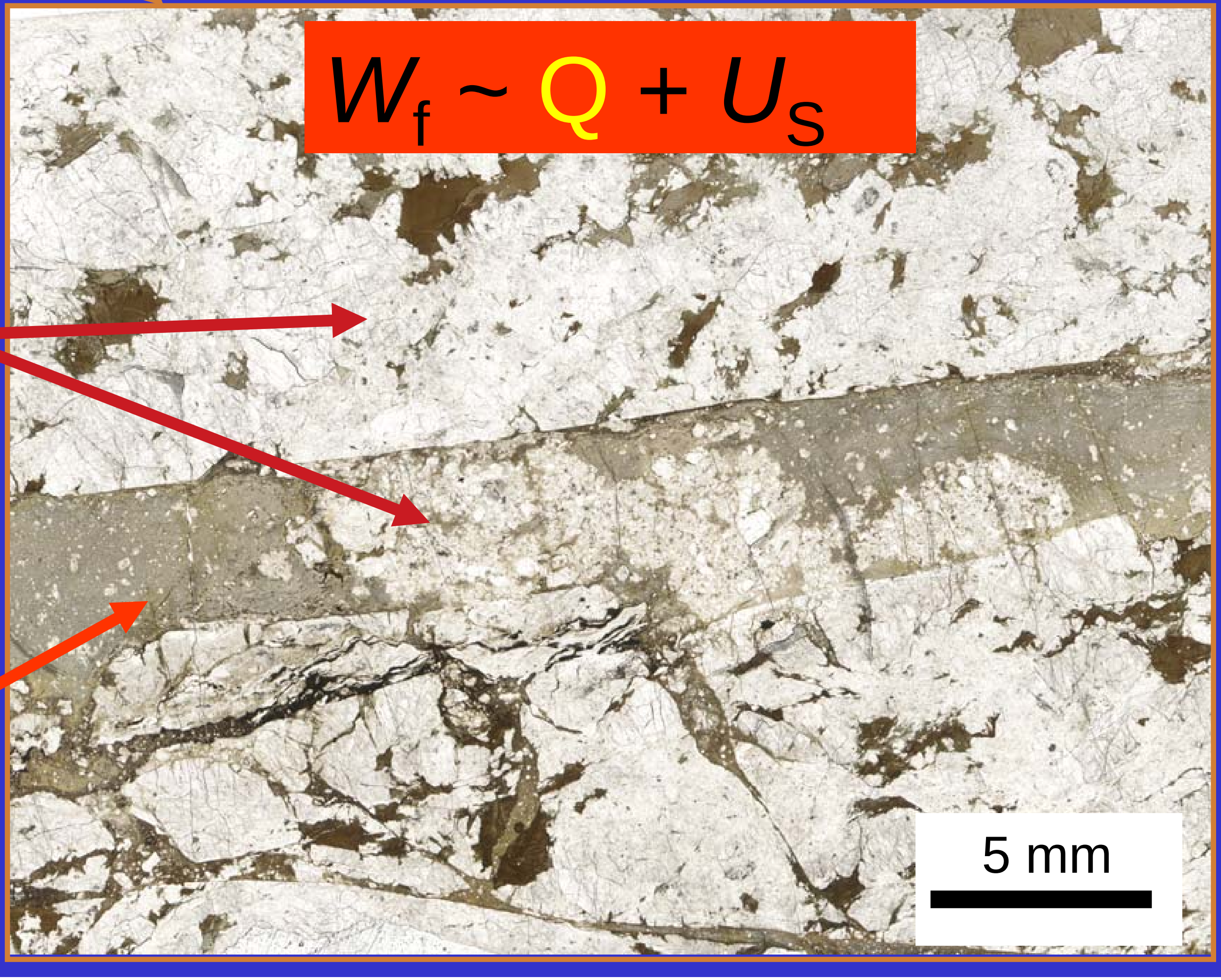
3) Fault strength during seismic slip

4) Earthquake energy budgets

Frictional work W_f is partitioned in (Kostrov & Das, 1988):

