Earthquake fault dynamics: Insights from laboratory experiments

INGV

S. Nielsen

G. Di Toro, A. Niemeijer, E. Spagnuolo, M. Violay, S. Smith, N. De Paola, A. Bistacchi, G. Pennacchioni, F. Di Felice, G. Romeo, R. Han, T. Hirose, K. Mizoguchi, M. Cocco, T. Shimamoto.

This research is funded by the European Research Council

Acknowledgements

S. Nielsen (1)
G. Di Toro (1, 2)
A. Niemeijer (1, 4),
E. Spagnuolo (1),
M. Violay (1),
S. Smith (1),
N. De Paola (5),
A. Bistacchi (6),
G. Pennacchioni (2),
F. Di Felice (1),
G. Romeo (1),
R. Han (7),
T. Hirose (7),
K. Mizoguchi (7),
M. Cocco (1),
T. Shimamoto (3),
...

(1) INGV

(2) Geoscienze, Uni. Padova

(3) HIROSHIMA UNIVERSITY

(4) Universiteit Utrecht

(5) Durham University

(6) UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

(7) Kochi Institute for Core Sample Research
Japan Agency Marine-Earth Science and Technology

erc

This research is funded by the
European Research Council

Earthquakes are caused by fracture and frictional slip on faults. *Friction* is a key parameter in understanding the physics seismic source.

Let's investigate friction under Earth crust conditions.

Fault surface in dolomite, Southern Alps, Italy

Friction law

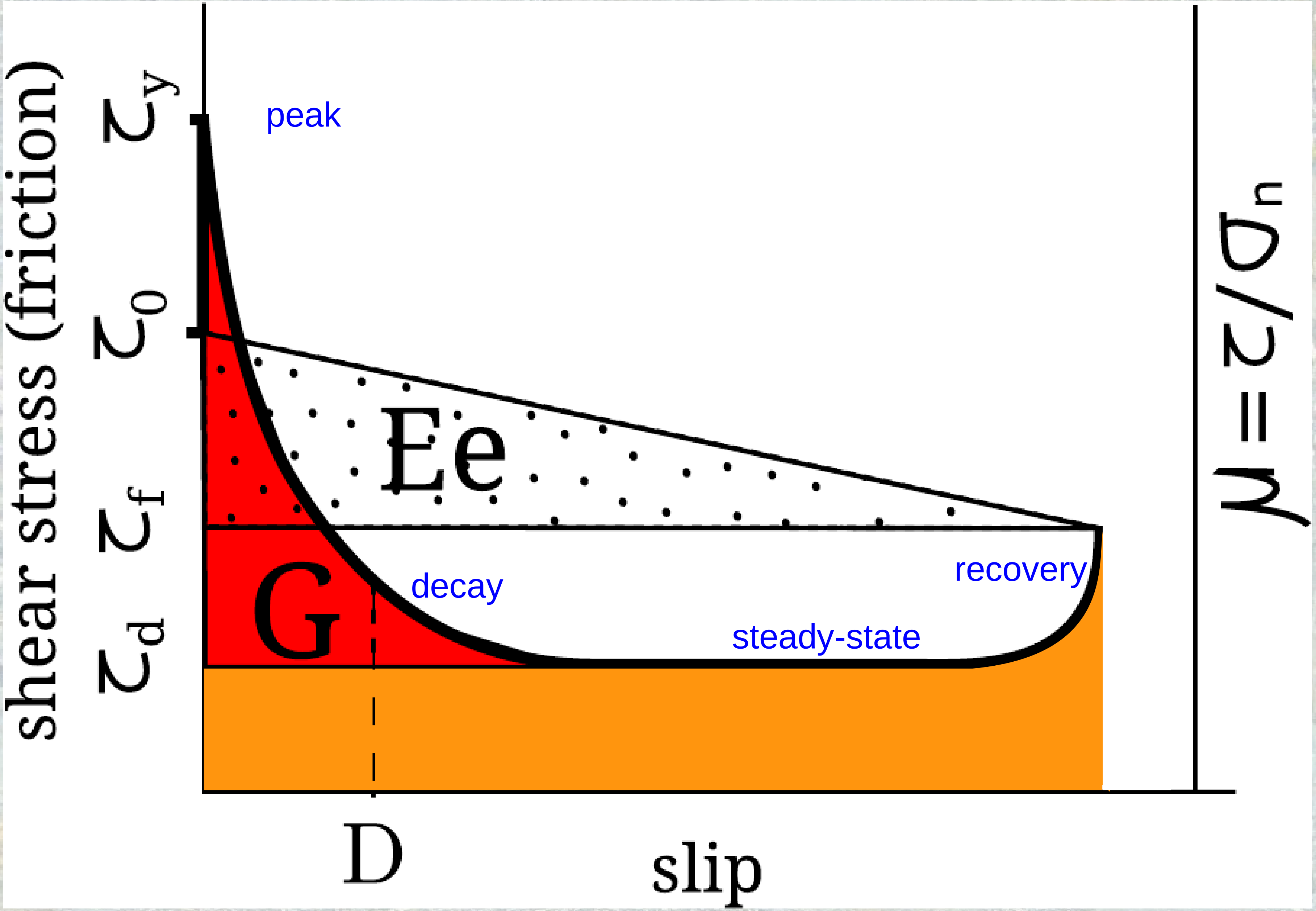
Arrest or propagation of dynamic rupture

Energy balance: dissipation, heat, seismic radiation

Slip velocity, rise time

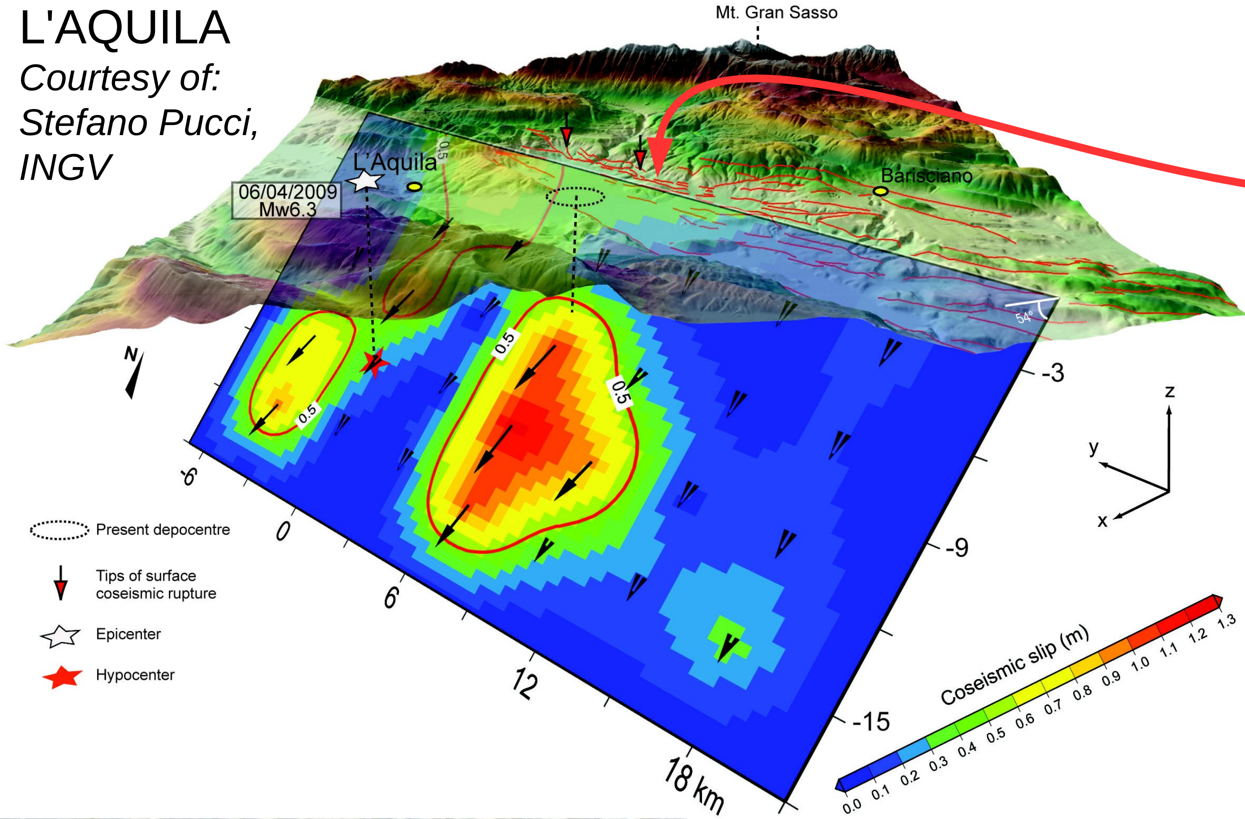
Rupture velocity

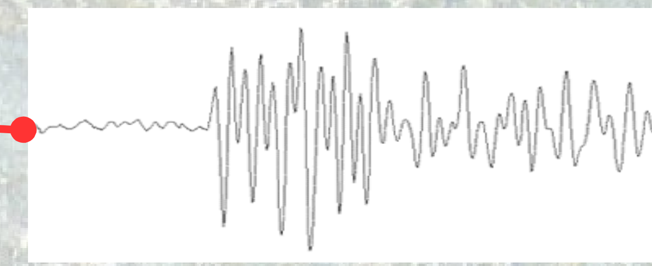
Friction and energy



L'AQUILA

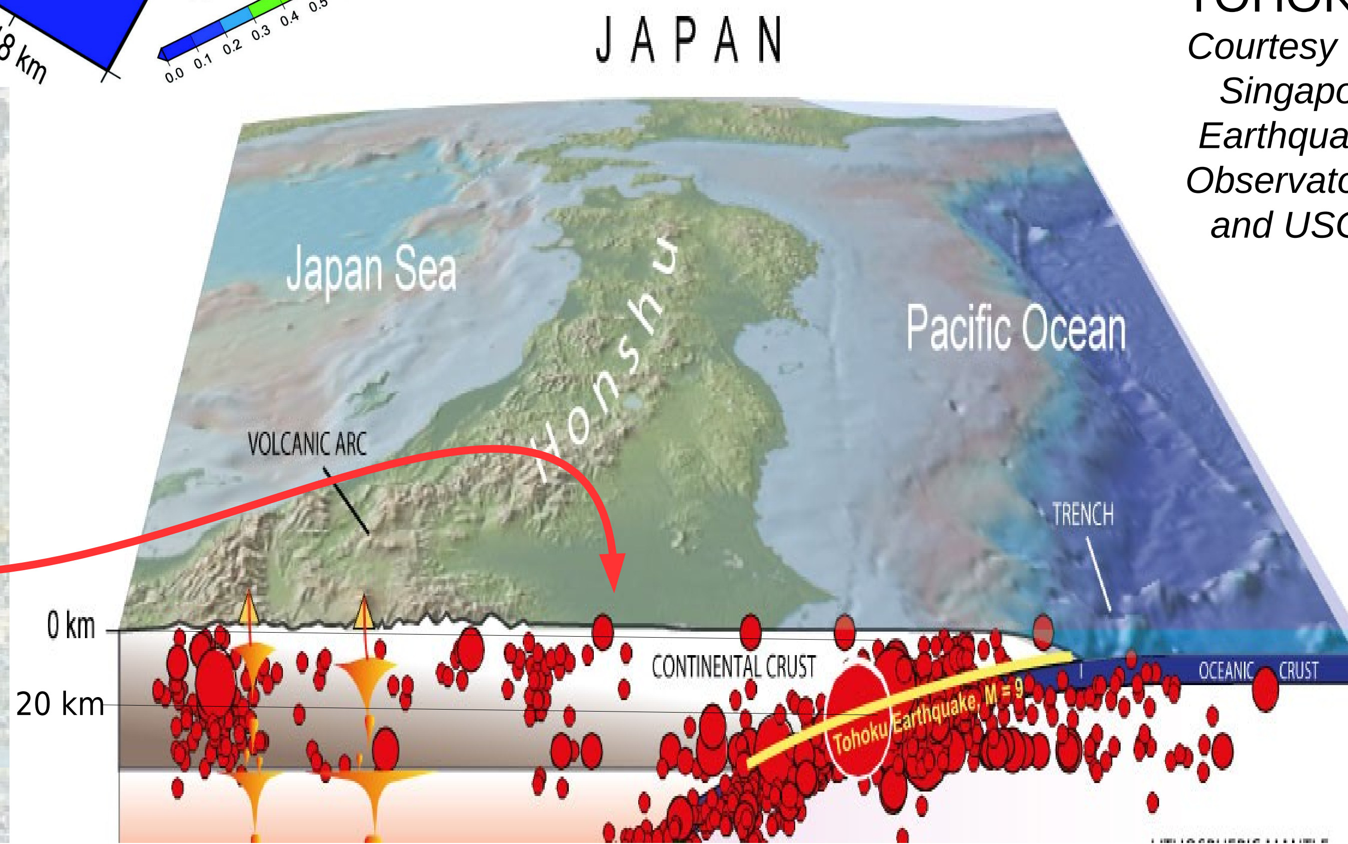
Courtesy of:
Stefano Pucci,
INGV





TOHOKU

Courtesy of:
Singapore Earthquake Observatory and USGS



No direct access to the "earthquake engine"...

Let's try to re-create it in the lab?

