Friction during earthquakes from rock deformation experiments

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EARTHQUAKE SOURCE PHYSICS ON VARIOUS SCALES

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Questions

For… Mother Nature

- How friction evolves during EQs?
- What we find in faults exhumed from seismogenic depths?

For… the lab

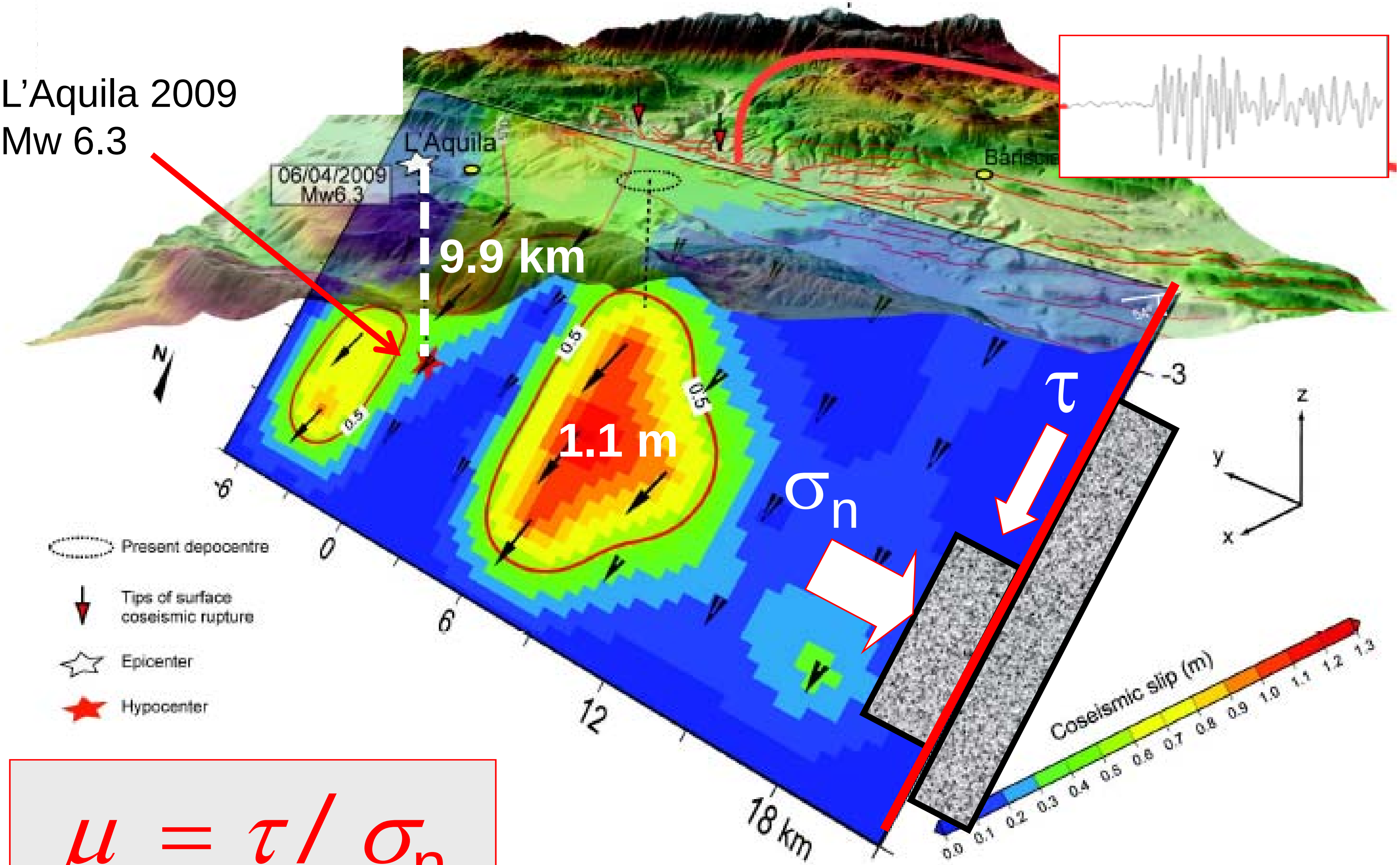
- How friction evolves at seismic slip rates?
- Which coseismic processes are triggered in the lab?
- Can we get a friction constitutive law?

From the lab to Nature...

- Do the processes triggered in the lab occur in nature?
- Are there evidences in nature that faults are weak during EQs?

EQs are due to **slip** on surfaces: **friction** (and fracture) is the key to understand EQs **physics.**

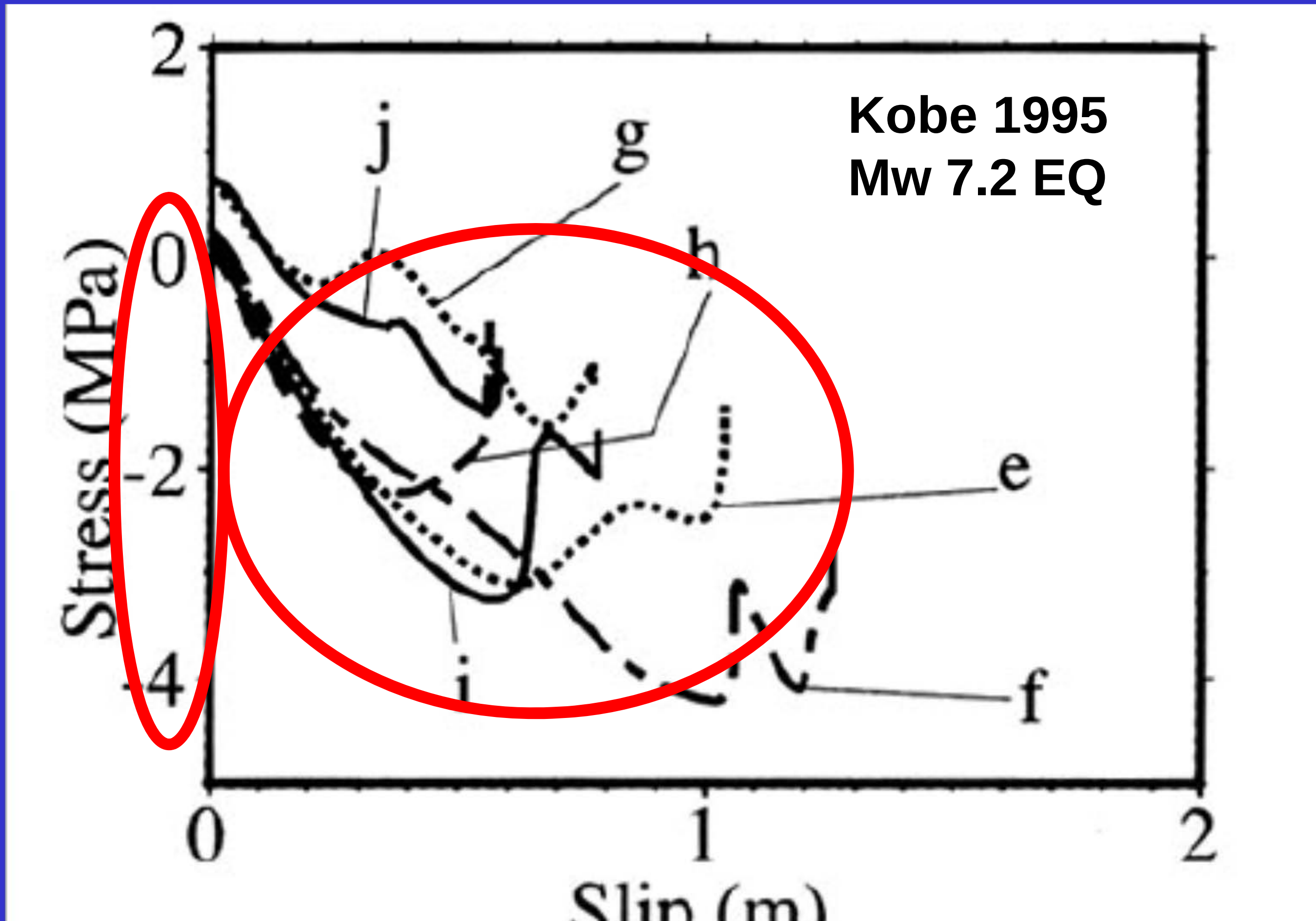
L'Aquila 2009
Mw 6.3



$$\mu = \tau / \sigma_n$$

Courtesy of S. Pucci

How stress evolves with slip during EQs?



Ide & Takeo, JGR 1997

Limitations:

1) Model dependent seismic inversion data.

2) Relative stress values.

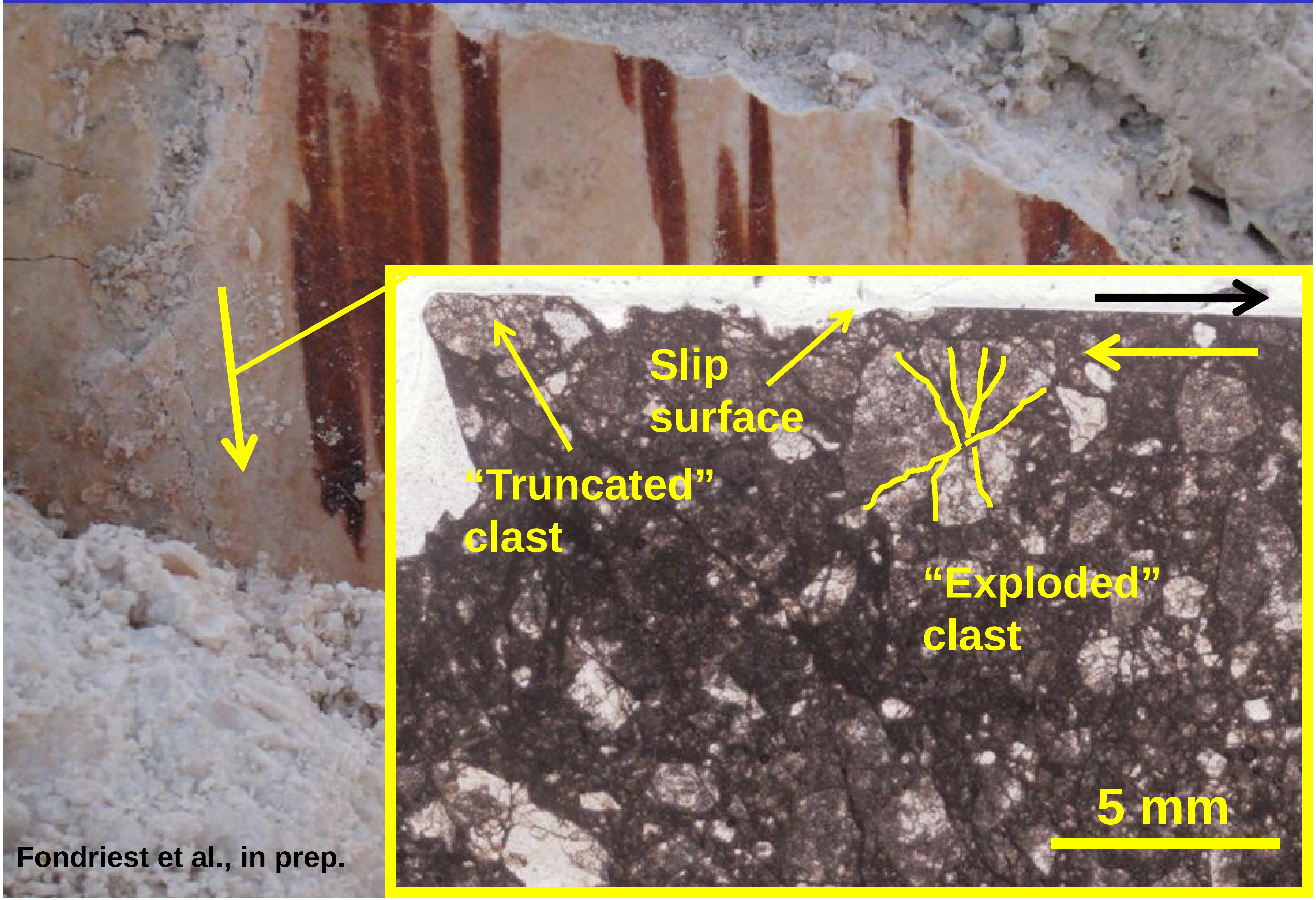
3) Seismic waves do not have the resolution to yield information on the processes activated during seismic slip .

What we find in natural faults exhumed from seismogenic depths? A couple of examples of the effects of extreme localization from the Italian Alps

Western Europe (Italian Touring Club)

The Foiana Fault Zone (exhumed from 2 km depth) cuts carbonate-bearing rocks (dolostones)

Mirror-like surfaces, truncated (and exploded) clasts



The Gole Larghe Fault Zone (exhumed from 9 km depth) cuts granitoid rocks

Pseudotachylytes: “glassy”, flow structures, microlites, etc.

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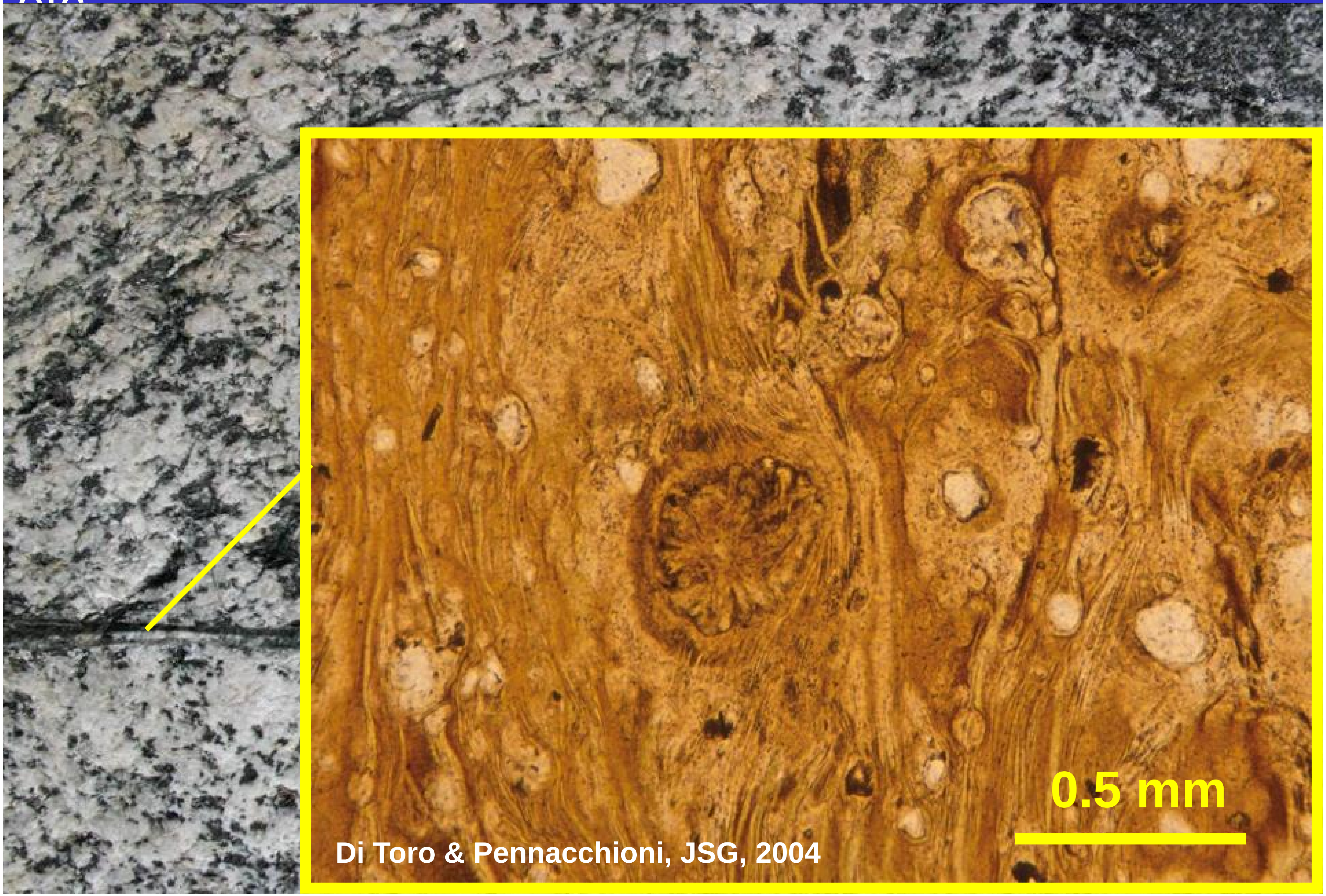

Questions

For… Nature

- How friction evolves during EQs?
- What we find in faults exhumed from seismogenic depths?

