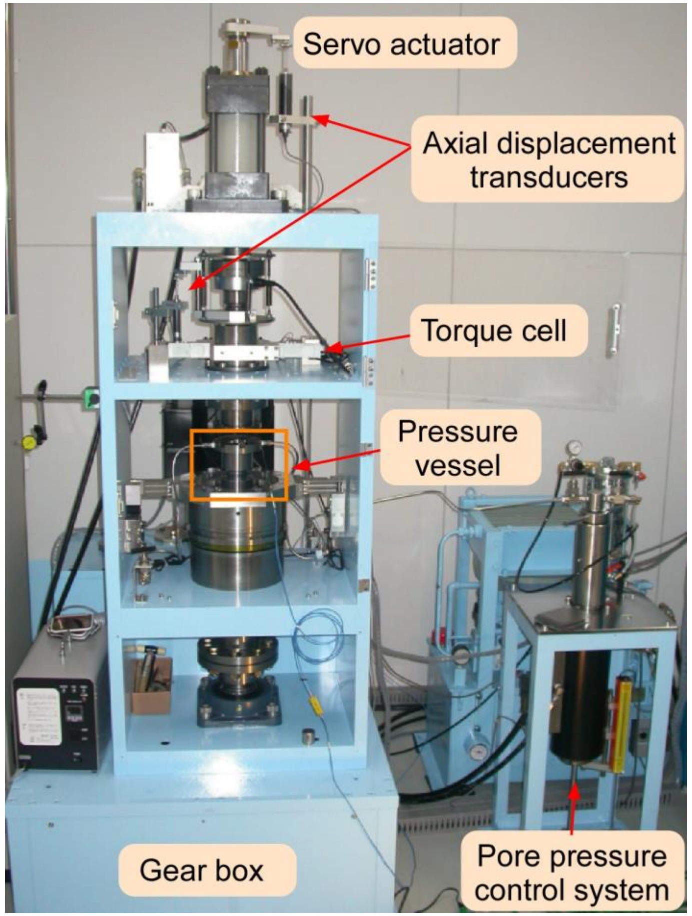
Fault strength evolution during the seismic cycle: Insights from the laboratory



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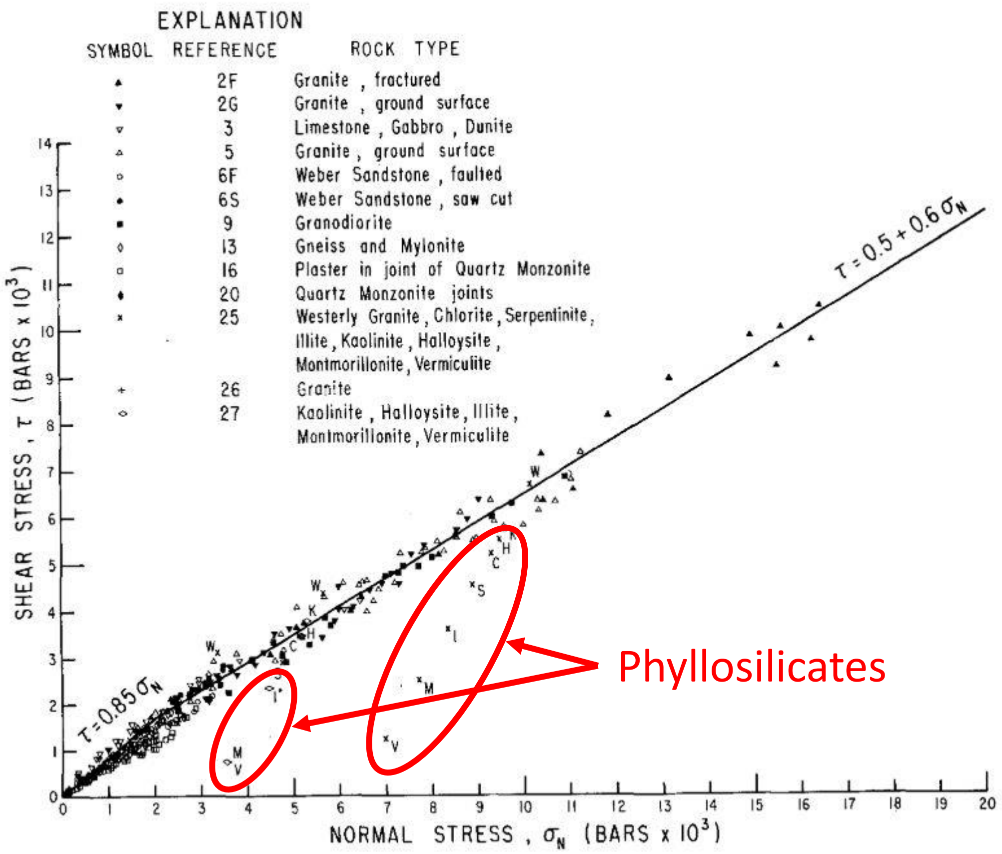
Byerlee's rule



