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Energy budget of laboratory earthquakes

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Thanks to:

@ ENS: **Samson Marty, Jérôme Aubry**, Blandine Gardonio, Harsha Bhat, Raul Madariaga

@ EPFL: **François Passelègue**

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European Research Council

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INSU

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ENS

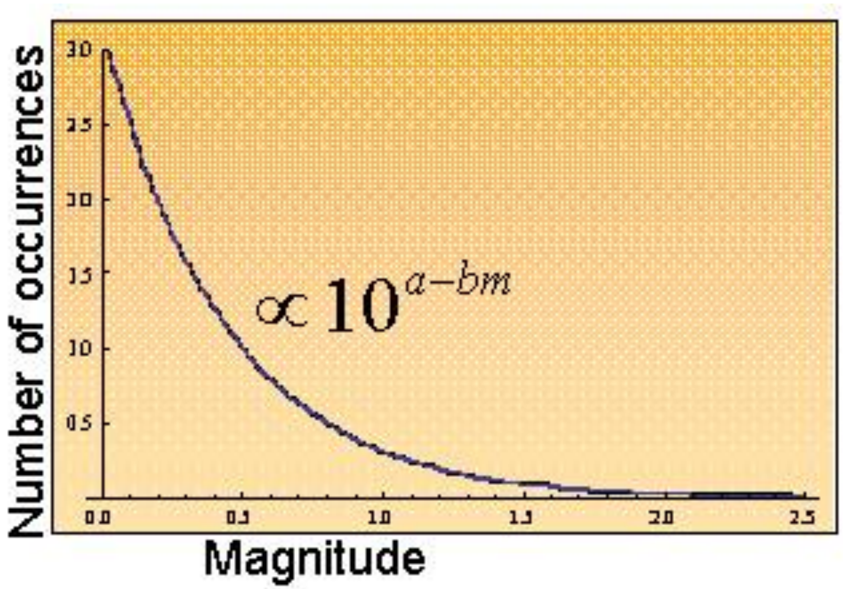
AGENCE NATIONALE DE LA RECHERCHE

ANR

Gutenberg-Richter Law (1949)

Beno Gutenberg, 1889-1960

Charles Richter, 1900-1985



Lesson

WHEN he was here last week, Dr. Einstein told about how he was in the Los Angeles earthquake but didn't know about it. He was walking on the campus of the California Institute of Technology with Dr. Beno Gutenberg, who is one of the leading world authorities on earthquakes and who had been brought to the California institute to do research work on the subject. The two scientists were deep in a discussion of, of all things, earthquakes. Their conversation was interrupted by a third scientist who came up and asked Dr. Gutenberg what he thought of the earthquake. Dr. Gutenberg thought he meant the Tokio quake and started to tell him what he thought of that. Then the news had to be broken to him that he had just gone through one, about three minutes before. Dr. Gutenberg rushed to his laboratory, where he found his instruments recording furiously. Later he said he was keenly disappointed. He has devoted his life to a study of earthquakes but up to that day had never gone through one. When he finally did he didn't notice it.

The New Yorker, Mars 1933

Ohnaka's view: integrating 30 years of experimental rock fracture mechanics

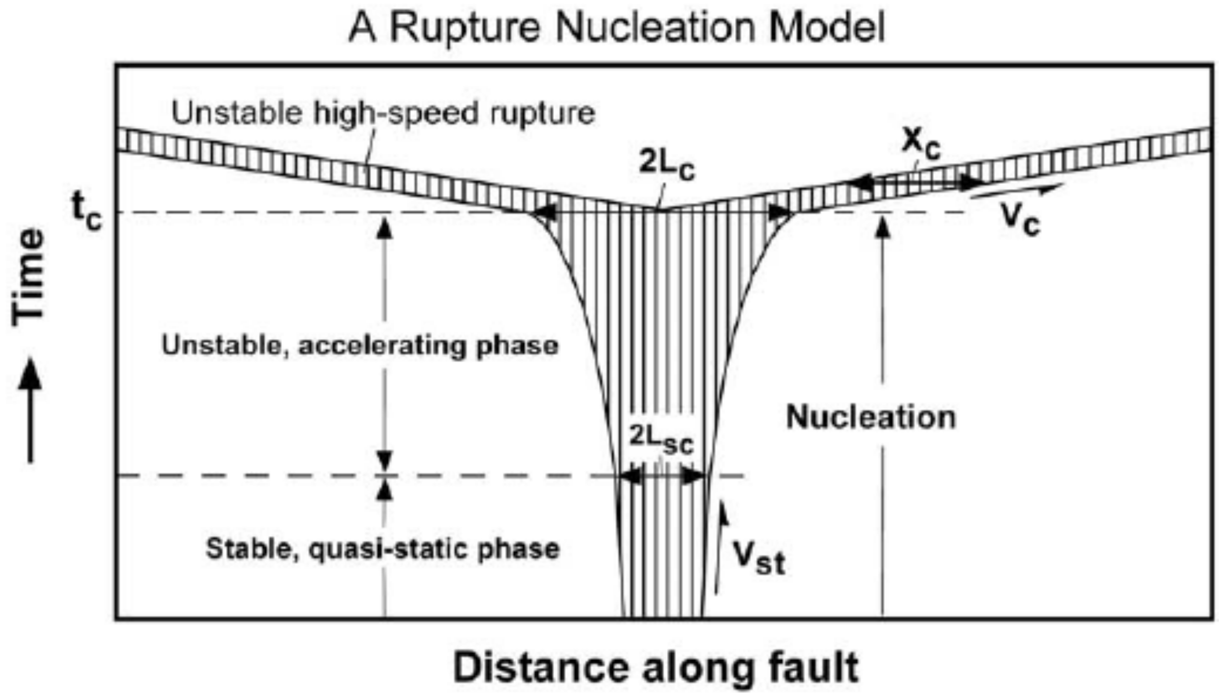


Figure 15. A physical model of rupture nucleation. Hatched portion indicates the zone in which the breakdown (or slip-weakening) proceeds with time.

Ohnaka 2003

Ohnaka's view: integrating 30 years of experimental rock fracture mechanics

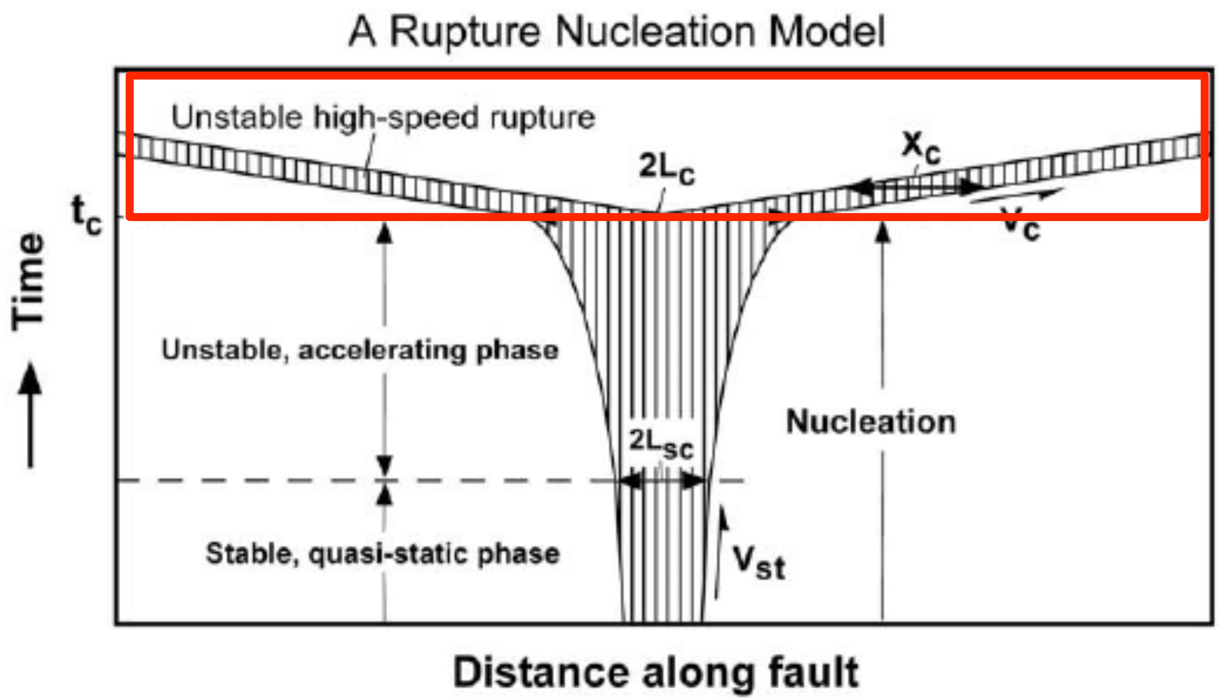
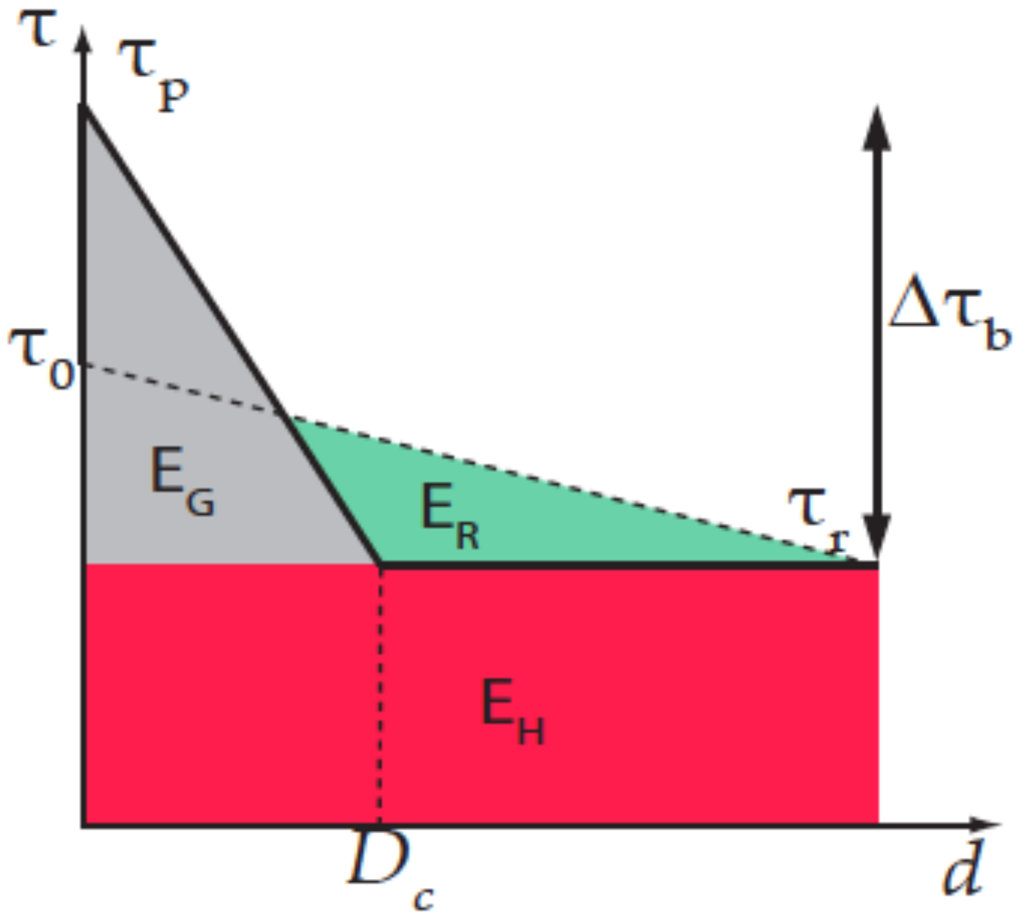


Figure 15. A physical model of rupture nucleation. Hatched portion indicates the zone in which the breakdown (or slip-weakening) proceeds with time.

Ohnaka 2003

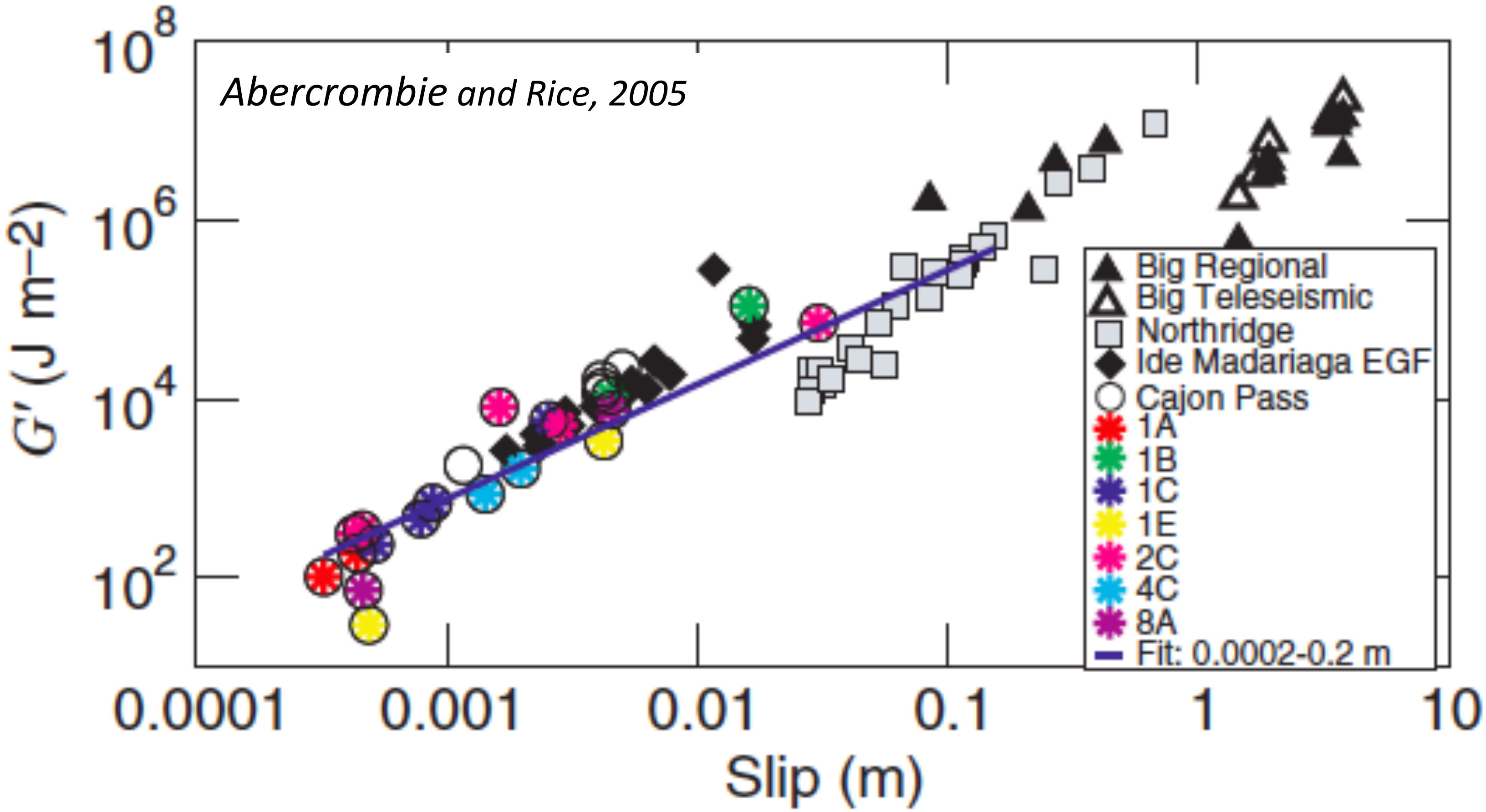
MOTIVATION



Energy partitioning during EQs

MOTIVATION

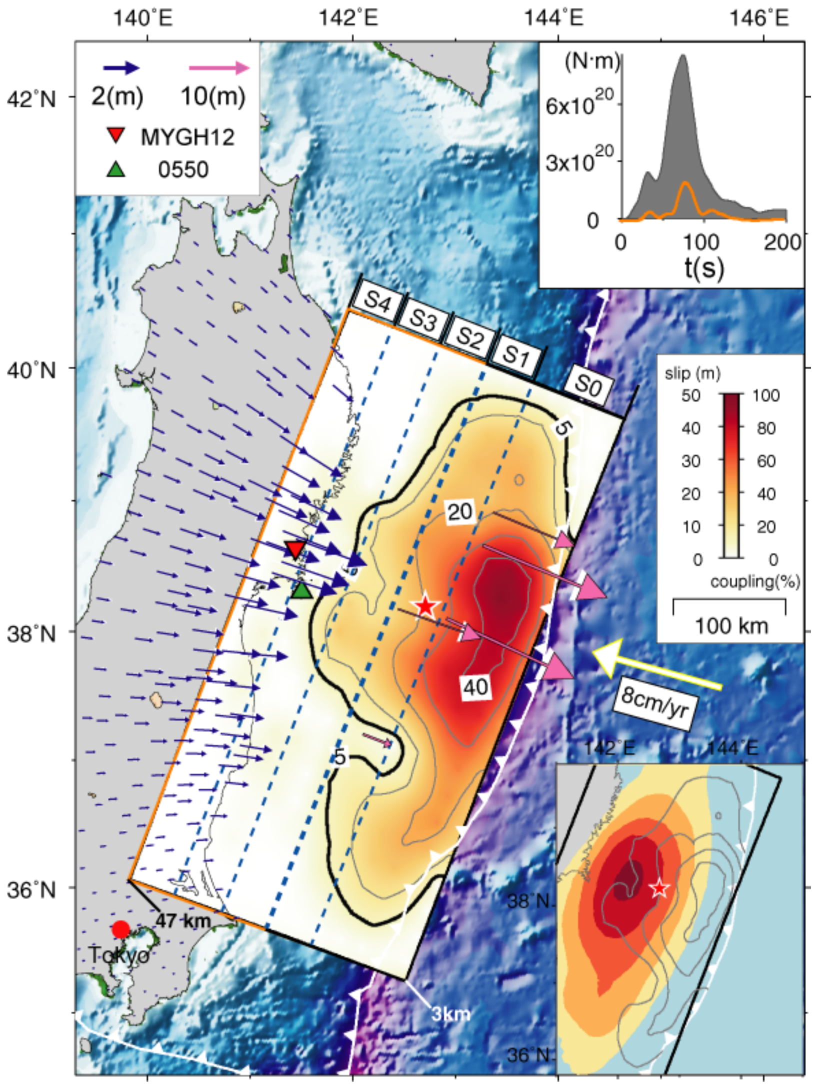
What controls fracture energy (weakening)?



For comparison, the fracture energy of Tohoku EQ ≈ 30-60 MJ/m²

Fulton et al. 2014

MOTIVATION



Fracture energy ≈ 30-60 MJ/m²

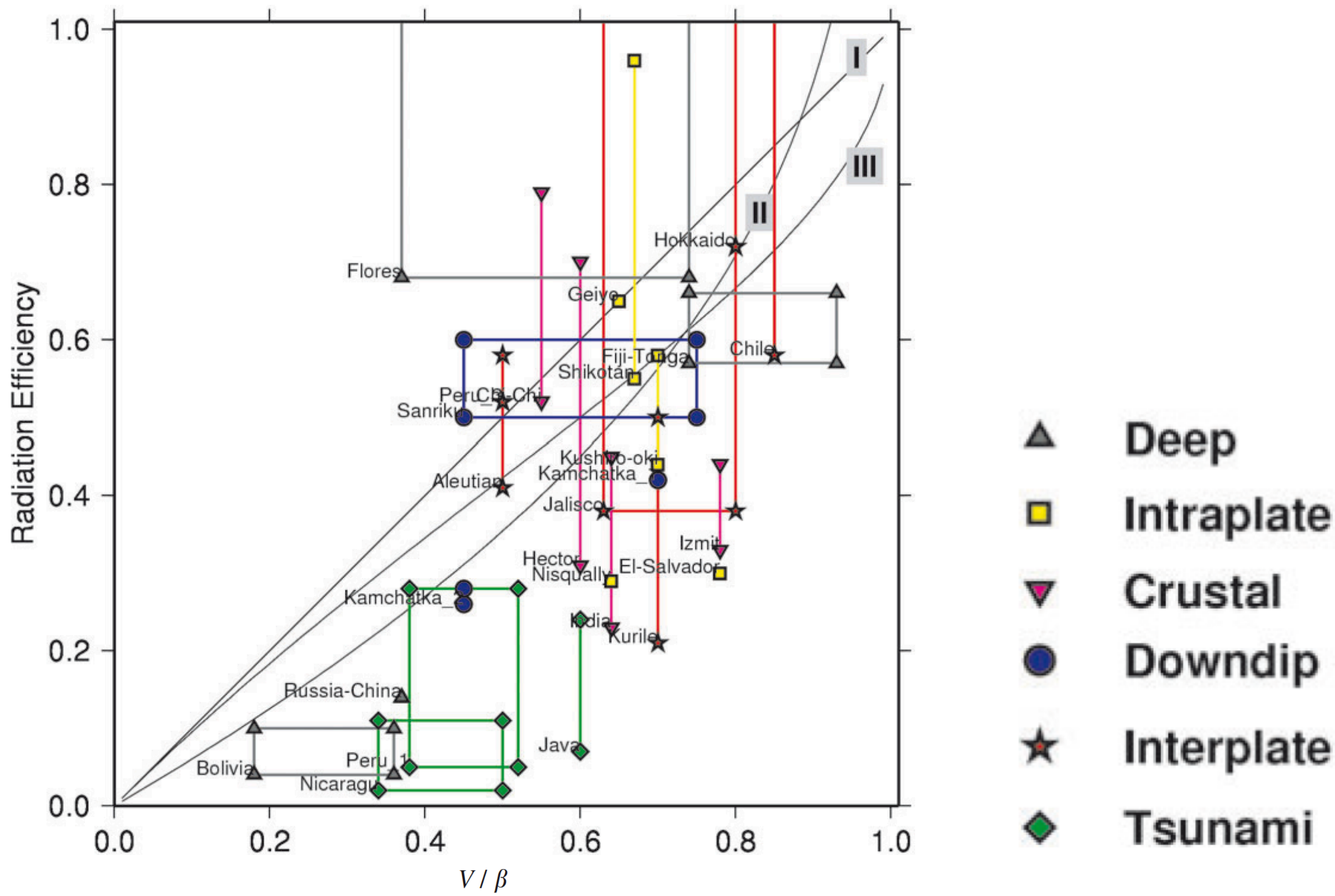
Fulton et al. 2014

Courtesy TO Observatory, Caltech

Tohoku earthquake (Mw=9.0, Japan, March 11th 2011):
Largest co-seismic slip ever observed

MOTIVATION

Radiation efficiency vs. Rupture speed



Venkataraman and Kanamori, 2004

Outline

- EQs in the lab.
- Fracture energy (breakdown work)
- Heat generation
- Radiation and rupture speed

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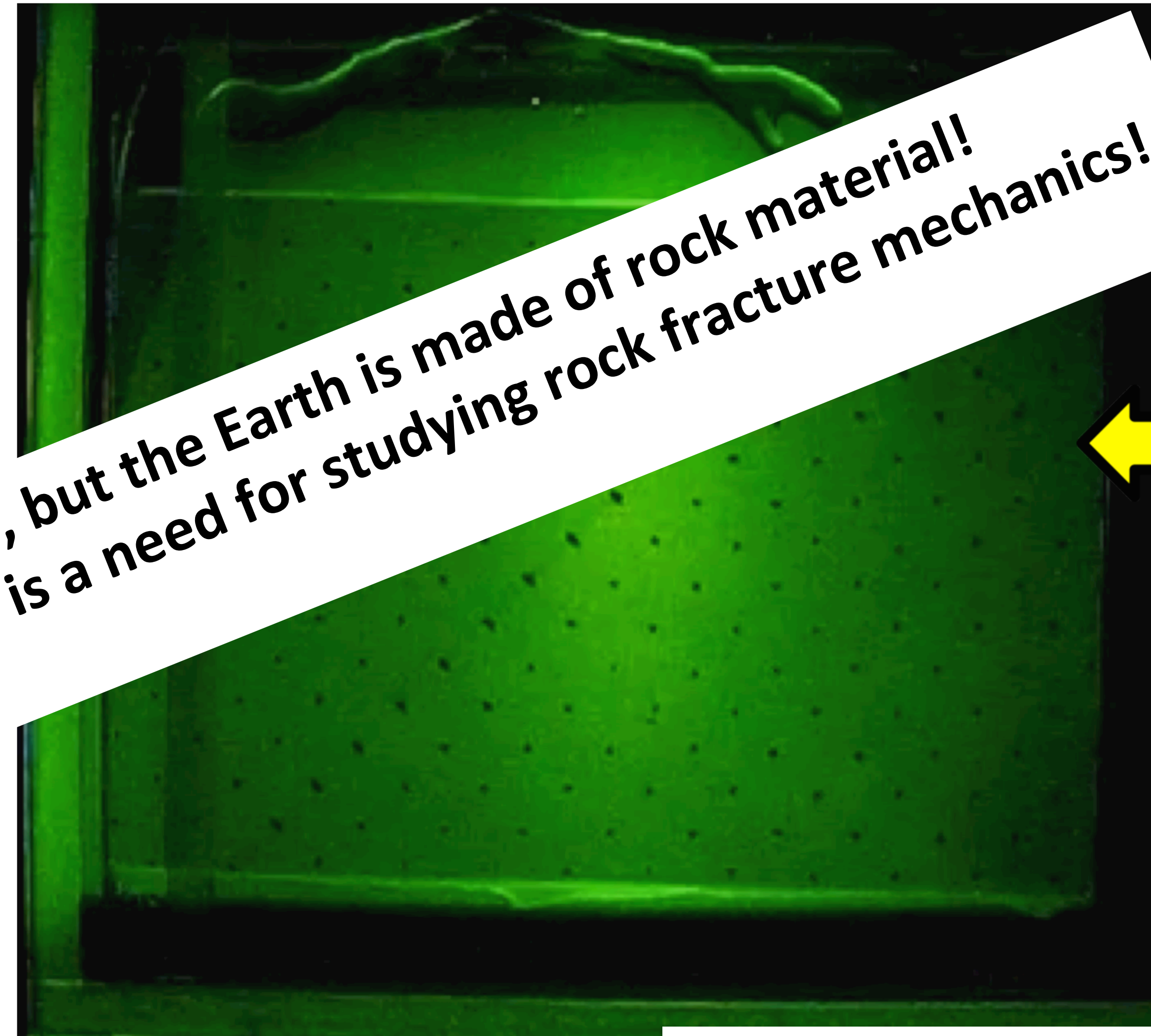
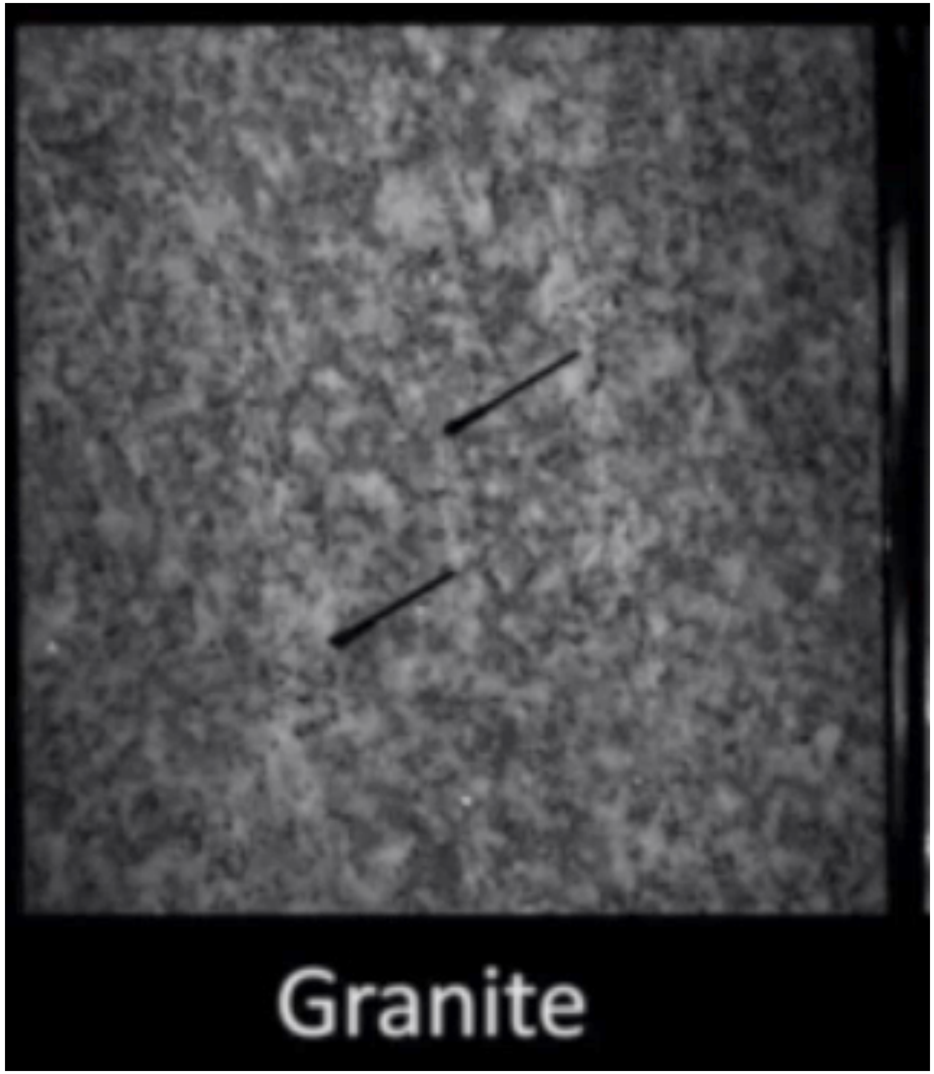
LABORATORY EARTHQUAKES



Yes, but the Earth is made of rock material!
So there is a need for studying rock fracture mechanics!