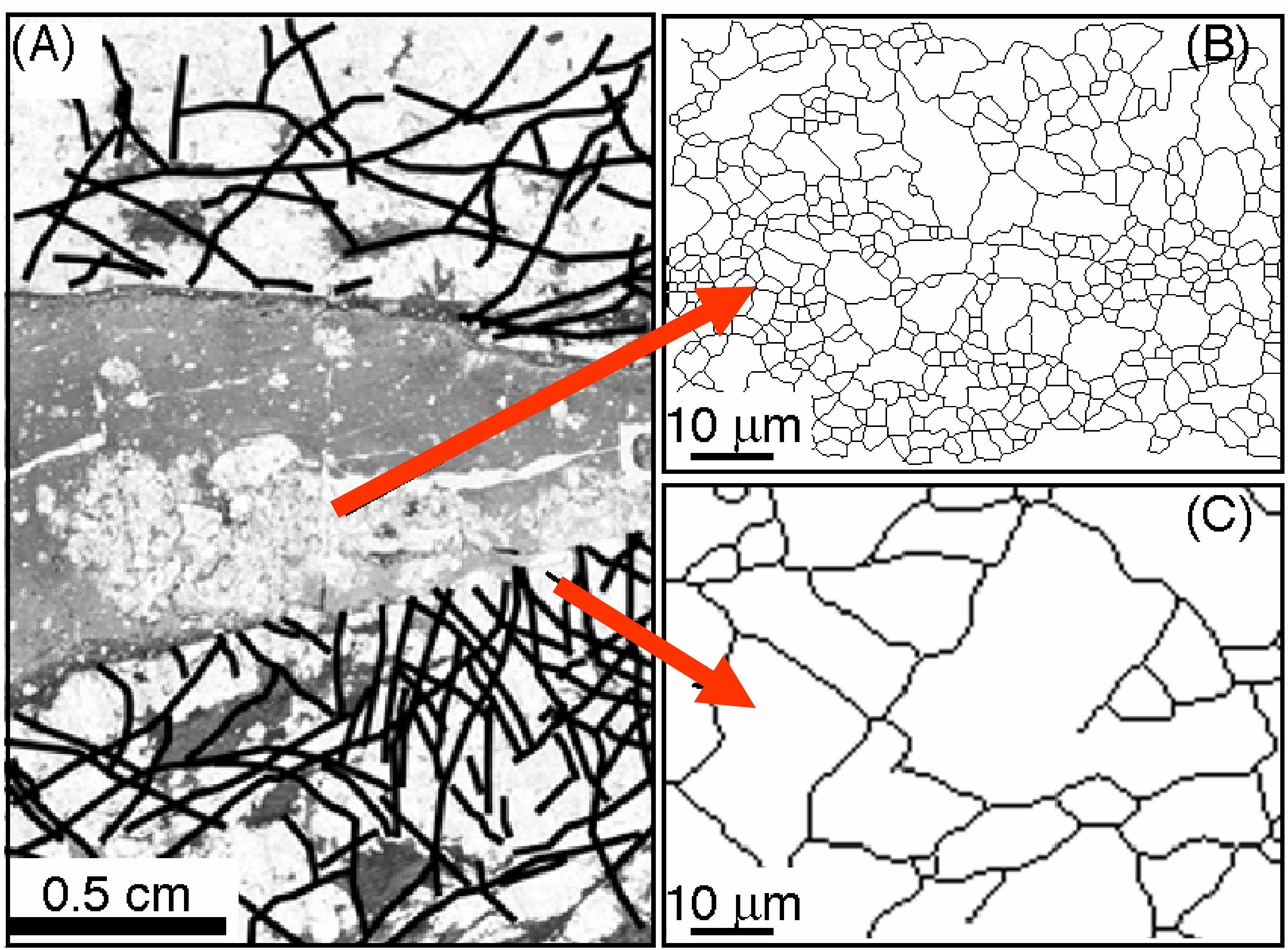
Surface energy
U_s: fracturing in the damage and in the slipping zone