For… the lab

- How friction evolves at seismic slip rates?
- Which coseismic processes are triggered in the lab?
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From experiments to nature…

- Do the processes triggered in the lab occur in nature?
- Are there evidences in nature that faults are weak during EQs?

Challenge … reproducing in the lab EQ deformation conditions:

- High slip rates (**0.1-10 m/s**)
- Large displacements (**up to 50 m**)
- High effective normal stresses (**> 50 MPa**)
- Sample confinement (gouge & fluids)
- Data reproducibility
- Velocity or stress control?

HVRFE are performed in **torsion apparatus** (MTS 809 at Padua University).

σ_n < 10 MPa
***v* = 0.001- 400 mm/s**
d = 40 mm
Max torque 1100 Nm

Industrial testing apparatus (metals, fibers, etc.)

Ferri et al., JGR, 2011
Tisato et al., JSG, 2012

and **rotary shears** (HV-1 designed by Shimamoto, 1990)

σ_n < 25 MPa

***v* = 0.1- 2.5 m/s**

d = infinite

Power 7.5 kW

[Hirose, Ph.D. thesis, 2001]

Nov. 2009 SHIVA (Slow to HIgh Velocity Apparatus)

INGV (designed by Italian Team at INGV in Rome)

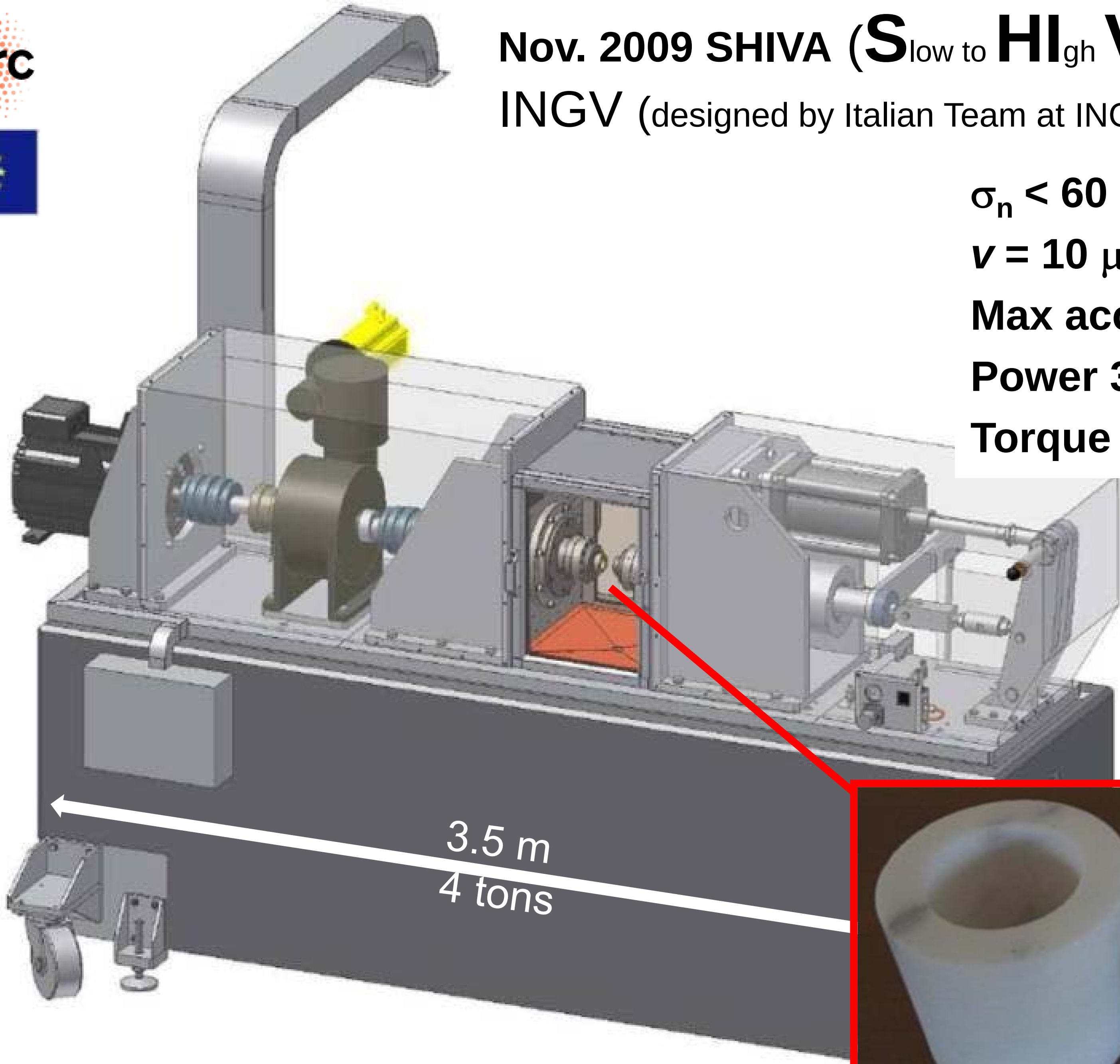
σ_n < 60 MPa

v = 10 μm/s – 6.5 m/s

Max acc. = 70 m/s^2

Power 300 kW

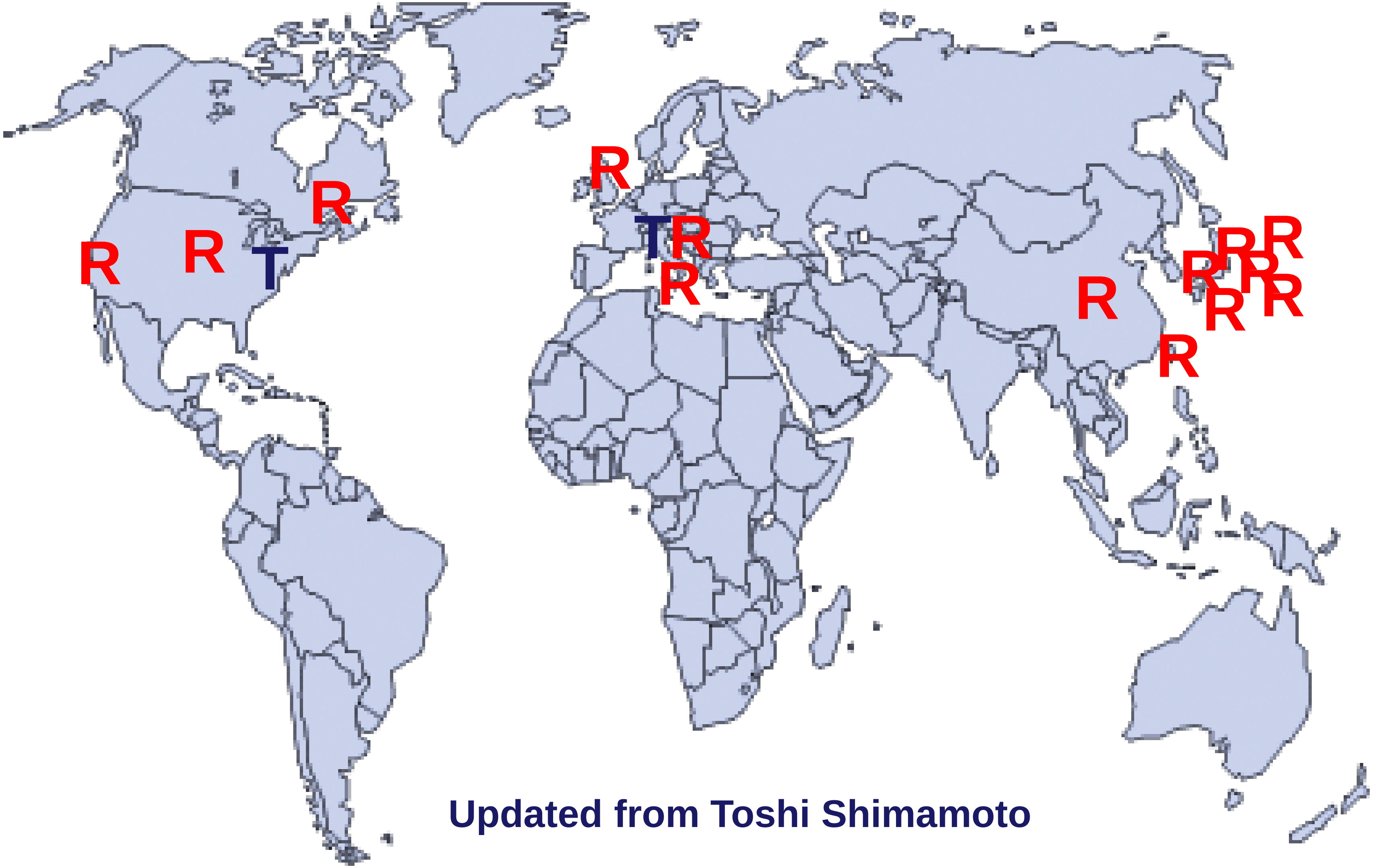
Torque 1100 Nm



Di Toro, Nielsen et al., Rendiconti Lincei, 2010

SHIVA owns an environmental/vacuum chamber equipped with a mass spectrometer. Pressurizing system. Facilities for fO_2.

Rotary (R) and testing (T) machines designed or used in HV (V> 0.3 m/s) experiments. Most installed in last 3 yrs.

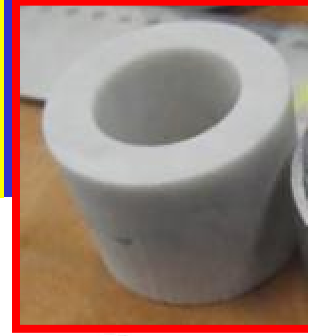


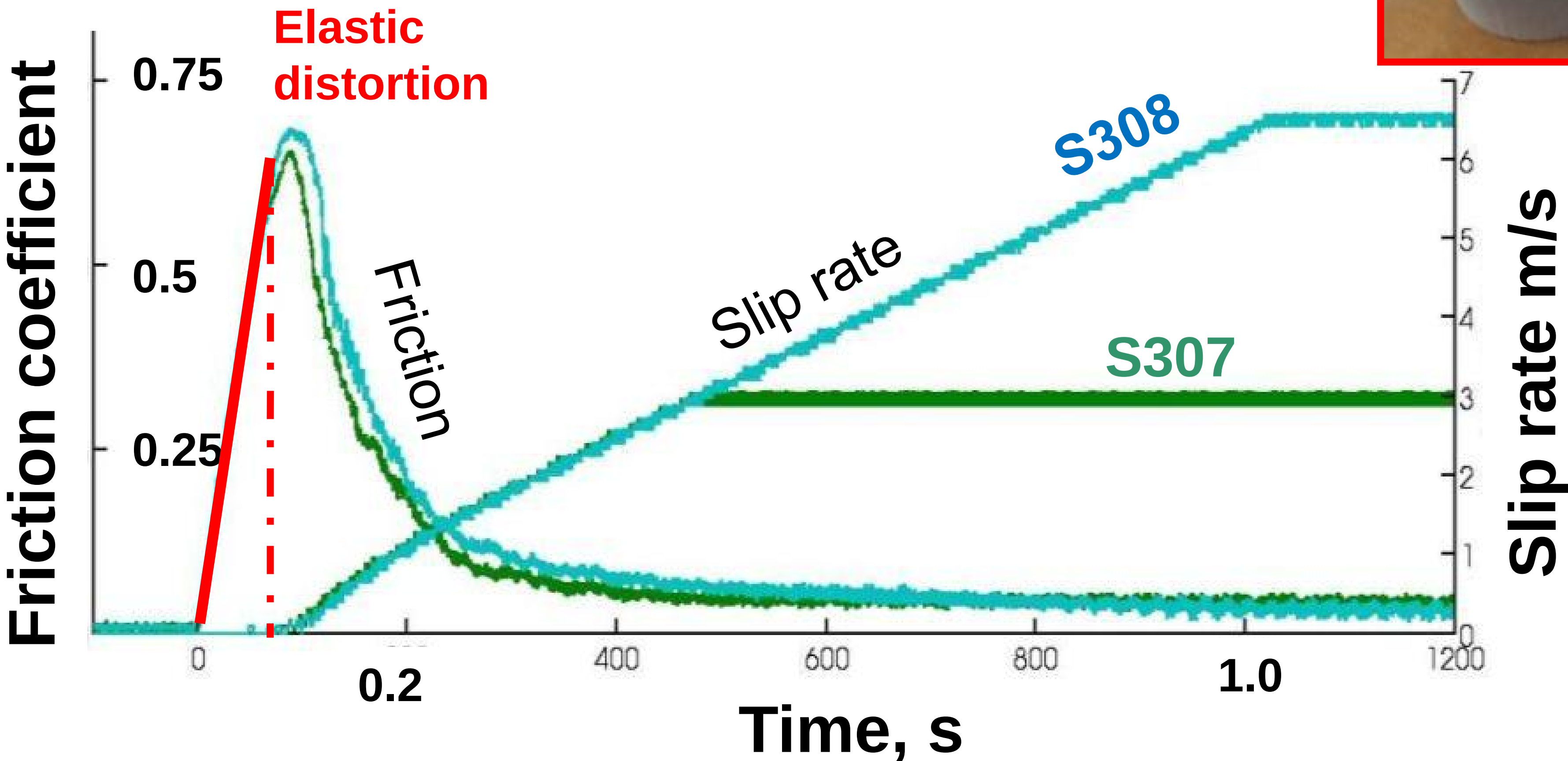
Updated from Toshi Shimamoto

SHIVA: high acquisition rates (25 kHz) and reproducibility of experimental data. Mandatory to obtain a friction constitutive equation.

Rock = Carrara marble (>99% calcite)

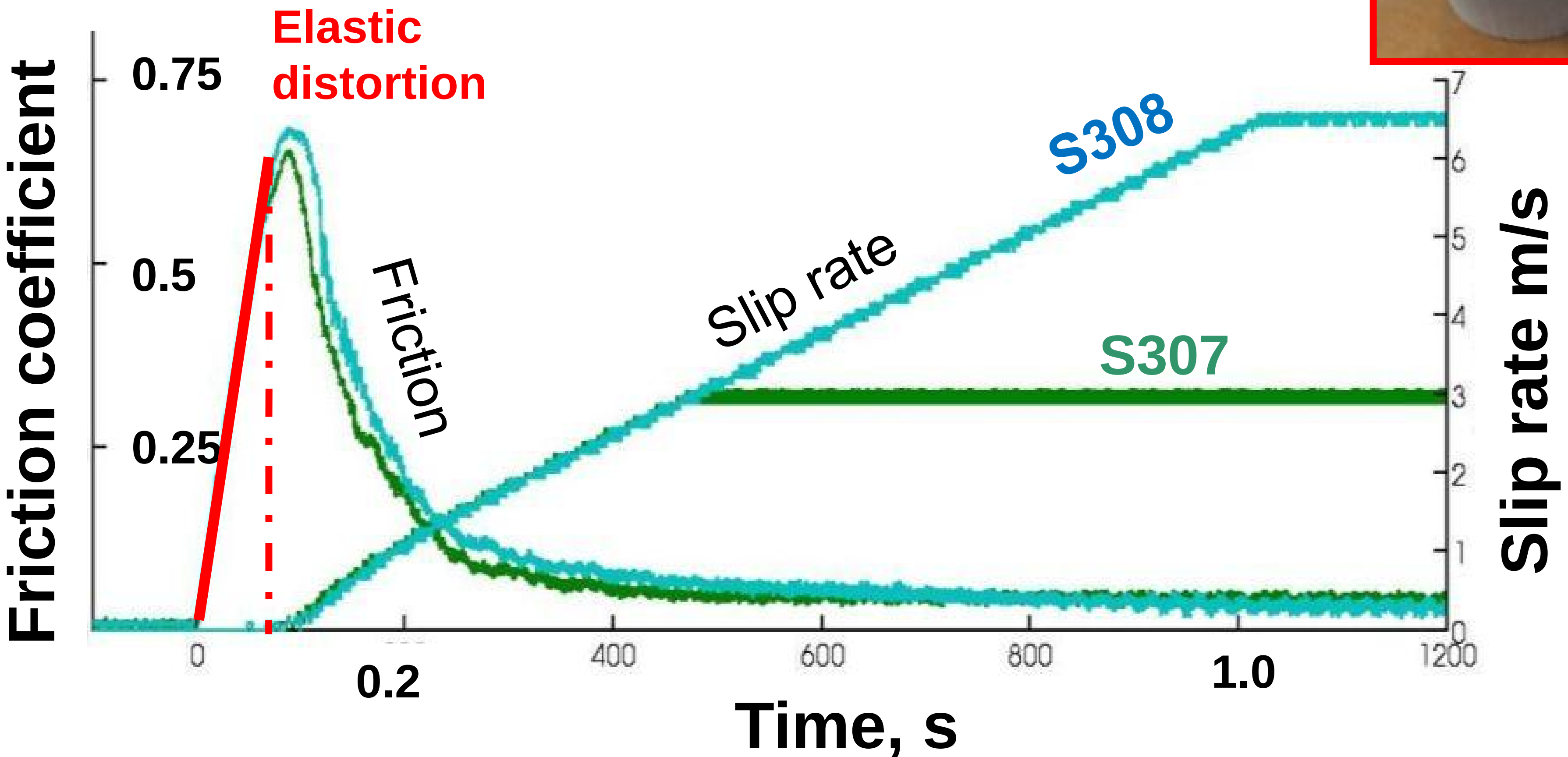
V **= 3 & 6.5 m/s**
σ_n = 20 MPa
acc = 9 m/s^2





Spagnuolo et al., in prep.