Byerlee (1978) Friction of rocks,
Pure and Applied Geophysics.

$$\text{Friction coefficient} = \frac{\text{Shear stress}}{\text{Normal stress}}$$

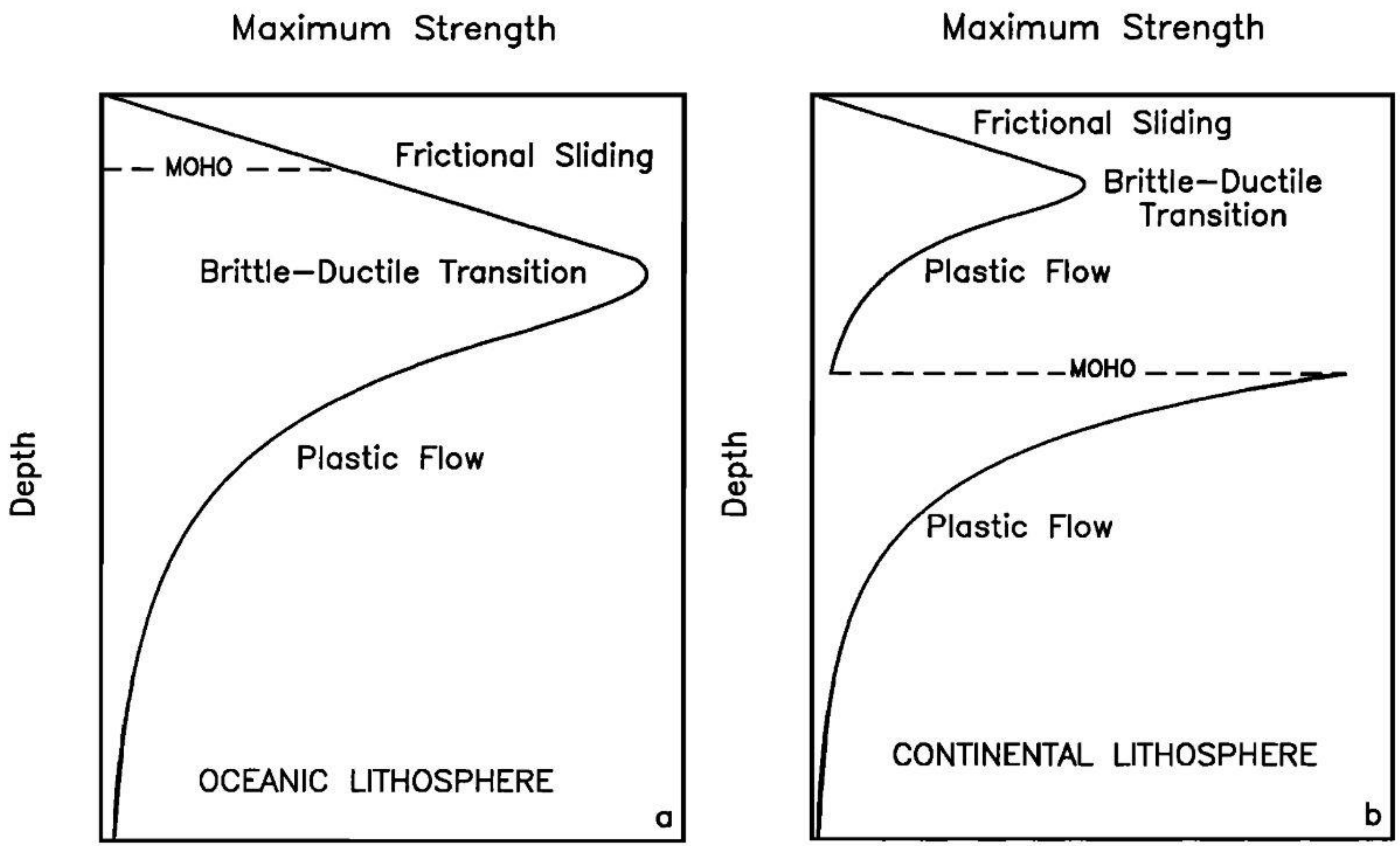
For most geological materials:

$$0.6 \le \mu \le 0.85$$

There are some exceptions where:

$$\mu < 0.6$$

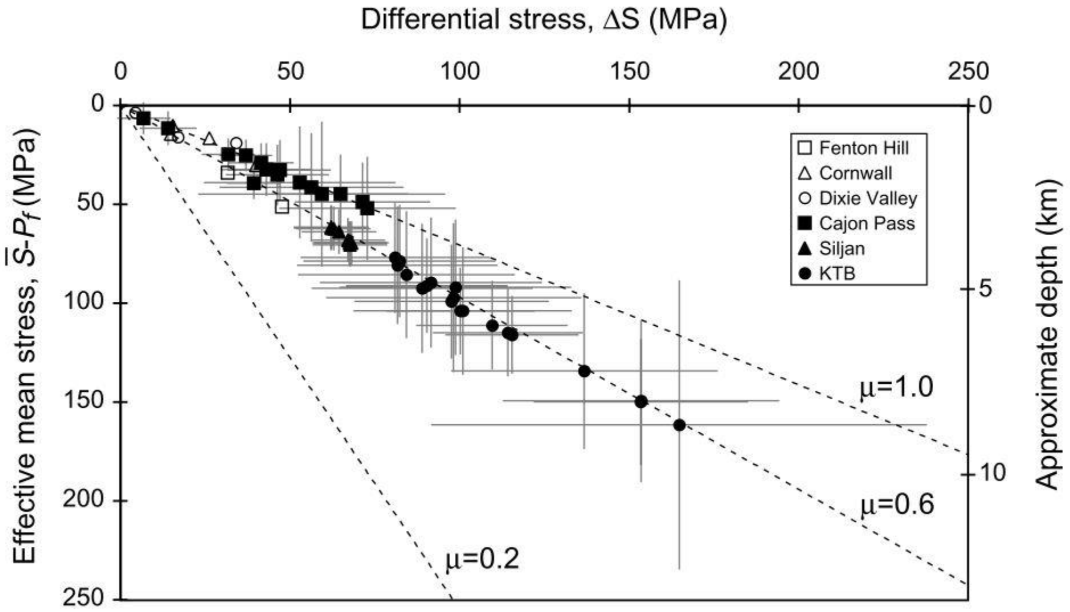
Lithospheric strength profiles



Kohlstedt et al., (1995),
Journal of Geophysical Research

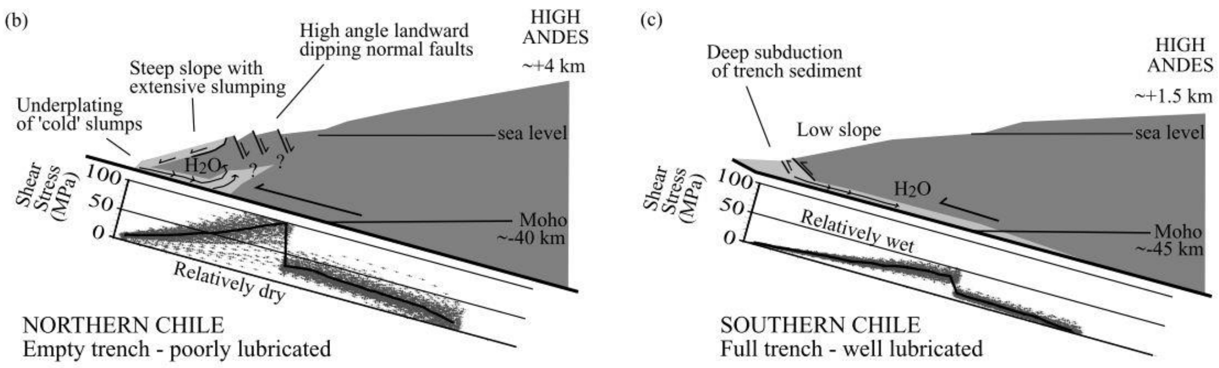
How strong are faults in nature?