Heat Q:
heating and melting



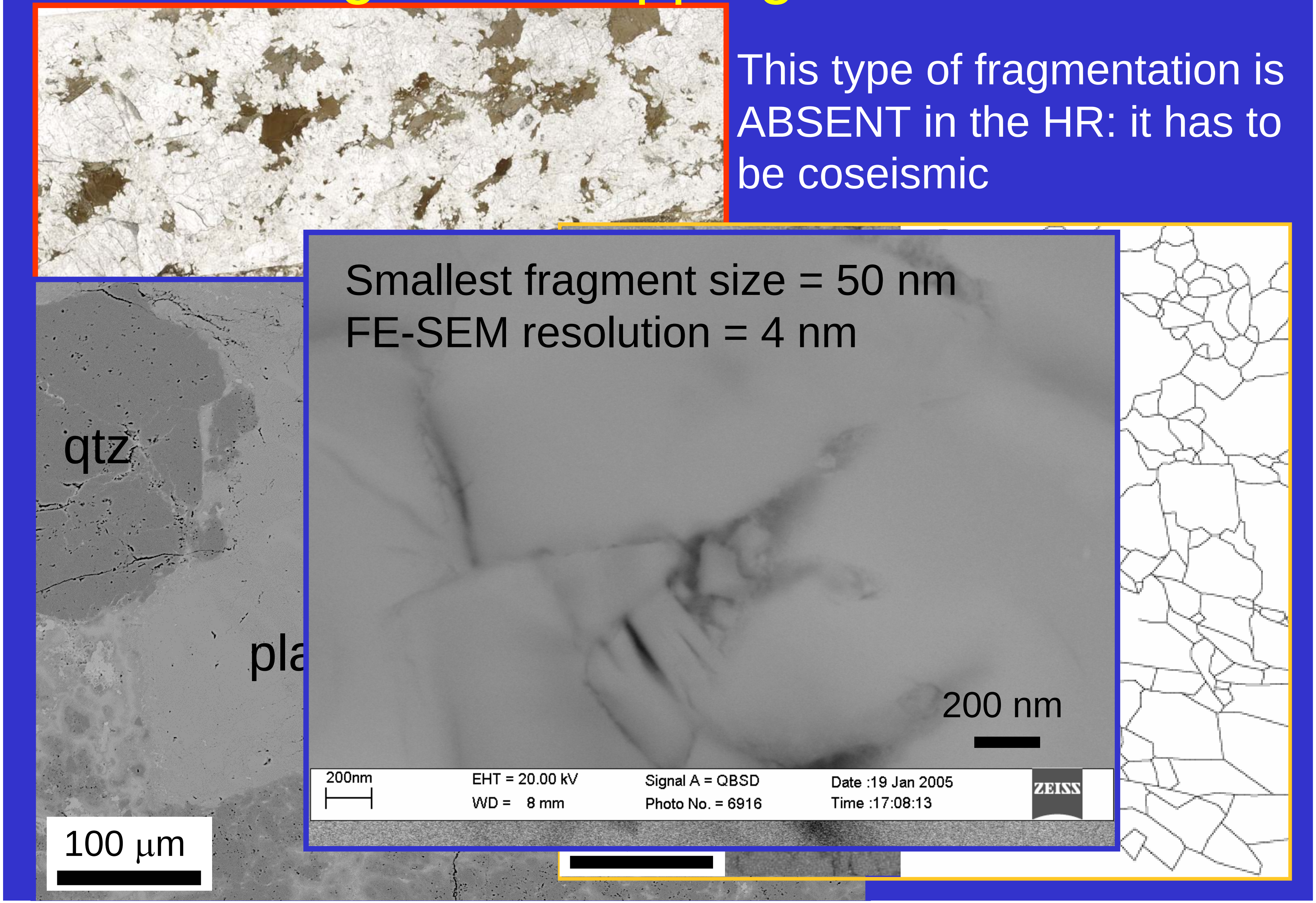
$$W_f \sim Q + U_S$$

Surface density in the damage zone is negligible compared to that in the slipping zone



Fracturing in the slipping zone

This type of fragmentation is ABSENT in the HR: it has to be coseismic



Smallest fragment size = 50 nm
FE-SEM resolution = 4 nm

Estimate of surface energy U_S

(Pittarello et al., submitted)

From Chester et al. (Nature, 2005)

