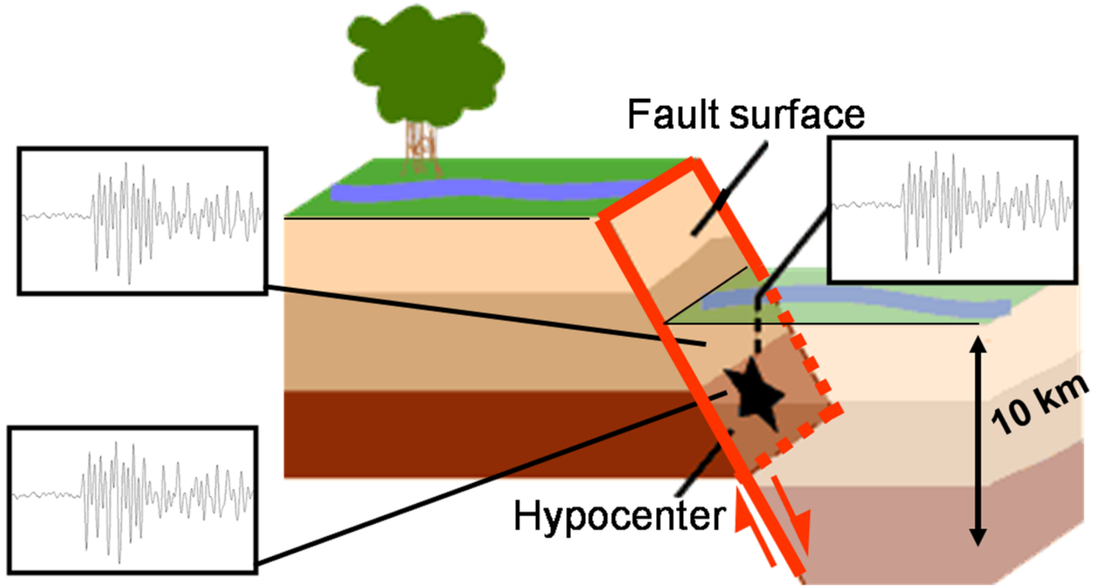
Gouge graphitization and dynamic fault weakening during the 2008 Mw 7.9 Wenchuan earthquake

Li-Wei Kuo, Haibing Li, Steven Smith,
Stefan Nielsen, Giulio Di Toro, John Suppe,
Sheng-Rong Song, Jialiang Si

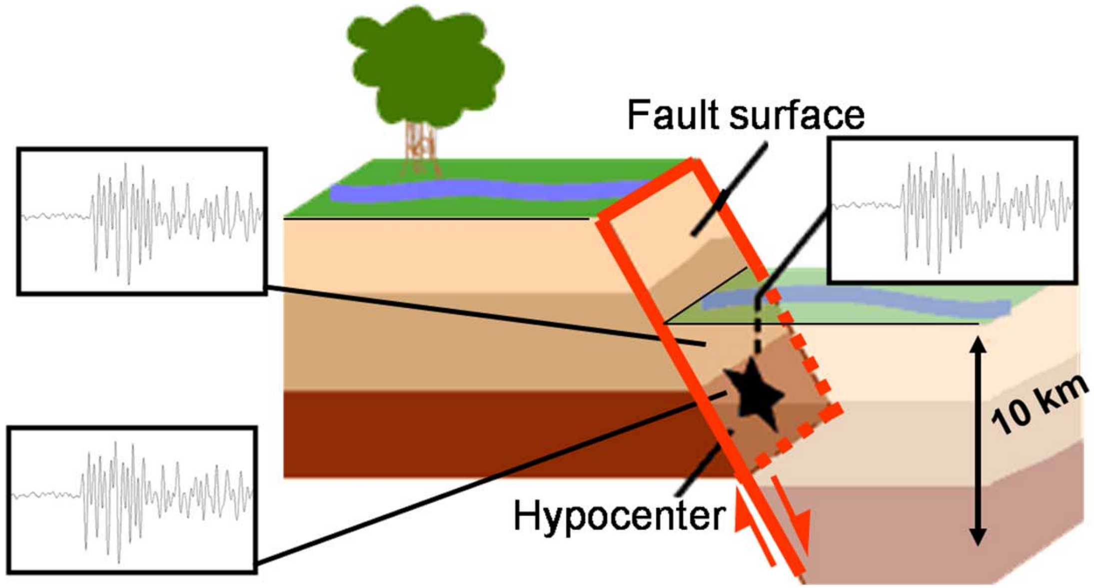
國家同步輻射研究中心
National Synchrotron Radiation Research Center

12/6 at NCU

What's in common

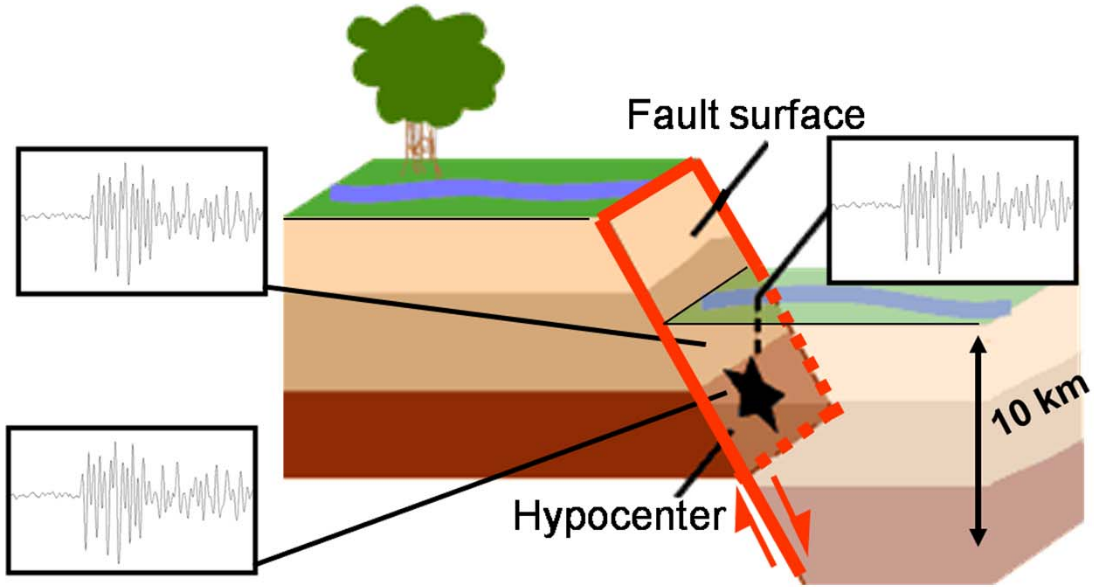


What's in common



- Hiding in somewhere
- Storing energies for next attacks (earthquakes)
- These attacks could not be avoided
- These attacks could not be predicated
- Never be the end

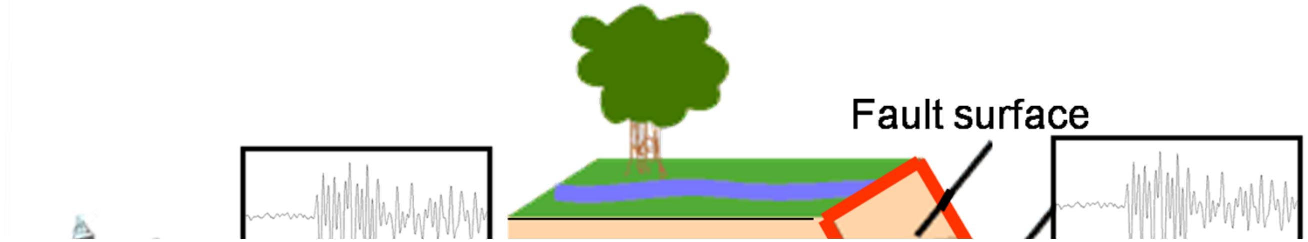
What's in common



- Hiding in somewhere
- Storing energies for next attacks (earthquakes)
- These attacks could not be avoided
- These attacks could not be predicated
- Never be the end

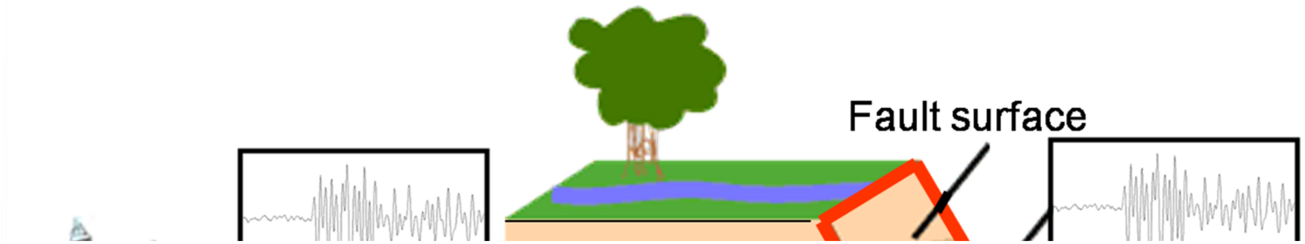
Approaching with multidisciplinary methods

What's in common



- Field survey: to quantify the architecture of fault zone
- Rock deformation experiments: to reproduce seismic slip condition (rock friction, fracture energy and frictional energy)
- Microstructural studies: to infer the physico-chemical processes during coseismic deformation in nature and experiments
- Seismological, geophysical and remote-sensed (GPS, InSAR) methods: to retrieve key parameters related to EQ source (seismic moment, static stress drop, radiated energy)

What's in common

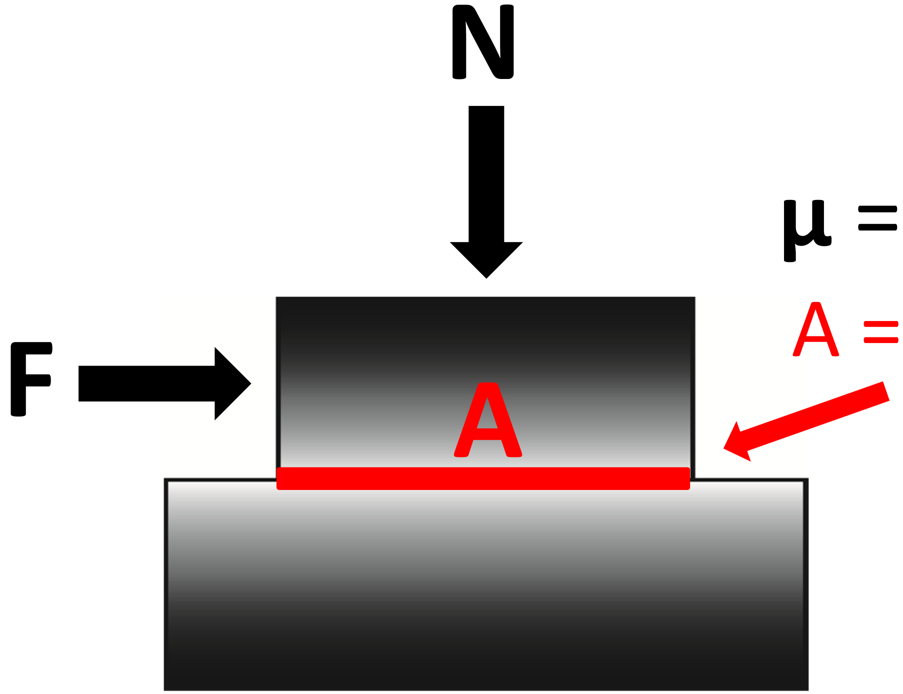


- Field survey: to quantify the architecture of fault zone
- Rock deformation experiments: to reproduce seismic slip condition (rock friction, fracture energy and frictional energy)
- Microstructural studies: to infer the physico-chemical processes during coseismic deformation in nature and experiments
- Seismological, geophysical and remote-sensed (GPS, InSAR) methods: to retrieve key parameters related to EQ source (seismic moment, static stress drop, radiated energy)

What is rock friction?

$\mu = F / N$

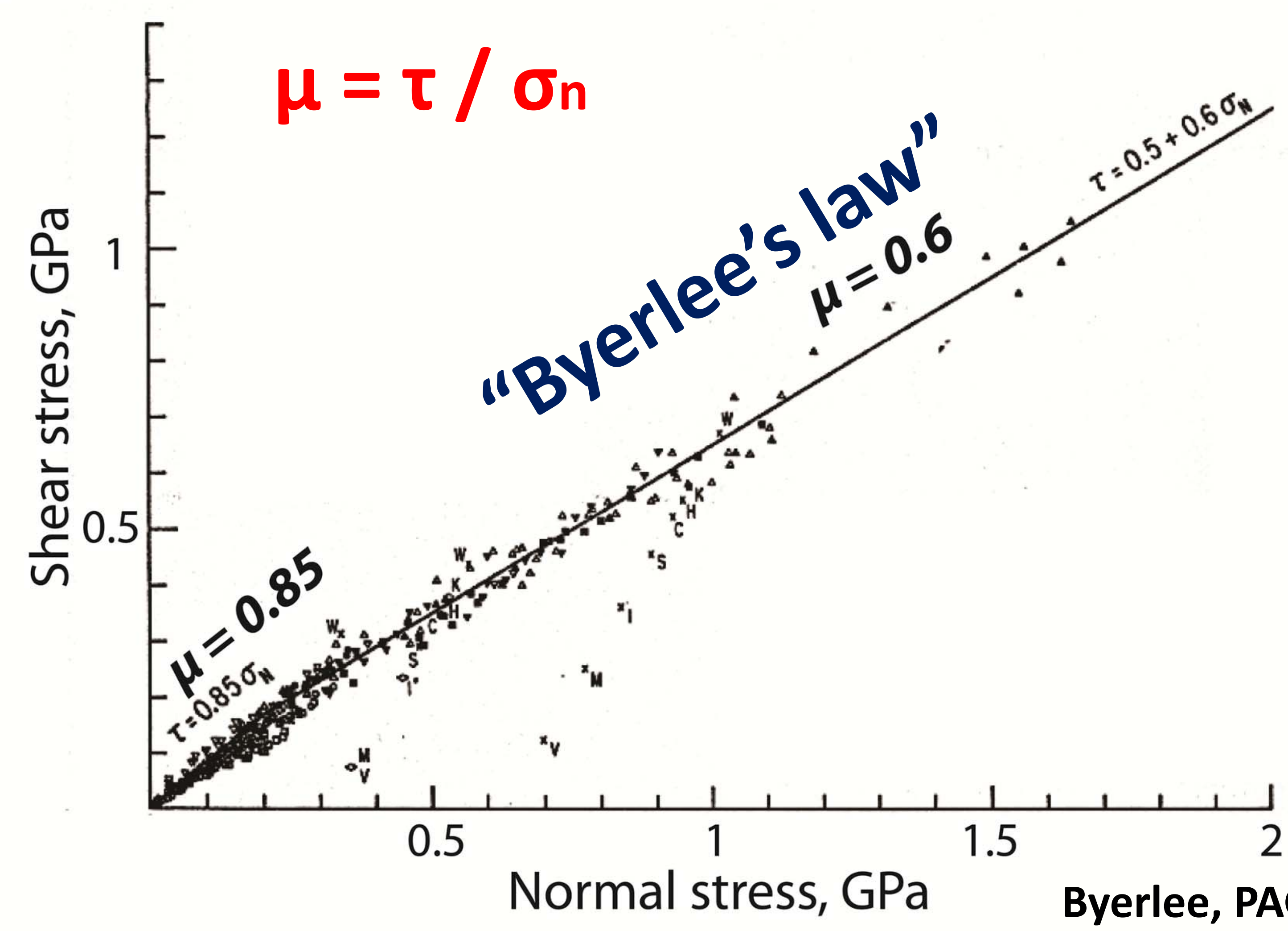
μ = friction coefficient



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

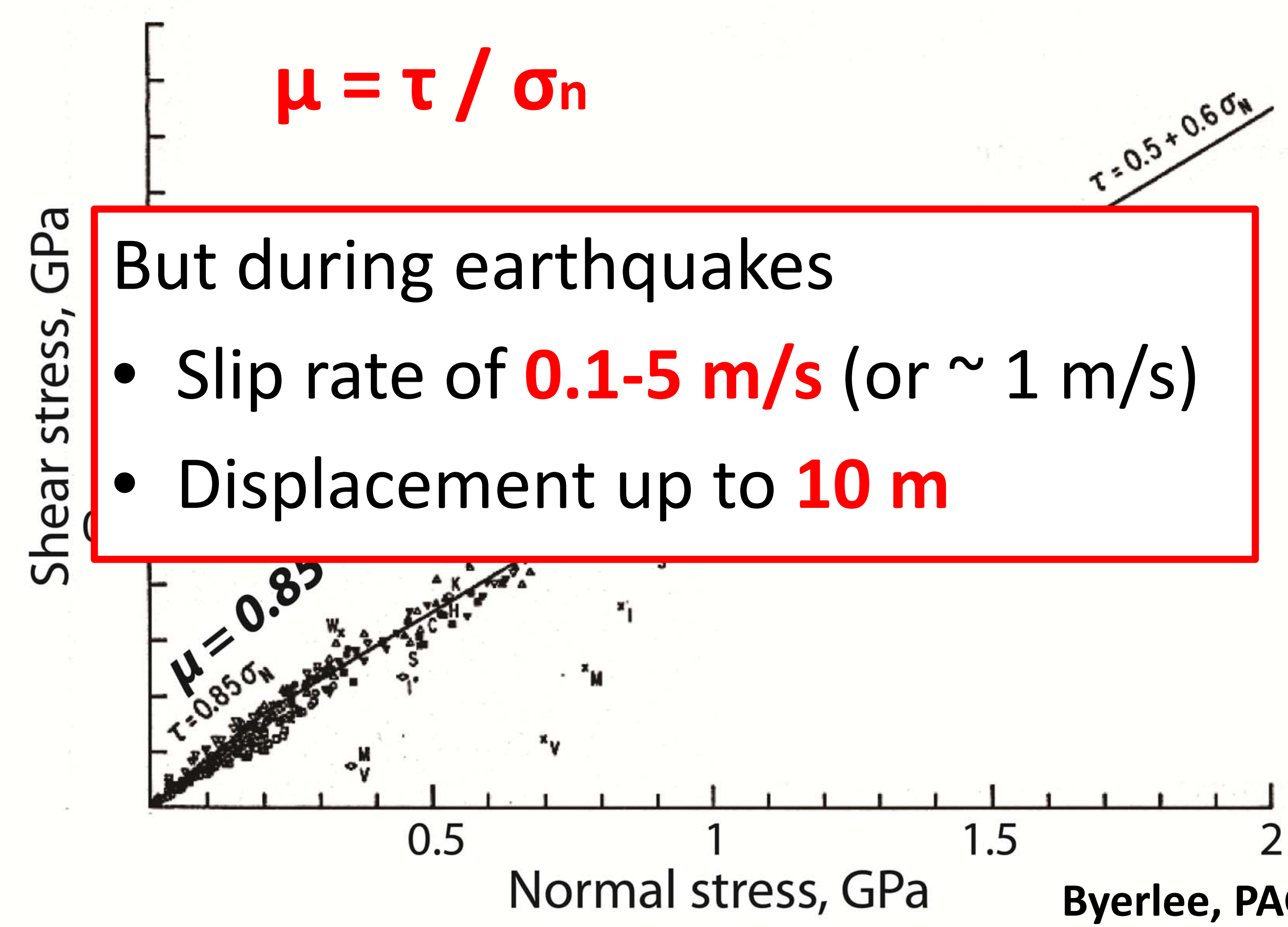
A = Nominal area of contact

At slow slip rates (< 1 mm/s) and for short displacement (< 1 cm) rock friction (μ) is **0.6-0.8**



Byerlee, PAGEOPH, 1978

At slow slip rates (< 1 mm/s) and for short displacement (< 1 cm) rock friction (μ) is **0.6-0.8**

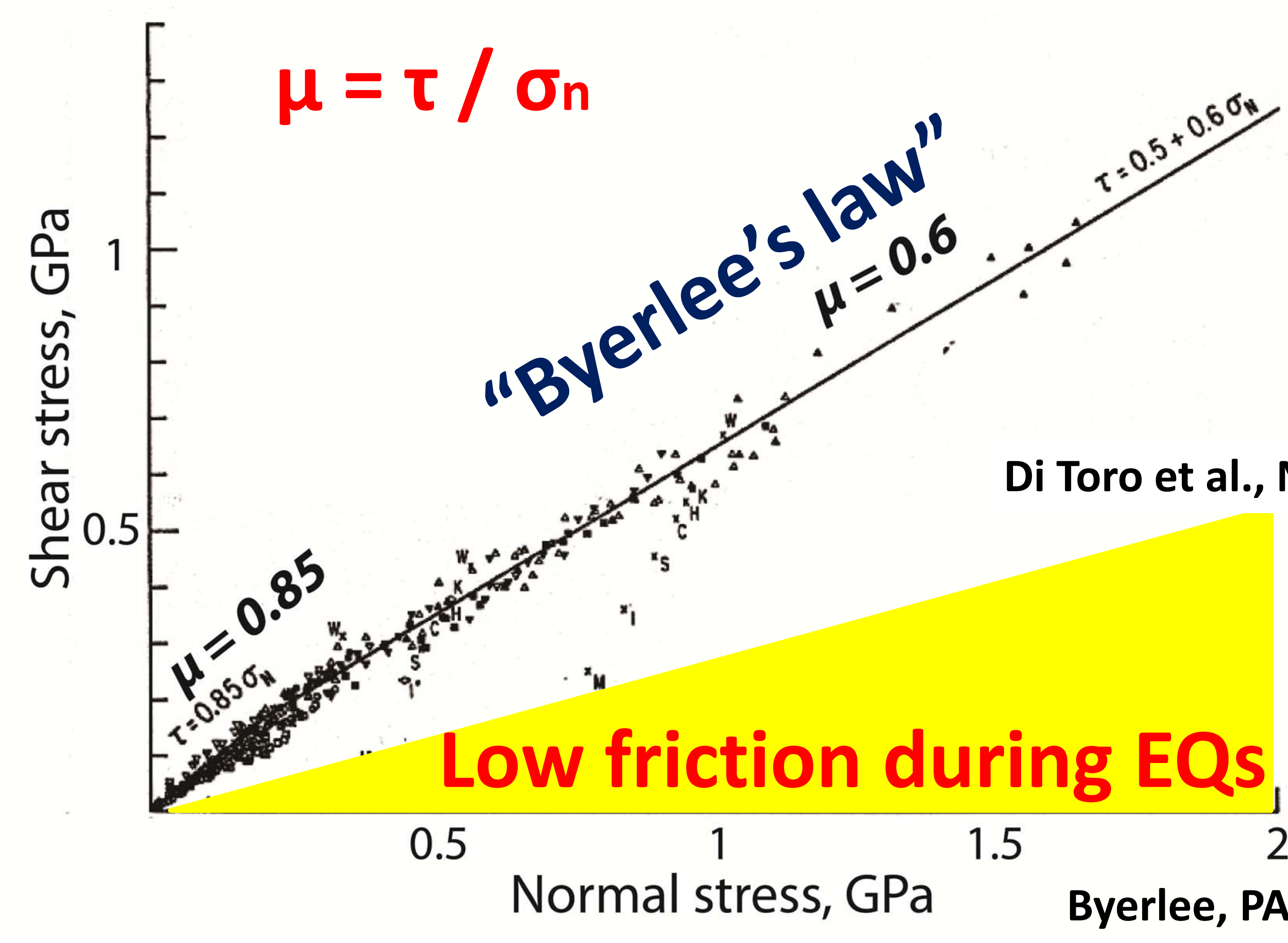


But during earthquakes

- Slip rate of **0.1-5 m/s** (or ~ 1 m/s)
- Displacement up to **10 m**

Byerlee, PAGEOPH, 1978

Under these extreme deformation conditions, μ could be < **0.2**



Di Toro et al., Nature, 2011

Byerlee, PAGEOPH, 1978

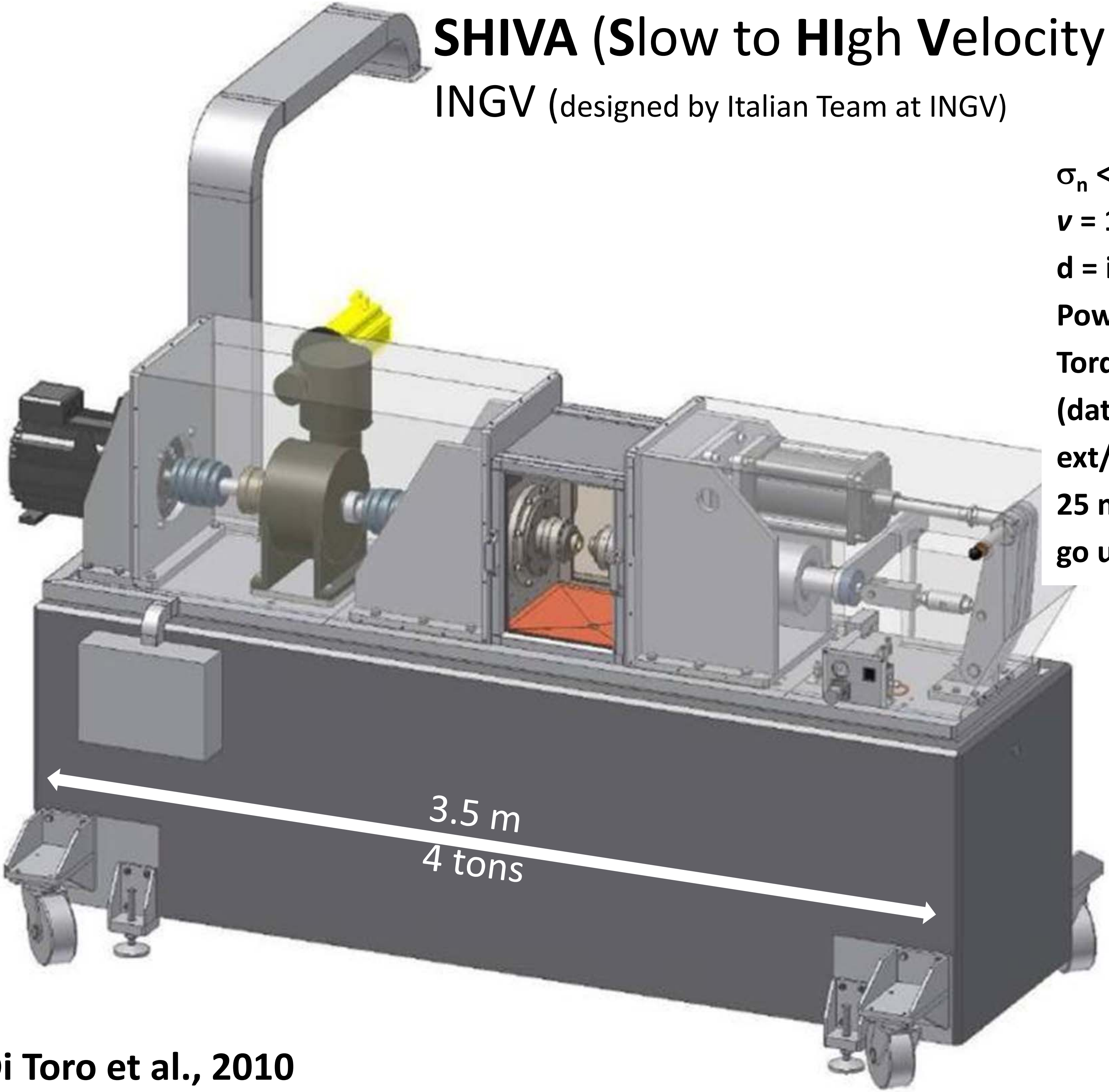
High Velocity Rock Friction Experiments (HVRFE) performed at seismic slip rates (**0.1-10 m/s**) may allow the:

- Determination of **dynamic friction** (and its evolution) during seismic slip
- Investigation of the **physico-chemical processes** occurring during simulated faulting
- Recognition of **mineralogical and microstructural indicators** within exhumed (or active) fault zones
- Identification of **fault weakening mechanisms**

SHIVA (**S**low to **HI**gh **V**elocity **A**pparatus)

INGV (designed by Italian Team at INGV)

σ_n < 70 MPa
v = 1 μm/s - 9 m/s
d = infinite
Power 270 kW
Torque 1100 Nm
(data for 50/30 mm ext/int diameter: with 25 mm diam., we can go up to 100 MPa)

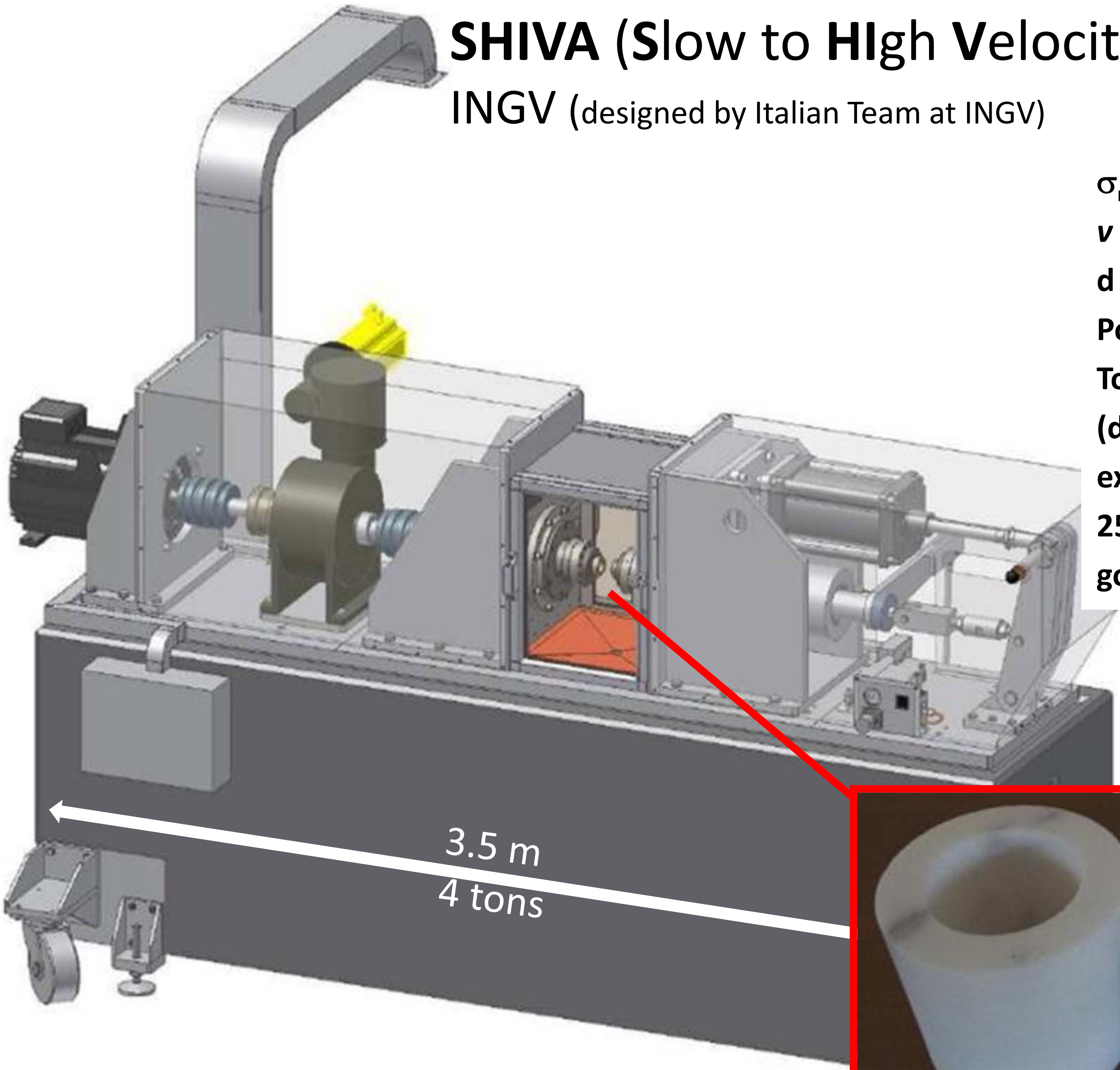


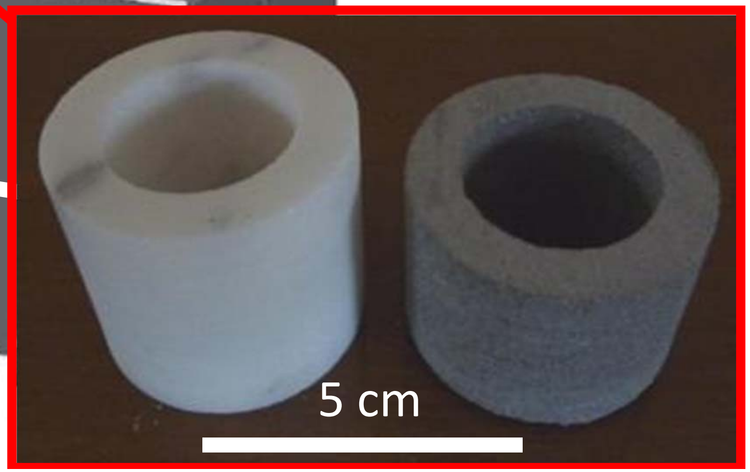
Di Toro et al., 2010

SHIVA (**S**low to **HI**gh **V**elocity **A**pparatus)

INGV (designed by Italian Team at INGV)

σ_n < 70 MPa
***v* = 1 μm/s - 9 m/s**
d = infinite
Power 270 kW
Torque 1100 Nm
(data for 50/30 mm ext/int diameter: with 25 mm diam., we can go up to 100 MPa)



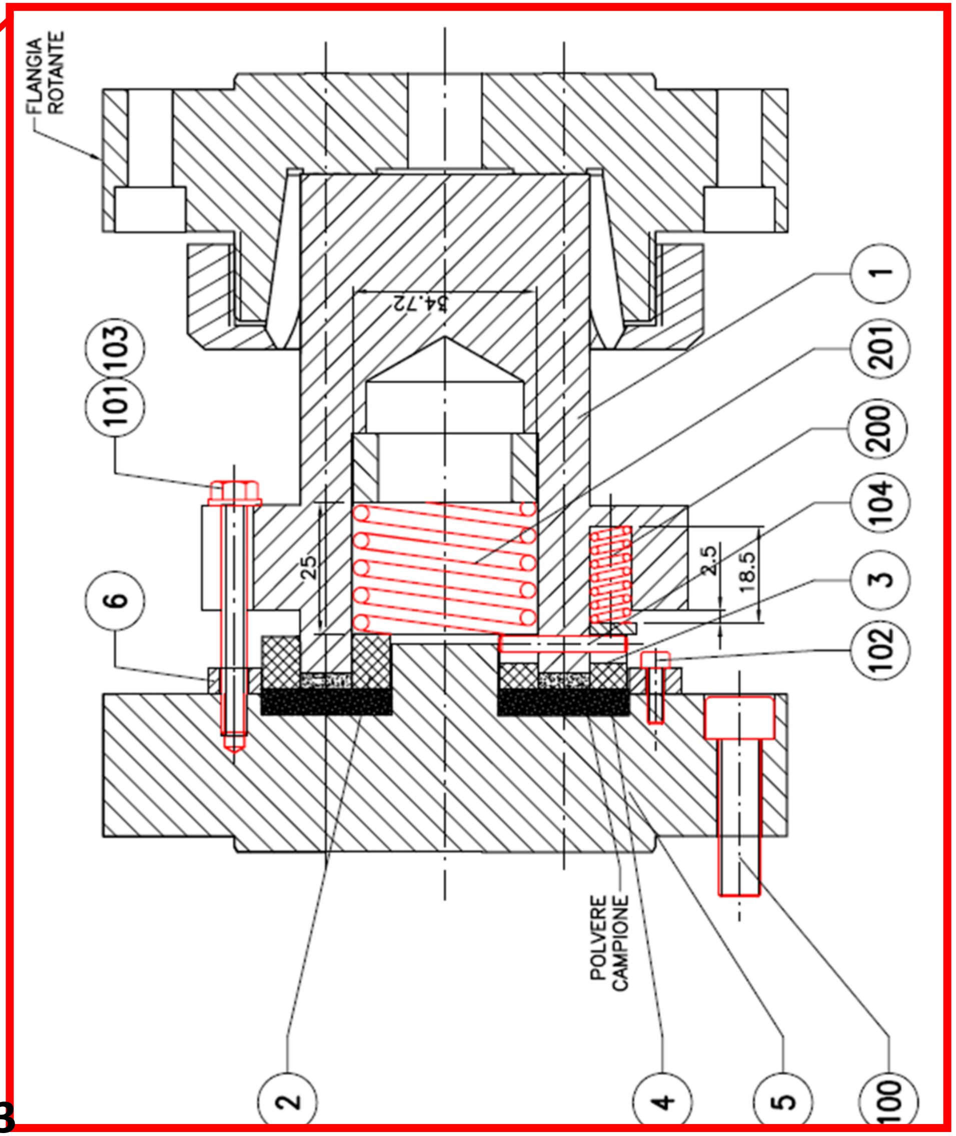


Di Toro et al., 2010

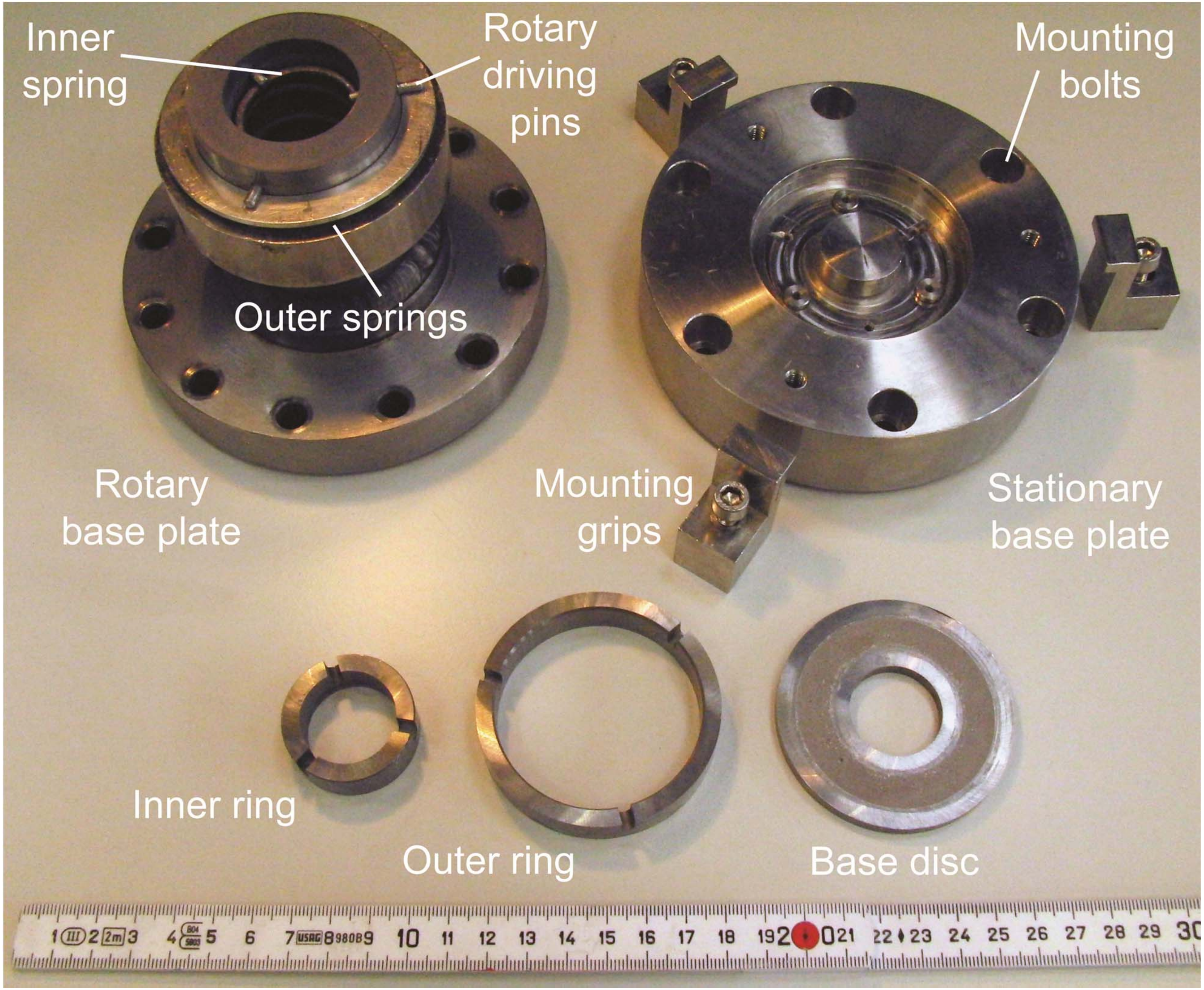
An environmental/vacuum chamber equipped with a mass spectrometer has been installed in 2010. We have facilities to control O2 fugacity in the experiments.

Experiments with gouges

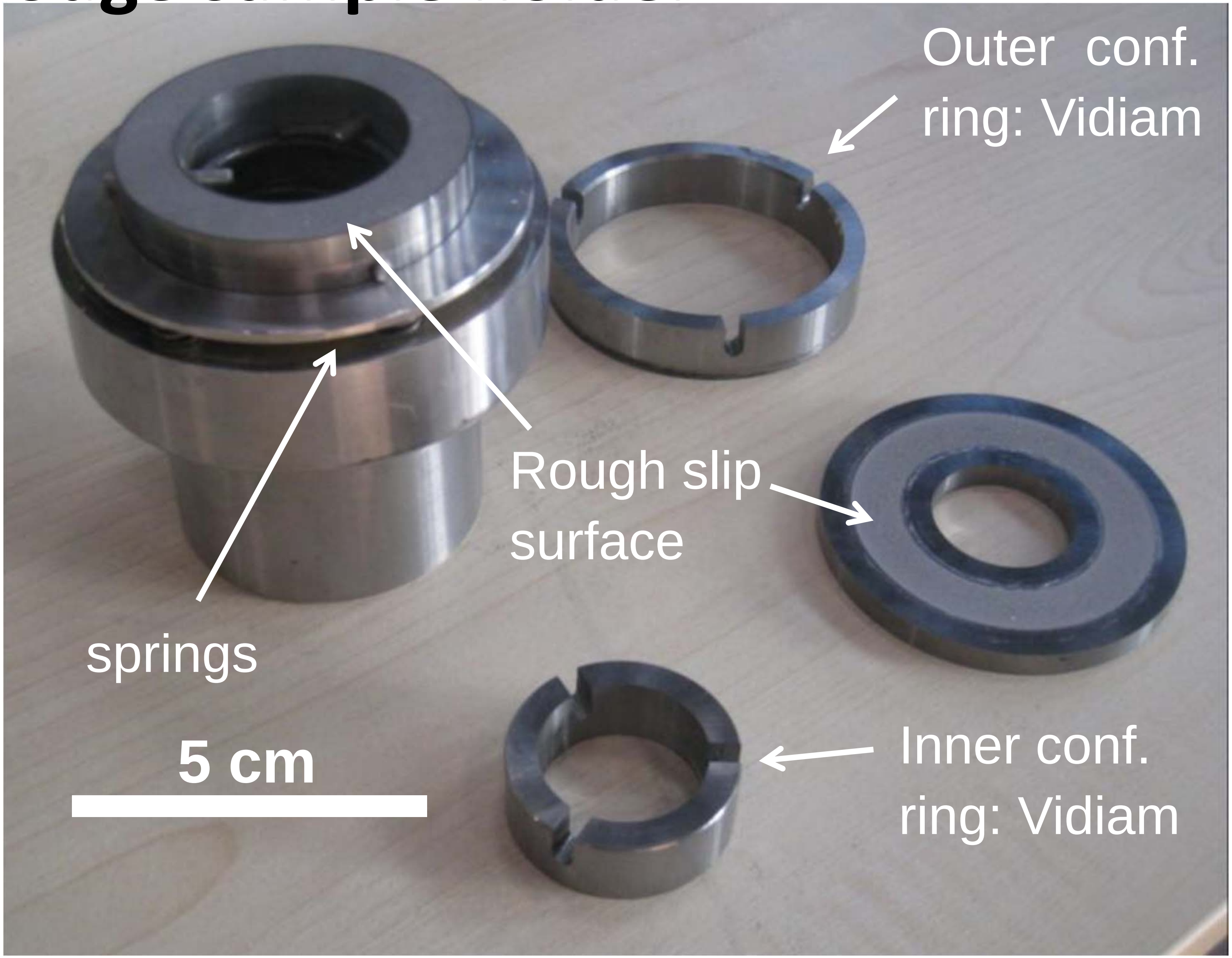
Sample holder to perform experiments with non cohesive rocks. We tested it up to 32 MPa normal stress and 6.5 m/s slip rate.



