The geology, physics and chemistry of earthquakes hosted in carbonate-built rocks

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INGV - Italy 1999

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http://erc.europa.eu/

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1) Earthquakes in carbonate-built rocks

2) Experimental results

Observations regarding friction in carbonates at seismic slip rates

3) Processes at seismic slip initiation

Fast moving dislocations and flash weakening in calcite

4) Processes during and at the end of seismic slip

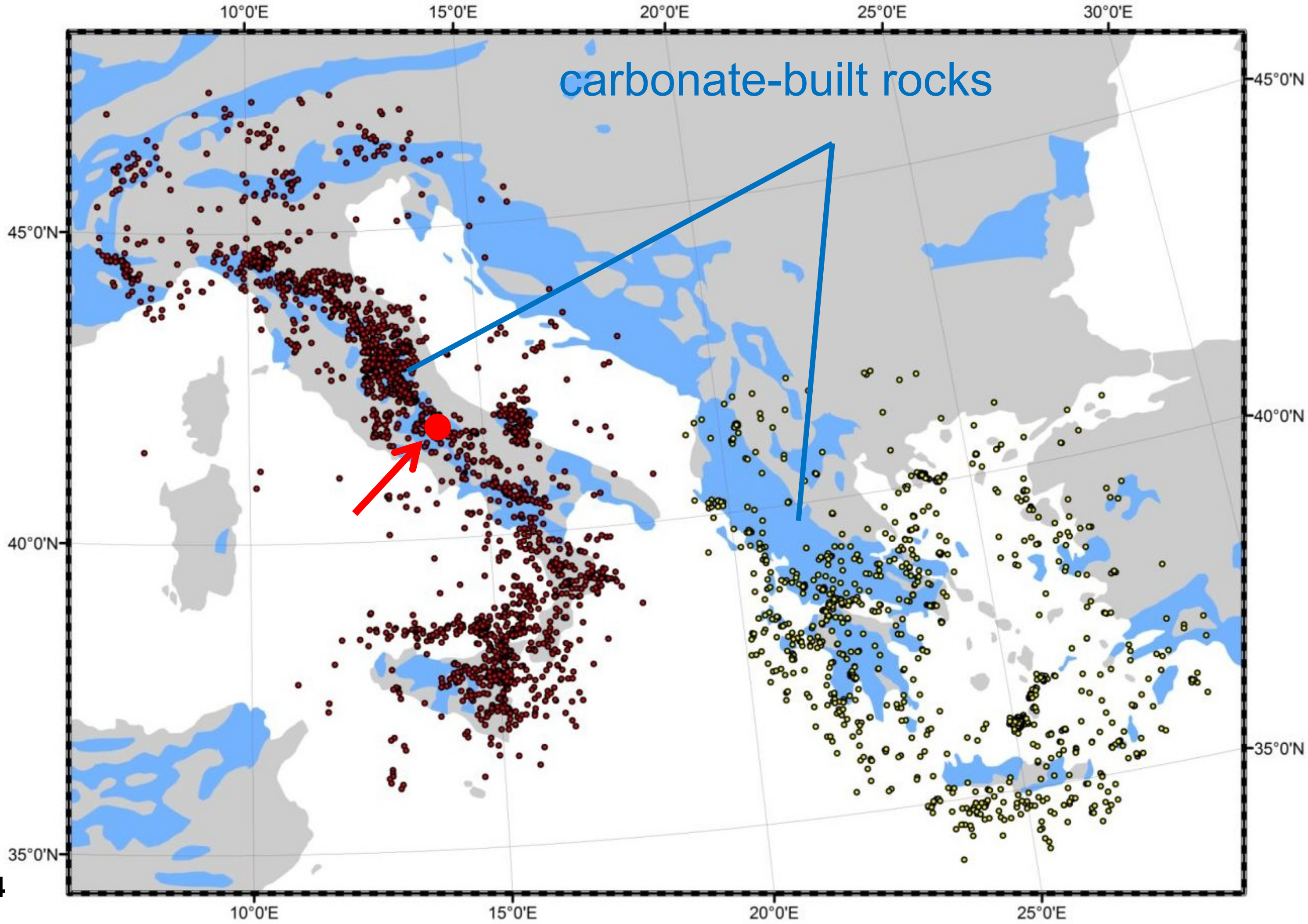
Grain Boundary Sliding and superplastic behavior

Why carbonates?

Epicenters overlap with thick sequences (4-10 km) of carbonate- built (calcite and dolomite) rocks (case for Italy and Greece).

Earthquakes with M > 1.8

- INGV catalogue 2005-2008
- Aristotle University catalogue 2012



Fondriest, PhD thesis, 2014

Why carbonates?

Carbonate-built fault zone exhumed from 2-3 km depth

(Campo Imperatore Fault Zone, Italy).

Demurtas et al., JSG 2016

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Mirror-like surfaces (Campo Imperatore Fault Zone, Italy).

Demurtas et al., JSG 2016

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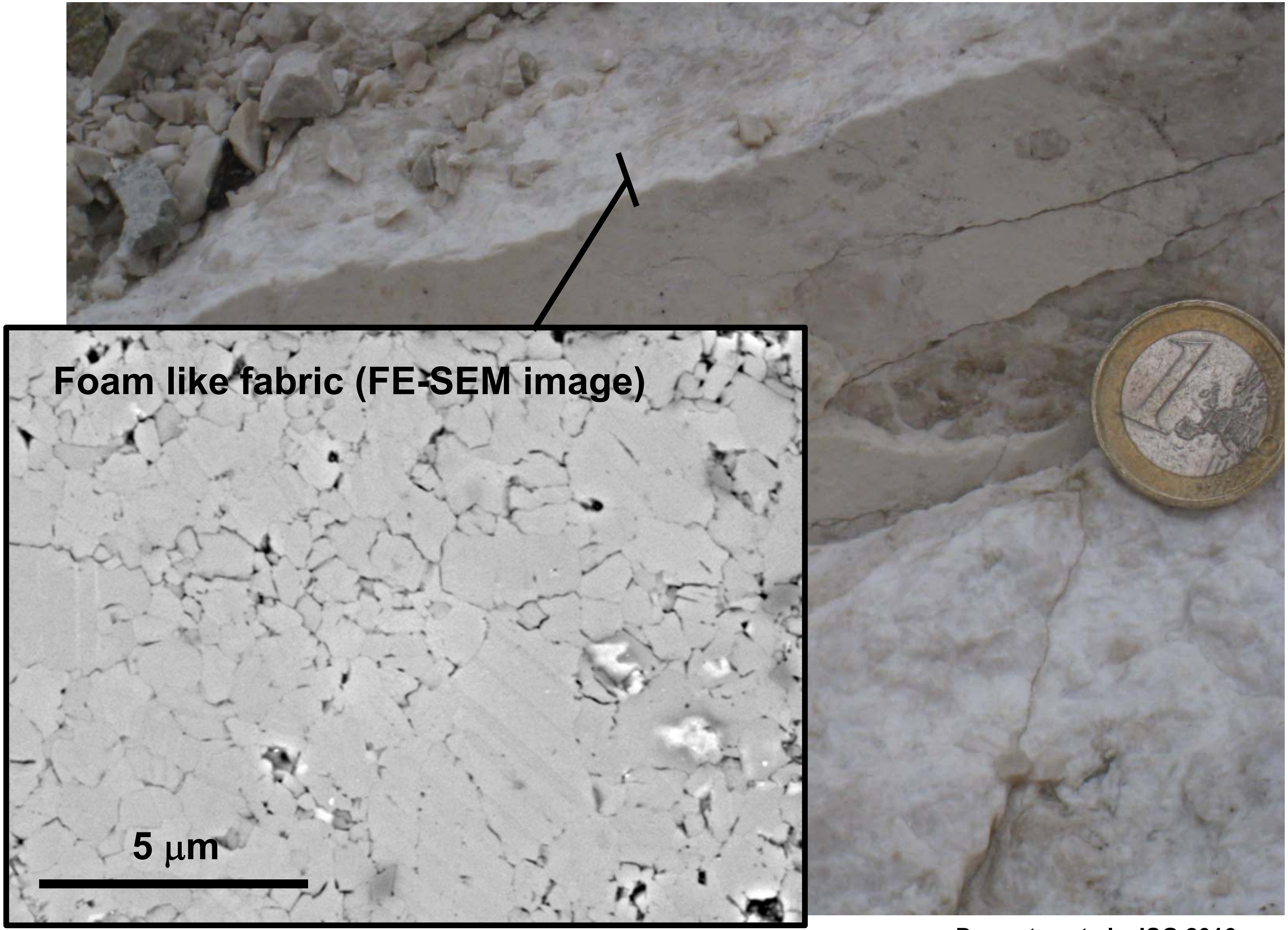
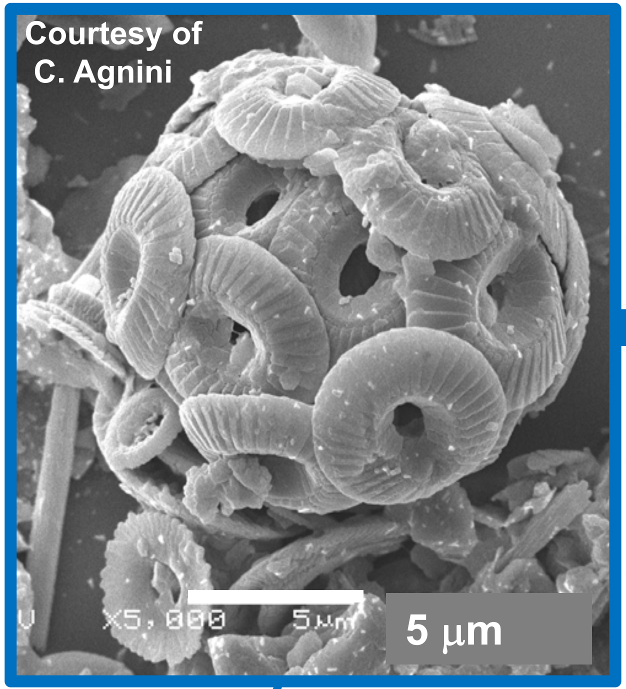
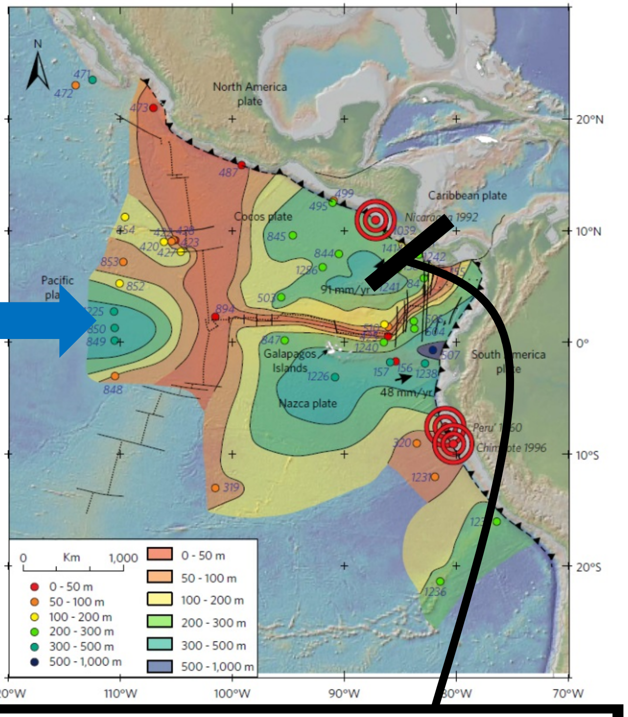


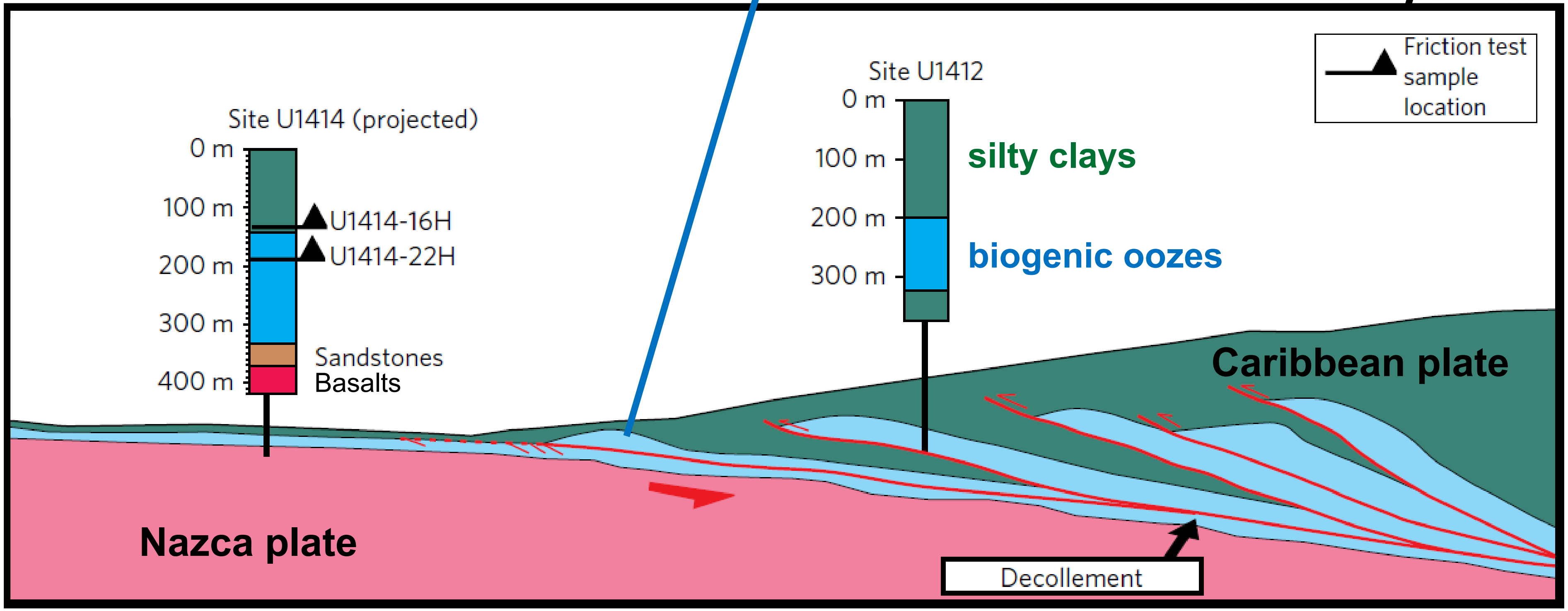
Demurtas et al., JSG 2016

Great earthquakes: Slip-up-to-the-trench in carbonate biogenic oozes in megathrusts earthquakes





Vannucchi et al., Nat. Geos. 2017



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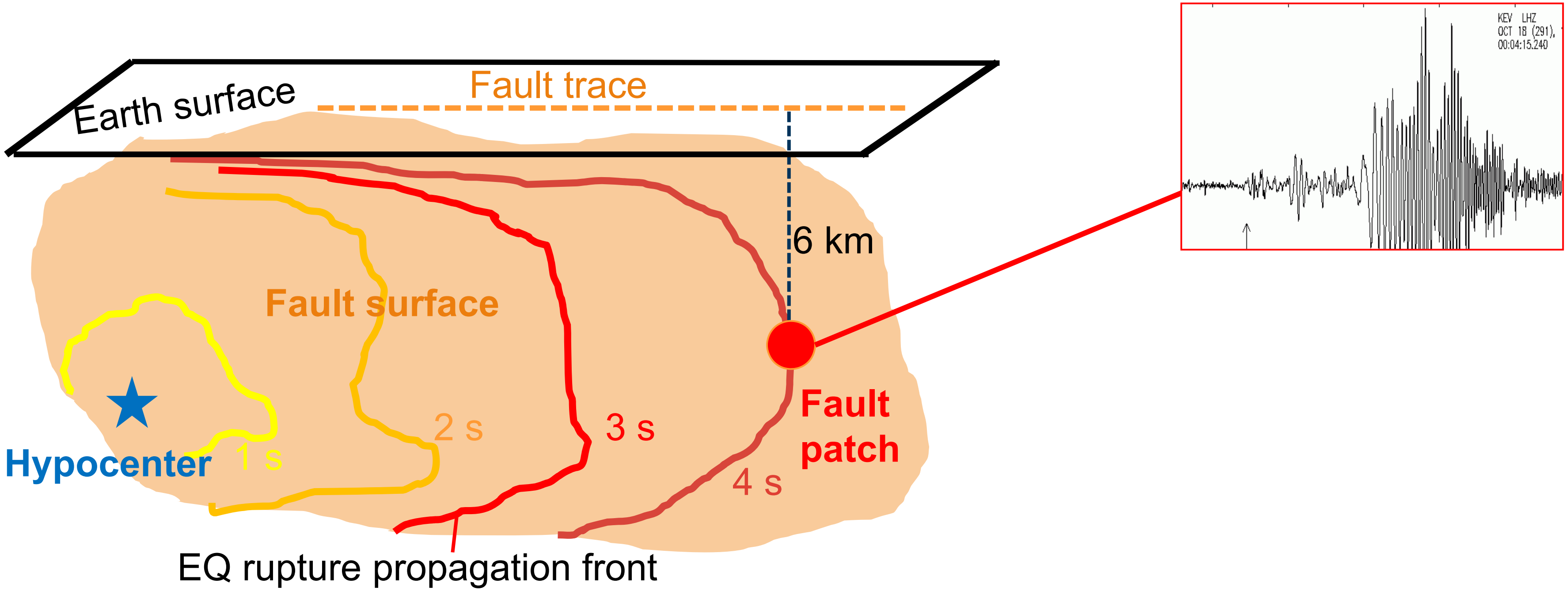
What happens in a fault patch at the passage of the EQ rupture front?



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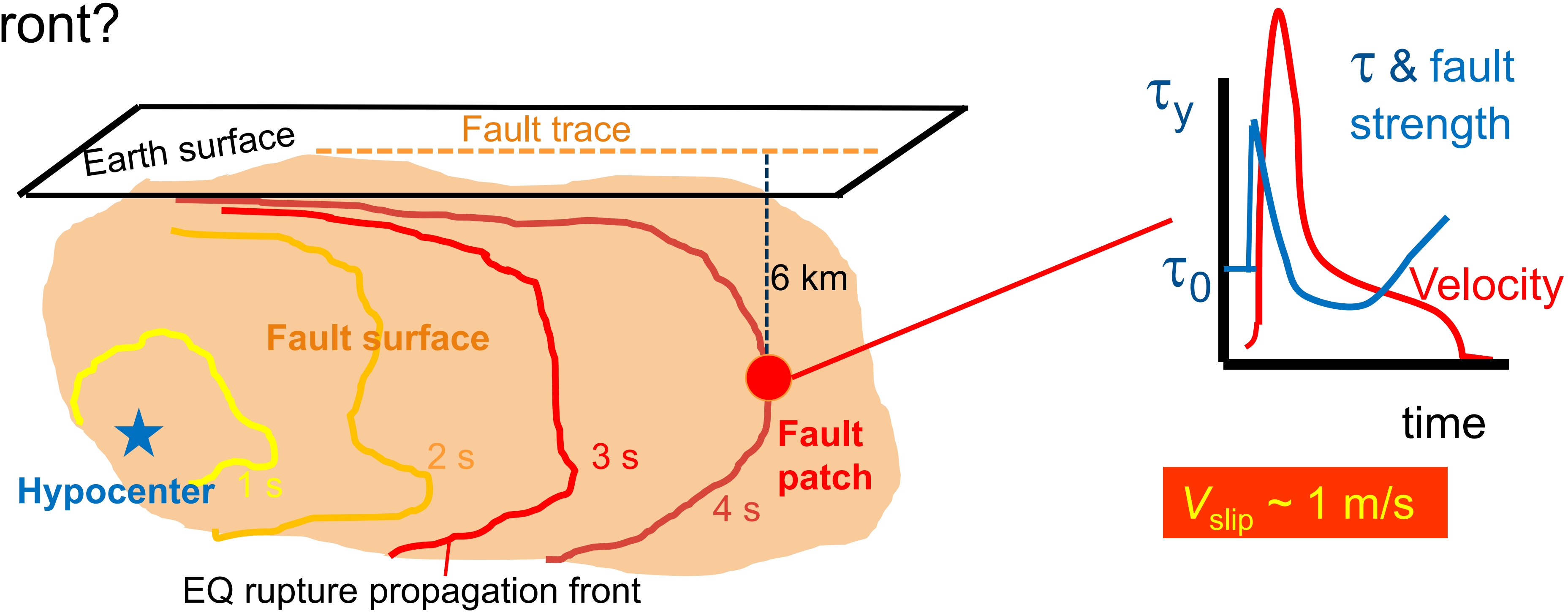


V_{slip} ~ 1 m/s

Frictional power dissipation (>10 MW/m^2)

τV_{slip}

Thermal: temperature increase

Mechanical: grain size reduction

Both result in mechano-chemical reactions (CO$_2$ emission, etc.) and control the frictional evolution at a fault patch.