Courtesy from Osamu Kuwano, ERI

Unconfined Rock failure of granite



Reproducing crustal depth in the lab

Theodore von Kármán
1881- 1963

The first triaxial Rig (*1910*)

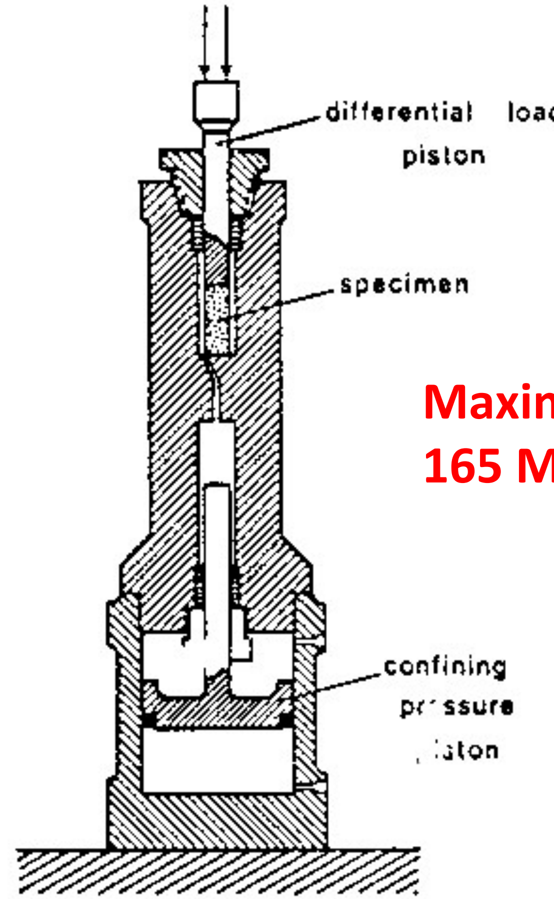
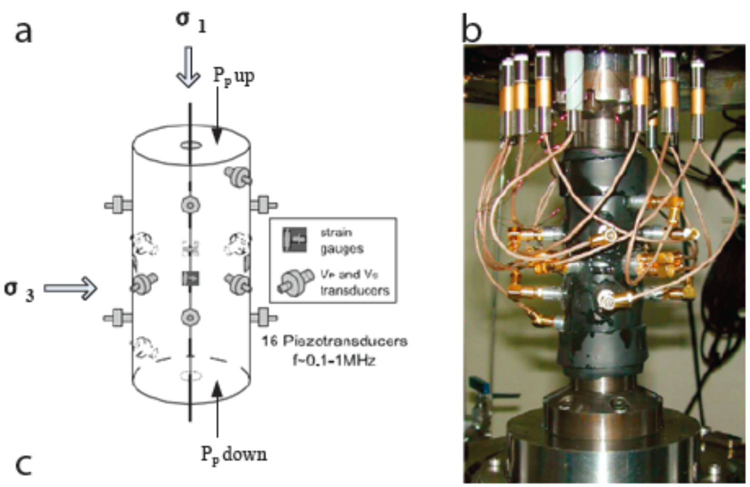
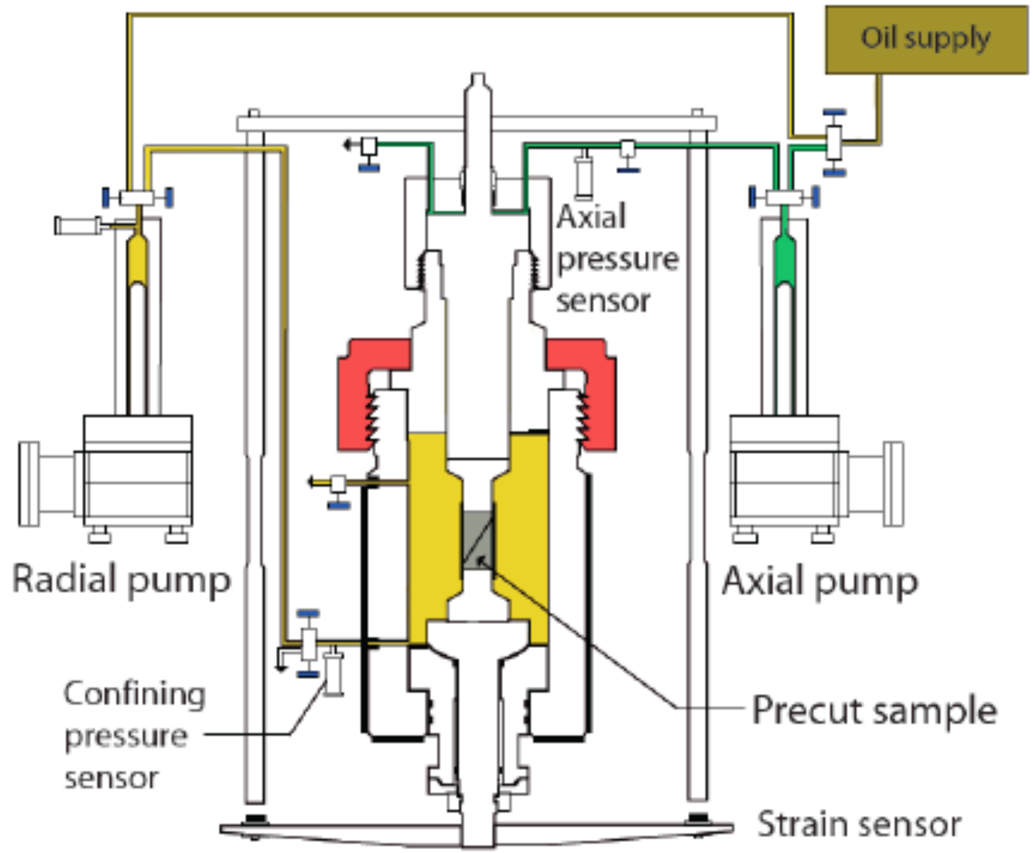


Fig. 3. Triaxial testing apparatus of von Kármán (1911), slightly simplified

Reproducing crustal depth in the lab

Triaxial apparatus - 100MPa/200°C





Scheme of the triaxial apparatus of the ENS

- Designed specially for acoustics
- Corrosive fluids injection (pH<3) in gas, water or supercritical phase
- Up to 100MPa confinement and pore pressure, 70 tons axial load

Stick-Slip as a Mechanism for Earthquakes

W. F. Brace; J. D. Byerlee

Science, New Series, Vol. 153, No. 3739. (Aug. 26, 1966), pp. 990-992.

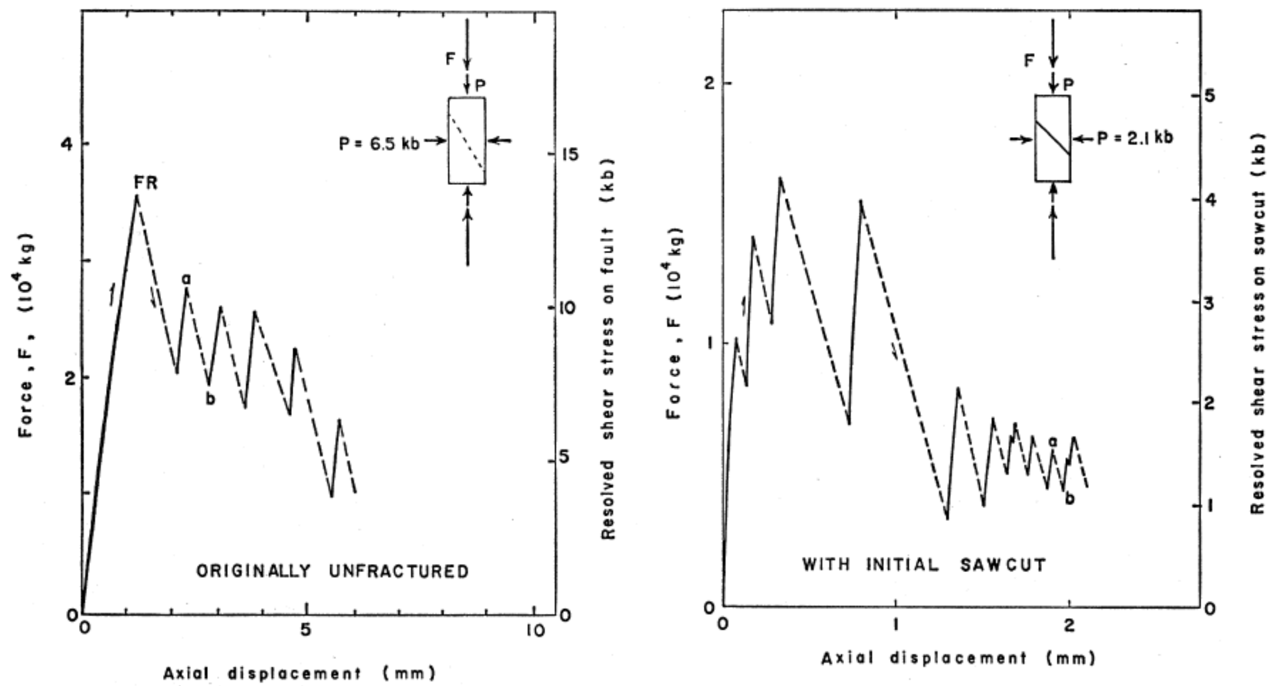
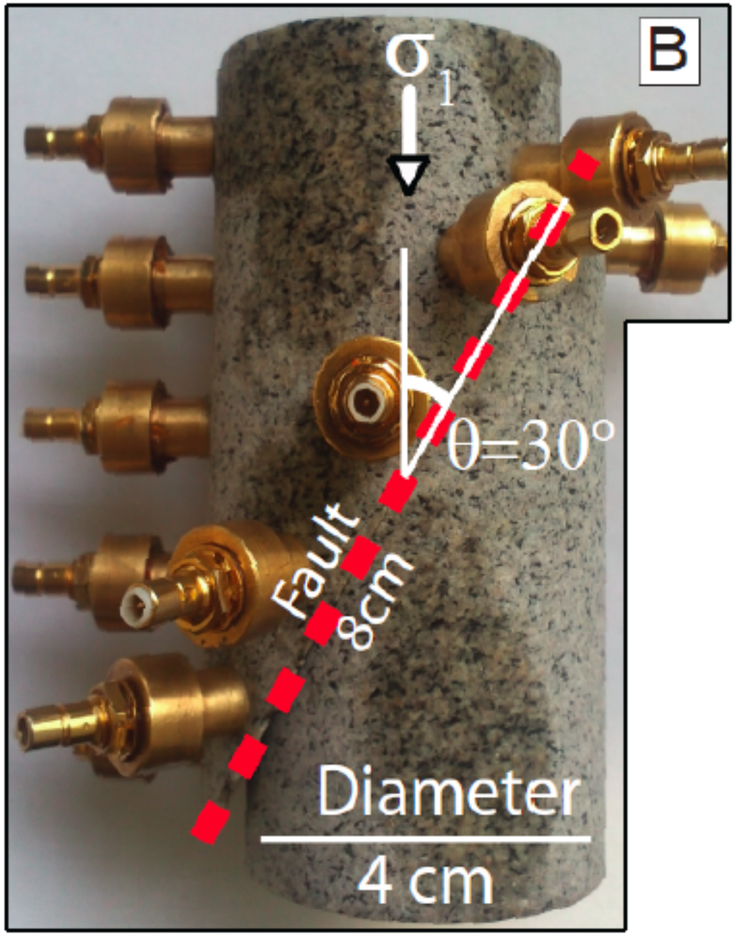
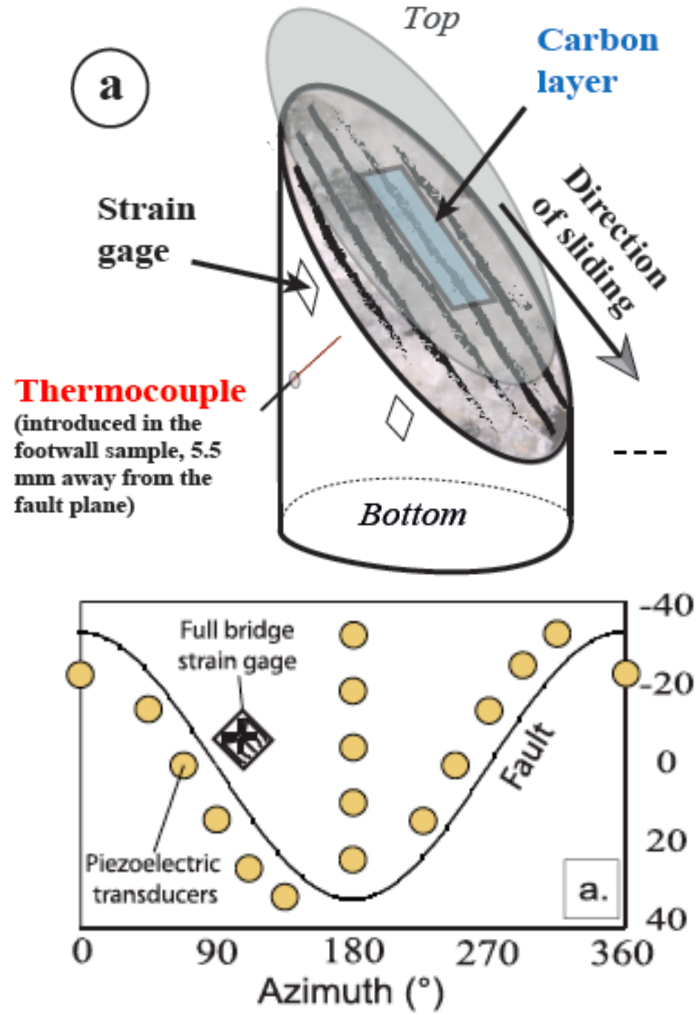


Fig. 1 (left). Force-displacement curve for the axial direction in a cylindrical sample of Westerly granite. Small diagram above the curve shows schematically how stress was applied to the sample. The sample fractured at point *FR* forming the fault which is shown as a dotted line in the small diagram. The exact shape of the curves during a stress drop (such as *ab*) is not known and is shown dotted. *P* is confining pressure. Fig. 2 (right). Same as Fig. 1 except that the sample contained a sawcut with finely ground surfaces as shown schematically (small figure) by a heavy line.

Stick-Slip in rocks (exp. set-up)

Saw cut Westerly granite – strain rates: 1-10 μm/s





Foreshocks and off-fault damage: FF AE Sensors

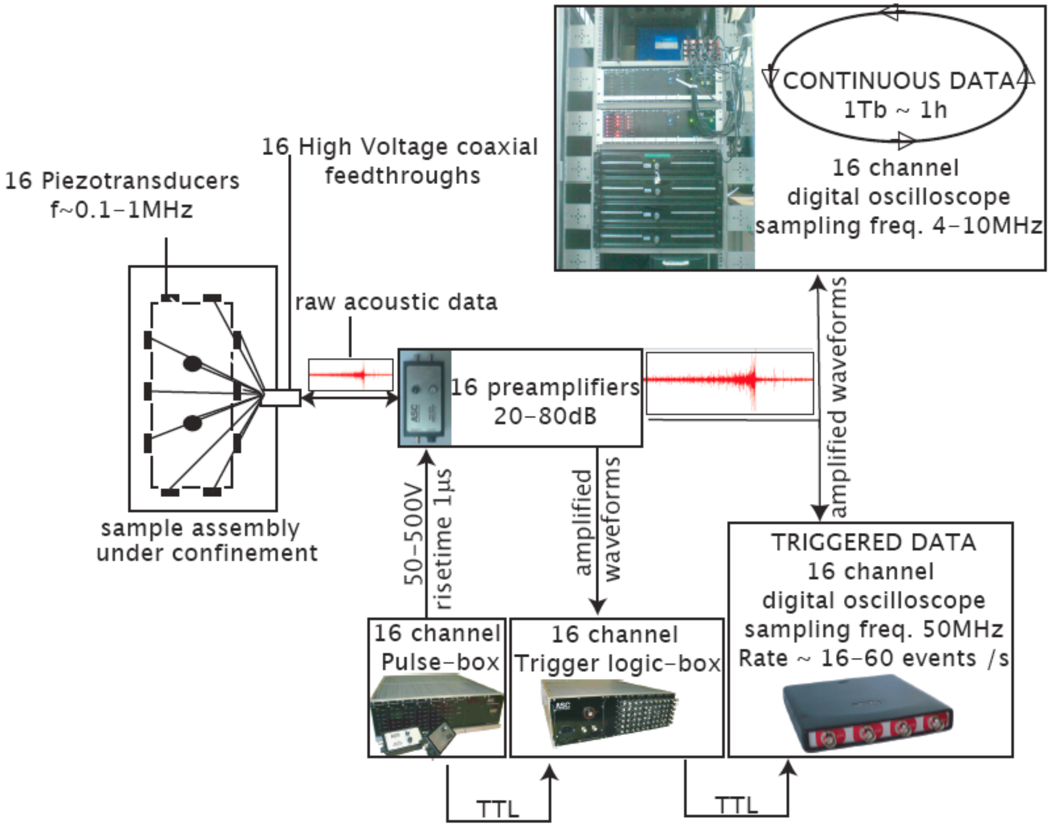
Rupture speed: NF AE sensors

Fracture energy: Dyn. Strain gage

Heat: Thermocouple and Carbon layer

Recording nano to micro seismicity in the lab

Acoustic Recorder – 16 channels



- Continuous acoustic wfms recorded using Richter minisystem (ASC Ltd., 4 MHz sampling freq. on 16 channels)
- Triggered data - up to 16 events/ sec
- Each transducer can be used as source for velocity measures (P&S)

Outline

- EQs in the lab.
- Fracture energy (breakdown work)
- Heat generation
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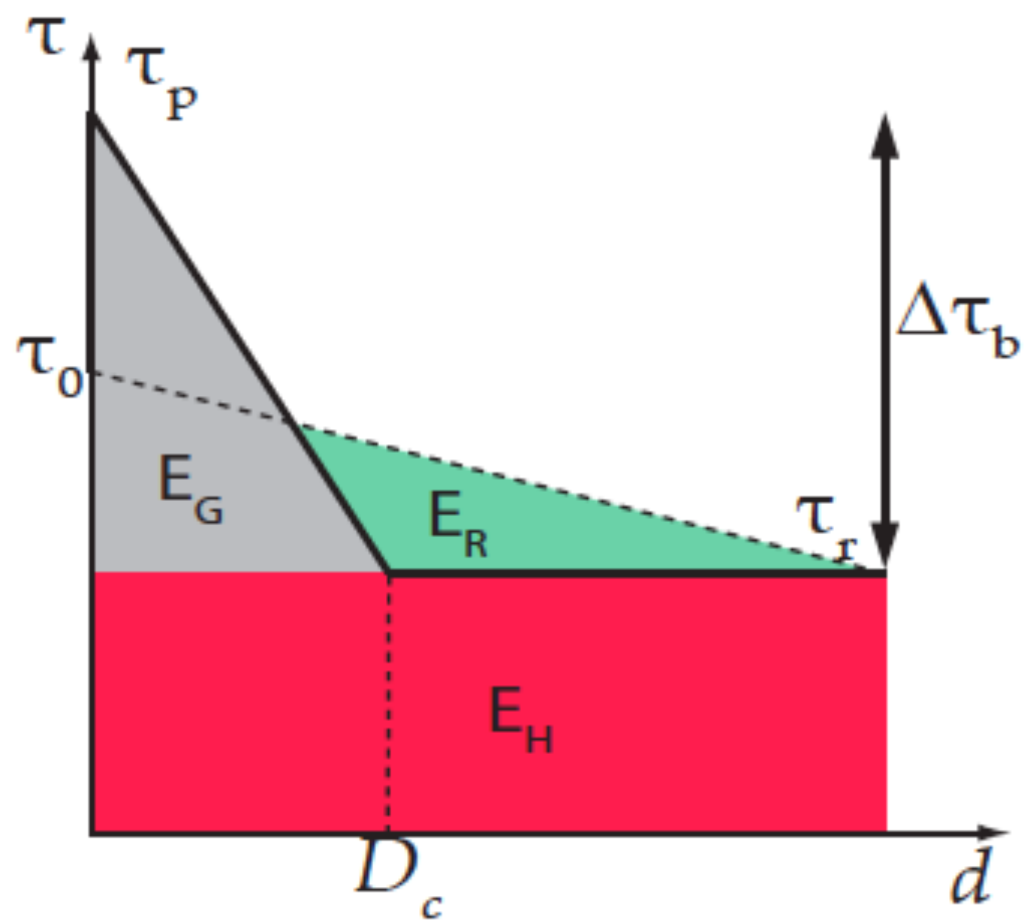
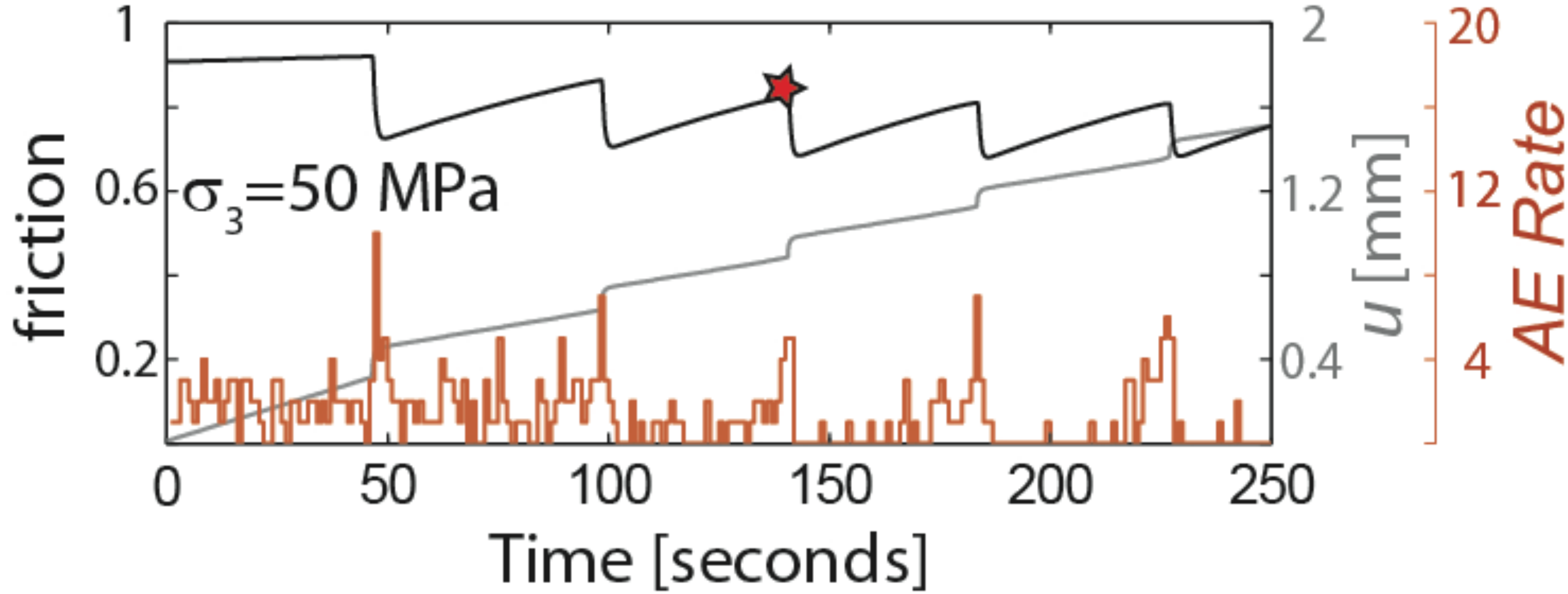
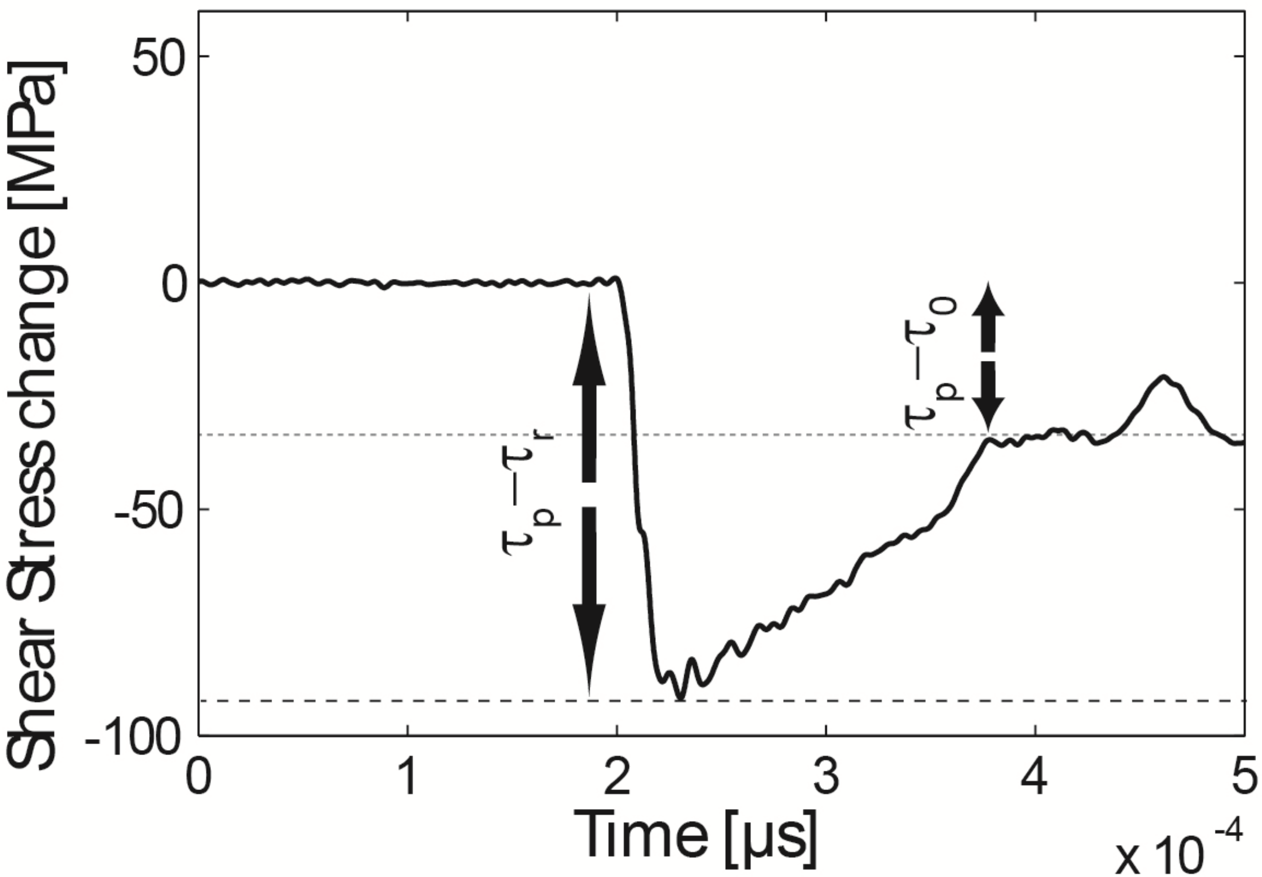
Energy partitioning during EQs