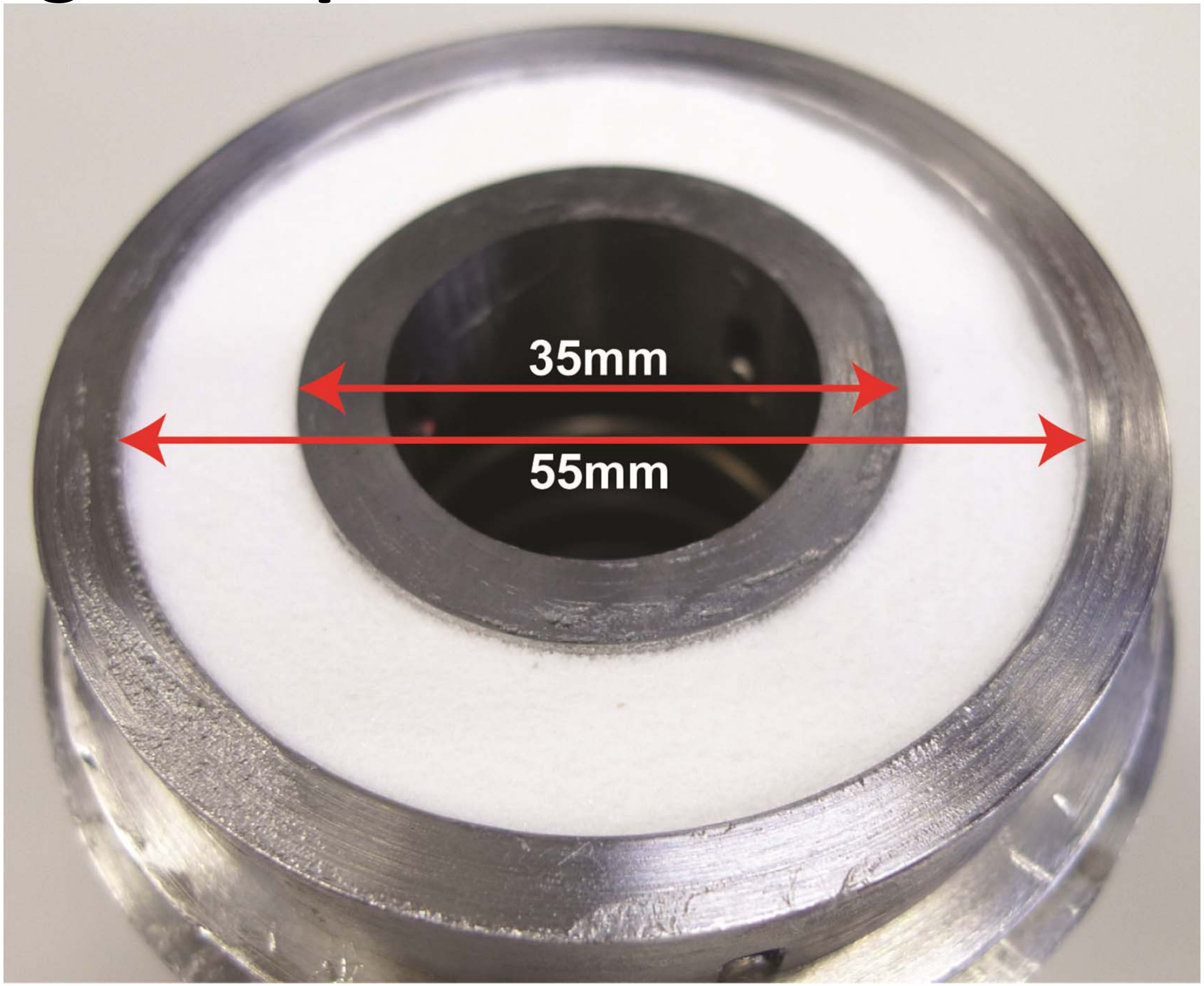
See the detail in Smith et al., Geology, 2013


Inner spring
Rotary driving pins
Mounting bolts
Outer springs
Rotary base plate
Mounting grips
Stationary base plate
Inner ring
Outer ring
Base disc

Gouge sample holder



Gouge sample holder



Gouge sample holder

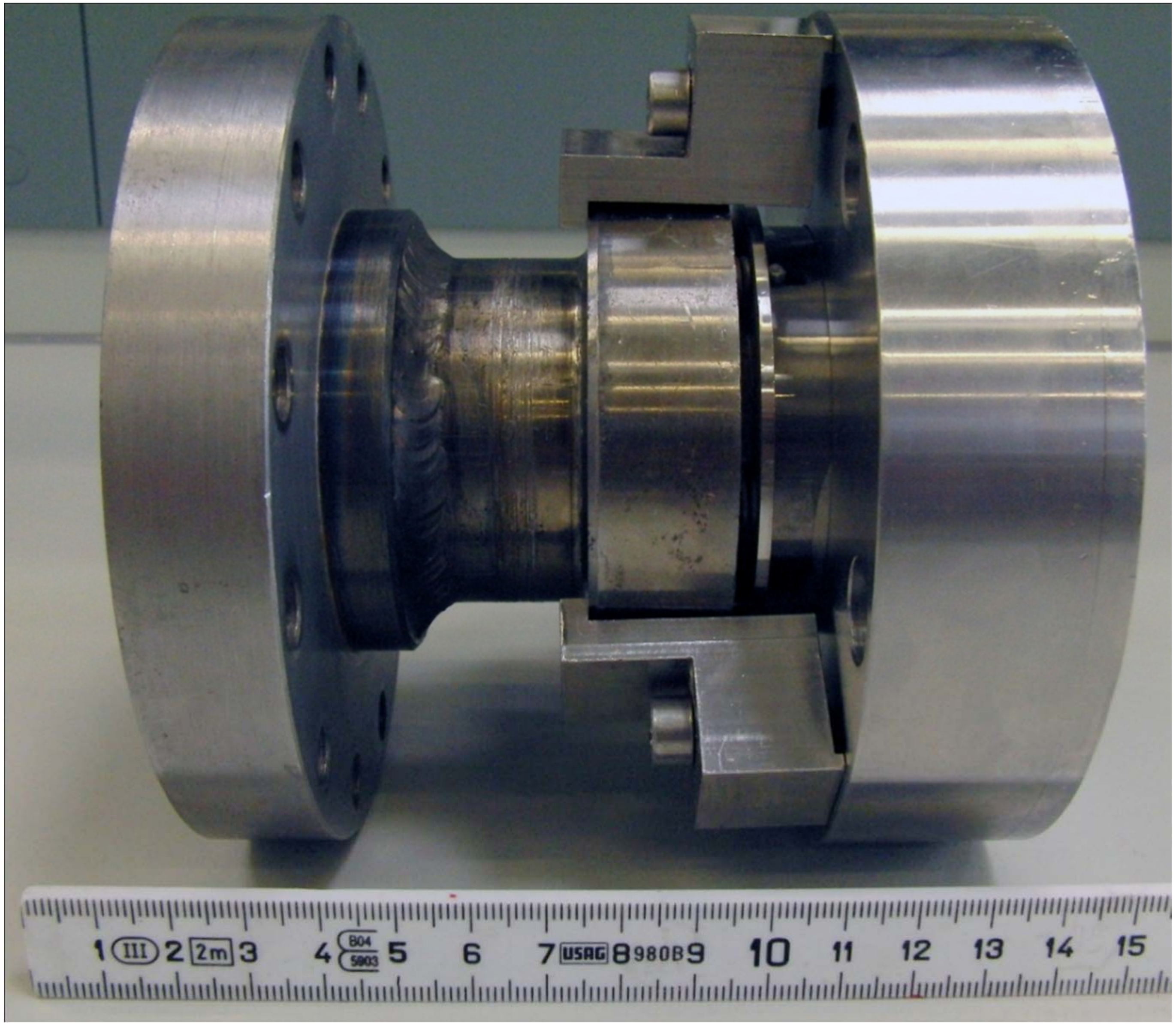
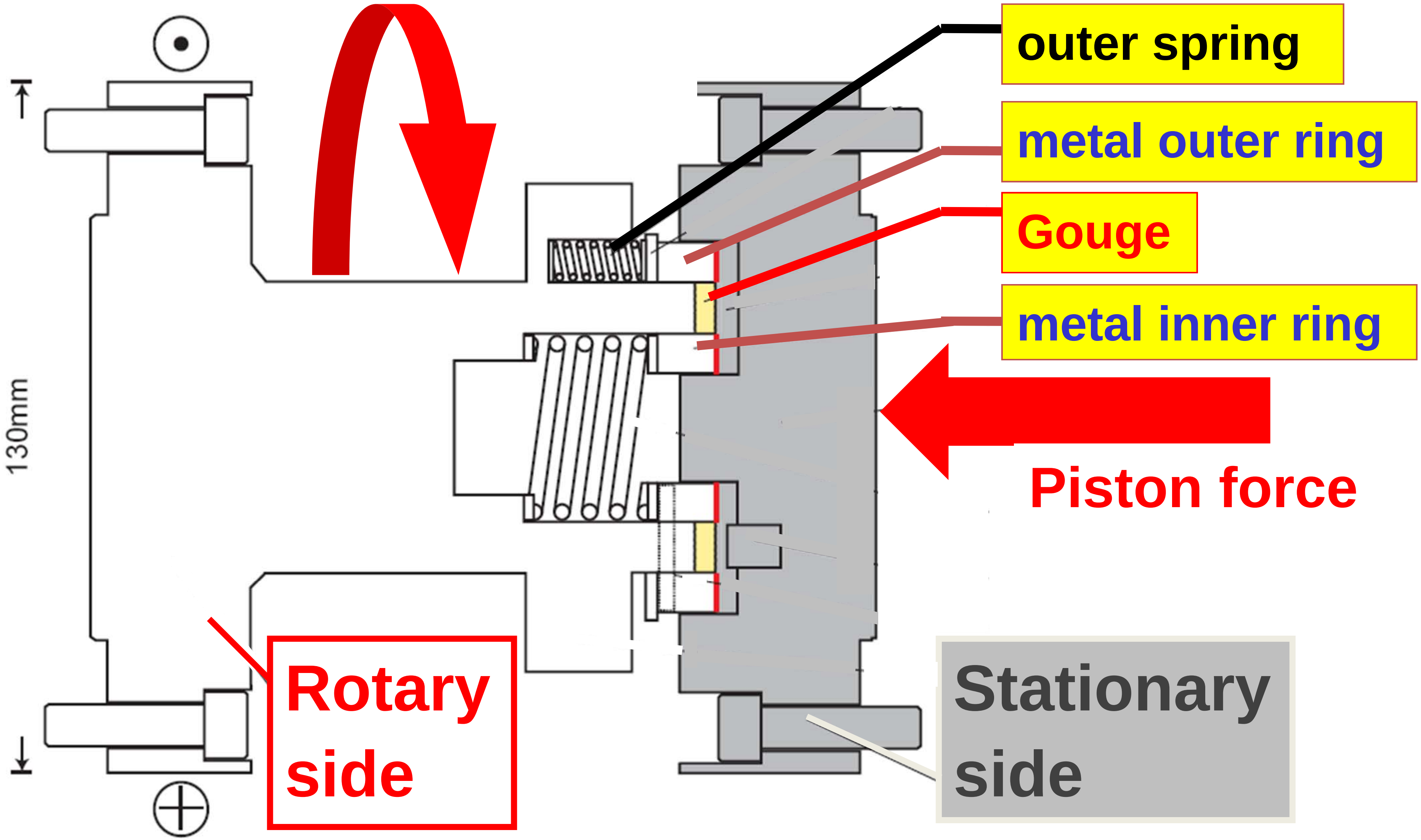
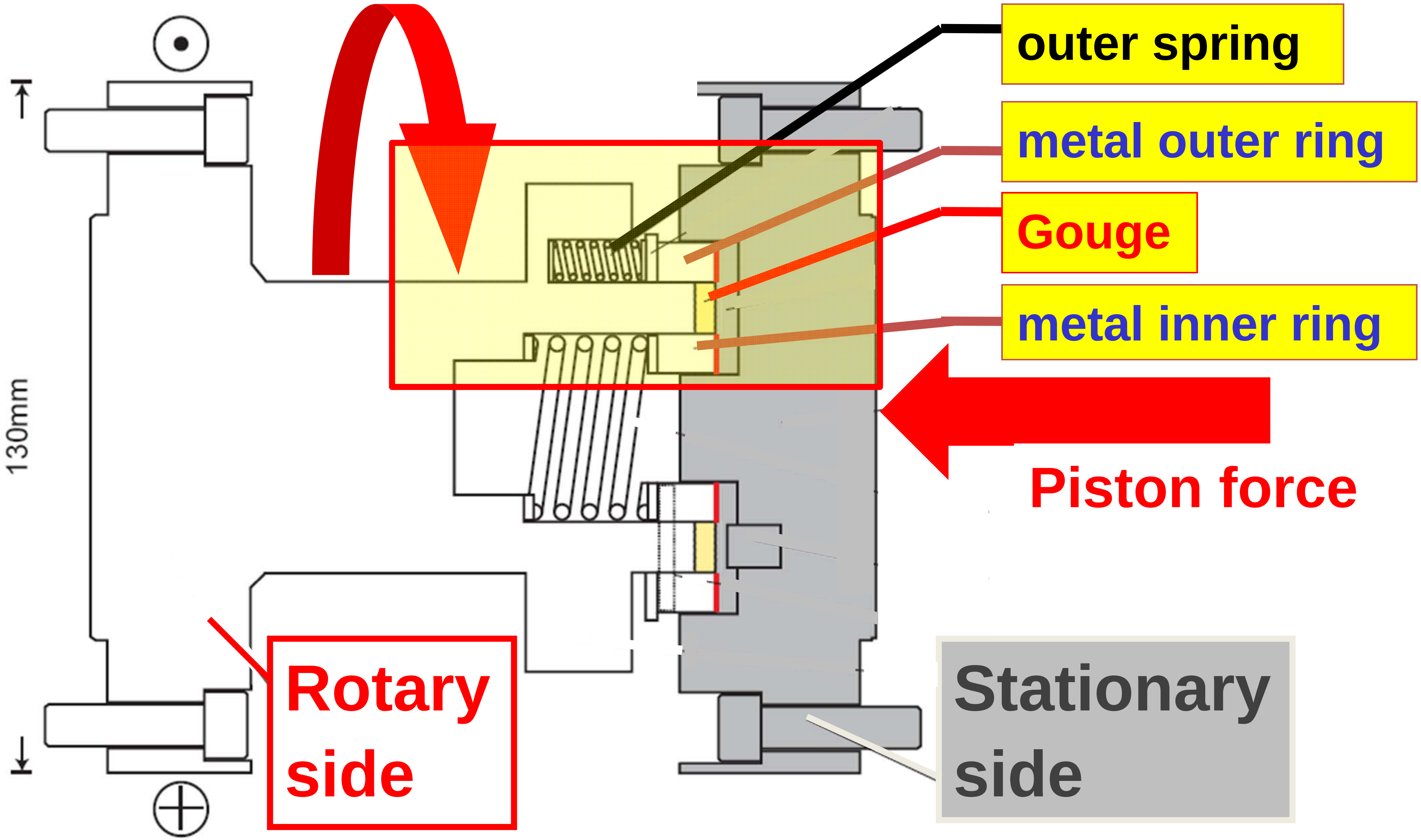
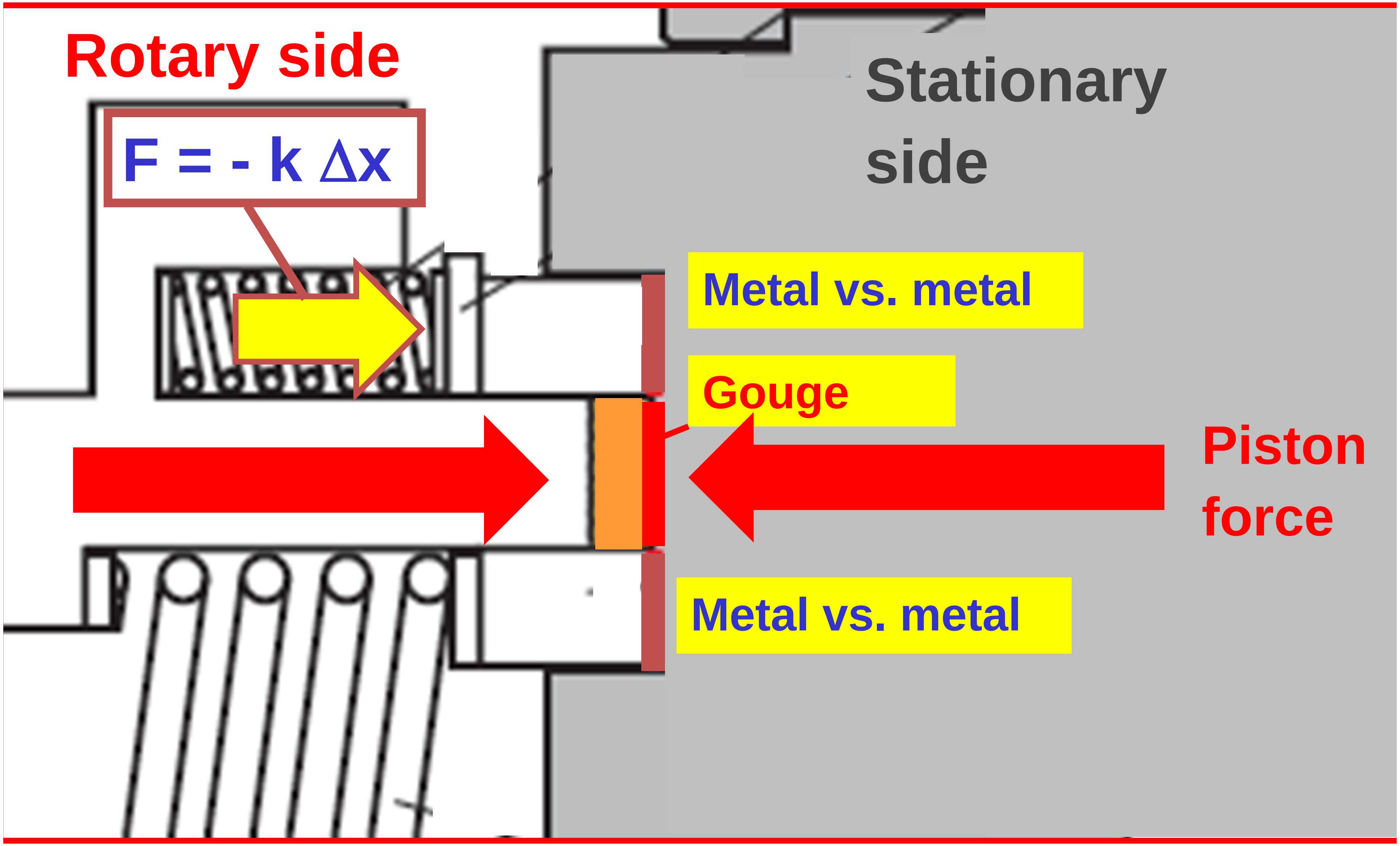


Photo of gouge holder in same orientation as previous diagram

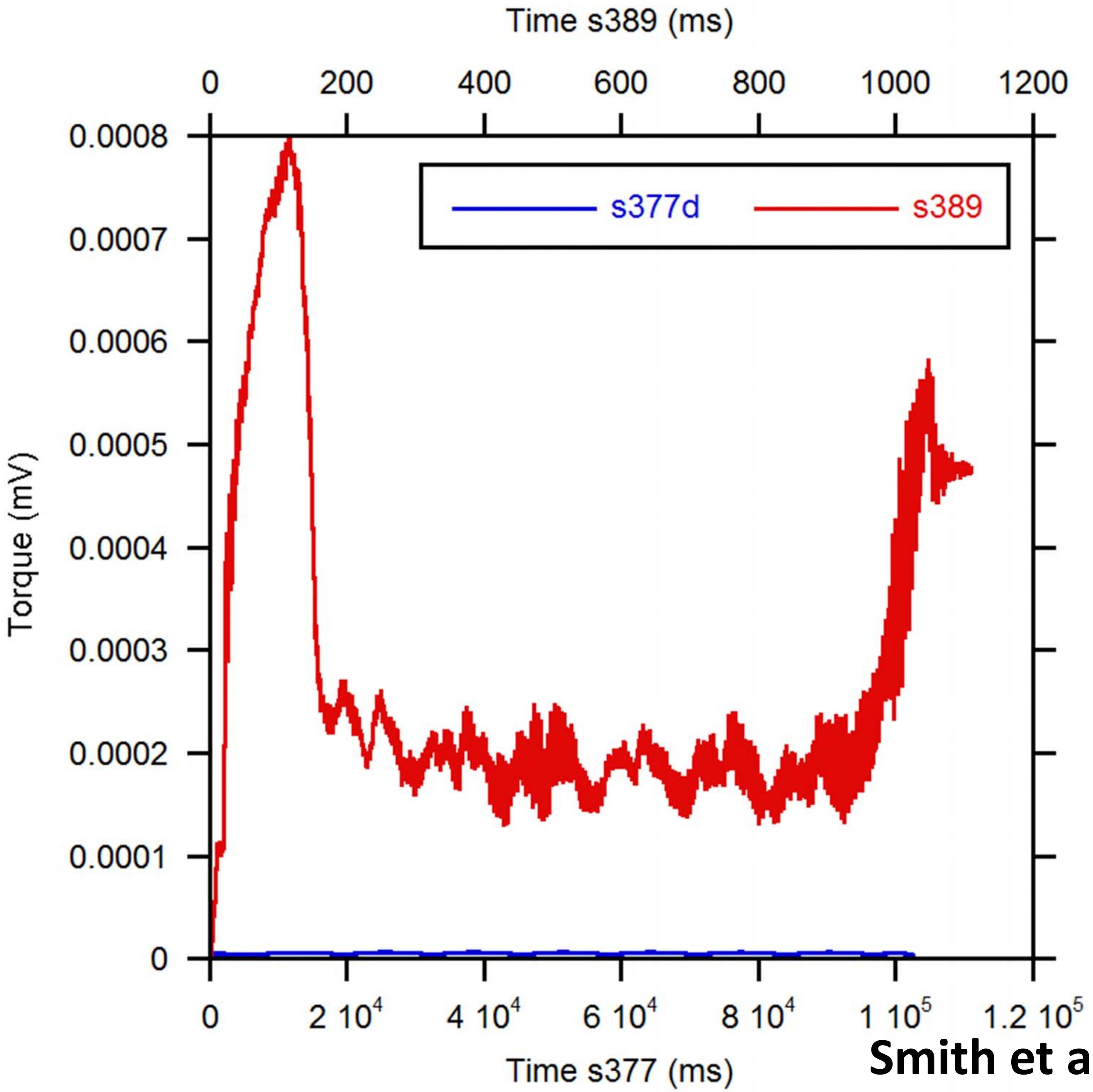

outer spring
metal outer ring
Gouge
metal inner ring
Piston force
130mm
Rotary side
Stationary side


outer spring
metal outer ring
Gouge
metal inner ring
Piston force
130mm
Rotary side
Stationary side

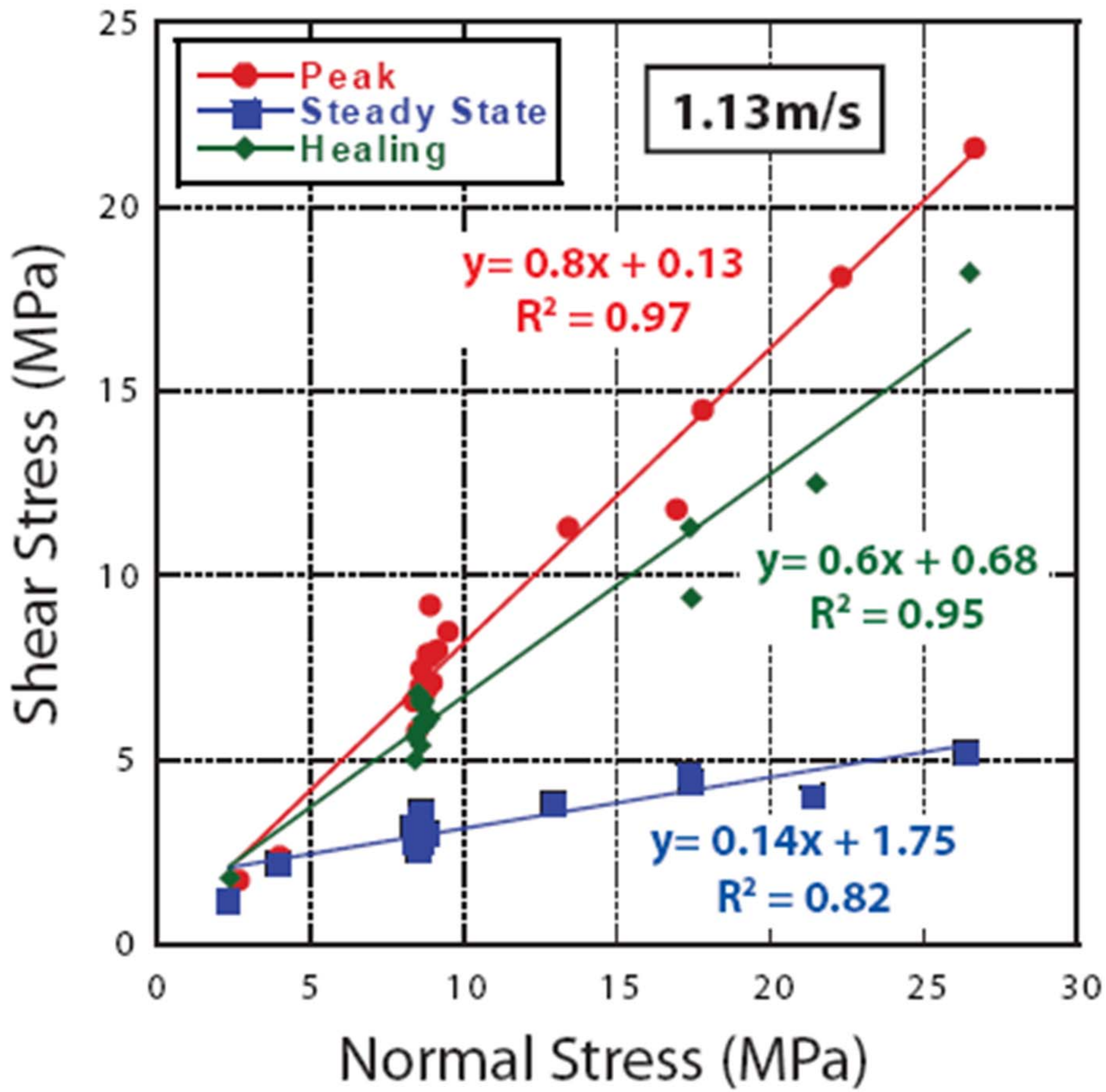


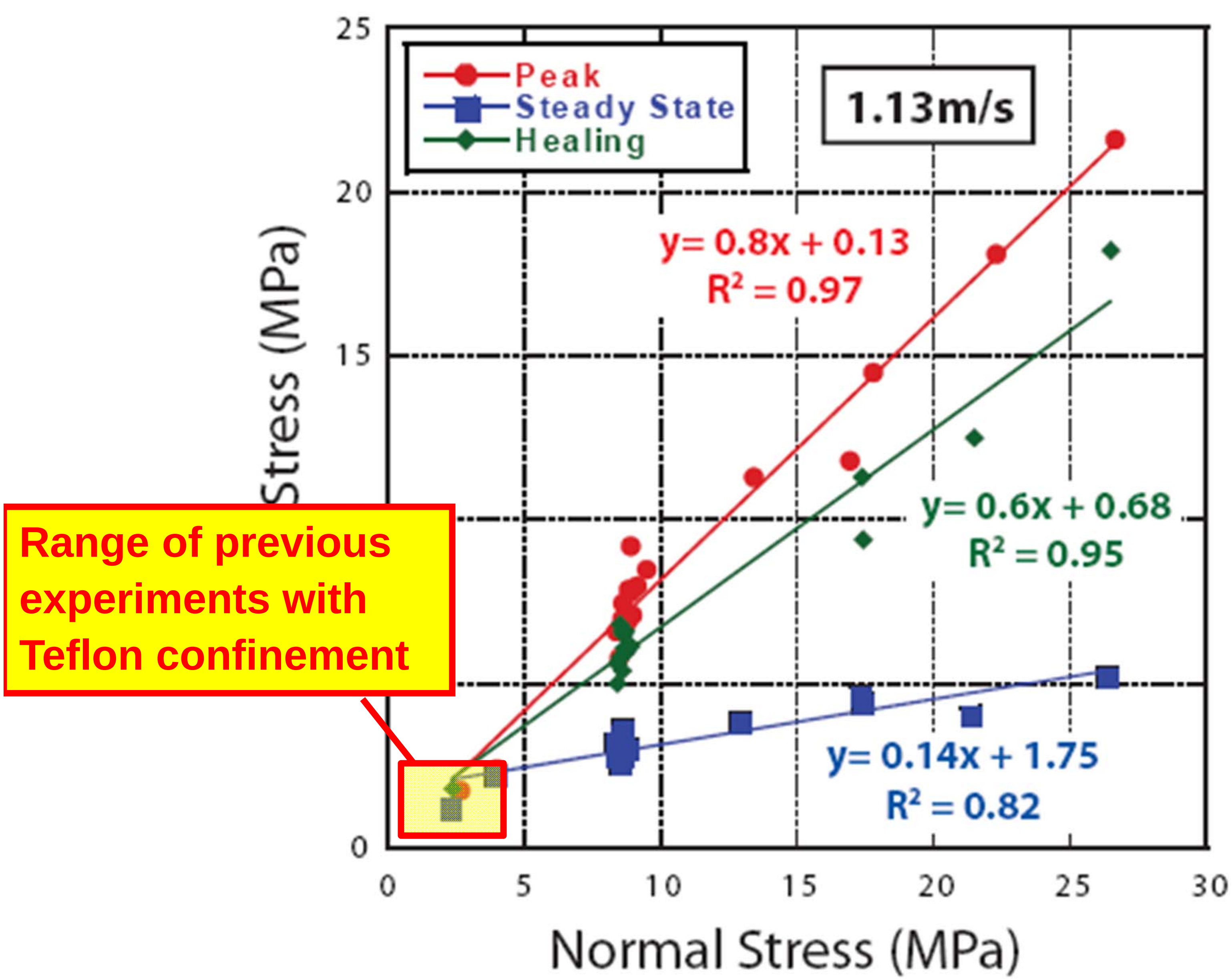
Rotary side
F = - k Δx
Stationary side
Metal vs. metal
Gouge
Piston force
Metal vs. metal