Nov. 2009 SHIVA (**S**low to **HI**gh **V**elocity **A**pparatus)

INGV (designed by Italian Team at INGV in Rome)

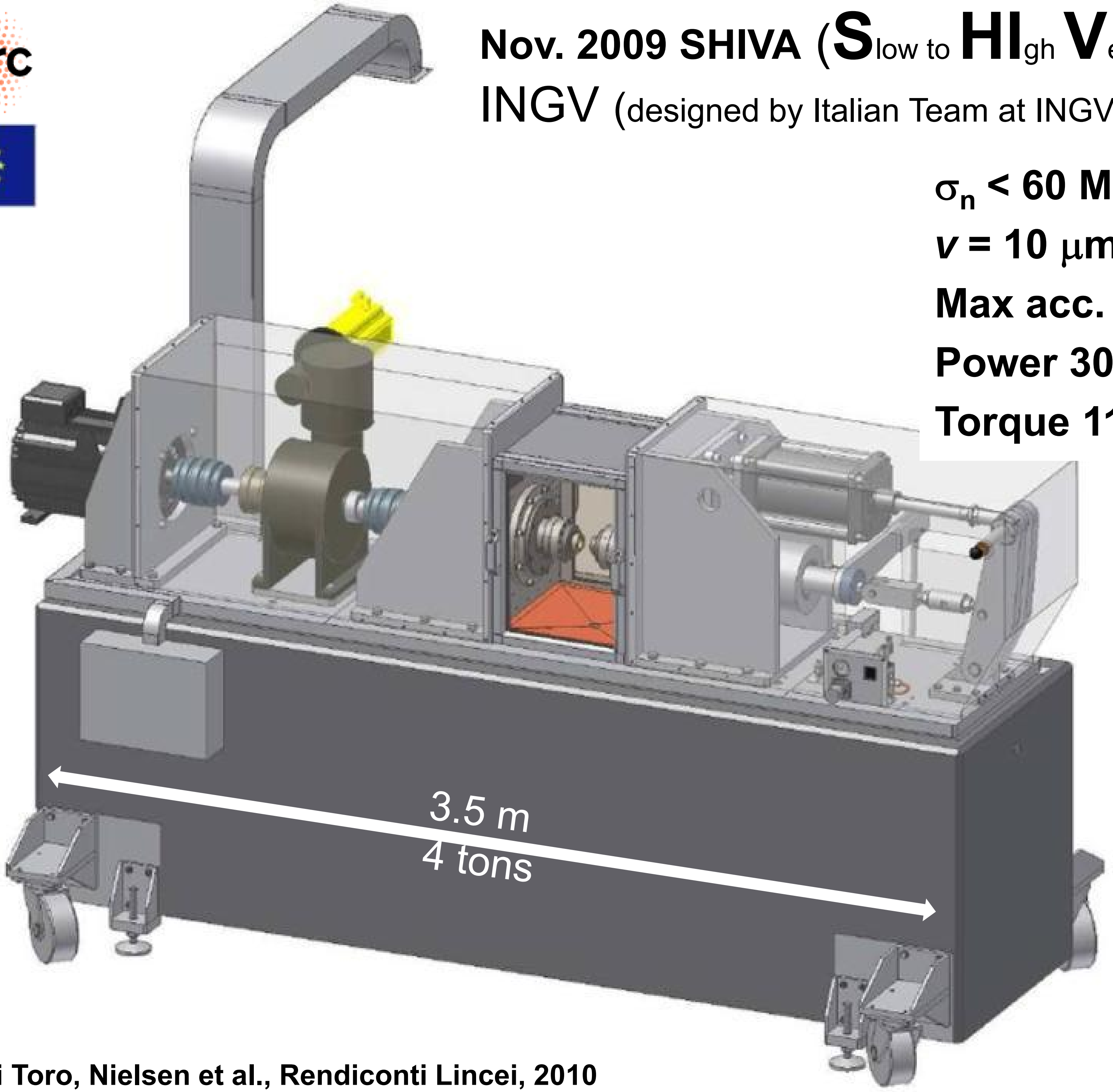
$\sigma_n < 60$ MPa

$v = 10\ \mu\text{m/s} - 6.5\ \text{m/s}$

Max acc. = $70\ \text{m/s}^2$

Power 300 kW

Torque 1100 Nm



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

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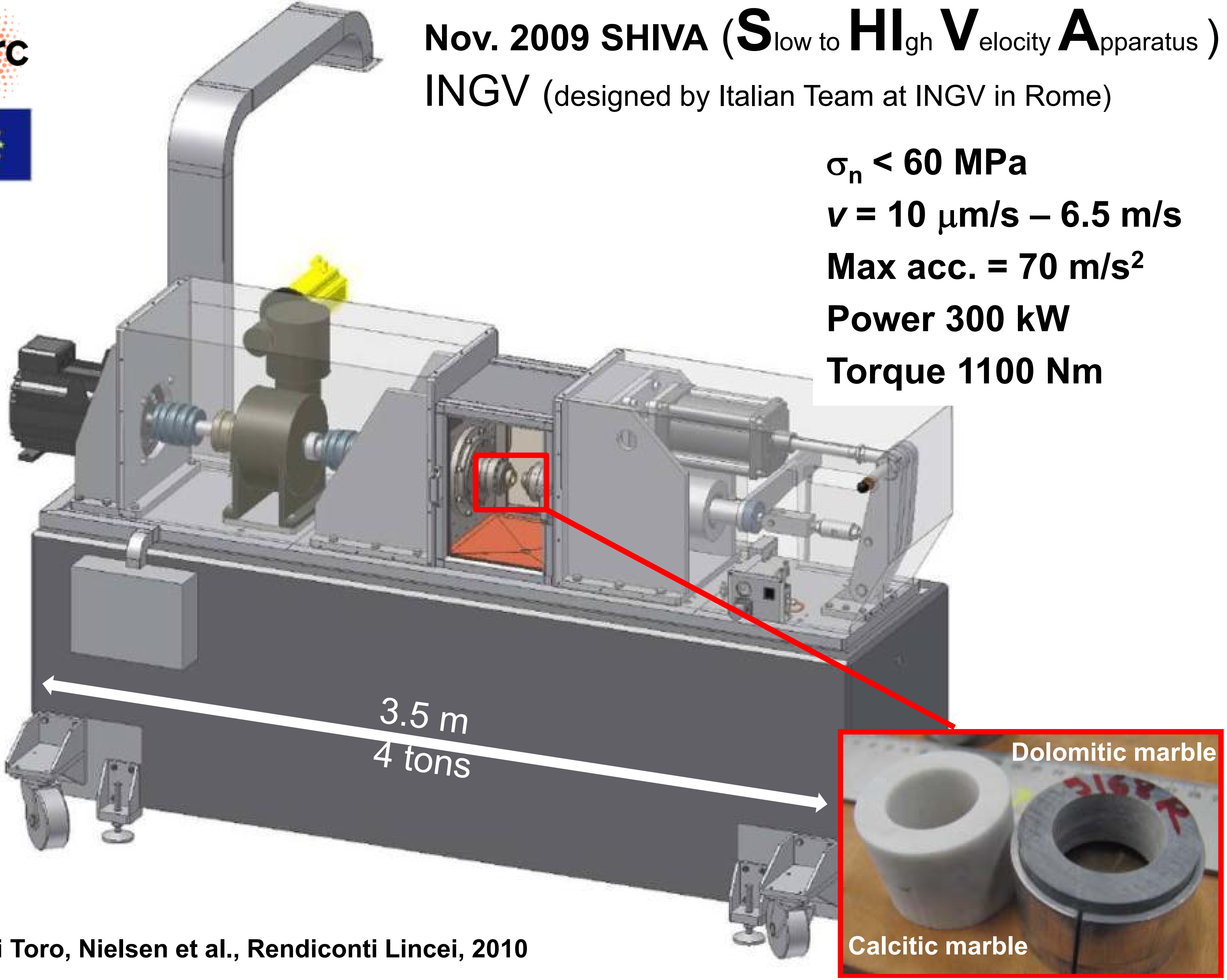
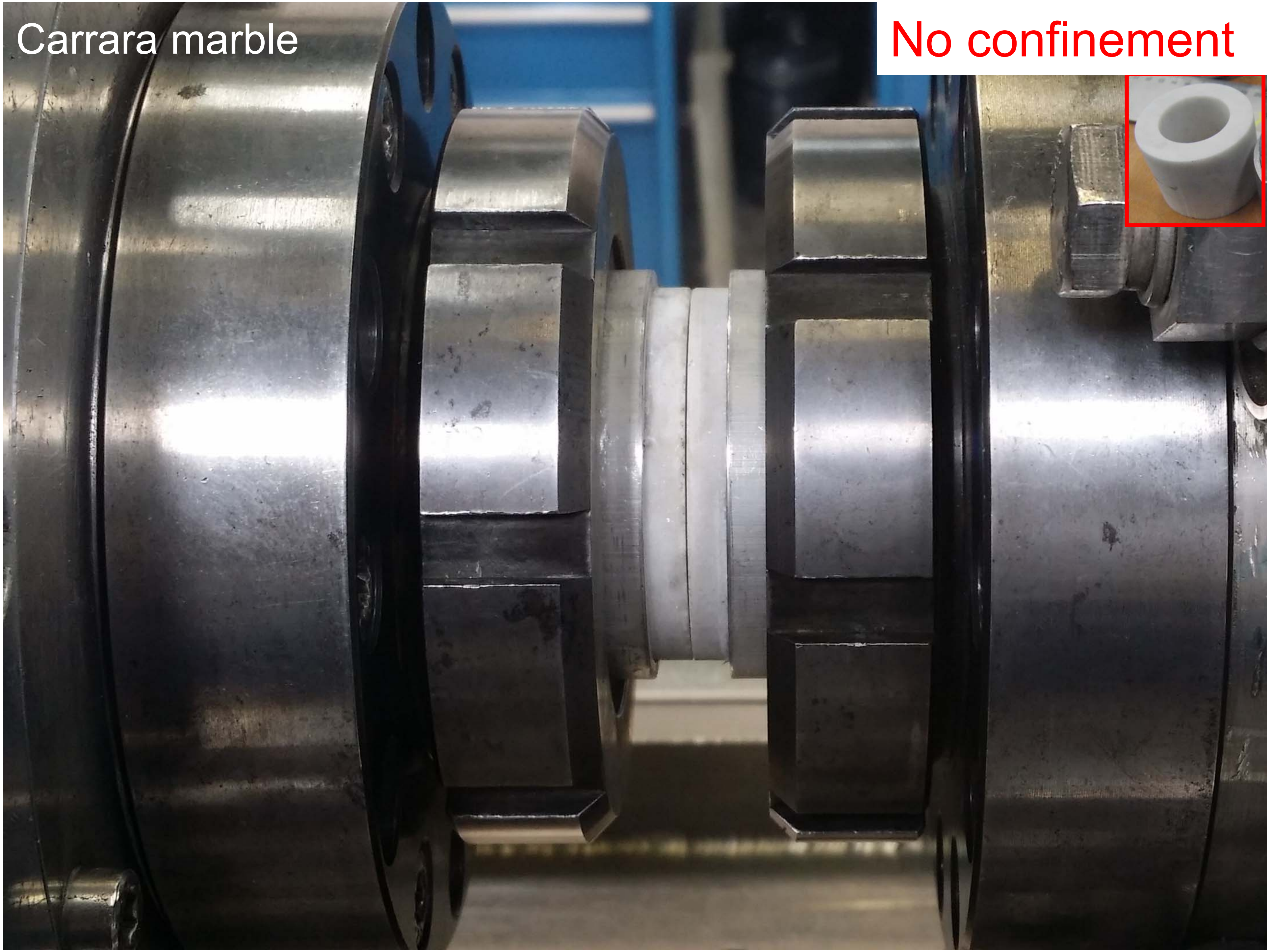


Di Toro, Nielsen et al., Rendiconti Lincei, 2010

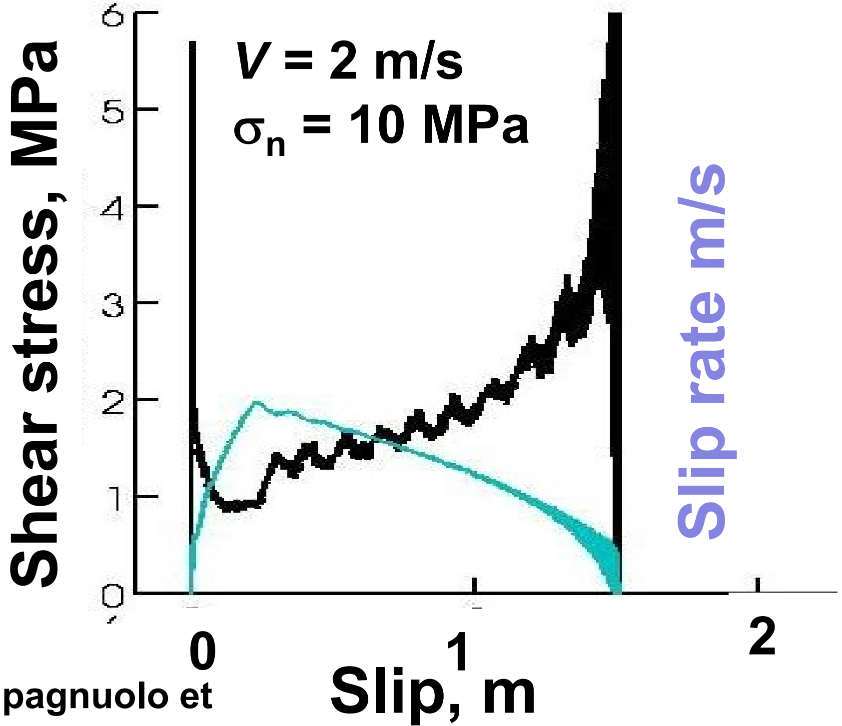
SHIVA owns an environmental/vacuum chamber equipped with a mass spectrometer. Fluid pressurizing system.

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



Carrara marble

No confinement

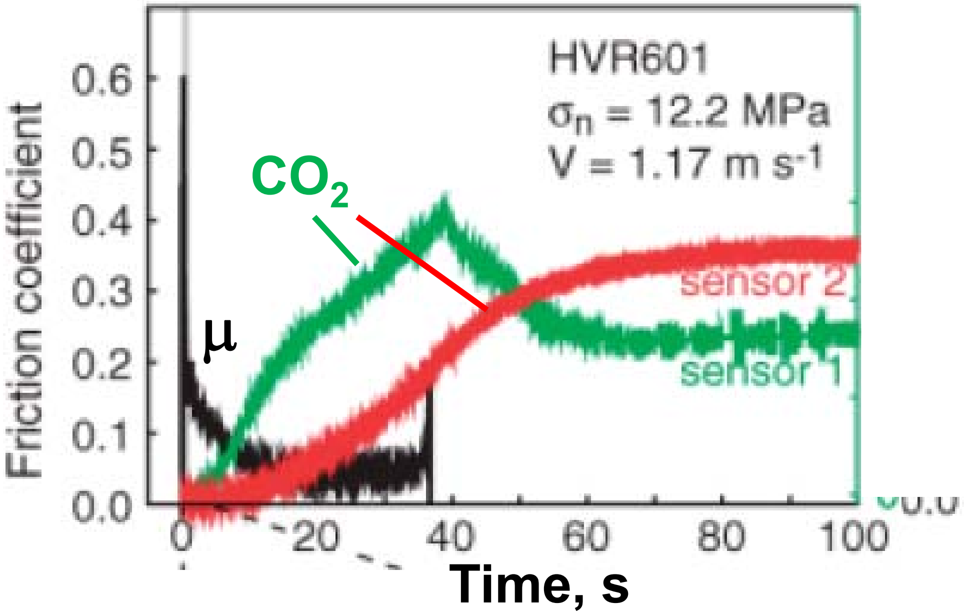


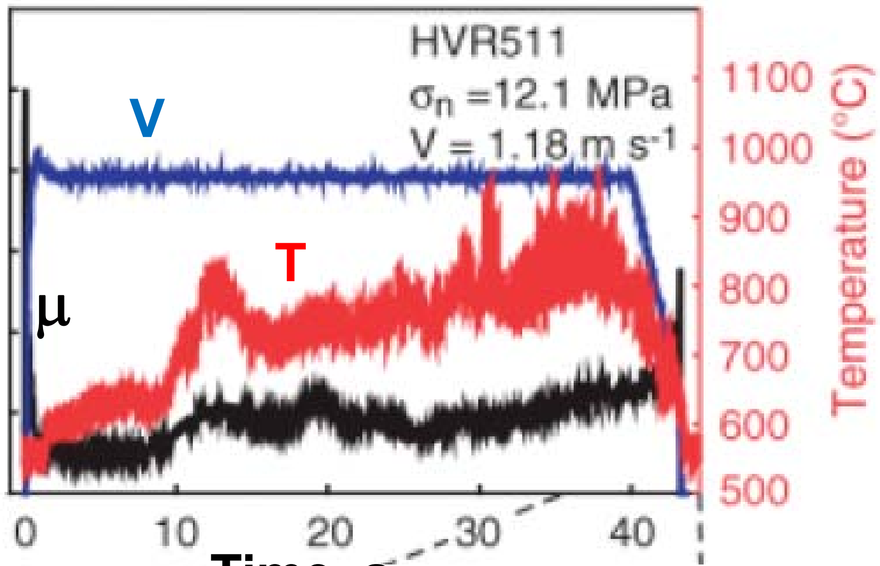
Spagnuolo et al., unpubl.

Strong velocity dependence

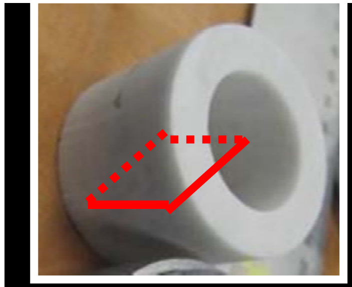
Temp. rise buffered by endothermic decarbonation reactions (T > 600° C)

$$CaCO_3 \rightarrow CaO + CO_2$$





Han et al., Science 2007



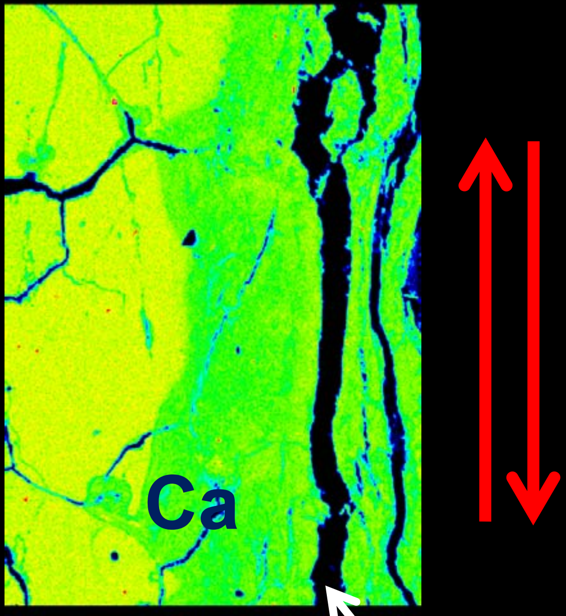
CALCITE
One breakdown reaction

DOLOMITE
Two breakdown reactions

T = 550°C $MgCa(CO_3)_2 \rightarrow MgO + (Ca,Mg)CO_3 + CO_2$

T = 800°C
$CaCO_3 \rightarrow CaO + CO_2$

T = 800°C
$(Ca,Mg)CO_3 \rightarrow MgO + CaO + CO_2$

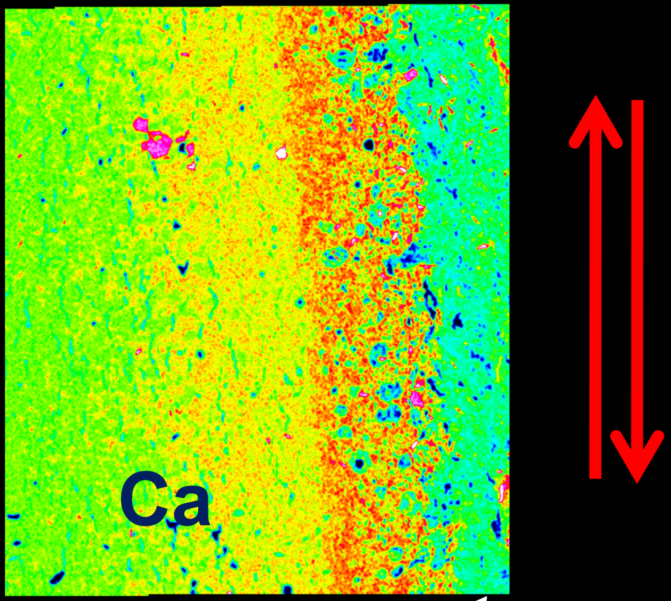


Slipping zone

EPMA map

Slip = 18 m
σ_n = 10 MPa
V = 6.5 m/s

100 μm



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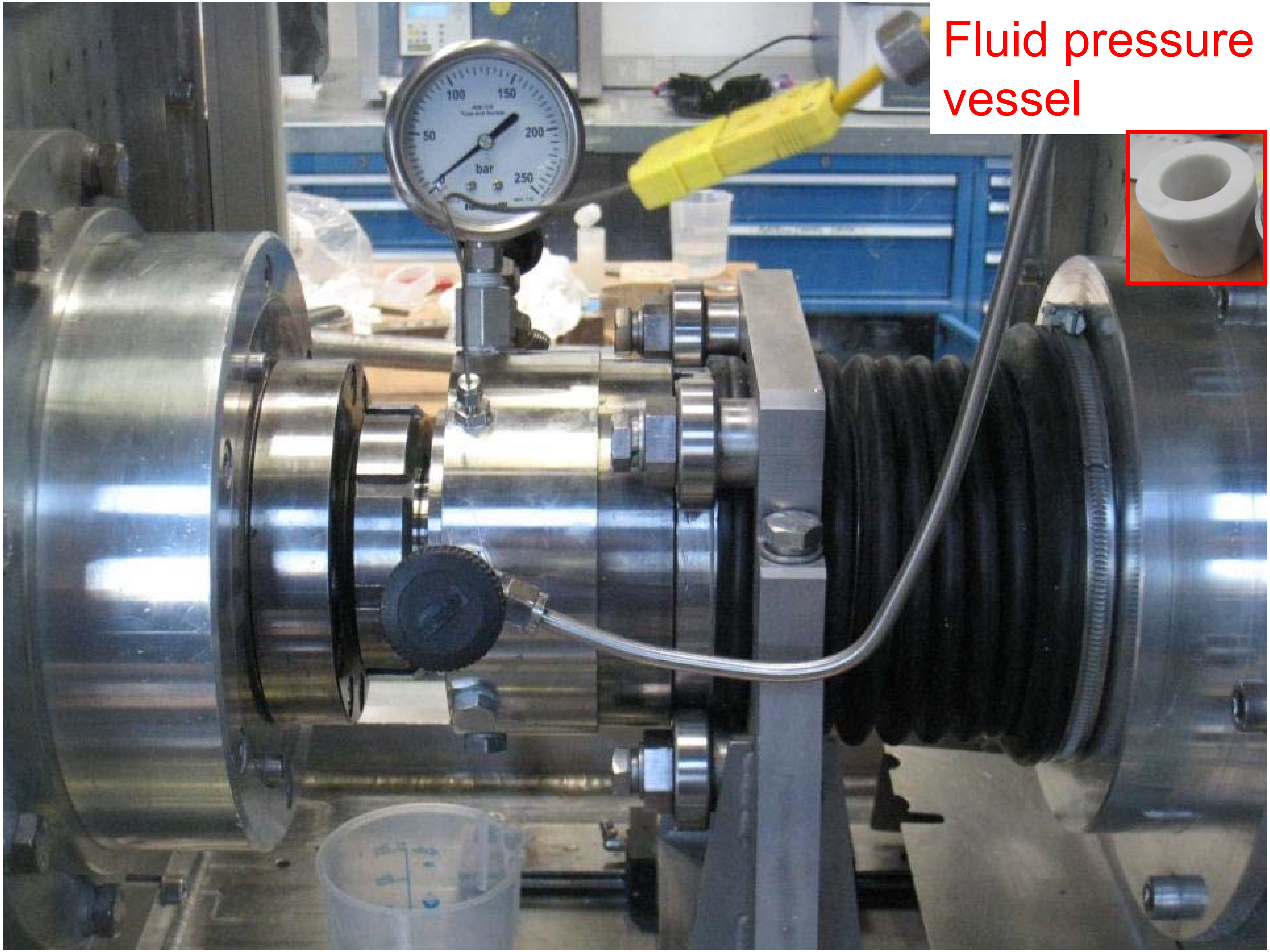
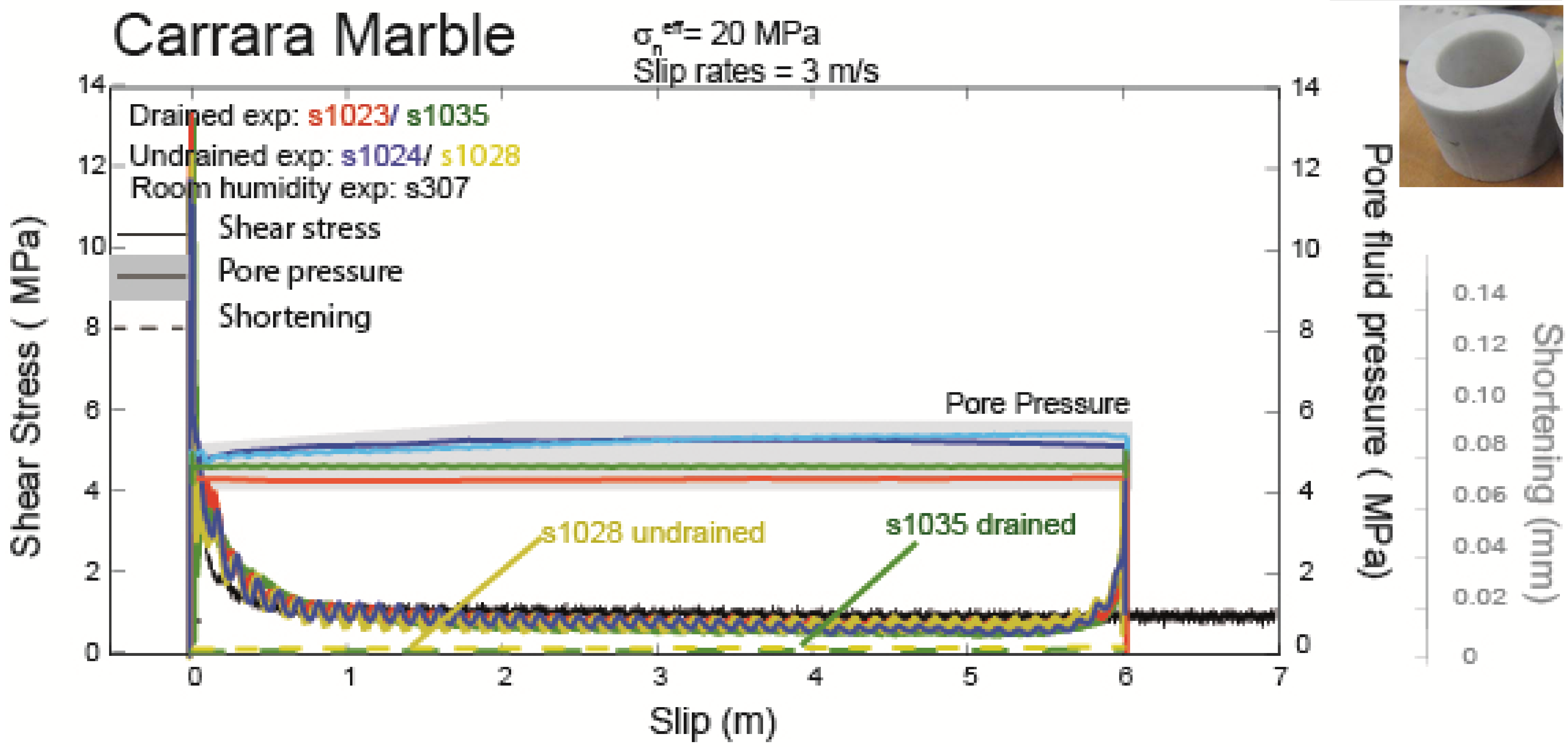