Playing with velocity functions: let's impose normal stress and slip rate and measure what rocks do



Spagnuolo et al., in prep.

FLASH HEATING AND WEAKENING

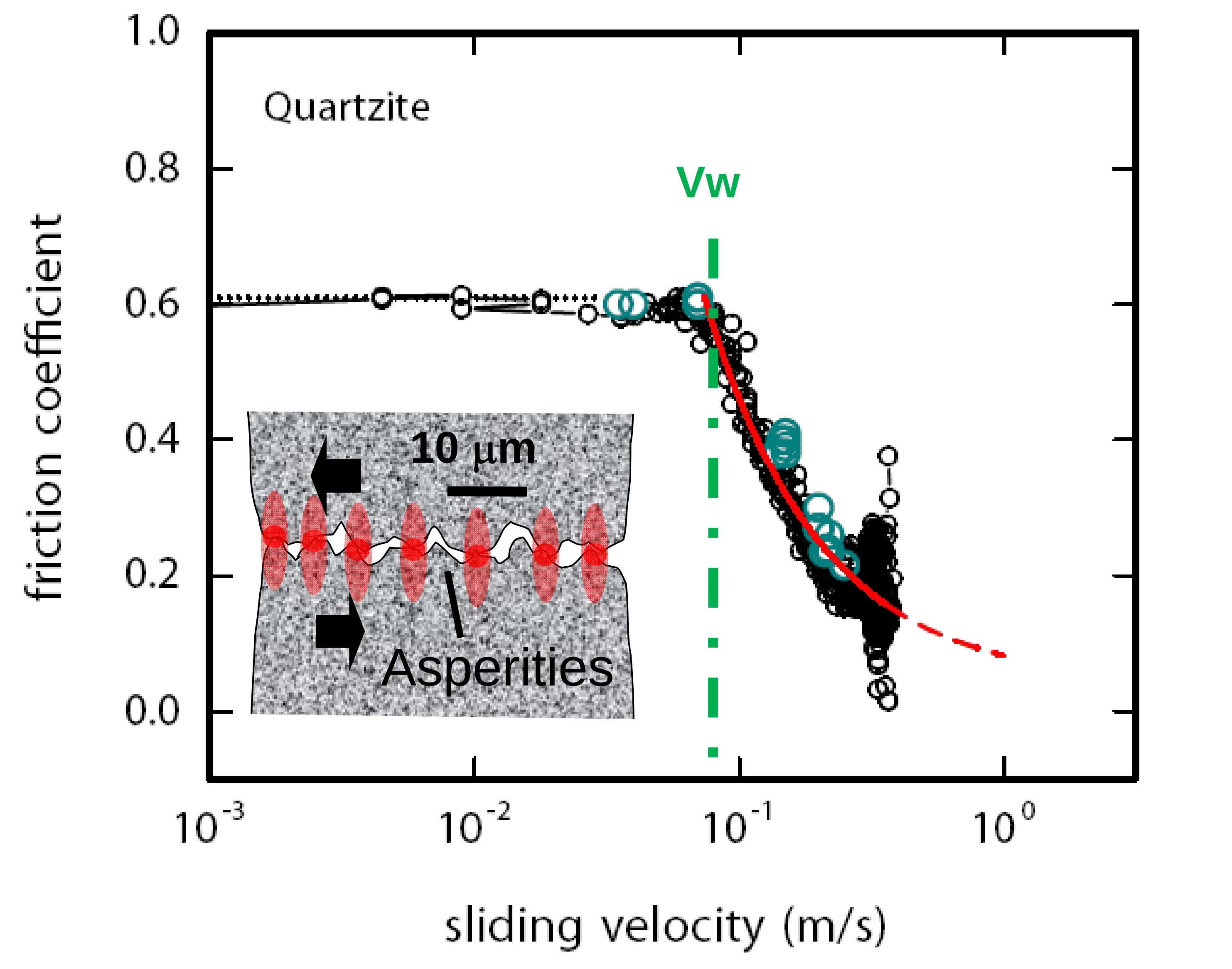
Rock = limestone (100% Calcite)

MOVIE
NOT
AVAILA
BLE

V **= 0.3 m/s**
σ_n **= 5 MPa**

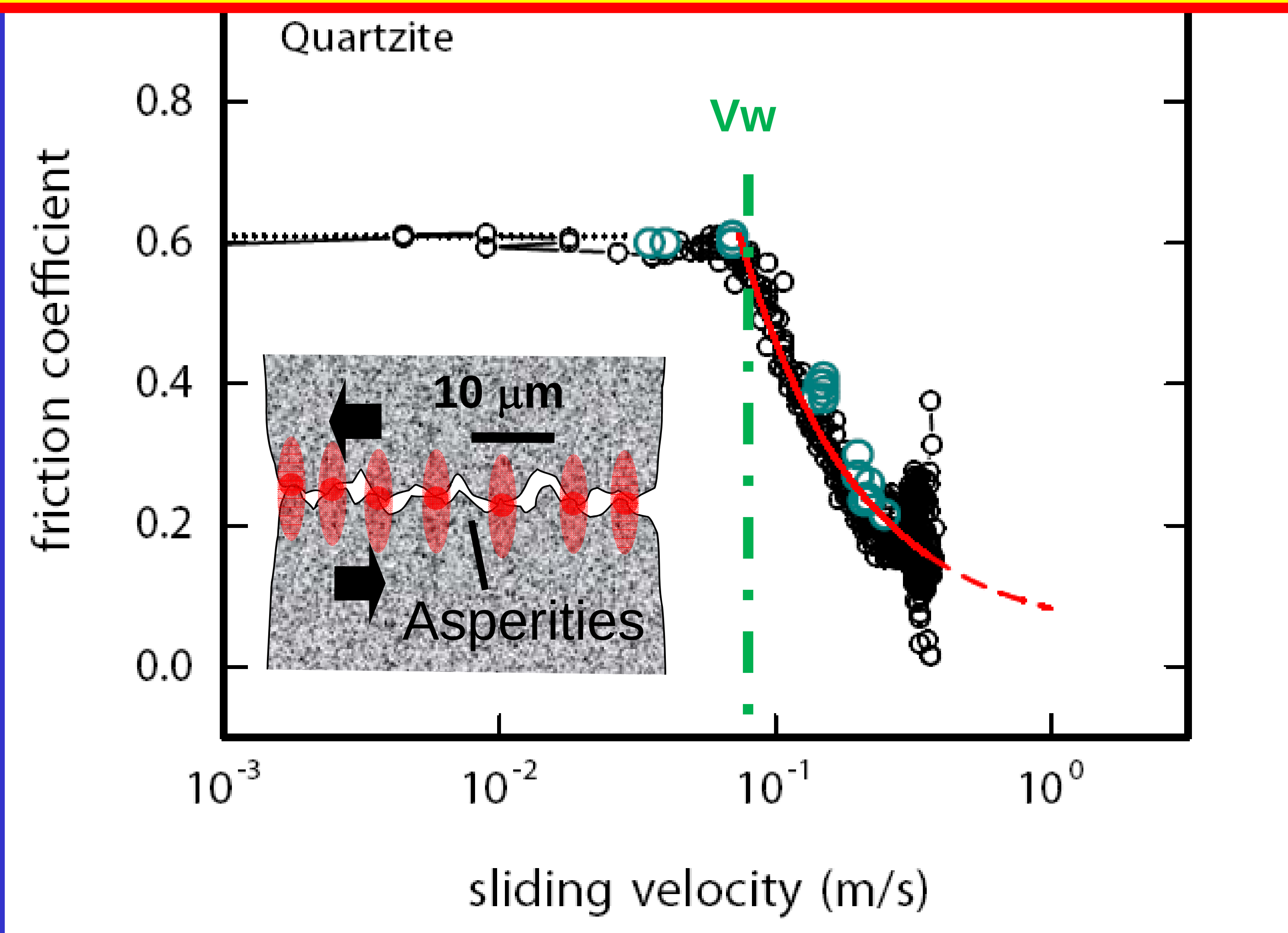
Tisato et al., JSG, 2012

Flash weakening: asperity-scale, low bulk **T (< 100 ºC),** strong velocity dependence, critical slip rate V_w



Rice, JGR, 2006; Beeler et al., JGR, 2008; Goldsby & Tullis, Science 2011

But what happens at larger normal stresses, slip and slip rates?



Rice, JGR, 2006; Beeler et al., JGR, 2008; Goldsby & Tullis, Science 2011

The bulk temperature increases (ΔT) (and abruptly if strain localizes):

$$\Delta T \propto \tau(t)V(t)\sqrt{t}$$

τ shear stress

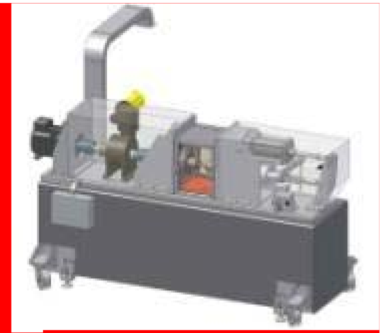
V slip rate

t time

1) ΔT proportional to $\tau(t)V(t)$ **or heat production rate** per unit area.

2) ΔT triggers further mechano-chemical reactions and phase changes (melting, CO_2 emission, etc.).

FLASH HEATING AND MELT LUBRICATION



v = 5 m/s, σ_n = 25 MPa
0 to 5 m/s in 0.1 s

Rock = gabbro

MOVIE AVAILABLE AT

http://www.youtube.com/watch?v=U-N38H5aicM&feature=related

Di Toro et al., Rendiconti Lincei, 2010, Niemeijer et al., JGR 2011

20 mm

HS infrared camera (1 frame per ms)

MOVIE NOT AVAILABLE

HS-camera: flash heating followed by strengthening and final weakening (=melt lubrication)

Rock = gabbro

v = 3 m/s, σ_n = 20 MPa,
0 to 3 m/s in 0.5 s

MOVIE NOT AVAILABLE

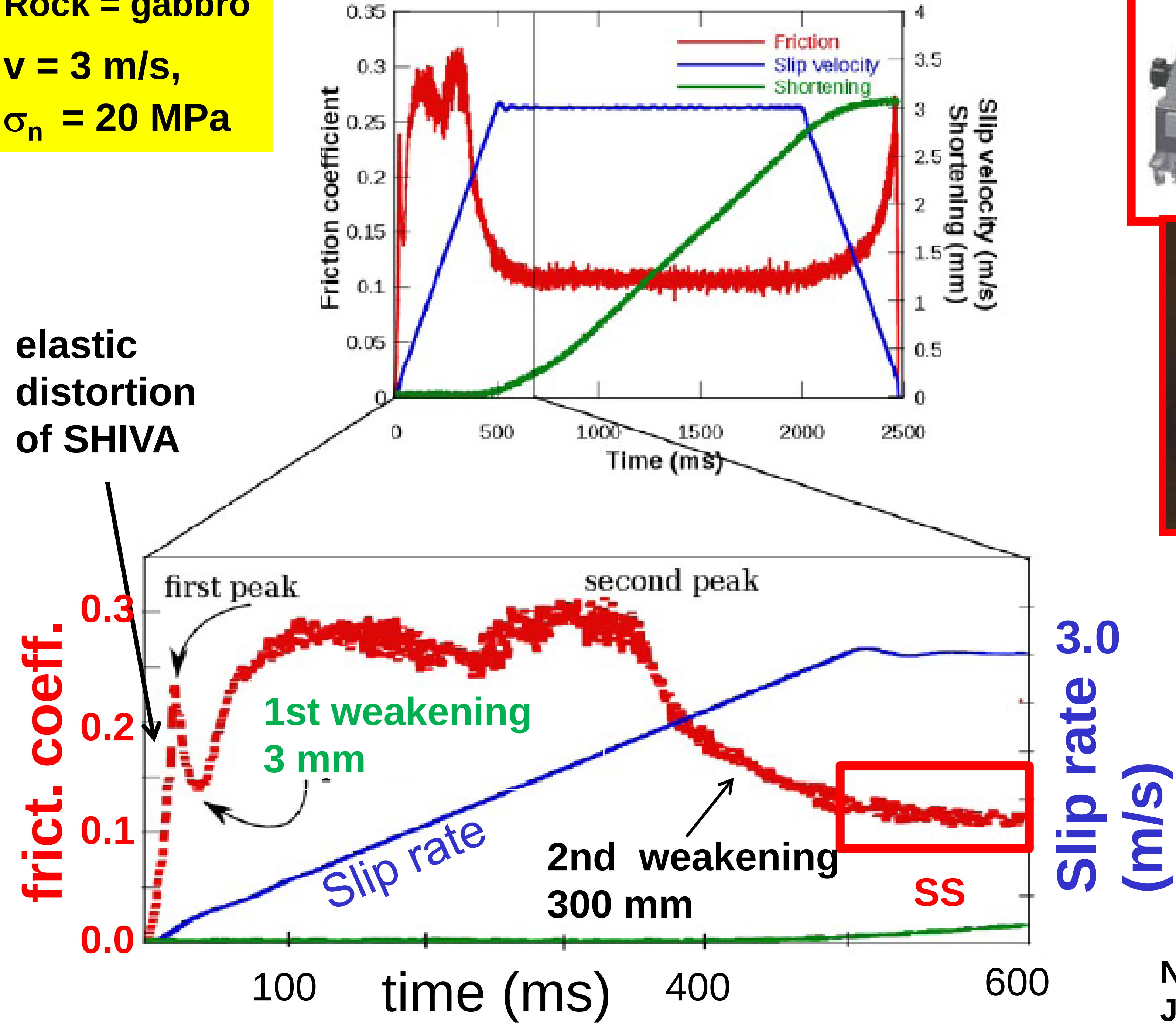
20 mm

Hirose and Shimamoto, JGR 2005
Niemeijer et al., JGR 2011

Rock = gabbro

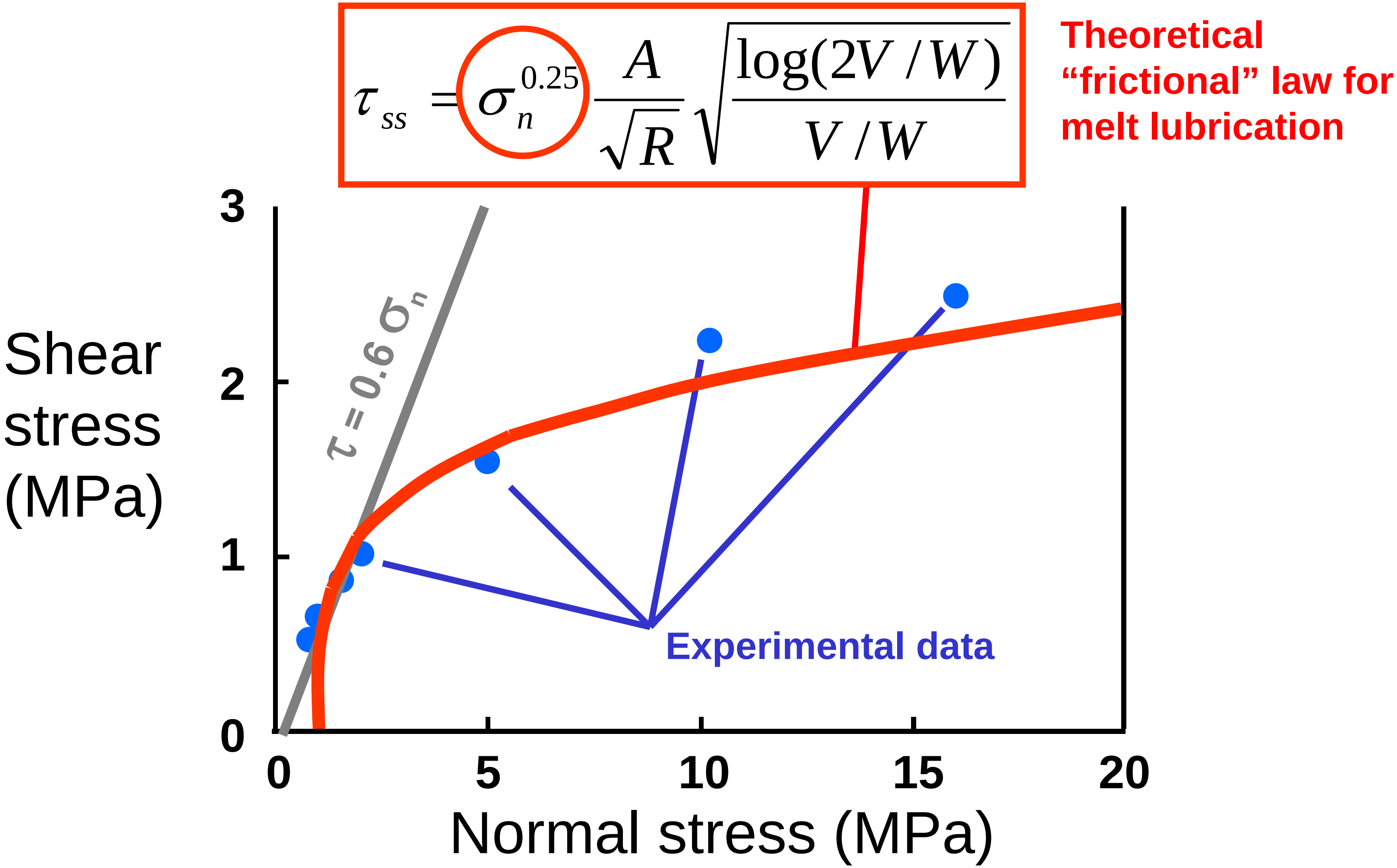
v = 3 m/s,

σ_n = 20 MPa



Niemeijer et al., JGR 2011

Melt lubrication: at steady-state, shear stress vs. normal stress is non-linear. Constitutive equation.