Stick-Slip motion



Static vs. dynamic stress drops



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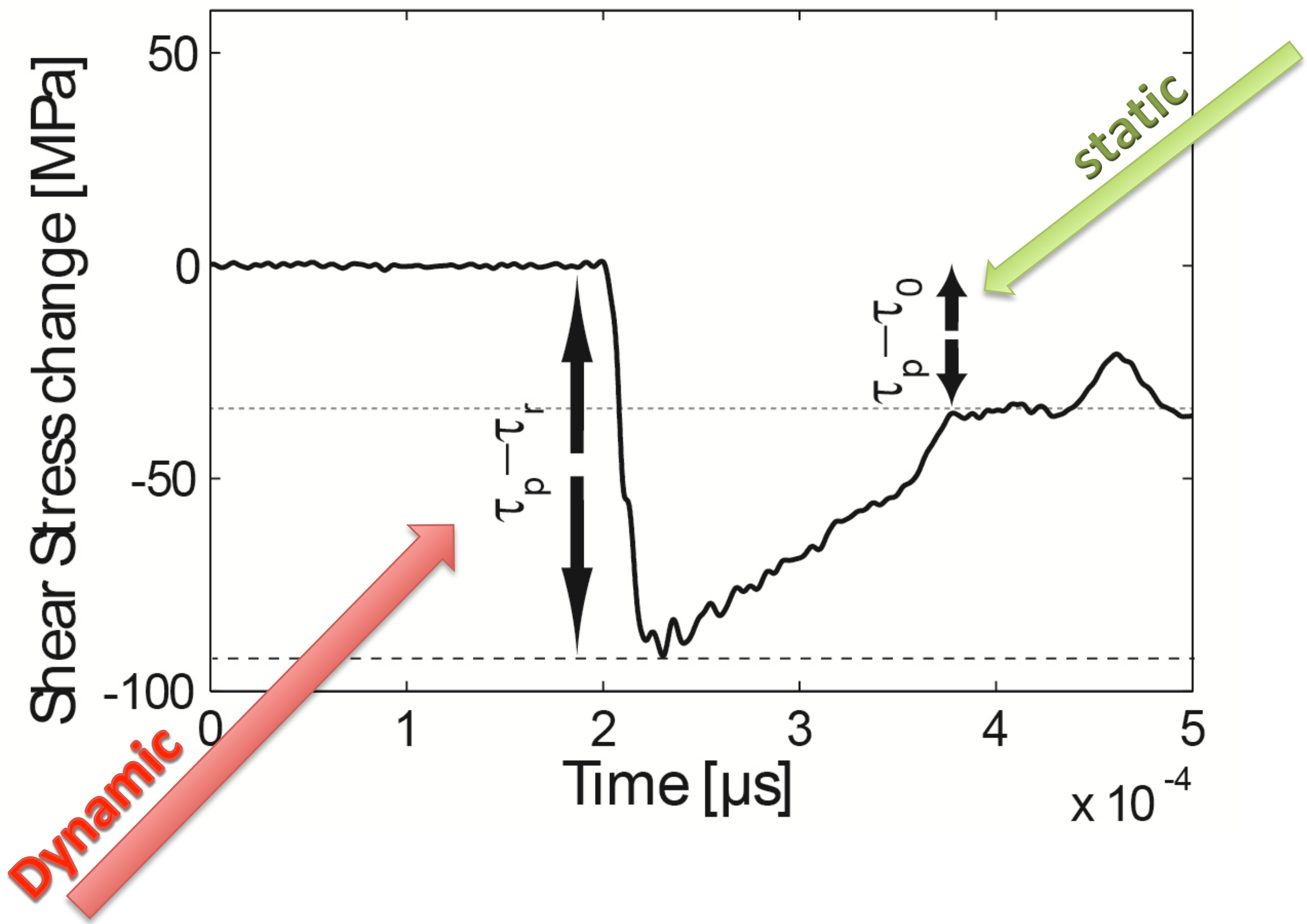
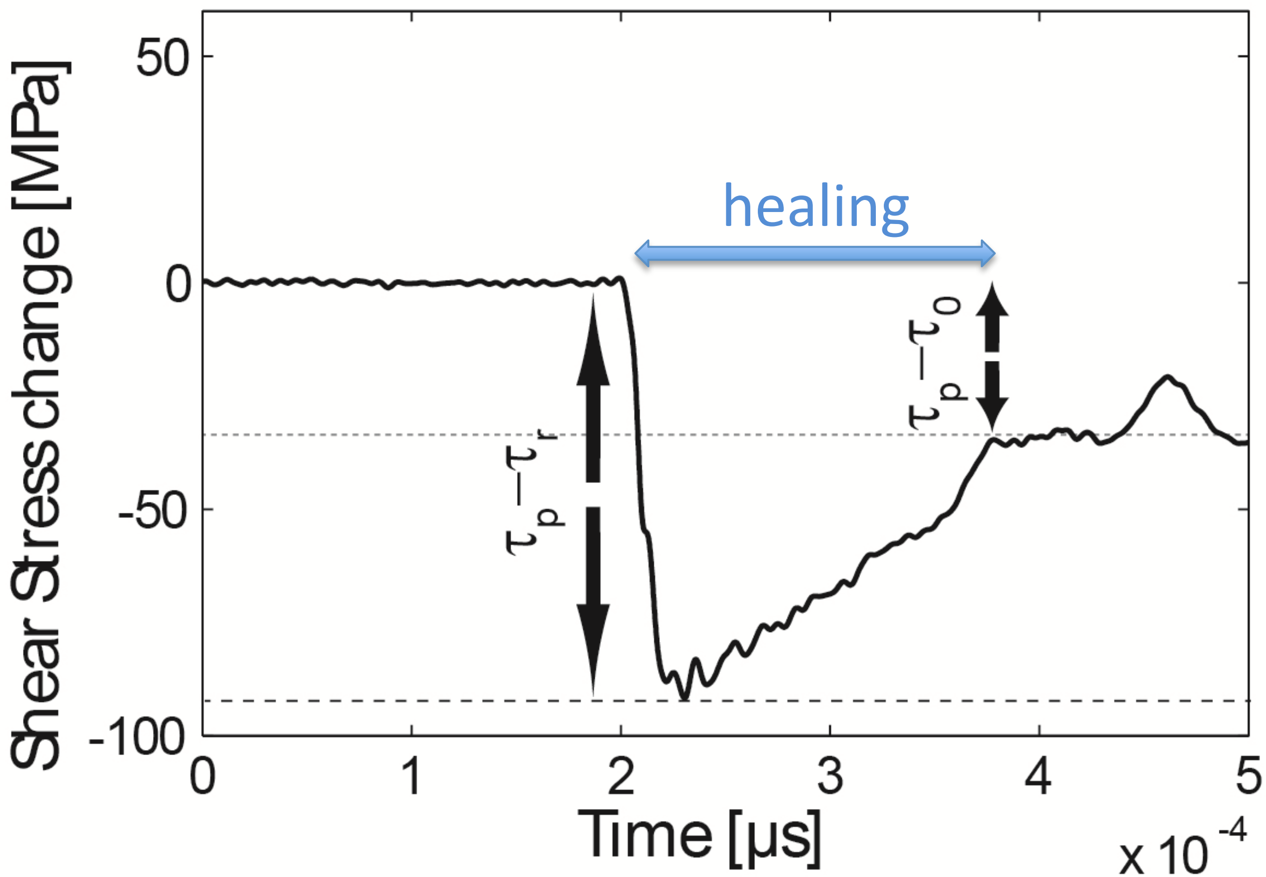


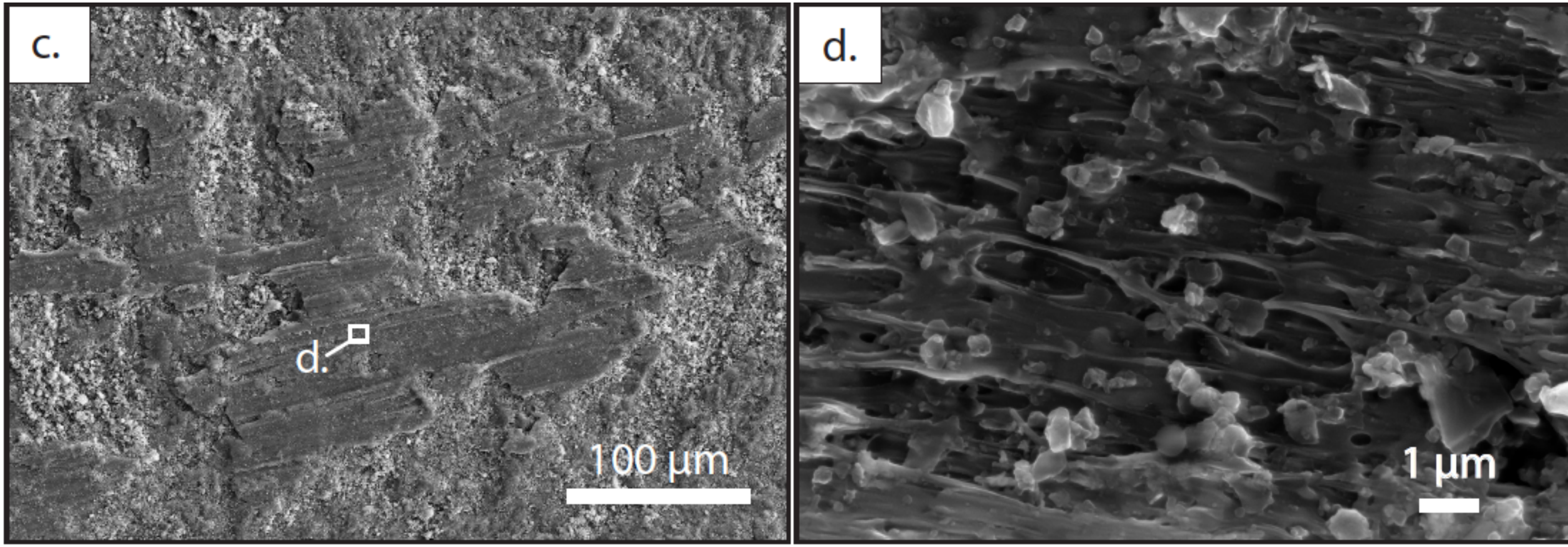
Static vs. dynamic stress drops



Static vs. dynamic stress drops

Molten asperity on fault surface

Westerly granite, Pc=70MPa



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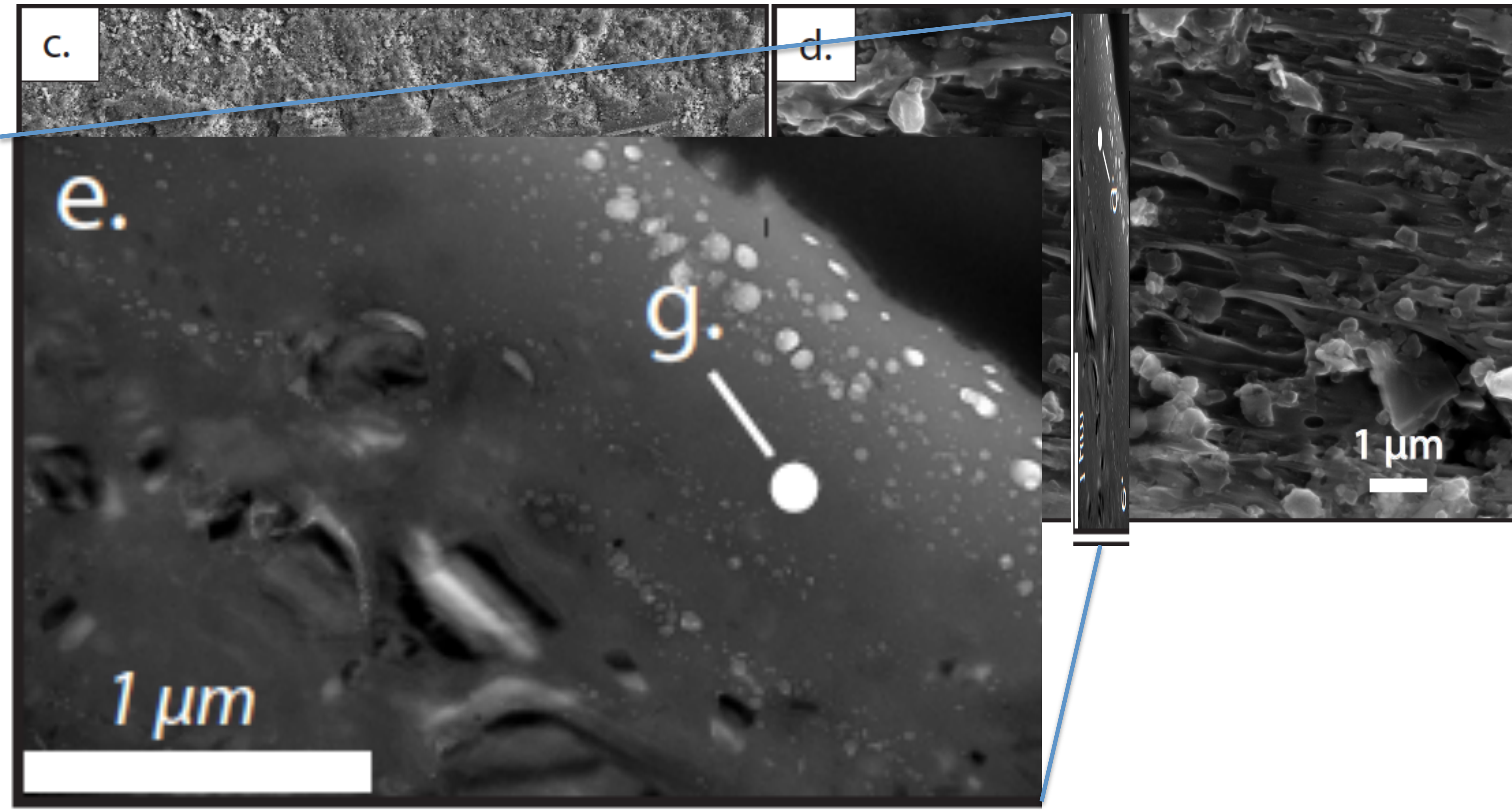

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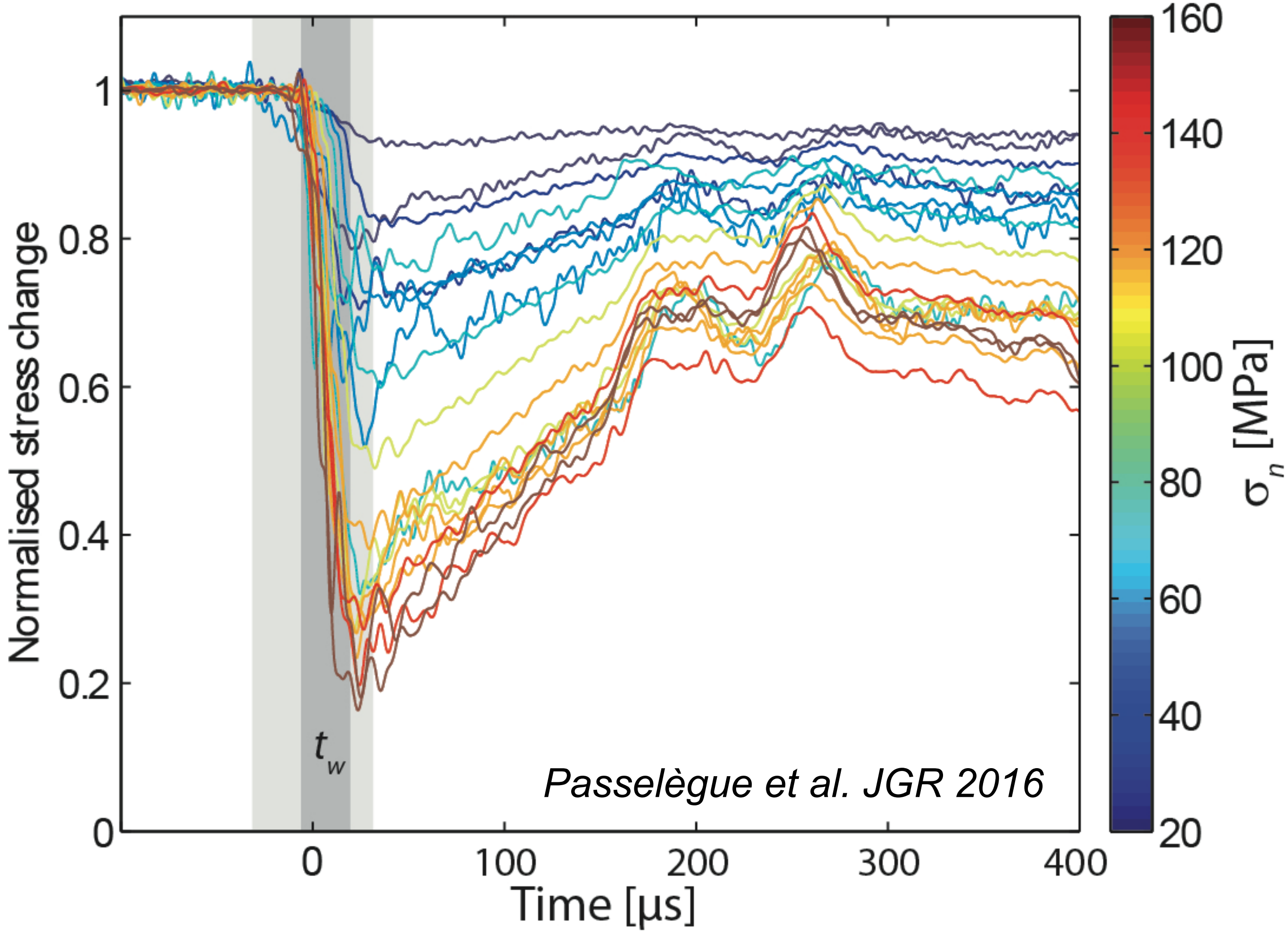
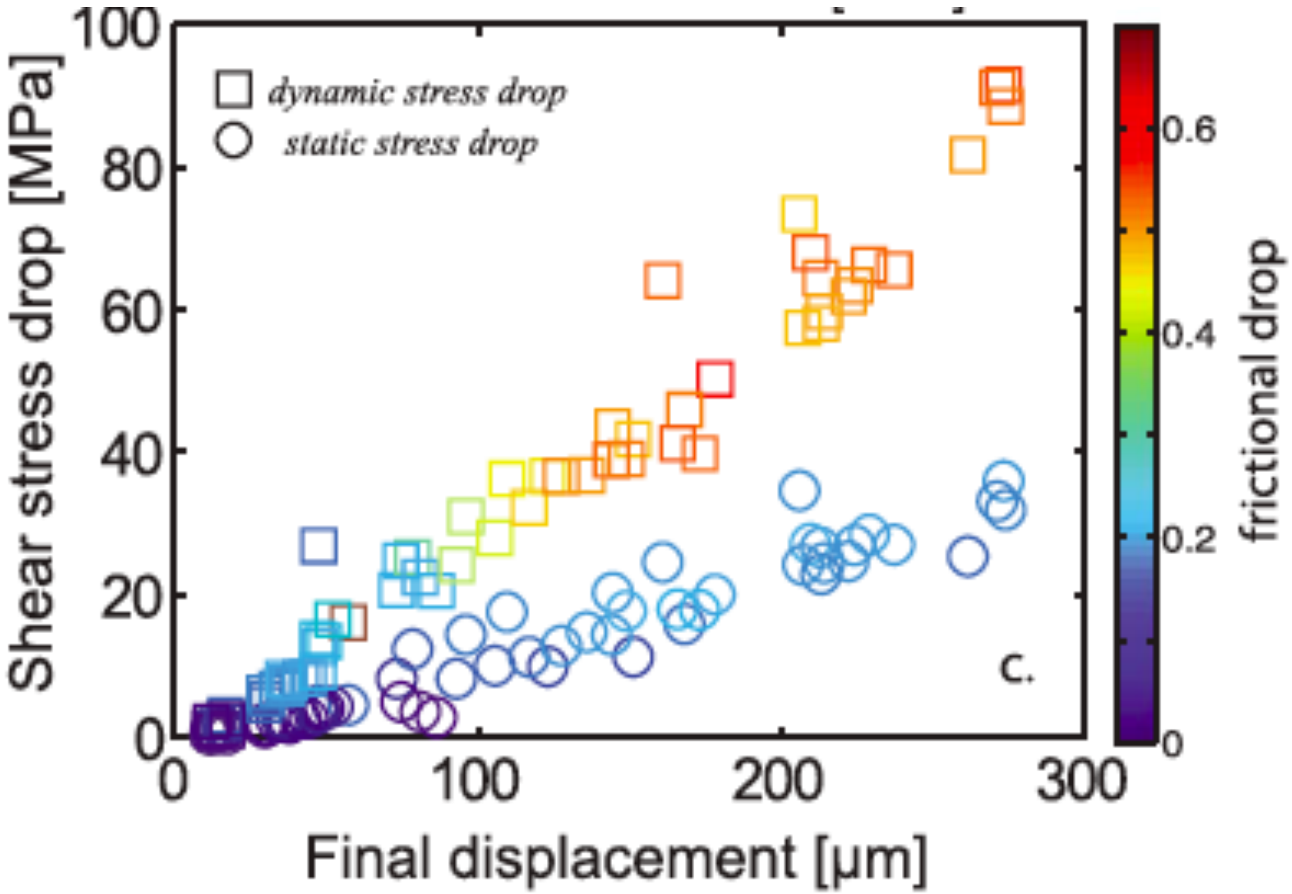
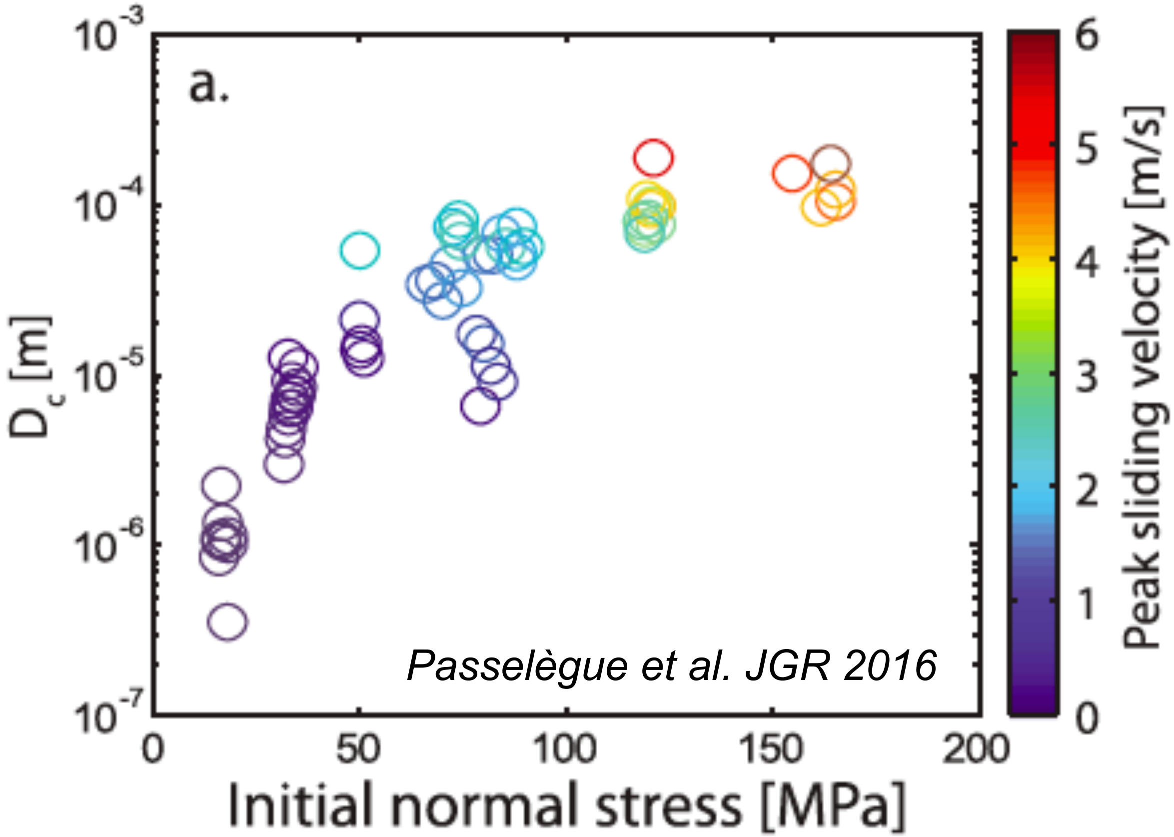


Static vs. dynamic stress drops

Passelègue et al. JGR 2016

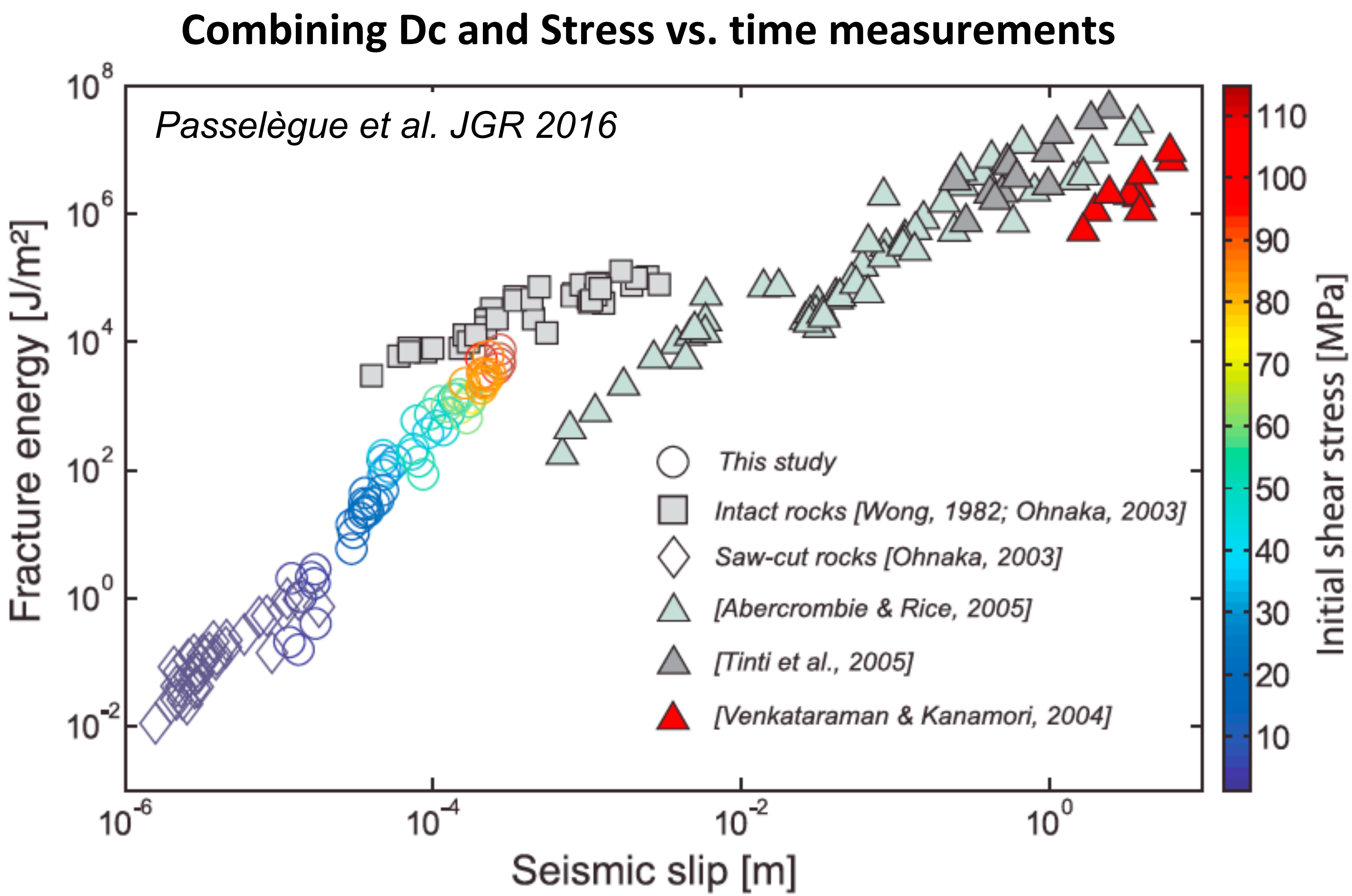


Measuring (+/-) Dc



With Ida, 1972 : $$D_c = \frac{16(1-\nu)}{9\pi} \frac{V_r t_c \sigma_n (f_s - f_d)}{\mu}$$

Fracture energy



G scales with displacement, also in the lab!