Calibration of sample holder with calcite powders

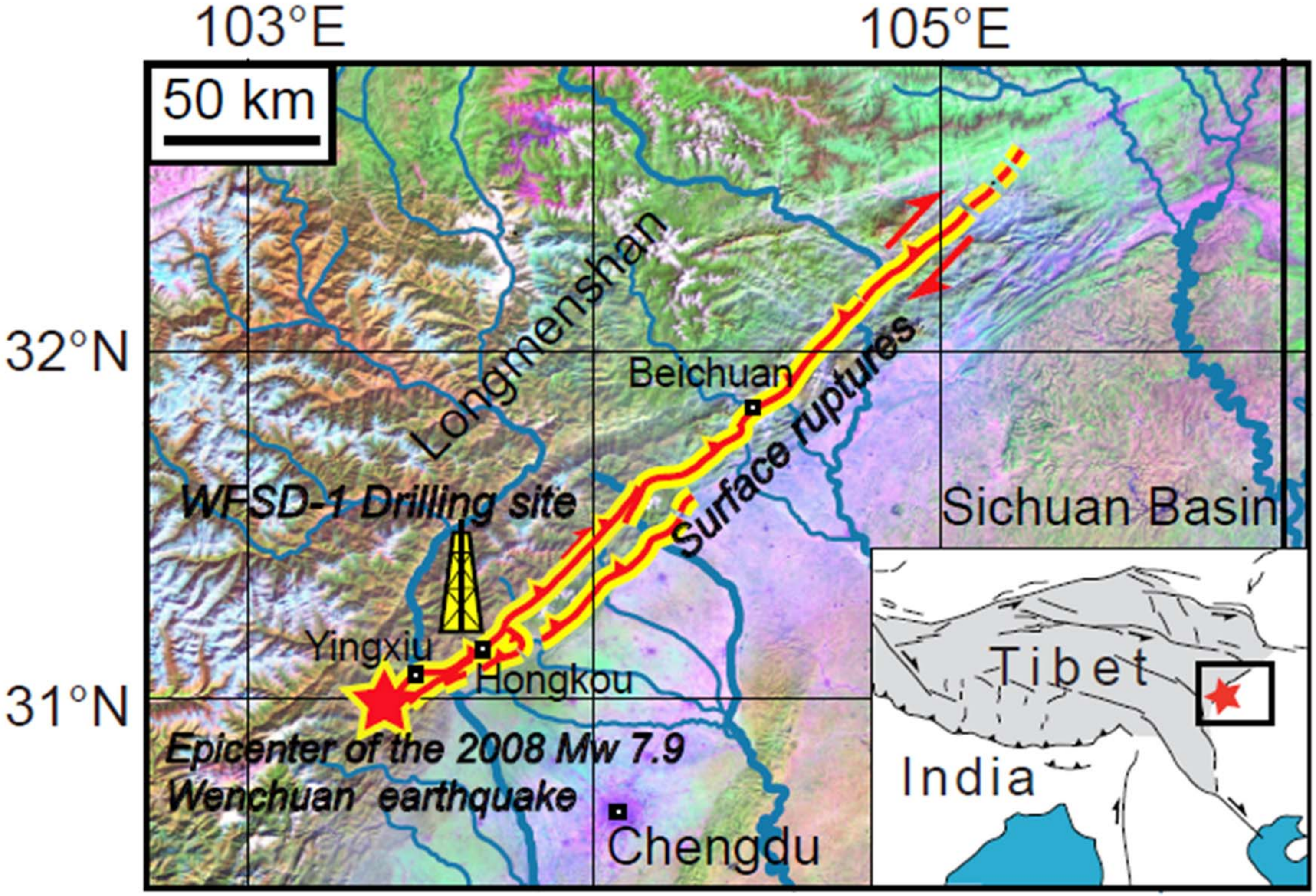


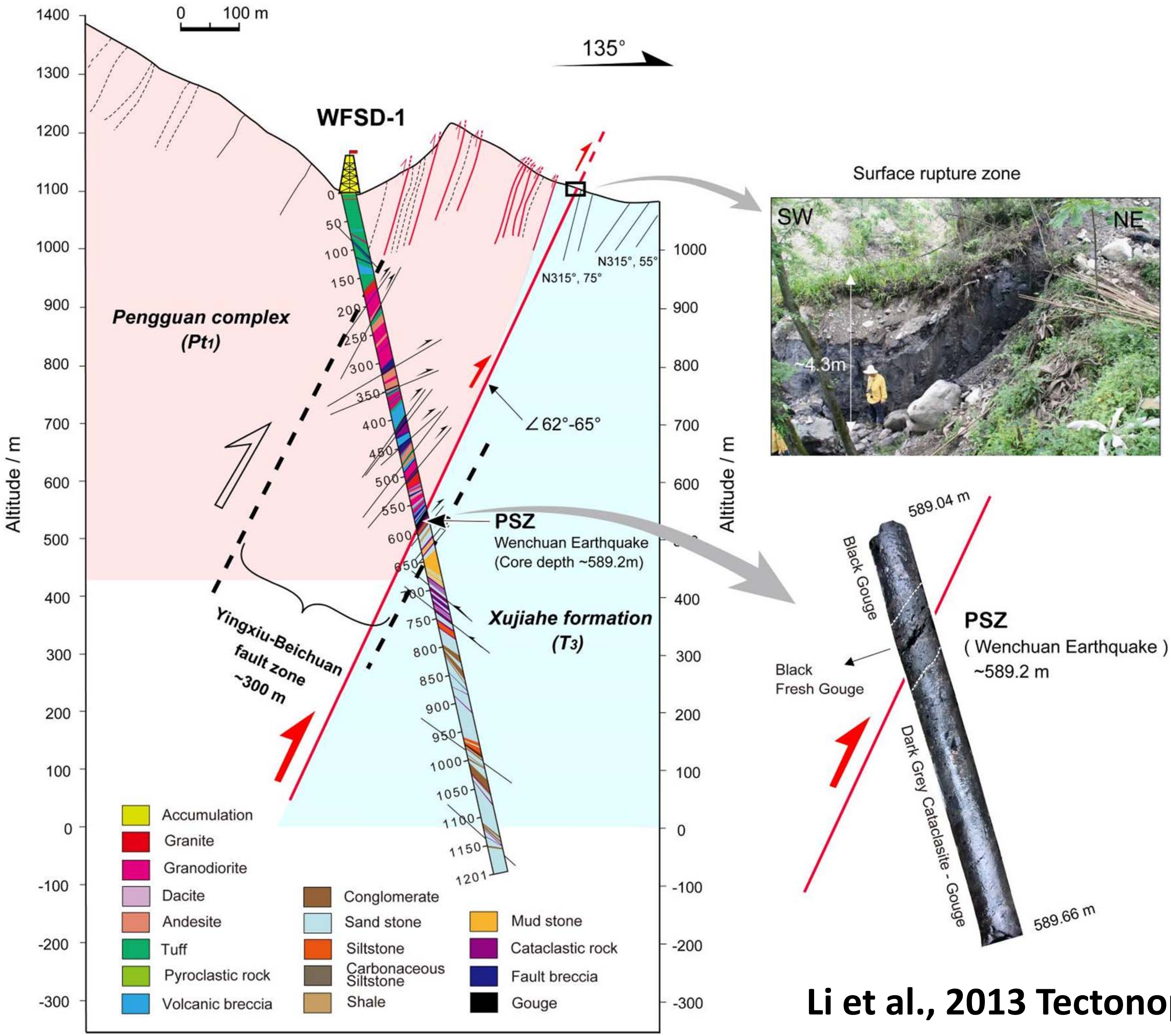
Smith et al., in prep.


Peak
Steady State
Healing
1.13m/s
y= 0.8x + 0.13
R² = 0.97
y= 0.6x + 0.68
R² = 0.95
y= 0.14x + 1.75
R² = 0.82
Shear Stress (MPa)
Normal Stress (MPa)
0
5
10
15
20
25
30

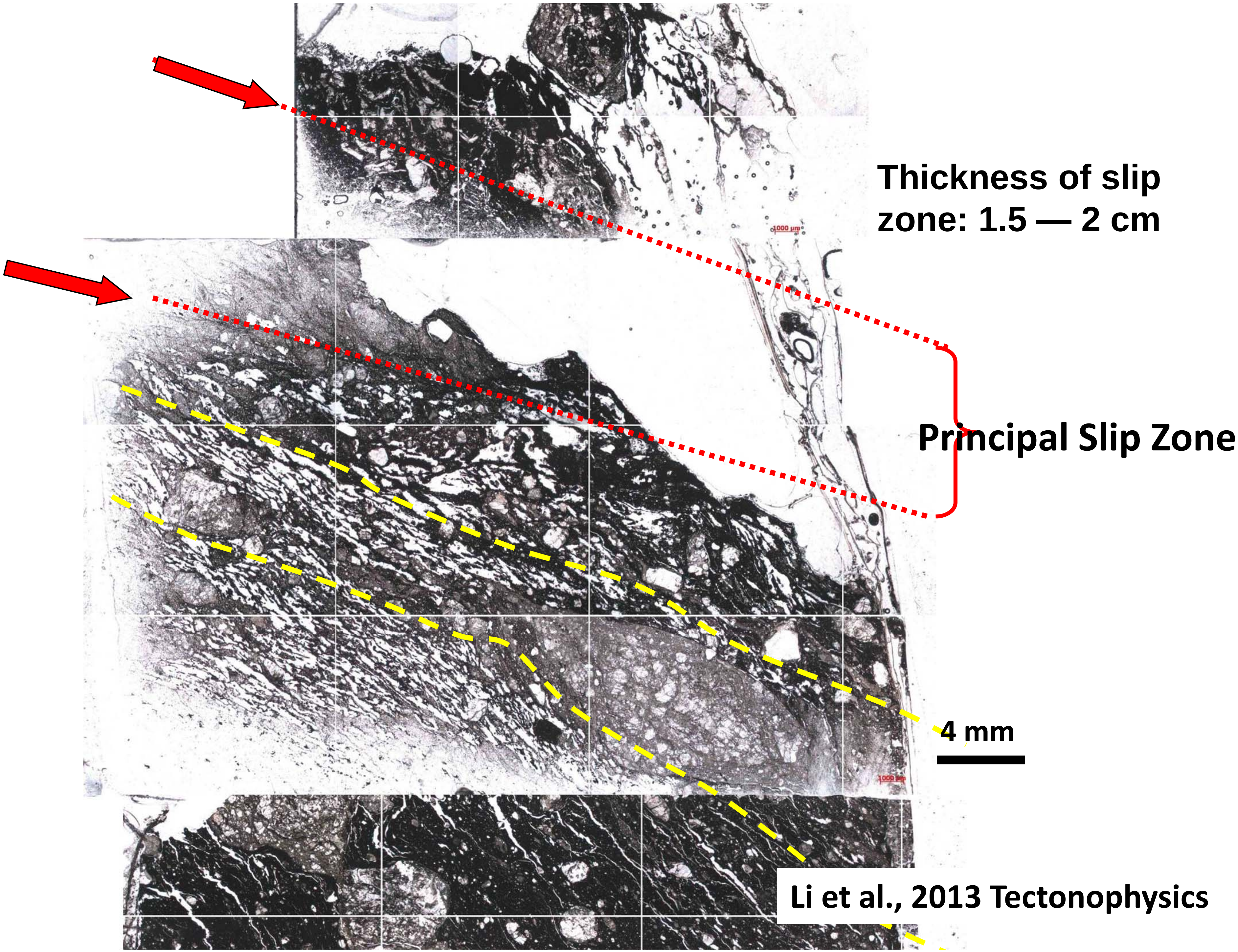

Peak
Steady State
Healing
1.13m/s
y= 0.8x + 0.13
R² = 0.97
y= 0.6x + 0.68
R² = 0.95
y= 0.14x + 1.75
R² = 0.82
Range of previous experiments with Teflon confinement
Stress (MPa)
Normal Stress (MPa)
0
5
10
15
20
25
30

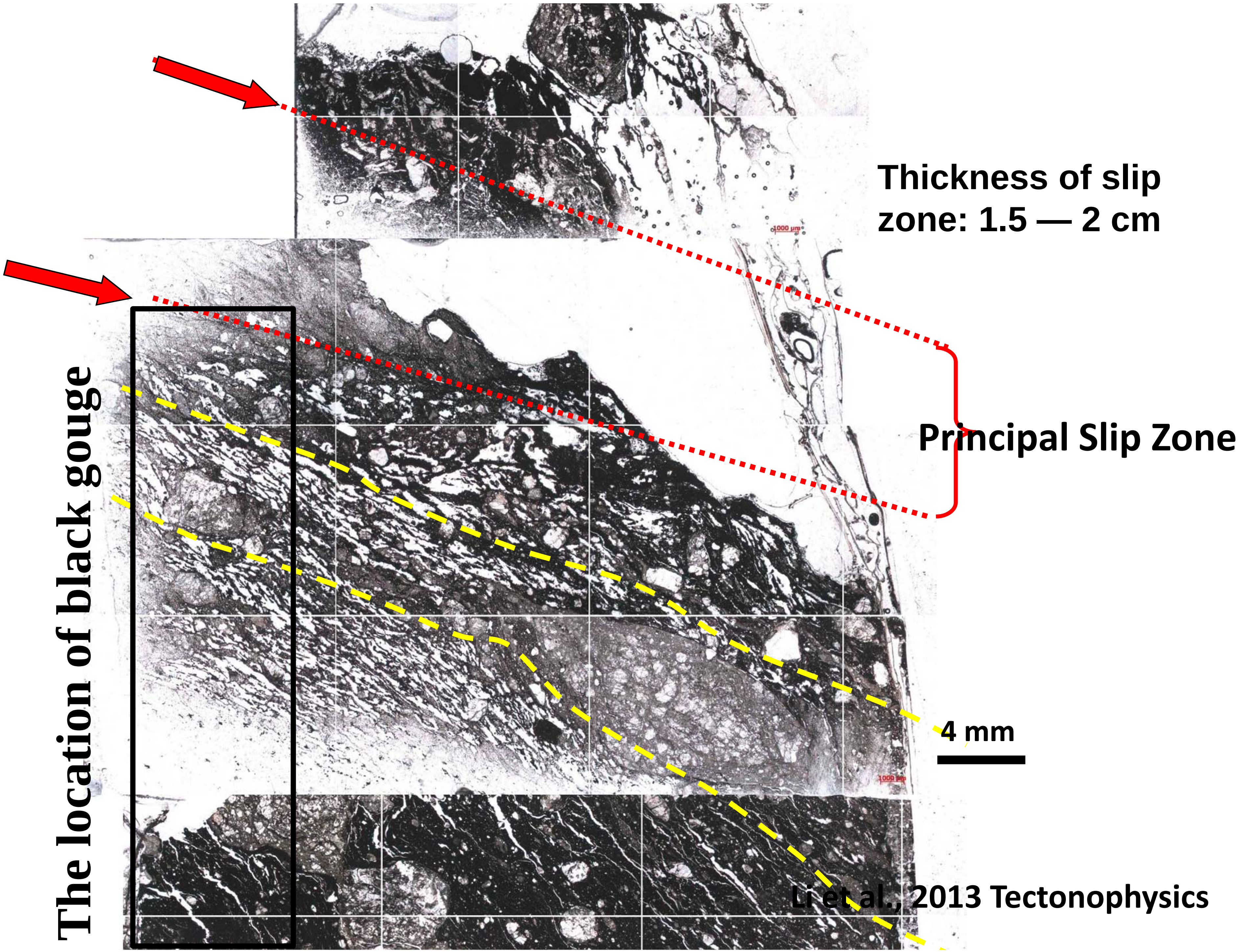
The 2008 Wenchuan earthquake (Mw 7.9) produced two major surface ruptures



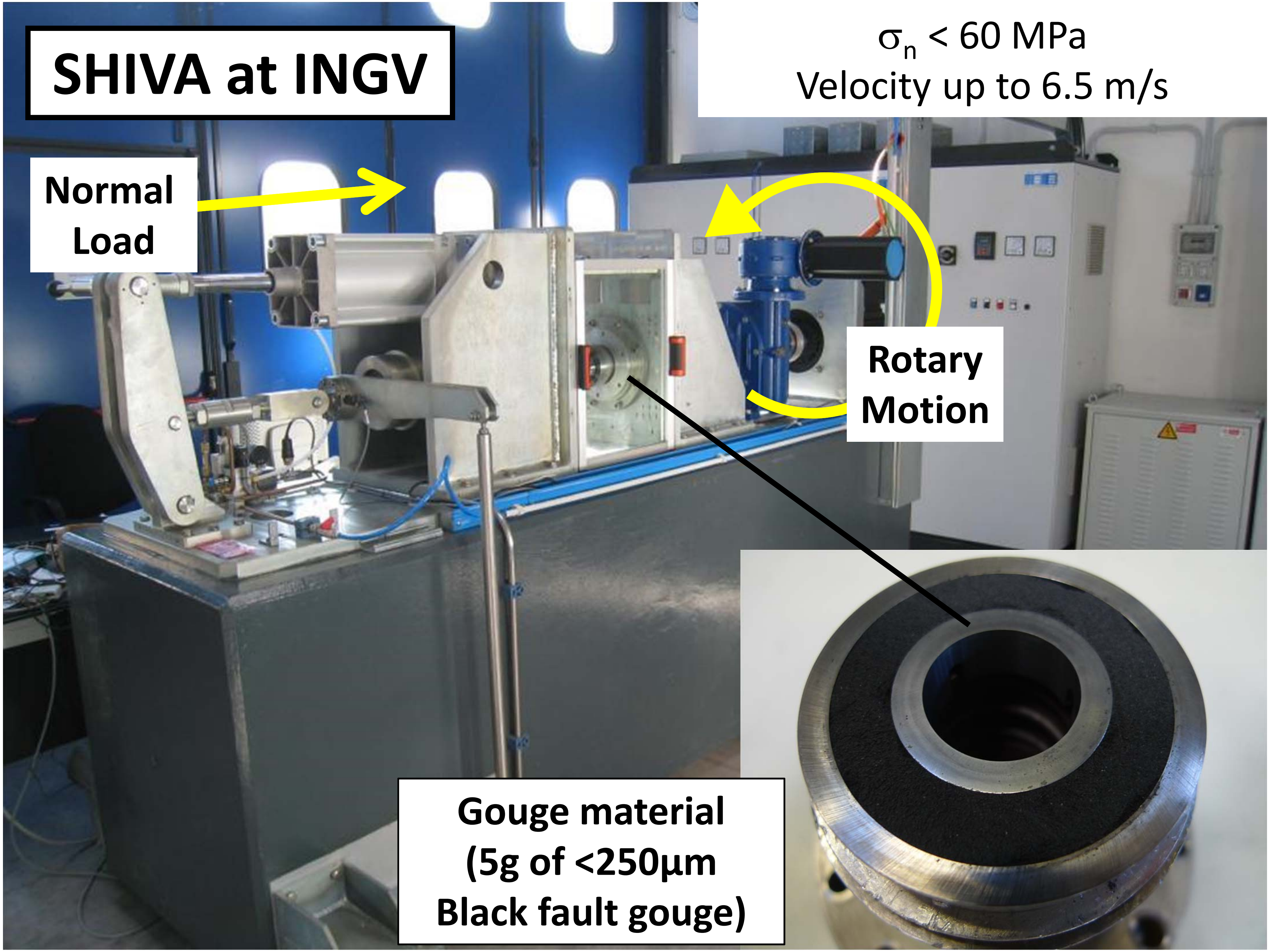


Li et al., 2013 Tectonophysics

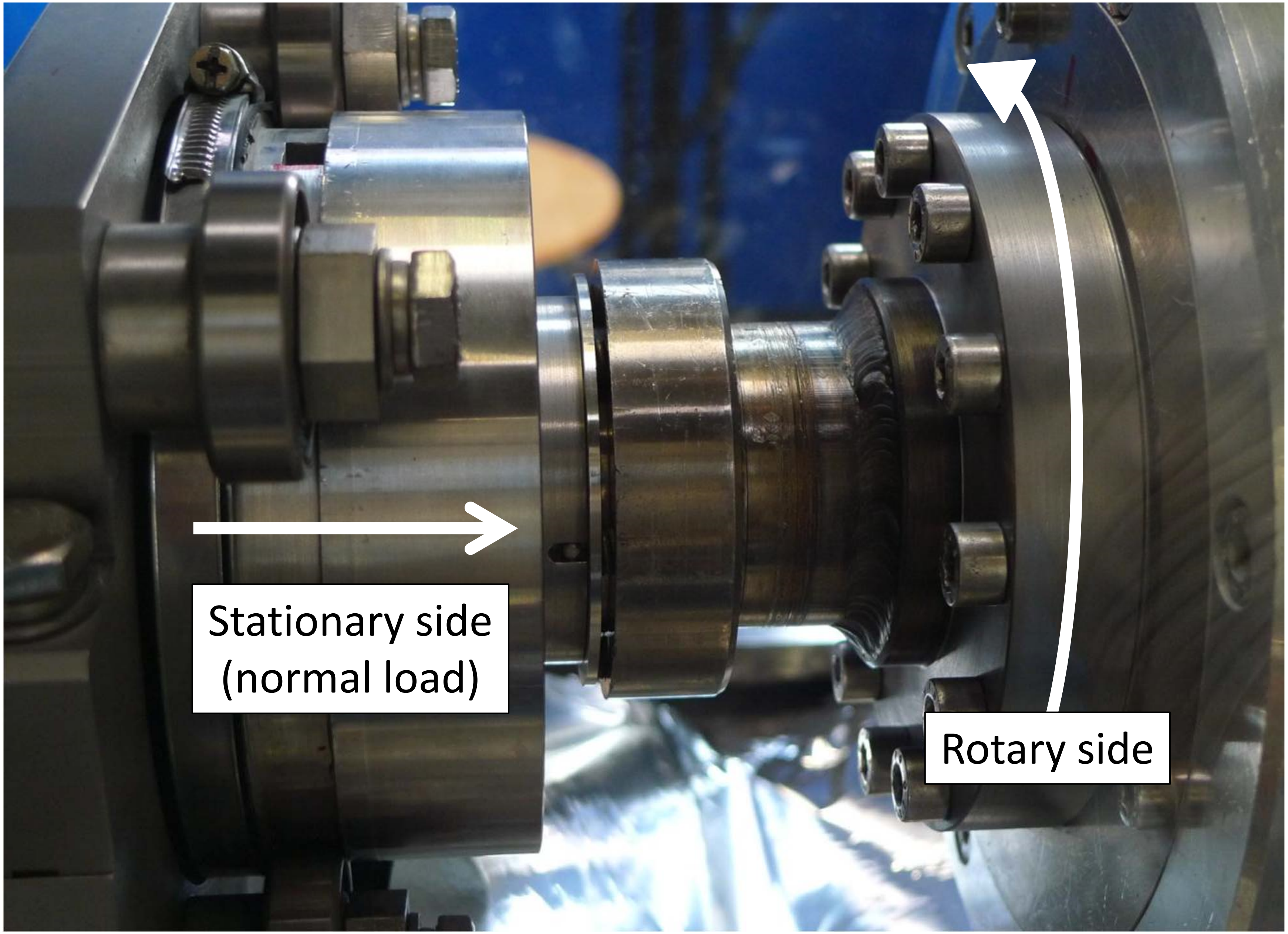

Thickness of slip zone: 1.5 — 2 cm
Principal Slip Zone
4 mm
Li et al., 2013 Tectonophysics