Nielsen et al., JGR 2008; 2010; GJI, 2010

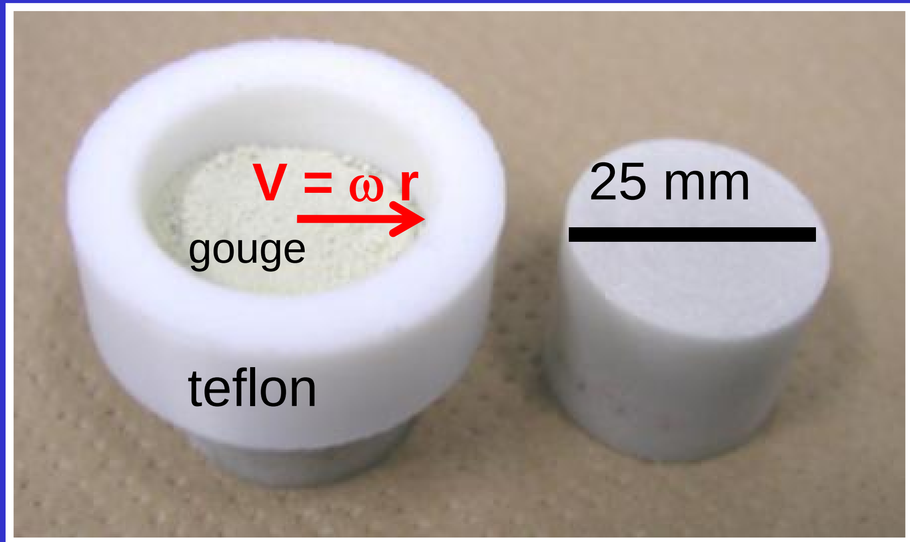
LUBRICATION IN GOUGES

The experimental issue of gouge and fluid confinement

Ideal confining medium:
low μ at T up to 1800ºC

Sample confinement
13th century
(by **Master Giotto**
Padua, ITA)

21st century
(by PhD student **Mizoguchi**
and **Master Shimamoto,**
Kyoto, JPN).



Limitations: most experiments at few MPa, F release, zero slip rate at the center.

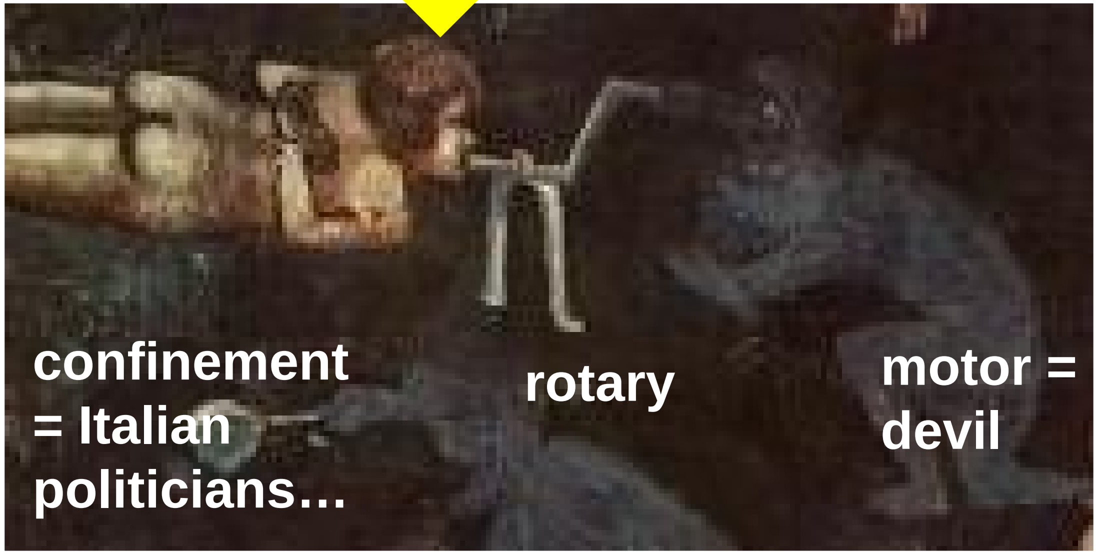
LUBRICATION IN GO

The experimental iss

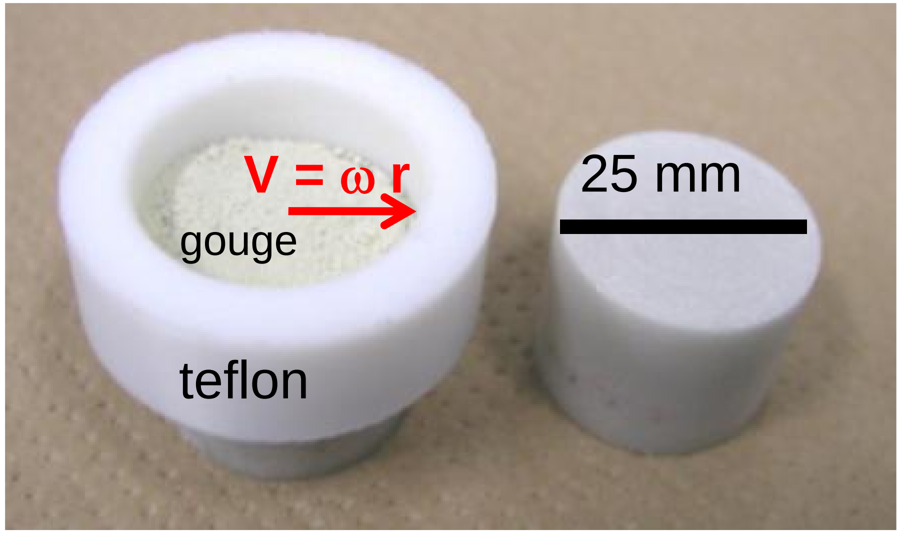
Confinement: the reviewer of your next rejected paper will work better?

Ideal confining medium:
low μ at T up to 1800ºC

Sample confinement
13th century
(by **Master Giotto**
Padua, ITA)



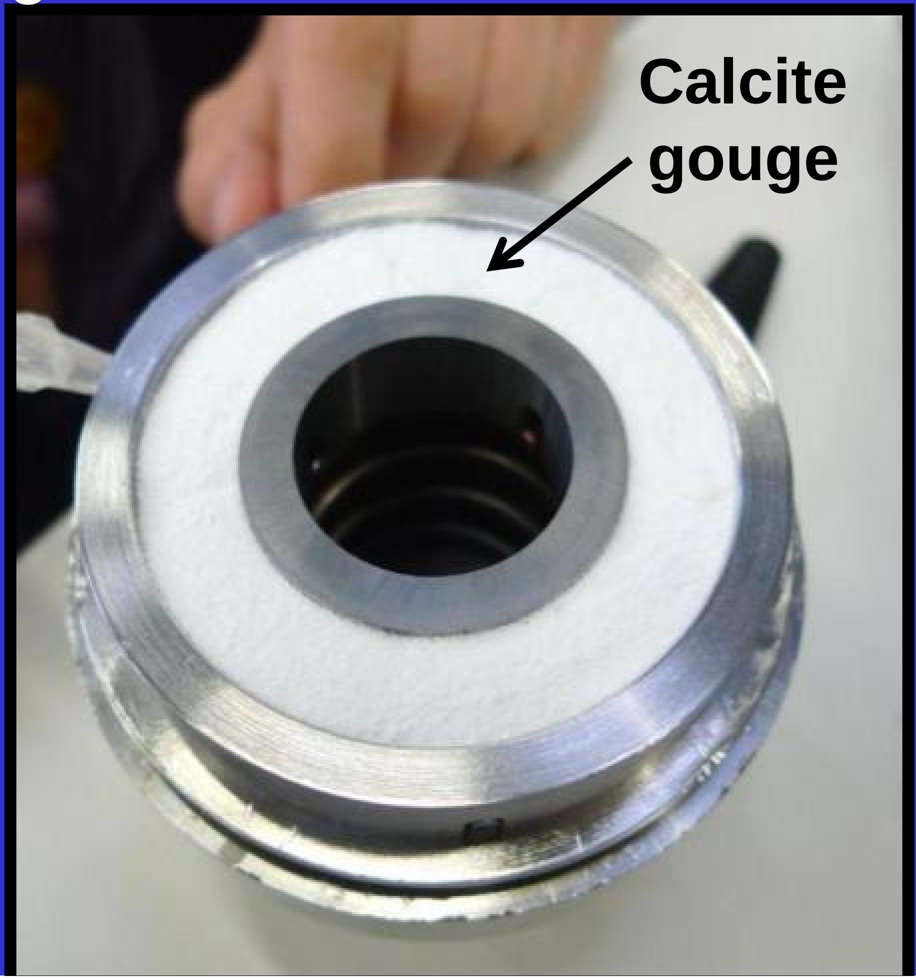
21st century
(by PhD student **Mizoguchi**
and **Master Shimamoto,**
Kyoto, JPN).

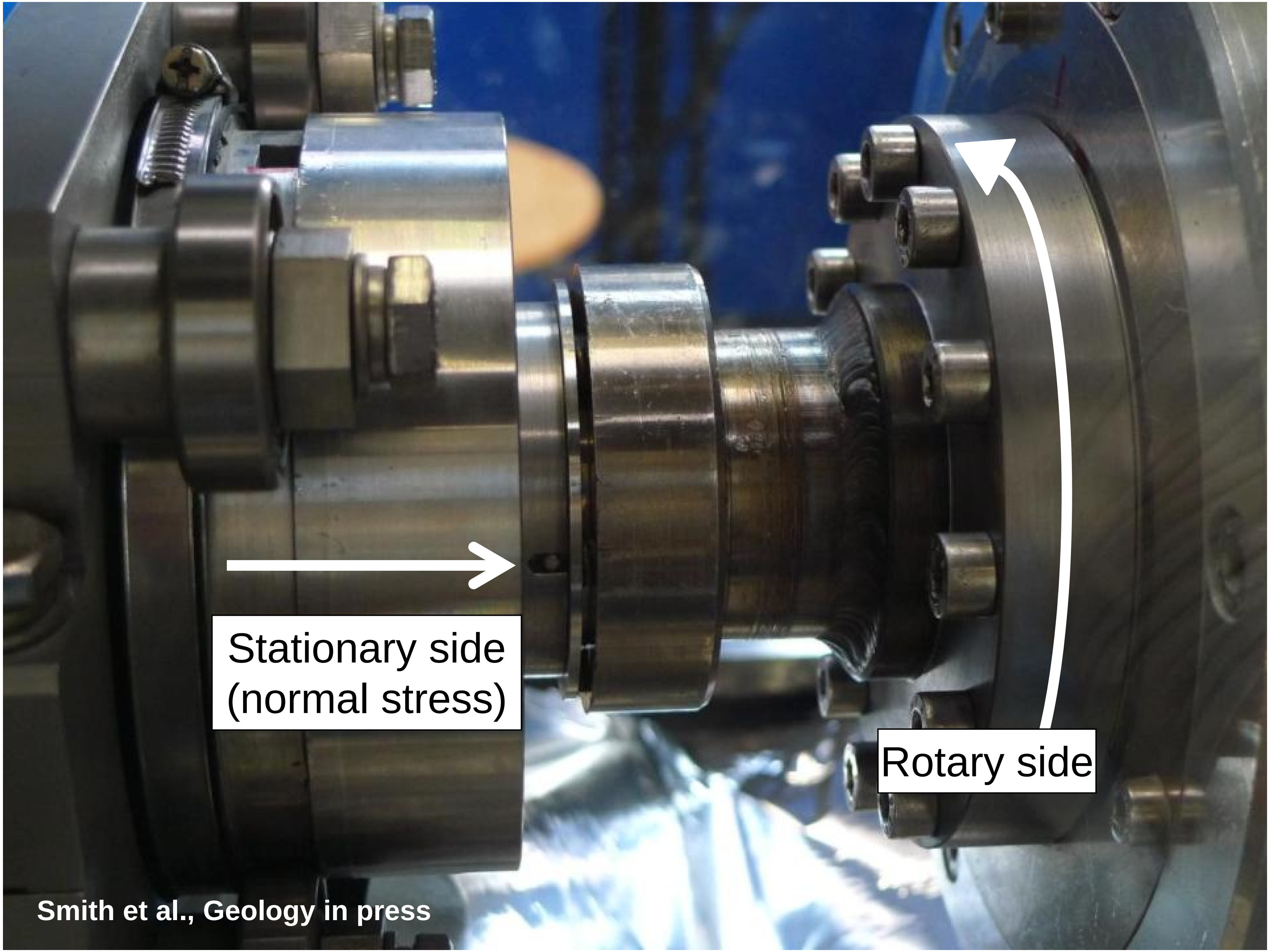


Limitations: most experiments at few MPa, F release, zero slip rate at the center.