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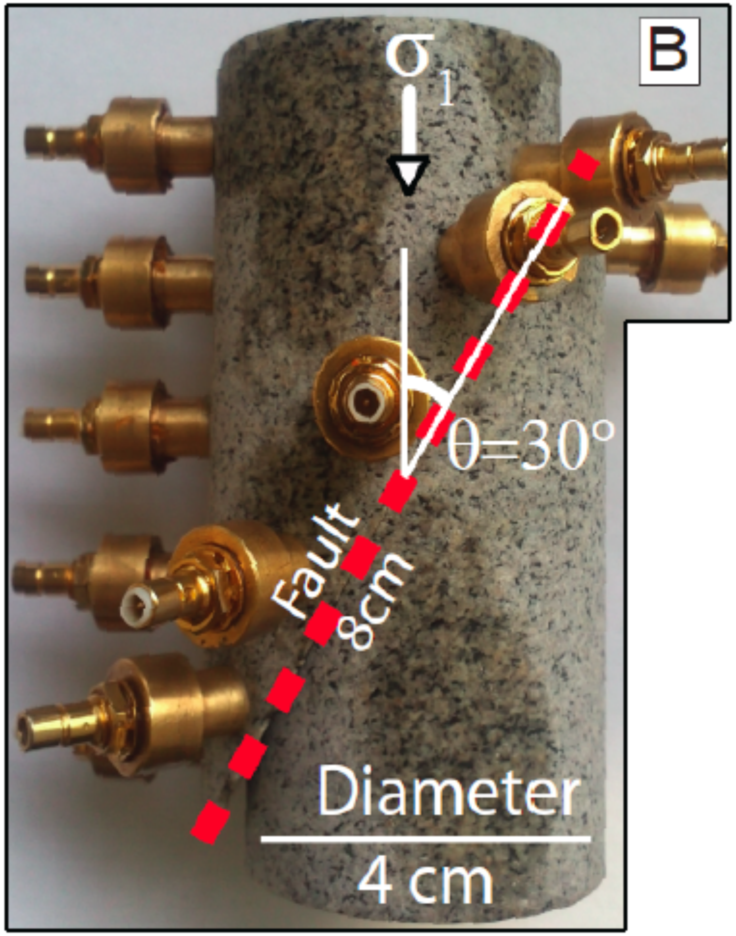
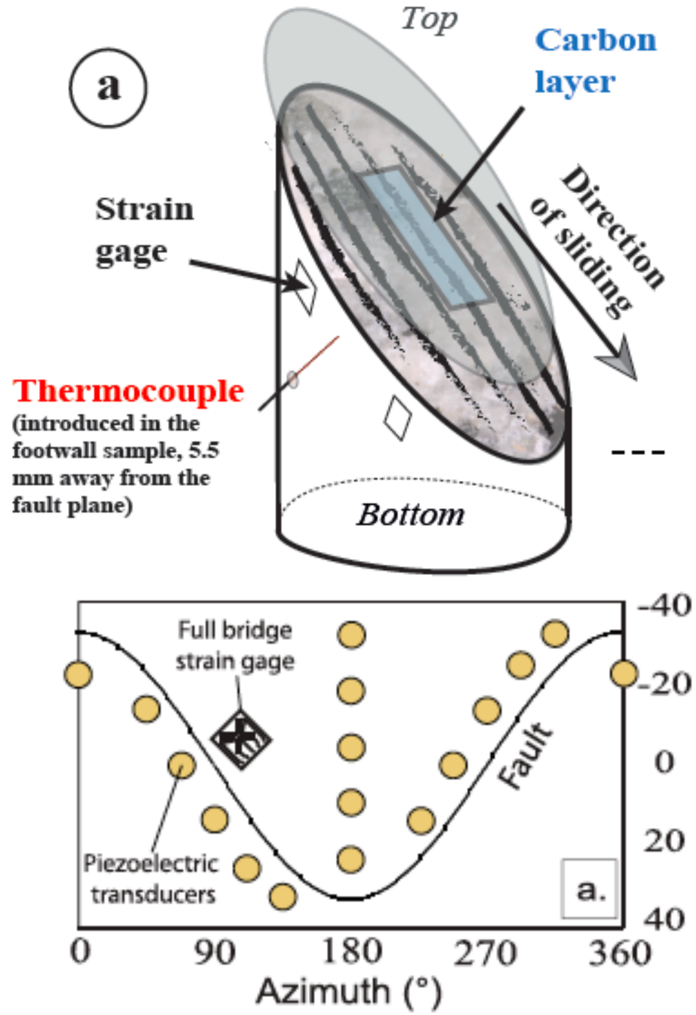




Foreshocks and off-fault damage: FF AE Sensors

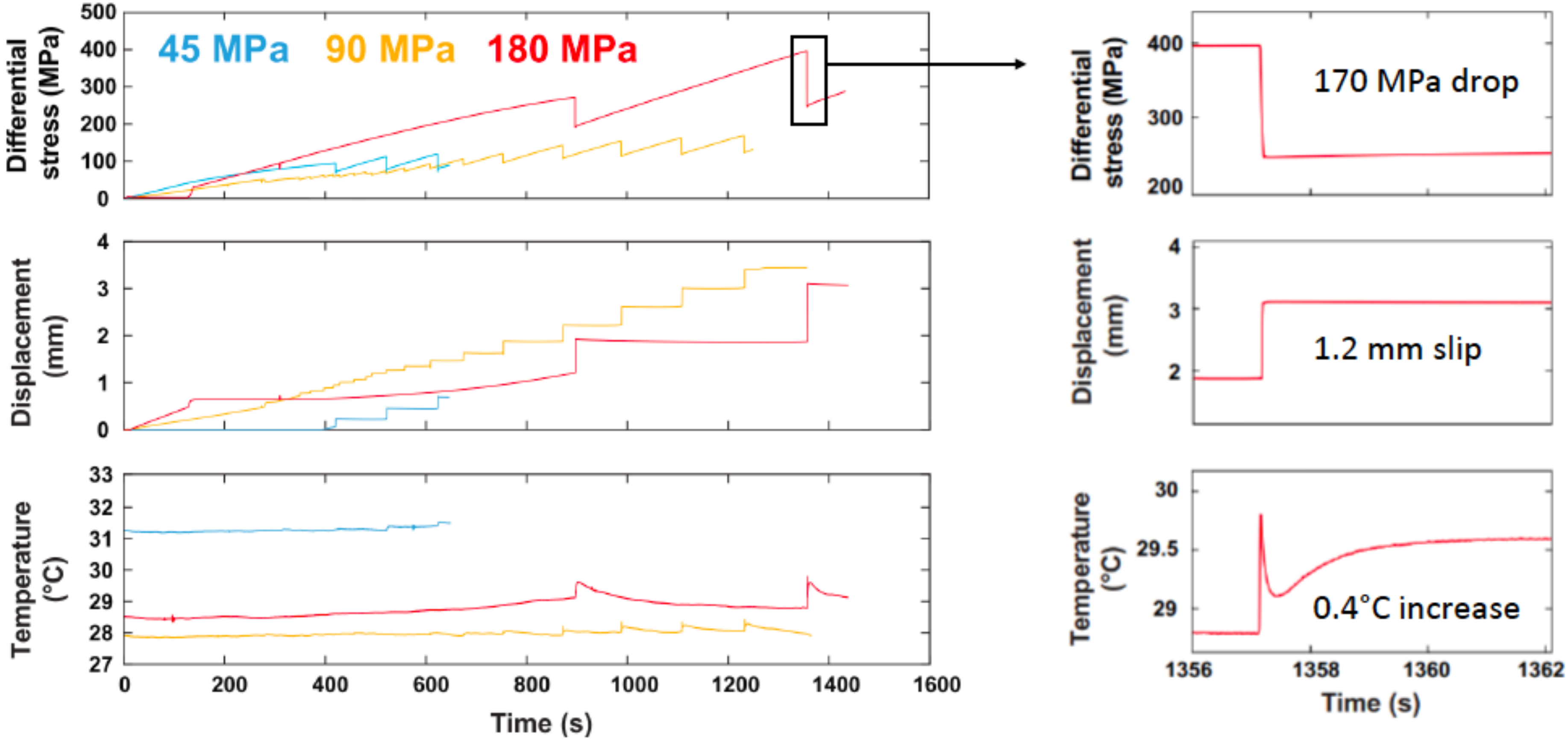
Rupture speed: NF AE sensors

Fracture energy: Dyn. Strain gage

Heat: Thermocouple and Carbon layer

Measuring Heat

Aubry et al. Sub.

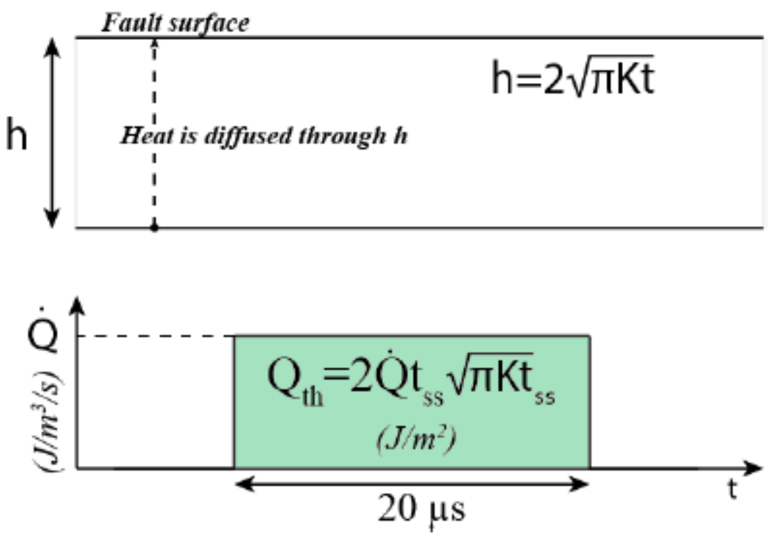


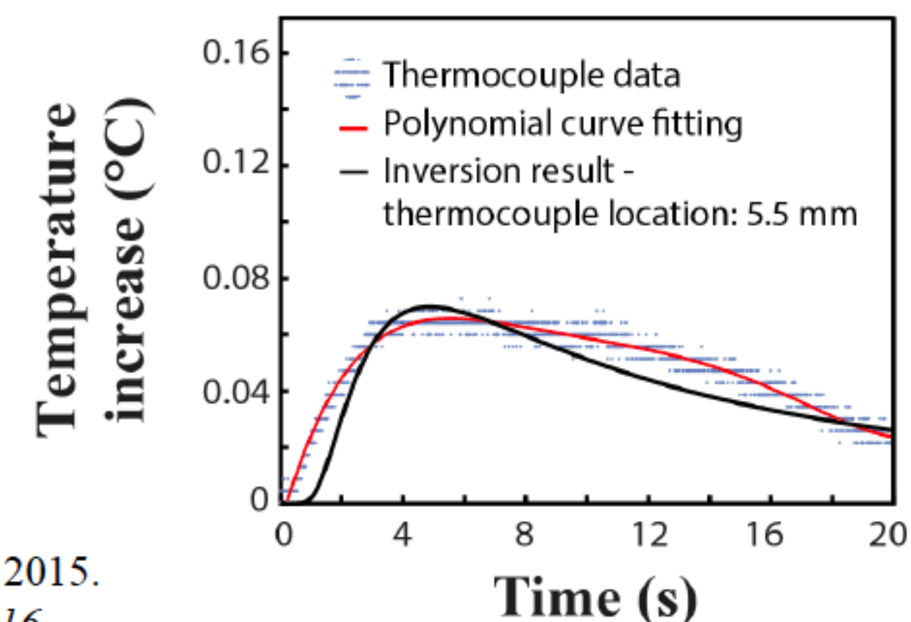
Measuring Heat

Heat diffusion model - Thermocouple data inversion

- Constant heat rate during stick slip duration $t_{ss} = 20\ \mu s$
- Heat produced on the fault and diffused within the sample

$$\rho C_p h \frac{dT_{th}}{dt} = \dot{Q} + K\frac{d^2Tth}{dy^2}$$

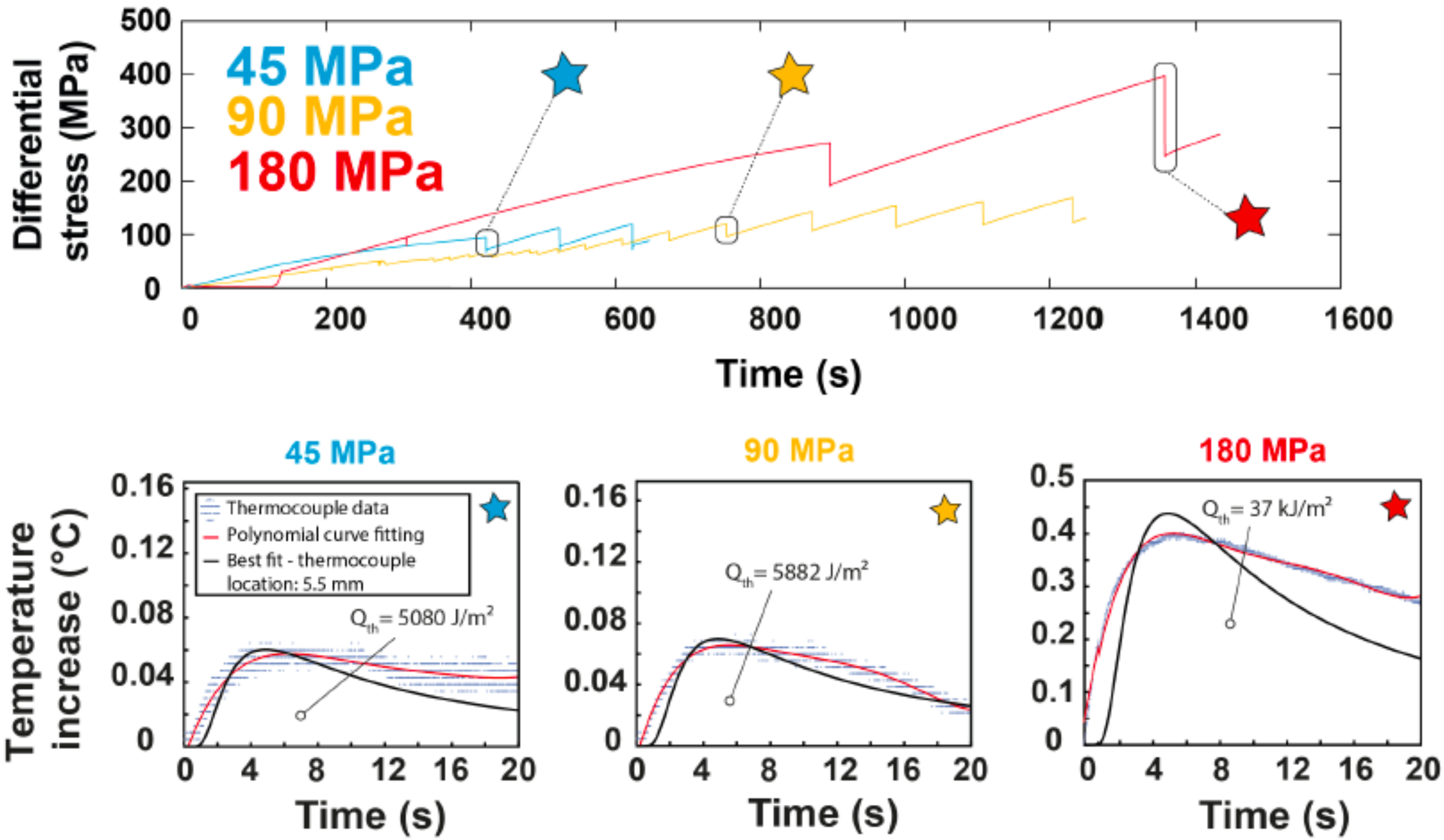




Thermal diffusivity K = $1.2e^{-6}\ m^2/s$; *Lockner et al.*, 2015.
Stick slip duration t_{ss} = $20\ \mu s$; *Passelègue et al., 2016.*

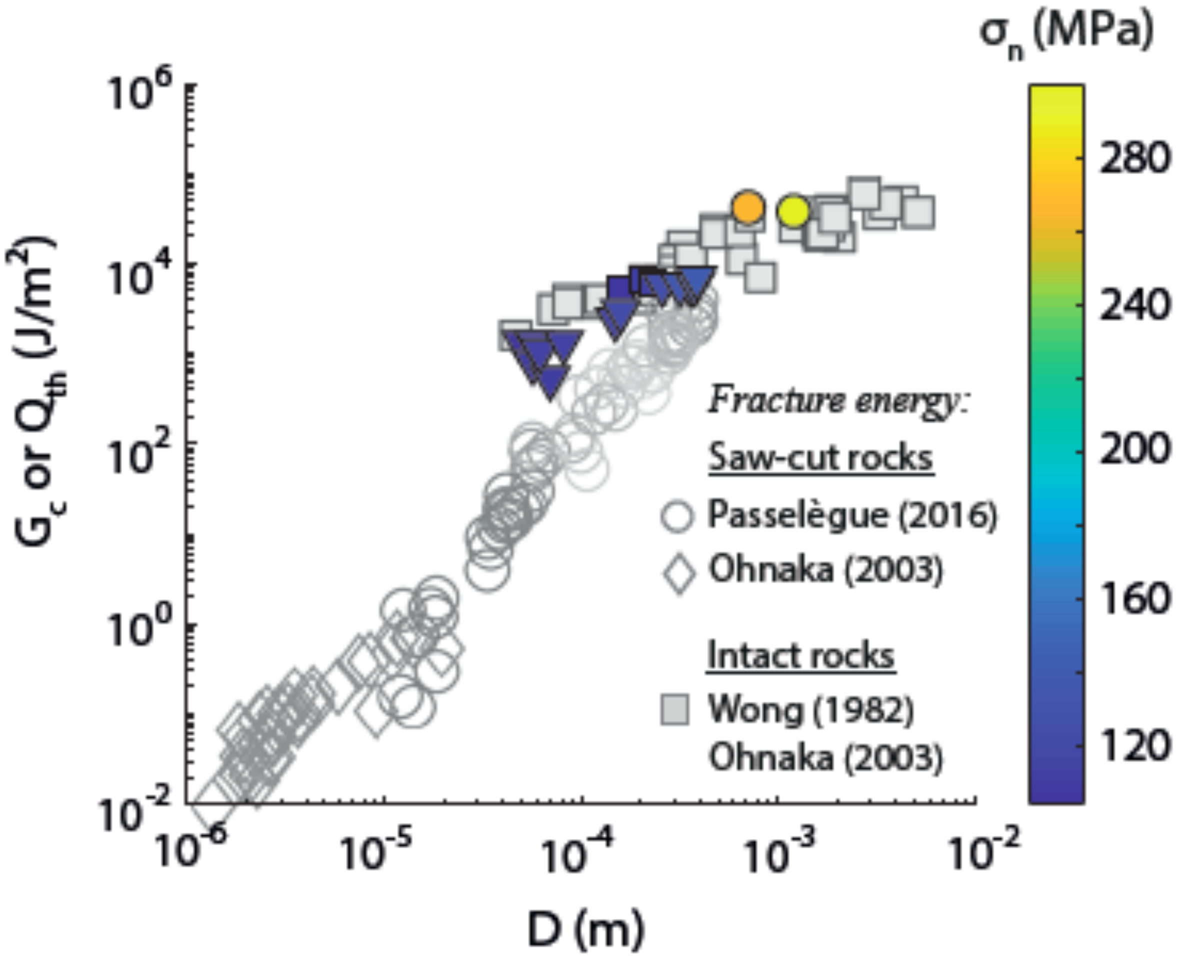
Measuring Heat

Frictional heat produced inferred from thermocouple



Fracture energy vs. Heat

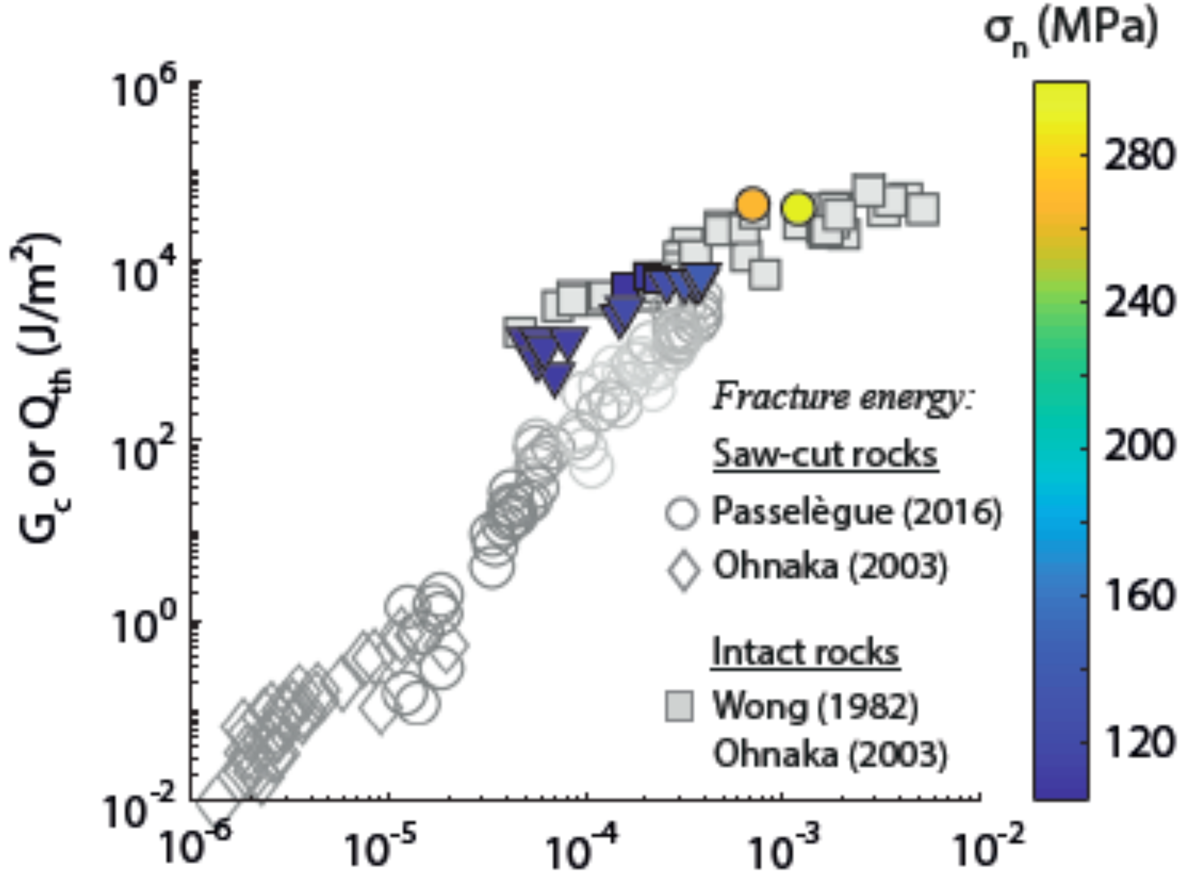
from two independent measurements!



H>>G for small slips (small stress drops)
but comparable at larger slip (large stress drops)

Fracture energy vs. Heat

from two independent measurements!

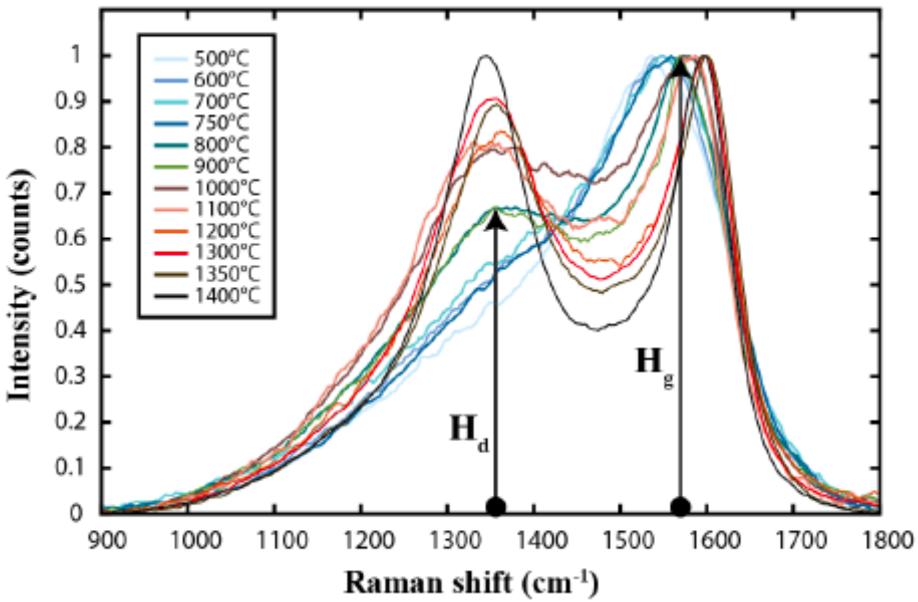


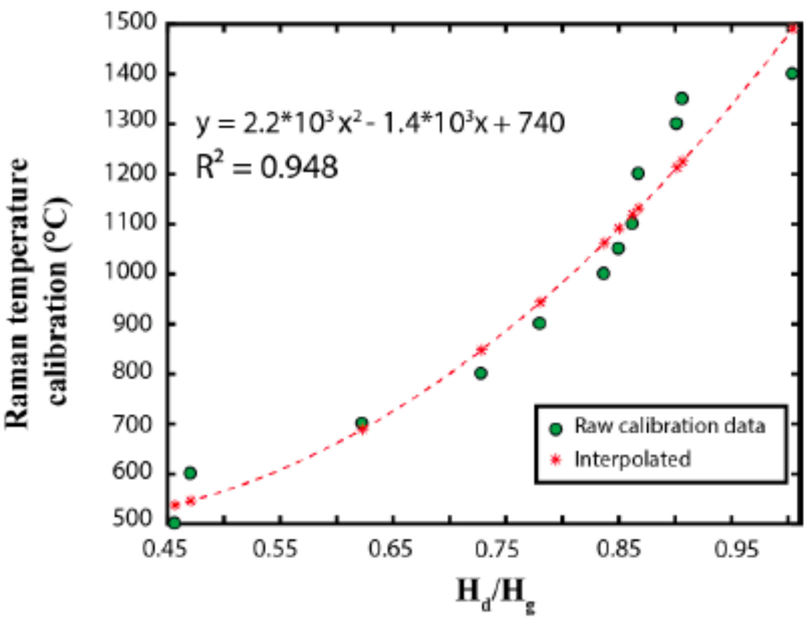
At large slips, Fracture energy (breakdown work) is dissipated into Heat (weakening is thermal)

Heat dissipation…

Mapping the interface by the help of amorphous carbon

Calibration made with **specific coated samples** (other than these for experiments) heated in an oven during 10 s.