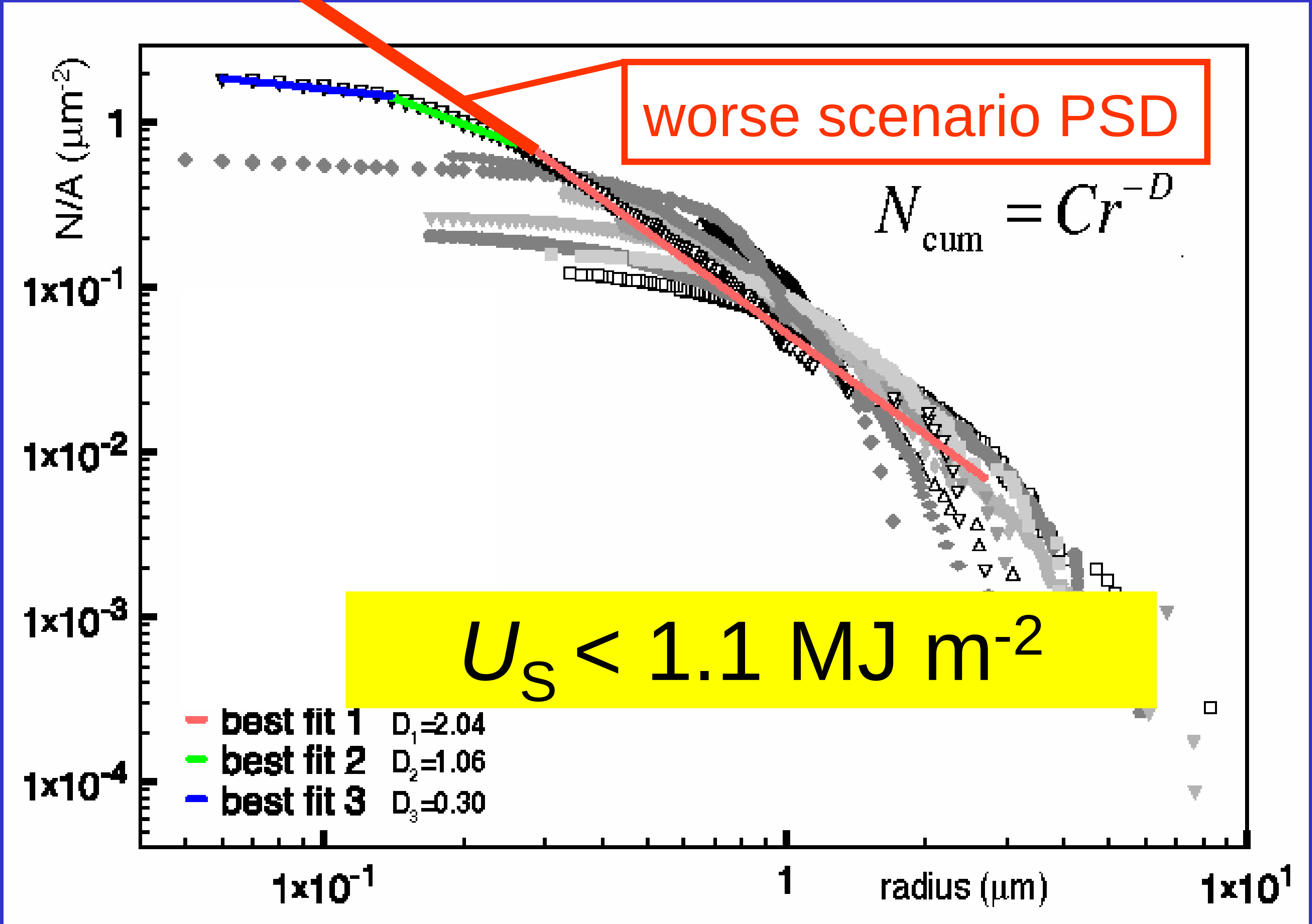
$$U_S \sim A_{SZ}\,\gamma_{max} \quad [\mathrm{J\ m^{-2}}]$$

A_{SZ} = new surface density in the **slipping zone**

γ_{max}= max. specific surface energy (10 J m^{-2} ,Bruce and Walsh, 1962)

PSD & estimate of U_S in slipping zone

Sph. shape and integrating above the fault thickn. (5.9 mm)



worse scenario PSD

$$N_{\mathrm{cum}} = Cr^{-D}$$

$U_S < 1.1$ MJ m^{-2}

Estimate of heat Q

$$Q = [(1-\phi)\, H + c_p\, (T_m - T_{hr})]\, \rho\, t \quad [\mathrm{J\ m^{-2}}]$$

ϕ	clast content in PT (20% → $\phi = 0.2$)
H	latent heat of fusion ($3.3\ 10^5$ J $\mathrm{kg^{-1}}$)
c_p	specific heat (1180 J $\mathrm{kg^{-1}\ K^{-1}}$)
T_m	melt temp. (~ 1450 °C)
T_{hr}	host rock temp.(~250 °C)
ρ	rock density (2700 kg $\mathrm{m^{-3}}$)
t	PT average fault thickness (5.9 mm)

$$Q \sim 27\ \mathrm{MJ\ m^{-2}}$$

$U_S < 1.1\ \mathrm{MJ\ m^{-2}}$

$Q \sim 27\ \mathrm{MJ\ m^{-2}}$

Most of the frictional work is exchanged as heat at 10 km depth.