Synopsis

- Friction controls earthquake physics
- No direct access to the “earthquake engine”
- Earthquake simulation in the lab: friction machines
- Examples of experiments and typical results
- Lubrication processes and rock types
- Extrapolating the results: faults are weak during earthquakes
- Conclusions and future research

Experimental machines

LOW STRAIN (old-style shear or rotary)

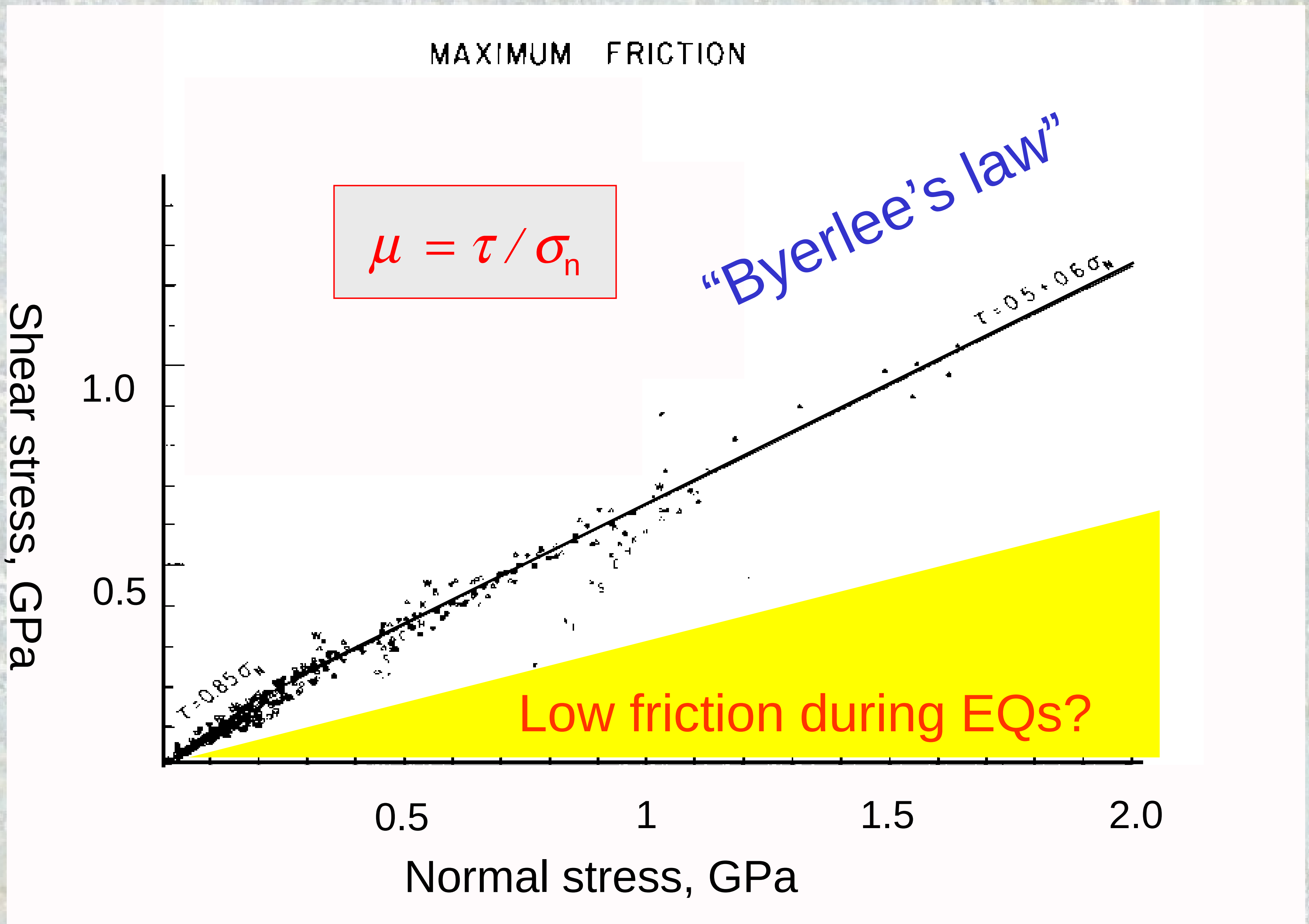
-

HVRF (High-velocity, Rotary Shear machines)

-

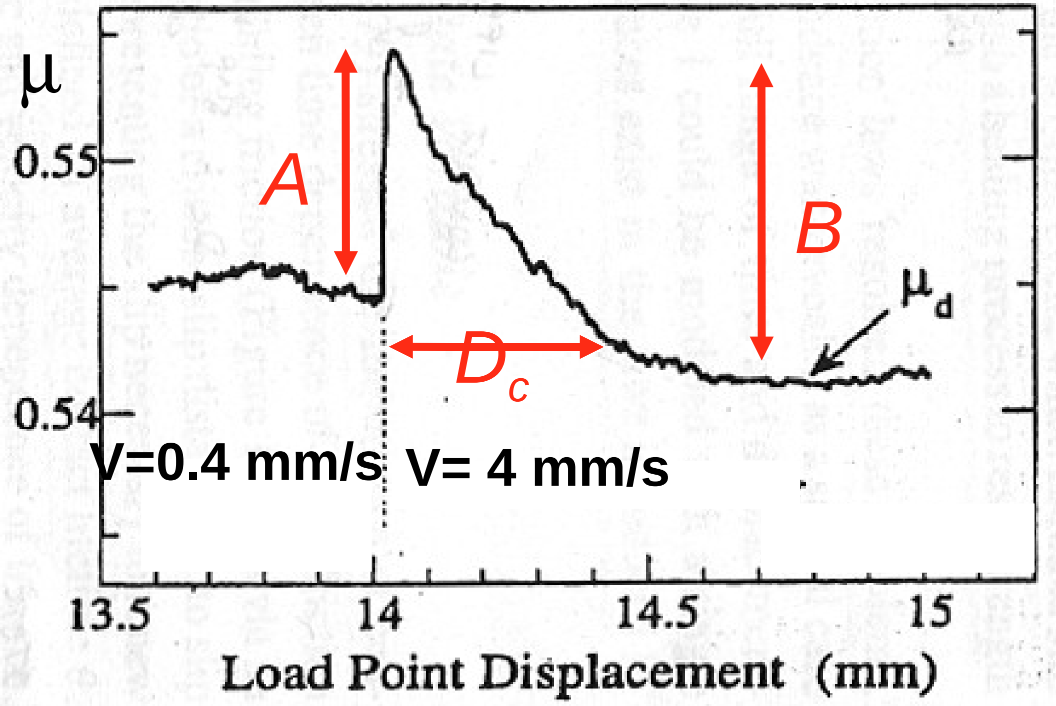
SHIVA (Slow to HIgh Velocity Apparatus)

Experimental machines are NOT designed to predict earthquakes!!
They help our understanding of earthquake physics and thus improve modeling and risk assessment.



[Byerlee, PAGEOPH,1978]

Rate and State



$$\mu = \mu_0 + A\ln\left(\frac{V}{V^*}+1\right) + B\ln\left(\frac{\Theta}{\Theta^*}+1\right) ,$$

$$\frac{d\Theta}{ds} = \frac{1}{V} - \frac{\Theta}{D_c} ,$$

[from Marone, 1998]

μ friction coeff.