Thickness of slip zone: 1.5 — 2 cm
Principal Slip Zone
The location of black gouge
4 mm
Li et al., 2013 Tectonophysics


SHIVA at INGV
σn < 60 MPa
Velocity up to 6.5 m/s
Normal Load
Rotary Motion
Gouge material (5g of <250µm Black fault gouge)

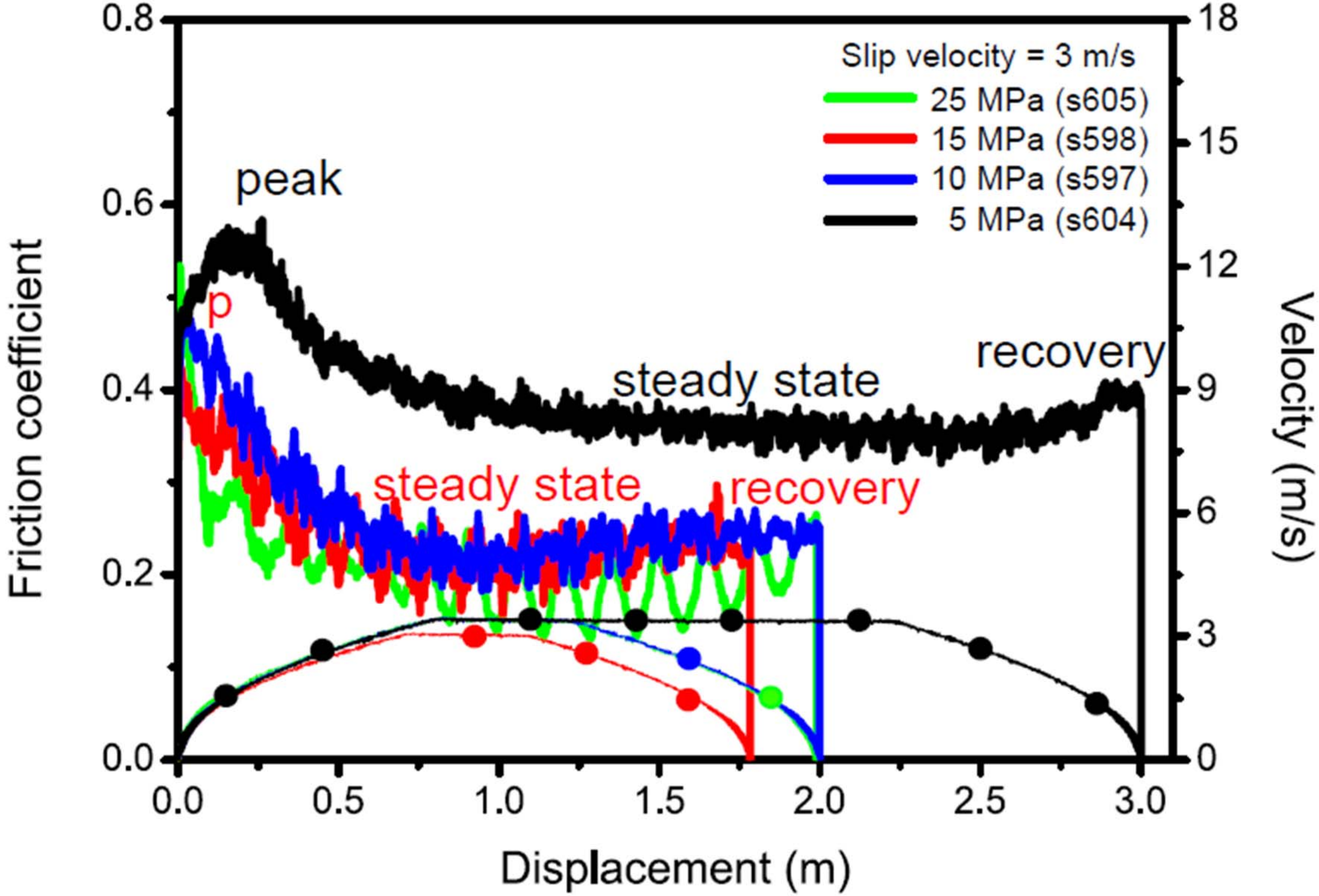
Tested up to **25 MPa normal stress** and 3 m s^{-1} slip velocity



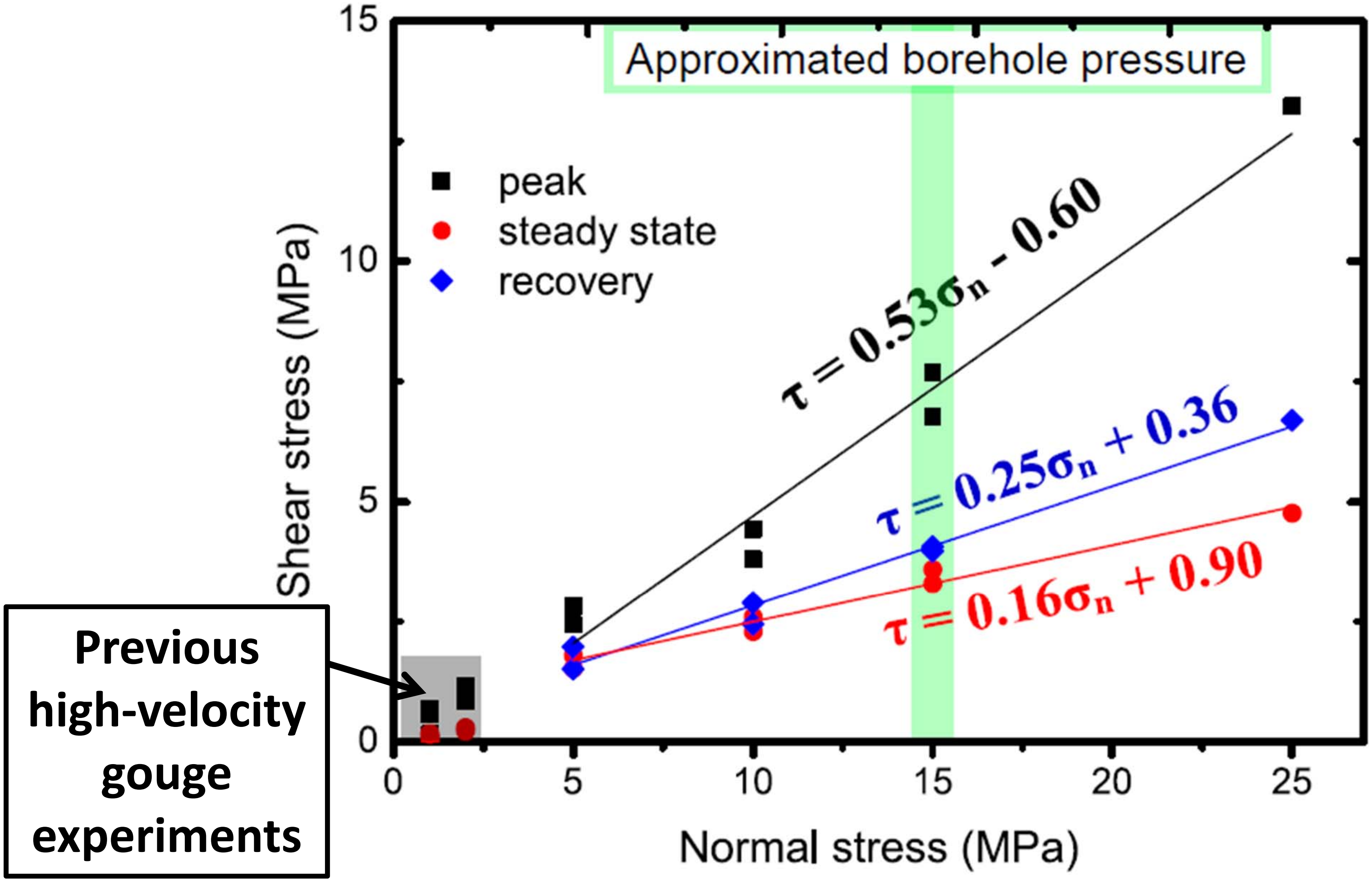
High Velocity Rock Friction Experiments (HVRFE) performed at seismic slip rates (**0.1-10 m/s**) may allow the:

- Determination of **dynamic friction** (and its evolution) during seismic slip
- Investigation of the **physico-chemical processes** occurring during simulated faulting
- Recognition of **mineralogical and microstructural indicators** within exhumed (or active) fault zones
- Identification of **fault weakening mechanisms**

Evolution of friction during “realistic” co-seismic slip pulses



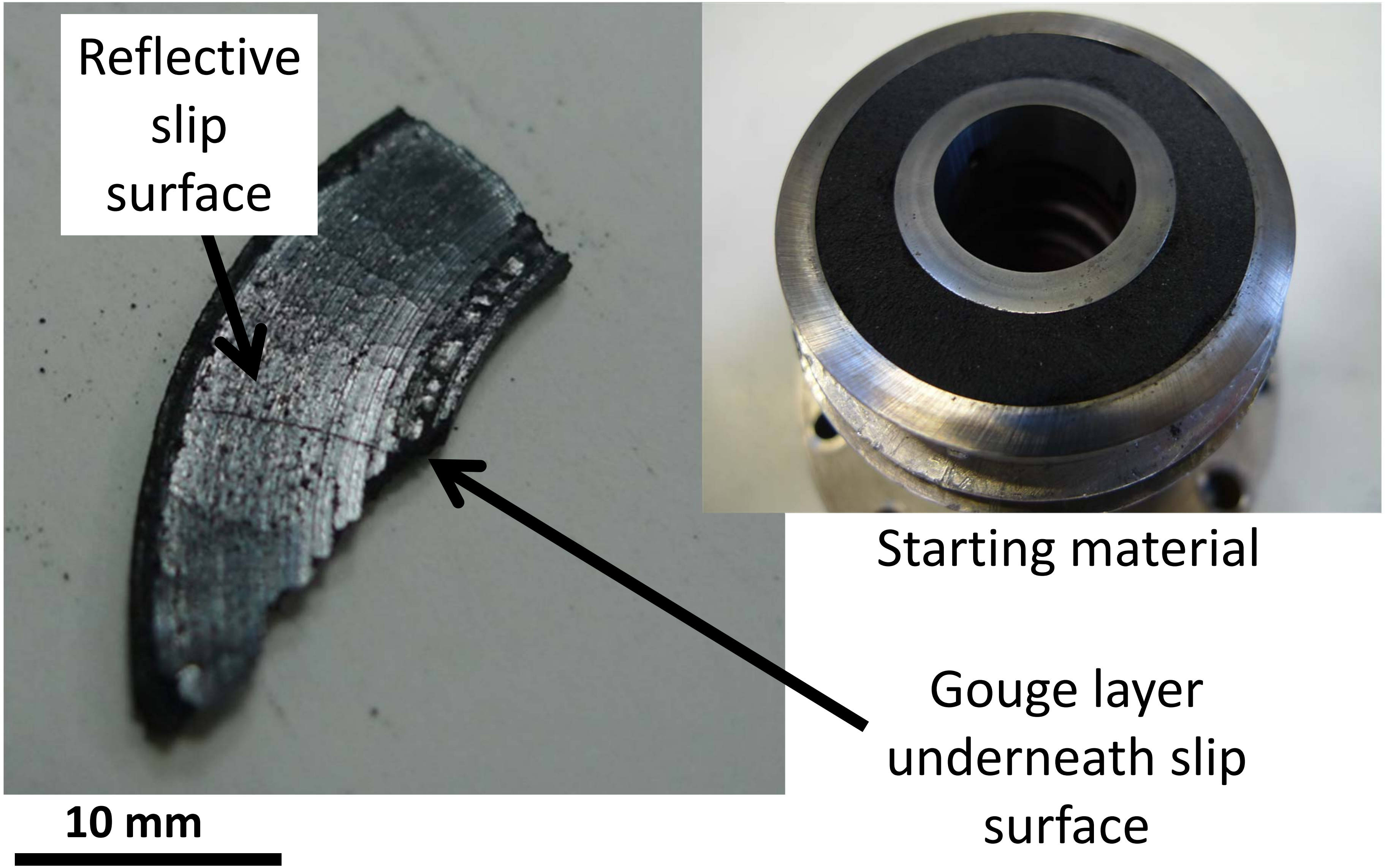
Fault gouges are dynamically weakened at **high normal stress** and **co-seismic slip velocities**



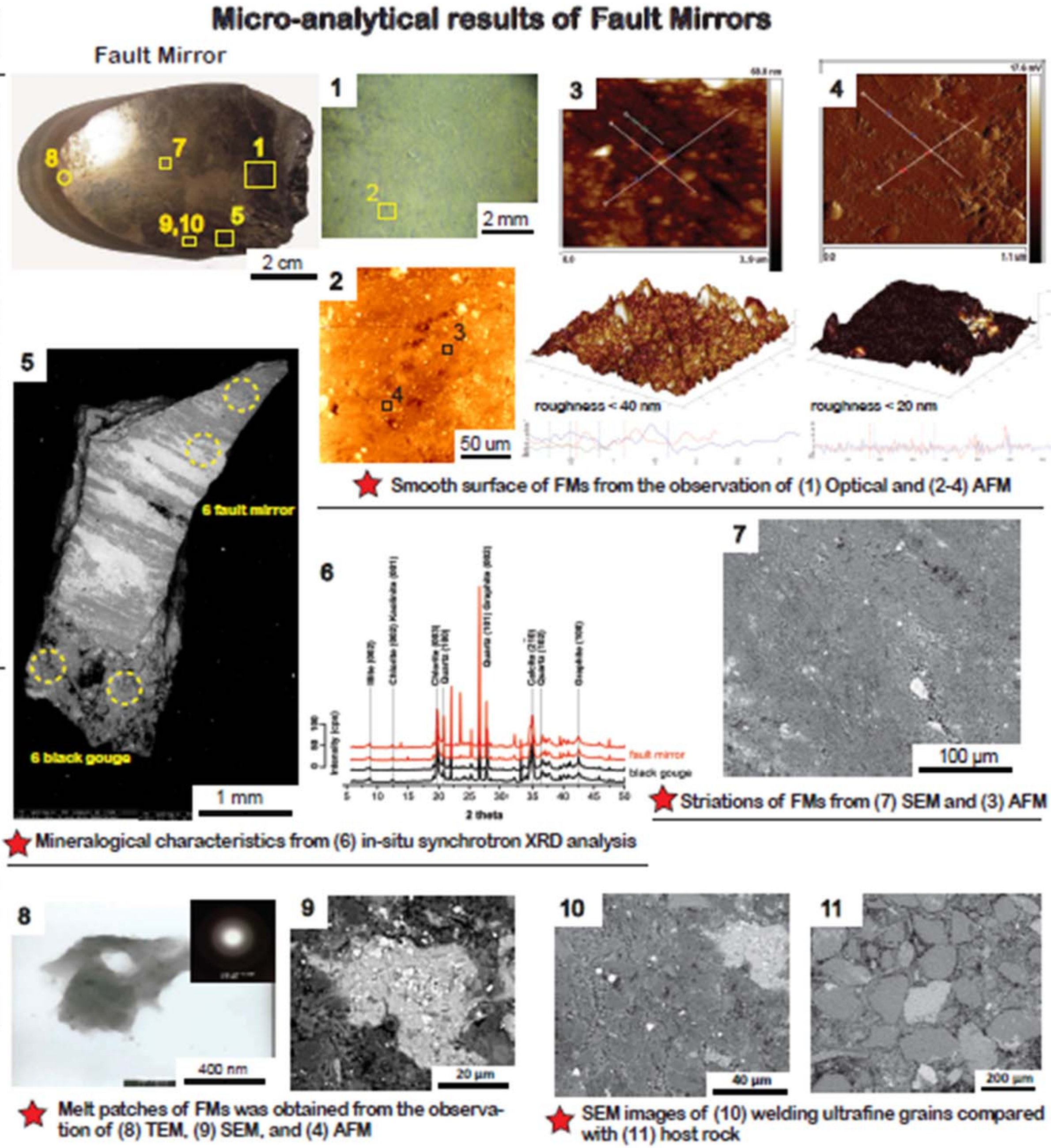
High Velocity Rock Friction Experiments (HVRFE) performed at seismic slip rates (**0.1-10 m/s**) may allow the:

- Determination of **dynamic friction** (and its evolution) during seismic slip ✓
- Investigation of the **physico-chemical processes** occurring during simulated faulting
- Recognition of **mineralogical and microstructural indicators** within exhumed (or active) fault zones
- Identification of **fault weakening mechanisms**

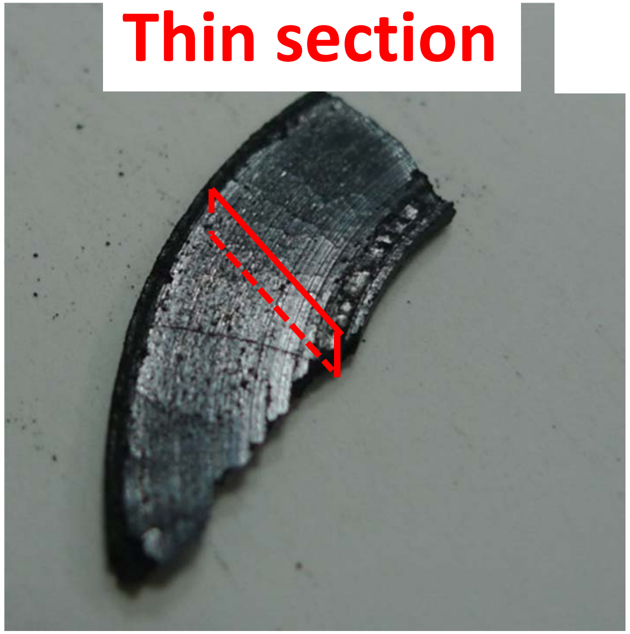
Fault gouges deformed at **co-seismic slip velocities** are cut by highly **reflective slip surfaces**