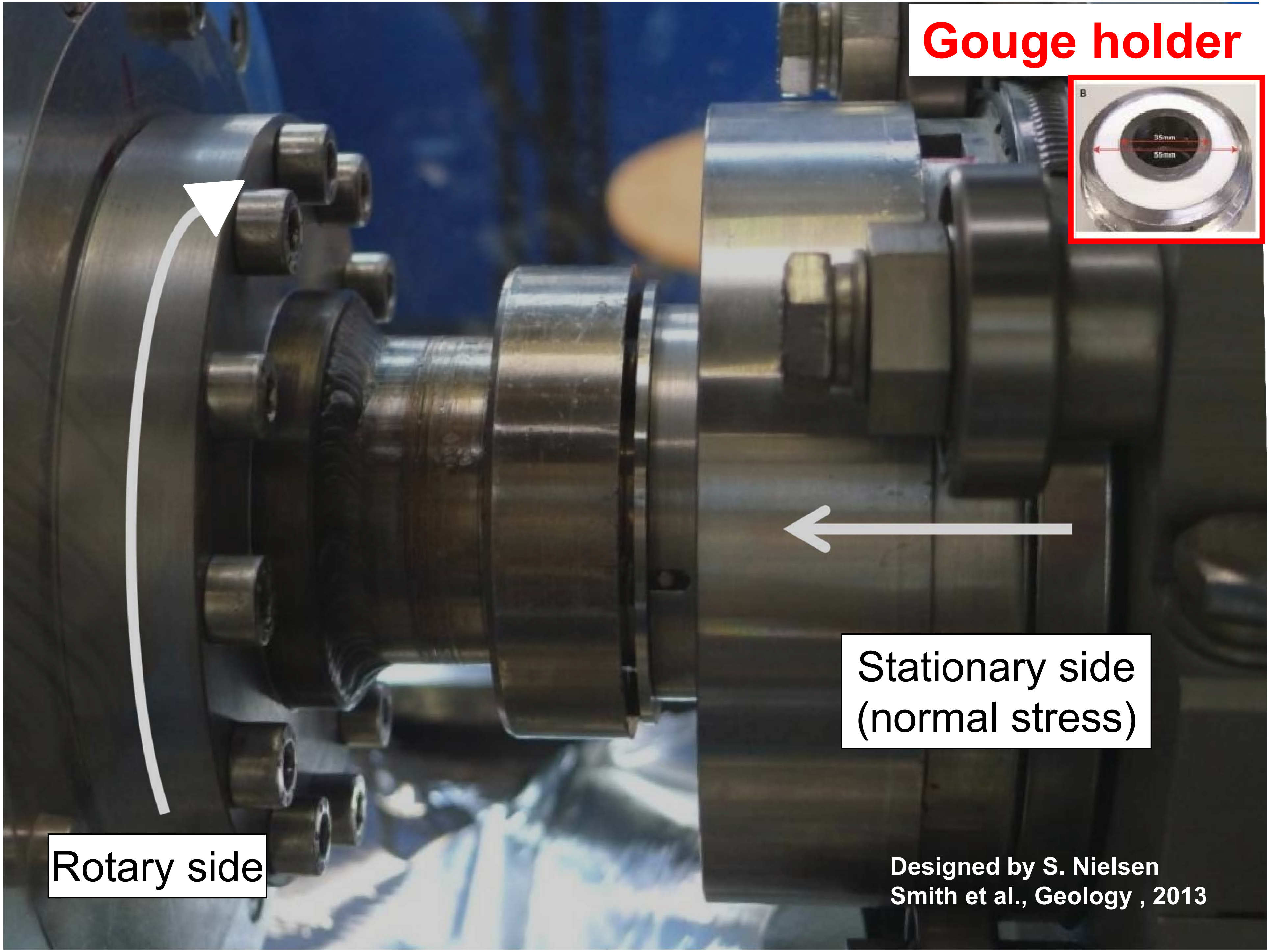
Fluid pressure vessel

Cohesive calcite-built rocks: thermo-mechanical pressurization contribution to weakening negligible.



- τ_{ss} similar under room humidity, drained and undrained conditions;
- Negligible shortening in all conditions;
- Small measured pore fluid overpressure

Violay et al., EPSL 2015



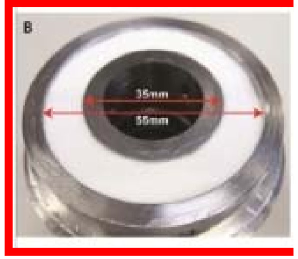
Gouge holder

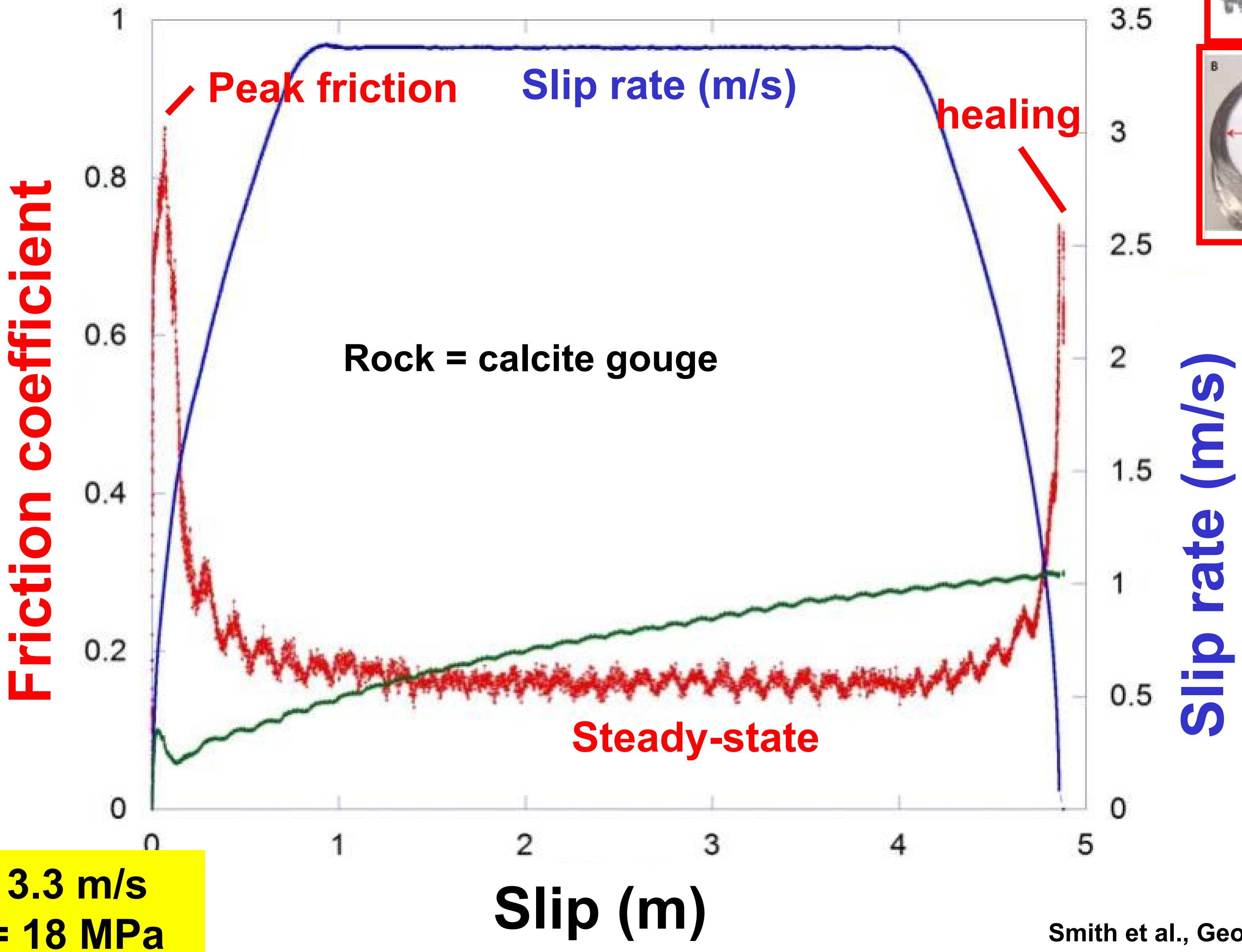
Rotary side

Stationary side
(normal stress)

Designed by S. Nielsen
Smith et al., Geology , 2013

Non-cohesive calcite-bearing rocks.
Friction: strong velocity-dependence.



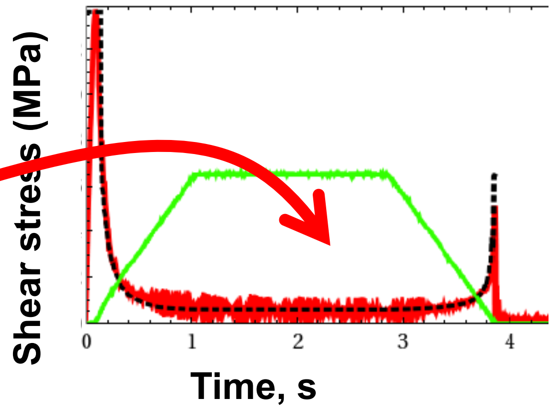


V = 3.3 m/s
σ_n = 18 MPa

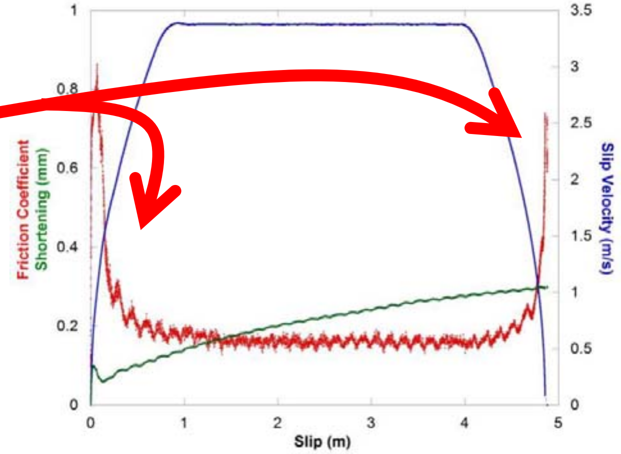
Smith et al., Geology , 2013

Any proposed process in carbonates should satisfy:

1) Low friction at V ~ 1 m/s



2) Strong dependence of friction with velocity



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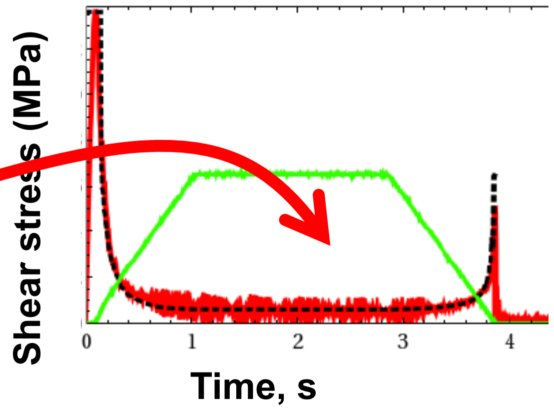

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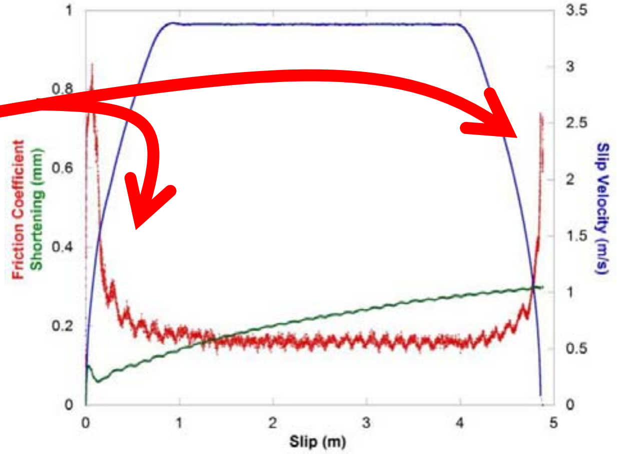

3) must occur in nature!

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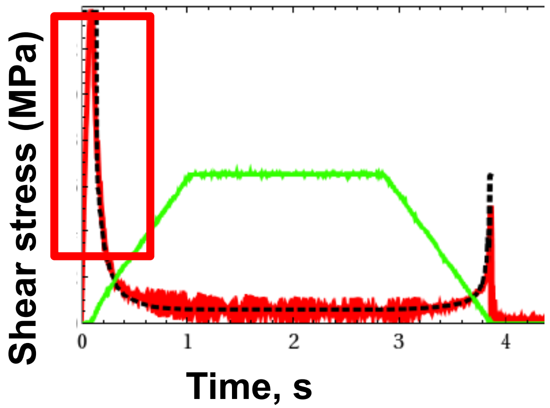

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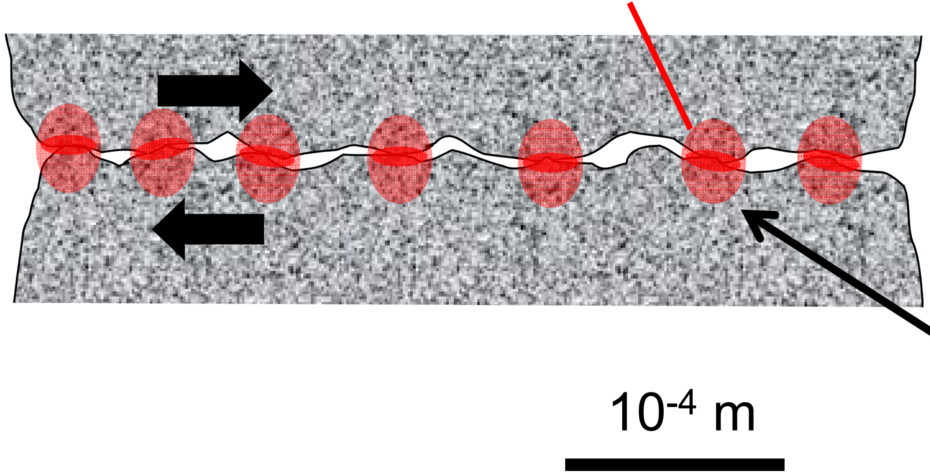
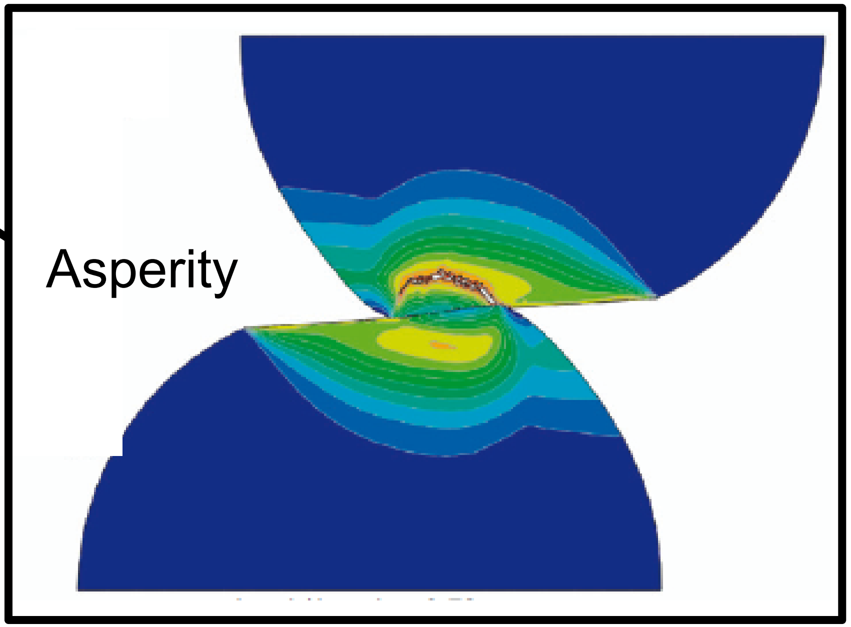
Flash heating (and weakening):

- short duration (<< 1 ms) asperity-scale process
- high “local” temperatures (**T > 800 °C)**
- low friction at low “bulk” **T (< 100 °C)**

Heat generation and diffusion

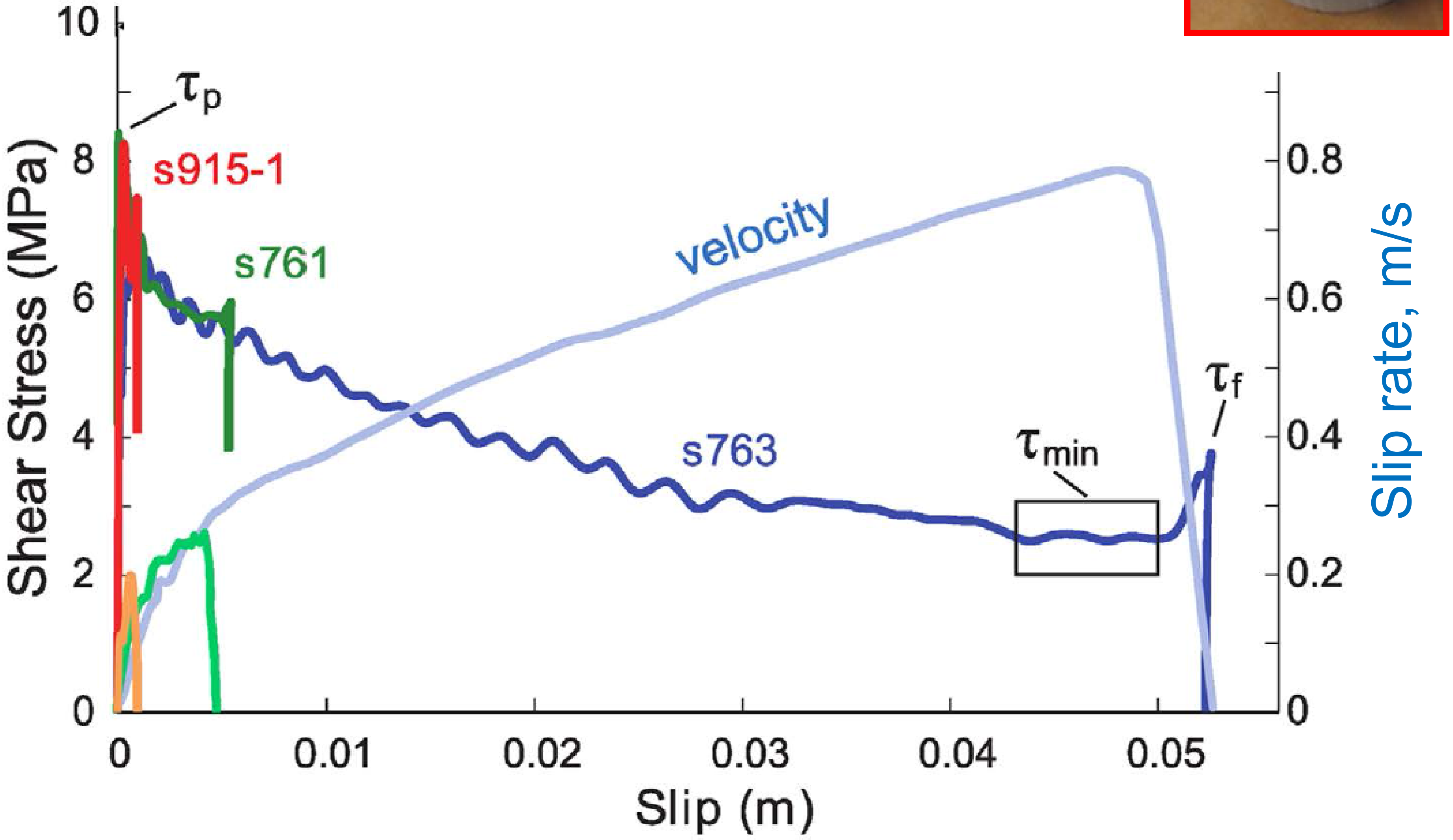


$$\Delta T \propto \mu \overset{\text{Contact stress (GPa)}}{\sigma_c} V_{slip}\sqrt{t_c}$$



Rice, JGR, 2006; Beeler et al., JGR, 2008; Goldsby & Tullis, Science 2011; Tisato et al., JSG 2012

Short slip experiments on cohesive Carrara marble (99 % calcite)