Strong faults



Townend and Zoback (2000), Geology

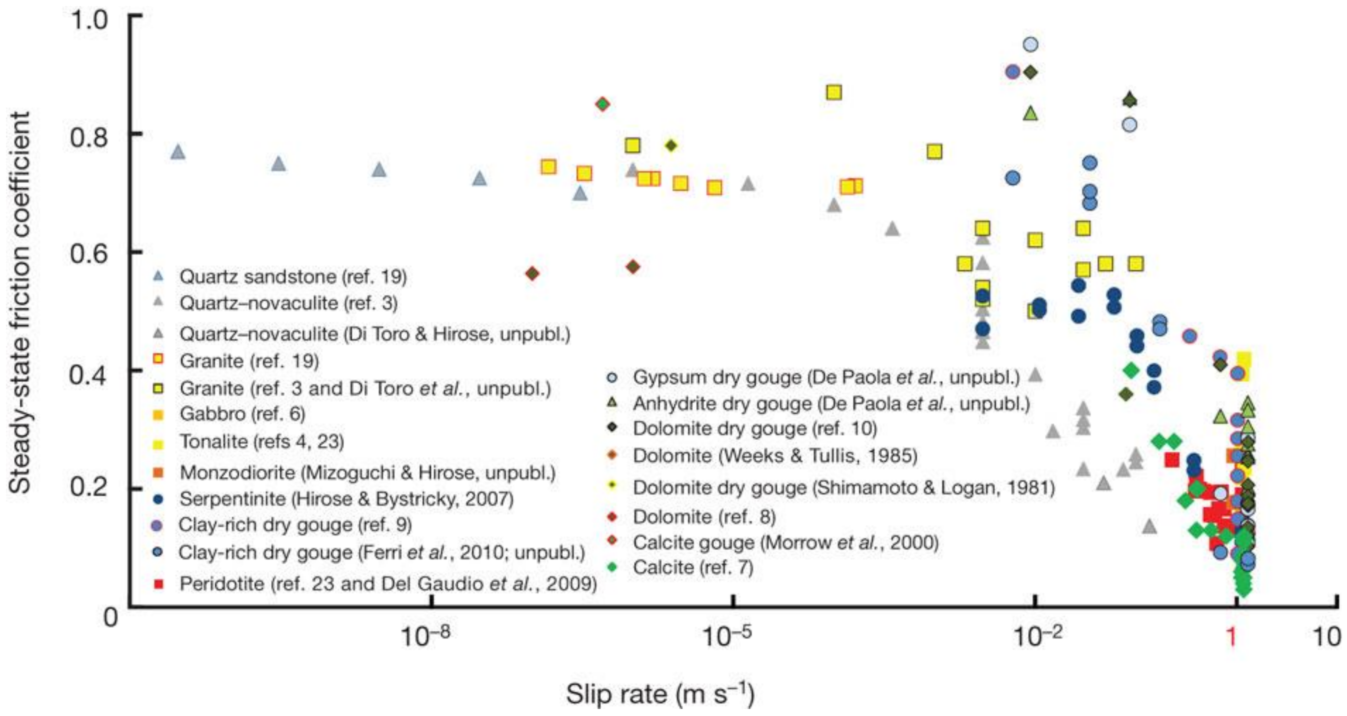
Weak faults



Lamb (2006), Journal of Geophysical Research

For review of strong and weak faults see:
Collettini et al., (2019), EPSL

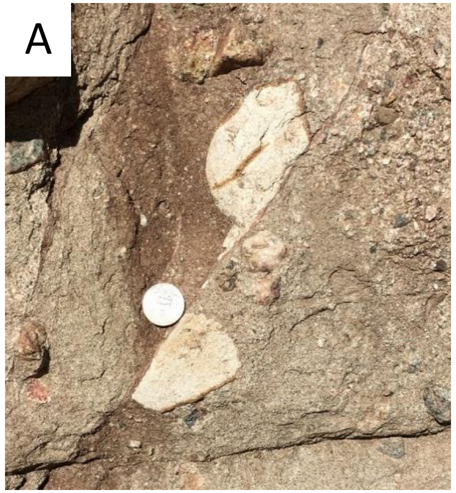
Coseismic fault strength



Di Toro et al., (2011), Nature

Part I: How does fault rock heterogeneity control fault strength and stability