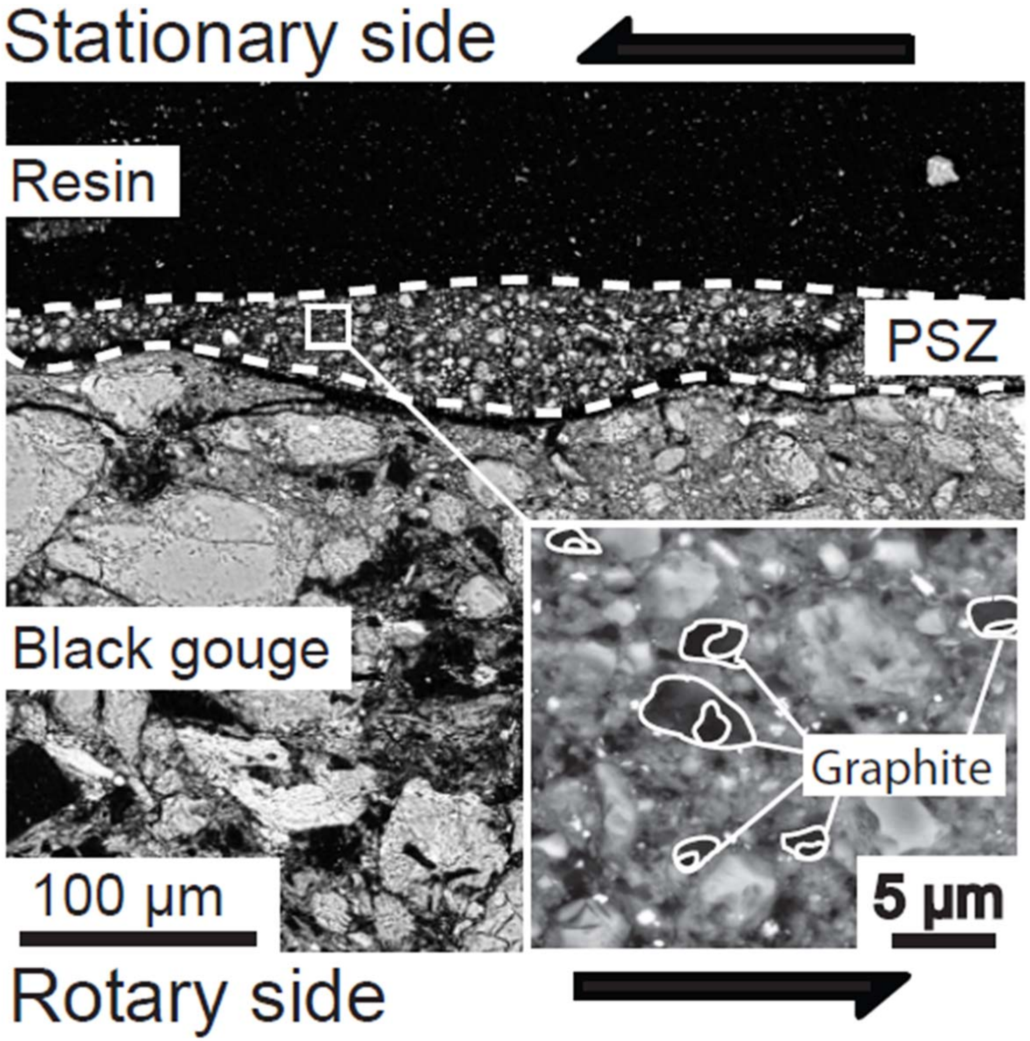


Fault gouges deformed at (**T33C-2645 fault mirrors** re cut by higl

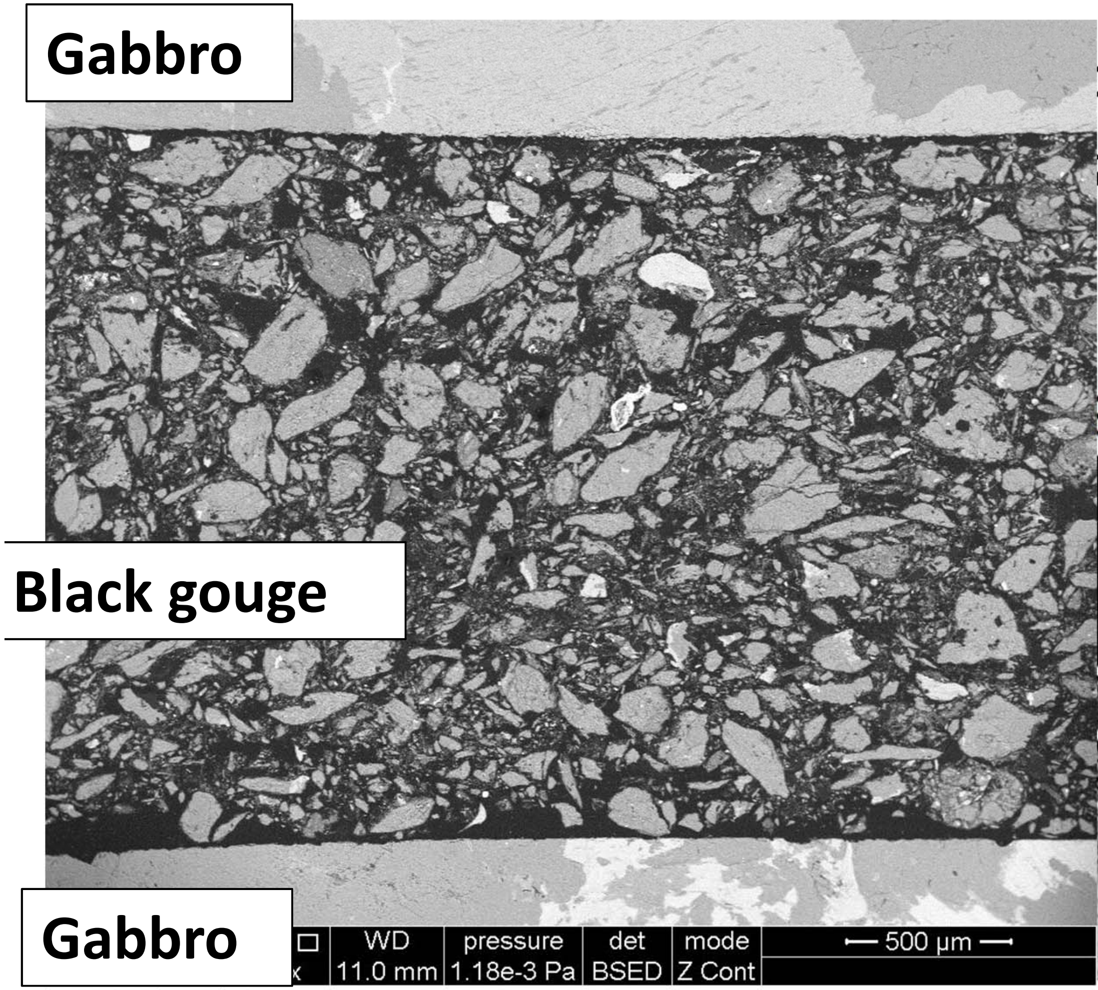


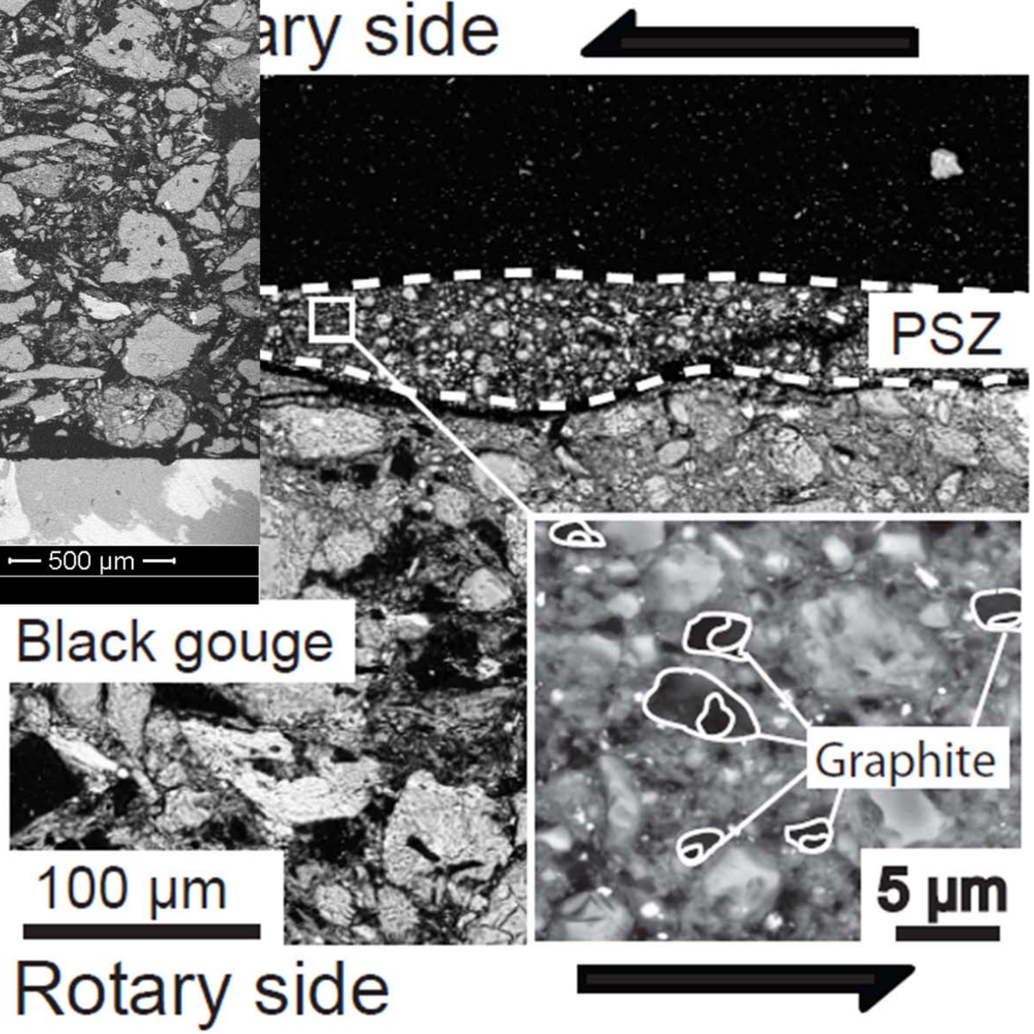
Change in deformation mechanism close to **slip surface**





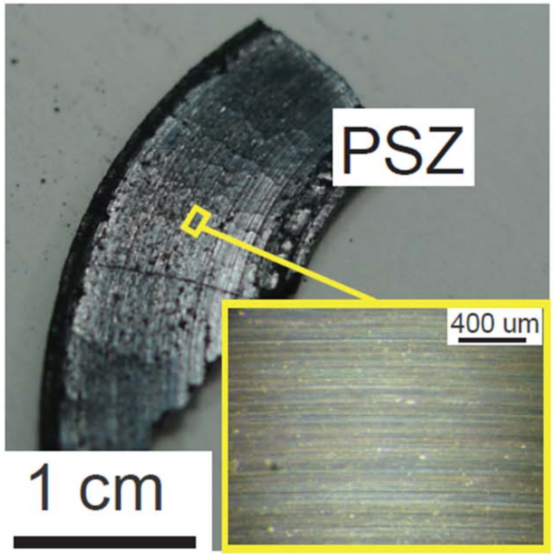
deformation mechanism
se to **slip surface**

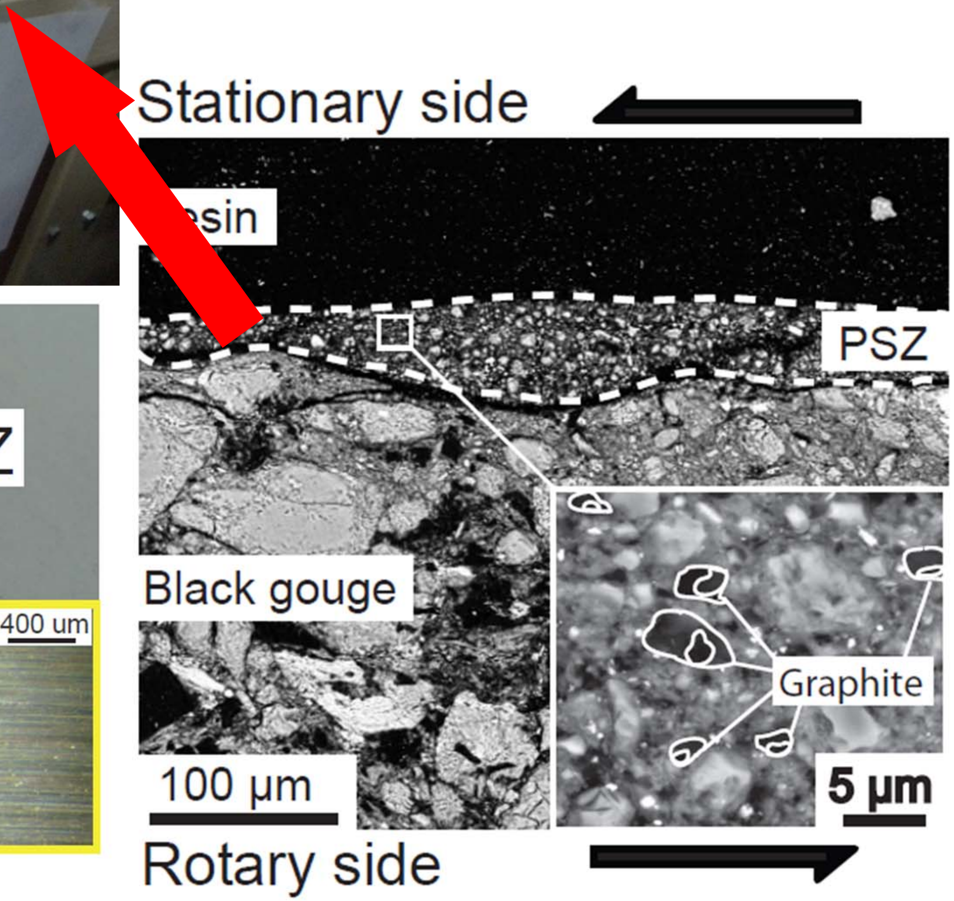




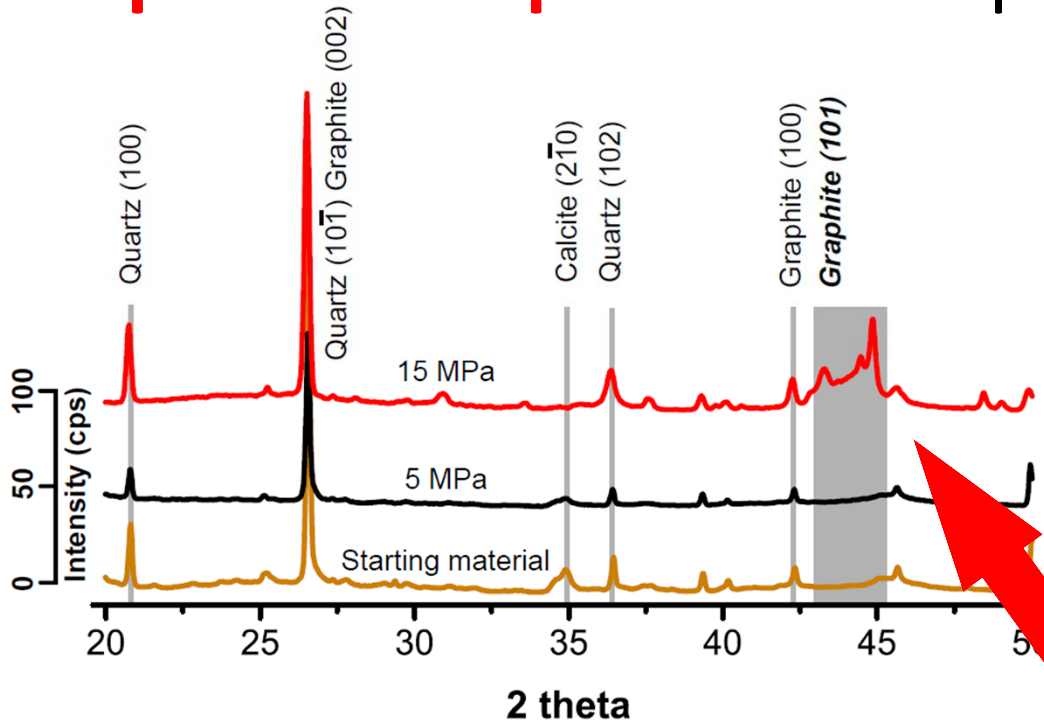
In-situ synchrotron XRD analysis

Experiment

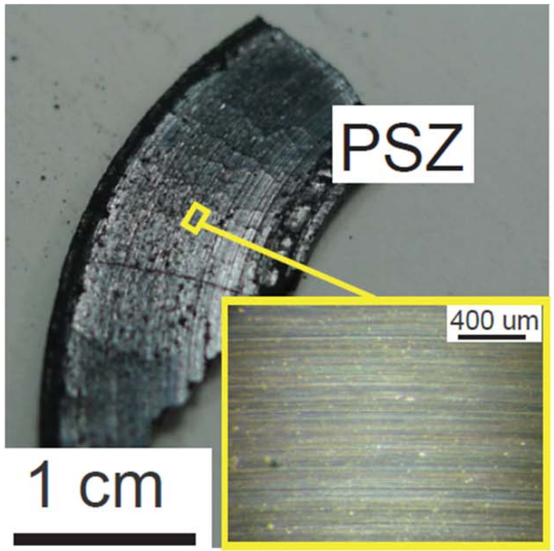


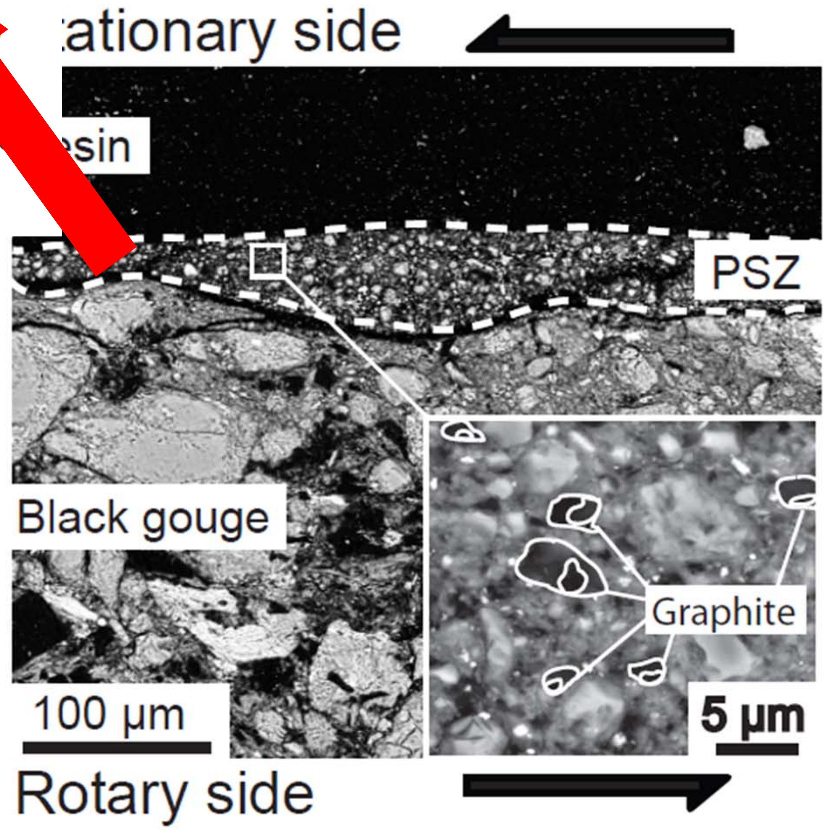


Graphitization process took place during EQs!!



Experiment





High Velocity Rock Friction Experiments (HVRFE) performed at seismic slip rates (**0.1-10 m/s**) may allow the:

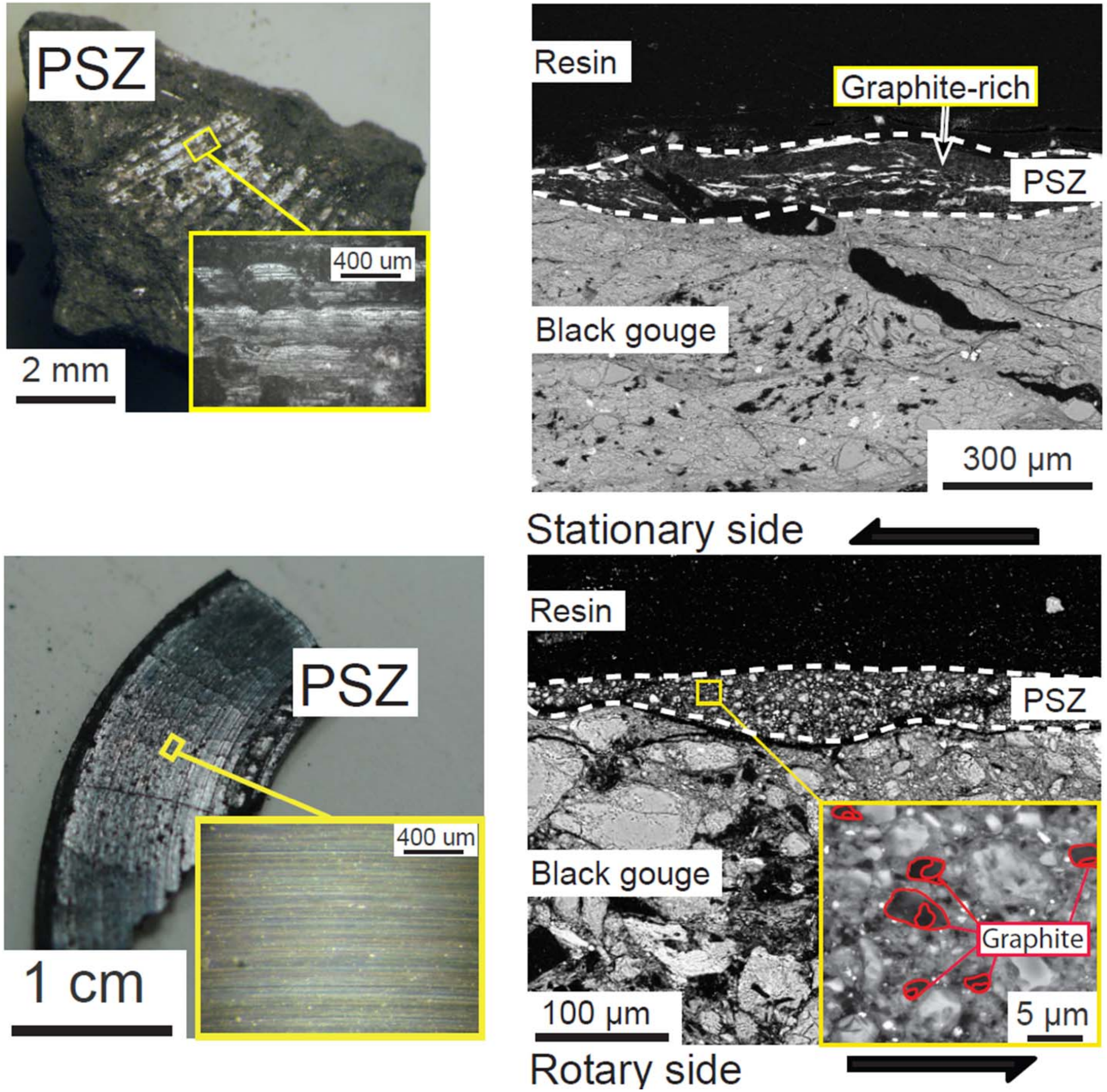
- Determination of **dynamic friction** (and its evolution) during seismic slip ✔
- Investigation of the **physico-chemical processes** occurring during simulated faulting ✔
- Recognition of **mineralogical and microstructural indicators** within exhumed (or active) fault zones
- Identification of **fault weakening mechanisms**

Are experimental products similar to natural ones?

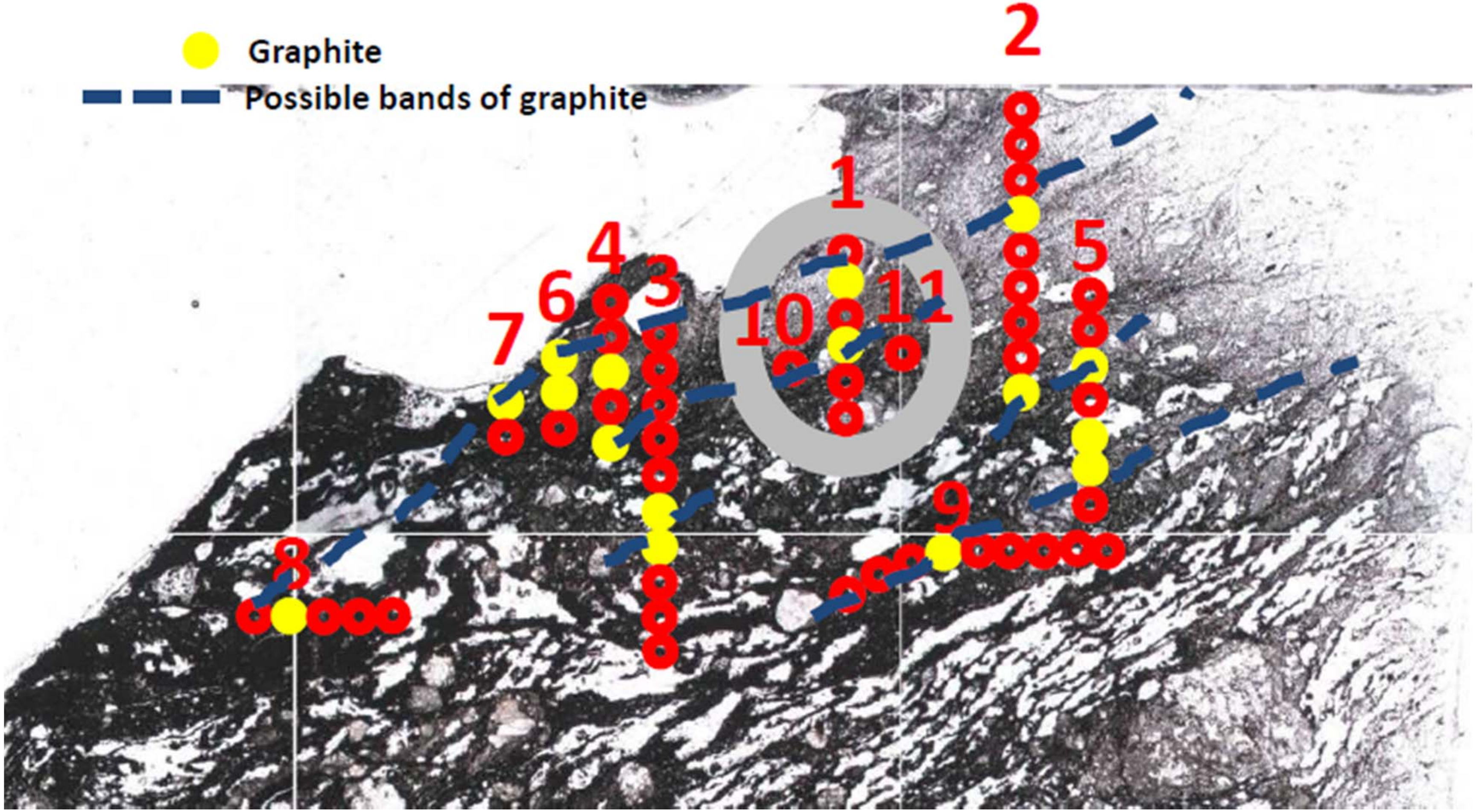
Yes (example for carbonaceous gouge).