Spagnuolo et al., Nat.Sci.Rep. 2015

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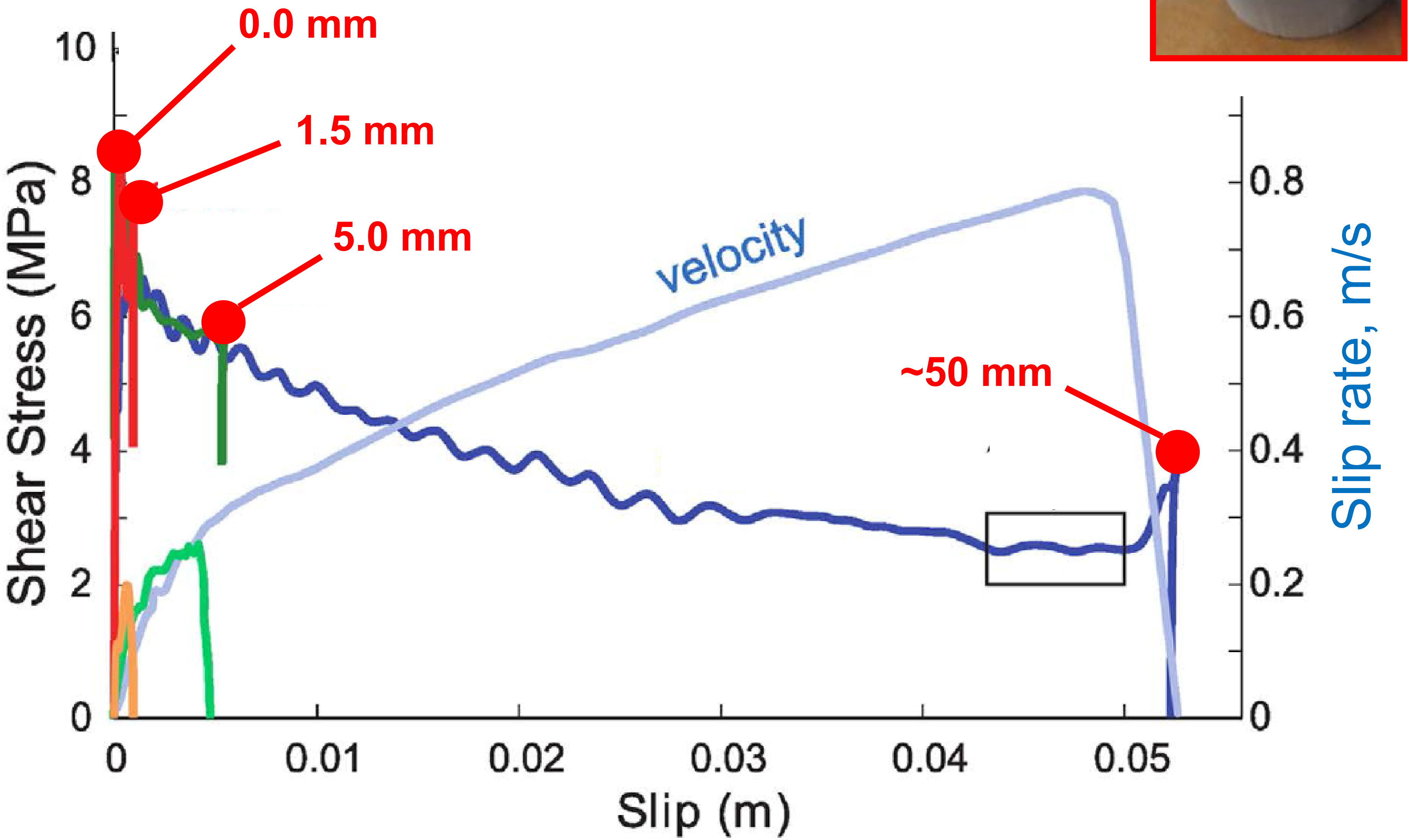
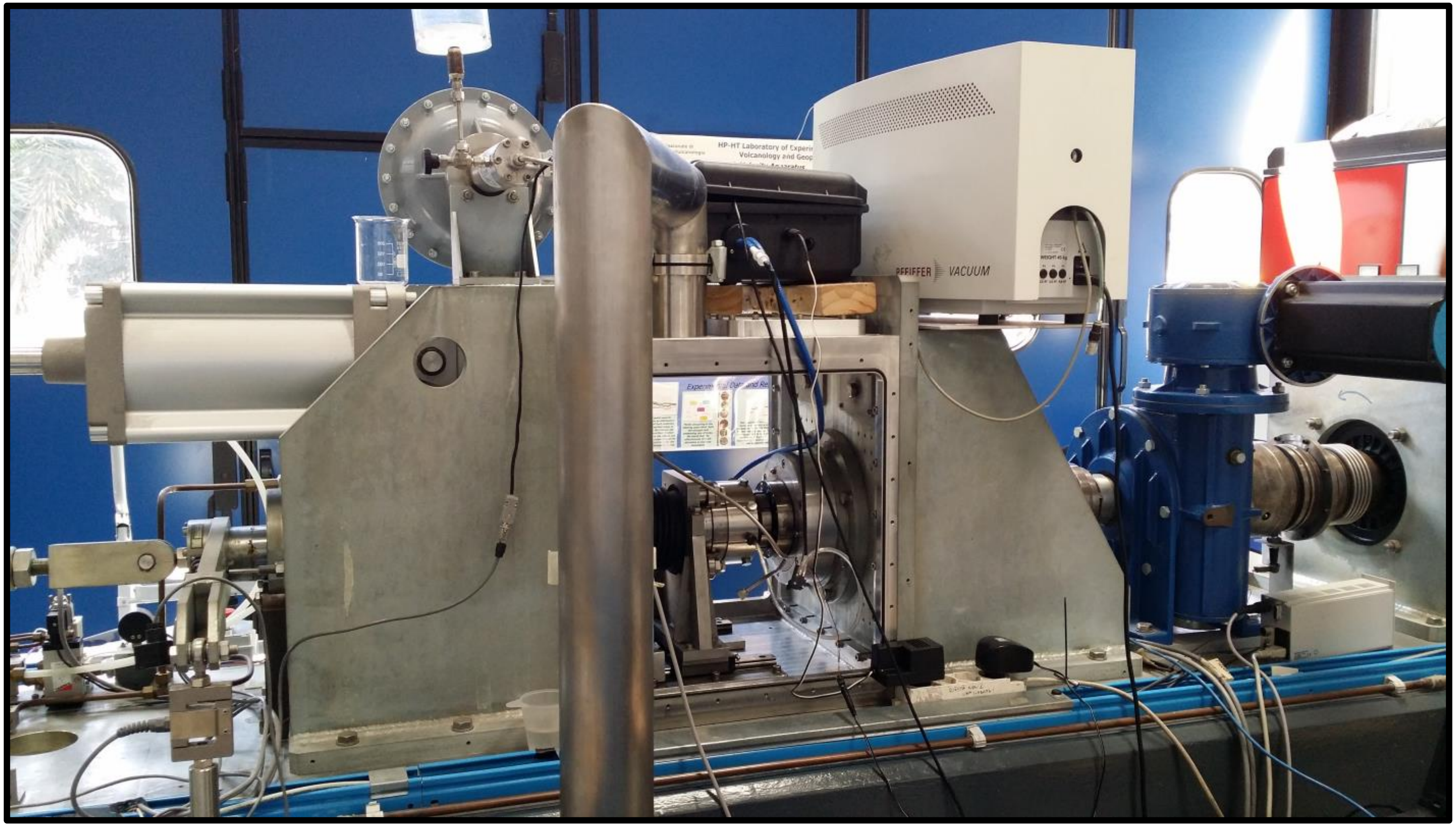


Spagnuolo et al., Nat.Sci.Rep. 2015

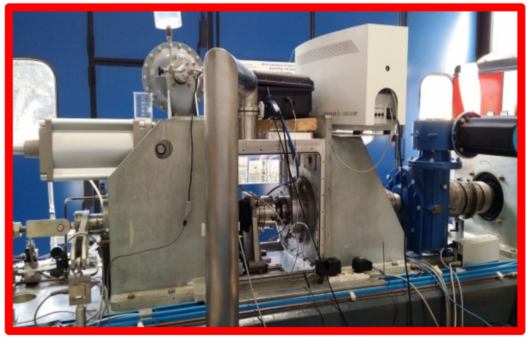
Experiments in vessel to determine gas emission during slip.
Mass spectrometer with cable inserted in vessel.



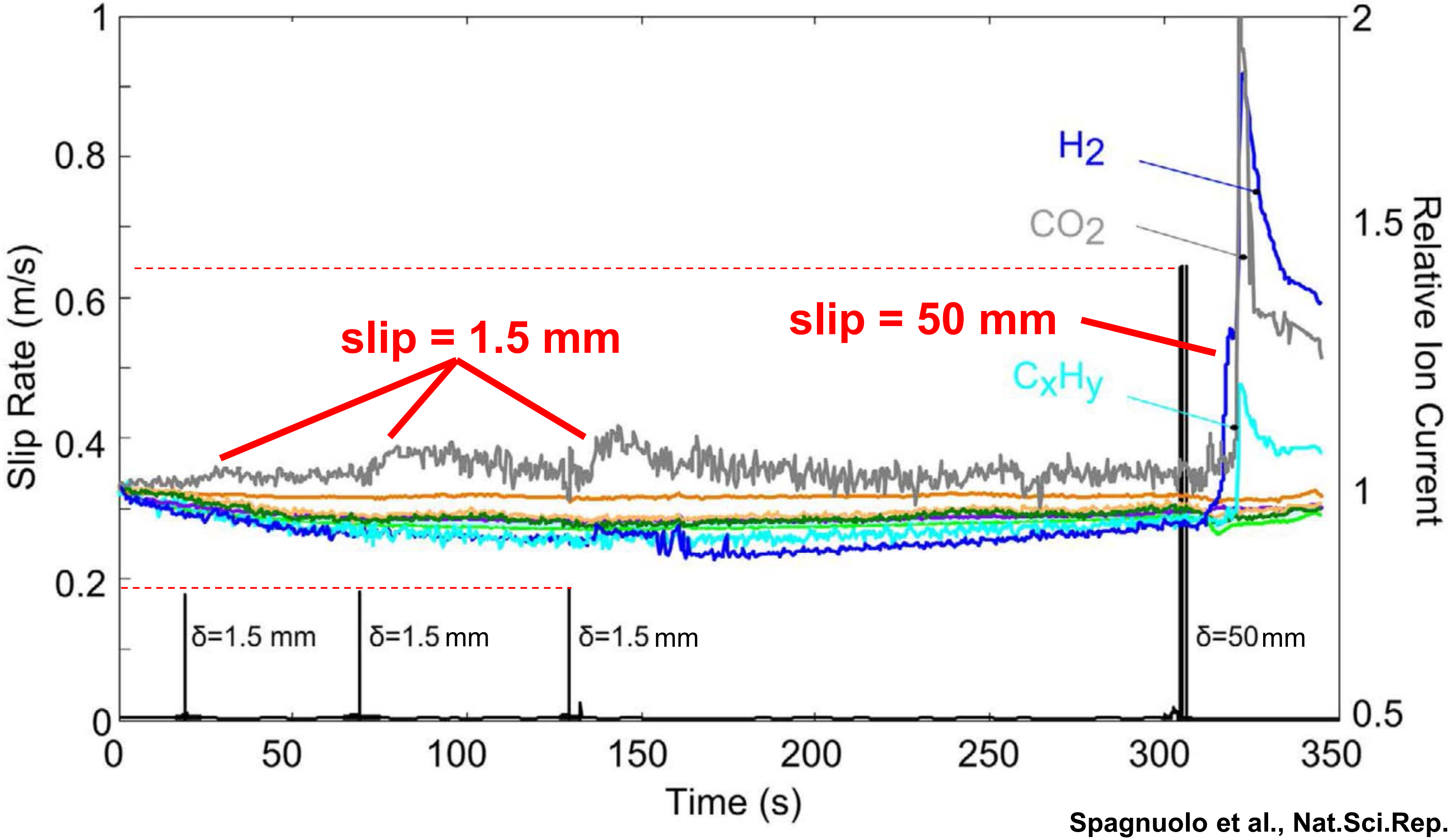
Spagnuolo et al., Nat.Sci.Rep. 2015

Slip resulted in emission of:

- CO_2 for slip = 1.5 mm.
- CO_2, H_2 and C_xH_y (methane) for larger slips.

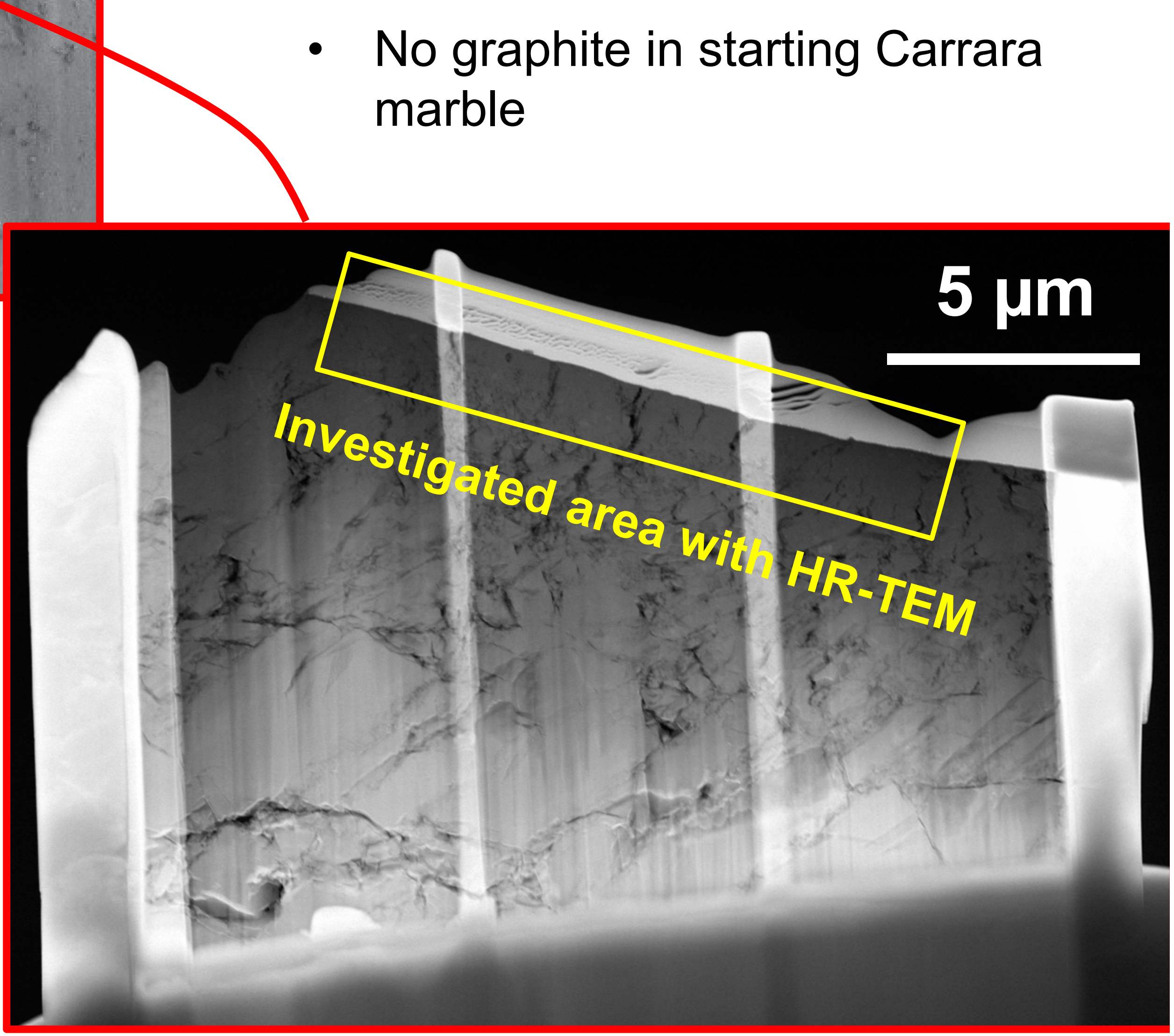


These chemical species were not detected in tests without rock samples.



Spagnuolo et al., Nat.Sci.Rep. 2015

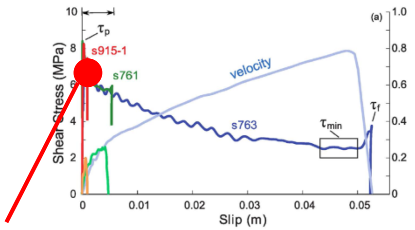
- Samples recovered with gloves and covered with Pt for FIB-SEM and TEM investigations.
- No graphite in starting Carrara marble



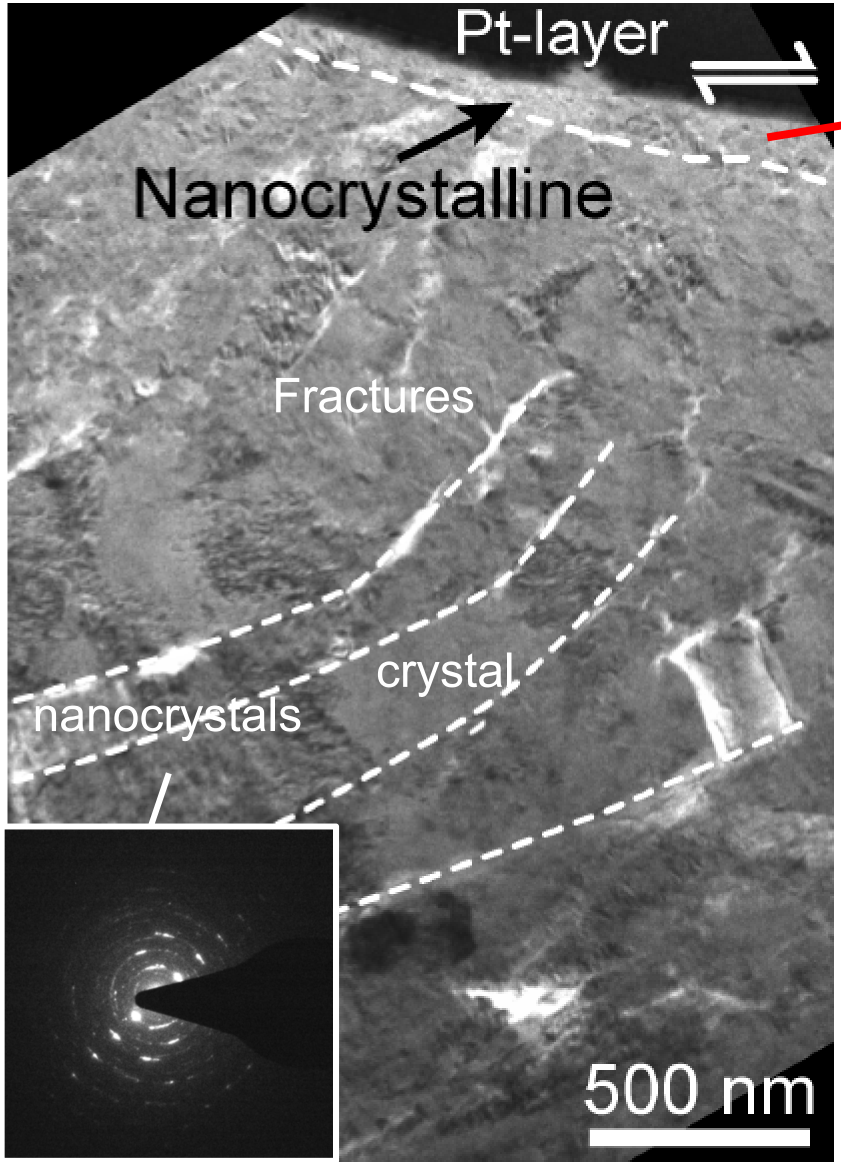
- Focused Ion Beam SEM.
- Electron transparent foils investigated with HRTEM

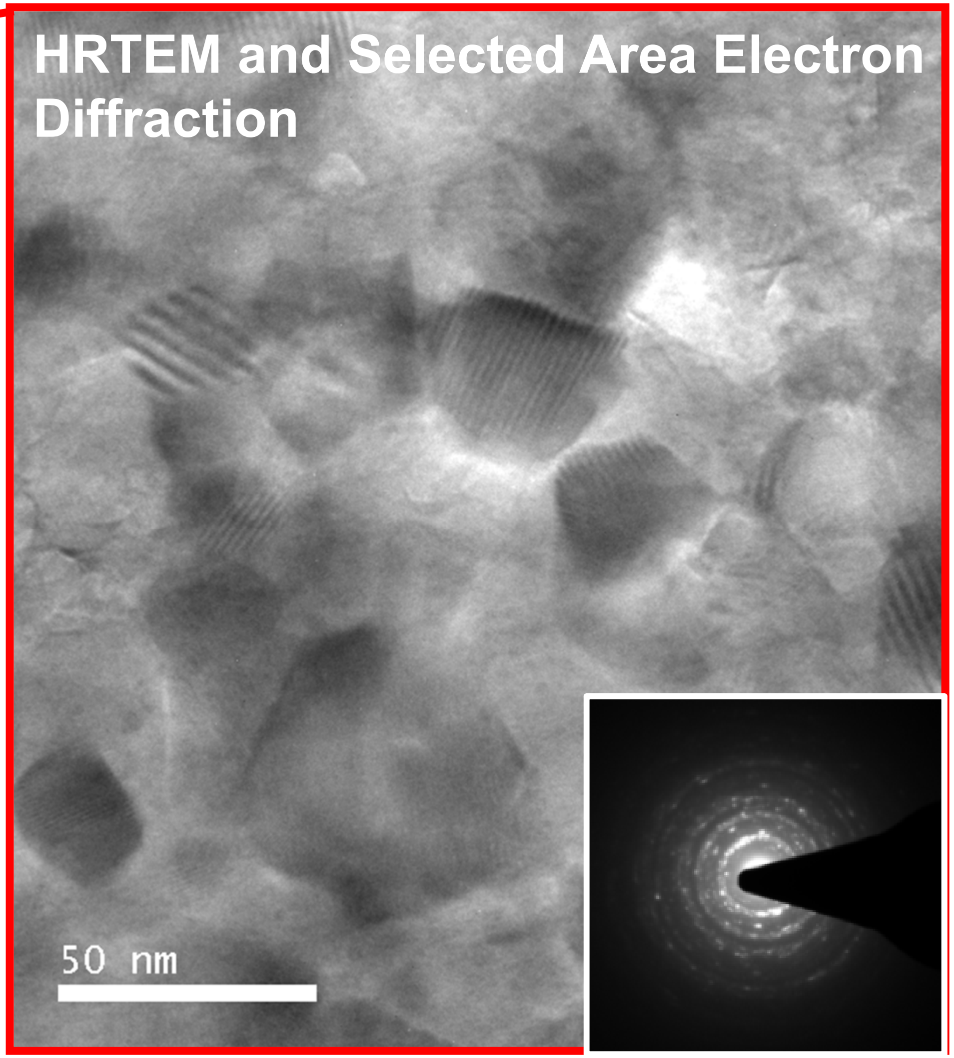
Spagnuolo et al., Nat.Sci.Rep., 2015

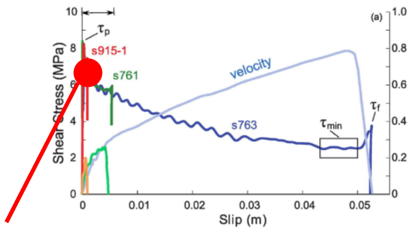
Nanograins beneath slip surface.
Nanograins domains limited by fractures and bent cleavages surfaces (mosaic-like structure).