A & ***B*** constants

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

θ (s) state variable

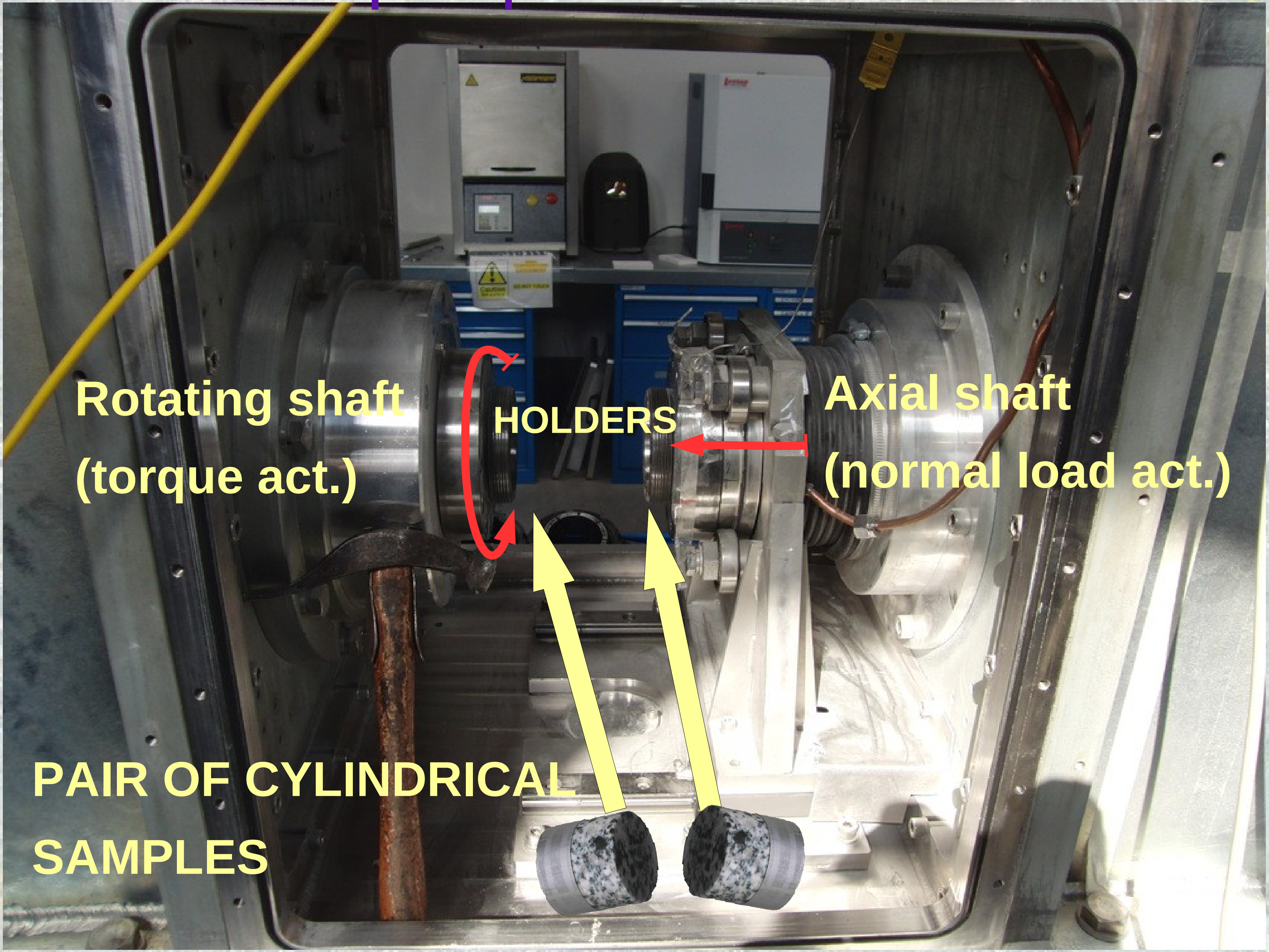
V slip rate - ***s*** slip

friction drop is small

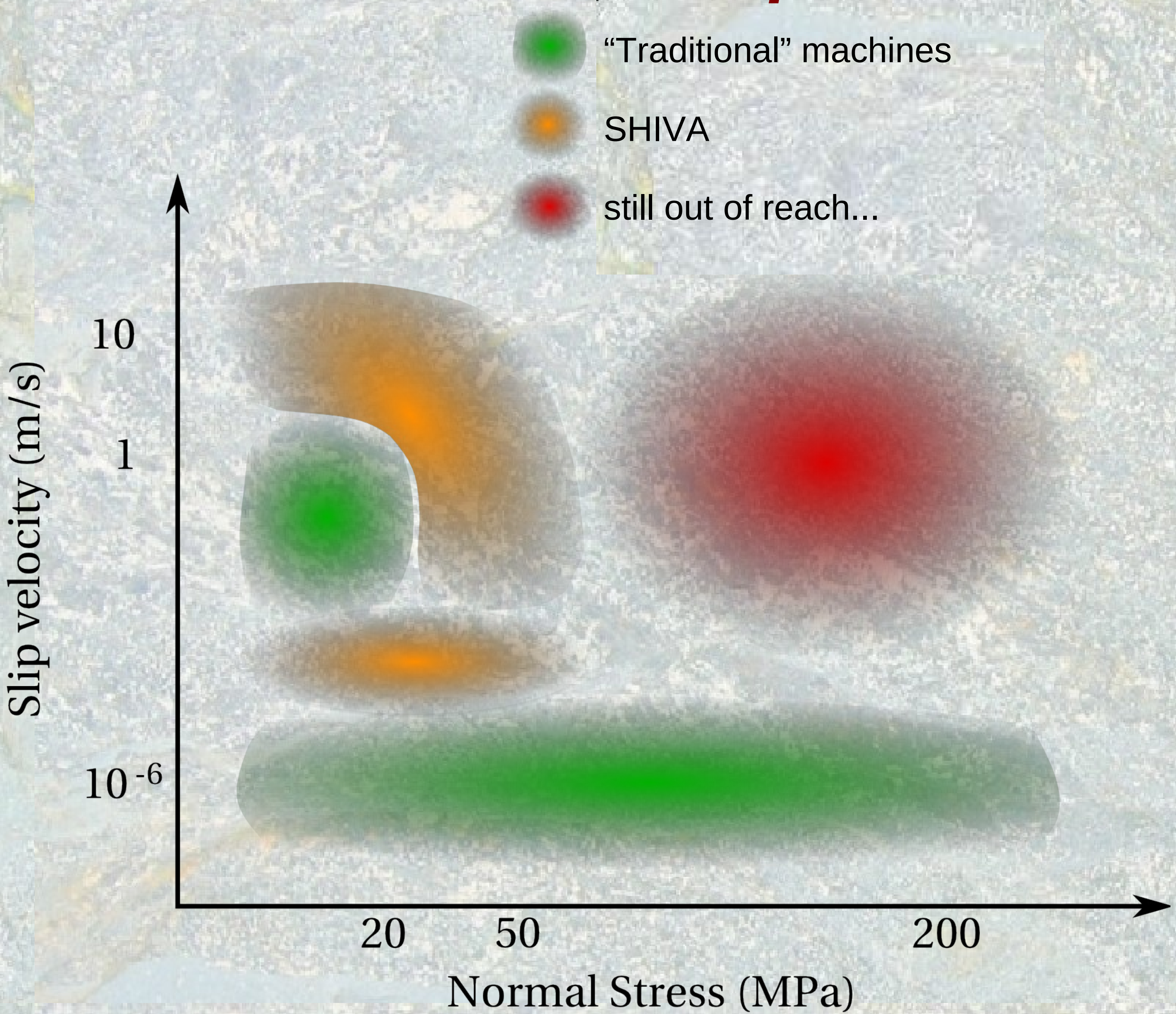
velocity dependance is small

stress and velocity cover only part of seismic faulting conditions

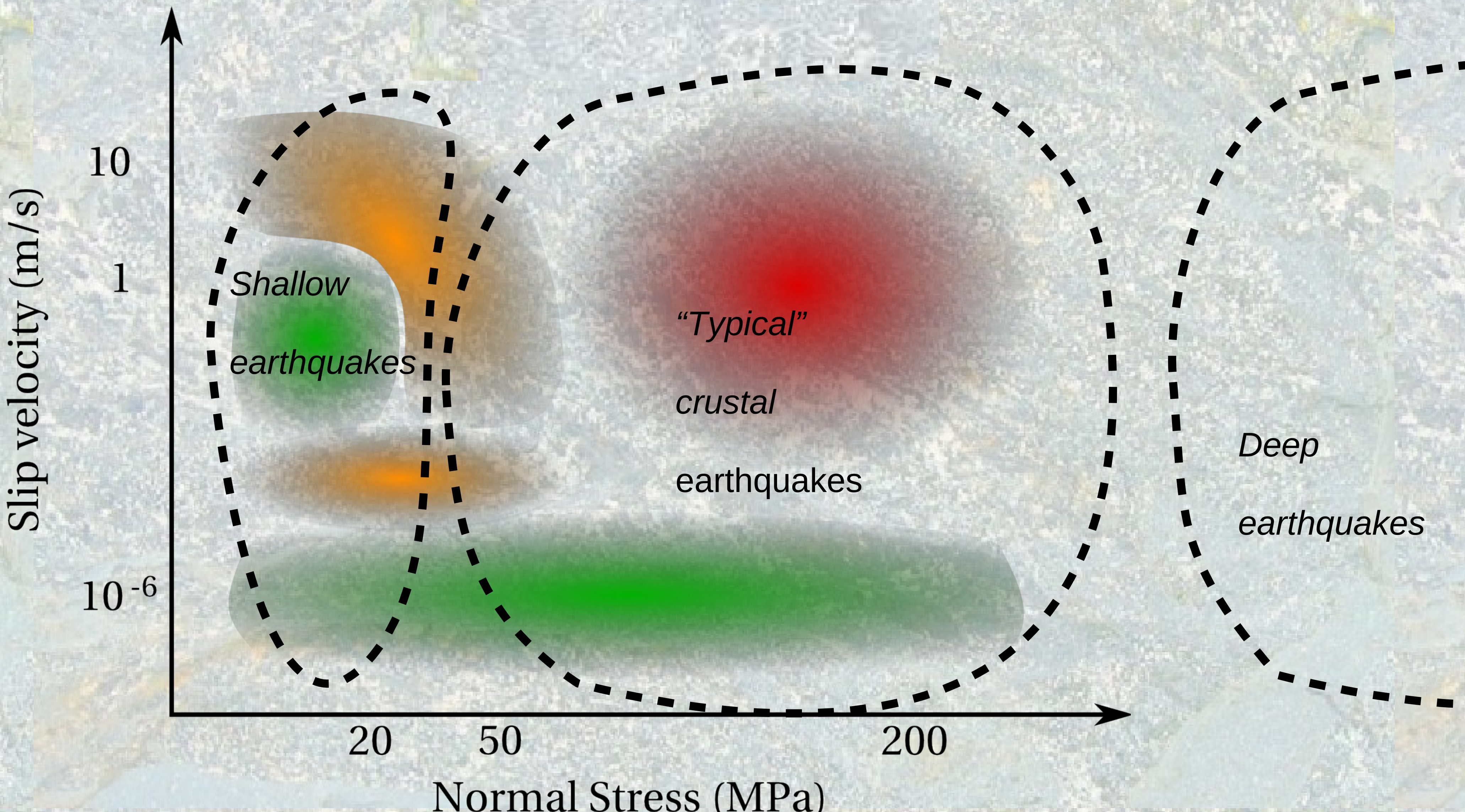
The principle of ROTARY machines



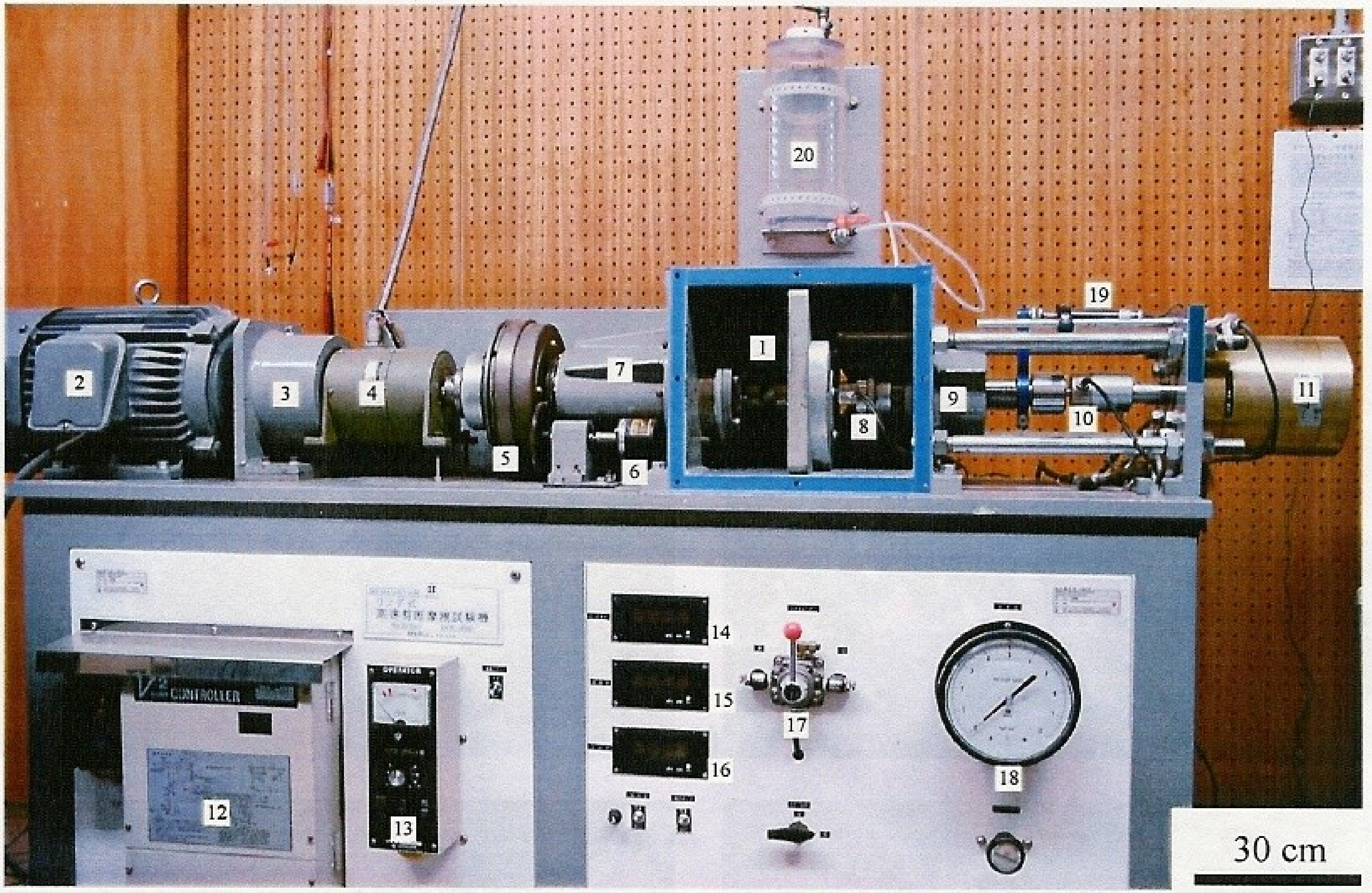
Experimental conditions



Experimental conditions and earthquake conditions



Machine “1”, Kyoto Univ., Japan, ca. 1990 (T. Shimamoto)



NIED 2007

Designed by

Mizoguchi

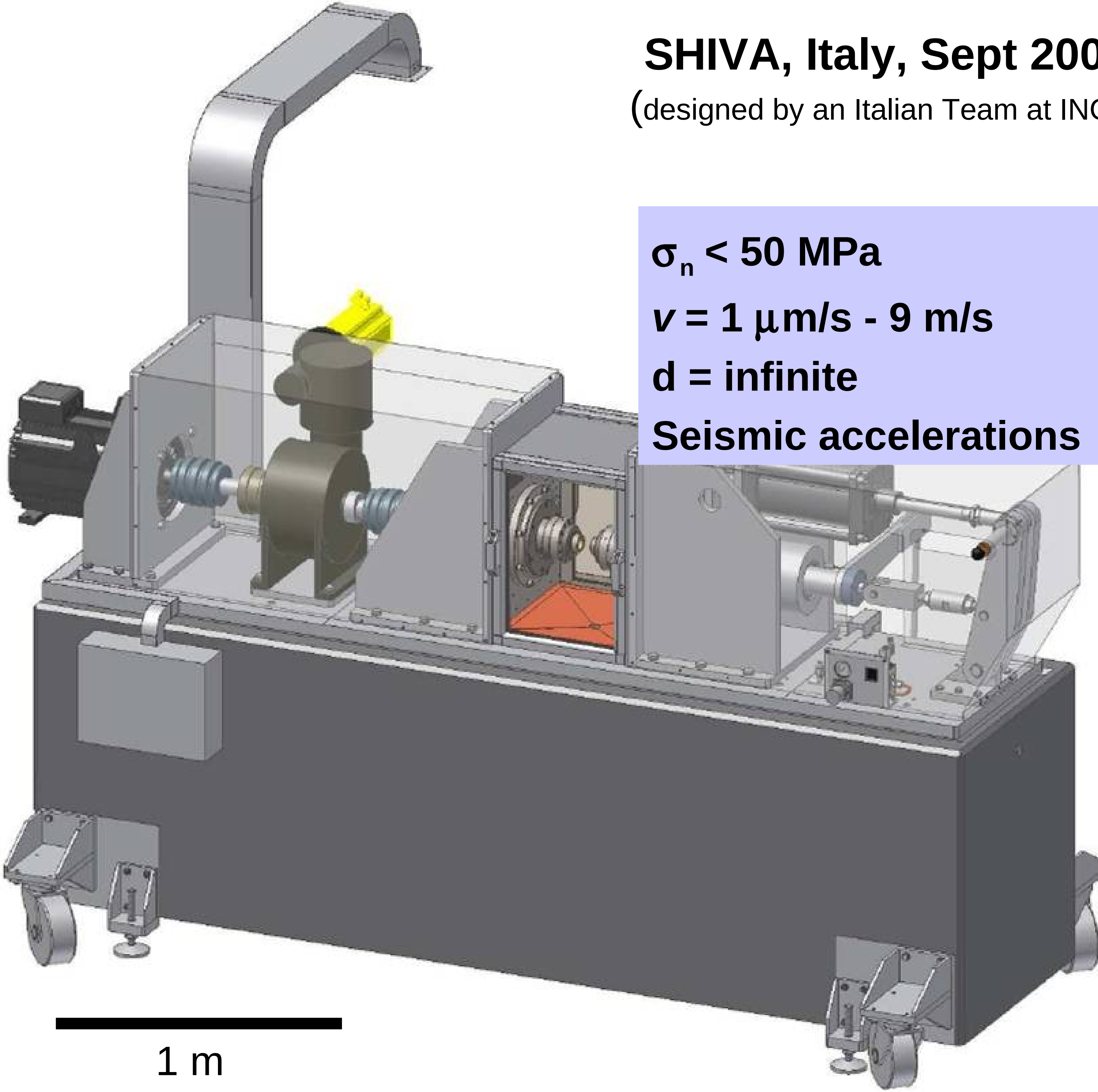
σ_n < 20 MPa

v = 0.1 μm/s - 10 m/s

d = infinite

SHIVA, Italy, Sept 2009

(designed by an Italian Team at INGV)