GOUGE LUBRICATION

Purpose-built gouge holder(metal confinement)

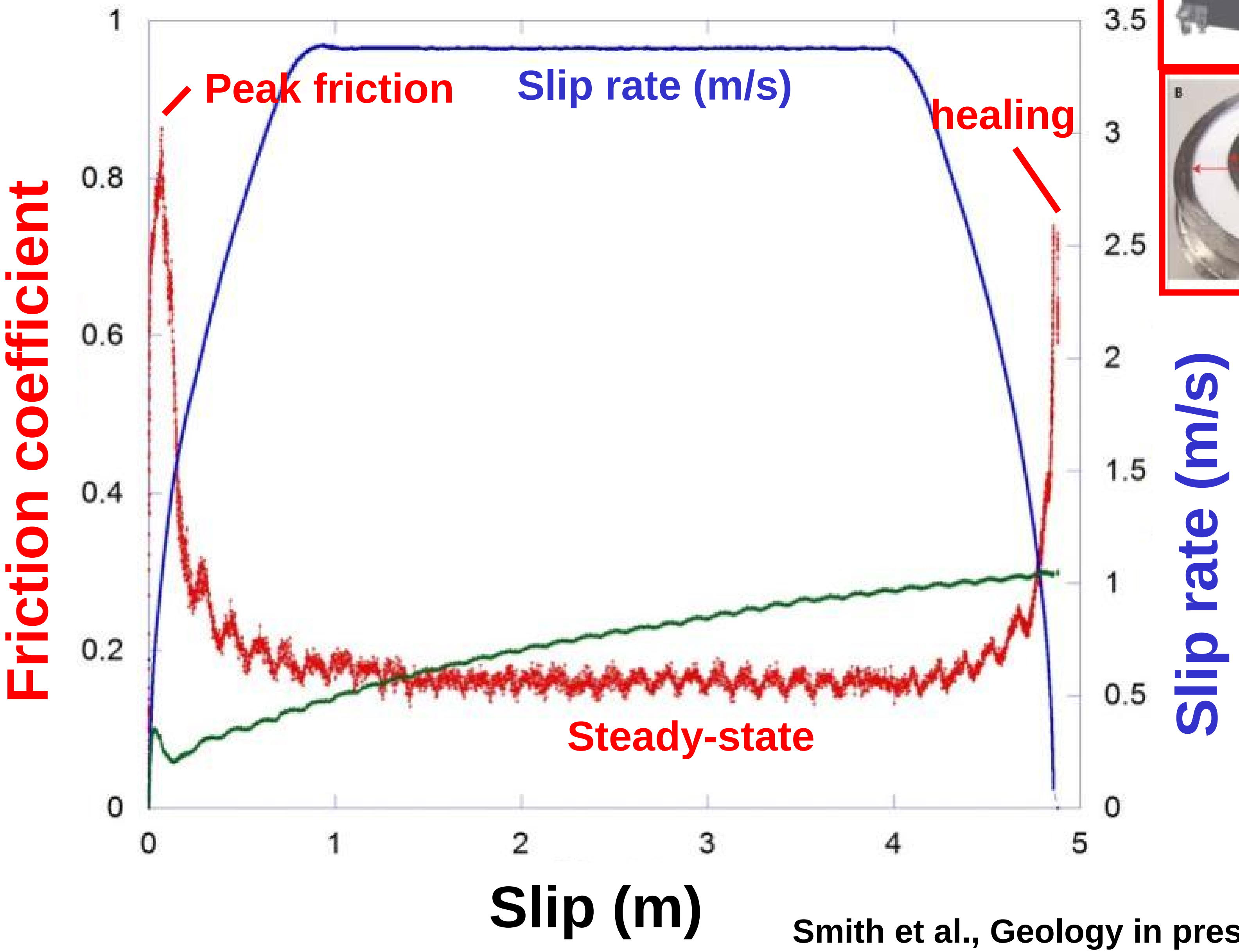



Stationary side
(normal stress)
Rotary side
Smith et al., Geology in press

Gouge lubrication at moderate normal stress

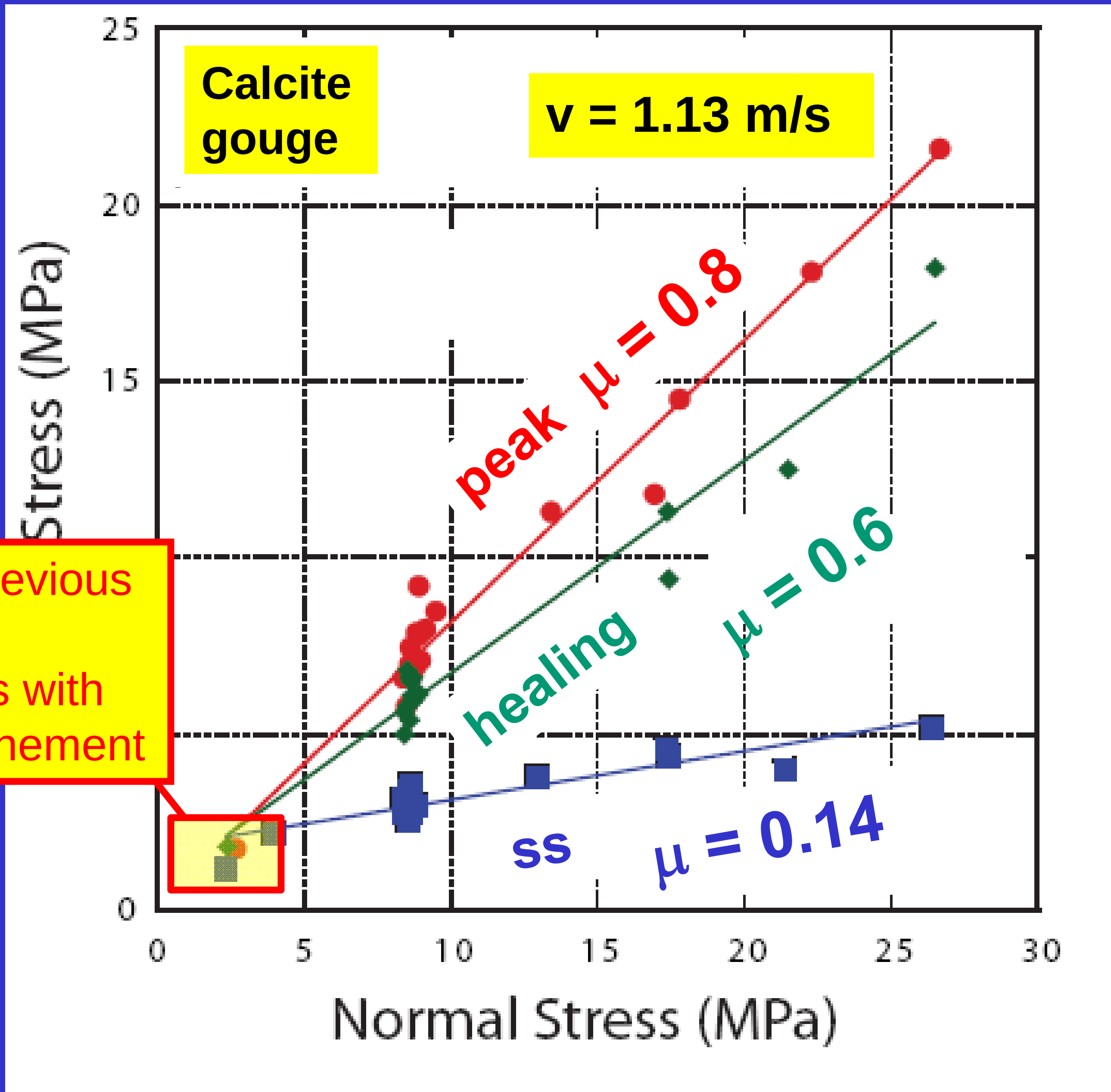
σ_n = 18 MPa

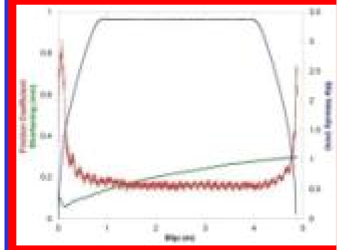
Rock = calcite gouge



Smith et al., Geology in press

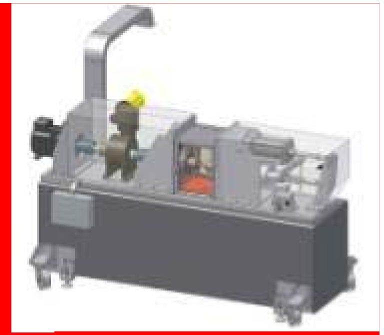
Gouge lubrication at moderate normal stresses





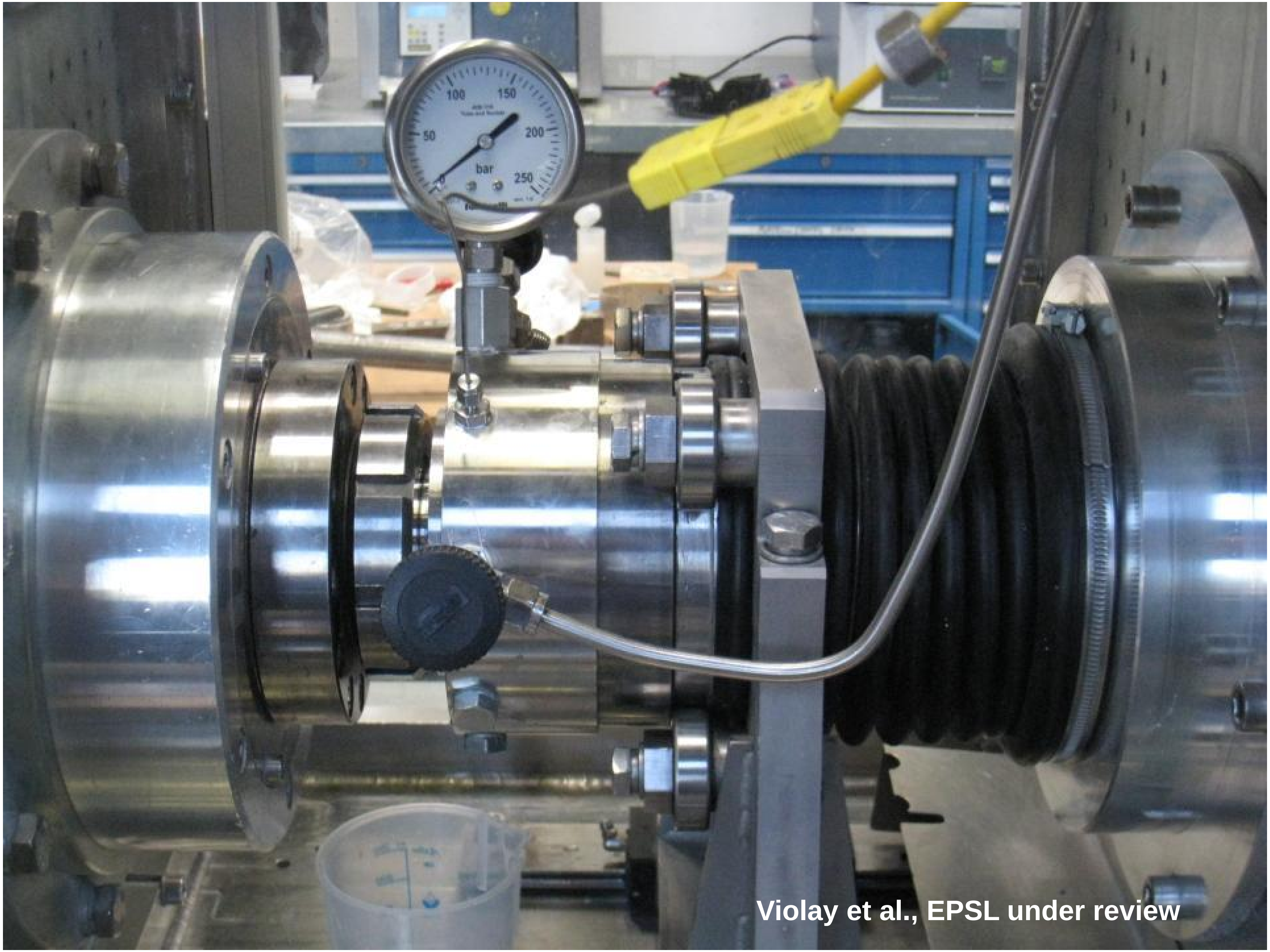
Smith et al., Geology in press

LUBRICATION WITH PORE FLUIDS

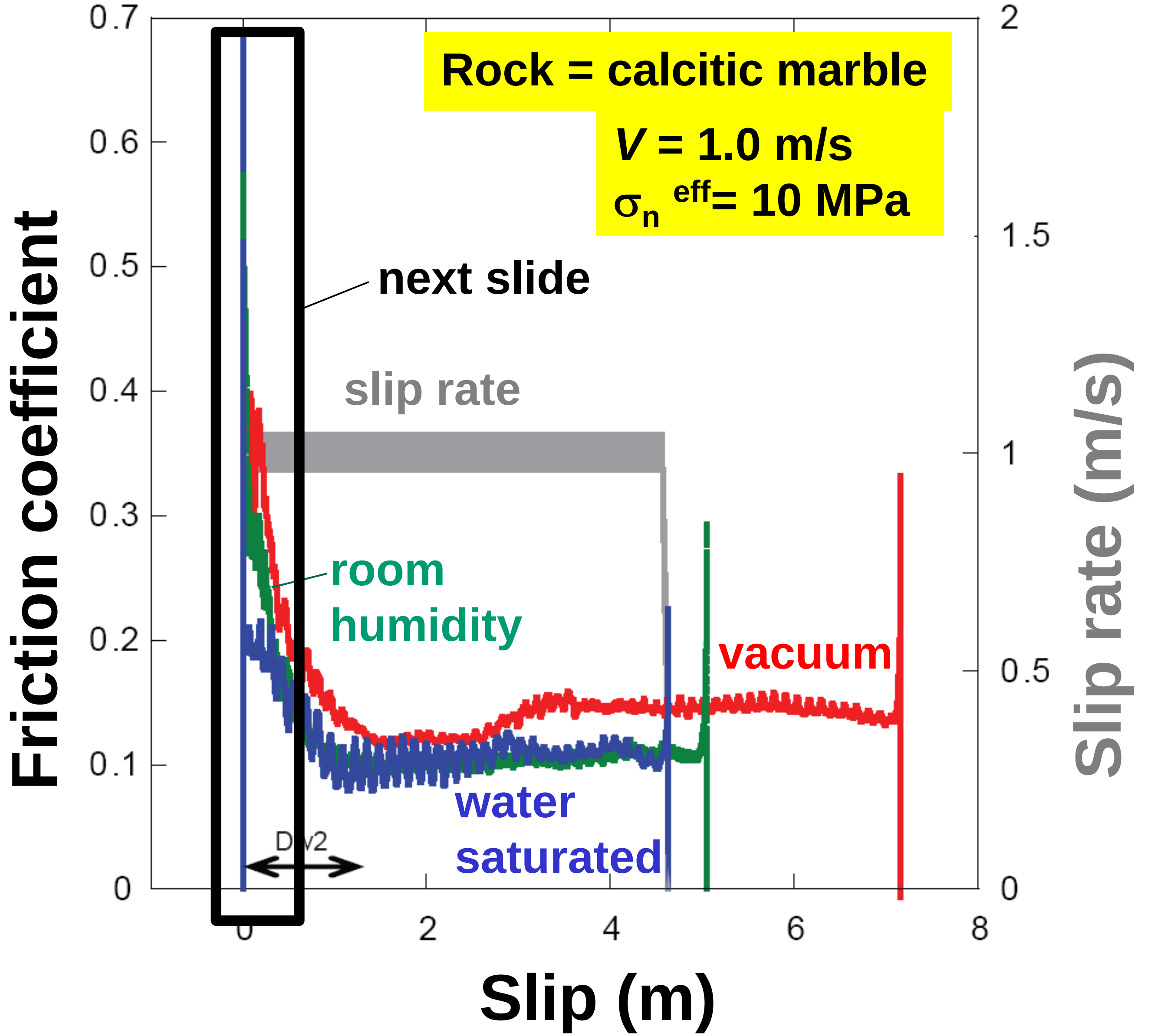


Fluid pressuriizing system

Pore pressure vessel
(modified from Hirose)

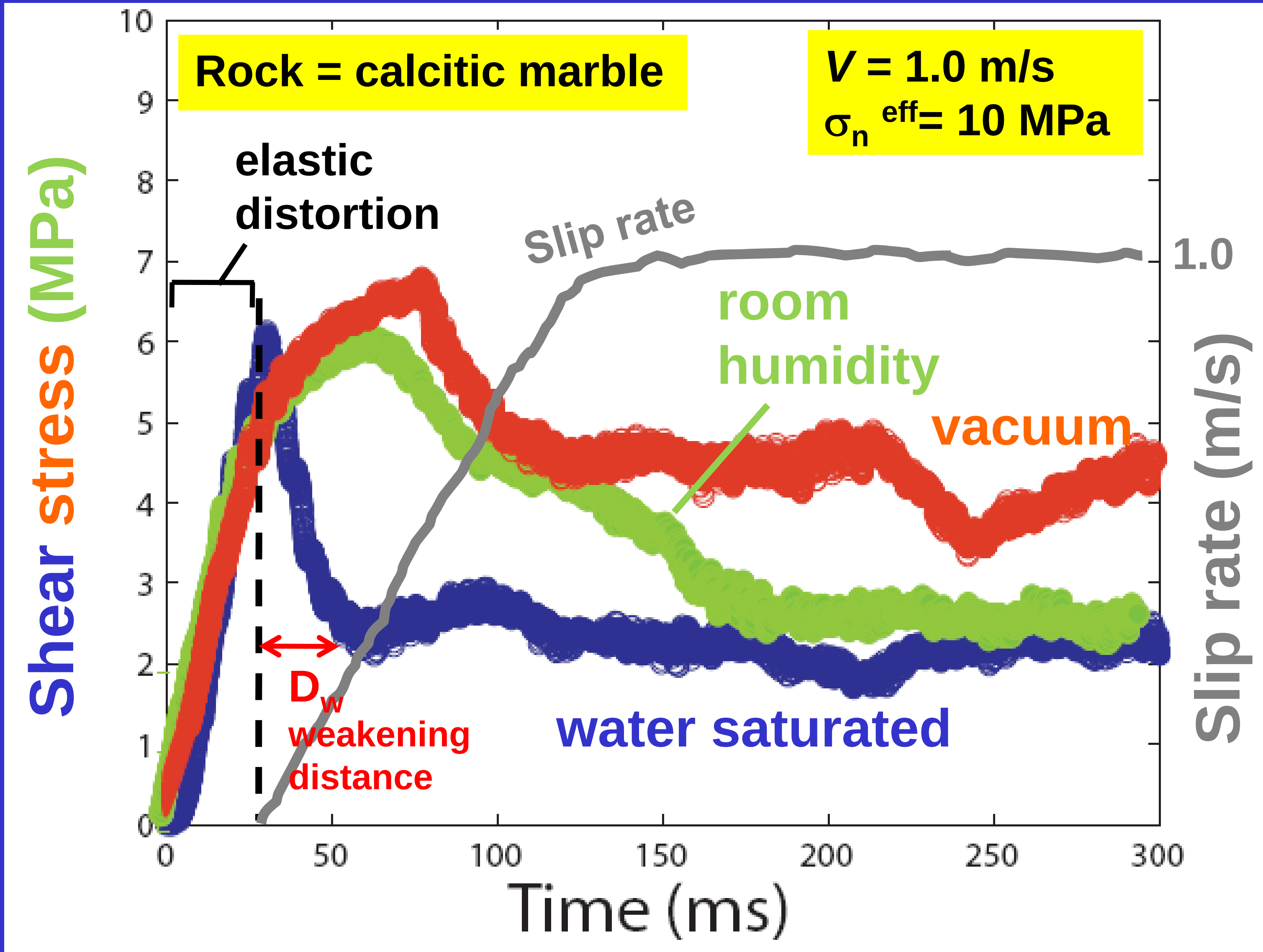

100
150
50
200
bar
250
Violay et al., EPSL under review

Steady-state friction: same under room-humidity, vacuum & water saturated conditions