Nature

Experiment



The occurrences of Graphite

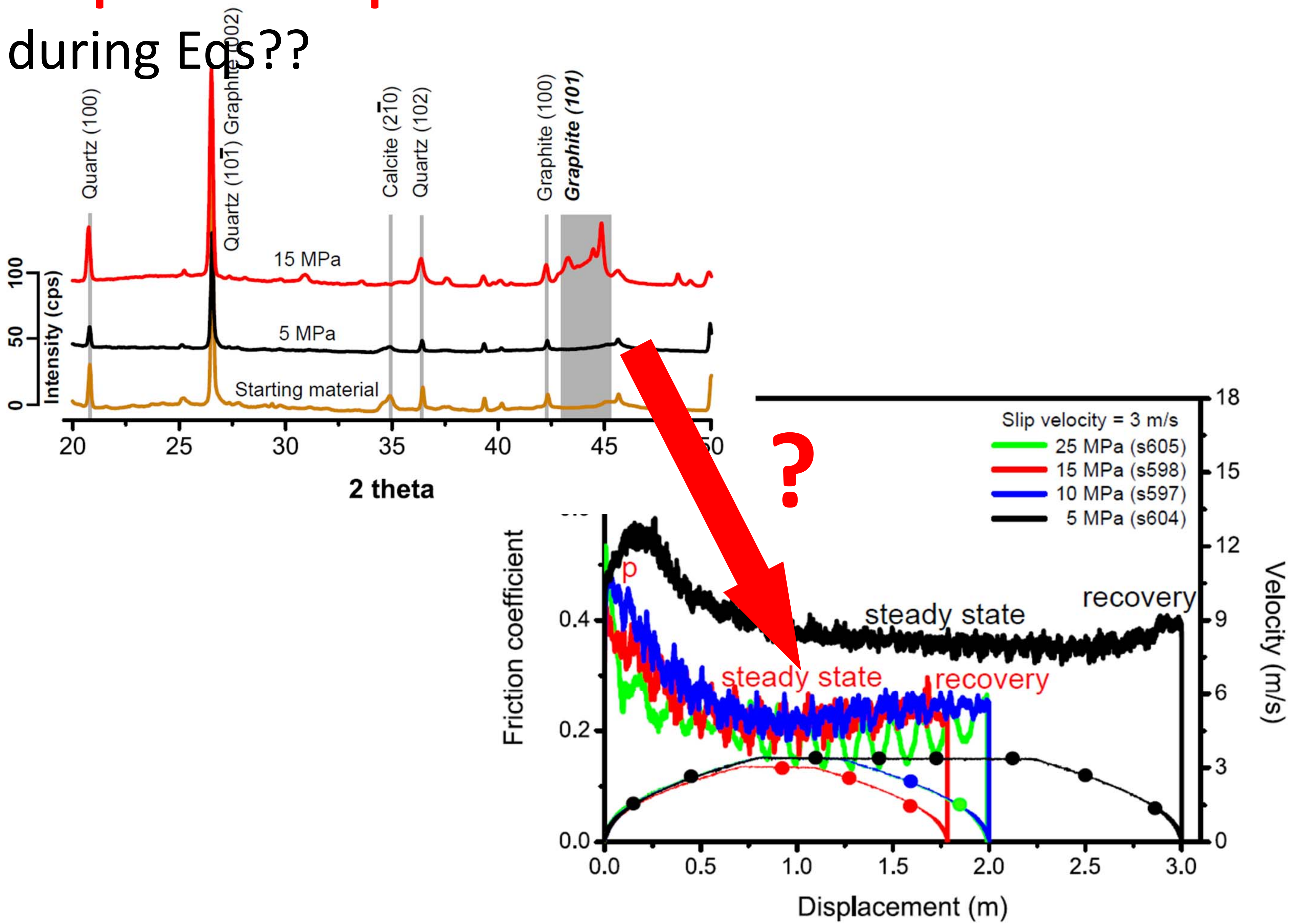


Li, unpublished data

High Velocity Rock Friction Experiments (HVRFE) performed at seismic slip rates (**0.1-10 m/s**) may allow the:

- Determination of **dynamic friction** (and its evolution) during seismic slip ✔
- Investigation of the **physico-chemical processes** occurring during simulated faulting ✔
- Recognition of **mineralogical and microstructural indicators** within exhumed (or active) fault zones ✔
- Identification of **fault weakening mechanisms**

Graphitization process seems to **lubricate the fault** during Eqs??



High Velocity Rock Friction Experiments (HVRFE) performed at seismic slip rates (**0.1-10 m/s**) may allow the:

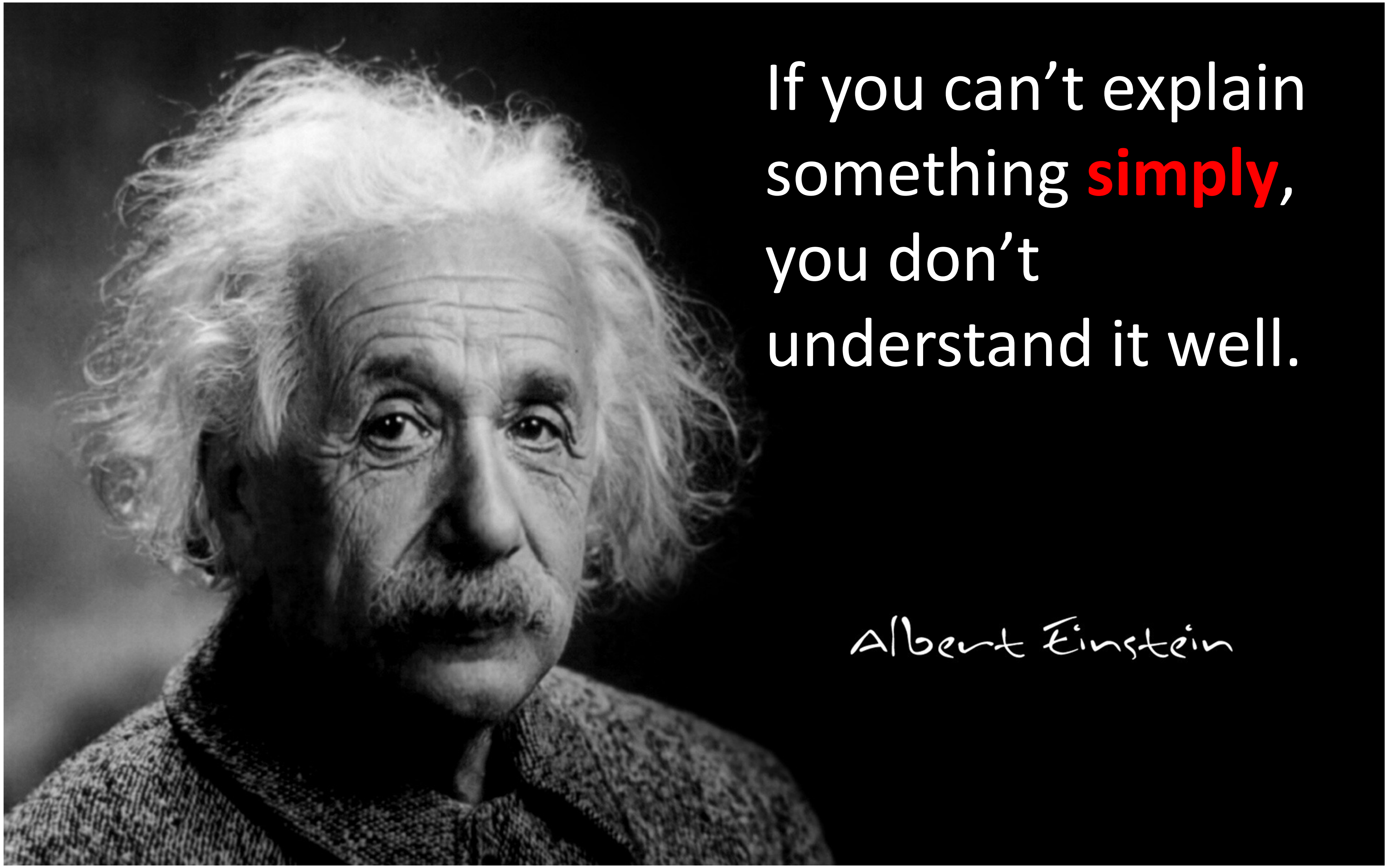
- Determination of **dynamic friction** (and its evolution) during seismic slip ✓
- Investigation of the **physico-chemical processes** occurring during simulated faulting ✓
- Recognition of **mineralogical and microstructural indicators** within exhumed (or active) fault zones ✓
- Identification of **fault weakening mechanisms**

Check in the future!!

Conclusion

- Experimental results indicate that the **Longmenshan fault** at this locality is extremely **weak**.
- **Graphitization** occurred due to frictional heating of carbonaceous materials.
- The associated product, **graphite**, could be used as **an indicator of transient frictional heating** during seismic slip in the upper crust.

Future works


If you can't explain something **simply**, you don't understand it well.
Albert Einstein

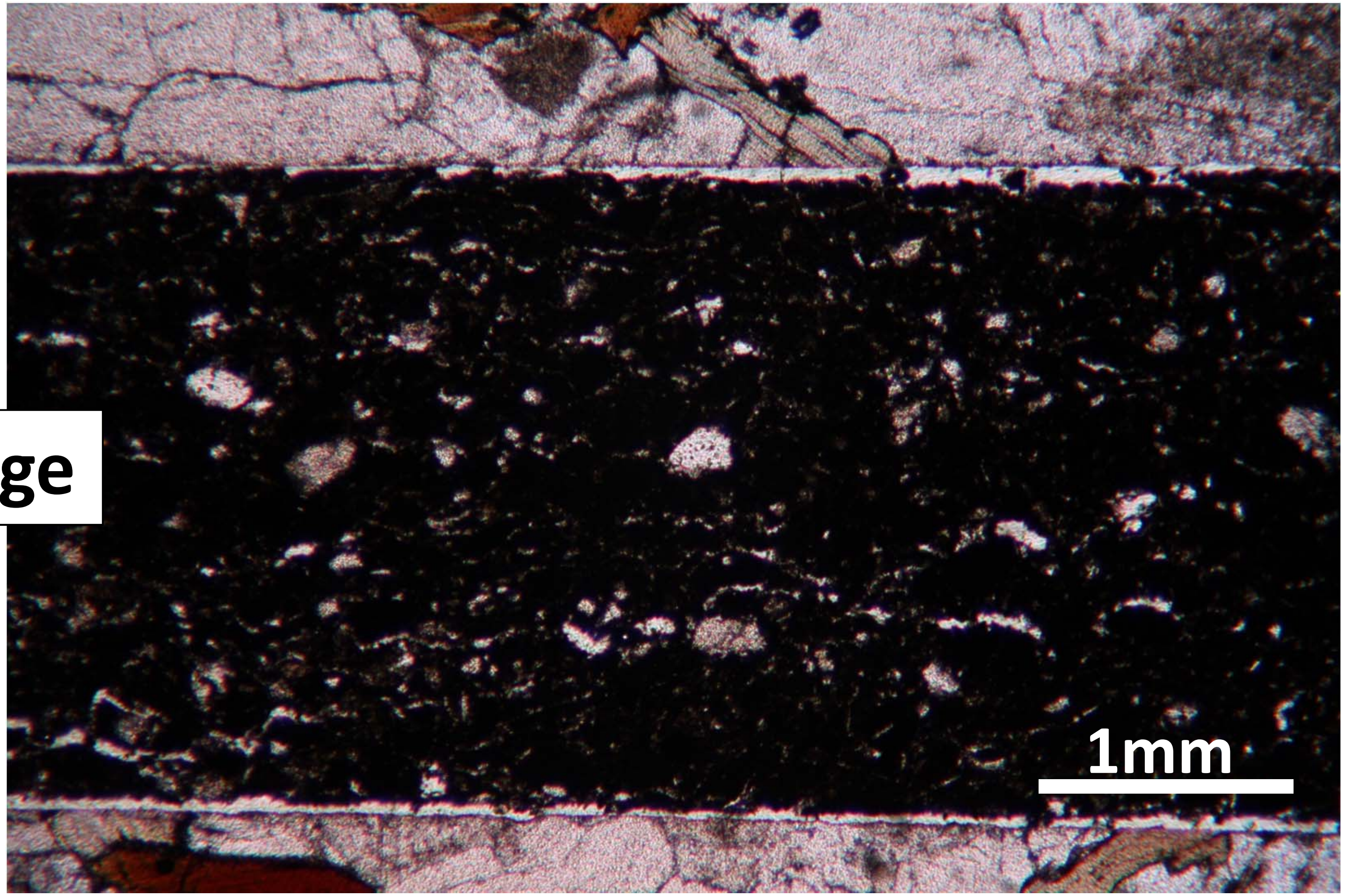
Thank you for your listening!!

Starting Material at 12 MPa without shearing (Optical)

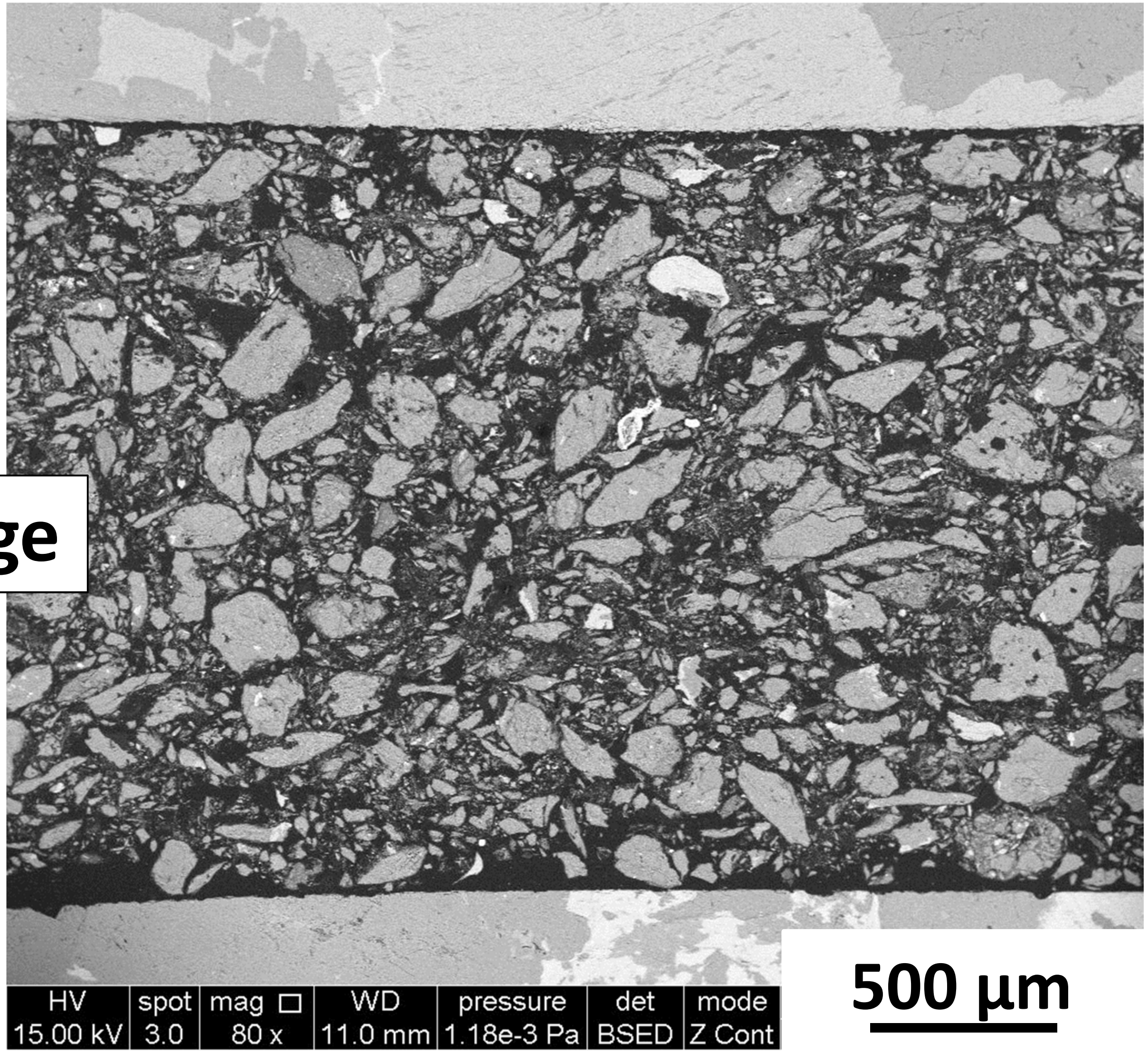
Gabbro

Black gouge

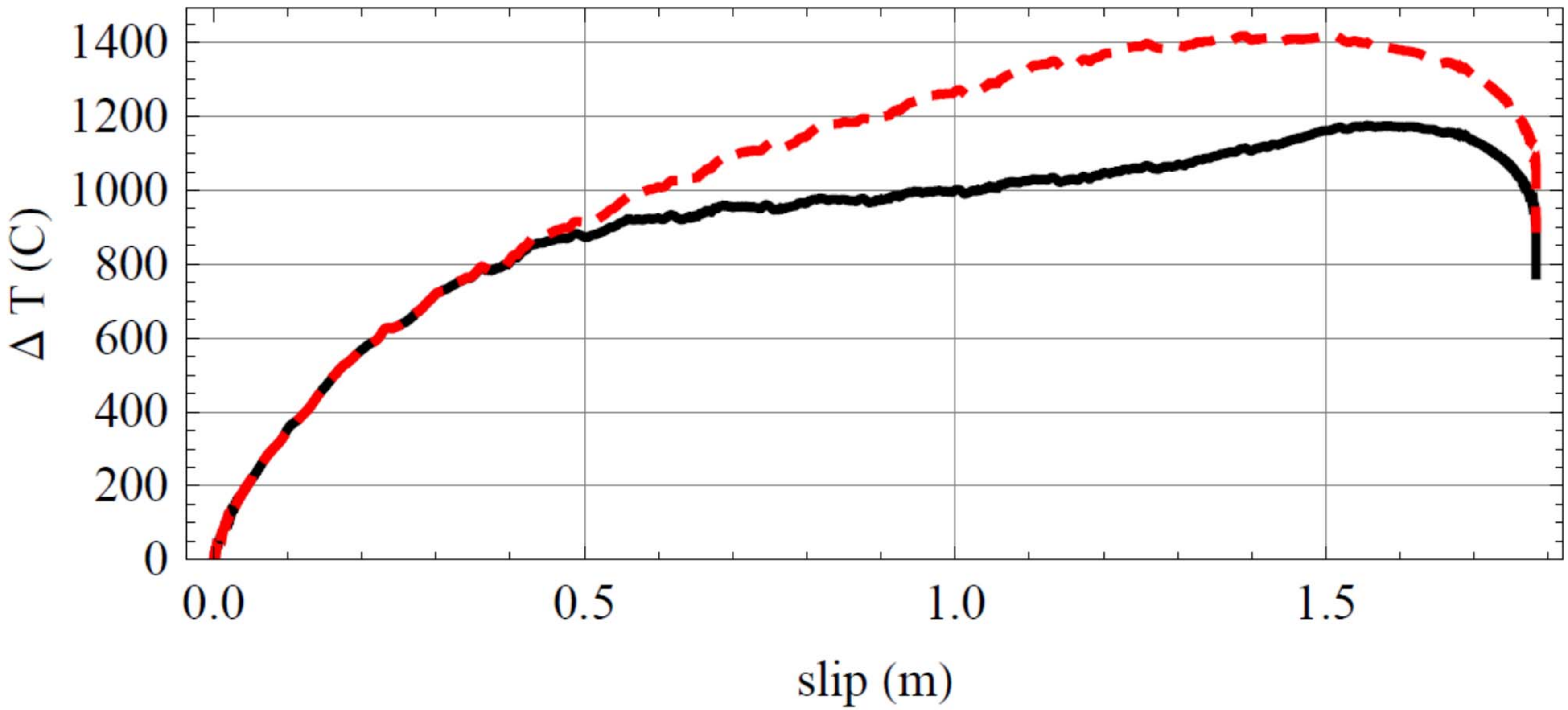
Gabbro



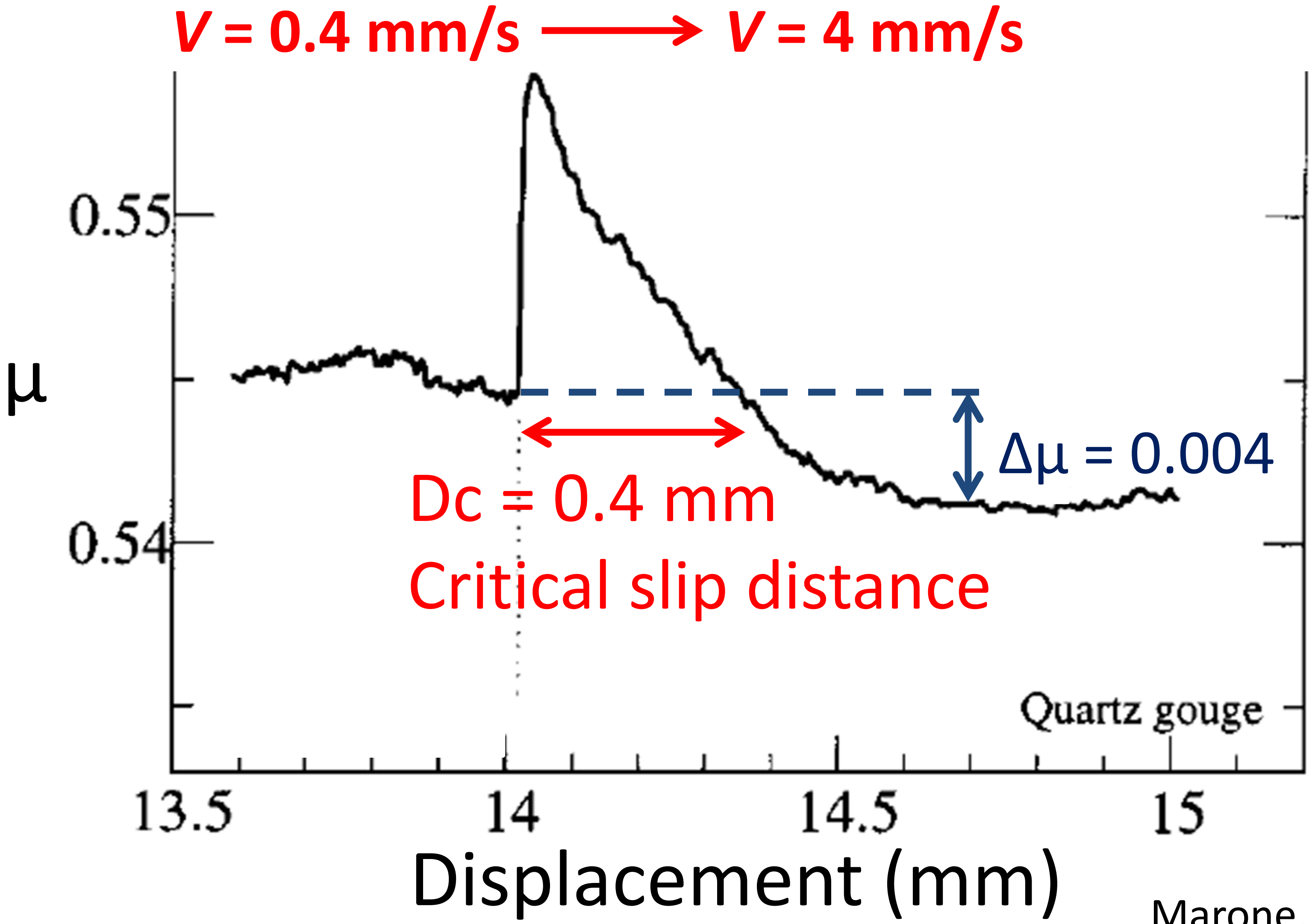
Starting Material at 12 MPa without shearing (SEM-BSE)



Computation of temperature evolution along the principal slip zone formed at 15 MPa



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



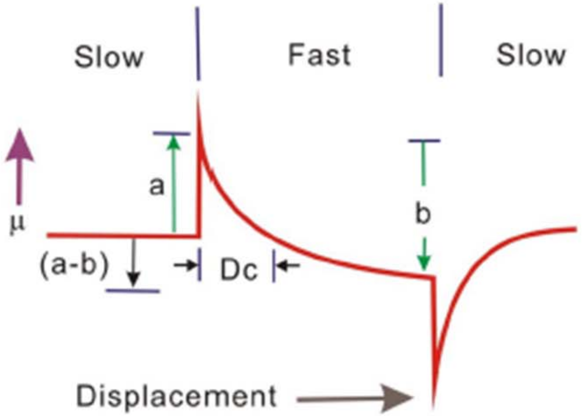
Marone, 1998

These experimental results found broad application in Earthquake mechanics (e.g., Dieterich-Ruina Law)