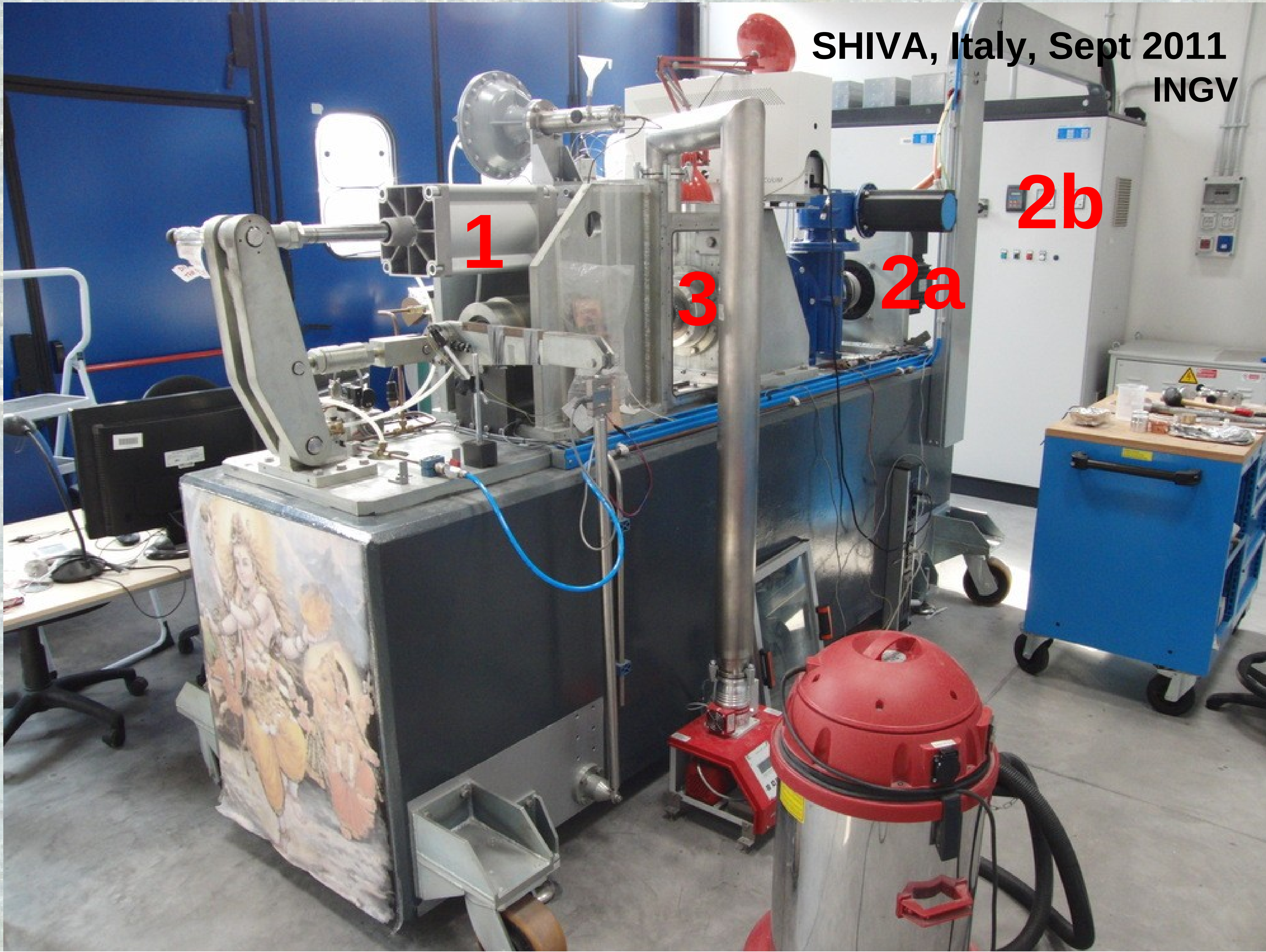


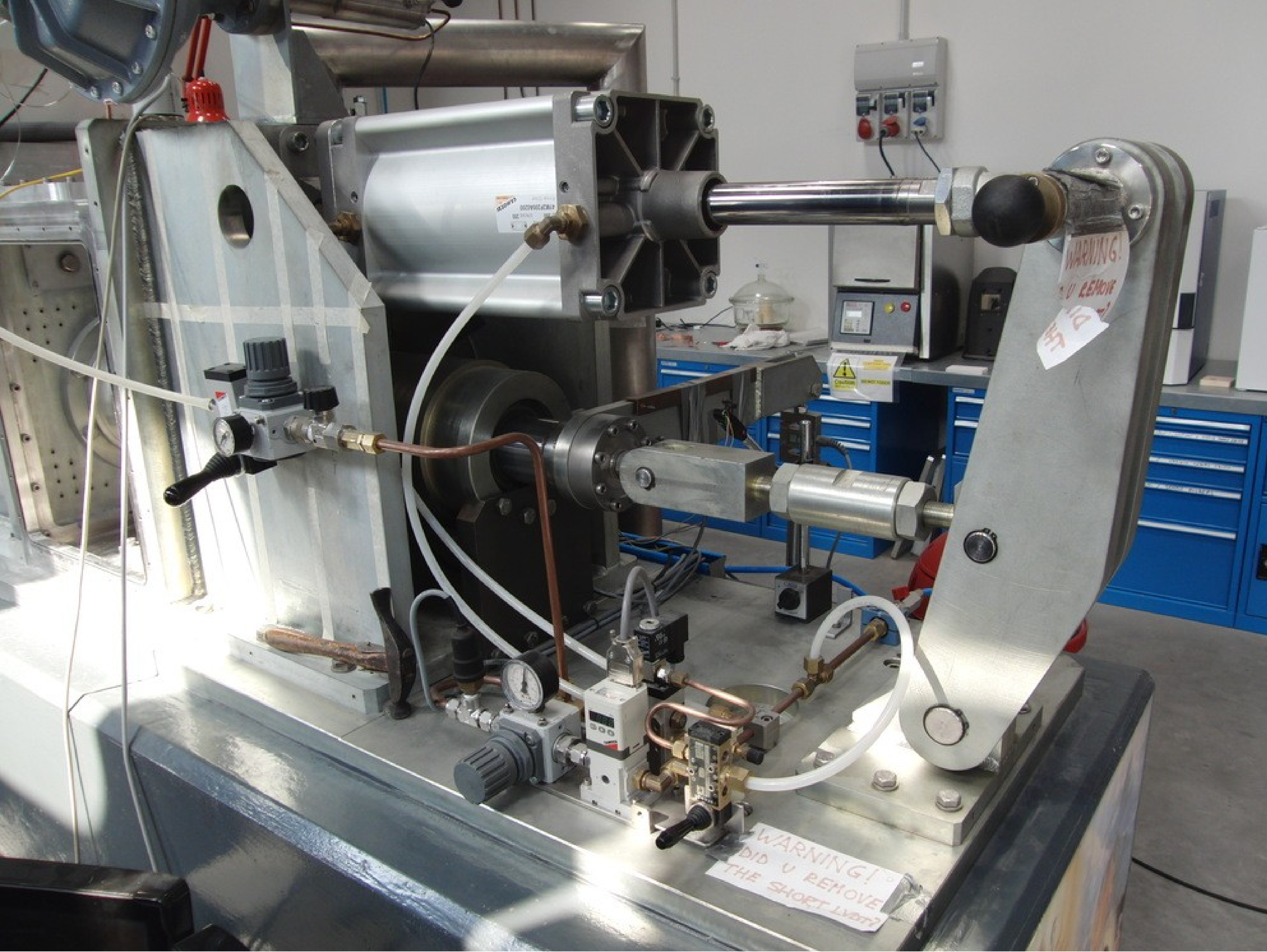
σ_n < 50 MPa

***v* = 1 µm/s - 9 m/s**

d = infinite

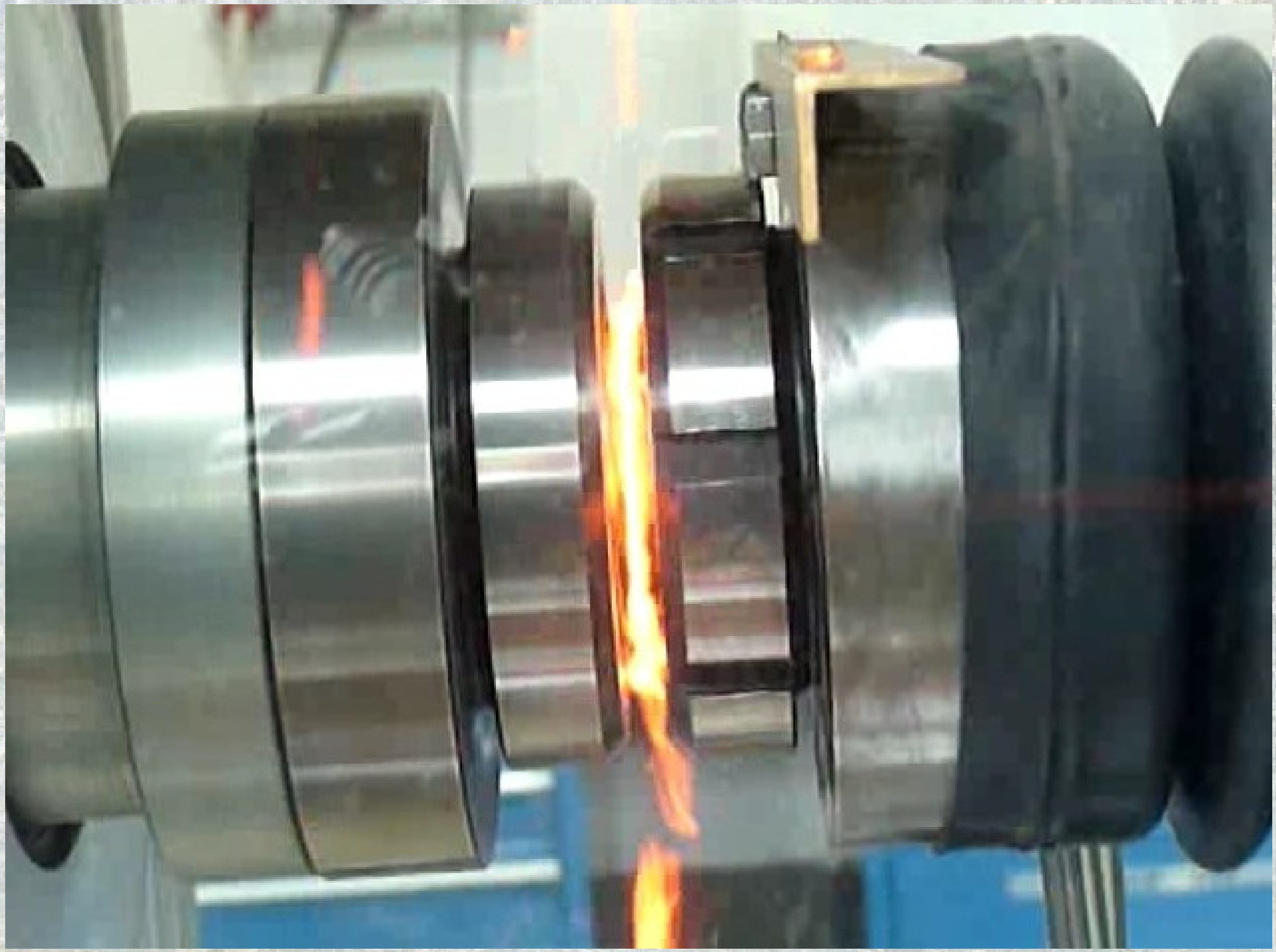
Seismic accelerations


SHIVA, Italy, Sept 2011
INGV
1
2b
3
2a


WARNING!
DID U REMOVE
THE SHORT LVDT?

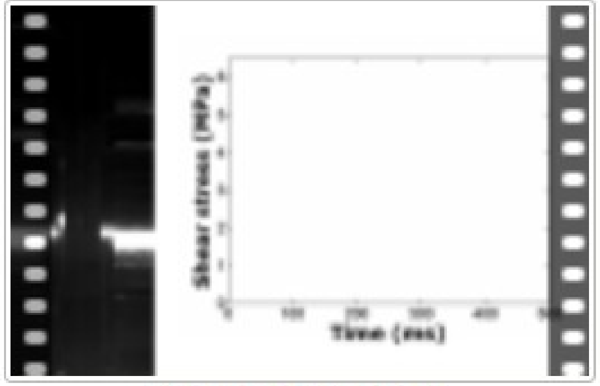

OmniStar™
PFEIFFER VACUUM

SERVO-CONTROL 200kW drive



Video examples of the experimental dynamics

s063gabbro.avi



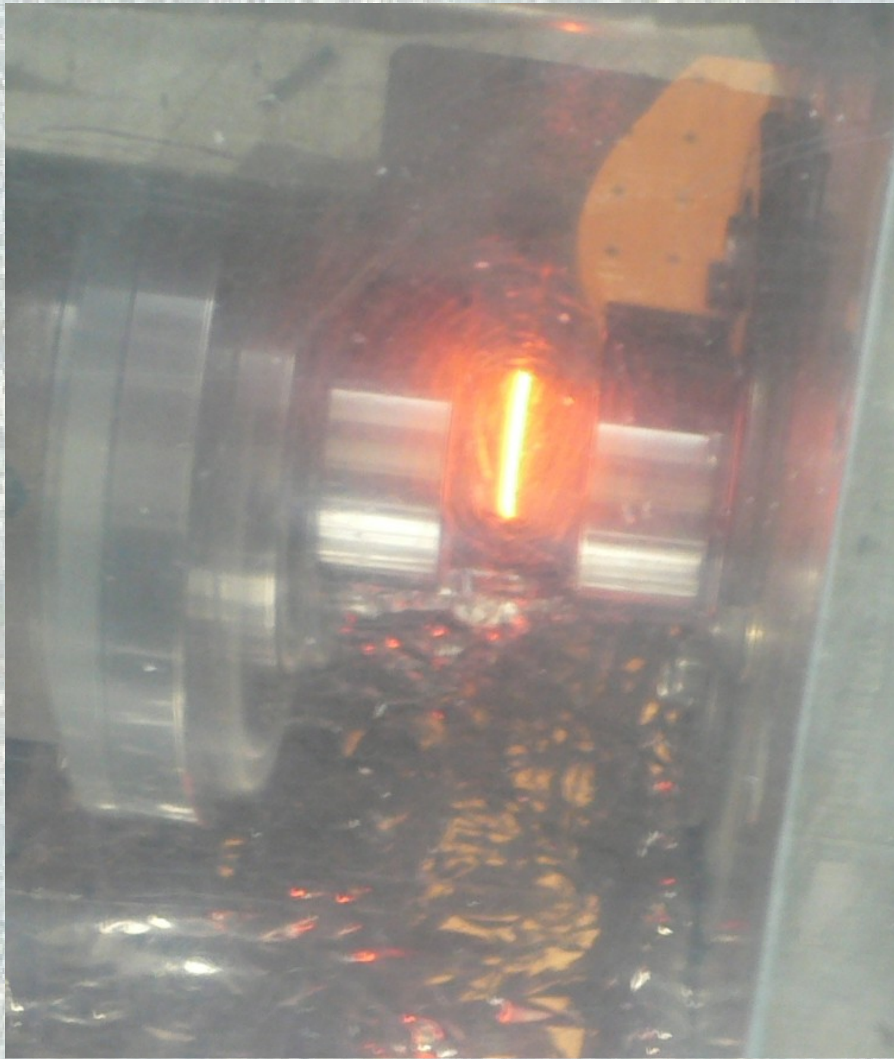
s051_combined.avi

Dry, slicatic rocks

--> melting

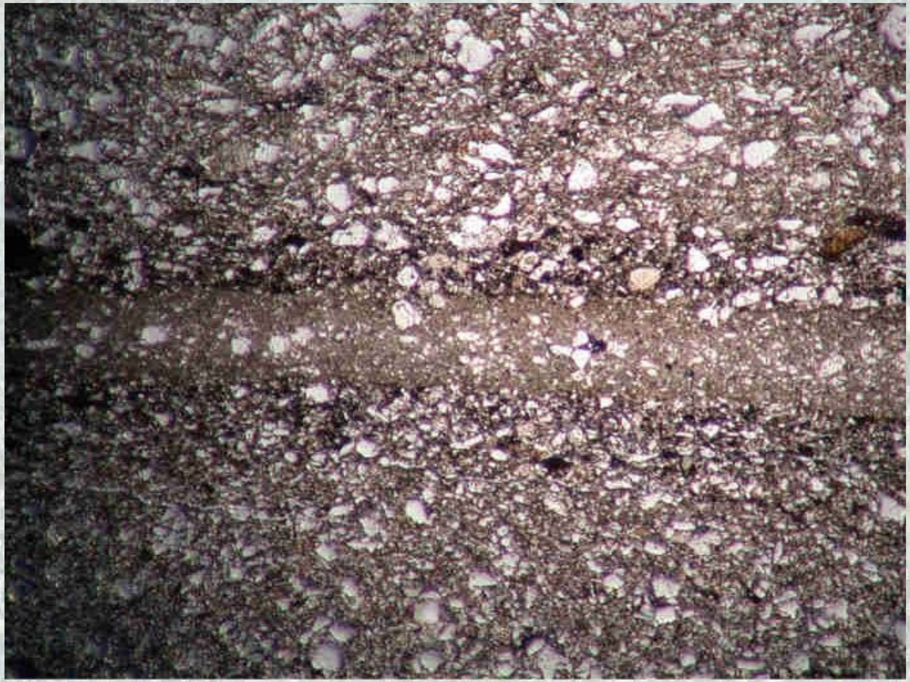
Natural faults

Lab



MYLONITE (Maine)

SILTSTONE



METAGABBRO (Premosello-Italian Alps)

What do we measure?