Slip = 1.5 mm




HRTEM and Selected Area Electron Diffraction



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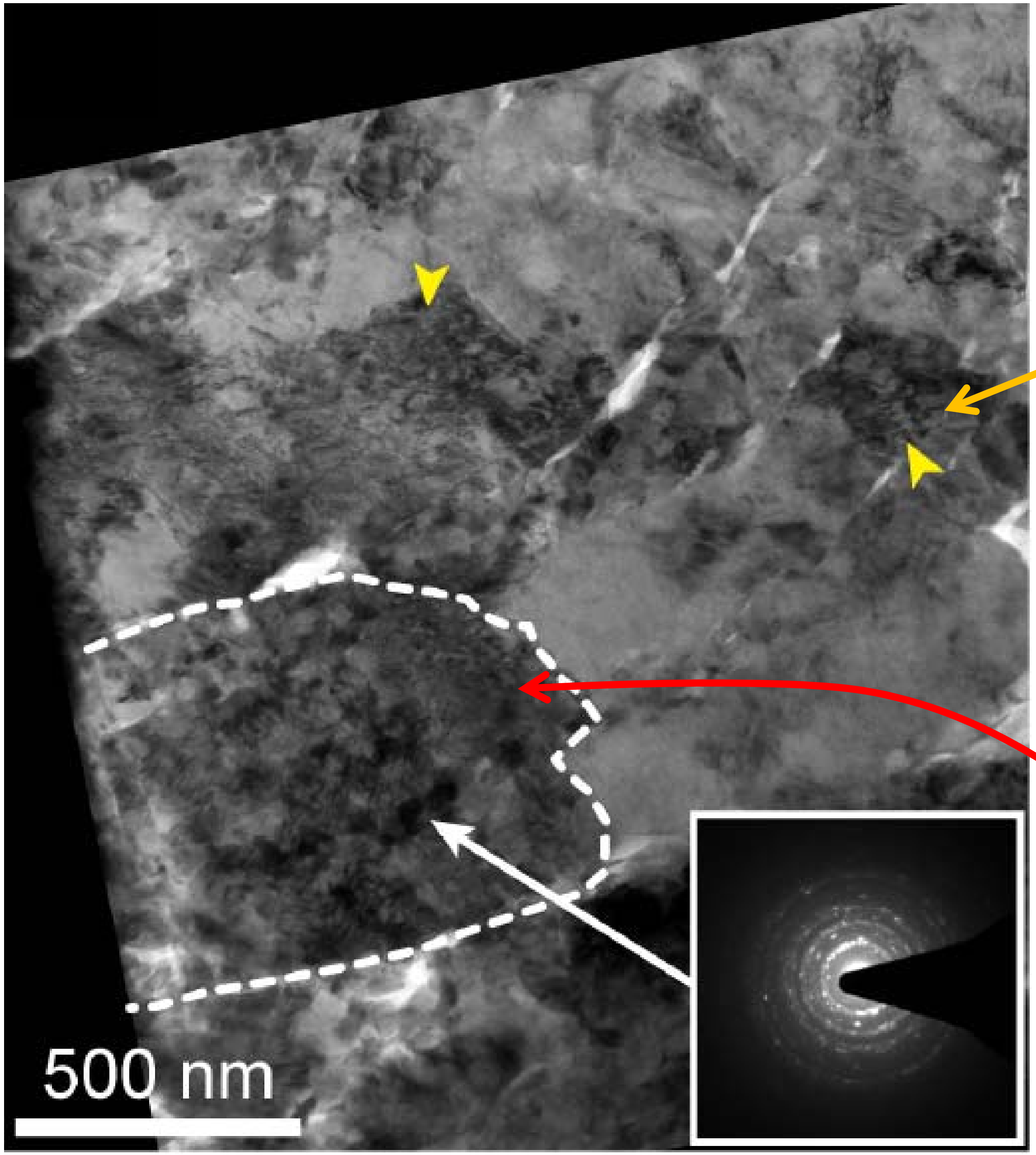
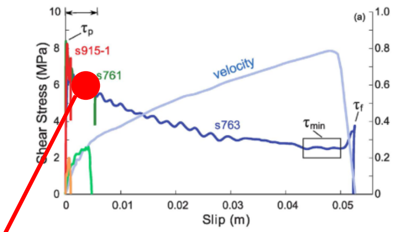


Inter-cleavage crystal domains with high dislocation density

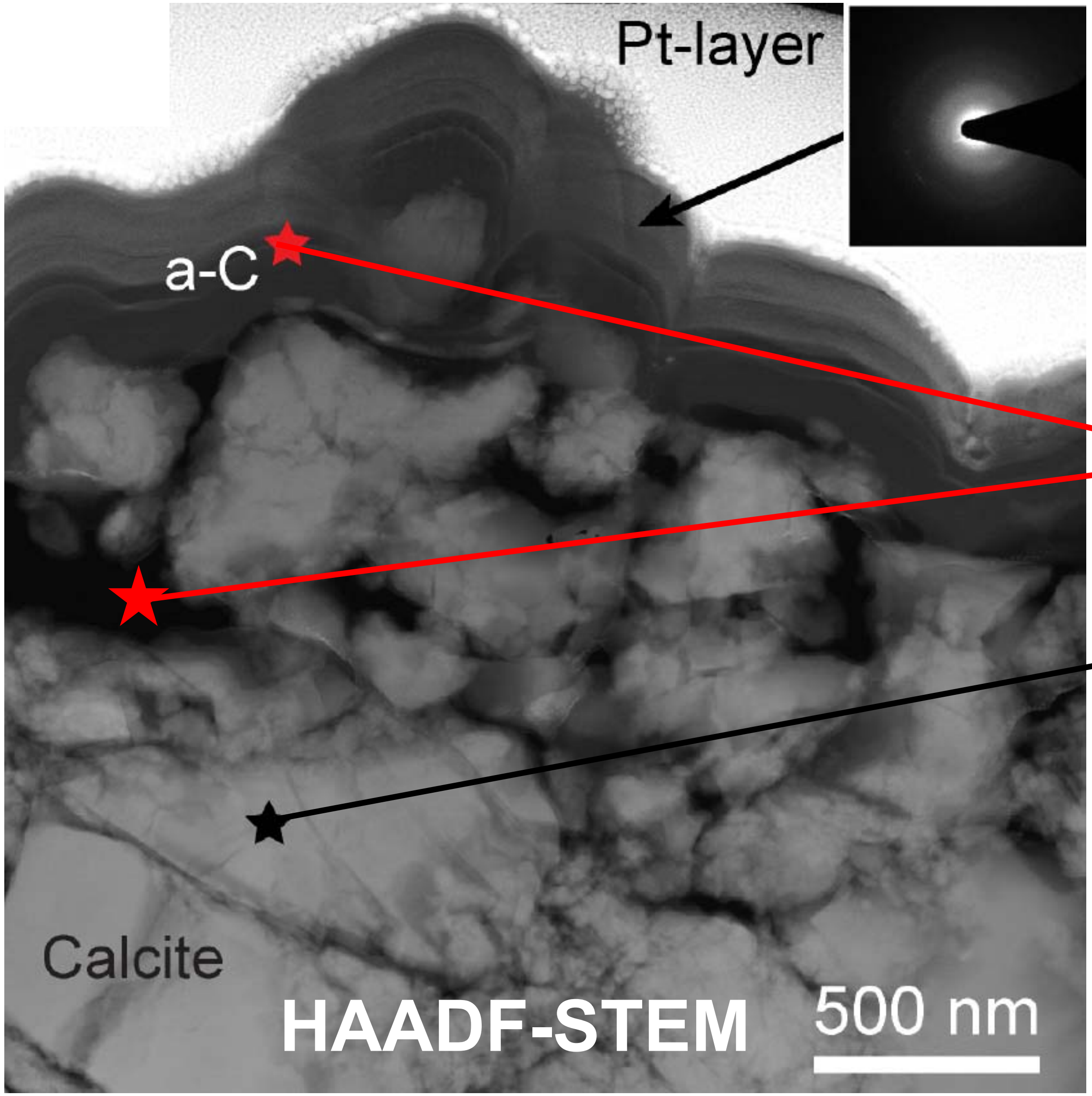
Polycrystalline mosaicism nanostructure

Spagnuolo et al., Nat.Sci.Rep., 2015

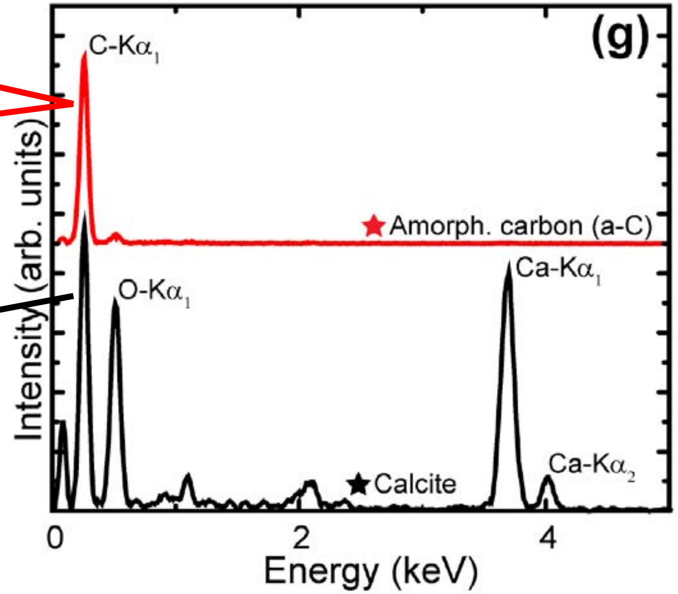
Amorphous carbon-phase in the slipping zone (EDS analysis)



Slip = 5 mm



Platinum

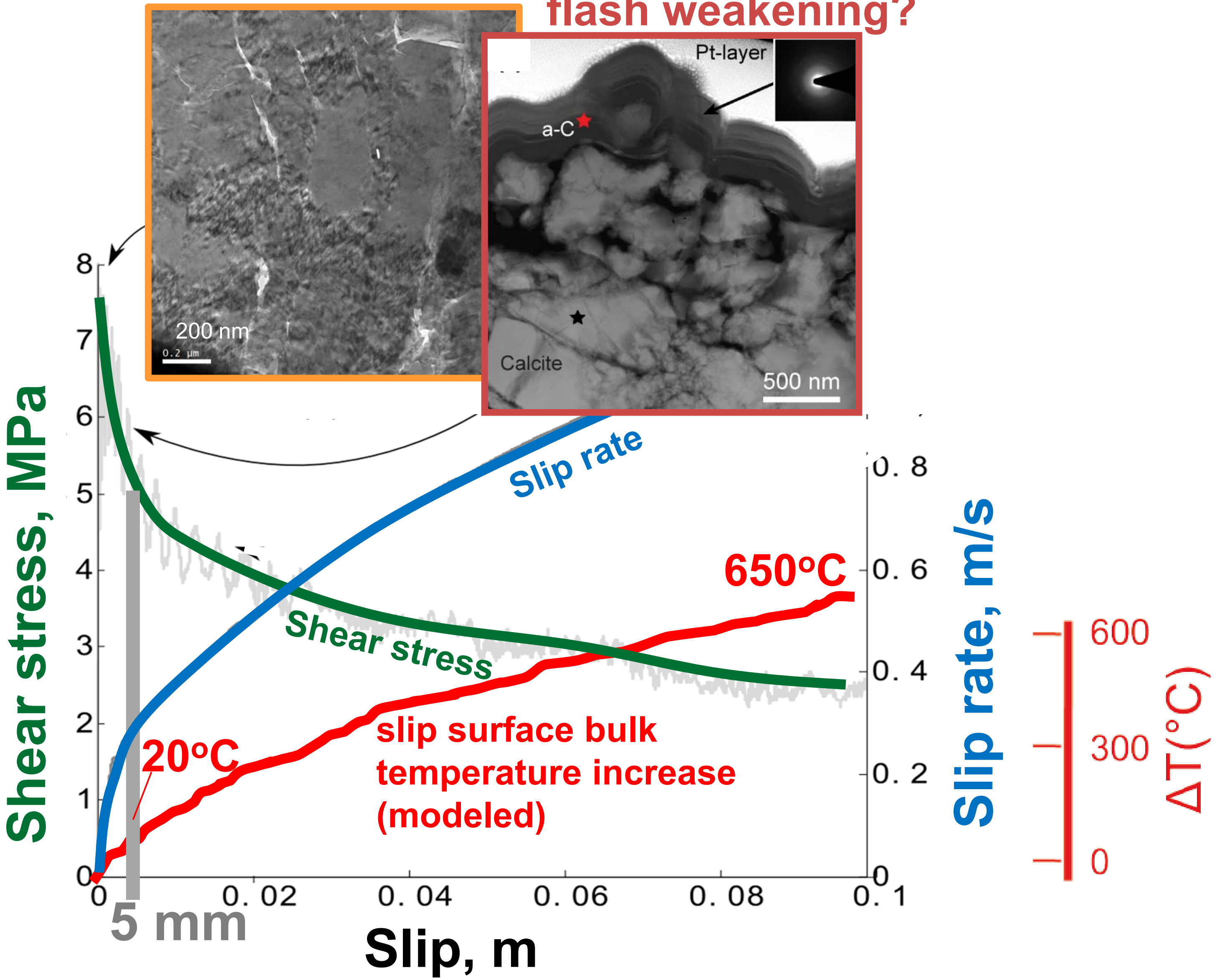


Spagnuolo et al., Nat.Sci.Rep. 2015

Bulk temperature increase

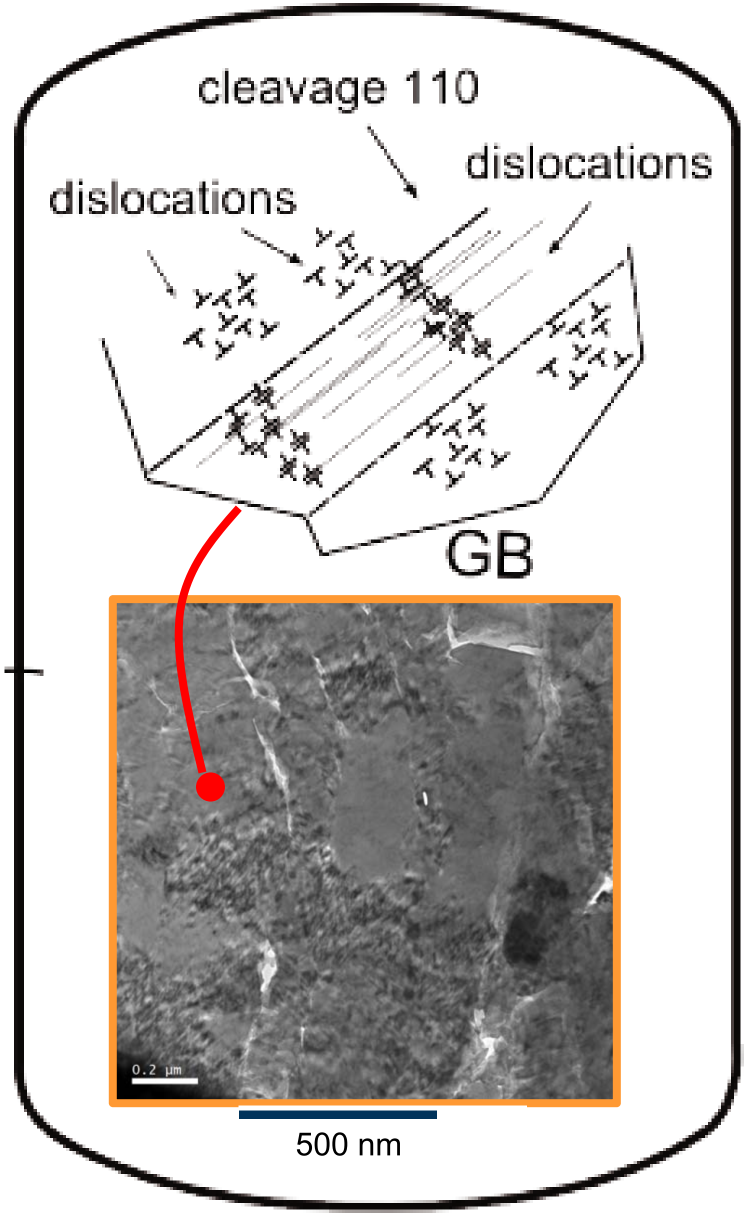
Nanograin formation?

Amorph. carbon: contribution to flash weakening?



Fast moving dislocations:

1) **Birth of dislocations** in crystals at asperity contacts due to abrupt increase in strain rate;



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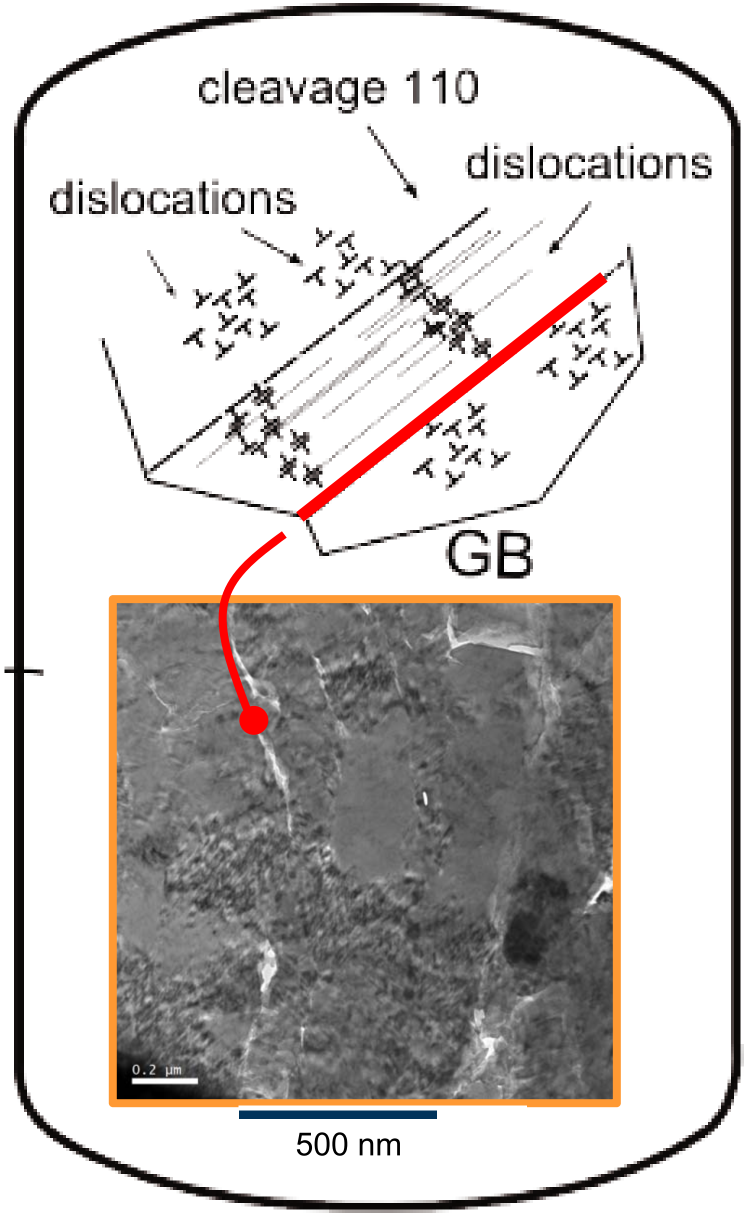
2) **Pile up of dislocations** at cleavage surfaces, microcracks, grain boundaries, etc.;



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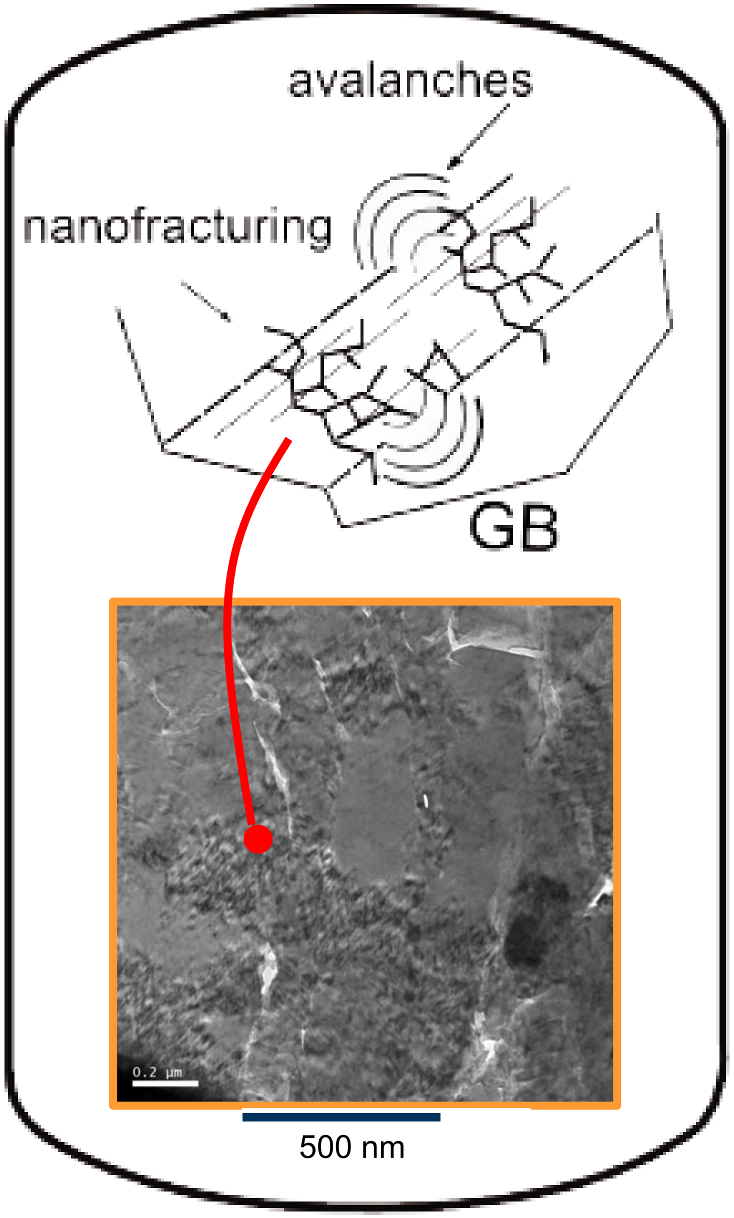