Geological vs Seismological energy budget

At a point of a fault

(Scholz, 1990):

$W_f = Q + U_S + W_g + E_S$

W_f = mechanical work done in faulting

Q = heat ⟷

U_s = surface energy ⟷

E_s = radiated energy

W_g= work against gravity

(Kanamori, 2004):

$\Delta W = E_H + E_G + E_R$

ΔW = elastic strain energy released in EQs

E_H = thermal energy

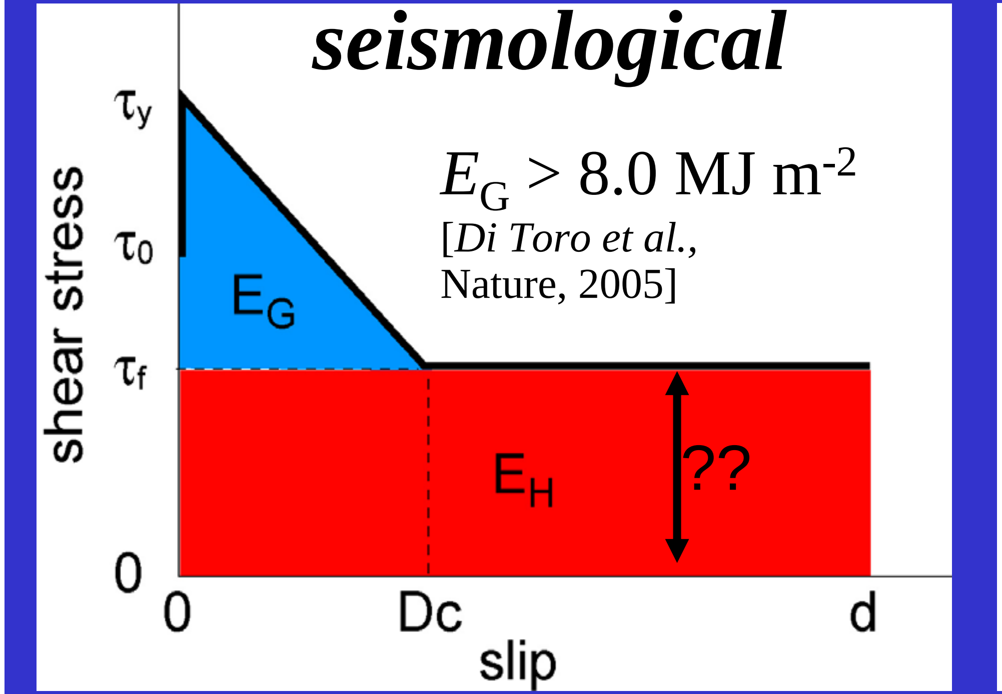
E_G = fracture energy

E_R = radiated energy

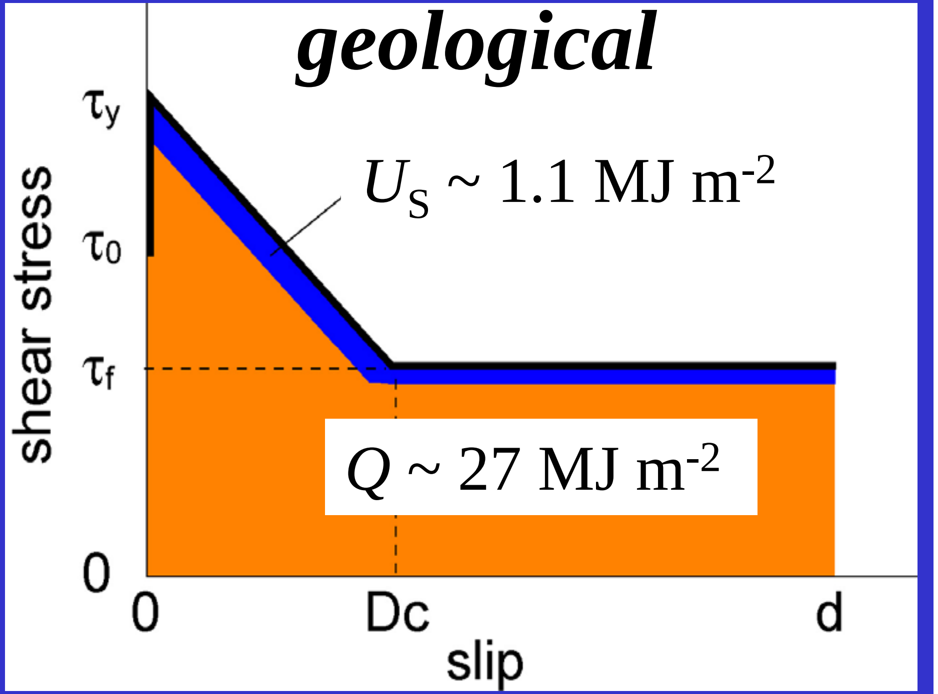
so…

Is there a relationship?