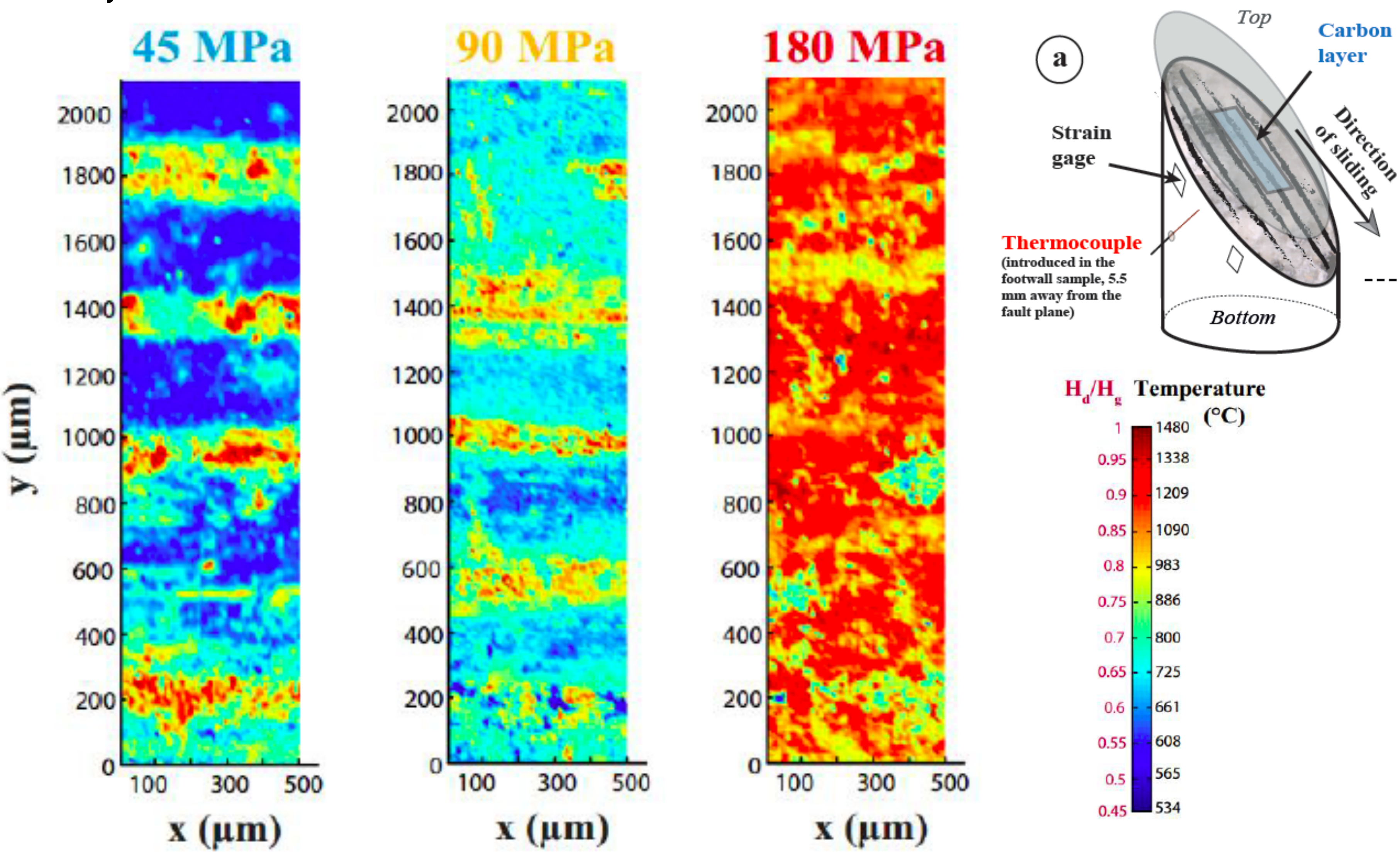


- **The more advanced the process of carbonization and the higher the ratio H_d/H_g.**
- **We are aware of kinetic problem (10 s heating) compared to the duration of stick-slip (20 µs).**

…is heterogeneous

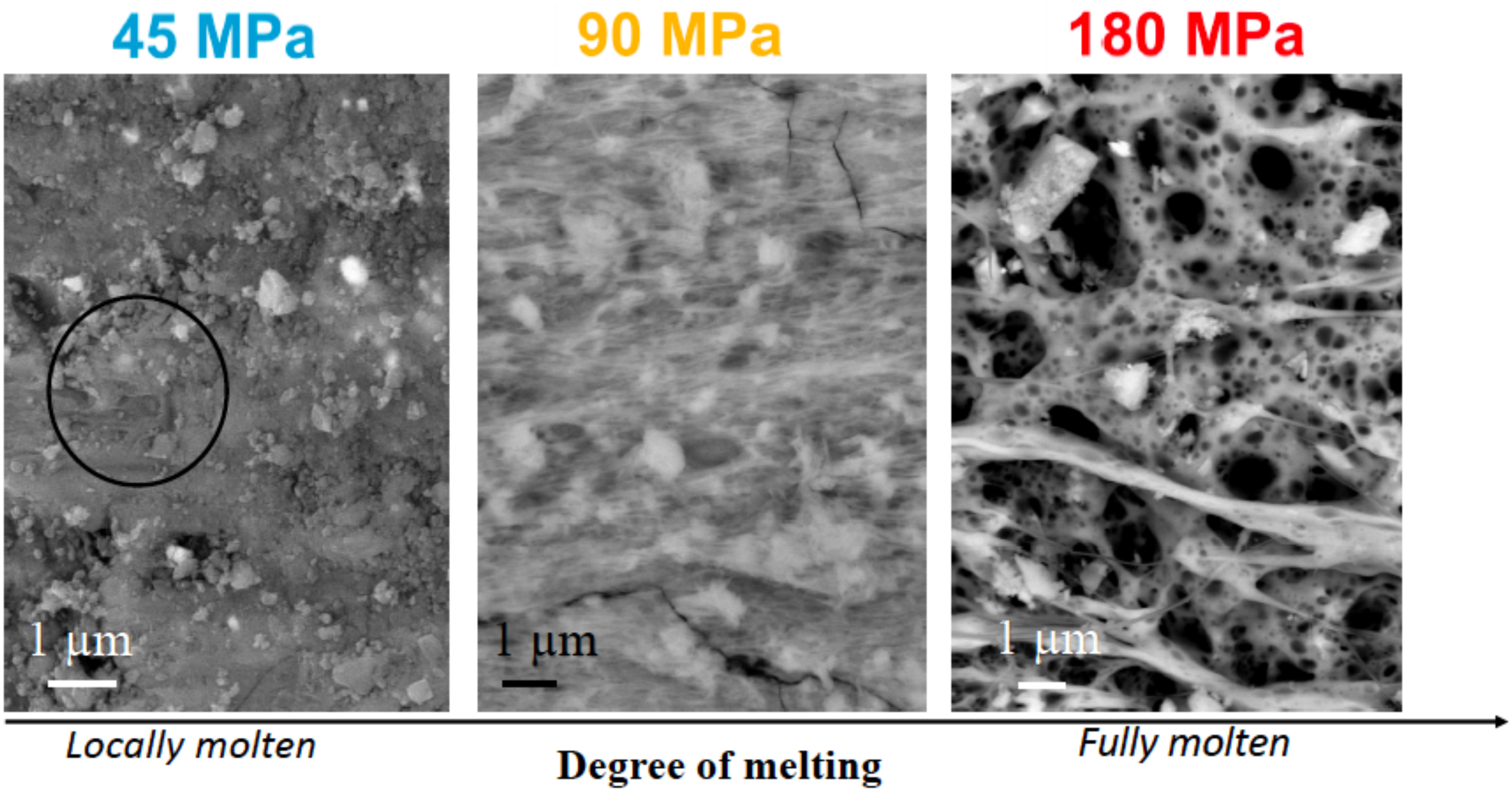
Temperature maps of the interface during frictional sliding

Aubry et al. Sub.



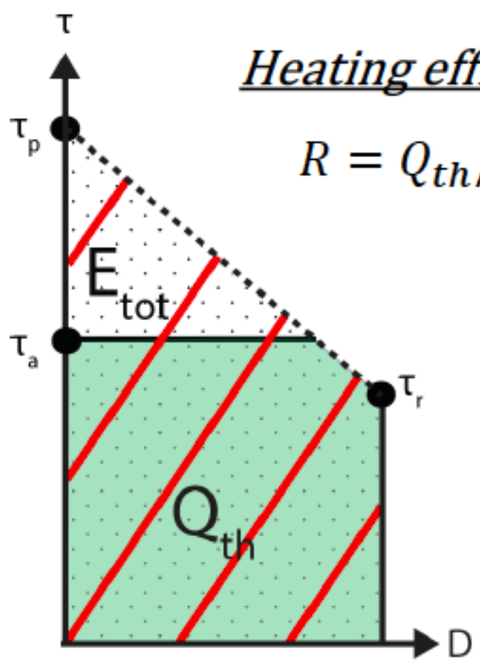
Transition from asperity to bulk surface melting

Microstructural evidences of melting



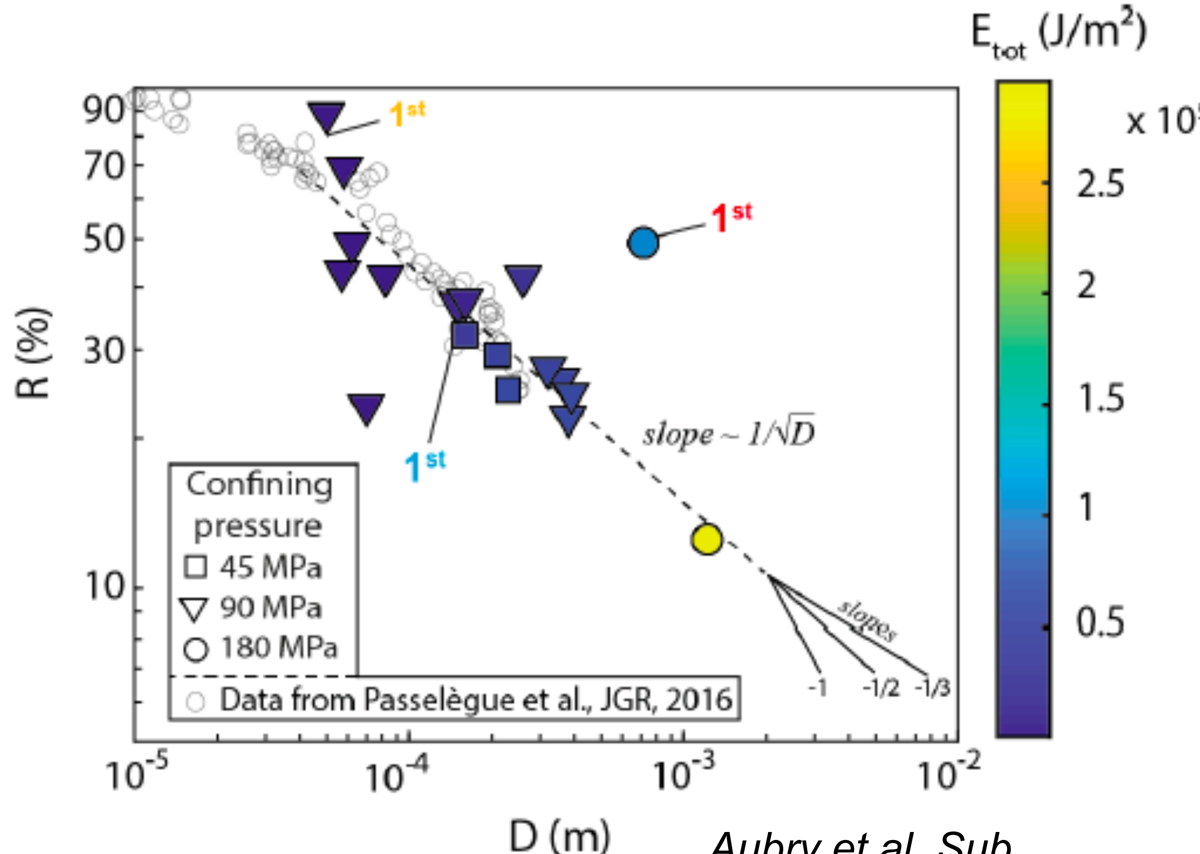
Aubry et al. Sub.

Heating efficiency



Heating efficiency:

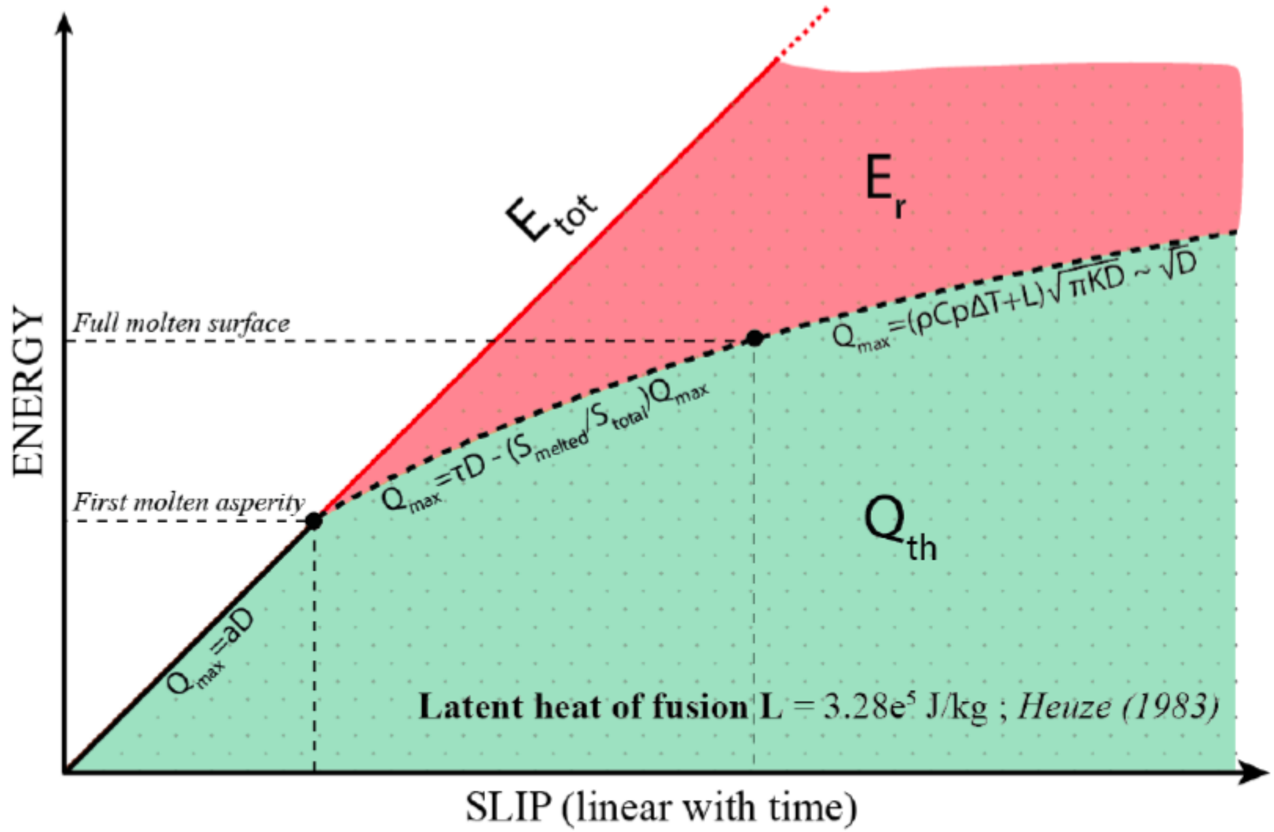
$$R = Q_{th}/E_{tot}$$



Aubry et al. Sub.

When looking at heat, rupture becomes more efficient with increasing sliding

Heating efficiency



Rupture becomes more efficient with increasing sliding
because heat is bounded
by melting (or phase change) temperature and heat diffusion

Outline

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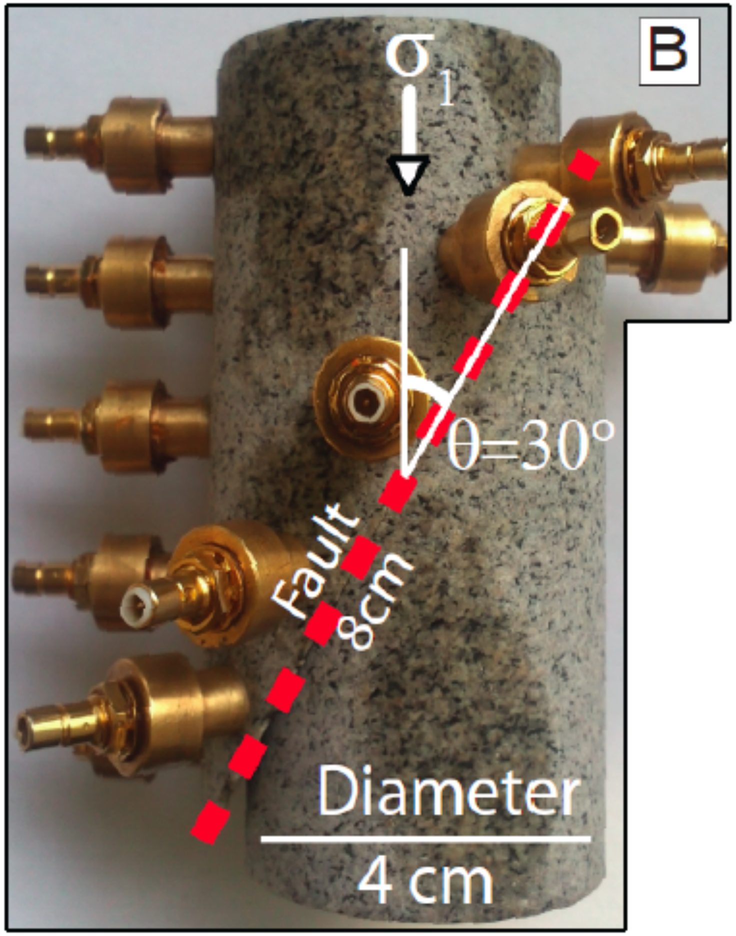
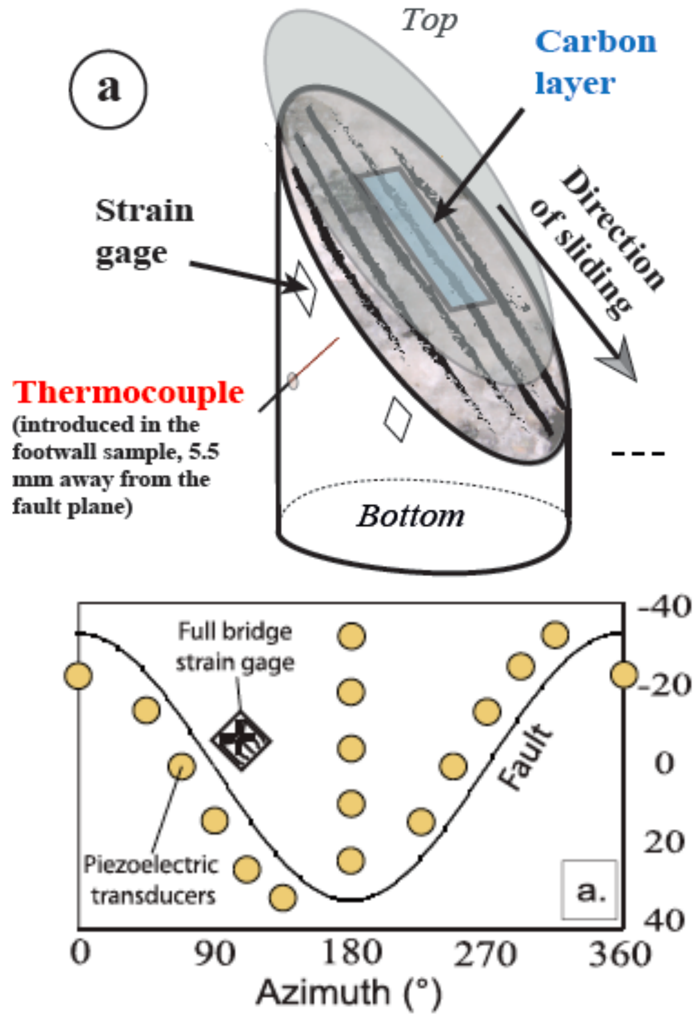
Stick-Slip in rocks (exp. set-up)

Saw cut Westerly granite – strain rates: 1-10 μm/s





Foreshocks and off-fault damage: FF AE Sensors

Rupture speed: NF AE sensors

Fracture energy: Dyn. Strain gage

Heat: Thermocouple and Carbon layer

Rupture speed

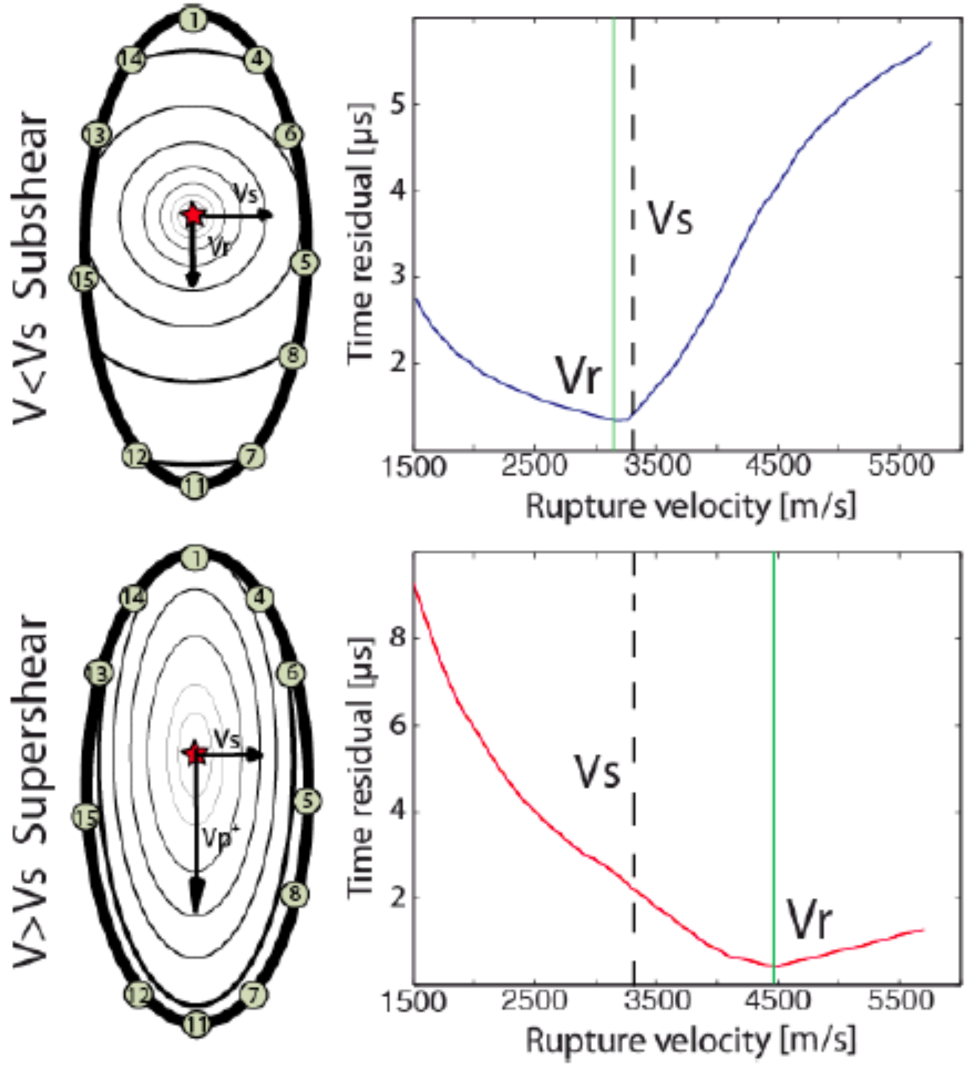
V_r estimated using arrival time of the rupture front passing by each sensor

Calculation of the theoretical arrival time on each sensor for
(i) nucleation point on the fault plane
(ii) different initiation times
(iii) different rupture front geometry

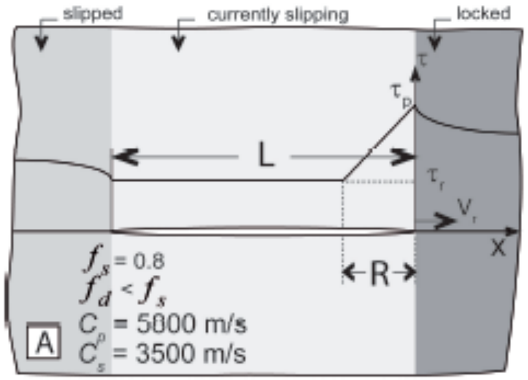
$$t^{th} = f(Vr, To, x, y)$$

Least square function between experimental and theoretical arrivals time

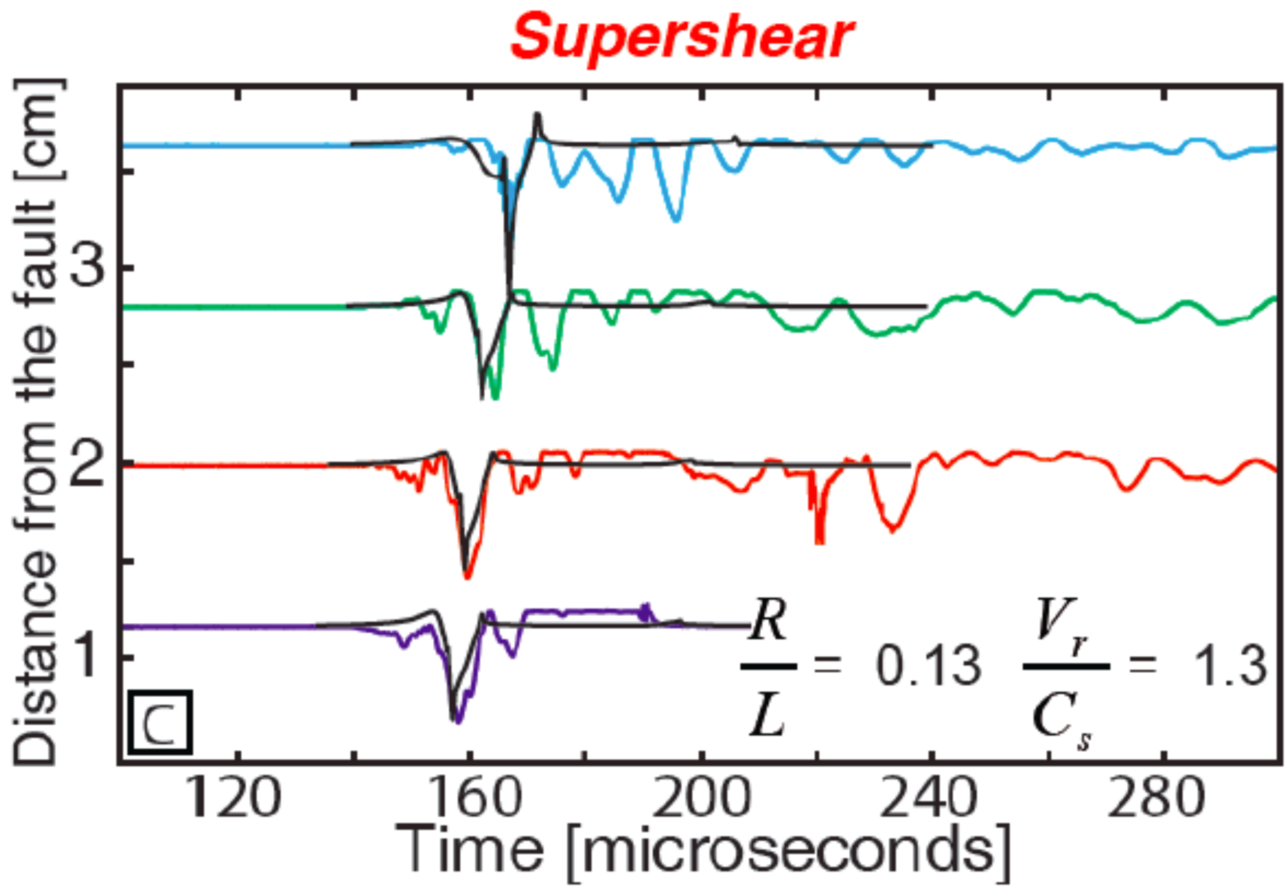
$$\min\left[\frac{\sum_N (dt^d - dt^{th})^2}{N}\right] \Rightarrow (x, y, To, Vr)$$



Comparison with synthetics

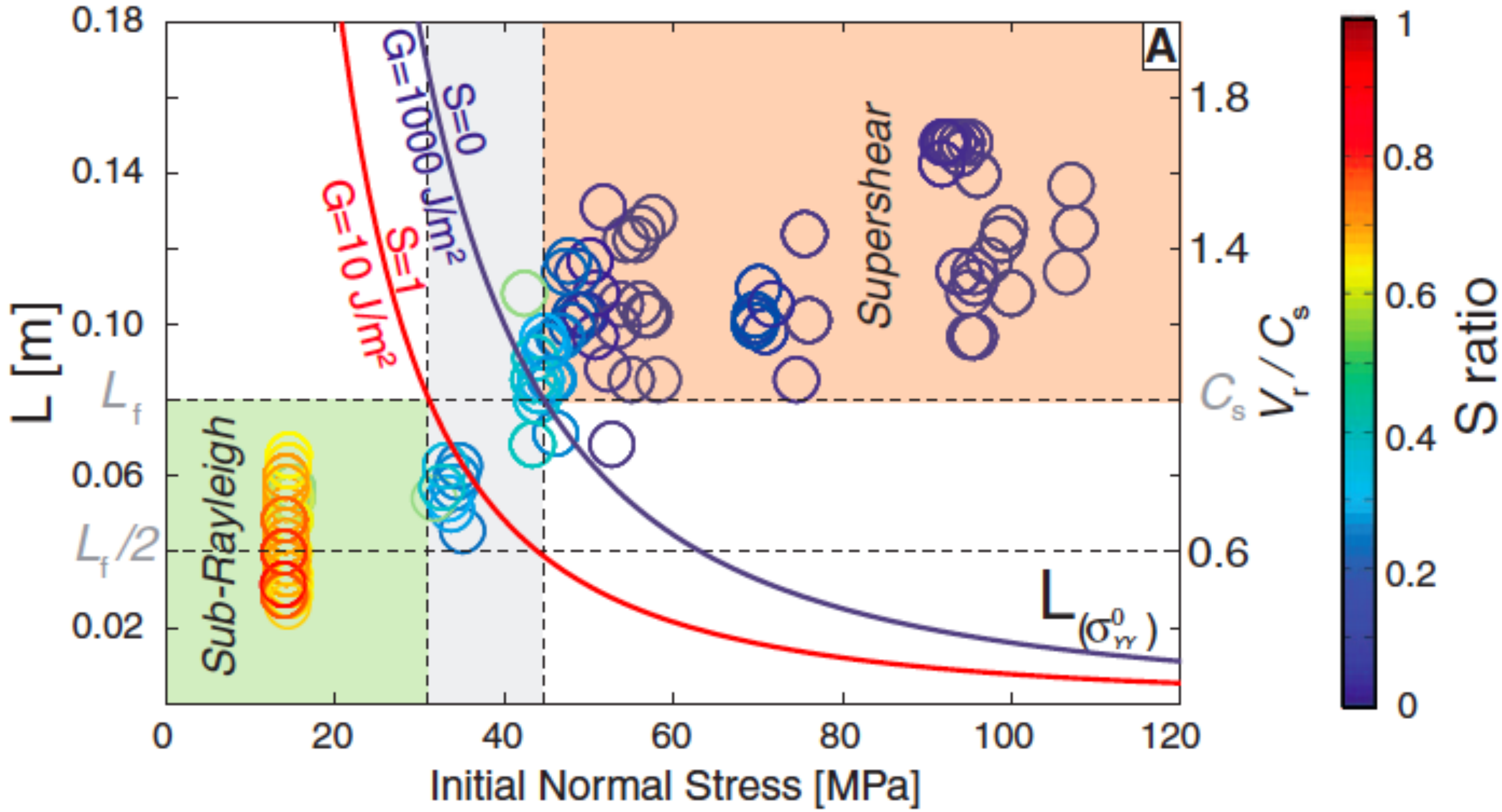


2D steady state
slip pulse model
(Dunham and Archuleta, 2005)