Rate- and State-Variable Friction Law

Constitutive law: laboratory observation

$$\tau = \left[\mu_0 + a \ln\left(\frac{V}{V_0}\right) + b \ln\left(\frac{V_0 \theta}{Dc}\right) \right] \bar{\sigma}$$



μ_0: friction for steady-state slip at velocity V_0

θ: state variable (Ruina, 1983)

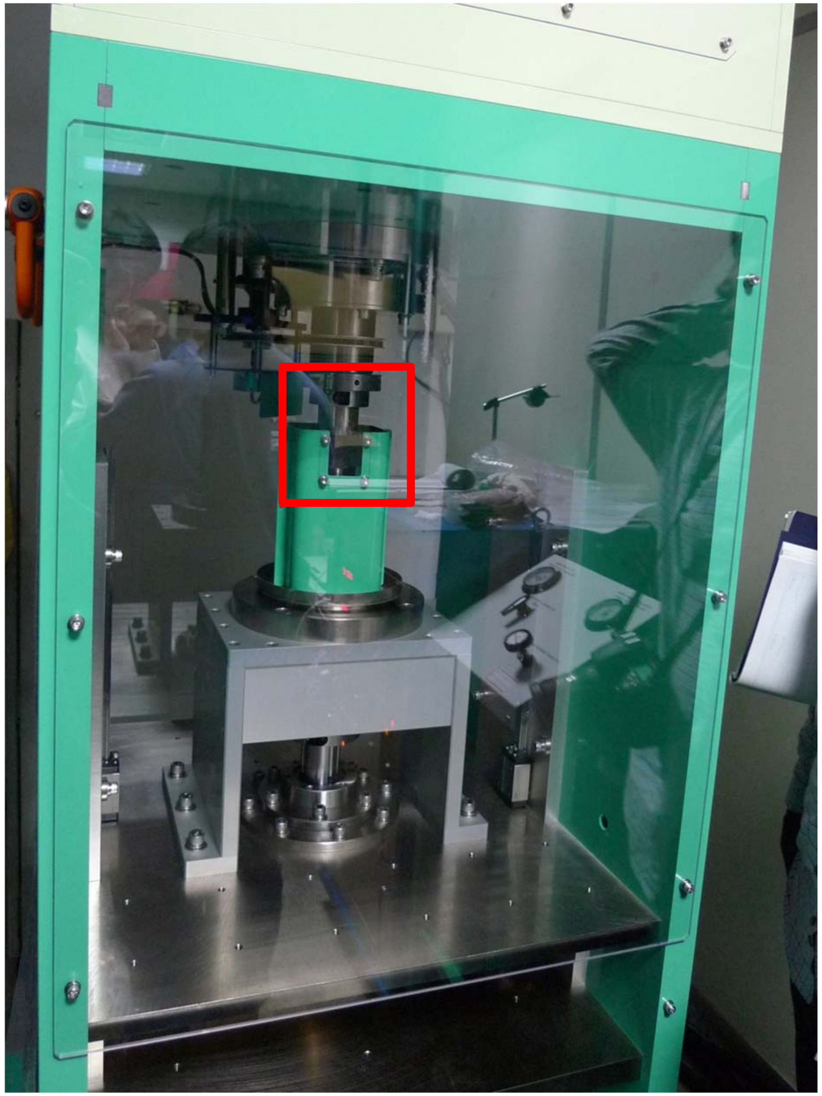
a and b: empirical constants

Dc: critical slip distance

V: frictional slip rate

$$\dot{\theta} = 1 - \left(\frac{V\theta}{D_c}\right)$$

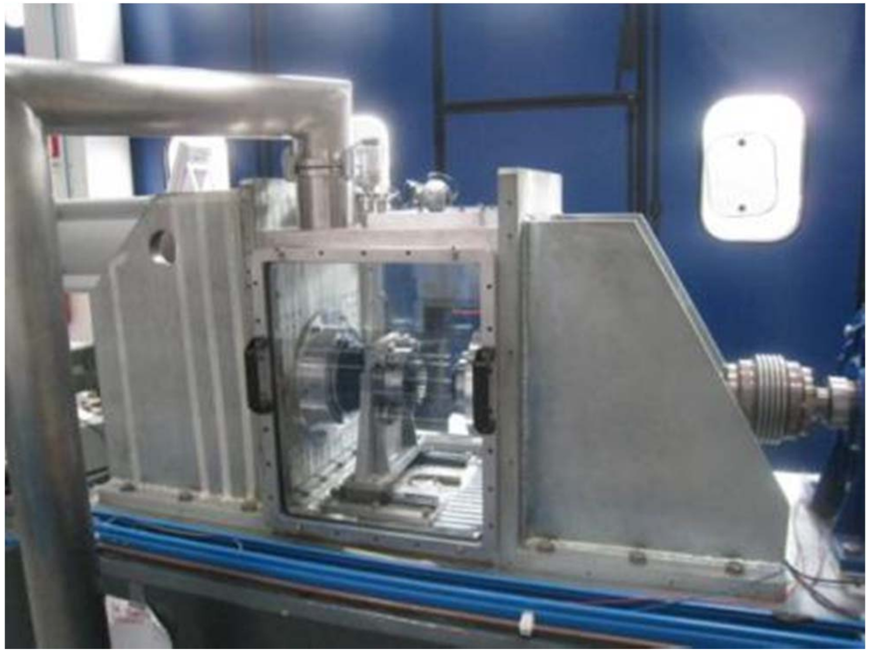
HVRFE are conducted in **rotary shears**



$\sigma_n < 25$ MPa
v = 50 μm/s – 1.3 m/s
d = infinite

Low to high velocity friction apparatus at NCU

Details of the vacuum environmental chamber and vacuum pump (the red box in the right photo).

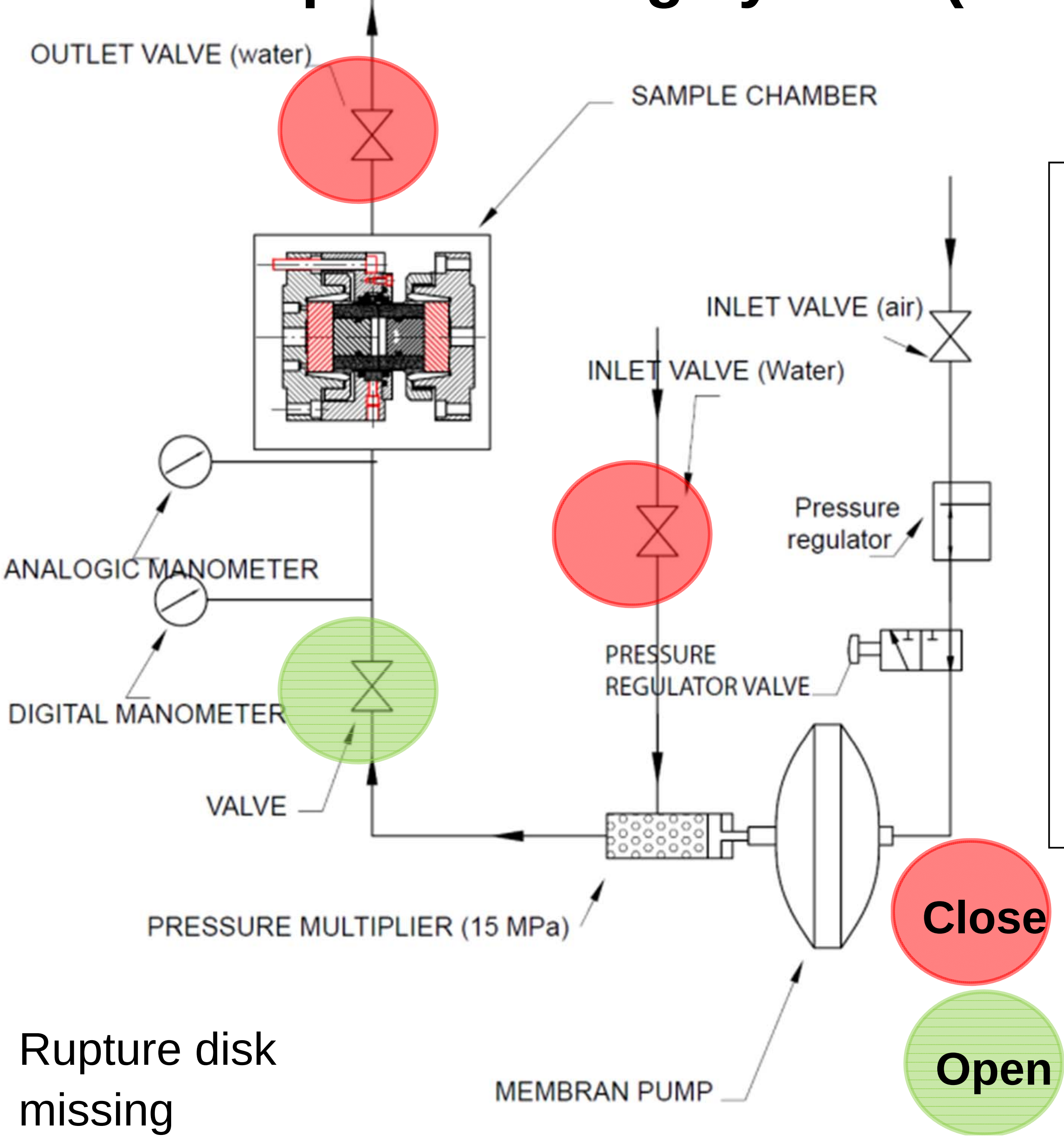


Pore fluids Experiments

Fluid pressuriizing system

Pressure vessel (modified from Hirose)

Fluid pressurizing system (drained config.)



- Pressure effect
- Petrophysical effect
- Chemical effect
- Thermal effect
- …

Rupture disk
missing

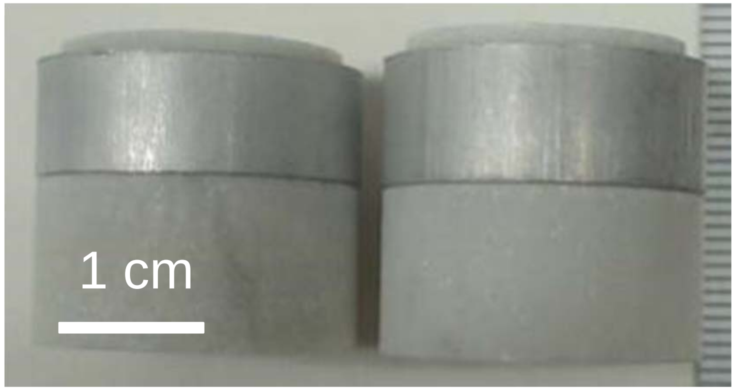
Summarizing, SHIVA:

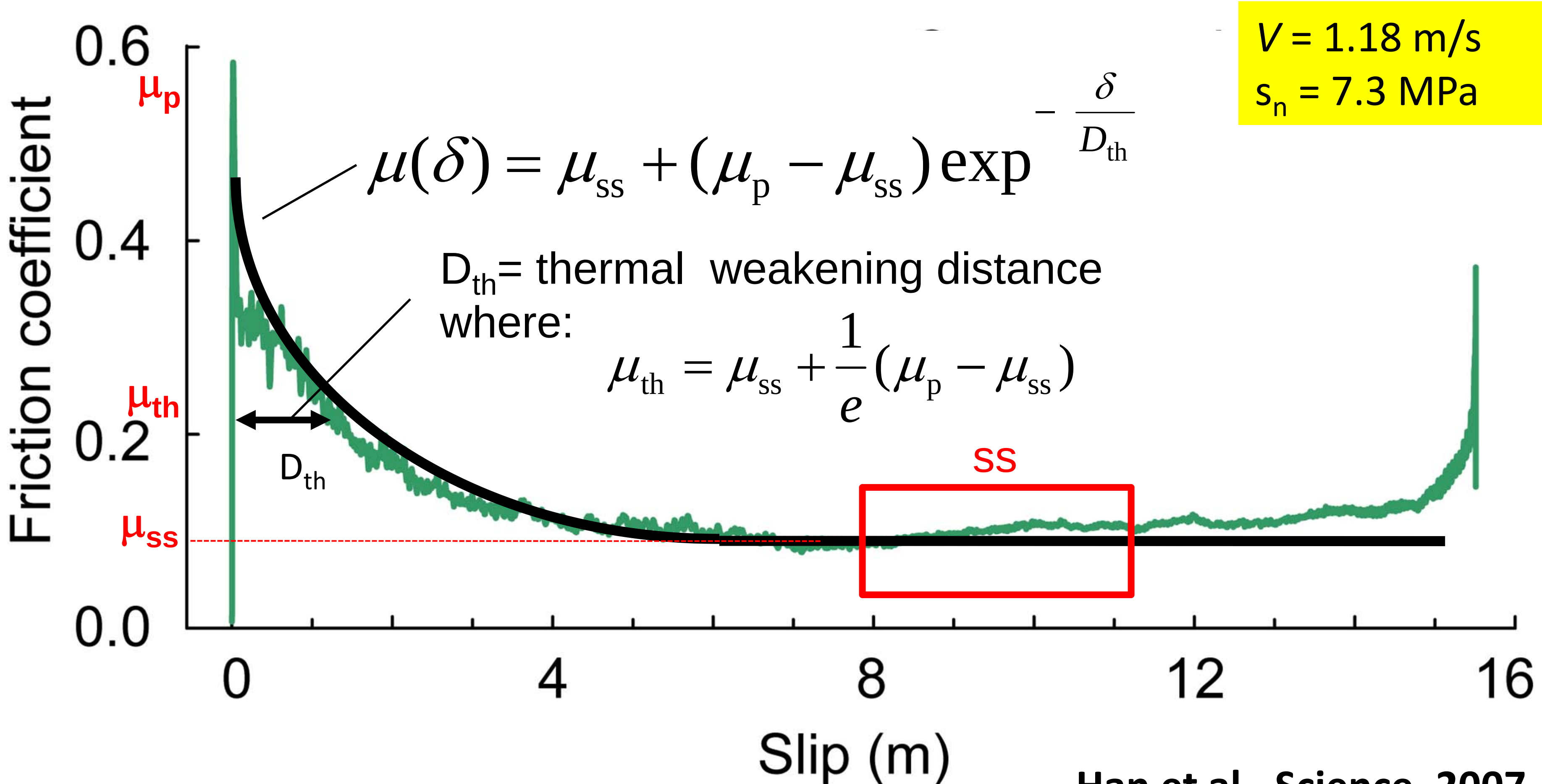
1) performed about 500 experiments.
2) can apply (> 100 MPa in samples of 25 mm in diameter; up to 70 MPa in samples 50/30 ext/int diameter).
2) imposes slip rates from 0.01 mm/s to 6.5 m/s in samples 50/30 ext/int diameter
3) imposes abrupt accelerations (under maximum load, from 0 to 6.5 m/s in 0.1 s)
4) imposes infinite displacement
5) owns different control systems the allow to run experiments with imposed velocity functions and that allow to run experiments under shear stress control (this makes SHIVA the only rotary shear able to do this – and better reproduces natural conditions).
6) owns a pressure vessel (already tested up to 3.0 m/s) that allows to perform experiments up to 15 MPa fluid pressure
7) owns a specifically designed non-cohesive rock sample holder tested up to 35 MPa and 6.5 m/s (note that the other rotary shear apparatus can work only up to 1 or 2 MPa at most with non cohesive rocks).
8) owns a vacuum / environmental chamber equipped with mass spectrometer (already tested) that allows to control oxygen fugacity during the experiments and to determine the composition of gas produced by chemical reactions during frictional sliding
9) owns transducers that allow to record AEs during the experiments
10) owns high-speed camera, infra-red thermal camera and thermocouples that allow measure the temperature evolution during the experiment.

Example: thermal decomposition in calcite-bearing rocks

Low μ

Weakening: exponential decay

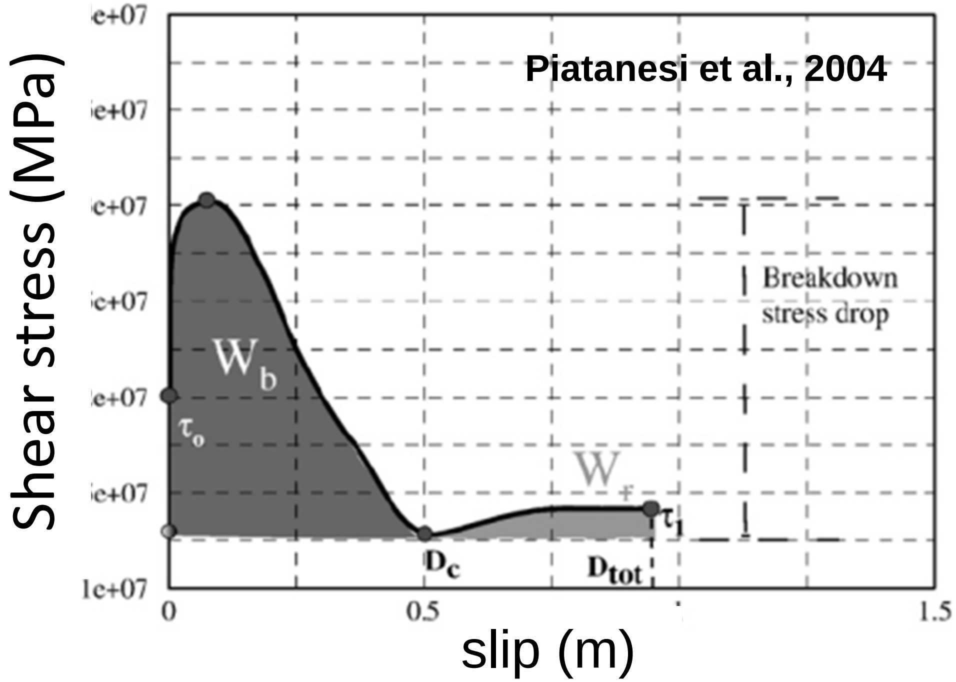




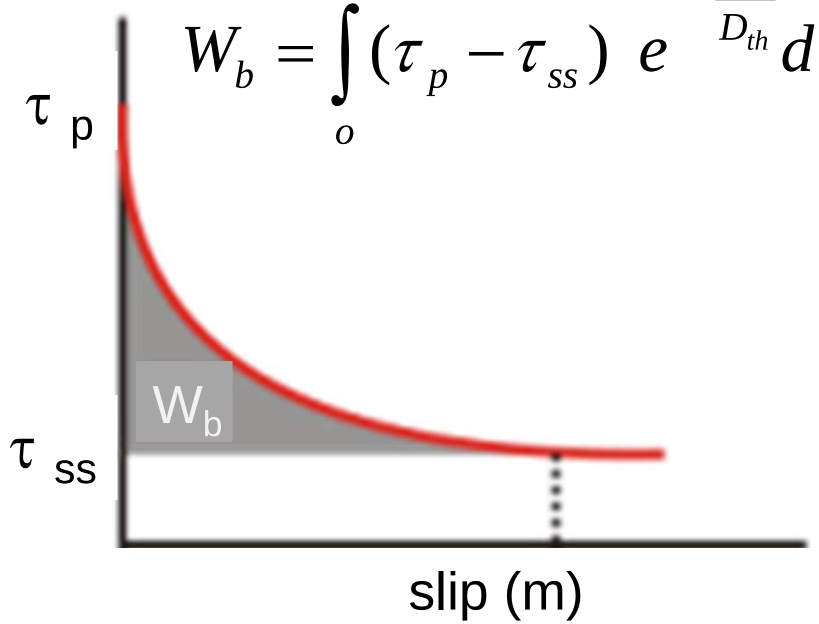
Han et al., Science, 2007

Are there seismological data that might match the experimental observations?

Breakdown works W_b (energy spent at a point of a fault to allow rupture propagation) measured in experiments are in the range of seismological estimates.



$$W_b = \int_o^{\infty} (\tau_p - \tau_{ss})\ e^{-\frac{\delta}{D_{th}}} d\delta$$



Nature (M > 5.5)

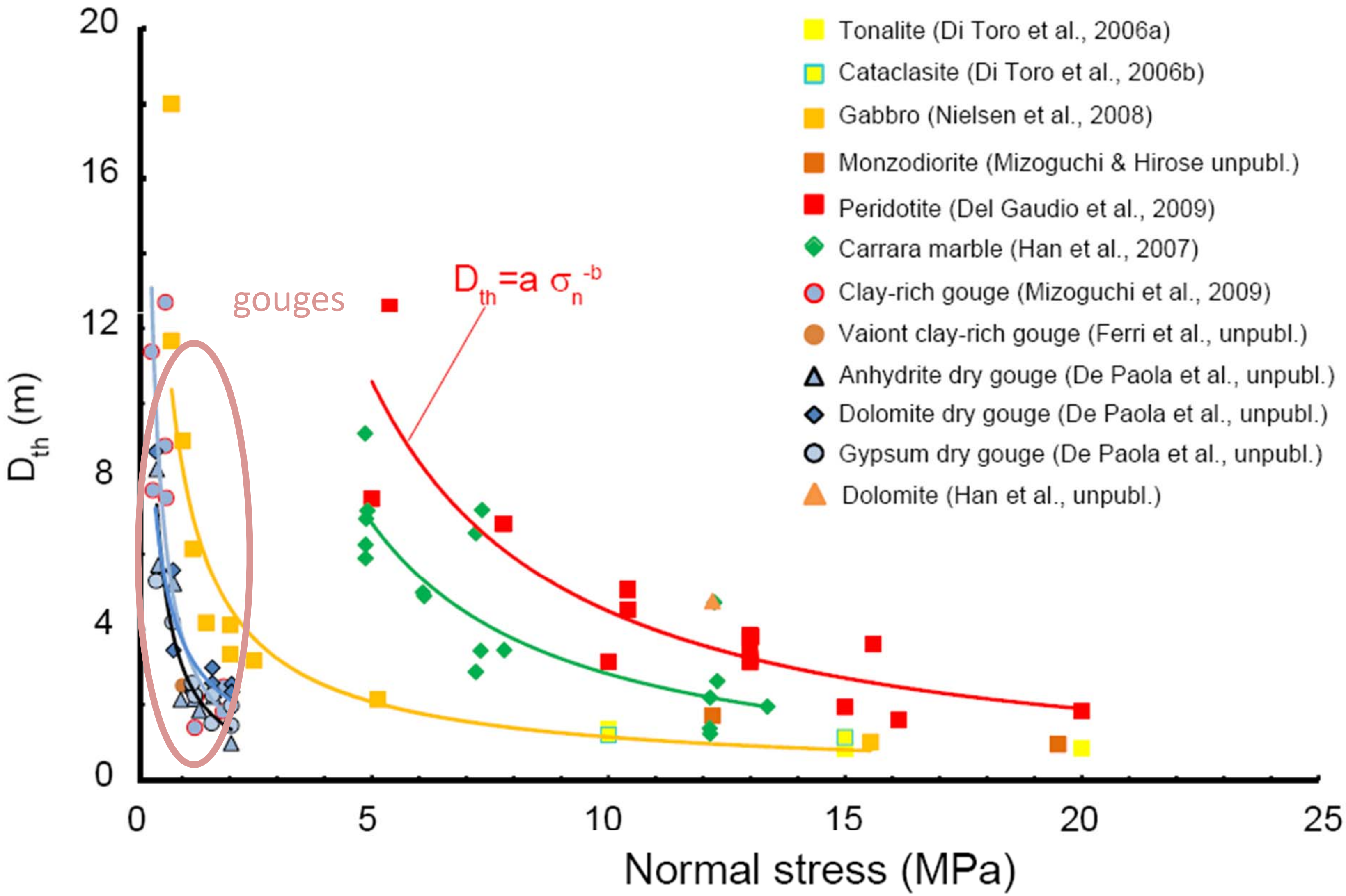
1 – 90 MJ m^{-2}

Experiments

1 – 42 MJ m^{-2}

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

Extrapolation of experimental data to seismogenic depths (σ_n ~100 MPa) suggests D_{th} << 1 m.



Di Toro et al., Nature, 2011