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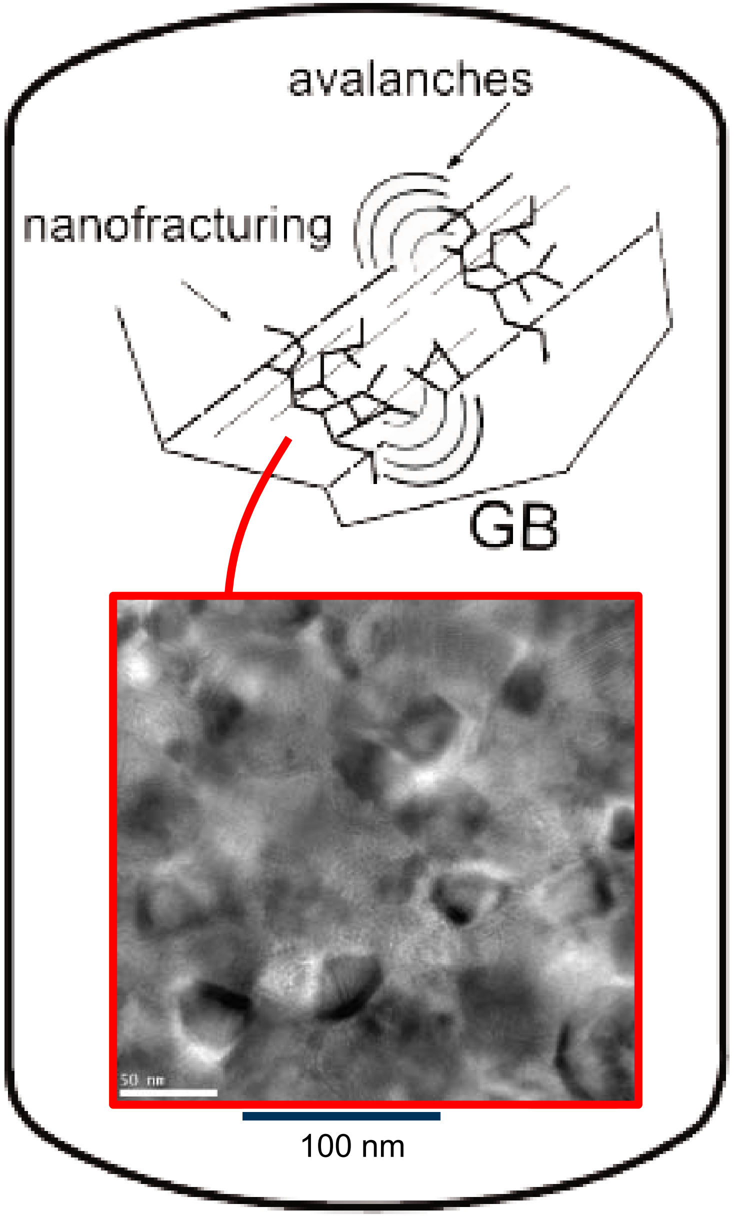

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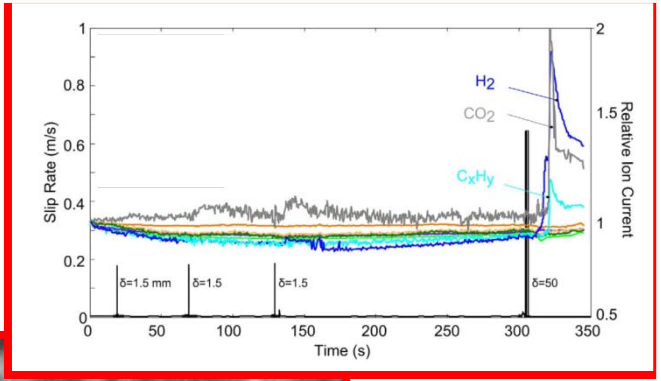
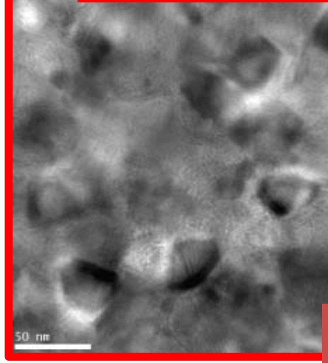
2) **<u>Pile up of dislocations</u>** at cleavage surfaces, microcracks, grain boundaries, etc.;

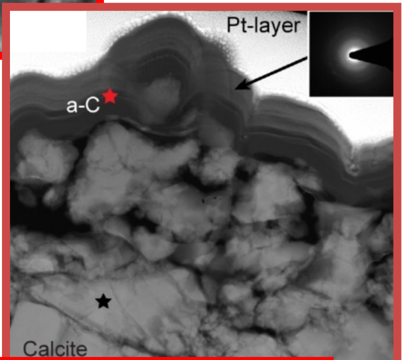
3) **<u>Dislocations avalanches</u>:** kinetic energy converted into heat and (nanoscale) T and P increase in the lattice (possibly several 1000 K and GPa, respectively). Effects:

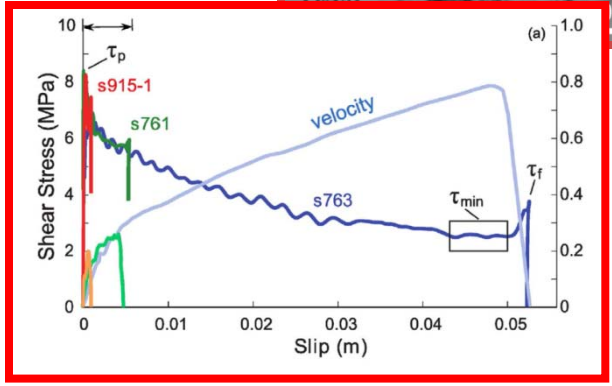
- Release of CO$_2$
- Grain size reduction
- **Formation of amorphous carbon at asperity contacts and flash weakening (friction coefficient ~0.15**: Yu et al., Surf. Coat. Tech., 2007)

Spagnuolo et al., Nat.Sci.Rep. 2015









Estimate of T increase due to fast moving dislocations:

$$\Delta T \leq \frac{k_s\, l^{\frac{1}{2}} \boxed{v_{\mathrm{dis}}}}{16\pi\lambda}\left(\frac{2\lambda}{C_p\, \rho \boxed{v_{\mathrm{dis}}}\, b}\right)^{\frac{1}{2}}$$

$$k_s = \frac{\pi G\, b}{4a}(\delta x)^{-\frac{1}{2}}$$

Hall-Petch shear stress intensity for pile up

l	calcite grain size (0.3 mm)
G	shear modulus calcite (35 GPa)
λ	thermal conductivity calcite (5.54 N s^{-1} K^{-1})
Cp	thermal capacity calcite (1 kJ kg^{-1} K^{-1})
ρ	calcite density (2700 kg m^{-3})
b	Burgers vector (0.49 nm)
a	$= 2(1-v)(2-v)$ with v the Poisson ratio
δx	dislocation spacing at tip of pile-up (= Burgers vector)
$\boxed{v_{dis}}$	velocity of dislocations, estimated from dislocation density, $\rho_{dis} = 10^{12} - 10^{14}$ m^{-2} and bulk strain rate 10^4 s^{-1} :

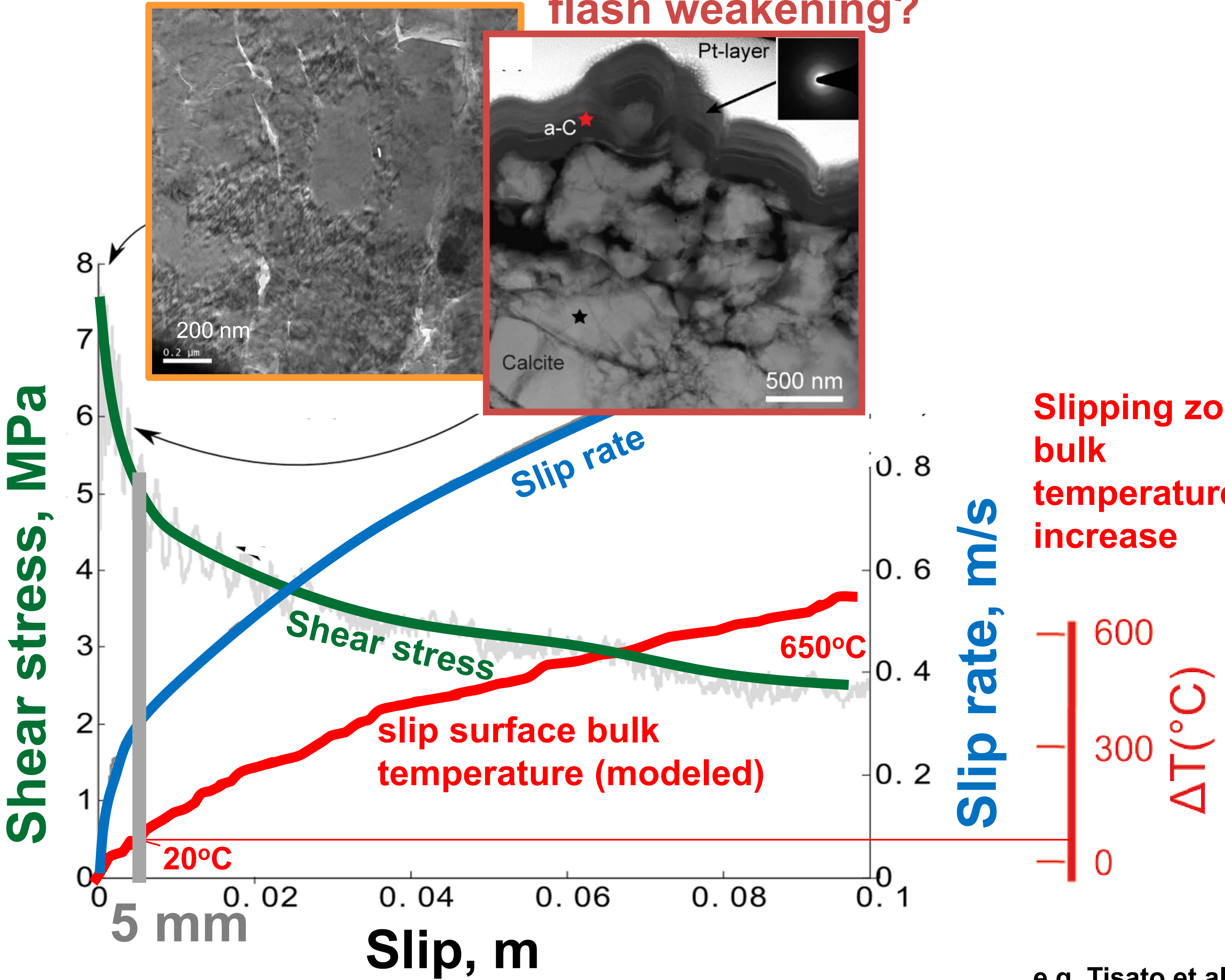
$$\dot{\gamma} = b\, \rho_{dis}\, v_{dis}$$

Armstrong & Elba, 1989

Bulk temperature increase

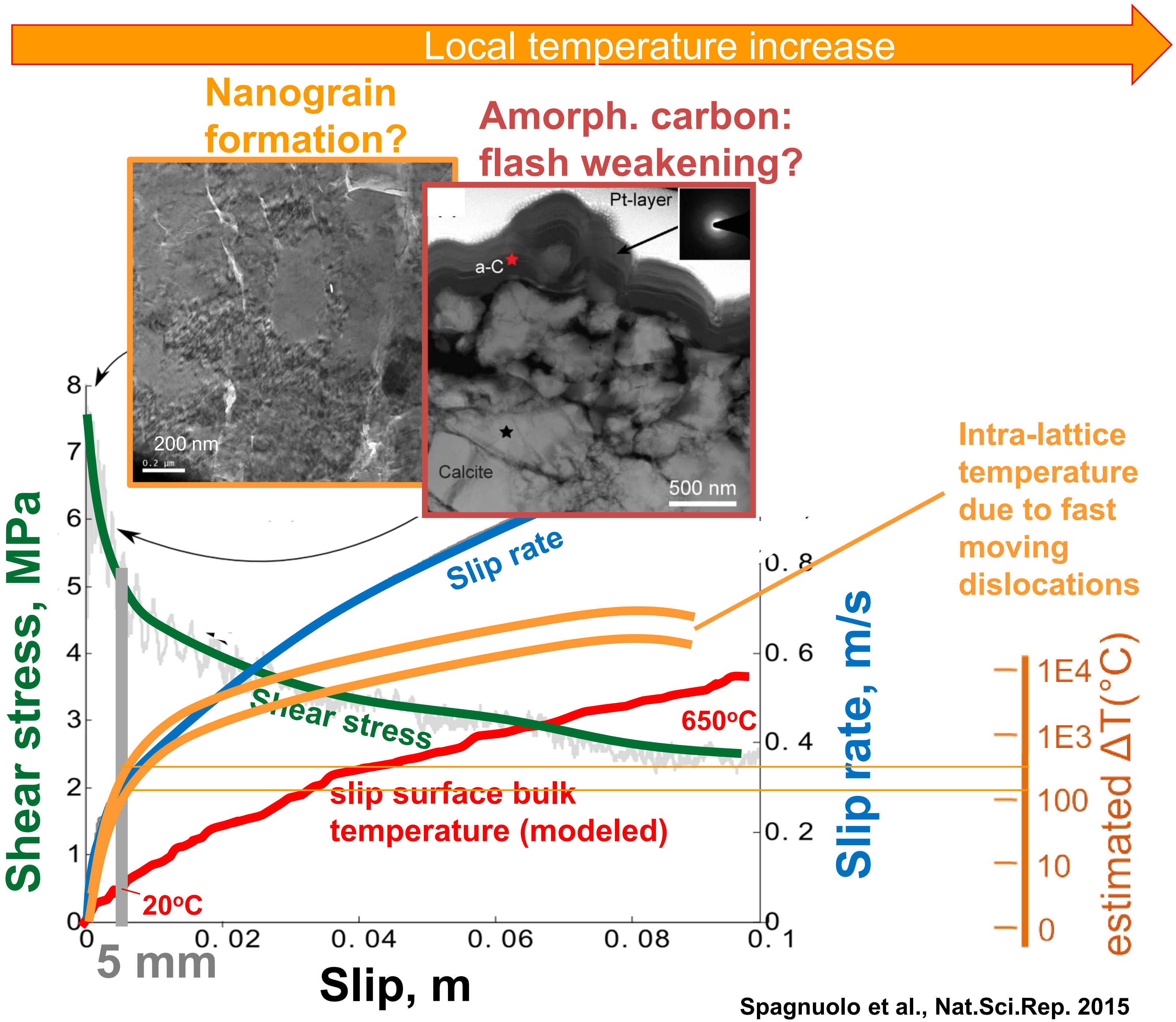
Nanograin formation?

Amorph. carbon: flash weakening?



Slipping zone bulk temperature increase

e.g. Tisato et al., JSG 2012



Local temperature increase

Nanograin formation?

Amorph. carbon: flash weakening?

Intra-lattice temperature due to fast moving dislocations

Spagnuolo et al., Nat.Sci.Rep. 2015

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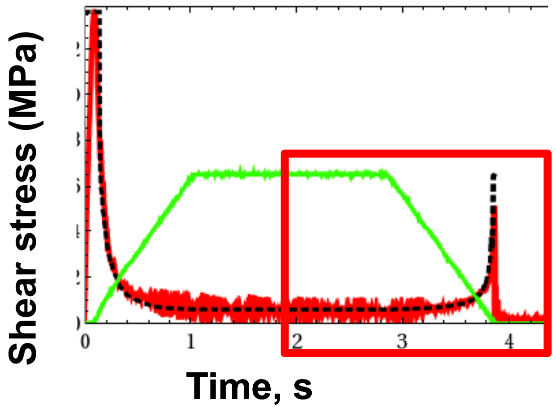
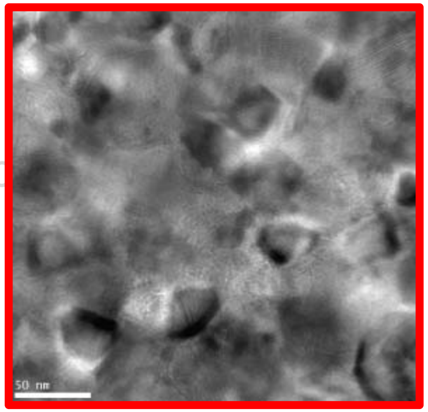


1) Earthquakes in carbonate-built rocks

2) Experimental results

Observations regarding friction in carbonates at seismic slip



3) Processes at seismic slip initiation

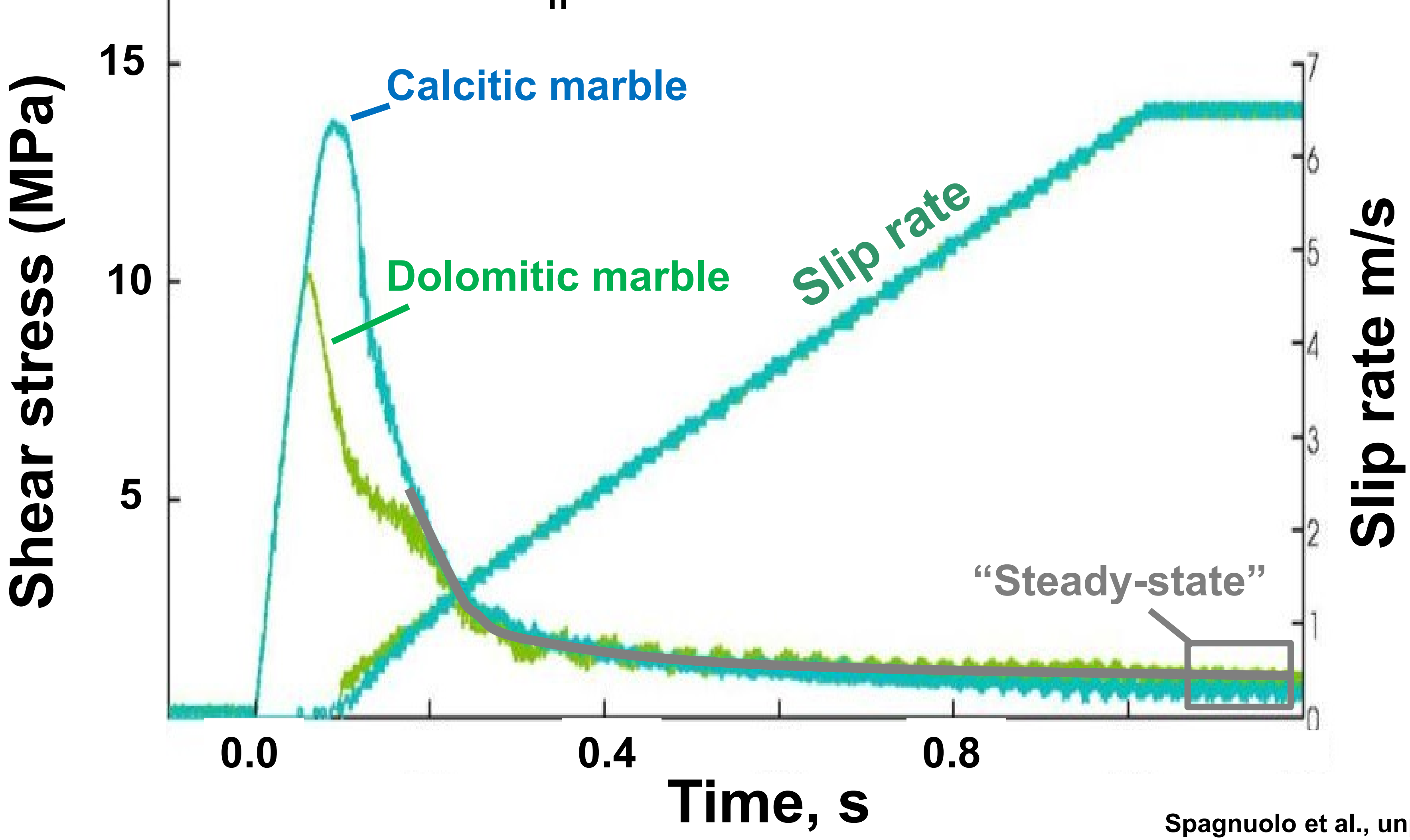
Fast moving dislocations and flash weakening in calcite

4) Processes during and at the end of seismic slip

Grain Boundary Sliding and superplastic behavior

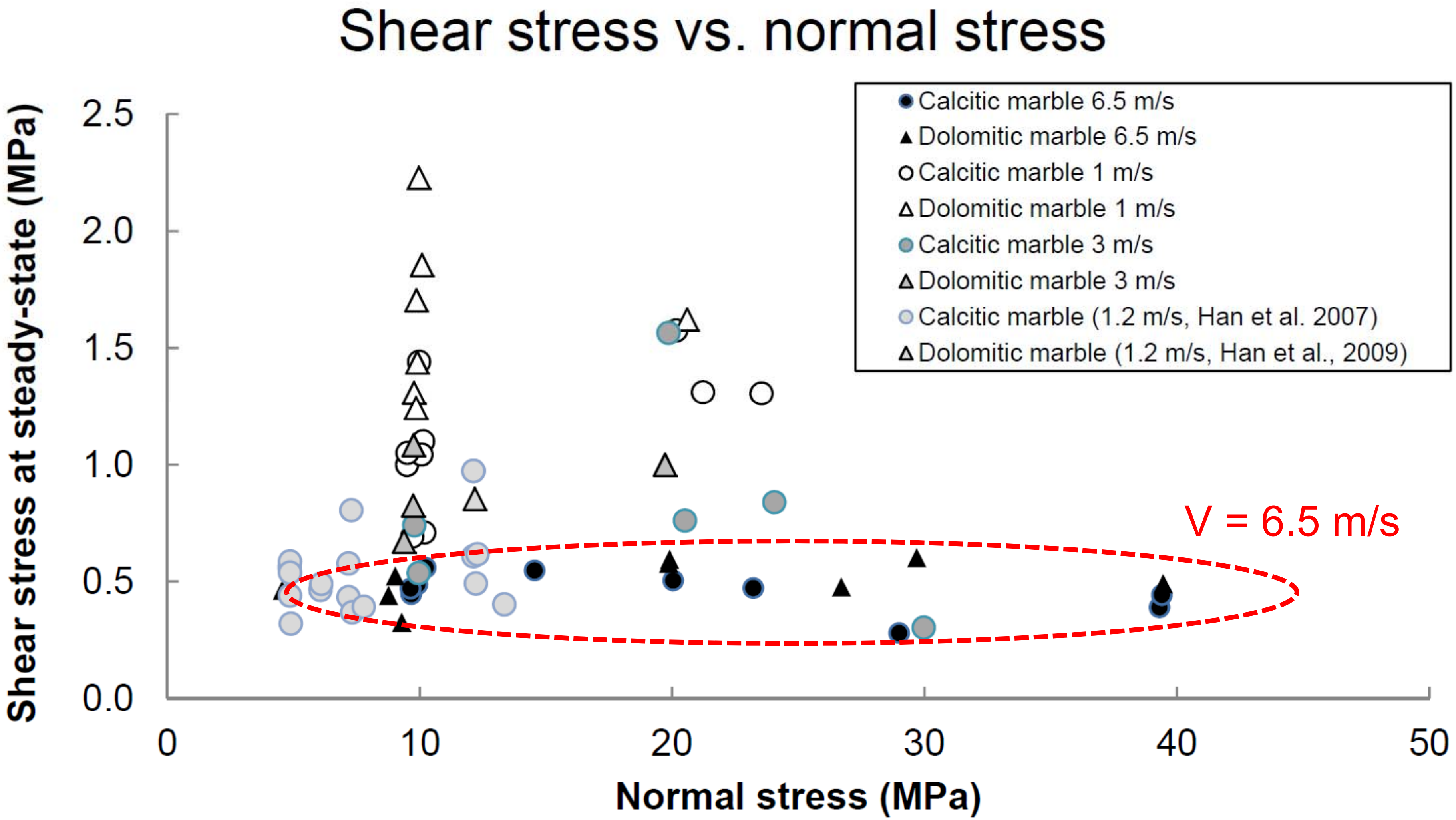
Dolomite- and calcite-built rocks have similar “frictional” strength at steady-state.