Passelegue et al, 2013

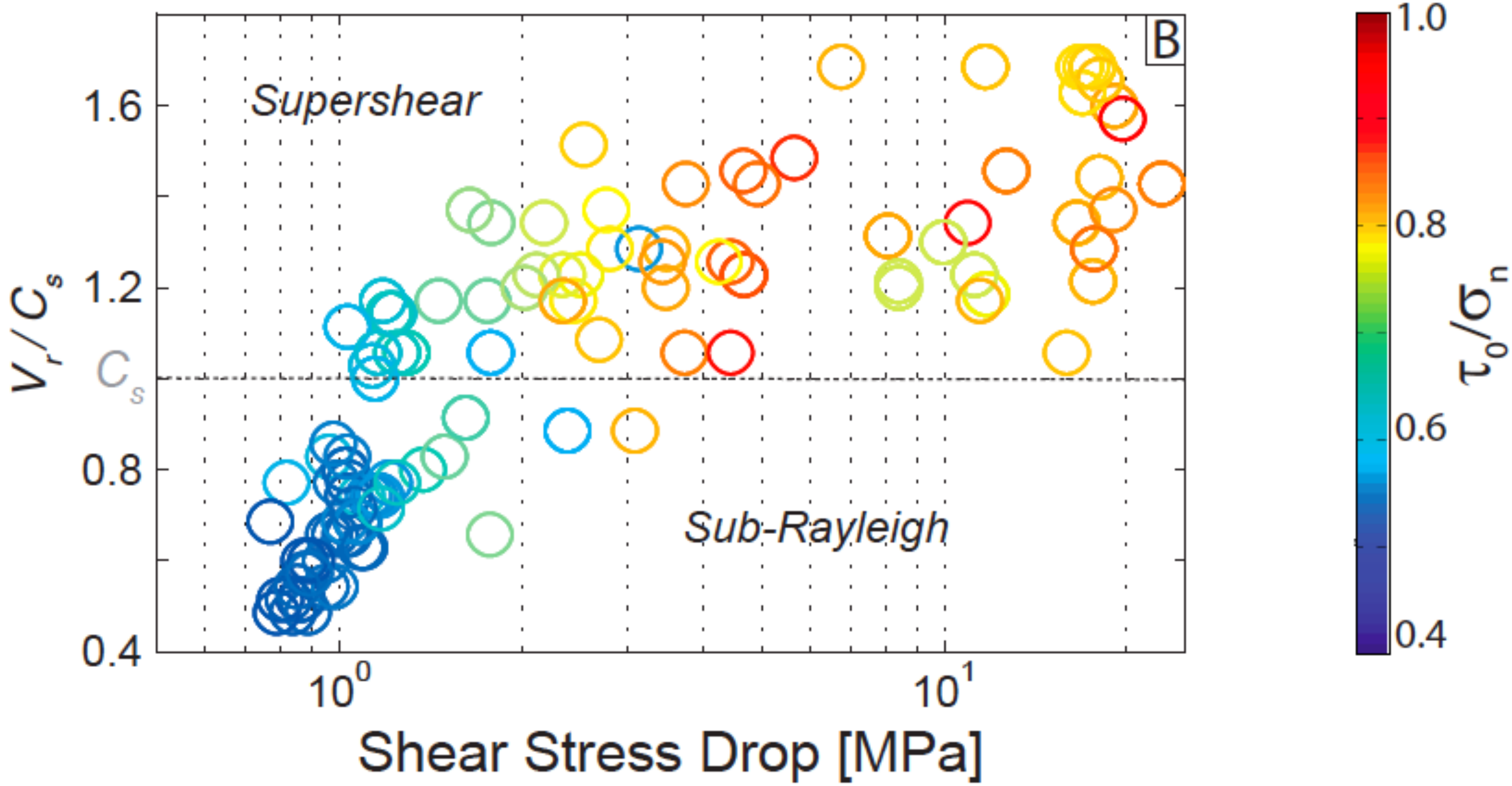
Rupture speed, S ratio and lc



Passelegue et al, Science 2013

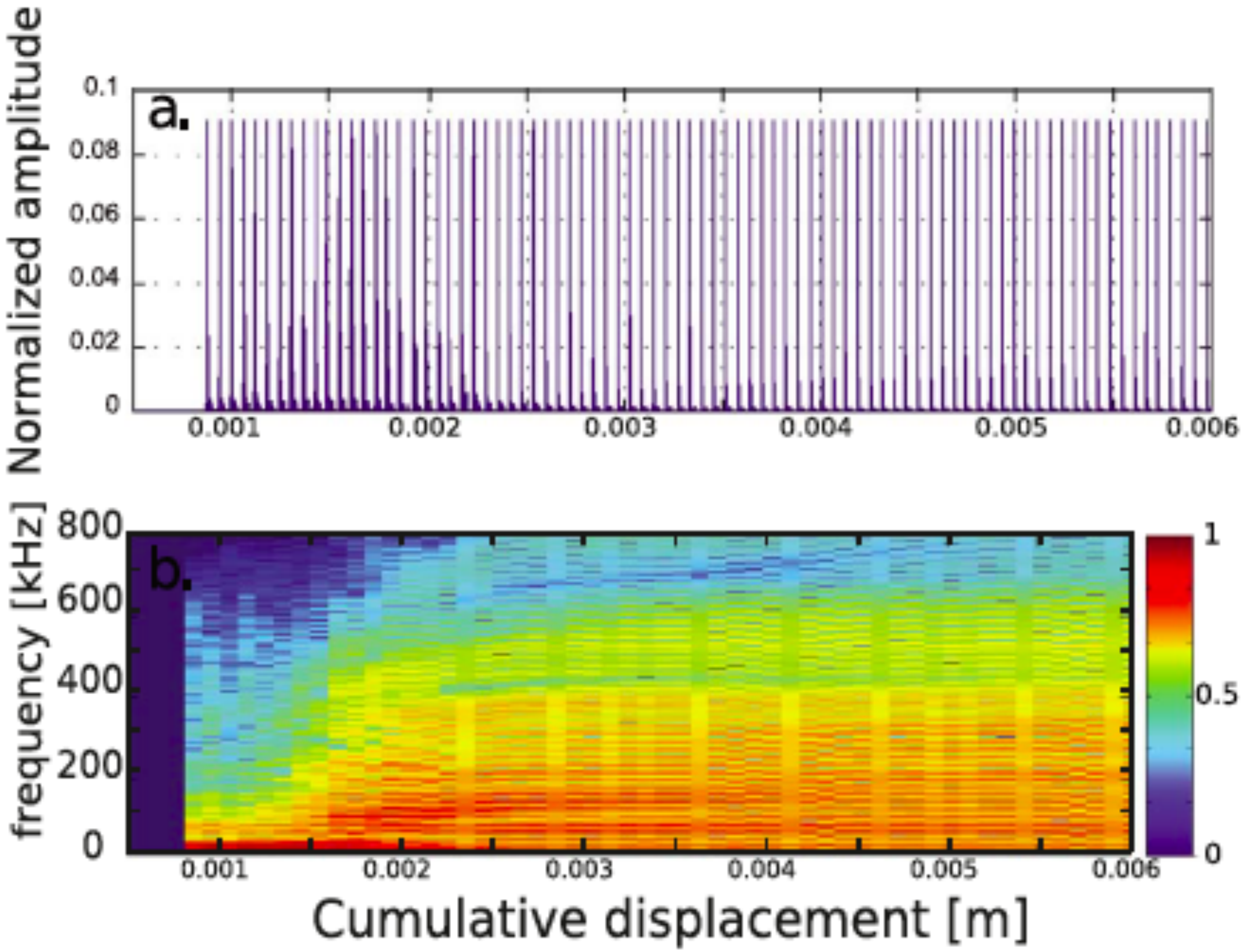
Stress drop and rupture speed

Typical earthquake and asperity range



Passelegue et al, Science 2013

Transition from sub-R to supershear HF radiation



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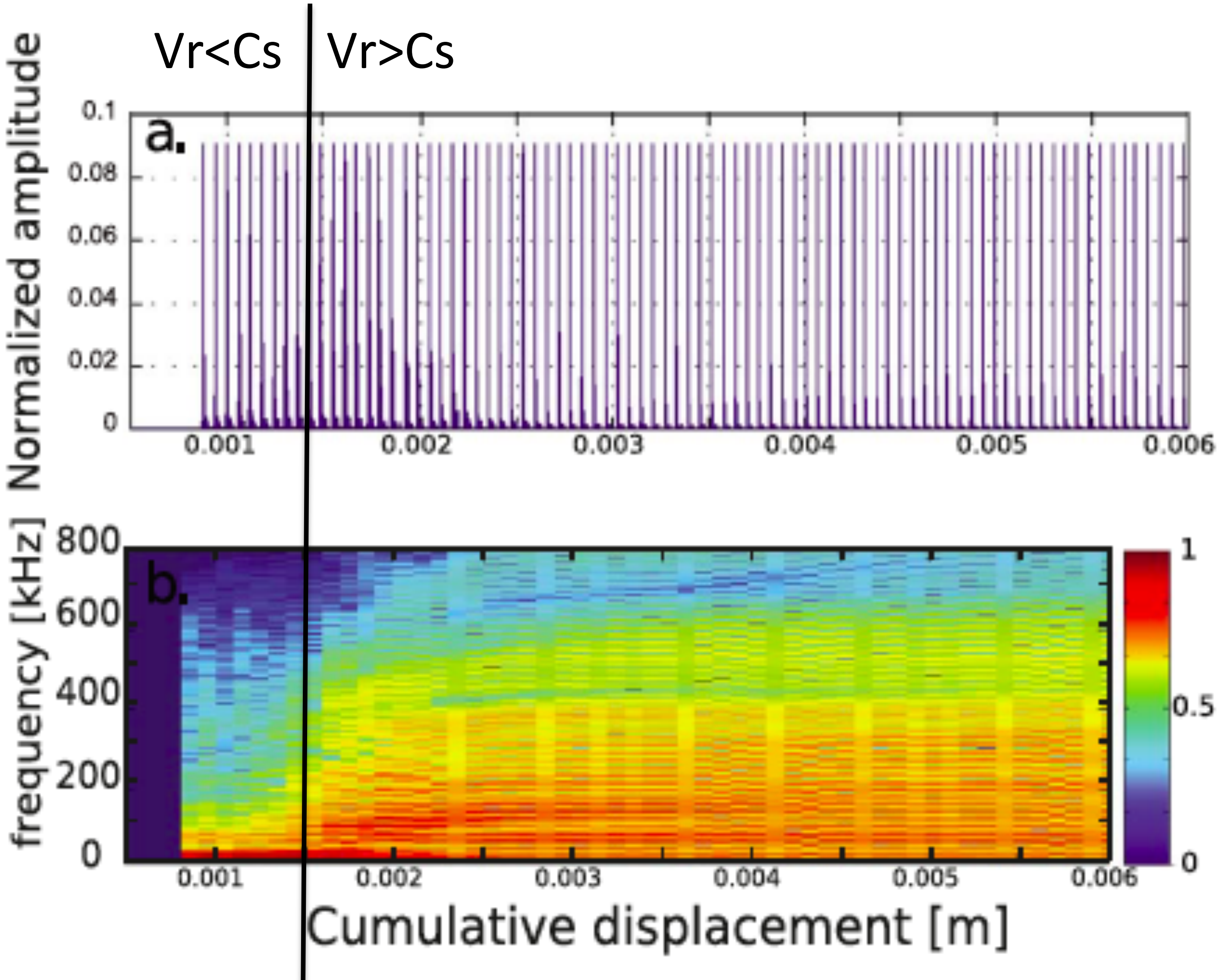
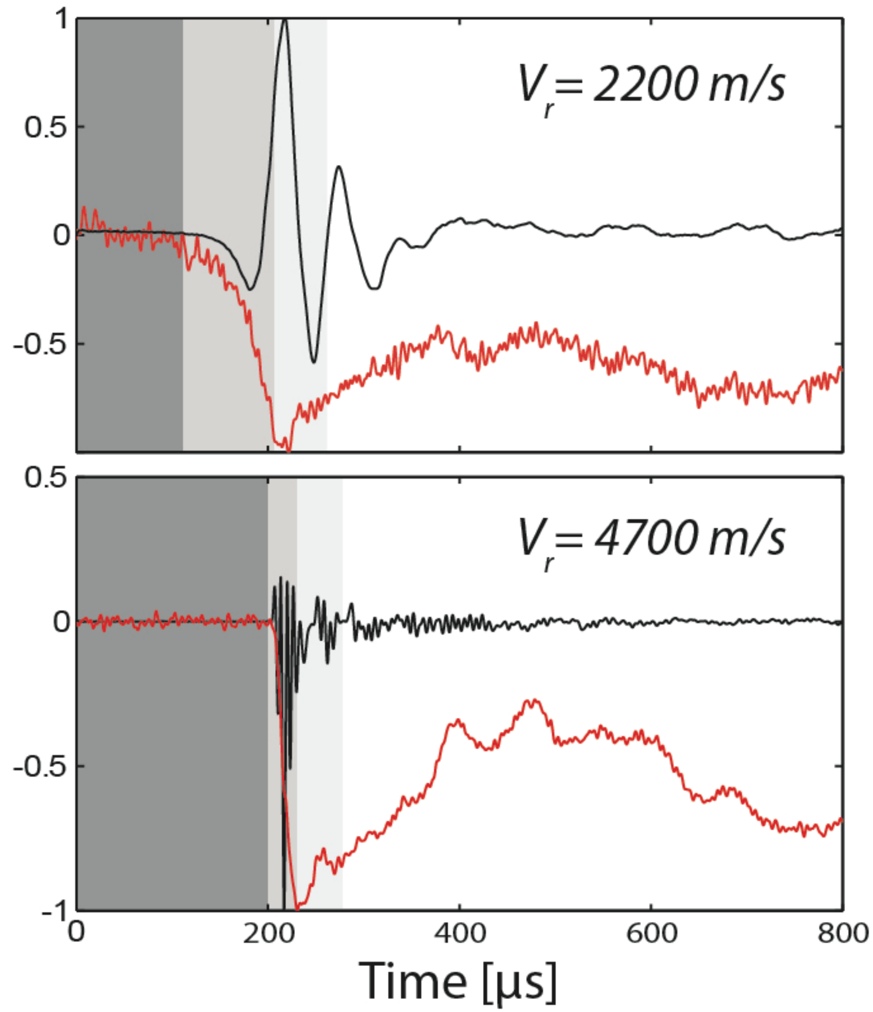
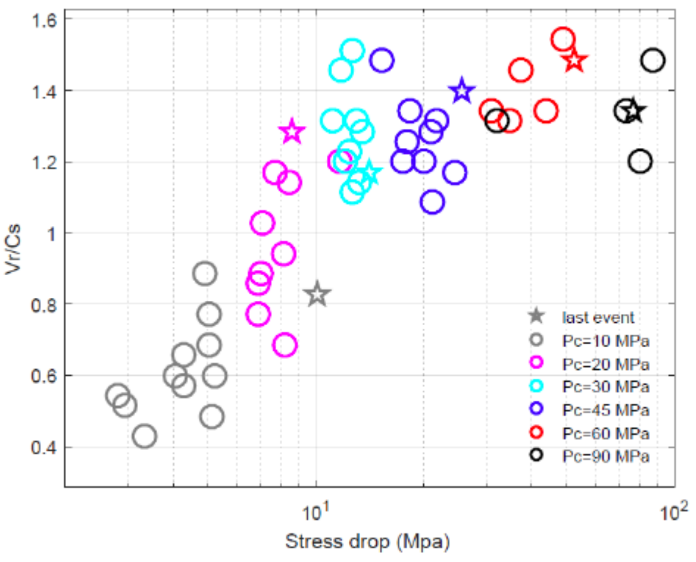


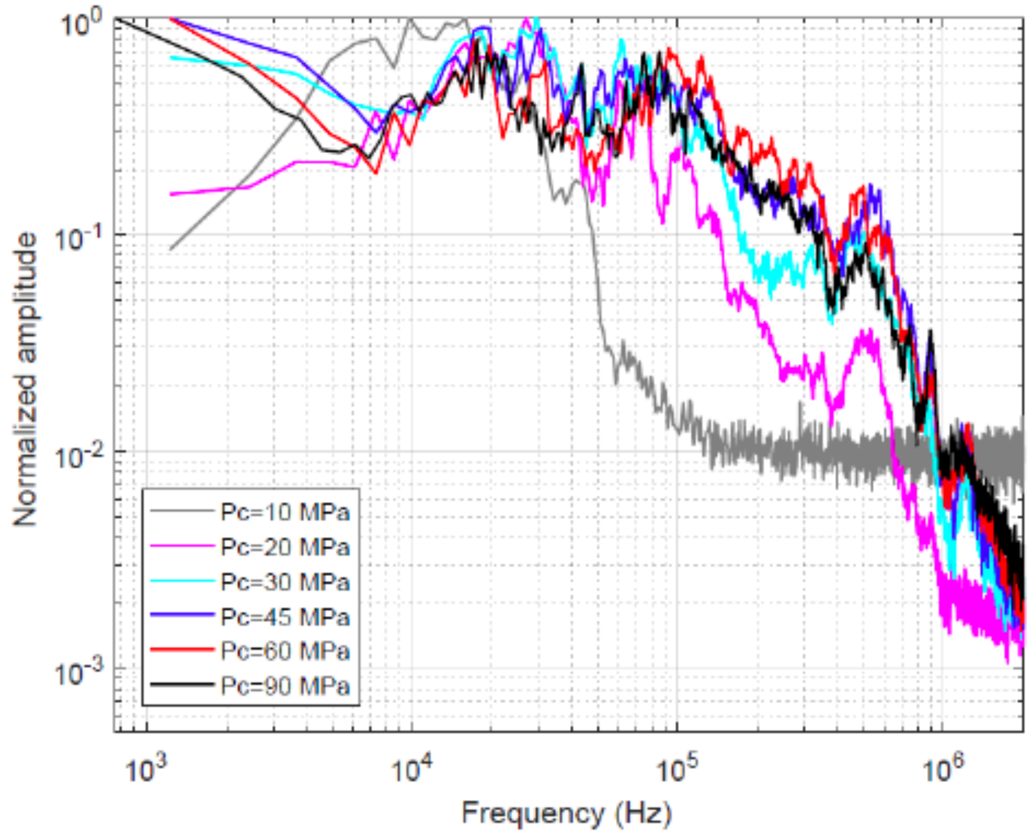
Rupture velocity and HF radiation

Normalized near field velocity (fault //) records



Off-fault damage (HF) radiation





Marty et al, in prep.

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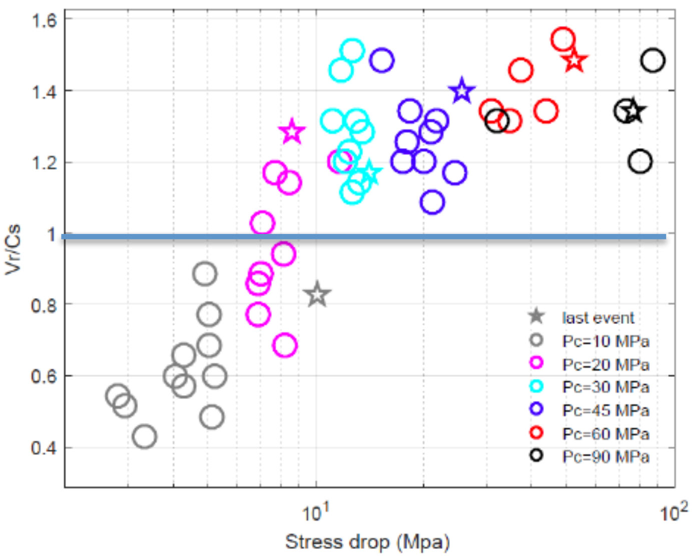

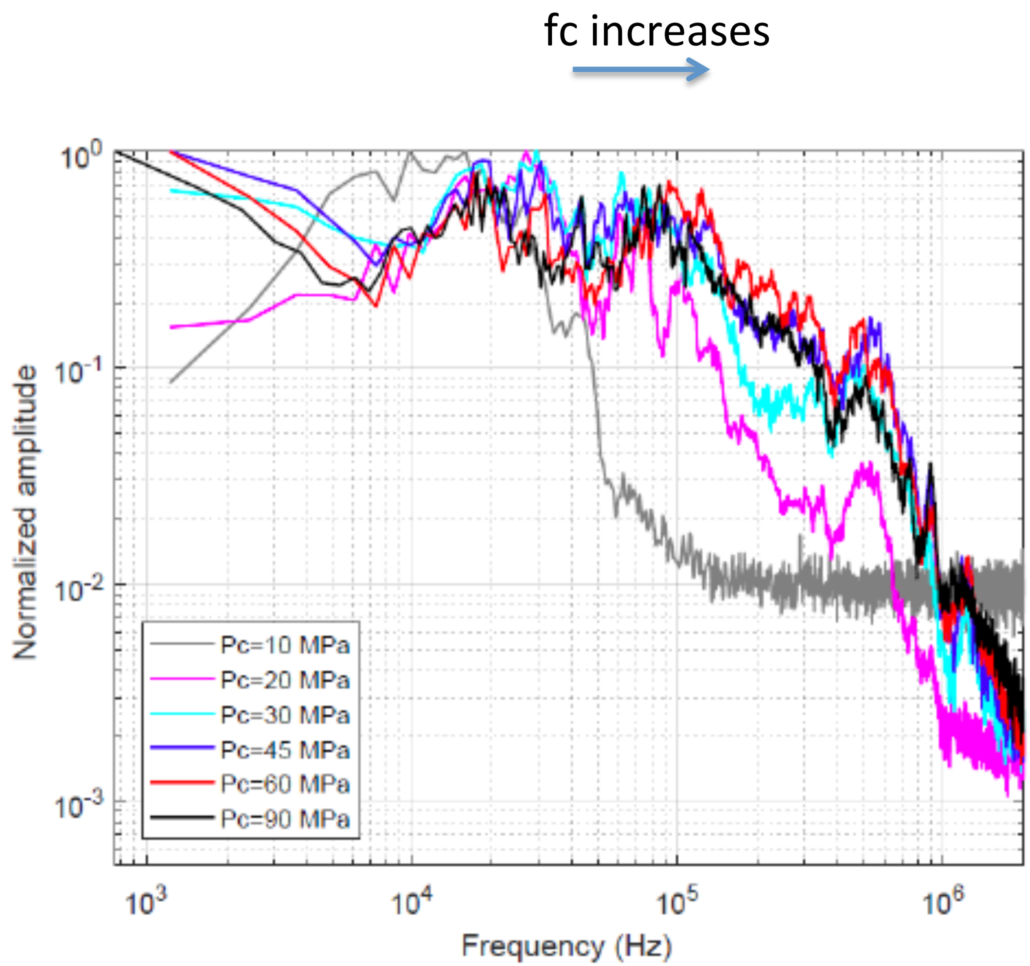

Marty et al, in prep.

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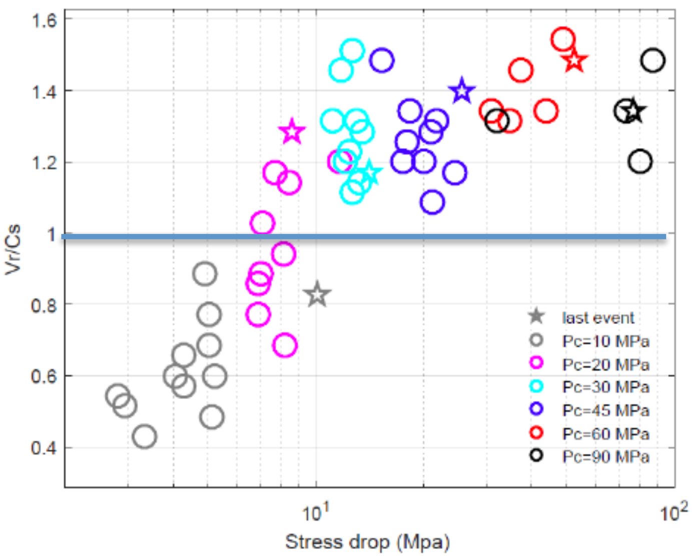
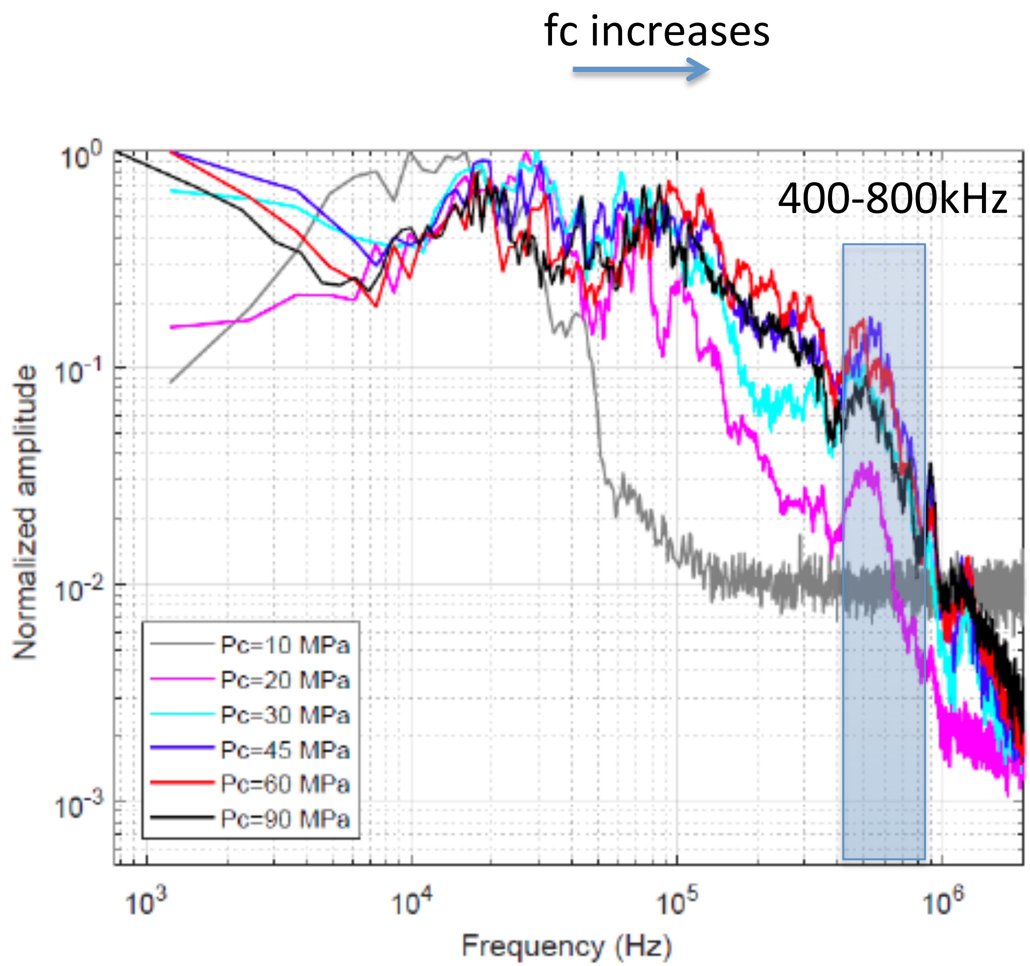
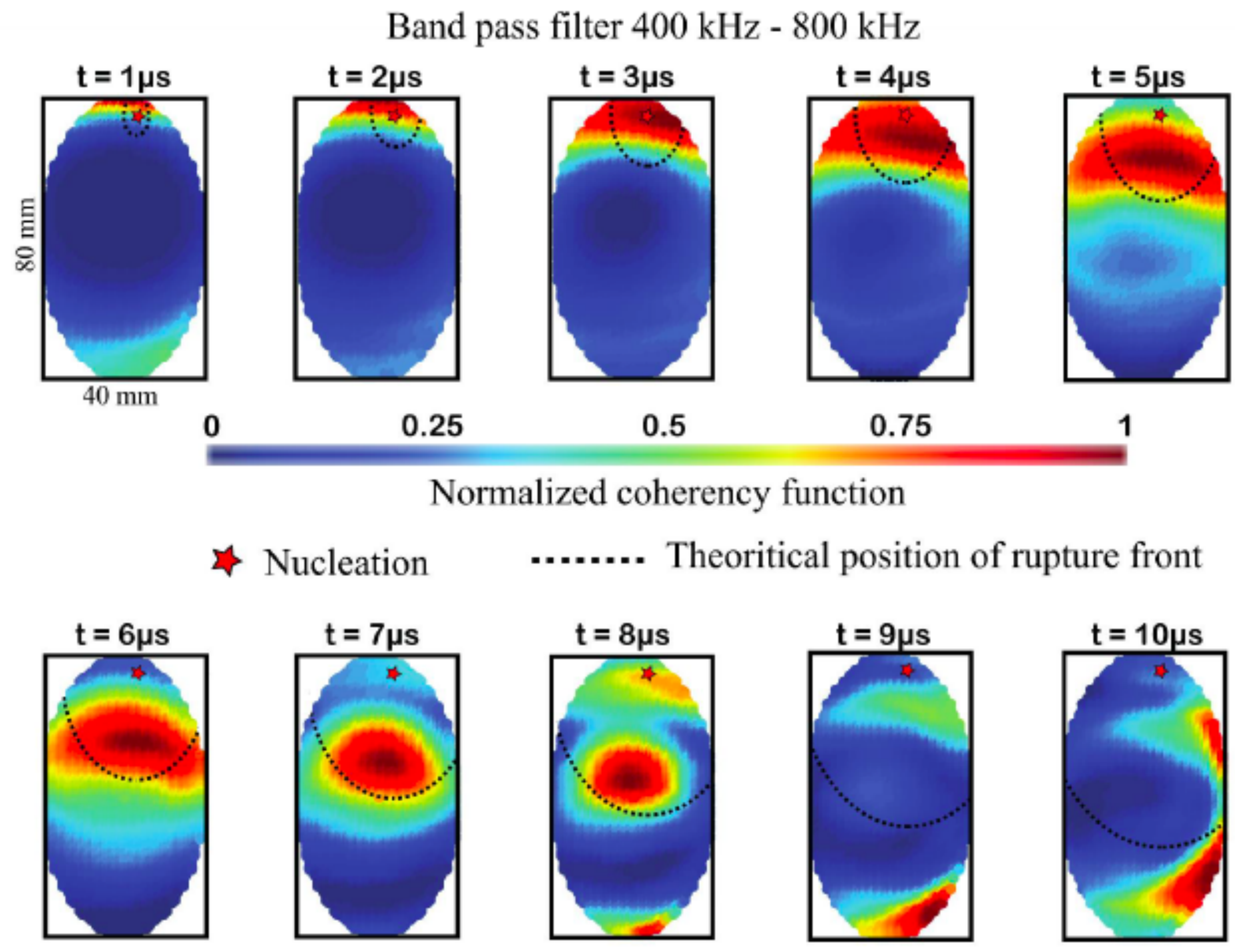




Marty et al, in prep.