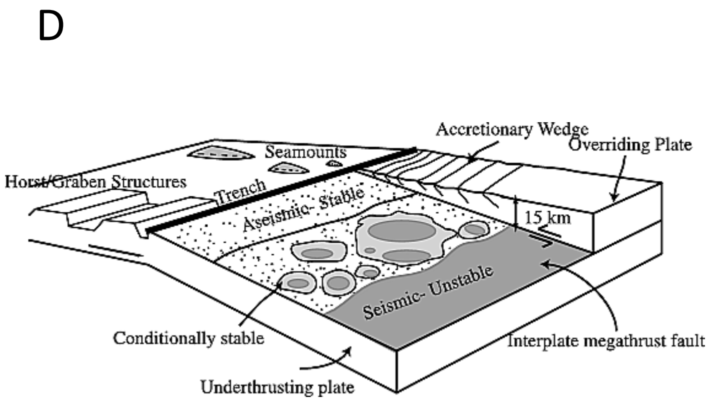
Fault zone heterogeneity



Punchbowl, California

Alpine Schist, NZ

Carboneras Fault, SE Spain

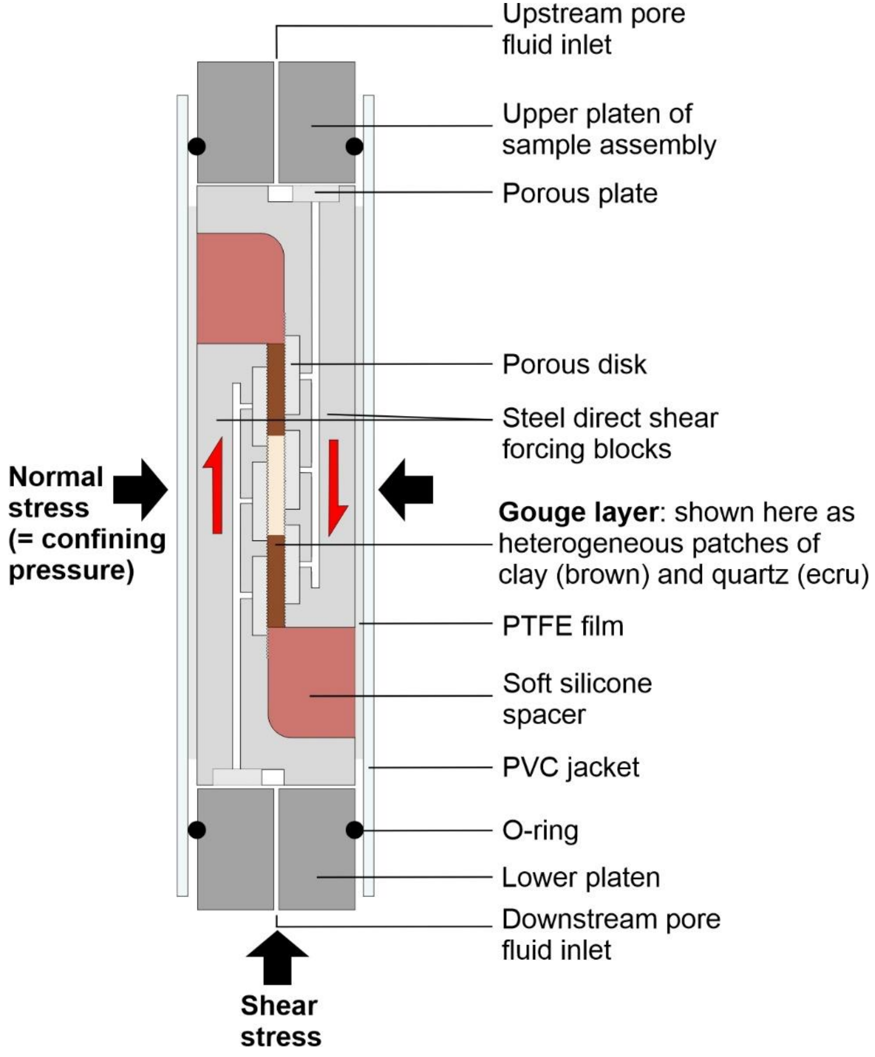


Bilek and Lay (2002)
Geophys. Res. Letters

cm-scale — **10's of meter-scale** — **km-scale** →

How does heterogeneity influence fault strength and stability?