FRICTIONAL resistance of the sample while it is sliding

SHORTENING of the sample under the effect of frictional wear

GAS EMISSIONS during the sliding

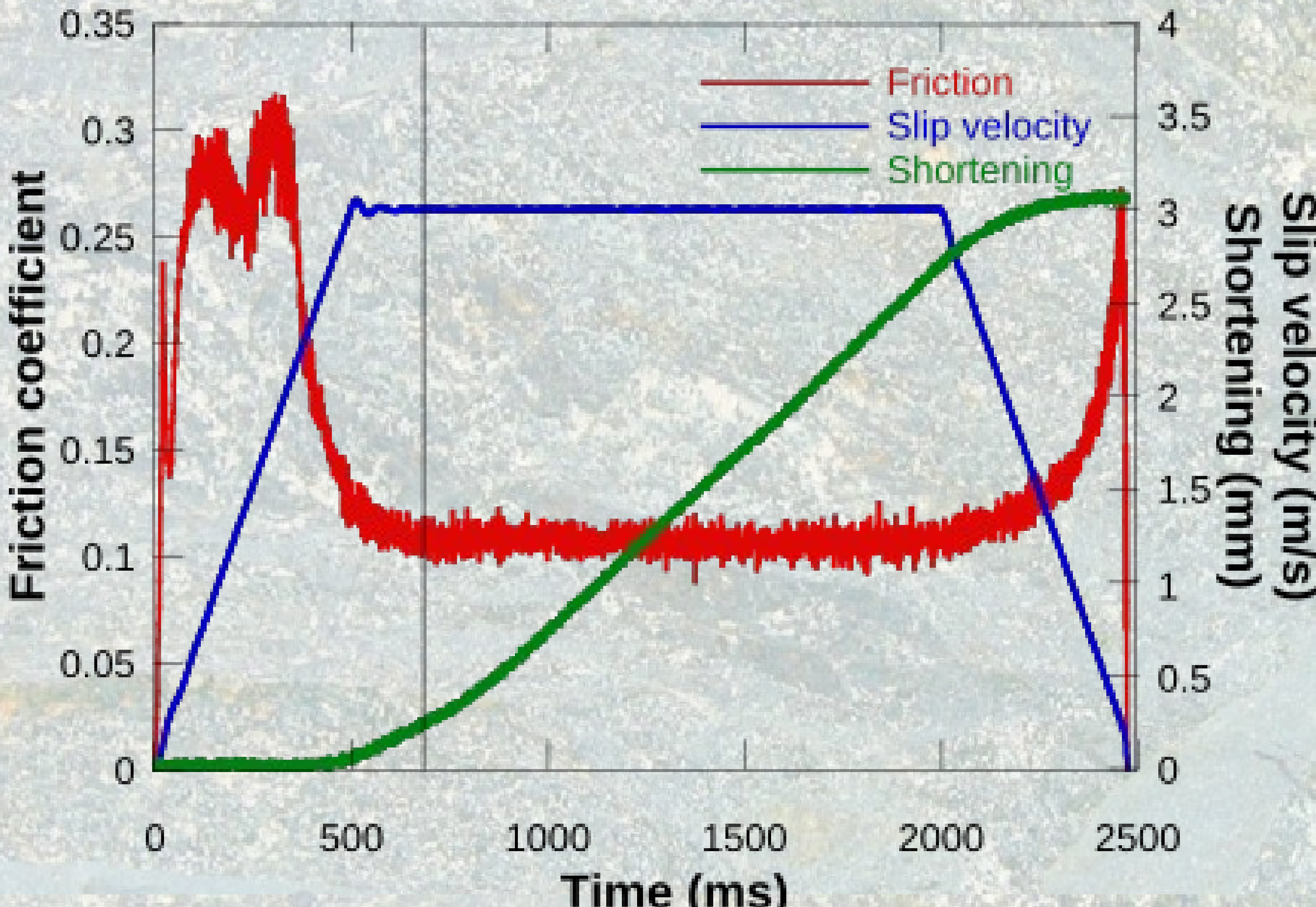
TEMPERATURES in or around the sample close to the slip surface

SLIDING VELOCITY is retrieved from rotative motion and sample radius

Example:

s051 - rings of gabbro at 3 m/s and 20 MPa

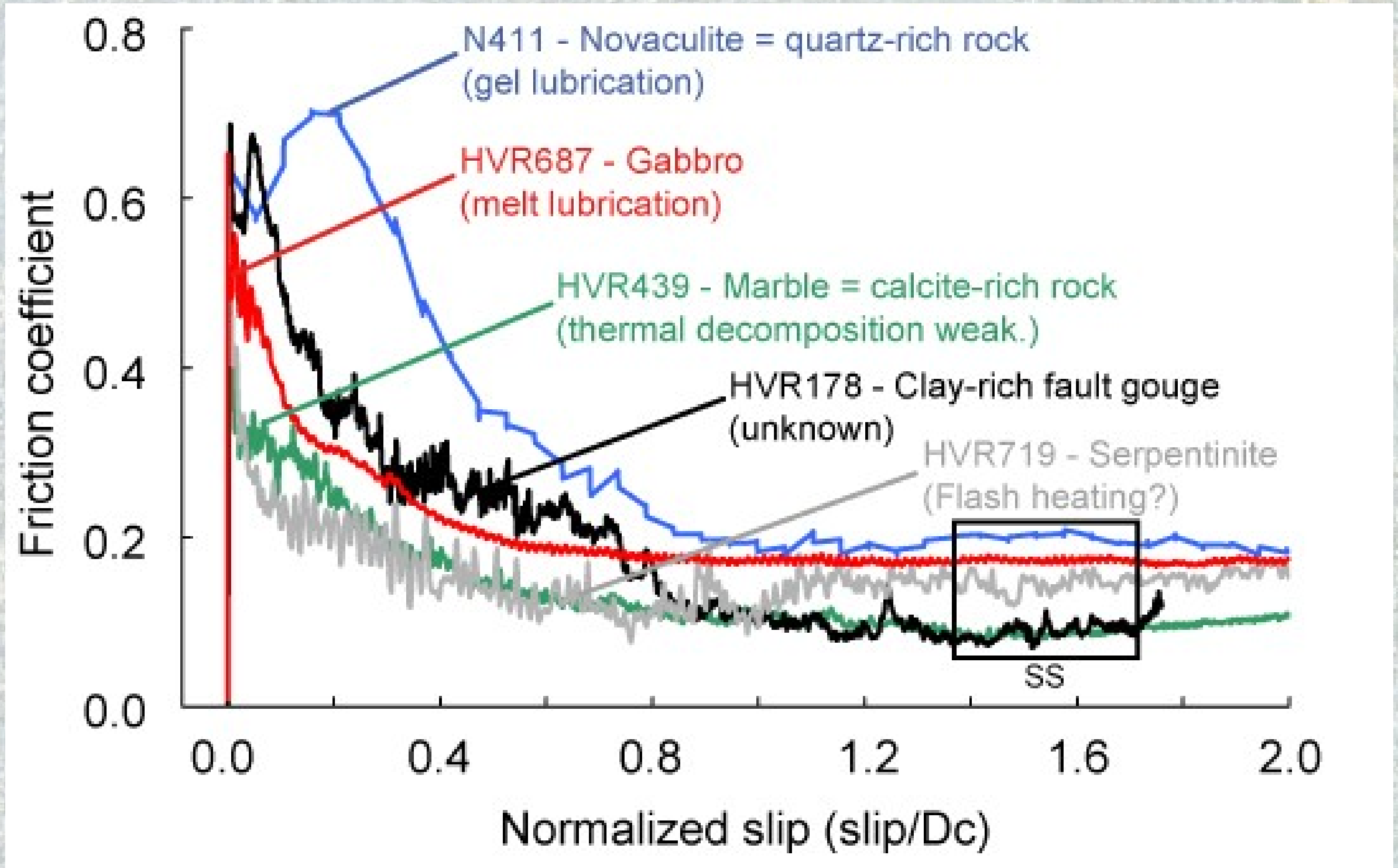
Acceleration = deceleration = 6 m/s^2



Synopsis

- Friction controls earthquake physics
- No direct access to the “earthquake engine”
- Earthquake simulation in the lab: friction machines
- Examples of experiments and typical results
- Lubrication processes and rock types
- Extrapolating the results: faults are weak during earthquakes
- Conclusions and future research

High velocity friction; lubrication

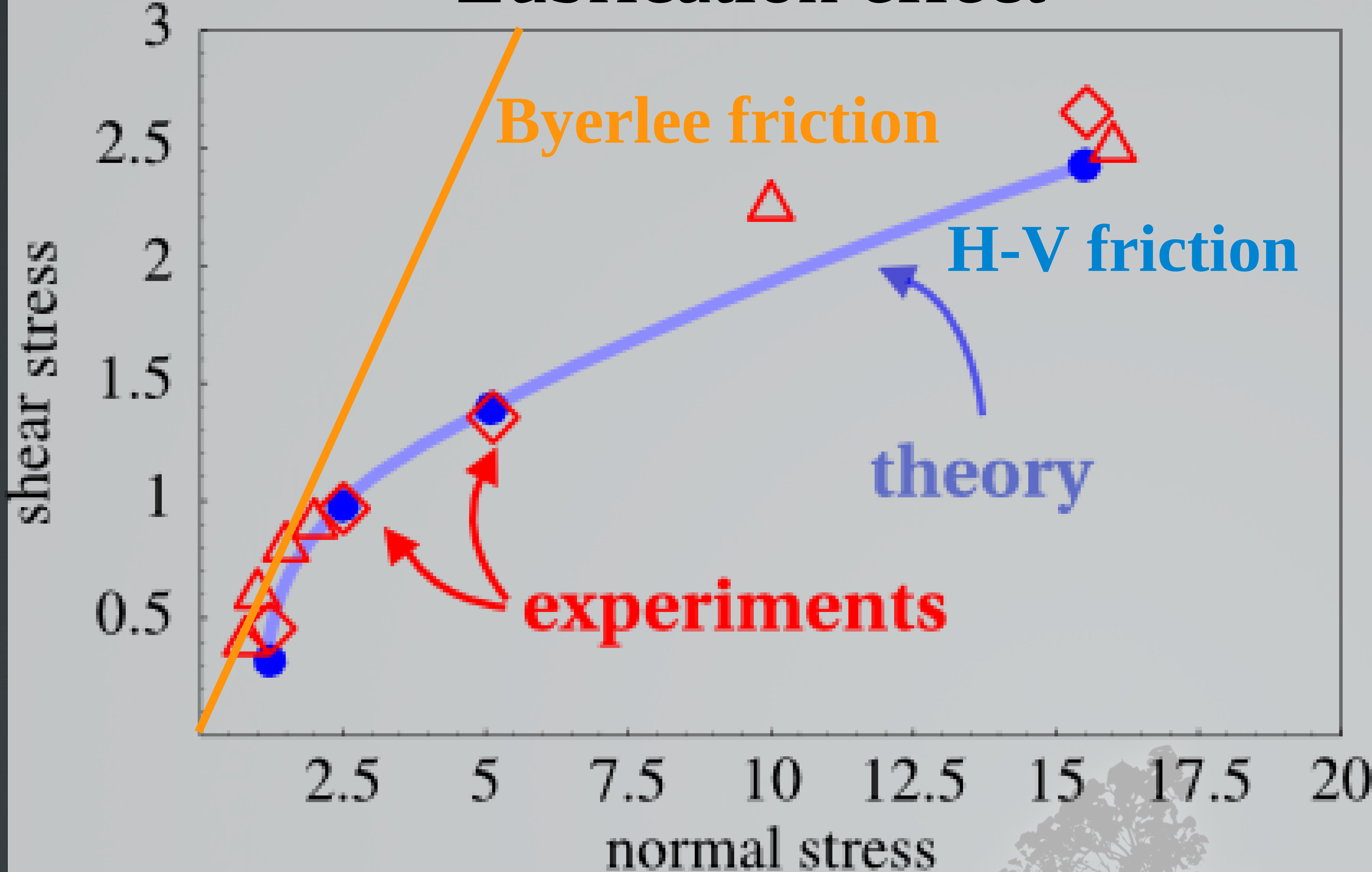


Large slip & slip-rate

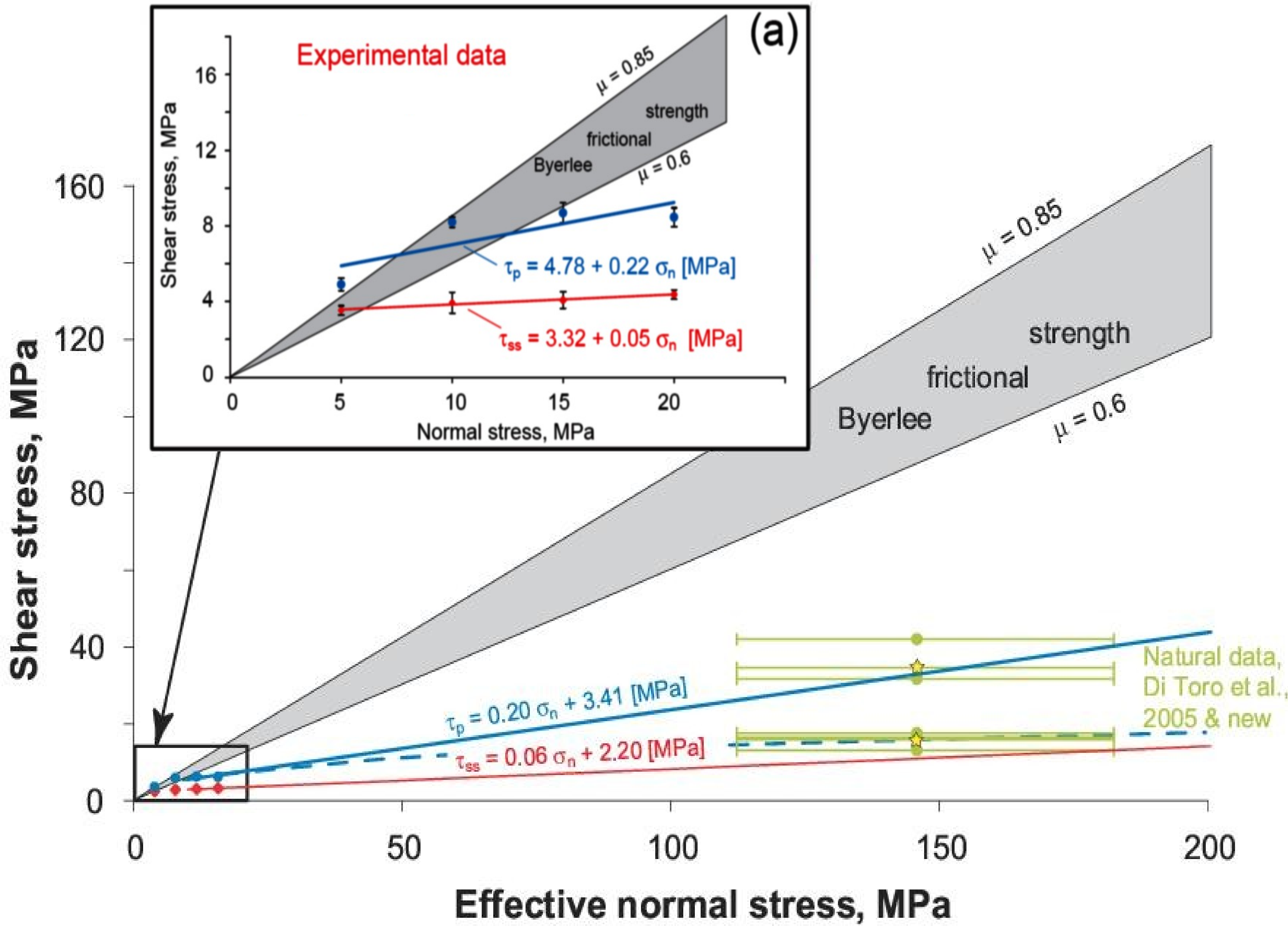
Intermediate normal stress

Considerable WEAKENING

Lubrication effect



Nielsen et al., 2008



After Di Toro et al., 2005

The key is **high work rate**
generating heat density

Heat density

Temperature increase

Specific heat of water,
evaporation,
fluid pressurization

Latent heat of chemical processes
and phase transitions (decarbonation,
gelification, dehydration, serpentinization,
poorly known tribolchemical processes...)