Seismological and geological energy budget



$E_G > 8.0$ MJ m^{-2}
[*Di Toro et al.*, Nature, 2005]



$U_S \sim 1.1$ MJ m^{-2}

$Q \sim 27$ MJ m^{-2}

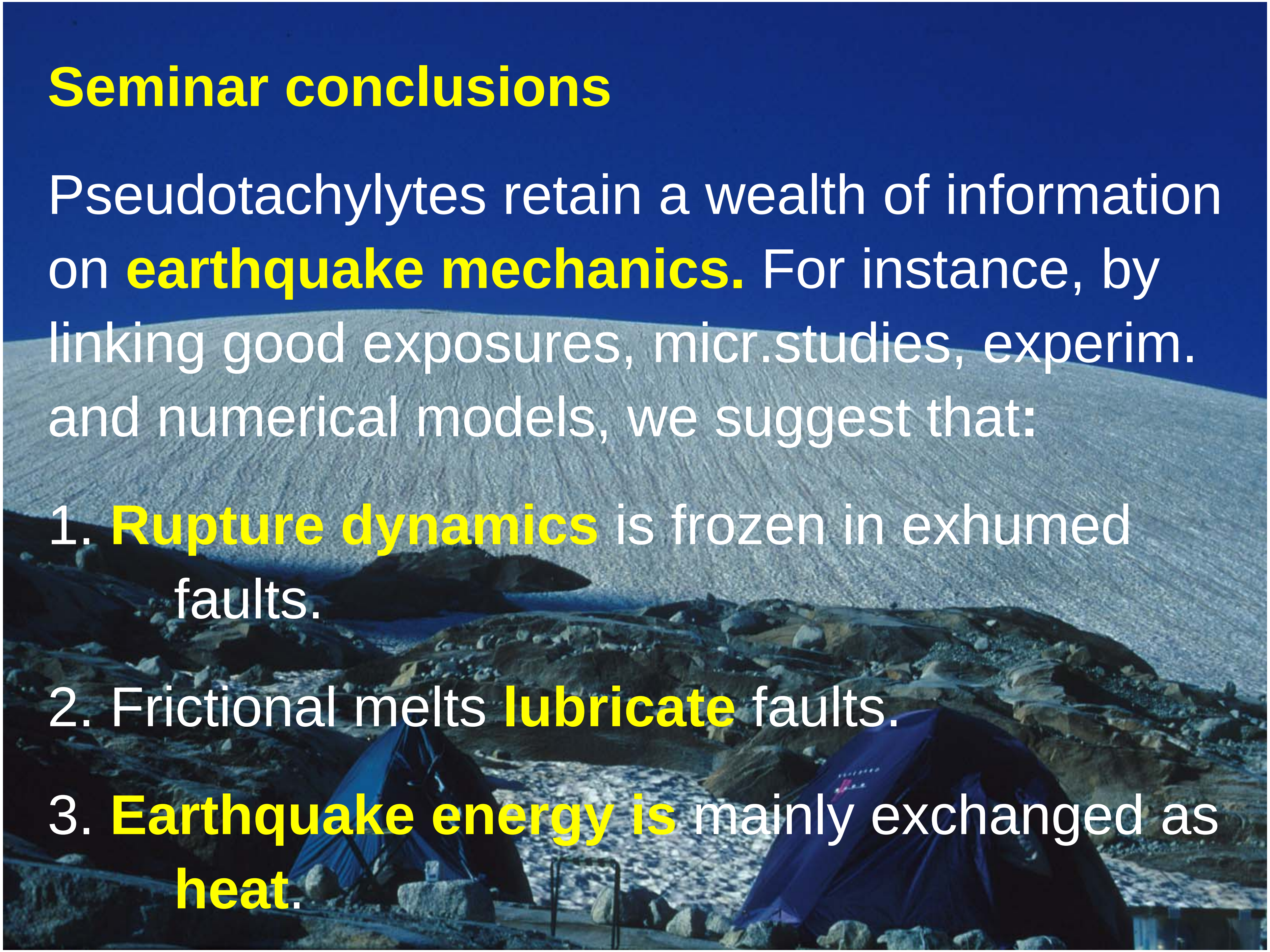
$$U_S \neq E_G \qquad Q \neq E_H$$

and $Q \sim E_G + E_H$

Conclusion

1) Most of the frictional work is exchanged as heat at 10 km depth.

2) Seismological and geologically-based energy budgets cannot be compared.



Seminar conclusions

Pseudotachylytes retain a wealth of information on **earthquake mechanics.** For instance, by linking good exposures, micr.studies, experim. and numerical models, we suggest that**:**

1. **Rupture dynamics** is frozen in exhumed faults.