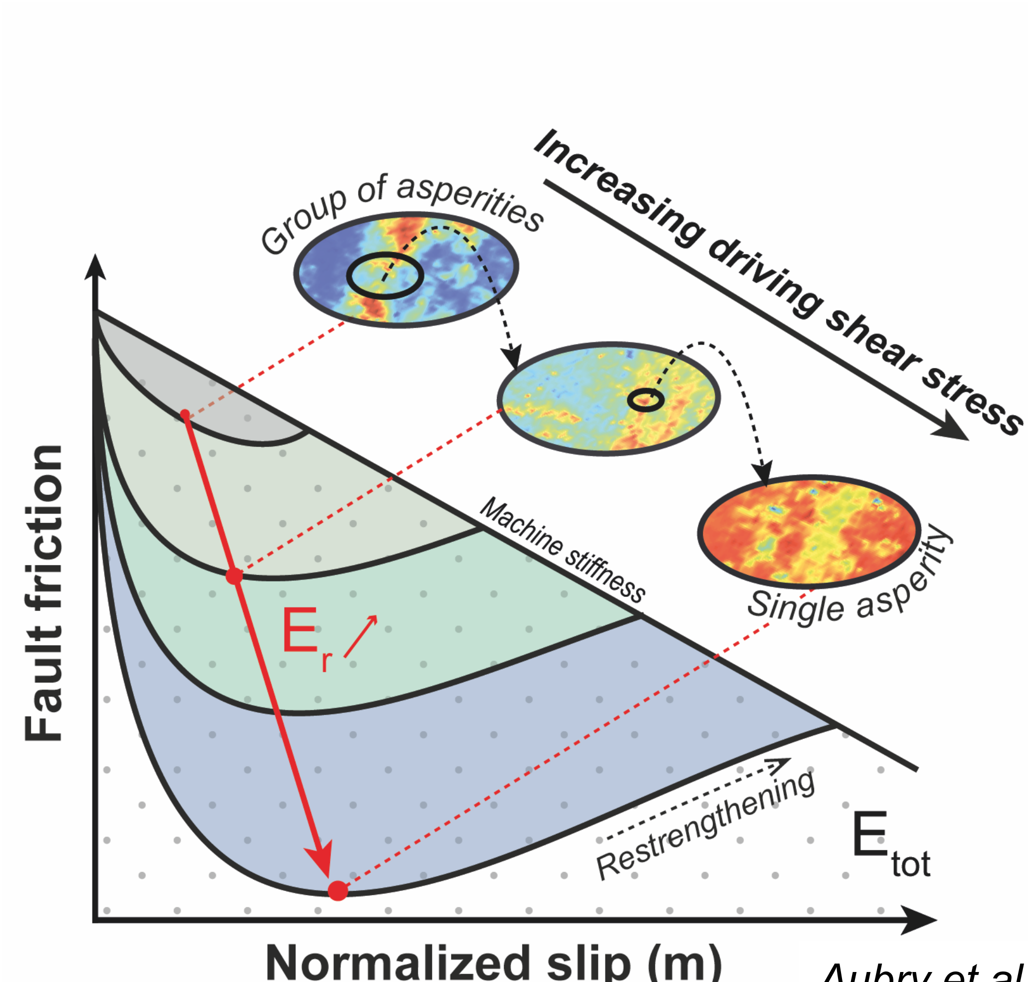
Off-fault damage (HF) radiation

Back projection of the HF content locates at rupture front



Marty et al, in prep.

Energy budget - summary



Aubry et al. Sub.

Conclusions

- **Flash melting on asperities (sliding velocities >m/s)** drives the discrepancy between static and dynamic stress drop and generate **high velocity ruptures**.
- **Fracture energy scales with final slip**, and at large slip, is mainly dissipated into heat (which triggers thermal cracking, so it's a feedback loop), because large slips are accompanied by near-total stress drops.
- **Faster (Supershear) ruptures are accompanied by HF radiation**. Back projection shows that this HF radiation originates at (or close to) rupture front (dynamic off-fault damage triggering and/or breakdown zone).
- **During sliding, heat generation is limited to asperities**. Increaseing seismic efficiency corresponds to the transition from the behavior of multiple asperities (low seismic efficiency) to that of a single asperity (high seismic efficiency).

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AT LABORATORY SCALE
BUT IN THE RIGHT σ-P-T CONDITIONS

Thanks for your attention!

Thanks to:

@ ENS: **Samson Marty, Jérôme Aubry**, Blandine Gardonio, Harsha Bhat, Raul Madariaga

@ EPFL: **François Passelègue**

@ IPGP: Frédéric Girault, Javier Escartin, Claudio Satriano

@ Durham U.: Stefan Nielsen

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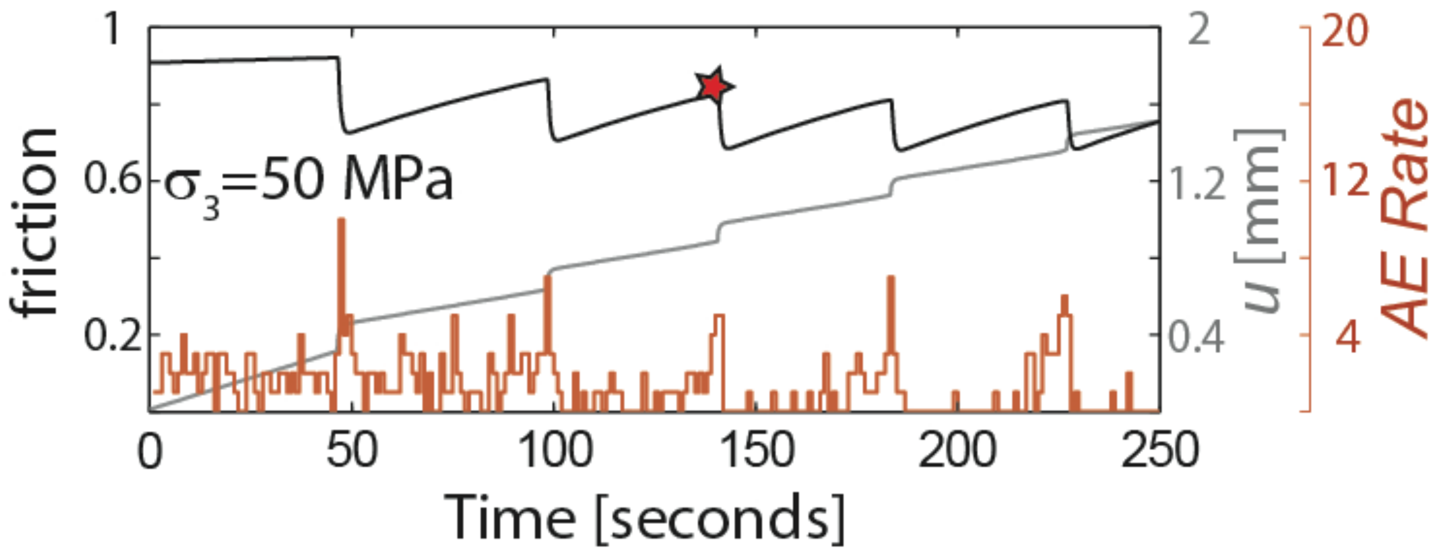
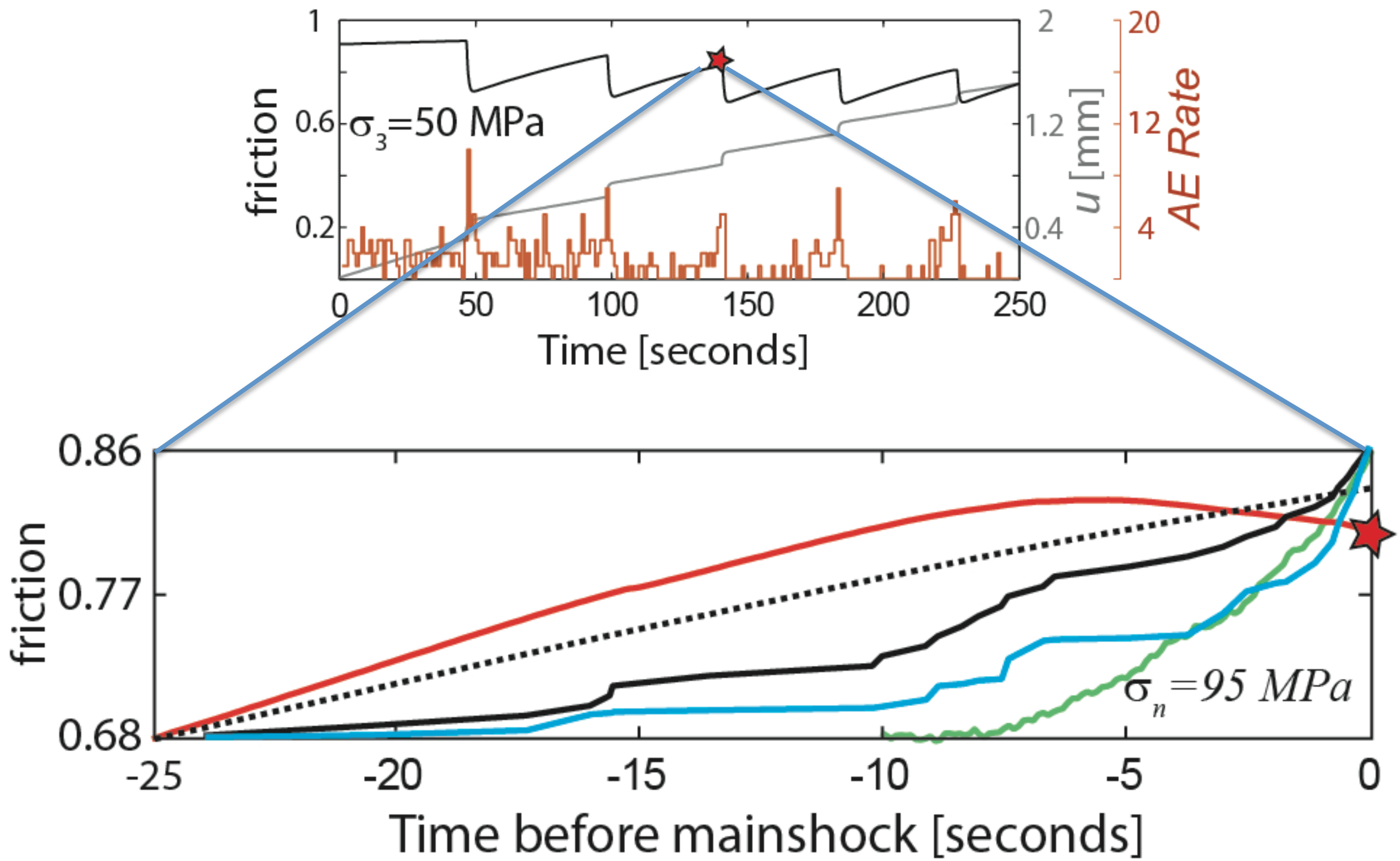
Precursories to Stick-Slip



Outline

- EQs in the lab.
- Precursory processes to Stick-slip
- Rupture Speed and off-fault damage
- Fracture energy (breakdown work)
- Heat generation

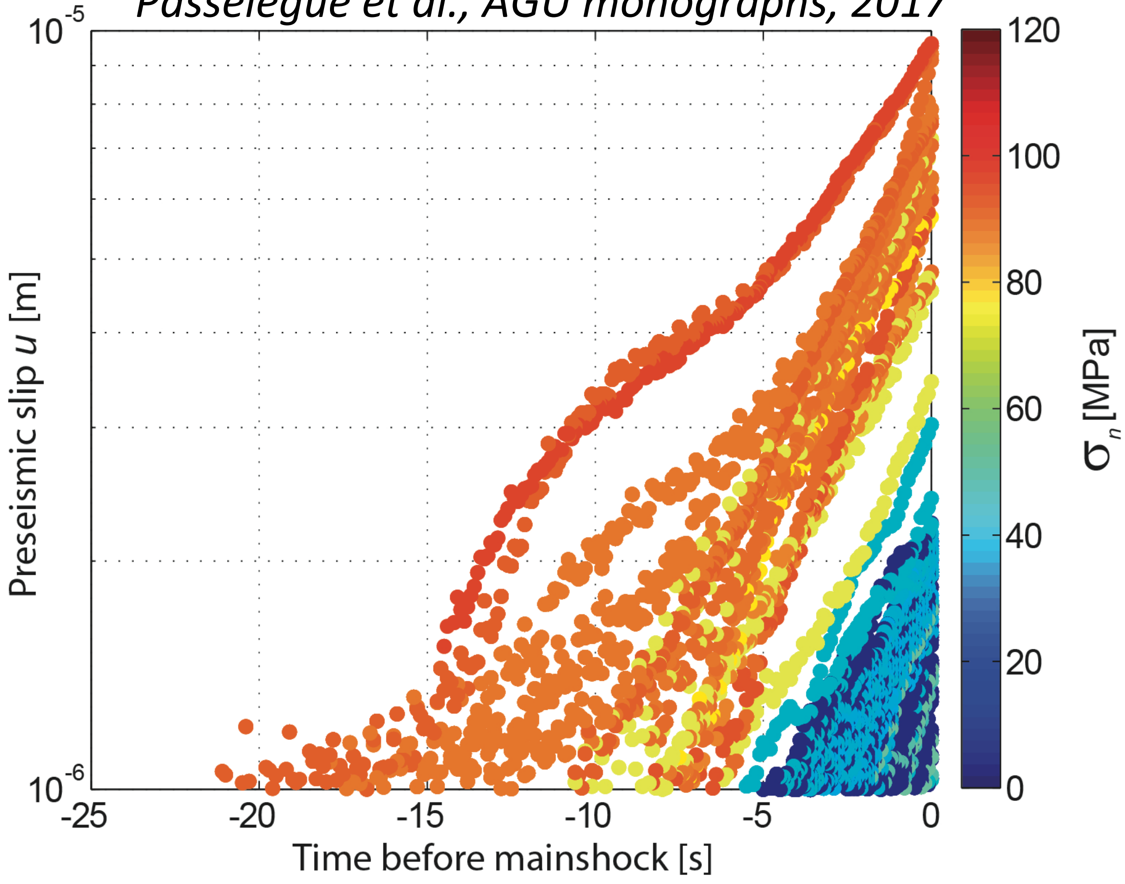
Precursories to Stick-Slip



Passelègue et al., AGU monographs, 2017

Precursory slip

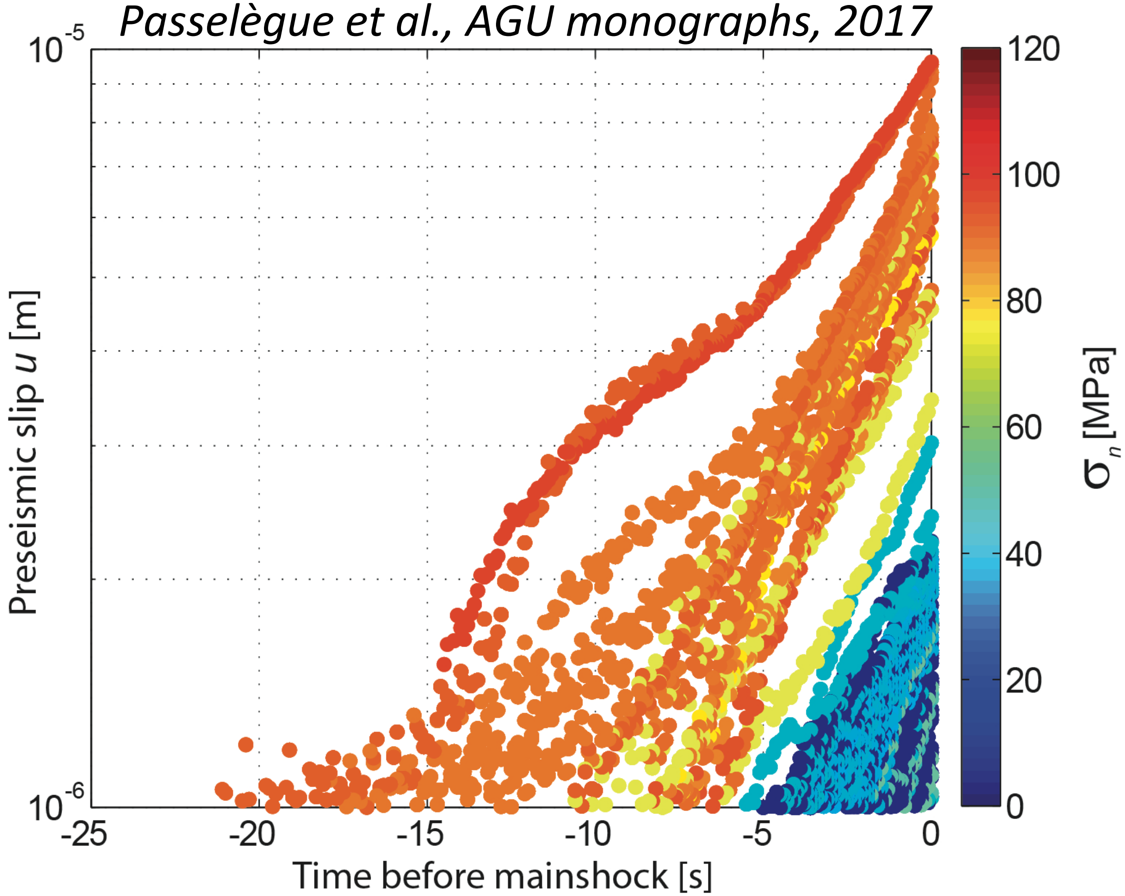
Passelègue et al., AGU monographs, 2017



$$u(t) = u_c e^{\frac{t}{t_c}}$$

Precursory slip

Passelègue et al., AGU monographs, 2017

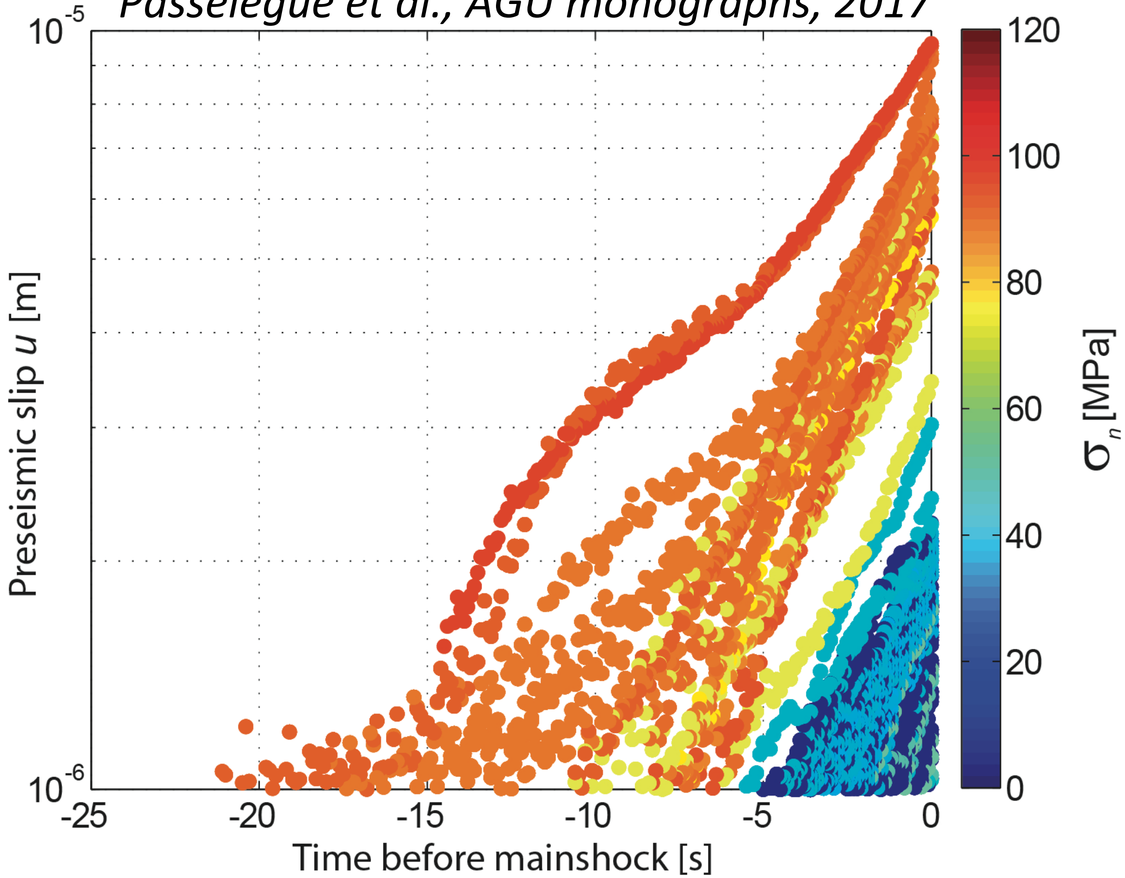


$$u(t) = u_c e^{\frac{t}{t_c}}$$

Here $t_c \approx cst \approx 7s$

Precursory slip

Passelègue et al., AGU monographs, 2017



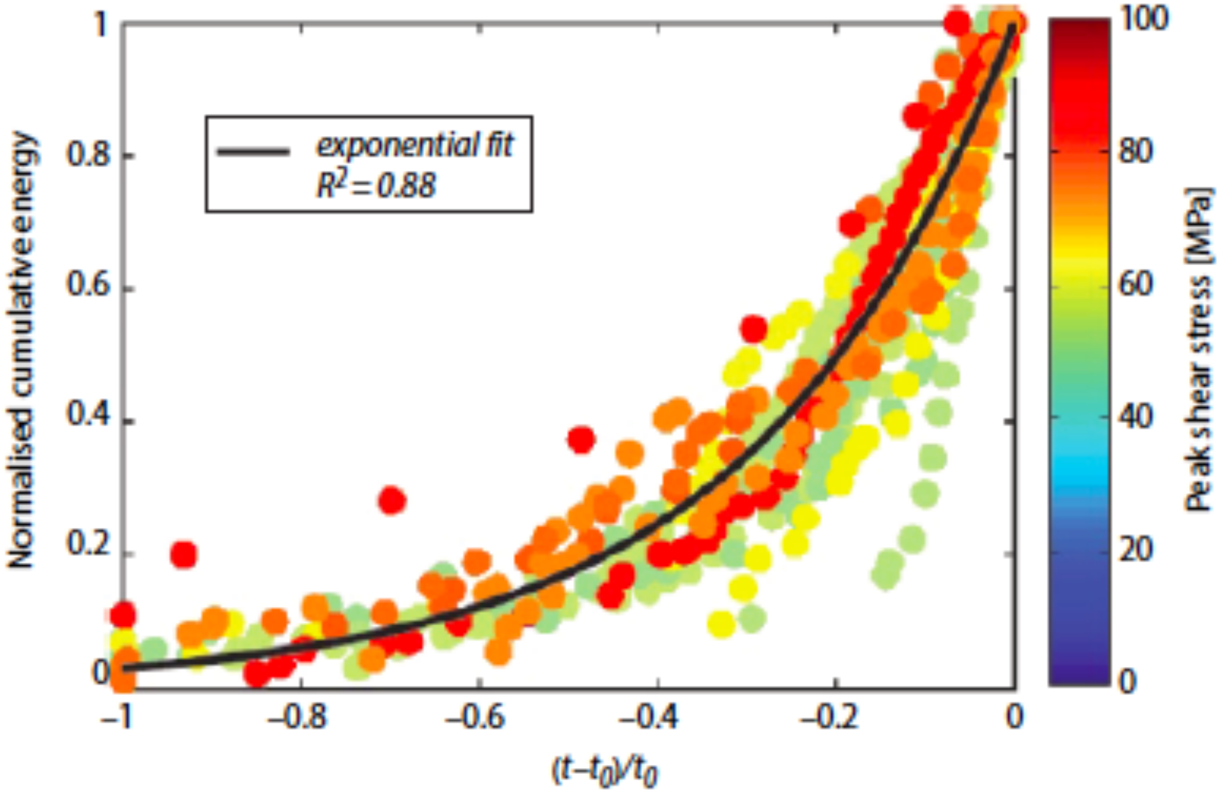
$$u(t) = u_c e^{\frac{t}{t_c}}$$

Here $t_c \approx$ cst $\approx$ 7s $\approx \dfrac{k\mu}{p_0}\dfrac{D_c}{f_s - f_d} = L_0/v_{r0}$