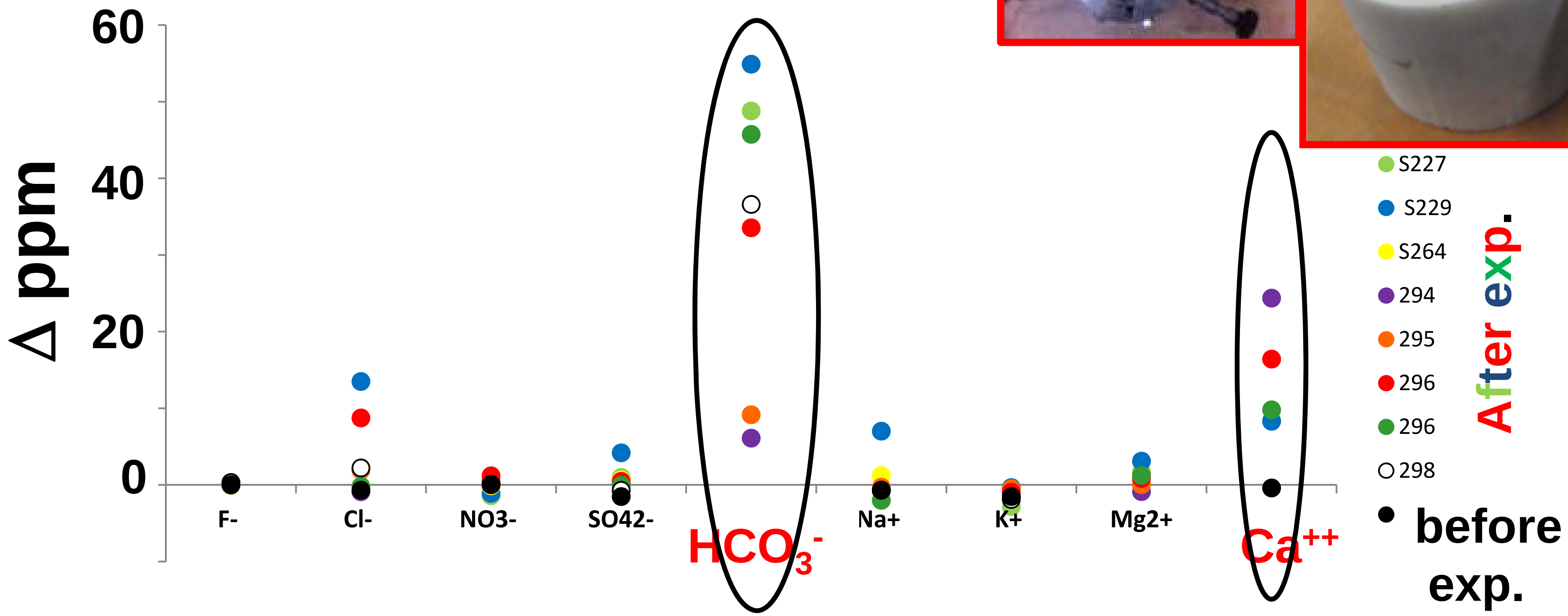
Violay et al., EPSL under review

Abrupt weakening for water-saturated conditions (D_w shorter, about 5 mm).



Violay et al., EPSL under review

Fluid analysis after experiments on calcitic marble in water.



Thermal decomposition of calcite:

$CaCO_3 = CaO + CO_2$ **T = 850°C**

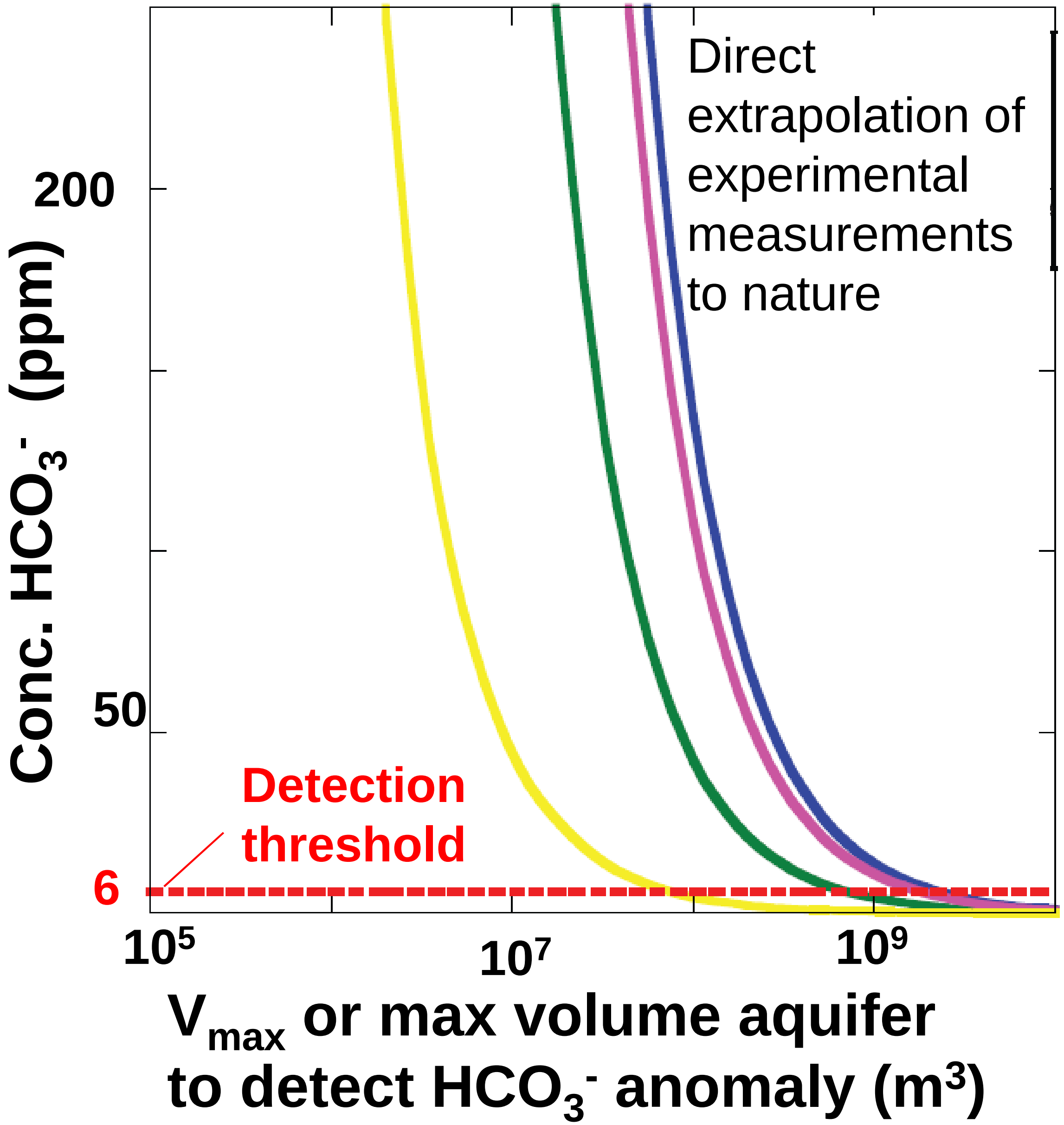
Geochemical signature of coseismic decarbonation recorded in aquifers located near to faults after EQs?

Violay et al., EPSL under review

Maximum aquifer volume to record seismic-induced decarbonation (for M_w 7 earthquakes).

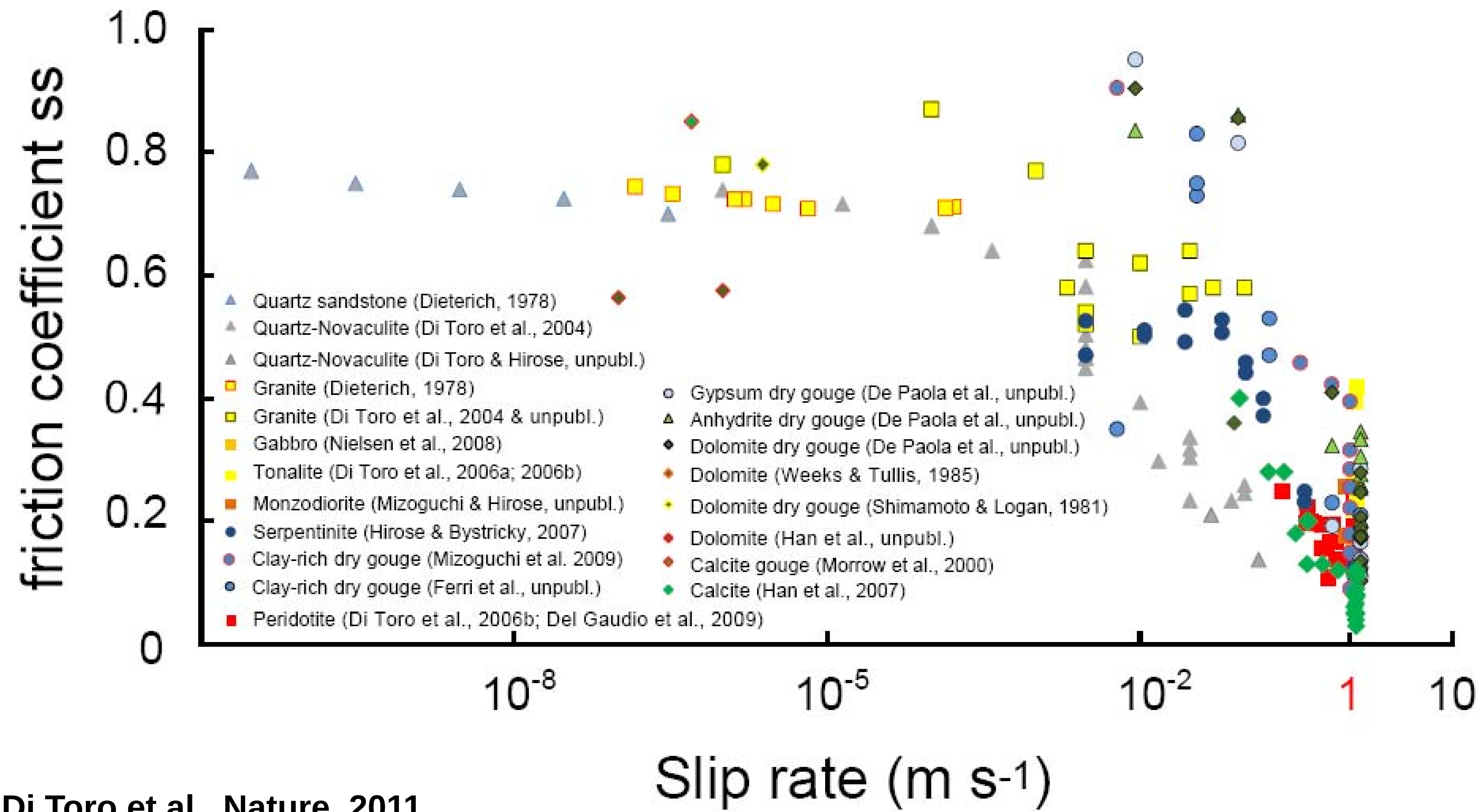
$$V_{nat} = \left(\frac{S_{nat} * V_{exp}}{S_{exp}} \cdot \frac{C_{exp}}{C_{nat}} \right)$$

V_{nat}	vol. aquifer
V_{exp}	vol. vessel exp.
S_{nat}	fault area nature
S_{exp}	fault area exp.
C_{nat}	$[HCO_3^-]$ nature
C_{exp}	$[HCO_3^-]$ exp.

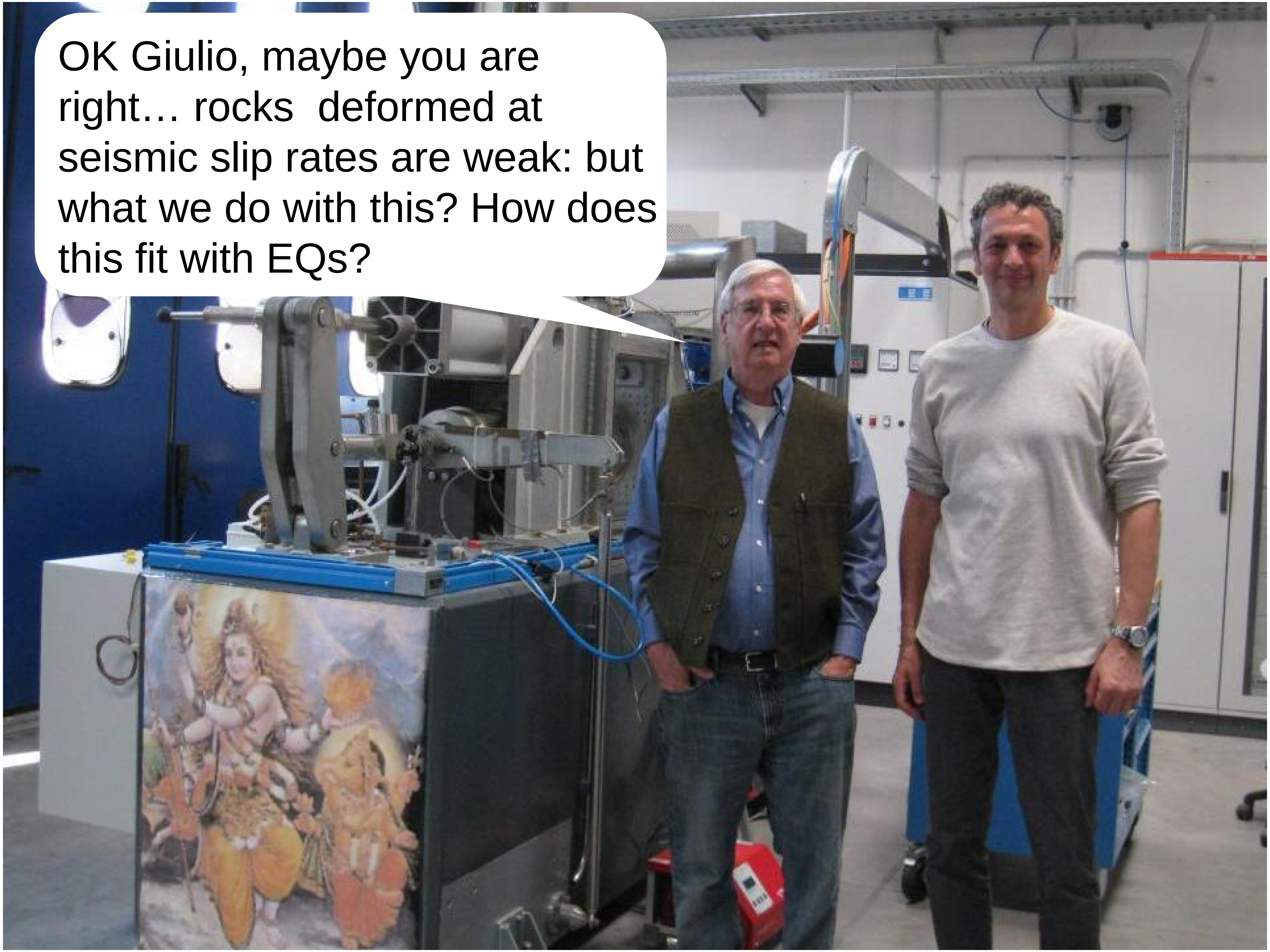


Violay, EPSL, under review
De Paola EPSL, 2011

Playing with velocity: friction is low at seismic slip rates independently of the weakening mechanism.



Di Toro et al., Nature, 2011


OK Giulio, maybe you are right… rocks deformed at seismic slip rates are weak: but what we do with this? How does this fit with EQs?


Don’t worry Chris,
it fits, it fits…


Damn… don't know how… let's try….