2. Frictional melts **lubricate** faults.

3. **Earthquake energy is** mainly exchanged as **heat**.

“Go my sons, ***buy stout shoes, climb the mountains****, search the valleys, the deserts, the sea shores, and the deep recess of the earth. Look for the various kinds of minerals, note their characters and mark their origin.*

Lastly, buy coal, ***build furnaces****, observe and* ***experiment without ceasing****, for in this way and in no other will you arrive at knowledge of the nature and properties of things”.*

*Marco Aurelio Severino, naturalist (****1580-1656****)*

Are these experimental data good?

Al melts at 660 ^{o}C, most minerals T > 1100 ^{o}C.

Al sustains the rock only at the beginning of sliding.

Slip rate and shear stress determination in solid specimens: equivalent slip velocity

$$v_e = \frac{4\pi \; R \, r_2}{3}$$

$$\tau = \frac{3 \; M}{2\pi \; r_2^3}$$

R = rotary speed

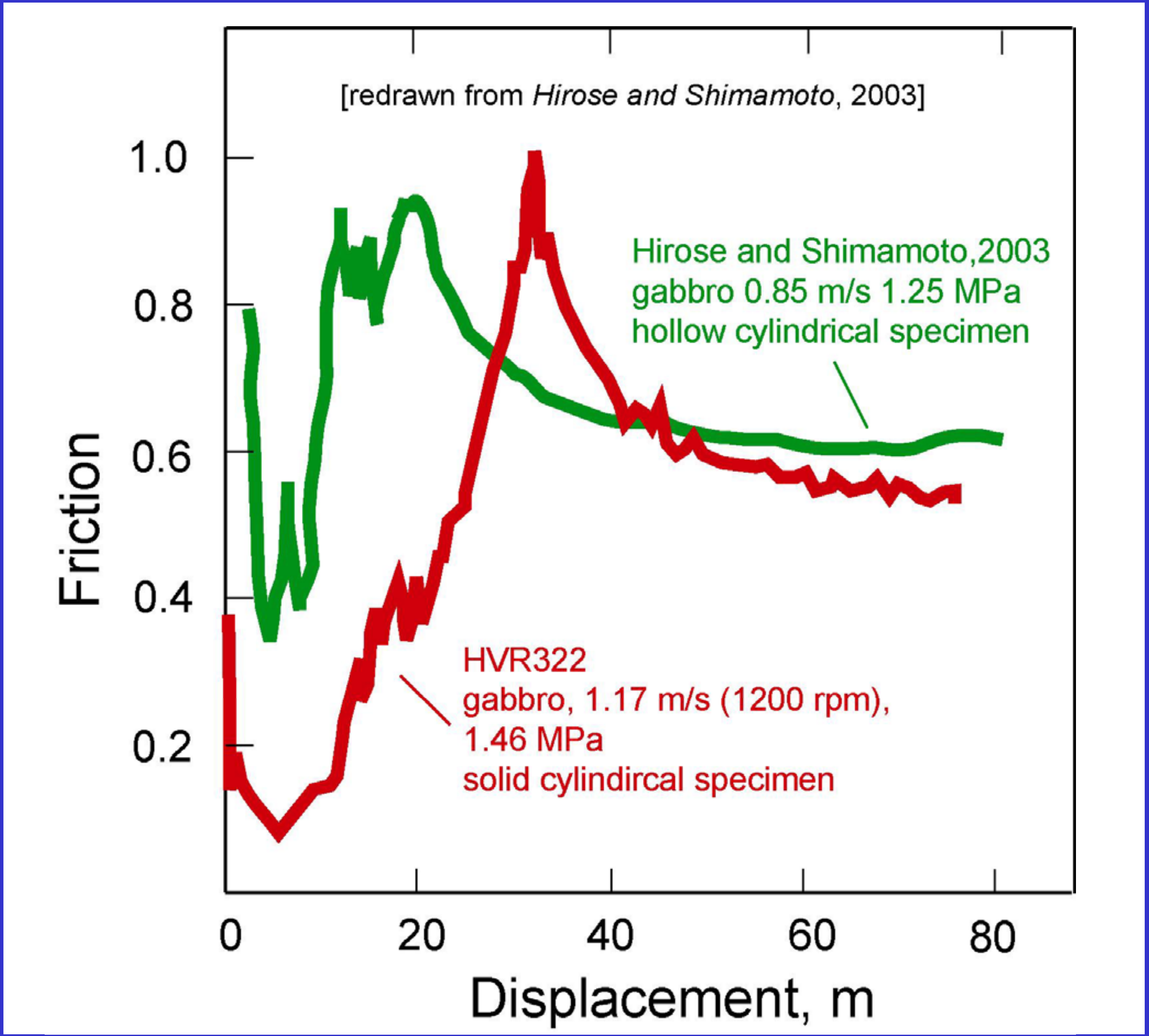
r_2 = outer sample radius

M = torque

Cylindrical and hollow shaped specimens yield very similar results.