From Latour et al., 2013

Foreshock dynamics

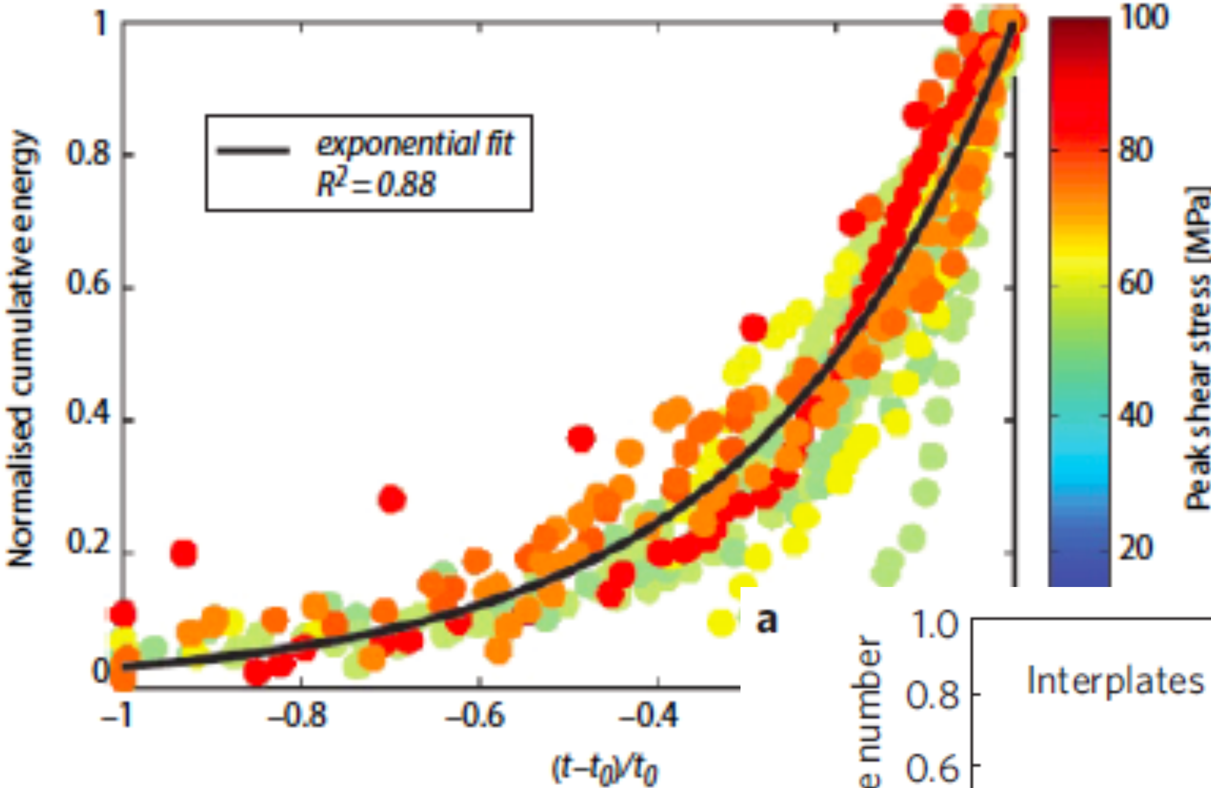
Passelègue et al., AGU monographs, 2017



$$\frac{M(t)}{M_p} = e^{\alpha \frac{(t - t_0)}{t_0}}$$

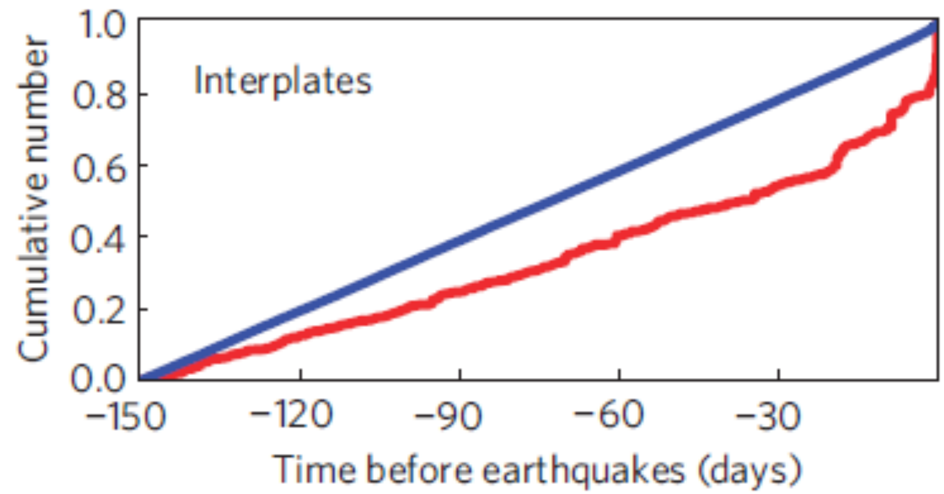
Foreshock dynamics

Passelègue et al., AGU monographs, 2017



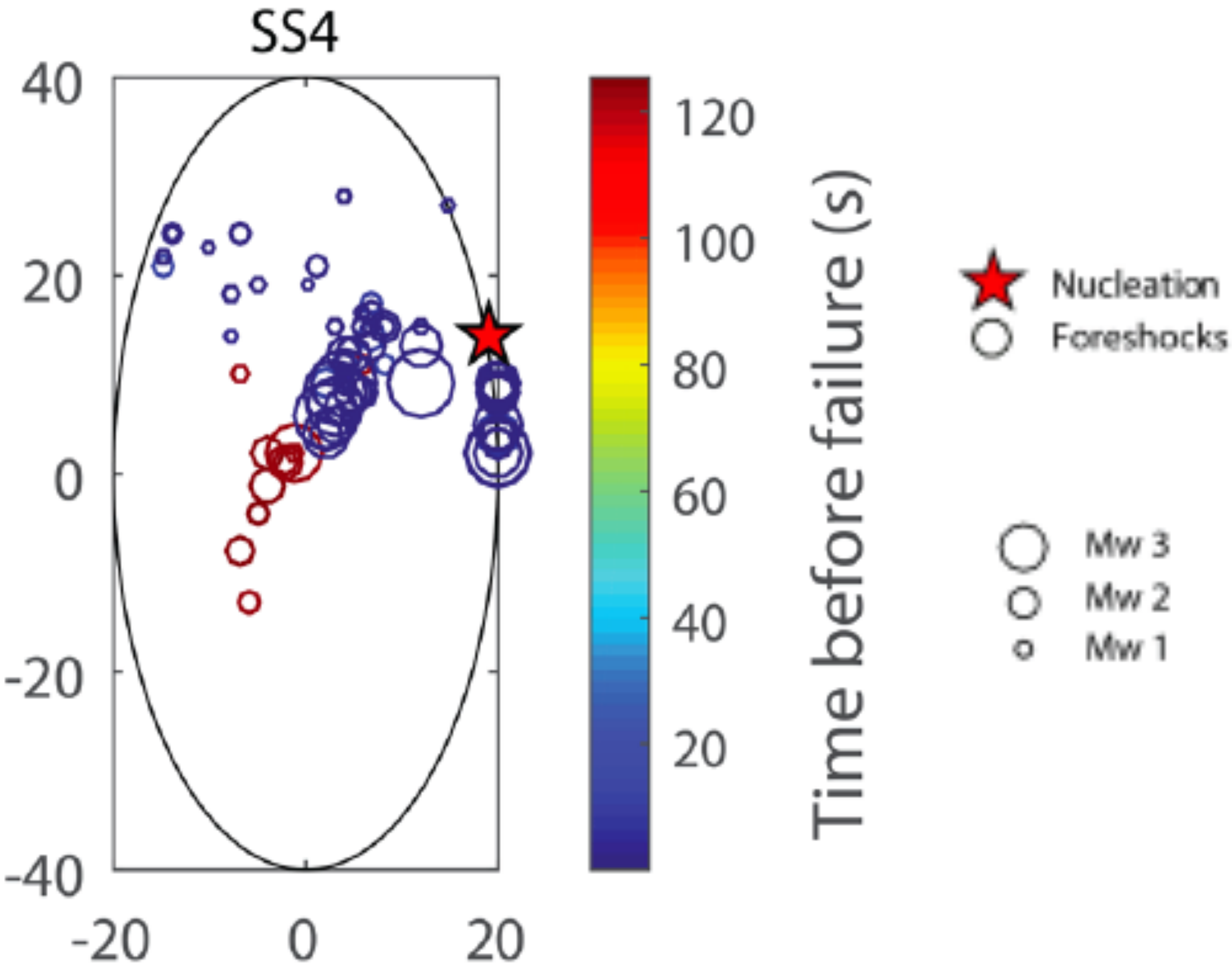
$$\frac{M(t)}{M_p} = e^{\alpha \frac{(t-t_0)}{t_0}}$$

Similar to
Bouchon et al., 2013



Foreshock dynamics

- Foreshocks are spatially and temporally correlated

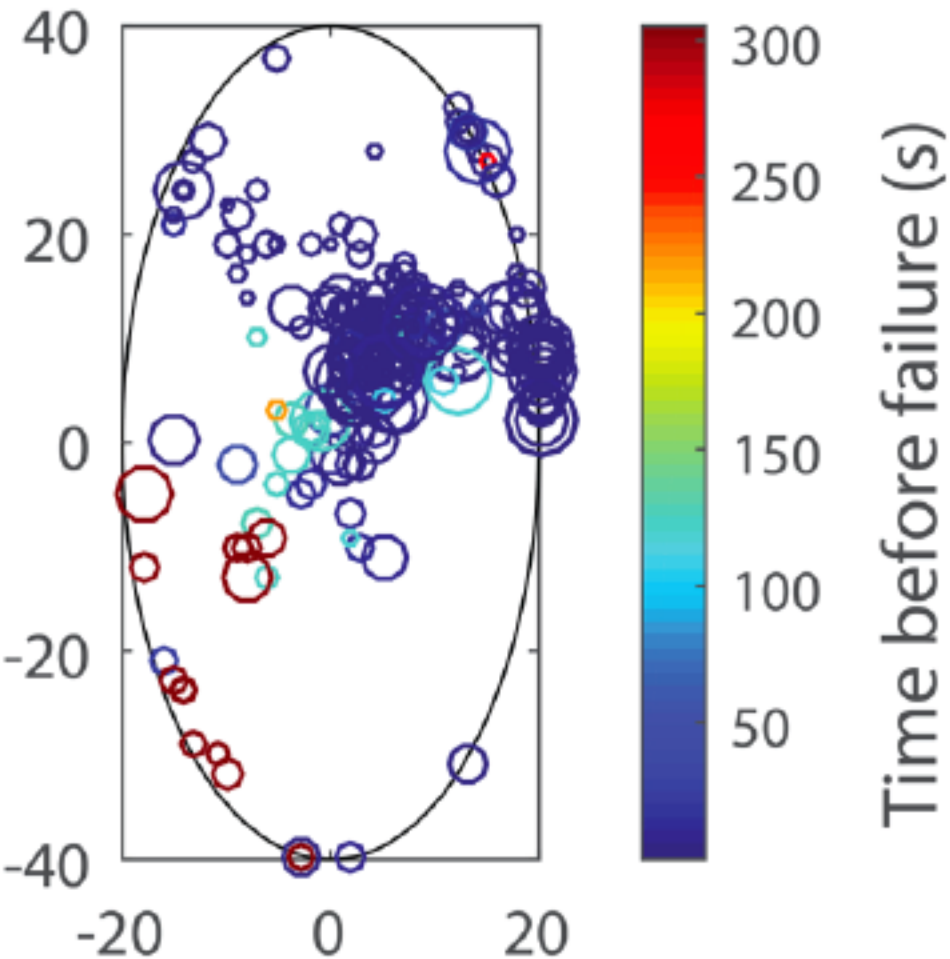


Marty et al. AGU, 2017

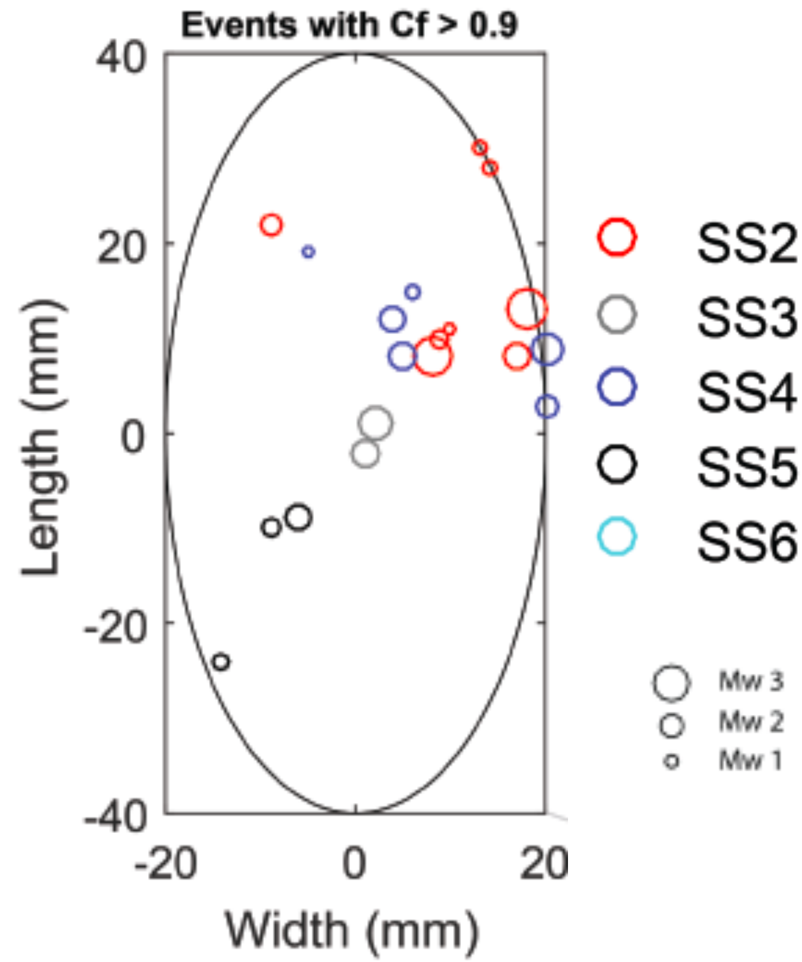
Foreshock dynamics

- Life of a single asperities during and over several cycles

All foreshocks



Repeaters/similar family of events



Marty et al. AGU, 2017

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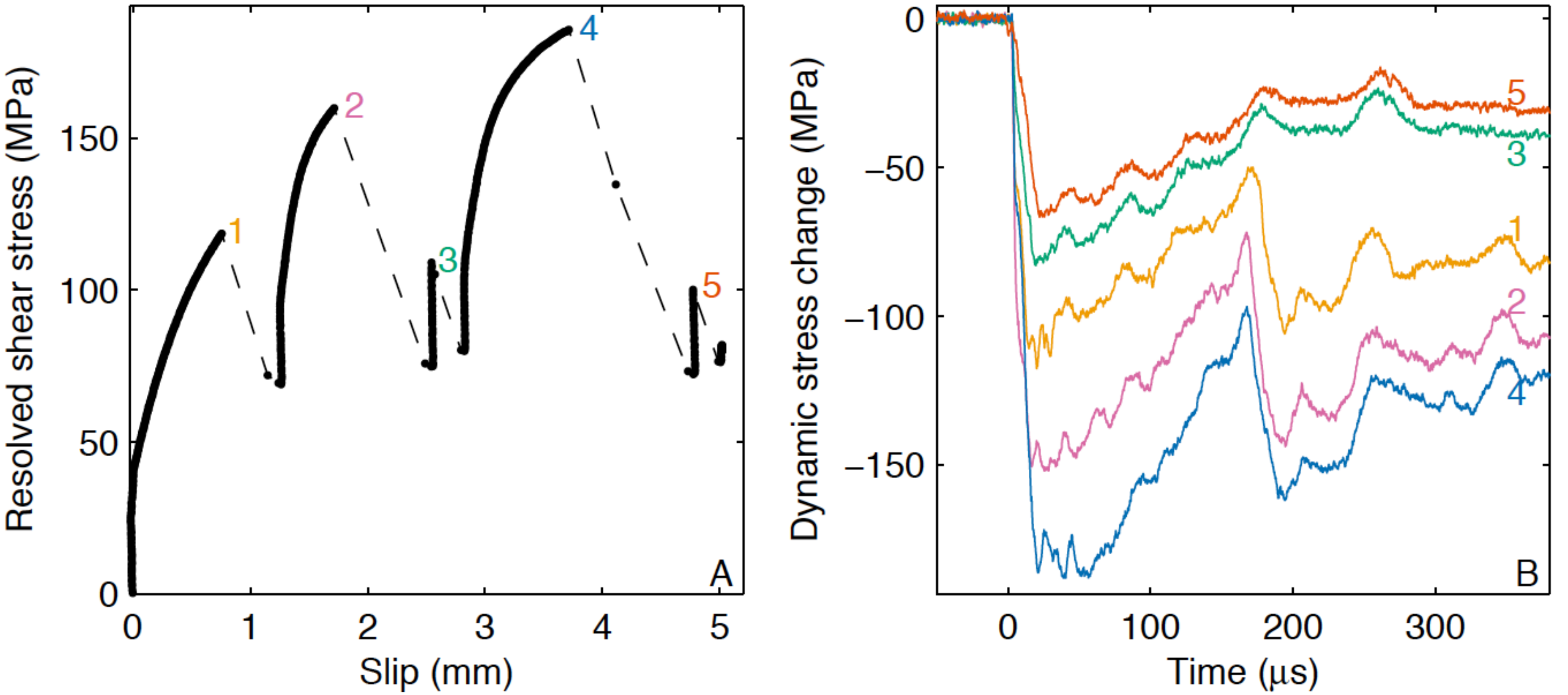
- Mineral coupling

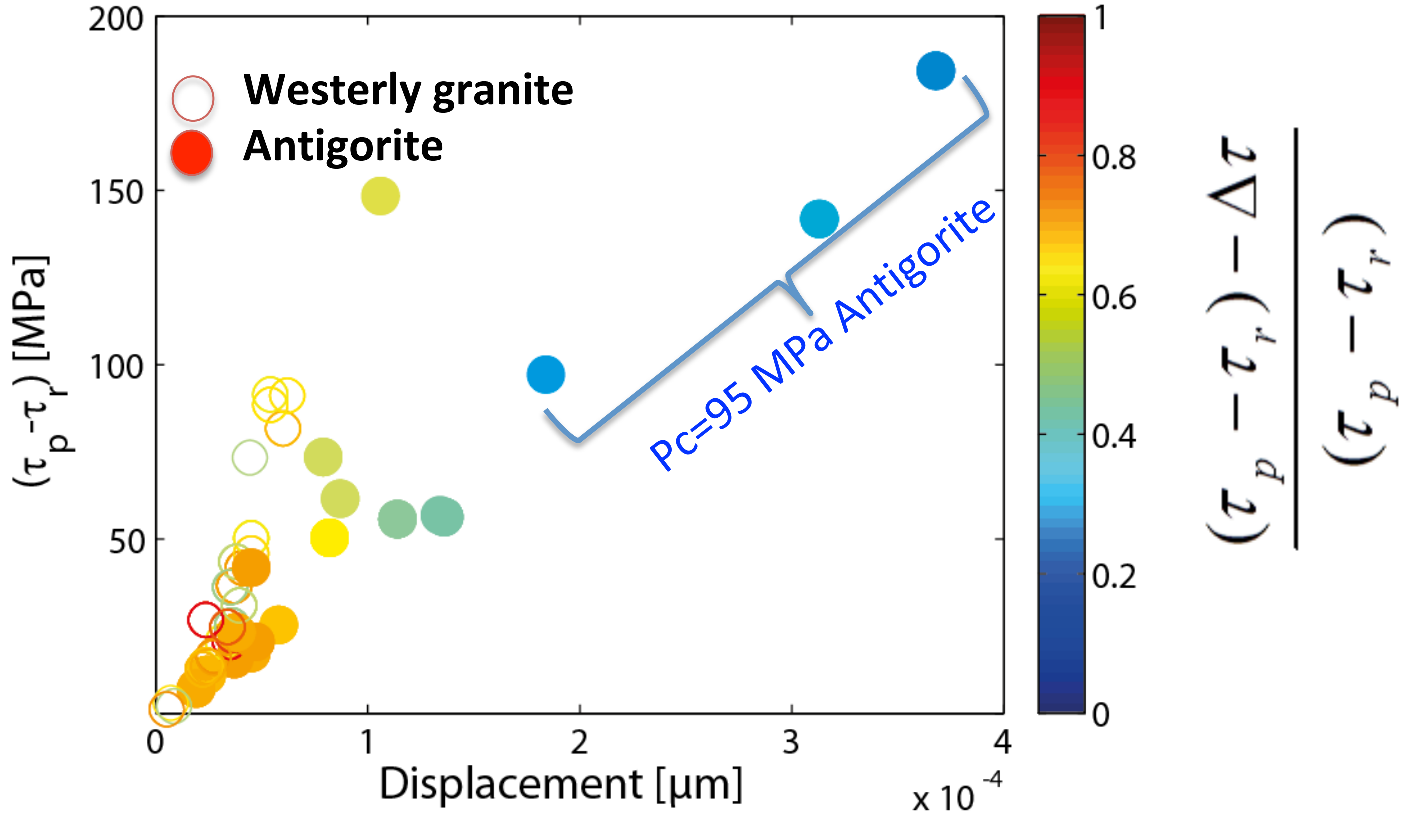
Mineral coupling

Saw cut Alpine Corsica Serpentinite (≈100% antigorite, Pc=95MPa)



Brantut et al., Geology 2016

Mineral coupling



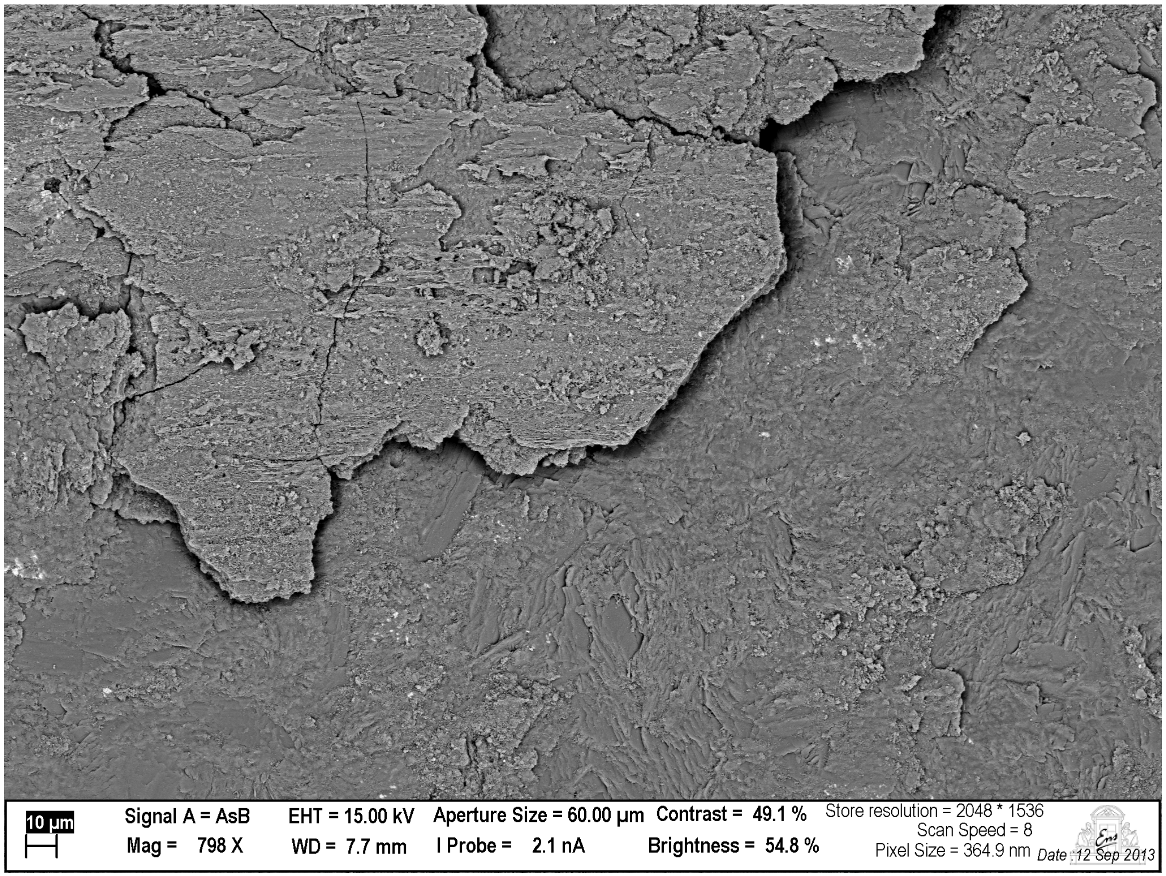
Displacement scales with stress drop

$$\Delta\sigma \approx C\mu D / L$$

Mineral coupling

Fault surface and fault gouge

Saw cut Alpine Corsica Serpentinite (≈100% antigorite, Pc=95MPa)



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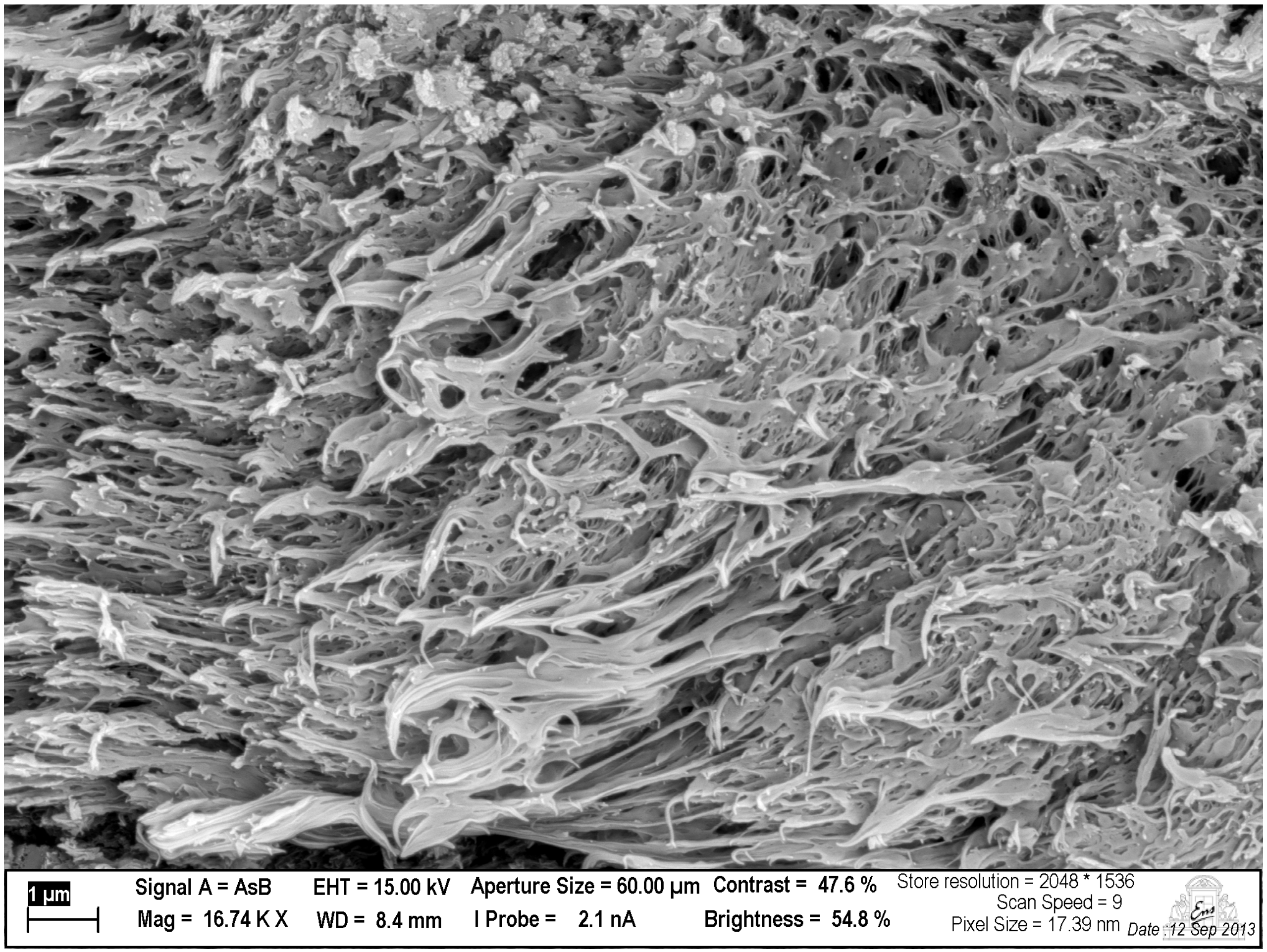

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