Questions

Nature

- How friction evolves during EQs?
- What we find in faults exhumed from seismogenic depths?

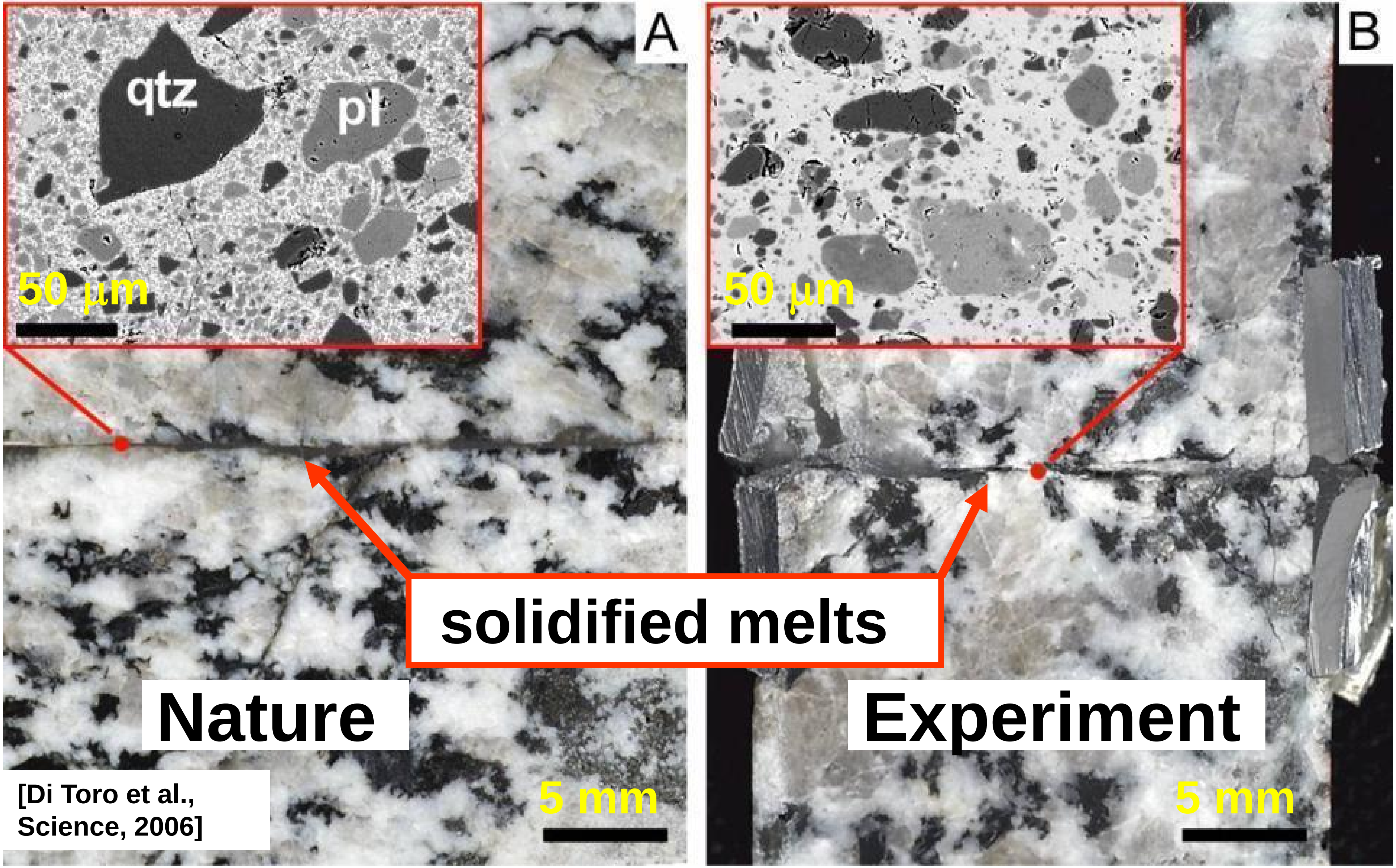
Experiments

- How friction evolves at seismic slip rates?
- Which coseismic processes are triggered in the exp.?
- Can we get a friction constitutive law?

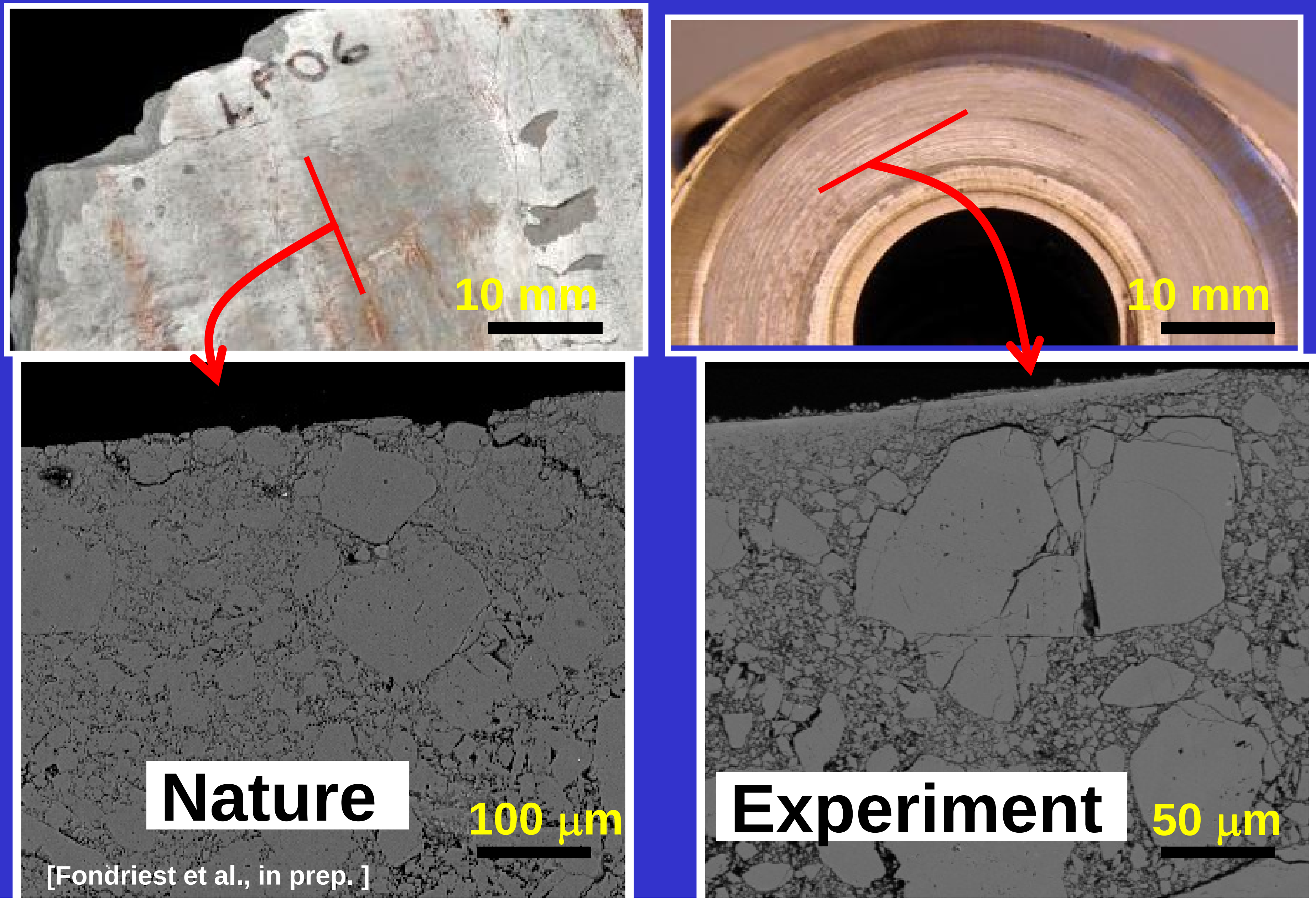
From experiments to Nature...

- Do the processes triggered in the lab occur in nature?
- Are there evidences in nature that faults are weak during EQs?

GEOLOGICAL EVIDENCES OF SIMILAR PROCESSES OCCURRING IN NATURE (melting in granitoid rocks)



Polishing and clast truncation in dolostone rocks



GEOLOGICAL EVIDENCES OF FAULT LUBRICATION

pseudotachylytes

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

Sibson, 1975

- τ shear stress
- t solidified melt thickness
- d coseismic fault slip
- ρ rock density
- E^* energy to heat and melt the rock

Estimates from seismic solidified melts suggest $\mu < 0.2$ (these values are supported by theoretical estimates)

Di Toro et al., 2006; 2009

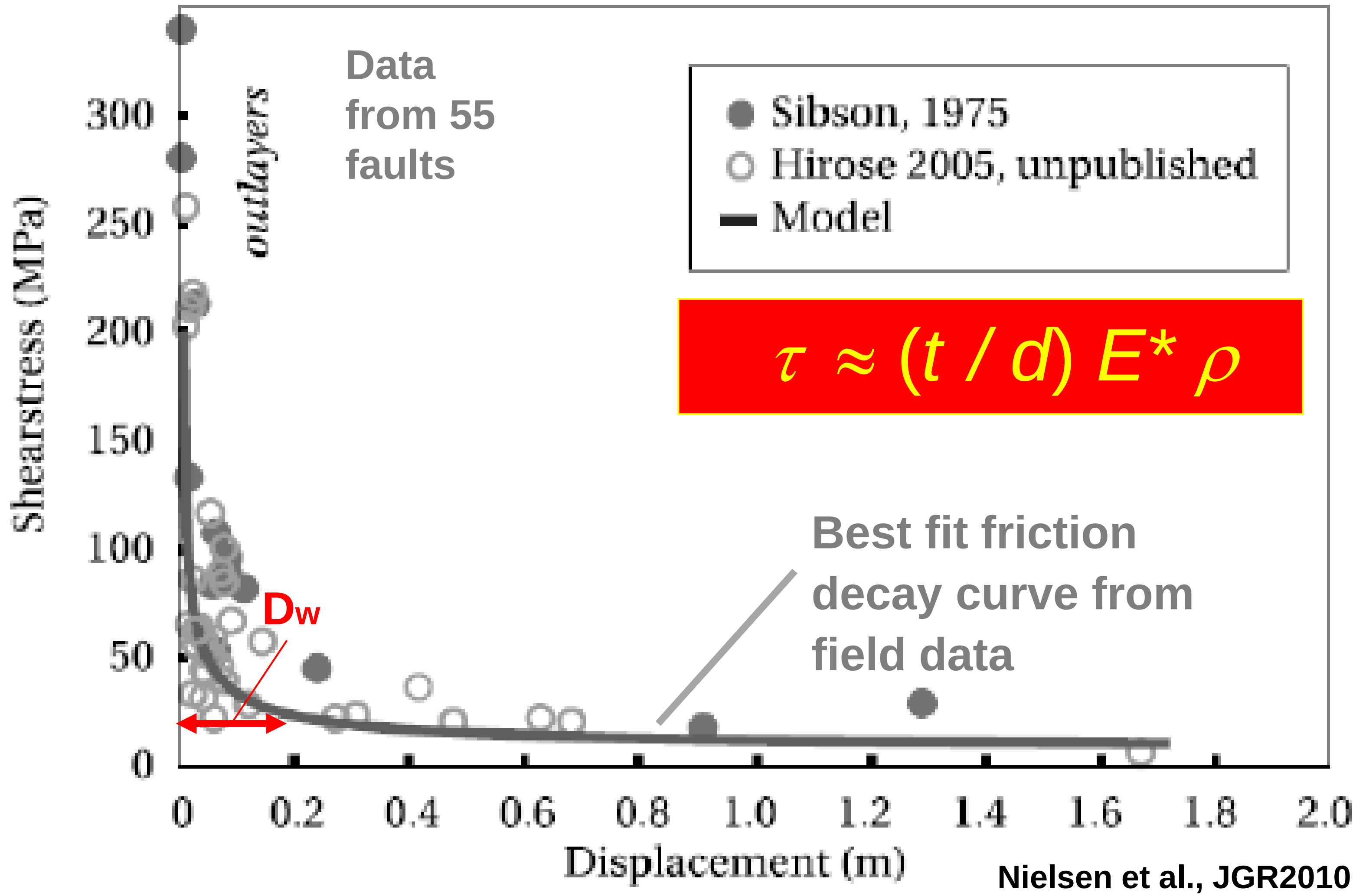
Pseudotachylyte thickness ***t*** measured in faults with increasing slip ***d***…

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

…suggest that:

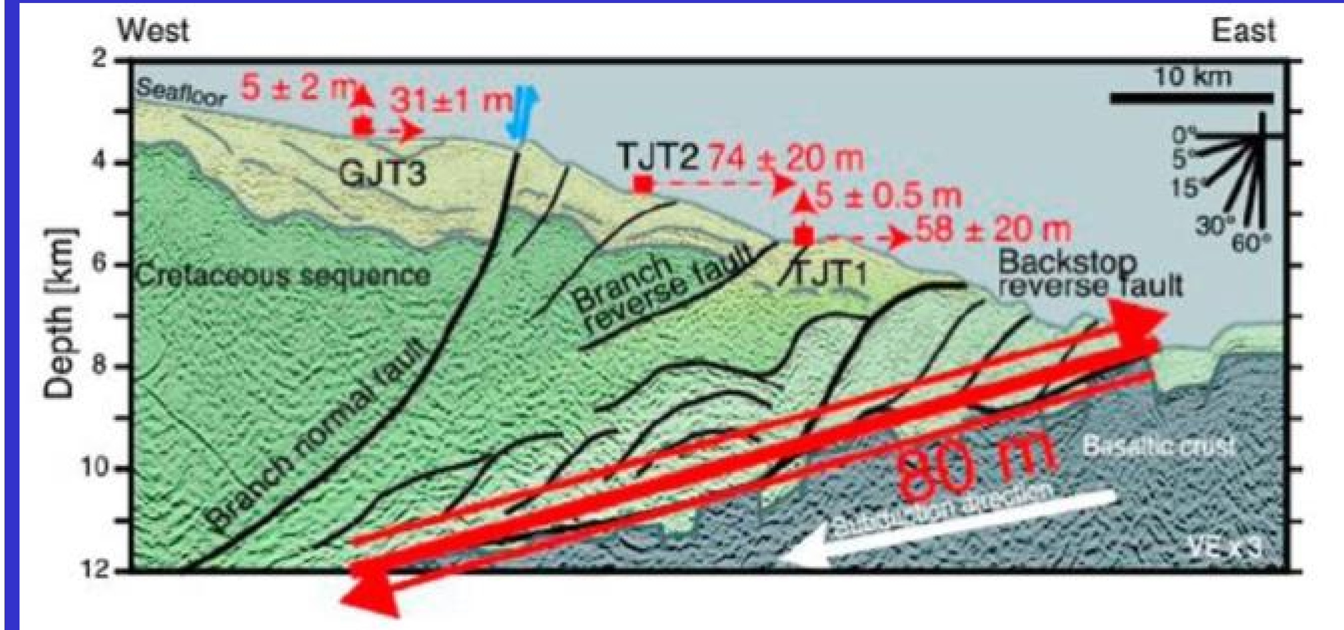
1) shear stress decreases with increasing slip;

2) D_w < 10 cm in the presence of melts



Nielsen et al., JGR2010

GEOPHYSICAL EVIDENCE OF FAULT LUBRICATION



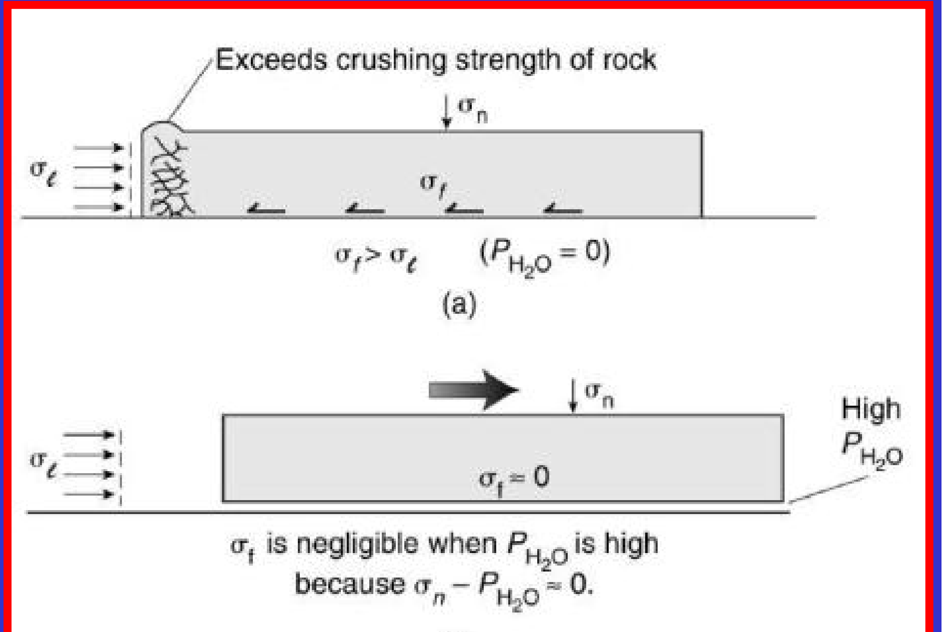
Tohoku 2011 M_w 9.0
up to 30-80 m of seismic slip;
total stress drop?