As aluminum melts at 650 ^{o}C, the external aluminum outer ring sustains the sample during initial sliding only.

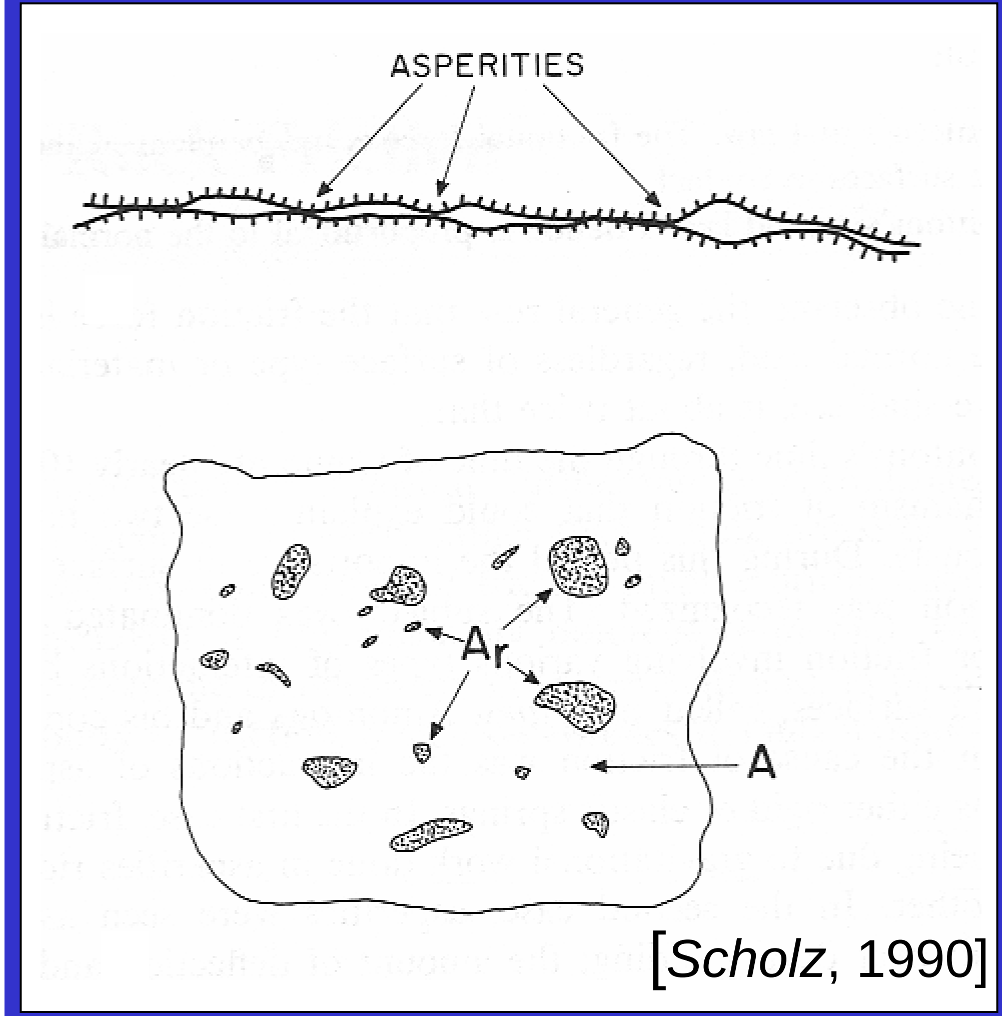
Are experimental data good?



Solid vs. ring shaped samples: similar behavior

Flash heating at the asperity contacts

[*Archard*, 1958/59]



[*Scholz*, 1990]

$$\Delta T \cong \mu_{ss} \frac{\pi \ r \ p_m}{4K} V$$

r = 10 μm asperity radius

p_m = 8.0 GPa quartz yield press.

K = 3.8 W m^{-1} K^{-1} thermal cond.

$T_{max} \sim 300\ ^{o}C$

Quartz melts at 1713 ^{o}C
[*Richet et al., 1982*]

Main fault rocks [Sibson, 2001]