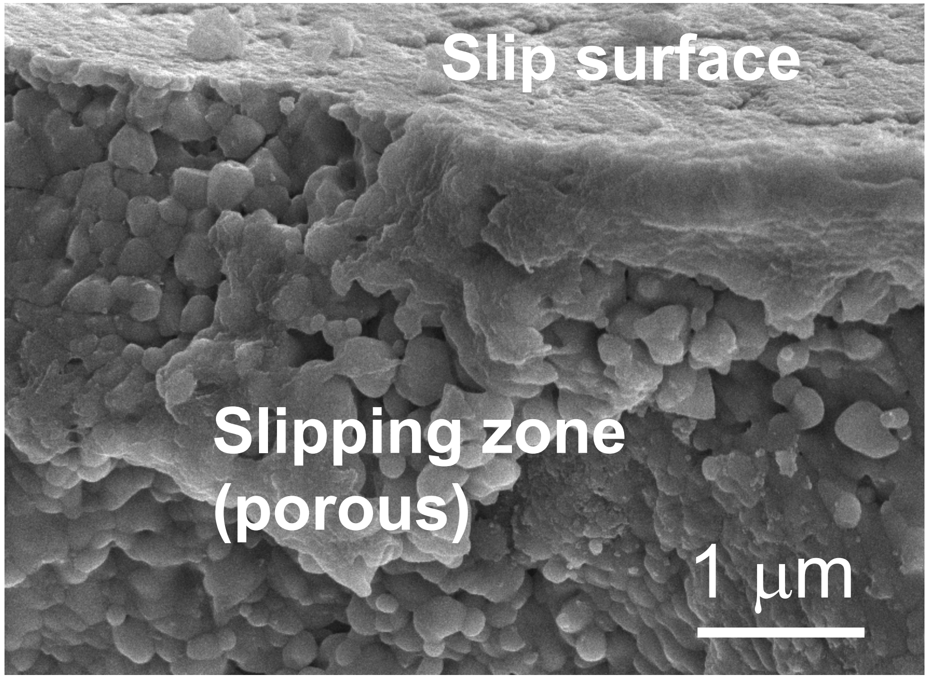
σ_n = 20 MPa

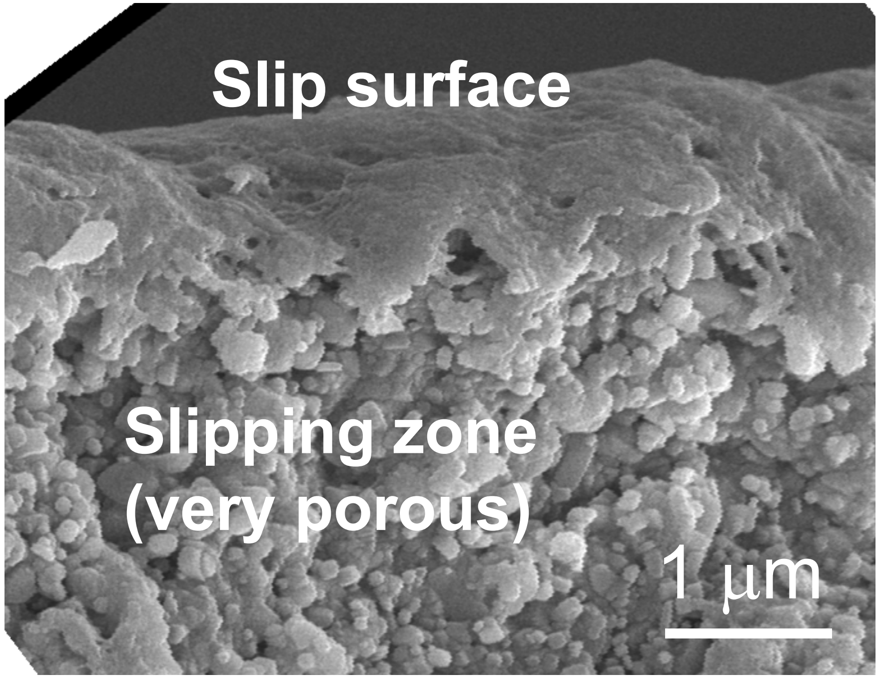


Spagnuolo et al., unpubl.

Dolomite- and calcite-built rocks have small to negligible shear stress dependence with normal stress, especially at large slip rates and normal stresses. **Typical of crystal-plastic processes.**







Calcitic Marble

Dolomitic Marble

Slip = 5 m

σ_n = 10 MPa

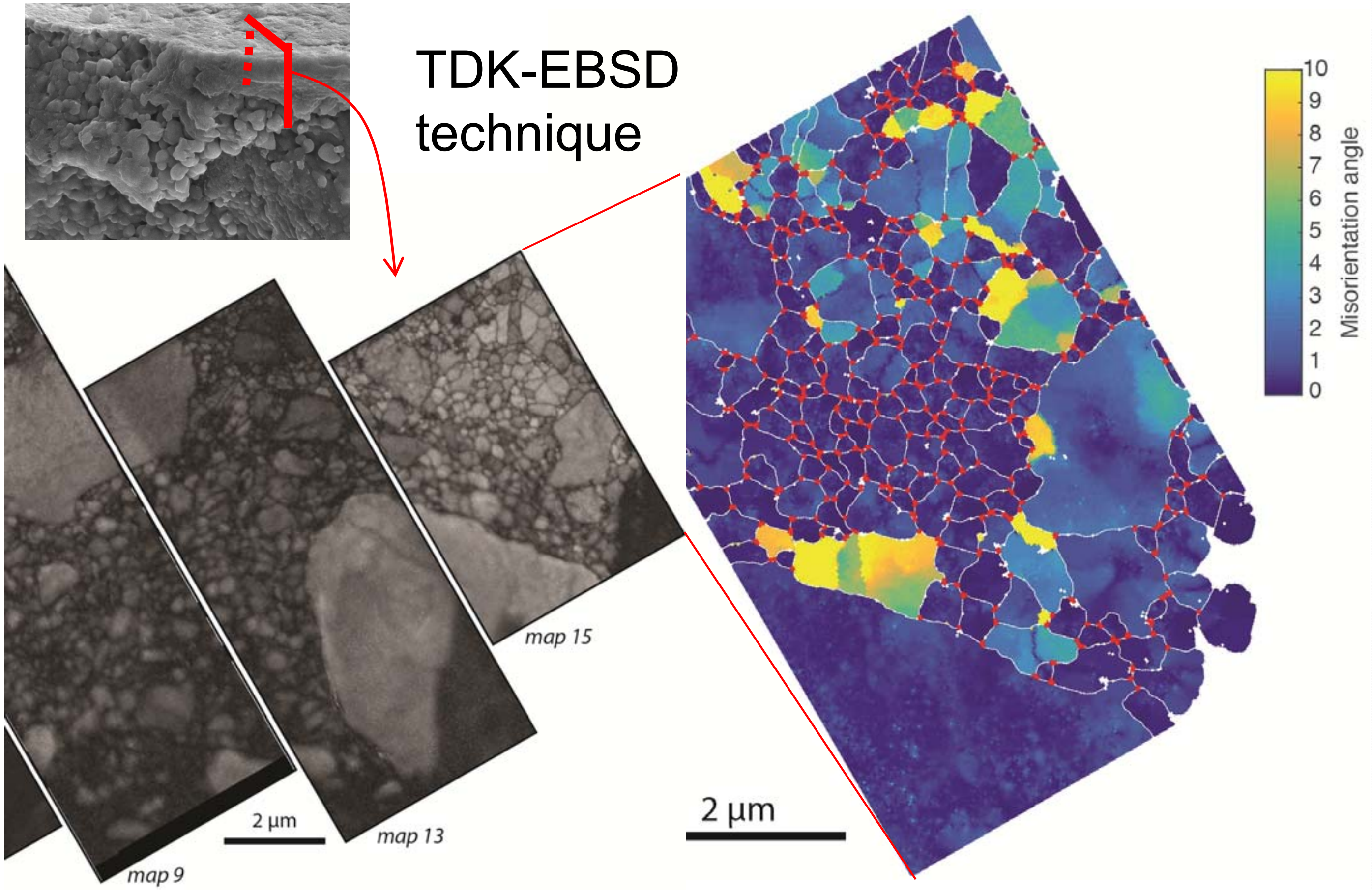
V = 1 m/s

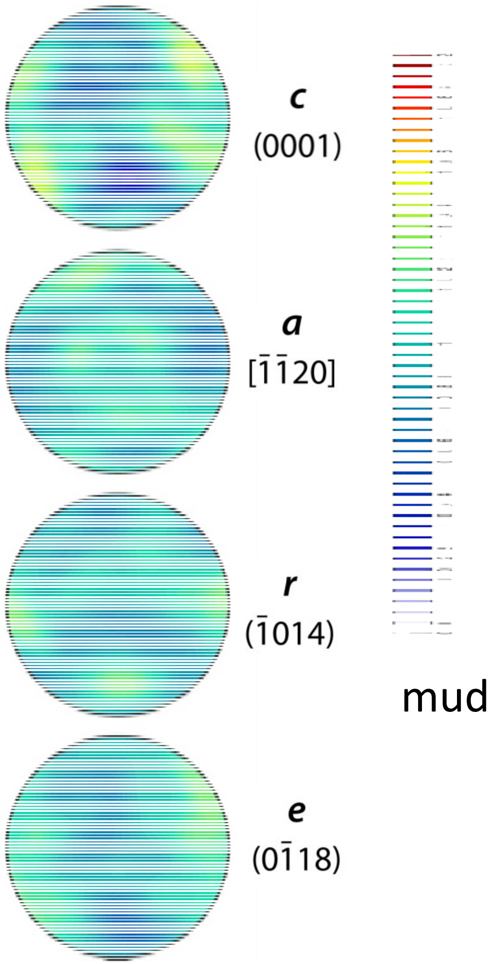
acc. = 6.5 m/s^2

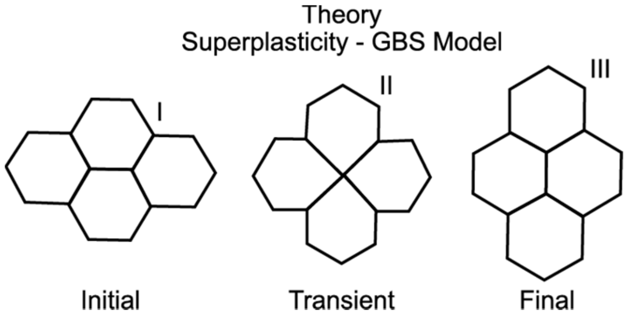
Microstructural similarities are impressive

Deformation mechanism: superplastic flow of calcite by grain boundary sliding aided by diffusion creep

TDK-EBSD technique





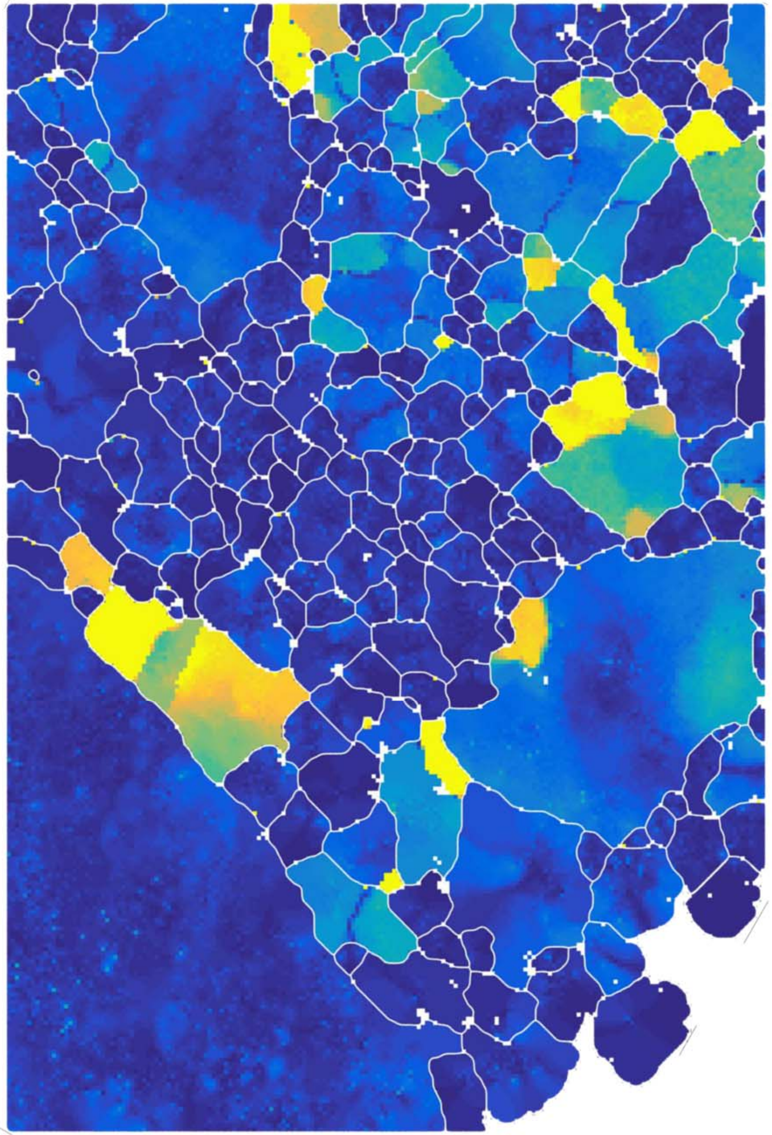


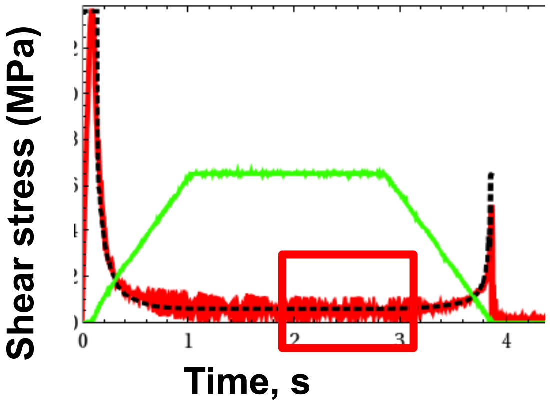
Recrystallized grains:

- straight boundaries + few pores
- triple and quadruple junctions
- very weak lattice preferred orientation

Demurtas et al., unpubl.

Superplastic behavior: grain boundary sliding aided by diffusion creep





$$\tau_{ss} = \left(\frac{\dot{\varepsilon}\, d^3\, exp^{H}\,/_{RT}}{A}\right)^{1/n}$$

$\dot{\varepsilon}$ = strain rate

H = apparent activation energy

A = pre-exponential factor

d = grain size

n = stress exponent

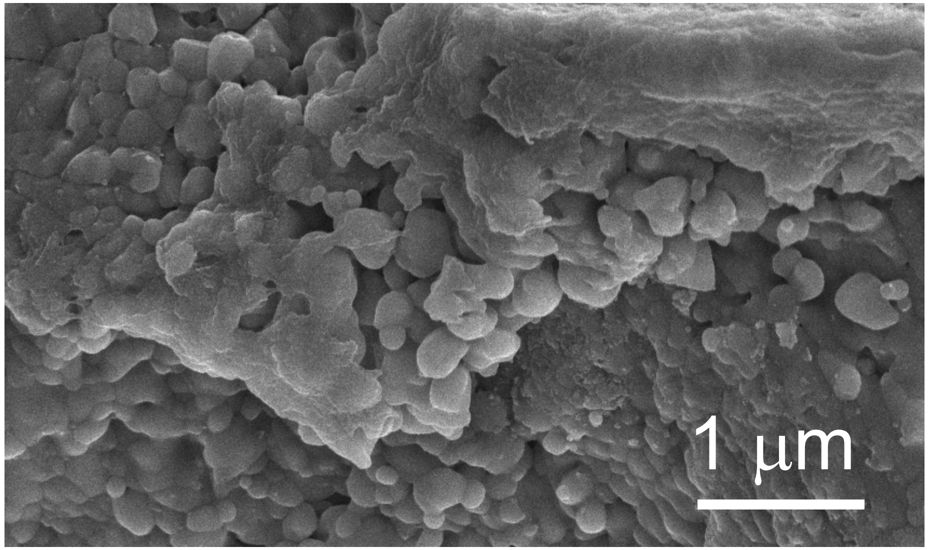
Rough extrapolation: no steady-state strain rate and temperatures; strain rates not well constrained

Verberne et al., 2014; De Paola et al., 2015; Green et al., 2015

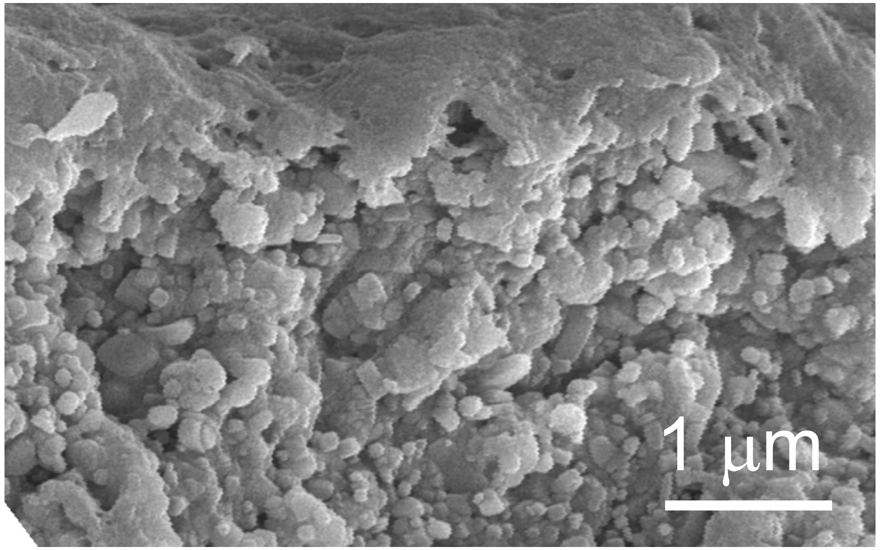
Grain size dependent: GBS & diffusion creep

De Paola et al., 2015

Green et al., 2015



Calcitic Marble



Dolomitic Marble

$$\tau_{ss} = \left(\frac{\dot{\varepsilon}\, d^3\, exp^{H}\ /_{RT}}{A}\right)^{1/n}$$

Schmidt et al., 1977

H = 213 KJ mole^{-1}

n ~ 1.7

$$\tau_{ss} = \left(\frac{\dot{\varepsilon}\, \mu\, d^3\, exp^{H^*}/_{RT}}{2\varepsilon_0\, \Omega}\right)^{1/n}$$