Dynamic fault slip, heat and friction:

- Large, fast slip means concentrated heat
- Heat triggers a variety of weakening mechanisms
- Under favourable conditions melt is produced

In its most straightforward manifestation, elevated heat density induces *temperature rise* and eventually yields to *melting*...

But not always!

(maybe even seldom)

Observed processes in HV rock friction:

Silica gel lubrication (quartz rocks)

Thermal decomposition and nanopowders (limestones)

Thermal decomposition and pressurization (dolostones)

Clay-gouge weakening, dehydration and press. (clay-gouges)

Flash heating (small slip amounts)

Melt lubrication (all silicate built rocks)

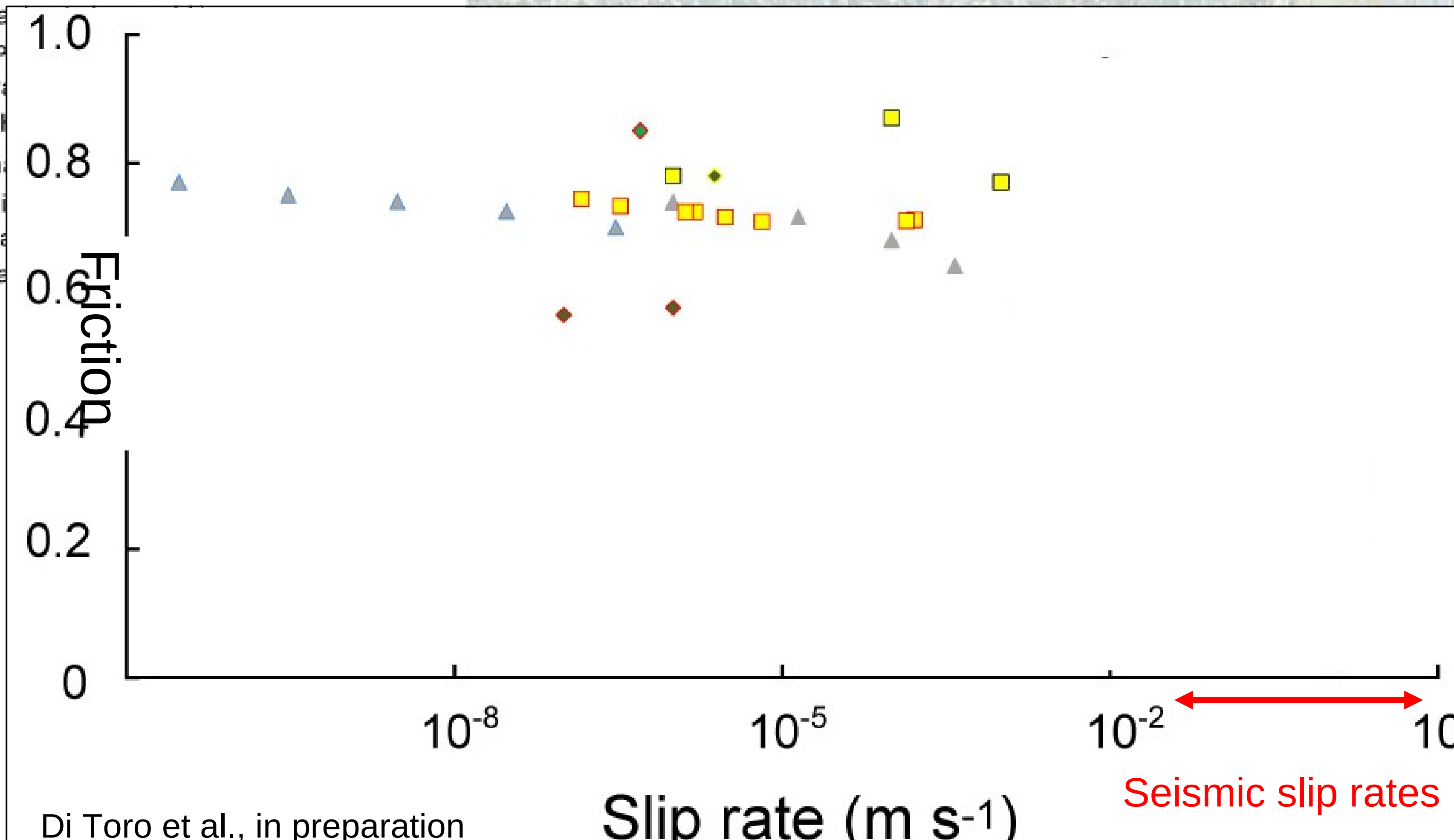
A very inclomplete classification of rock types and frictional processes

	Cohesive	*Non-cohesive & clays*
Silicatic	Melting Silica gel lubrication Flash heating Dehydration	
Carbonatic	Decarbonation Plastic yielding Dehydration Flash heating Nanopowder lub.	Flash heating Decarbonation Nanopowder lub.

For most process and rock types lubrication is observed at high velocity

Not much weakening..

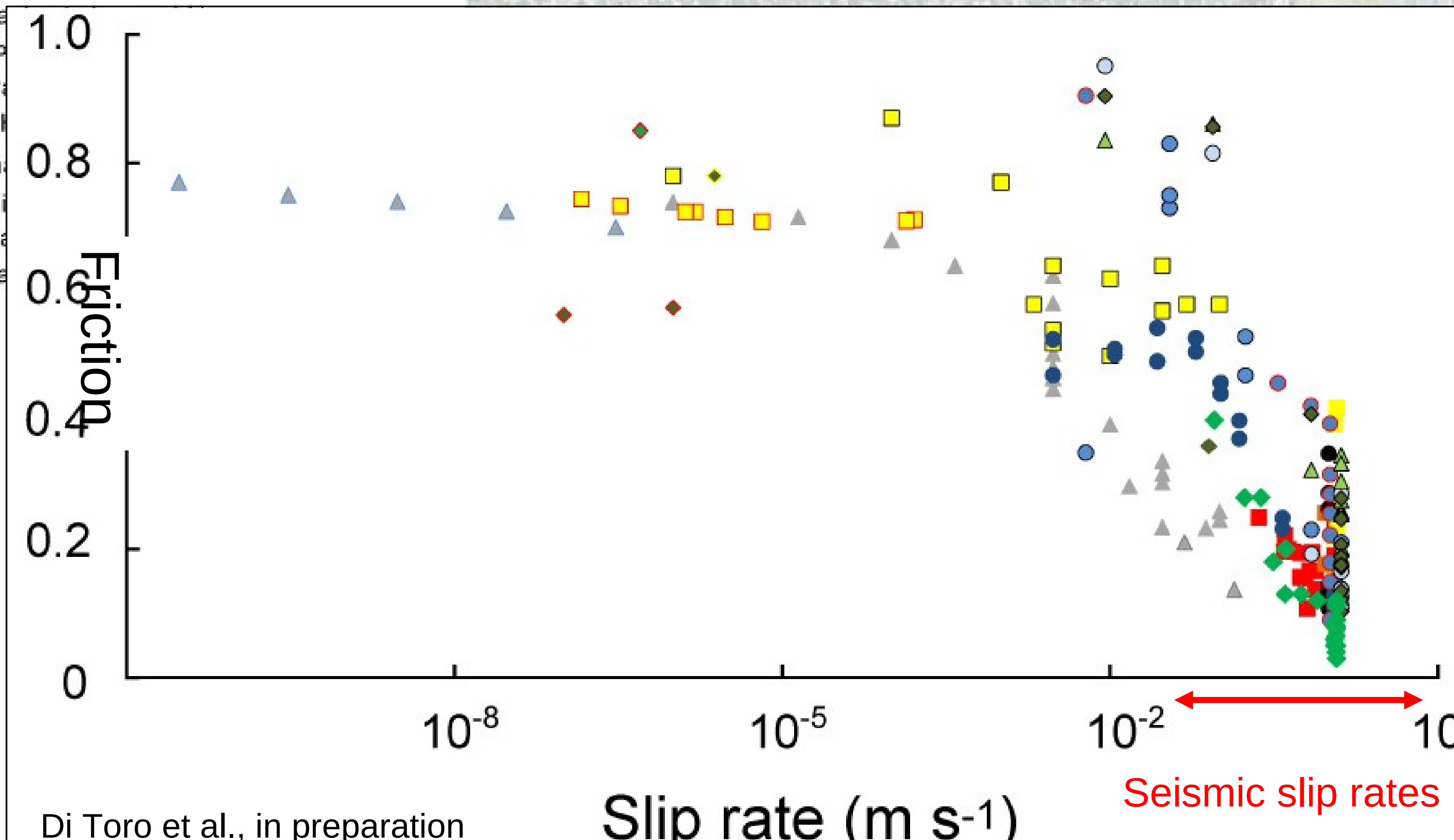
- Quartz sandstone (Dieterich, 1978)
- Quartz-Novaculite (gelification, Di Toro et al., 2004)
- Quartz-Novaculite (gelification, Hirose and Di Toro, 2005 unpubl.)
- Granite (Dieterich, 1978)
- Granite (Di Toro et al., 2004 & unpubl.)
- Peridotite (melting, Di Toro et al., 2006; Del Gaudio et al., 2009)
- Gabbro (melting, Nielsen et al., 2008; Hirose and Shimamoto, 2005)
- Tonalite (melting, Di Toro et al., 2006)
- Monzodiorite (melting, Mizoguchi and Hirose, unpubl.?)
- Tonalite (melting, field estimates, Di Toro et al., 2006)
- Serpentinite (dehydration, Hirose and Bystricky, 2007)
- Clay-rich dry gouge (dehydration, Mizoguchi et al., 2009)
- Clay-rich dry gouge (dehydration, Ferri et al., unpubl.)
- Gypsum dry gouge (De Pa
- Anhydrite dry gouge (De P
- Dolomite dry gouge (De P
- Dolomite (decarbonation, I
- Dolomite dry gouge (Shim
- Dolomite (Weeks and Tulli
- Calcite gouge (Morrow et a
- Calcite (decarbonation, Ha



Significant weakening around 0.1 m/s

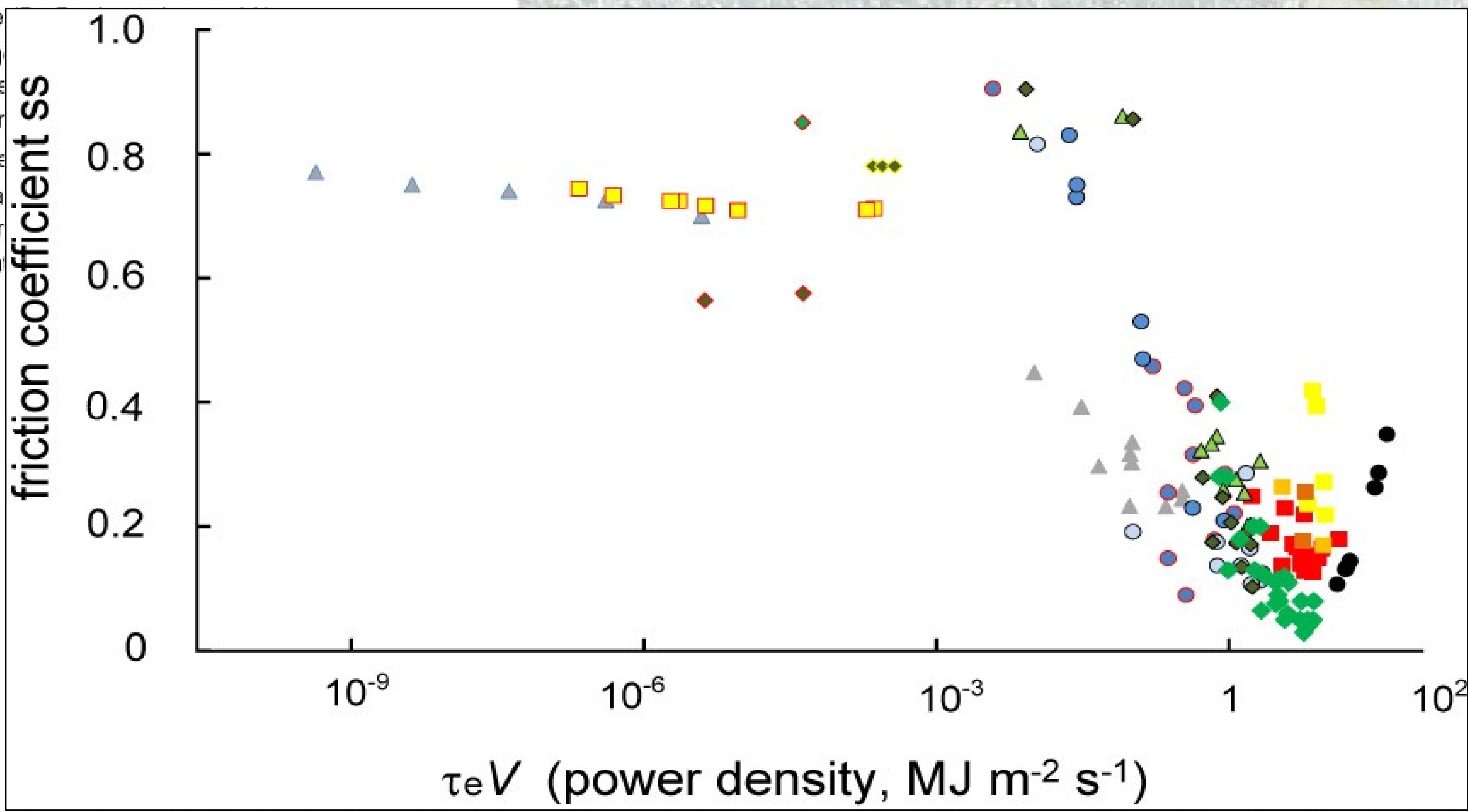
Different rock types (carbonates, silicates, ...)