Ito et al., GRL 2011
Yagi and Fukahata, GRL 2011

Force applied at the base will fracture the block.

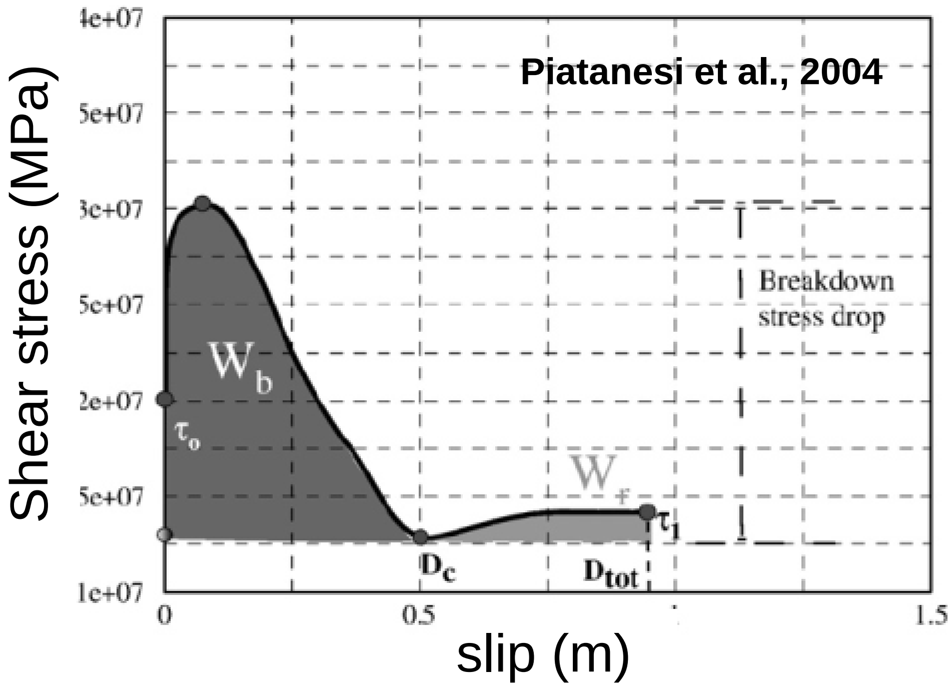
Large slip possible if base lubricated.

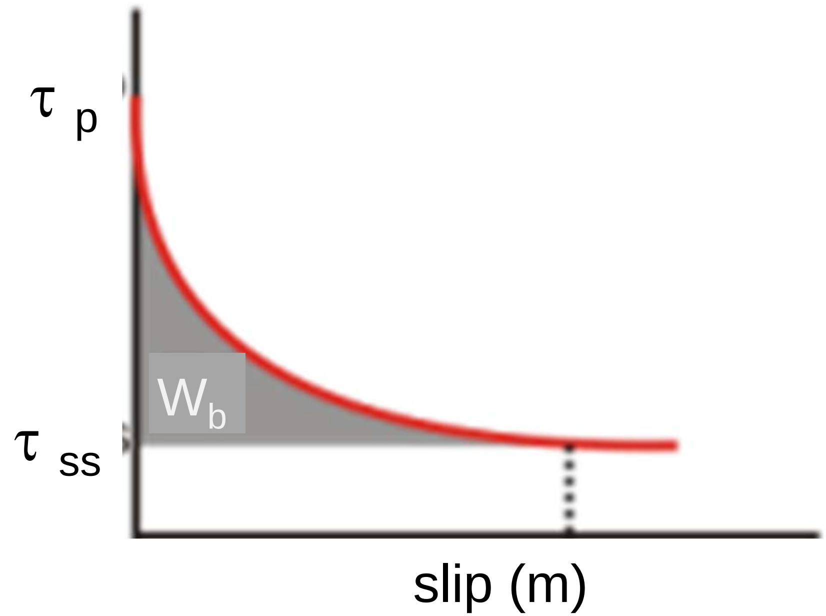
Hubbert & Rubey 1959



SEISMOLOGICAL DATA MATCHING EXPERIMENTAL OBSERVATIONS

Breakdown work W_b (or fracture energy) measured in experiments is in the range of seismological estimates.





Nature (M > 5.5)

1 – 90 MJ m^{-2}

Tinti et al., 2005; Abercrombie and Rice, 2005; Cocco & Tinti, 2008

Experiments

1 – 42 MJ m^{-2}

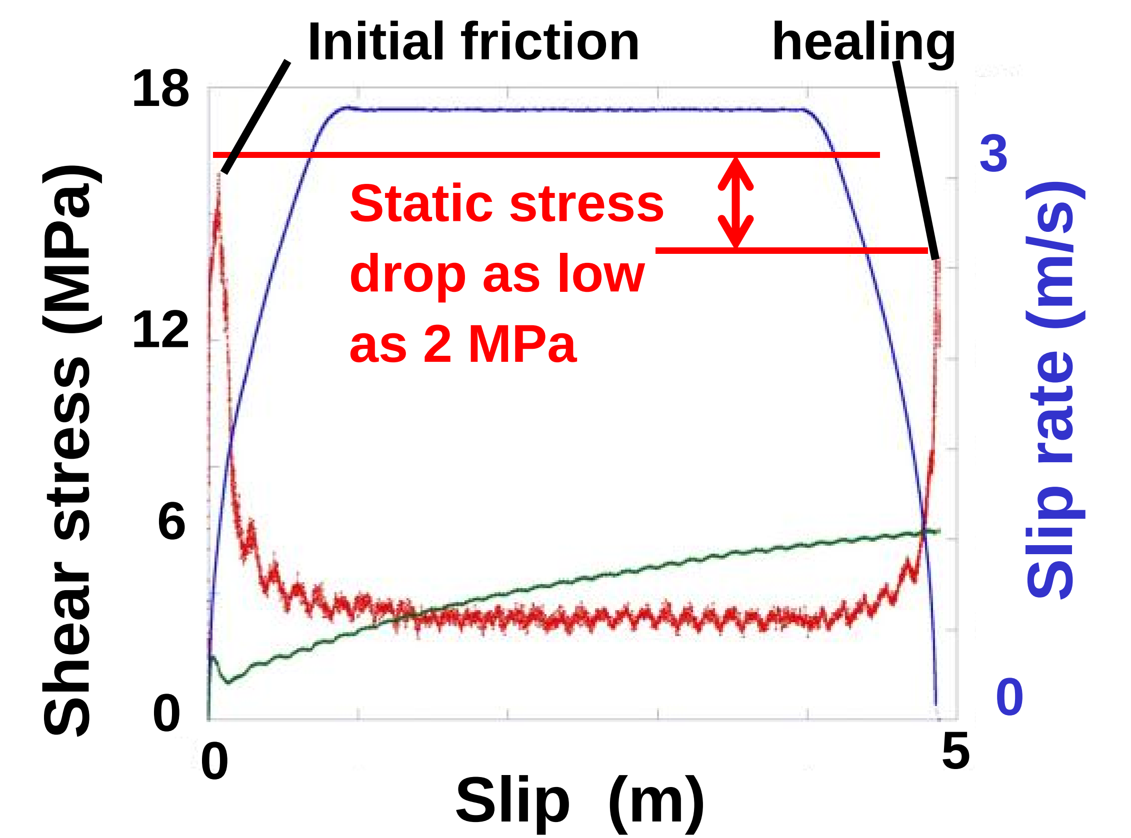
Di Toro et al., 2011; De Paola et a., 2011

Static stress drop paradox?

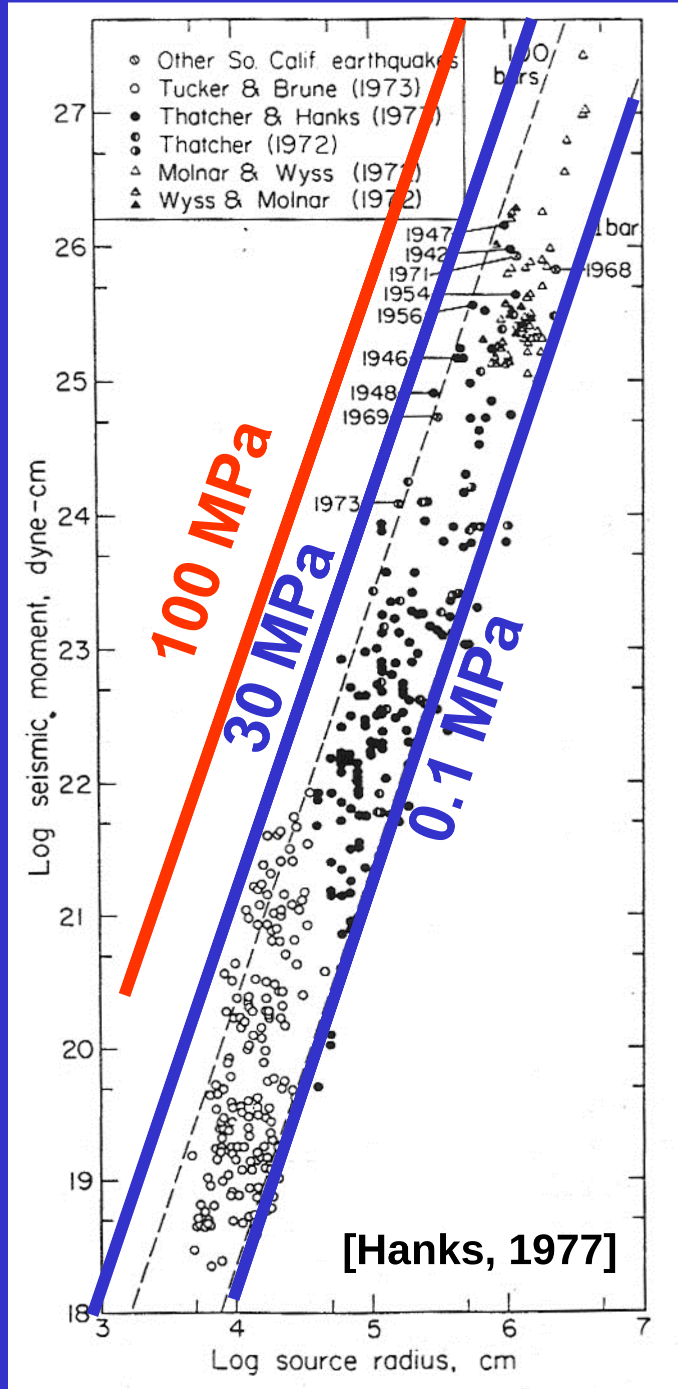
Seismological estimates of stress drops are low (< 30 MPa)

SHIVA: small static stress drops

Rock = calcite gouge σ_n **= 18 MPa**



Smith et al., Geology in press



Dynamic stress drop paradox?

For circular crack

E_r = radiated energy

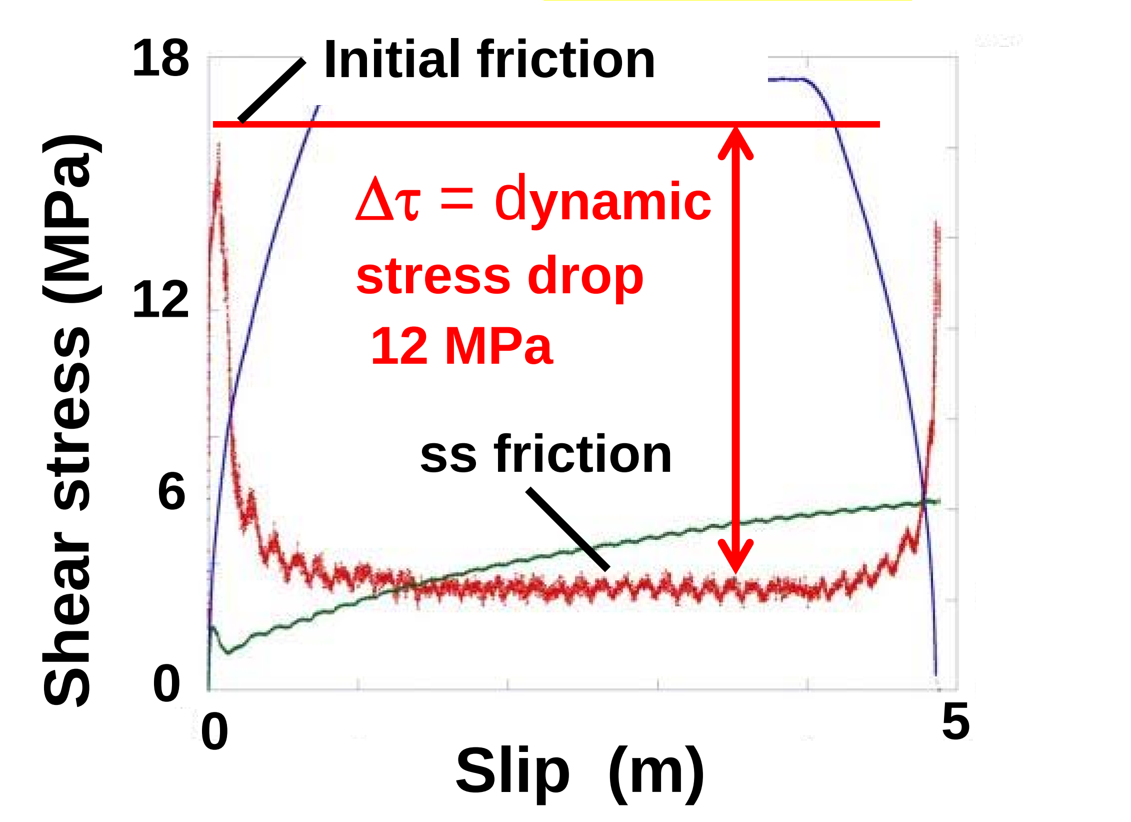
$\Delta\tau$ = dynamic stress drop

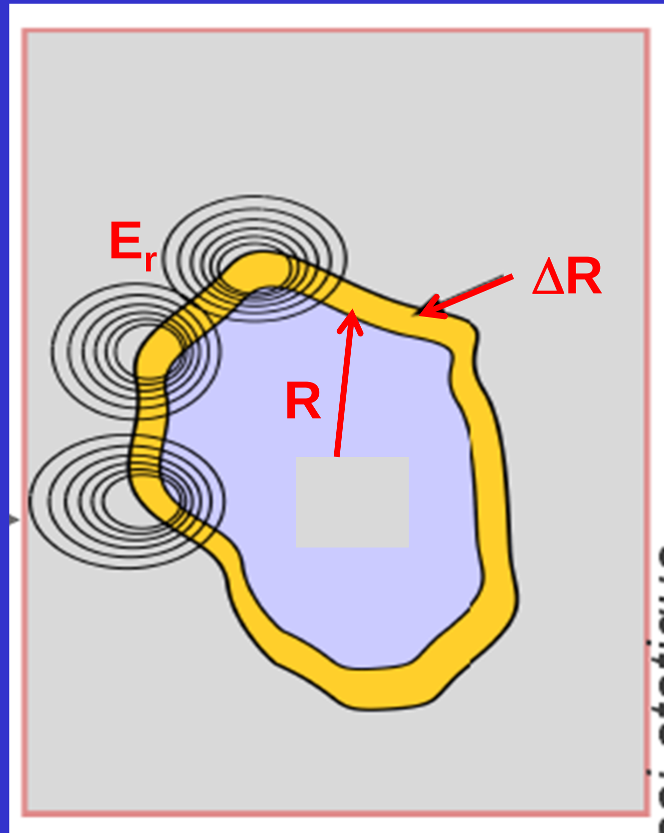
R and V_r = rupture radius and rupture speed

$$E_r \sim (\Delta\tau^2 R^3 / G)\, f(V_r)$$

1) initial friction might be low: heterogeneous stress distr.
2) *R* might not increase with EQ size: pulse-like rupture

Rock = calcite gouge σ_n = 18 MPa





Conclusions

1. Dedicated apparatus **reproduce the extreme deformation conditions** typical of seismic faulting.

2. HVRFE: **fault lubrication** & **empirical friction law**.

3. HVRFE: **experimental products, W_b, μ** and **D_w** are consistent with some natural observations (geological, seismological and geophysical).

4. Lubrication would result in large stress drops (no bugs survival…) but maybe there is **no stress drop paradox. Initial stress is likely heterogeneous** in faults.