Davis et al., 2008

H *= 280 KJ mole^{-1}

n ~ 1.3

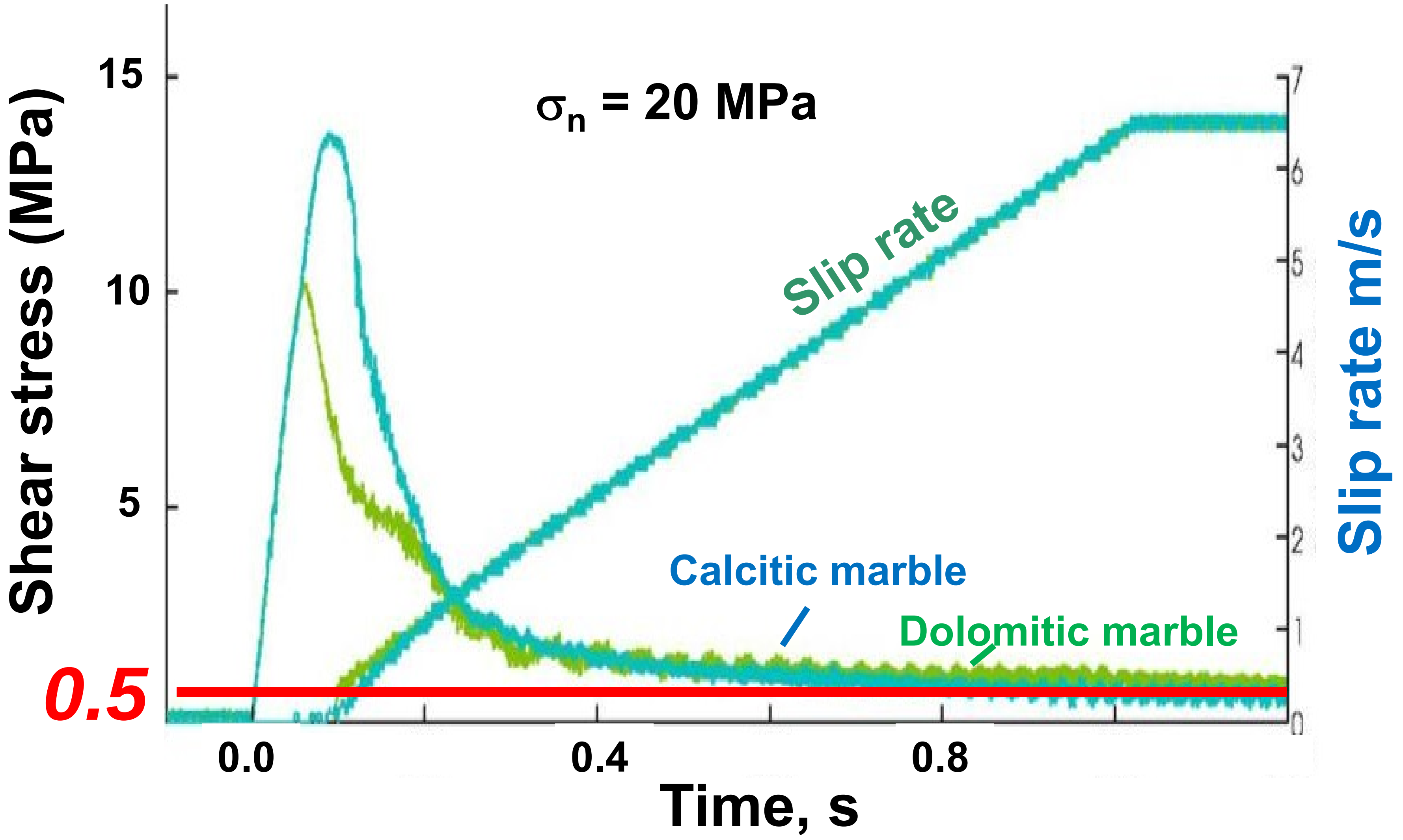
T = 850° C

20 < d < 200 nm

$100 < \dot{\varepsilon} < 10000$ s^{-1}

τ_{ss} → ***0.02-1.2 MPa***

τ_{ss} → ***0.03-7.5 MPa***



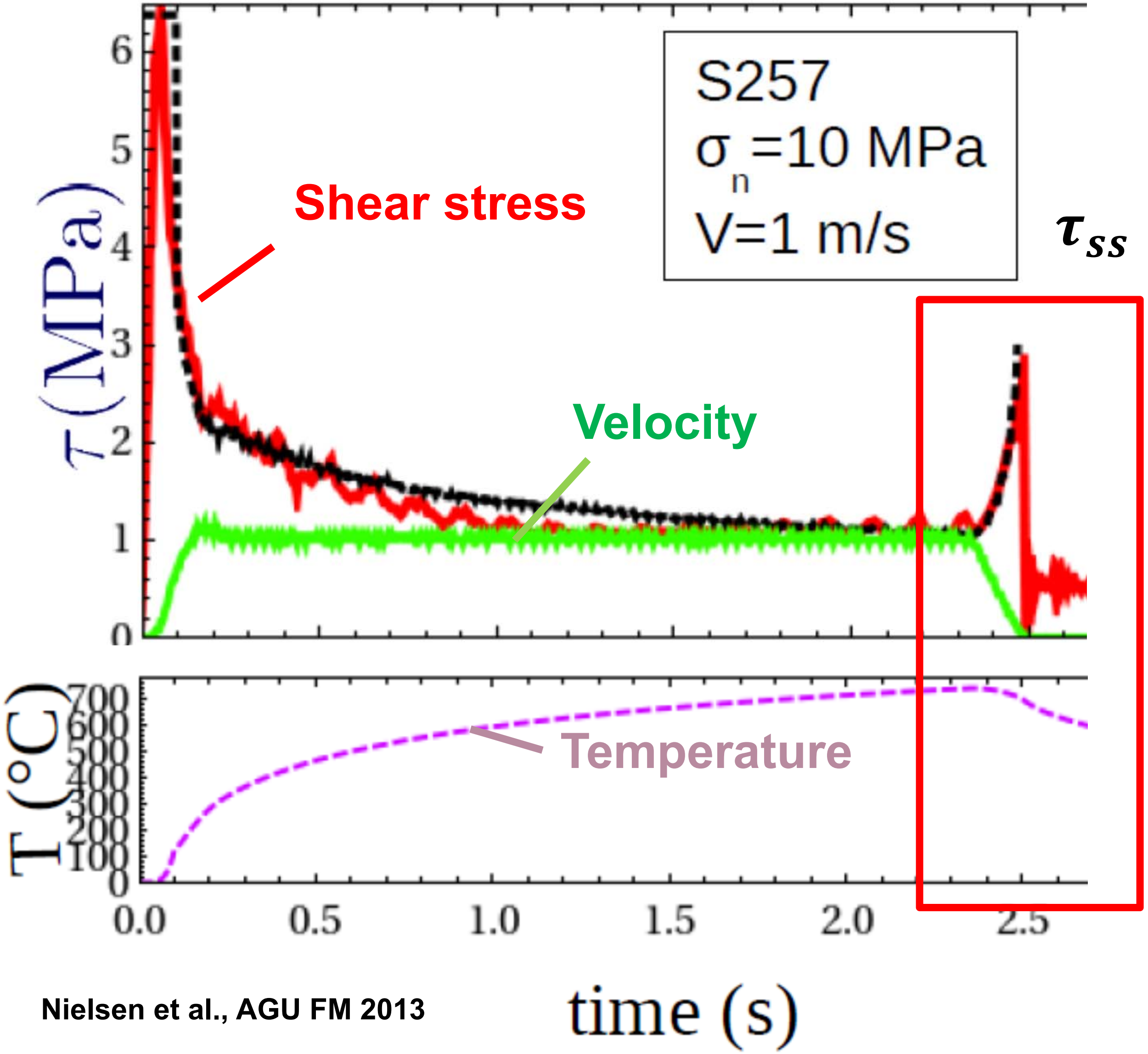
Calcitic Marble

$\tau_{ss} \rightarrow$ *0.02-1.2 MPa*

Dolomitic Marble

$\tau_{ss} \rightarrow$ *0.03-7.5 MPa*

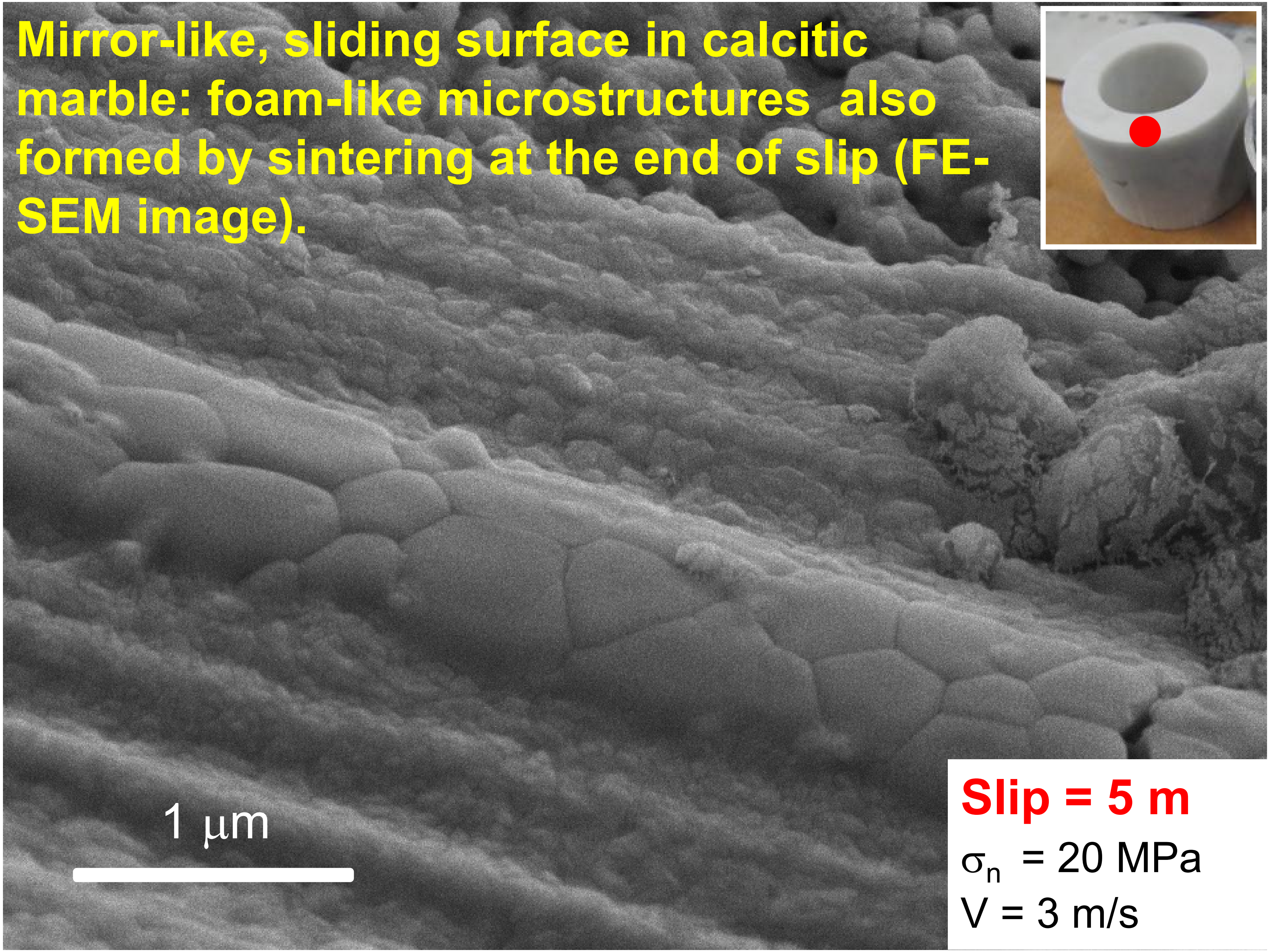
Grain size and T-dependent process may explain rapid shear stress recovery during cooling at slip deceleration



$$\tau_{ss} = \left(\frac{\dot{\varepsilon}\, d^3\, exp^{H/RT}}{A} \right)^{1/n}$$

Nielsen et al., AGU FM 2013

Mirror-like, sliding surface in calcitic marble: foam-like microstructures also formed by sintering at the end of slip (FE-SEM image).



Slip = 5 m

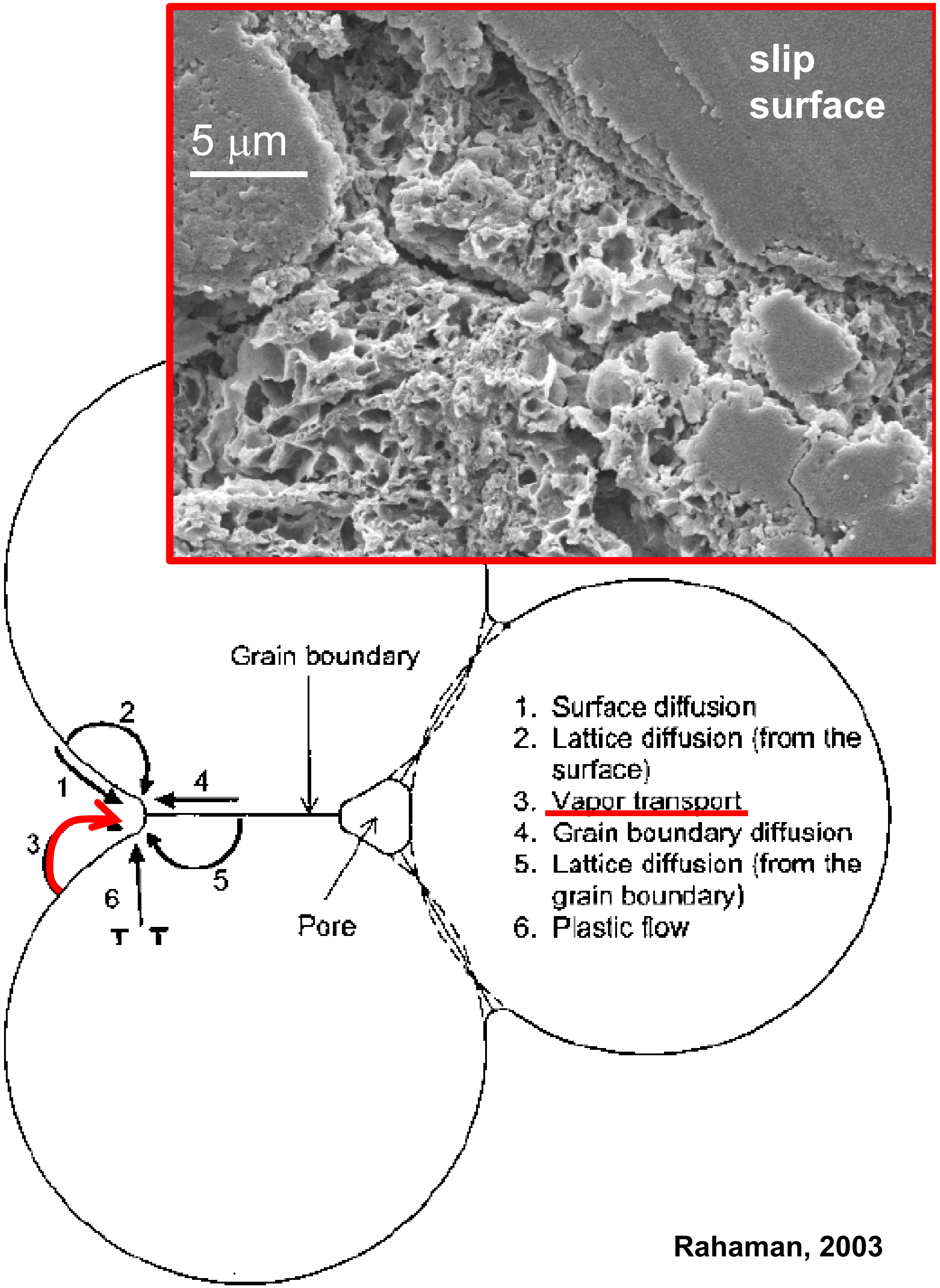
σ_n = 20 MPa

V = 3 m/s

Microporous fabric: pore-controlled advective process* (possibly **vapor transport**) propelled by CO_2 gas exhaust due to decarbonation.

Fast element migration:

- **efficient mass transfer** for grain boundary sliding during slip;
- **rapid sintering** of nanograins into a foam-like surface at end of slip.

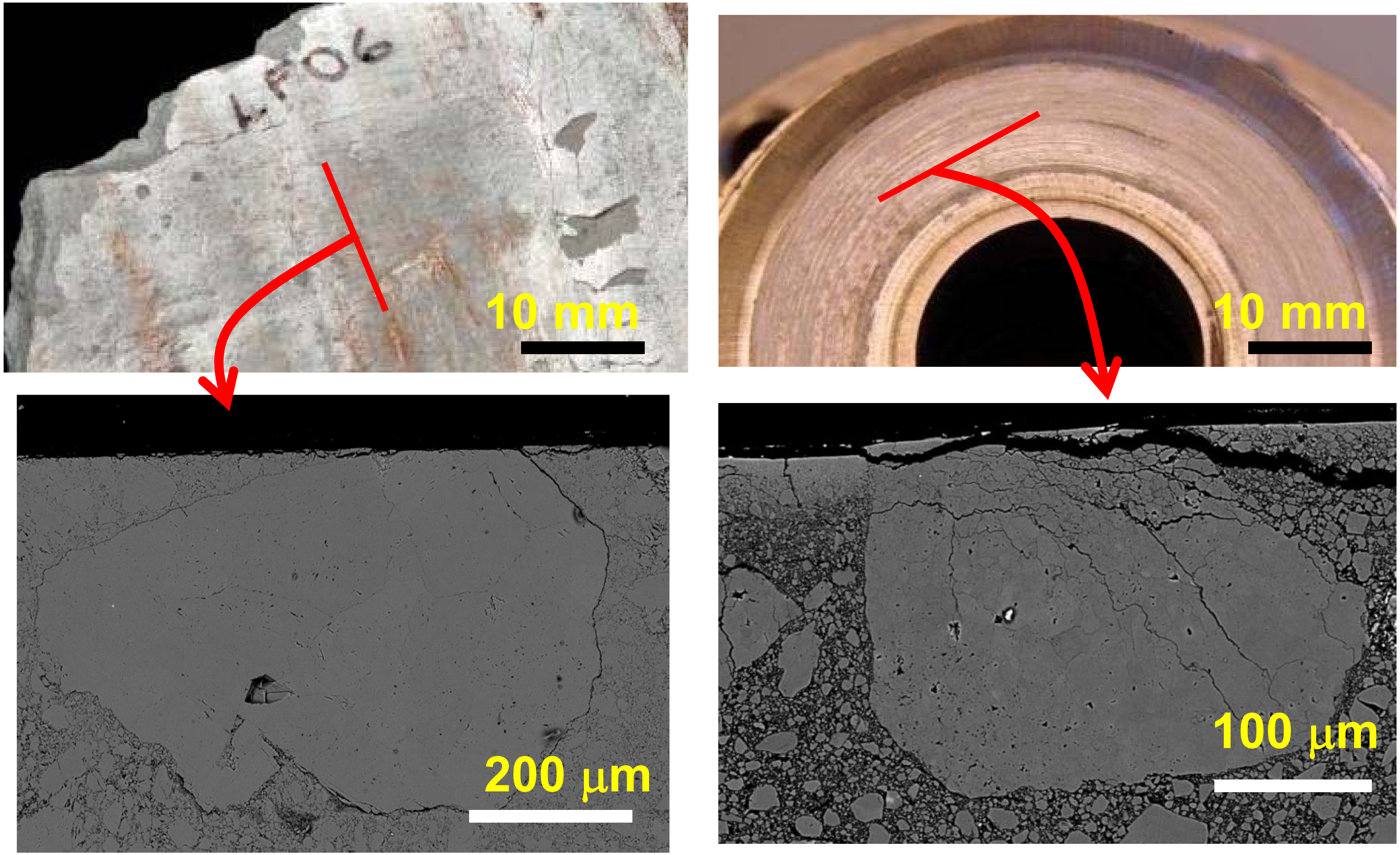


Rahaman, 2003

*permeability < $10^{-17} m^2$ in rexx calcite gouges (Rempe PhD Thesis).

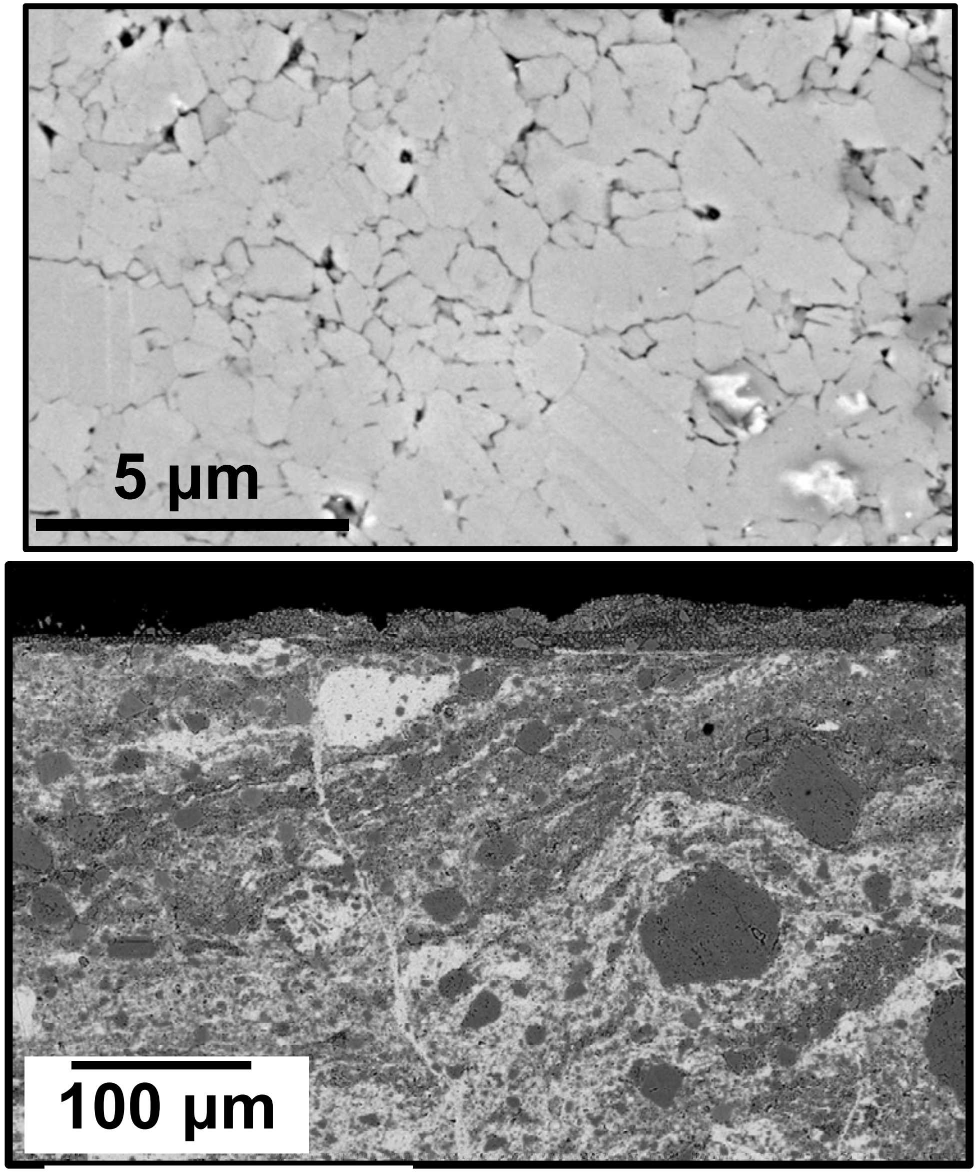
Do these processes occur in nature?

Exp. and natural microstructures are very similar: mirror-like surfaces, truncated clasts….

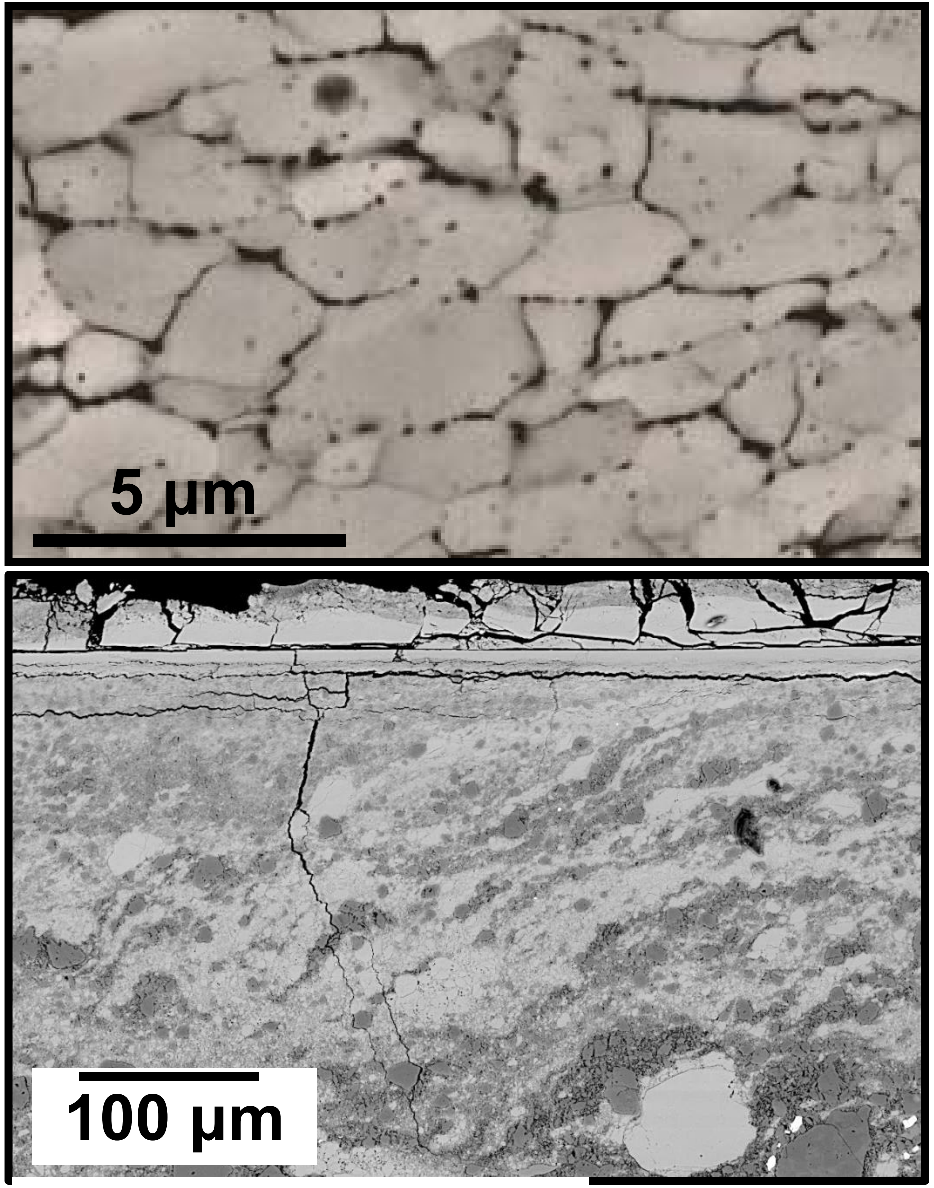


Nature (Foiana Fault zone, Fondriest et al., Geology 2013) **Experiment**

Exp. and natural microstructures are similar: possible re-crystallized calcite, foliated cataclasites, etc.



Nature (Campo Imperatore Fault zone, Demurtas et al., JSG 2016)



Experiment

Smith et al., 2013; 2017

Conclusions

1. Destructive (also megathrust) earthquakes occur in faults cutting carbonates.

2. The passage of the seismic rupture front induces abrupt slip accelerations and temperature-dependent fault weakening.

3. At slip initiation, formation of amorphous carbon at the asperity contacts may contribute to “flash weakening”.

4. With progressive seismic slip and bulk temperature increase, grain size dependent processes reduce fault strength.