- Quartz sandstone (Dieterich, 1978)
- Quartz-Novaculite (gelification, Di Toro et al., 2004)
- Quartz-Novaculite (gelification, Hirose and Di Toro, 2005 unpubl.)
- Granite (Dieterich, 1978)
- Granite (Di Toro et al., 2004 & unpubl.)
- Peridotite (melting, Di Toro et al., 2006; Del Gaudio et al., 2009)
- Gabbro (melting, Nielsen et al., 2008; Hirose and Shimamoto, 2005)
- Tonalite (melting, Di Toro et al., 2006)
- Monzodiorite (melting, Mizoguchi and Hirose, unpubl.?)
- Tonalite (melting, field estimates, Di Toro et al., 2006)
- Serpentinite (dehydration, Hirose and Bystricky, 2007)
- Clay-rich dry gouge (dehydration, Mizoguchi et al., 2009)
- Clay-rich dry gouge (dehydration, Ferri et al., unpubl.)
- Gypsum dry gouge (De Pa
- Anhydrite dry gouge (De P
- Dolomite dry gouge (De P
- Dolomite (decarbonation, I
- Dolomite dry gouge (Shim
- Dolomite (Weeks and Tulli
- Calcite gouge (Morrow et a
- Calcite (decarbonation, Ha



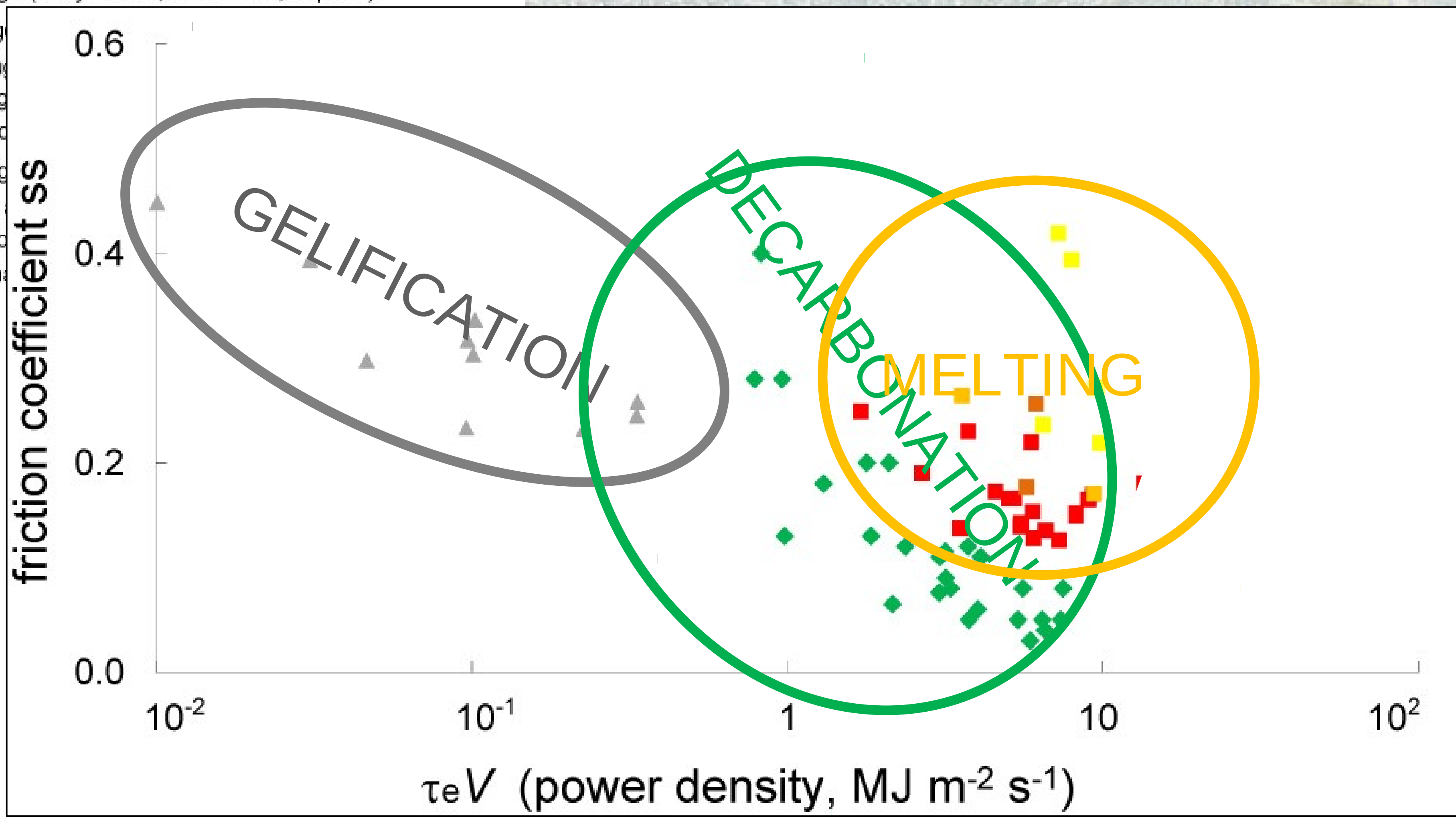
Work rate or power density

Quartz sandstone (Dieterich, 1978)
Quartz-Novaculite (gelification, Di Toro et al., 2004)
Quartz-Novaculite (gelification, Hirose and Di Toro, 2005 unpubl.)
Granite (Dieterich, 1978)
Granite (Di Toro et al., 2004 & unpubl.)
Peridotite (melting, Di Toro et al., 2006; Del Gaudio et al., 2009)
Gabbro (melting, Nielsen et al., 2008; Hirose and Shimamoto, 2005)
Tonalite (melting, Di Toro et al., 2006)
Monzodiorite (melting, Mizoguchi and Hirose, unpubl.?)
Tonalite (melting, field estimates, Di Toro et al., 2006)
Serpentinite (dehydration, Hirose and Bystricky, 2007)
Clay-rich dry gouge (dehydration, Mizoguchi et al., 2009)
Clay-rich dry gouge (dehydration, Ferri et al., unpubl.)
Gypsum dry gouge
Anhydrite dry goug
Dolomite dry gouge
Dolomite (decarbon
Dolomite dry gouge
Dolomite (Weeks a
Calcite gouge (Mor
Calcite (decarbona



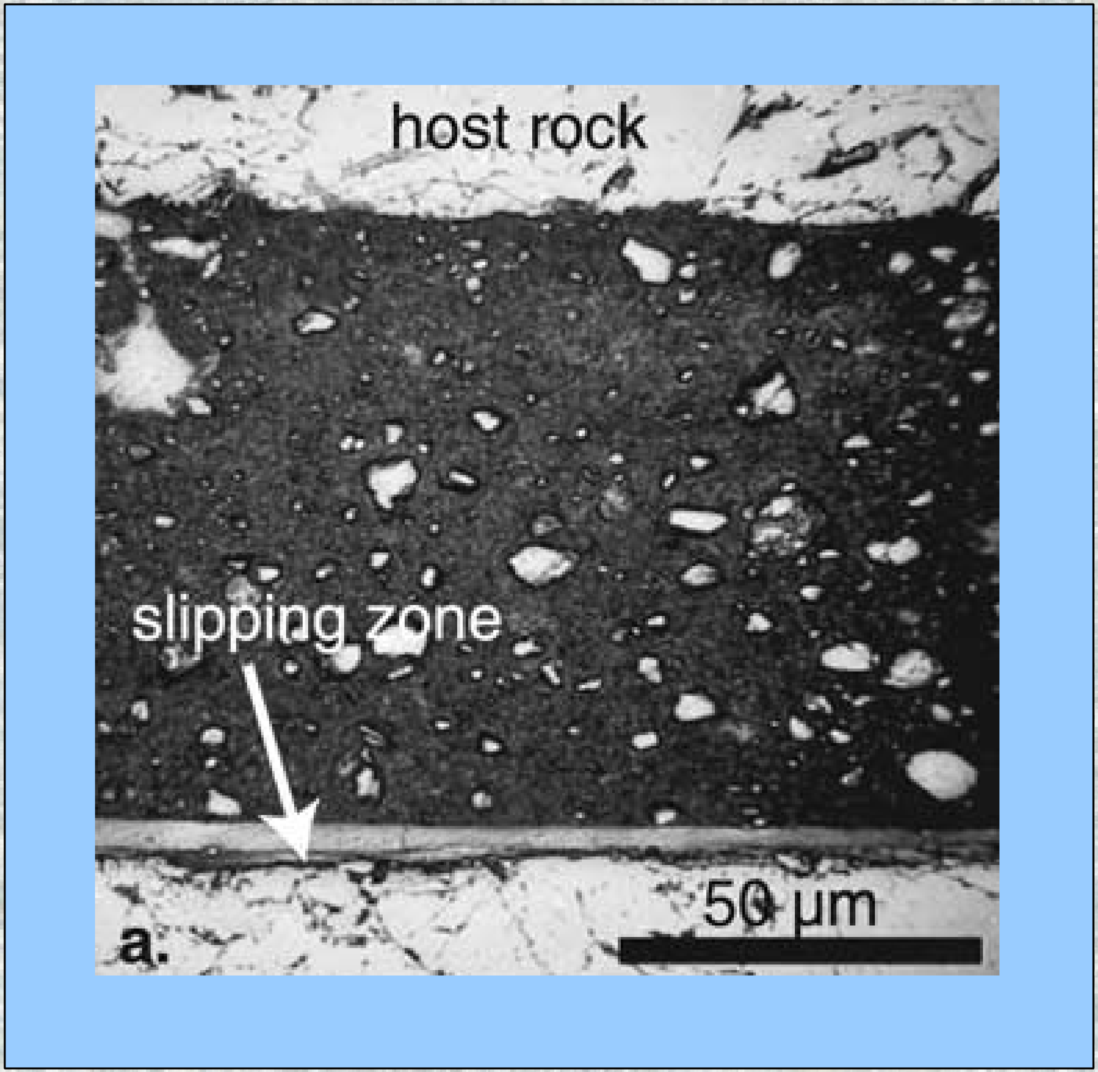
Cohesive Rocks: desaggregation in the results for various compositions suggest different thermal activation mechanisms.

- Quartz sandstone (Dieterich, 1978)
- Quartz-Novaculite (gelification, Di Toro et al., 2004)
- Quartz-Novaculite (gelification, Hirose and Di Toro, 2005 unpubl.)
- Granite (Dieterich, 1978)
- Granite (Di Toro et al., 2004 & unpubl.)
- Peridotite (melting, Di Toro et al., 2006; Del Gaudio et al., 2009)
- Gabbro (melting, Nielsen et al., 2008; Hirose and Shimamoto, 2005)
- Tonalite (melting, Di Toro et al., 2006)
- Monzodiorite (melting, Mizoguchi and Hirose, unpubl.?)
- Tonalite (melting, field estimates, Di Toro et al., 2006)
- Serpentinite (dehydration, Hirose and Bystricky, 2007)
- Clay-rich dry gouge (dehydration, Mizoguchi et al., 2009)
- Clay-rich dry gouge (dehydration, Ferri et al., unpubl.)
- Gypsum dry goug
- Anhydrite dry goug
- Dolomite dry goug
- Dolomite (decarbo
- Dolomite dry goug
- Dolomite (Weeks
- Calcite gouge (Mo
- Calcite (decarbona

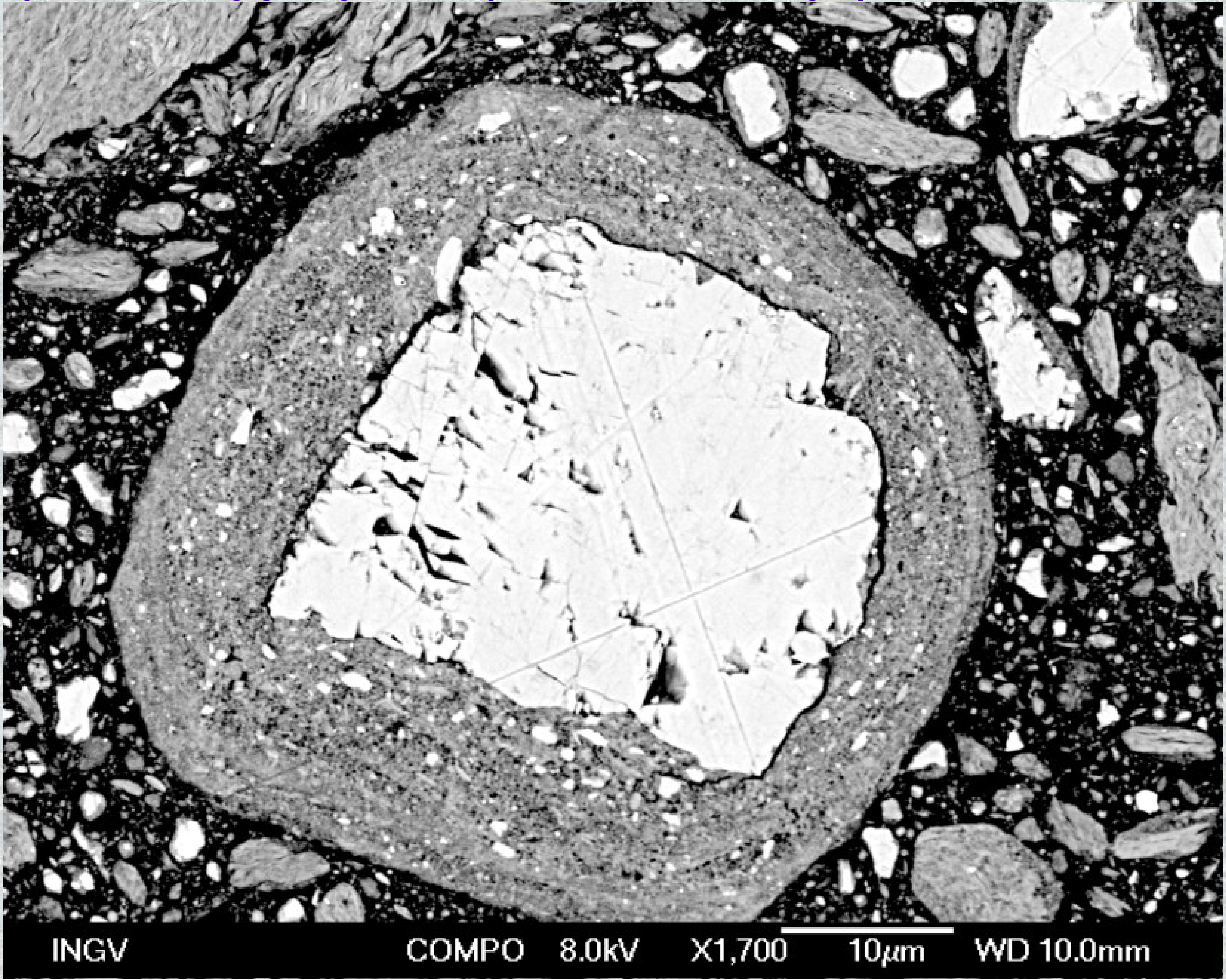


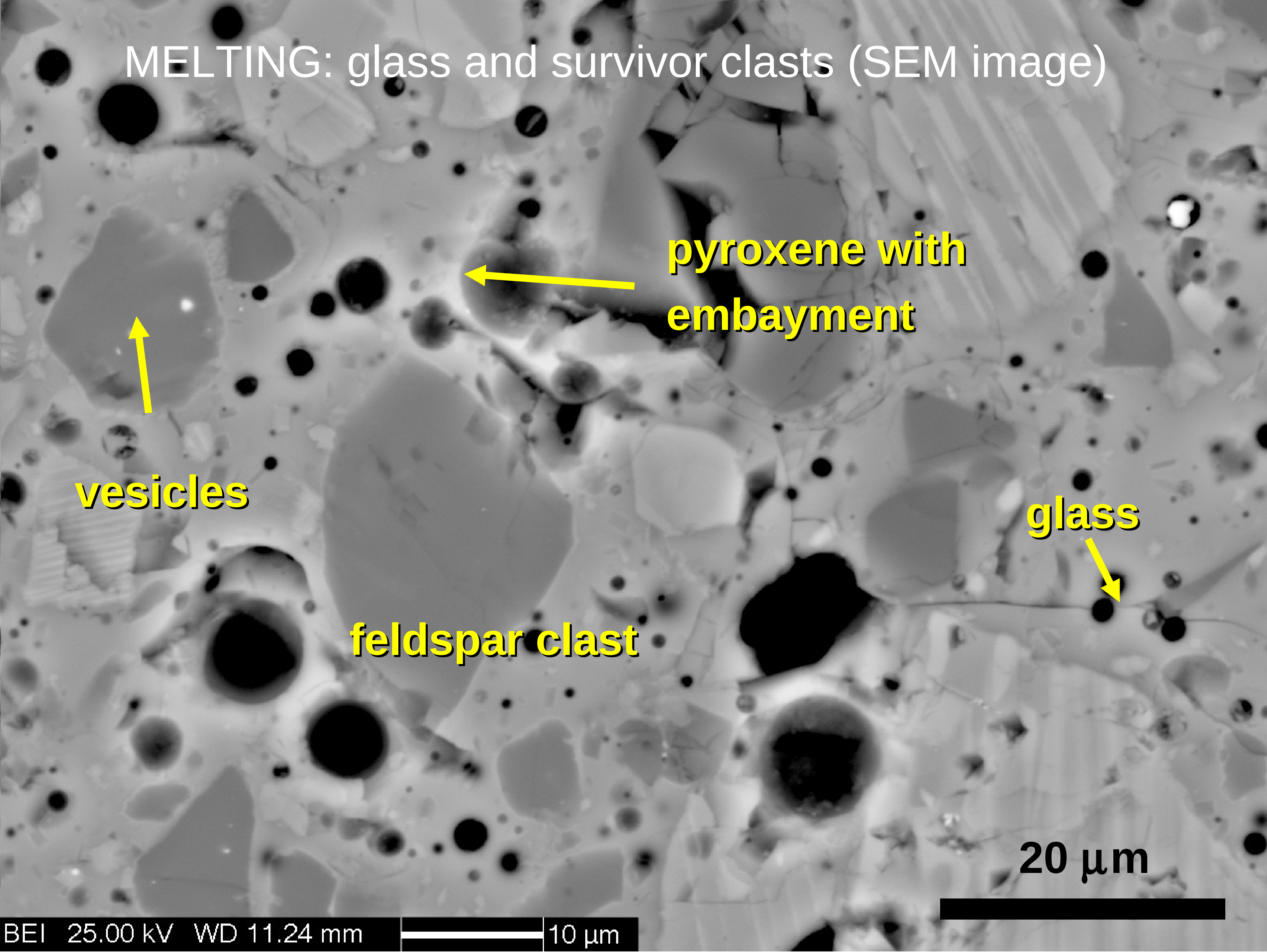
with gouge - Brantut et al., 2008

- *Fault zone rich in kaolinite*
- *dehydratation at ~1m/s, ~1 MPa*



Clay-clast aggregates (FE-SEM image) (e.g., Bouteraud et al., 2008)





MELTING: glass and survivor clasts (SEM image)
pyroxene with embayment
vesicles
glass
feldspar clast
20 µm
BEI 25.00 kV WD 11.24 mm
10 µm

Synopsis

- Friction controls earthquake physics
- No direct access to the “earthquake engine”
- Earthquake simulation in the lab: friction machines
- Examples of experiments and typical results
- Lubrication processes and rock types
- Extrapolating the results: faults are weak during earthquakes
- Conclusions and future research

Extrapolation

How to upscale lab to EQ conditions?

Larger σ_n,V, accelerations

Larger size than sample

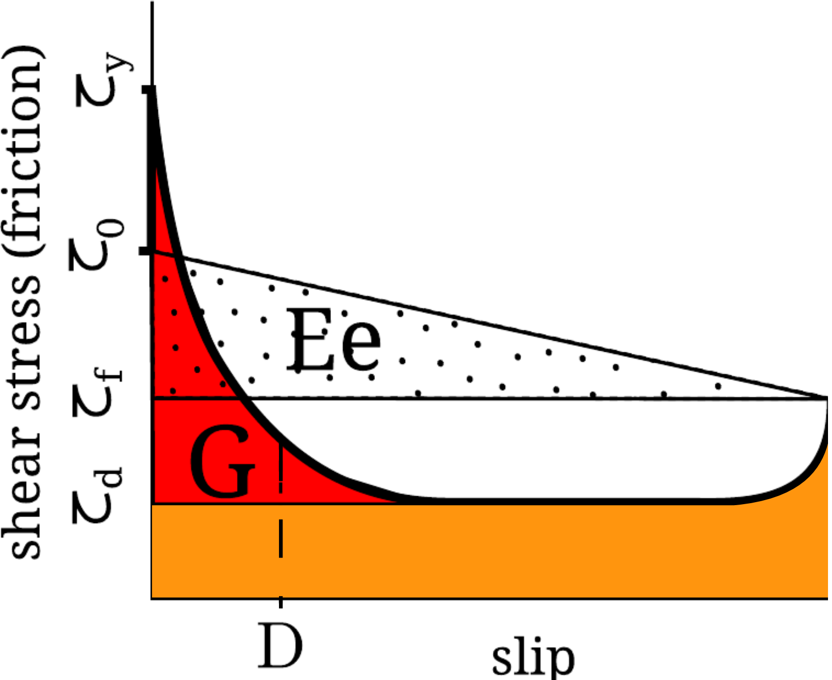
Complex slip time-history

Complex geometry

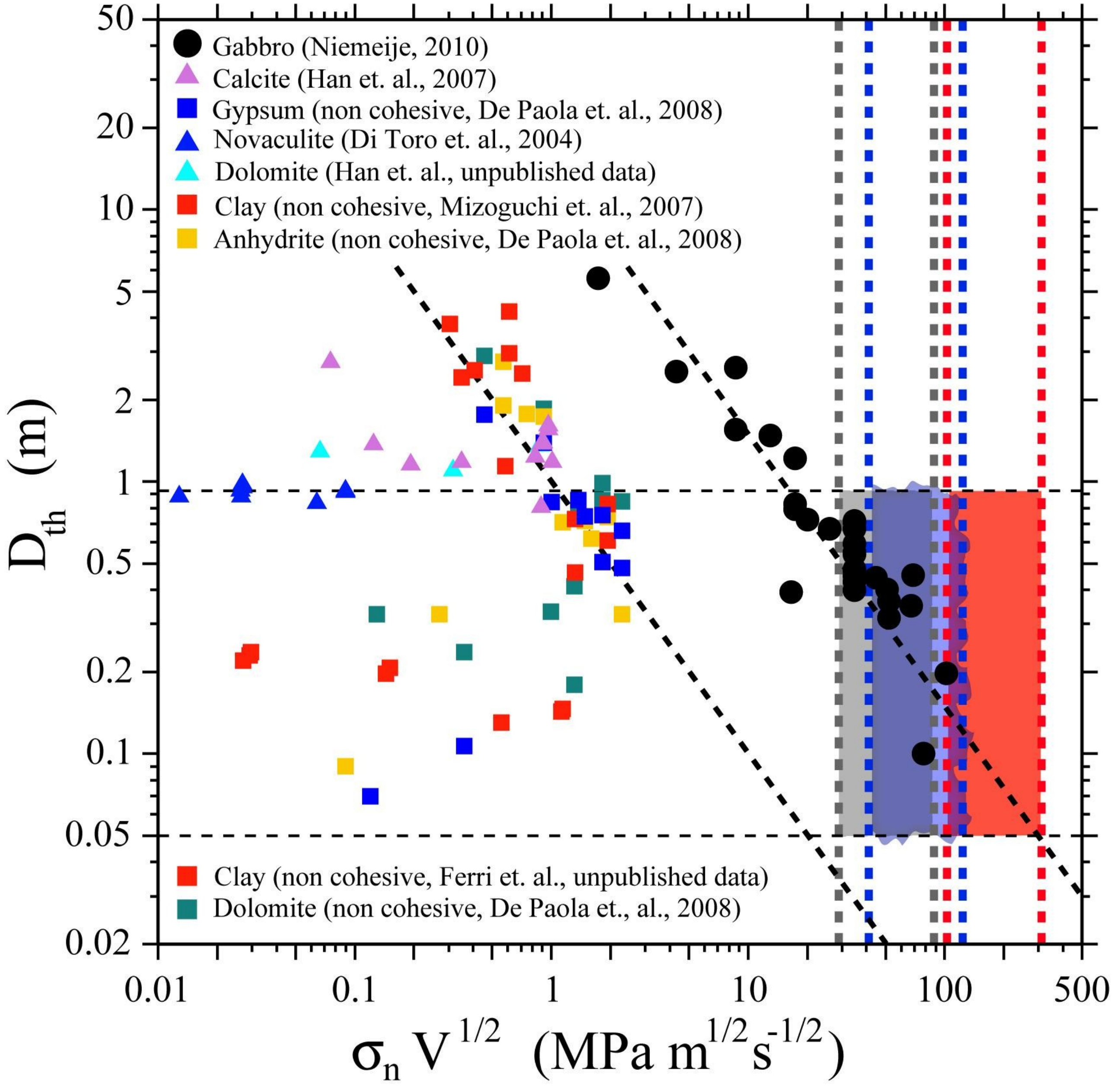
Different petrology/chemestry

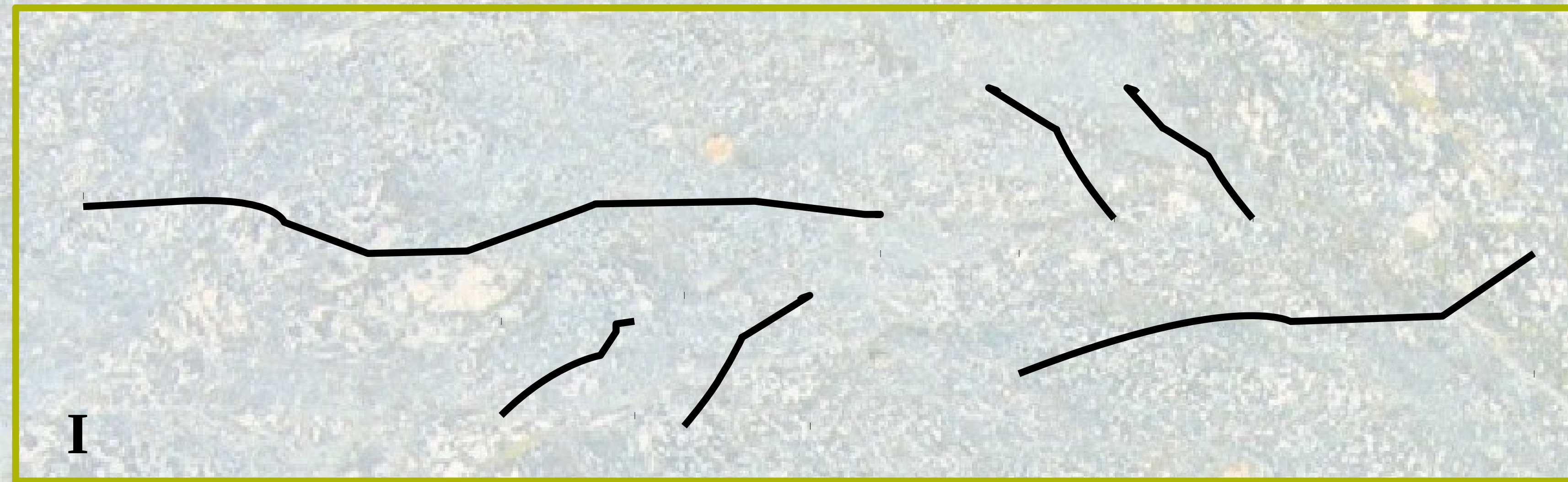
Different fabric

Extrapolation



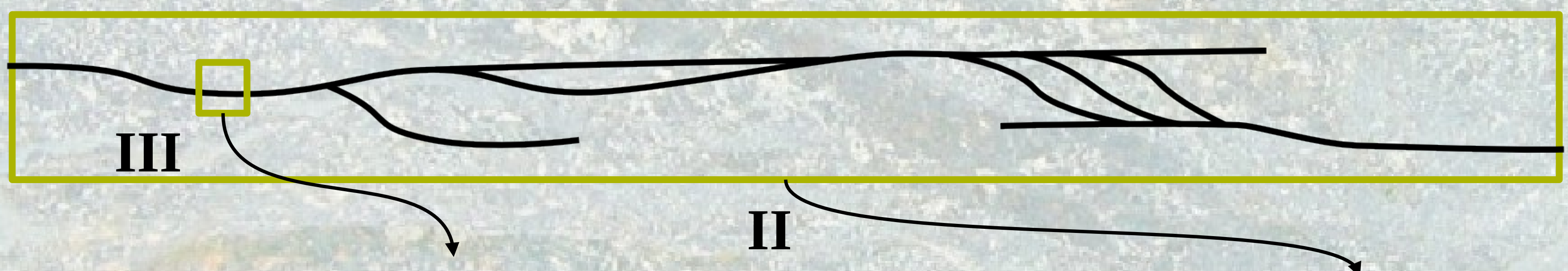
$= \tau/\sigma_n$





SEISMICITY, statistics of a fault population, correlations, criticality....:

the process from a global point of view – YESTERDAYS TOPIC



LAB:

small portion of a fault - scale 2 - 5 cm

SISMO:

“global” rheology of the whole fault

Conclusions

- No direct access to the “earthquake engine”
- Earthquake simulation in the lab: friction machines
- High POWER (hich slip vel. and normal load combined) yields lubrication
- Various lubrication processes depending on rock types
- Extrapolating the results: power laws and geometry problems
- We barely start to measure and understand...