Methods: How does heterogeneity affect fault strength?



<u>Experimental conditions</u>:

Confining pressure = 60 MPa

Pore-fluid pressure = 20 MPa

Effective normal stress = 40 MPa

Velocity steps of 0.3 to 3 $\mu m \cdot s^{-1}$ and back are applied throughout the experiment so that the rate-and state friction parameters can be analysed.

2 types of fault gouge used:

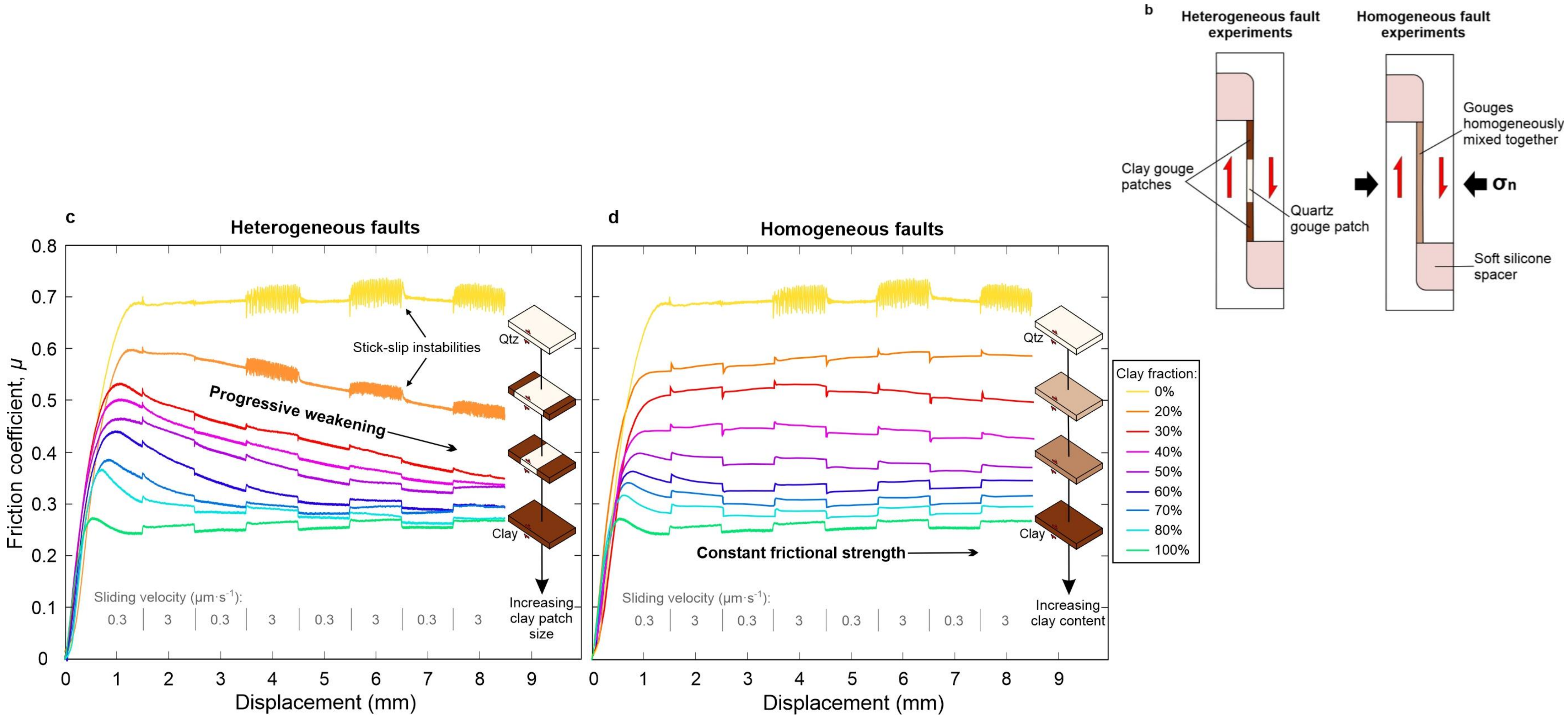
Quartz (rate-weakening)

Kaolinite clay (rate-strengthening)

Both gouges are <5 µm grain size

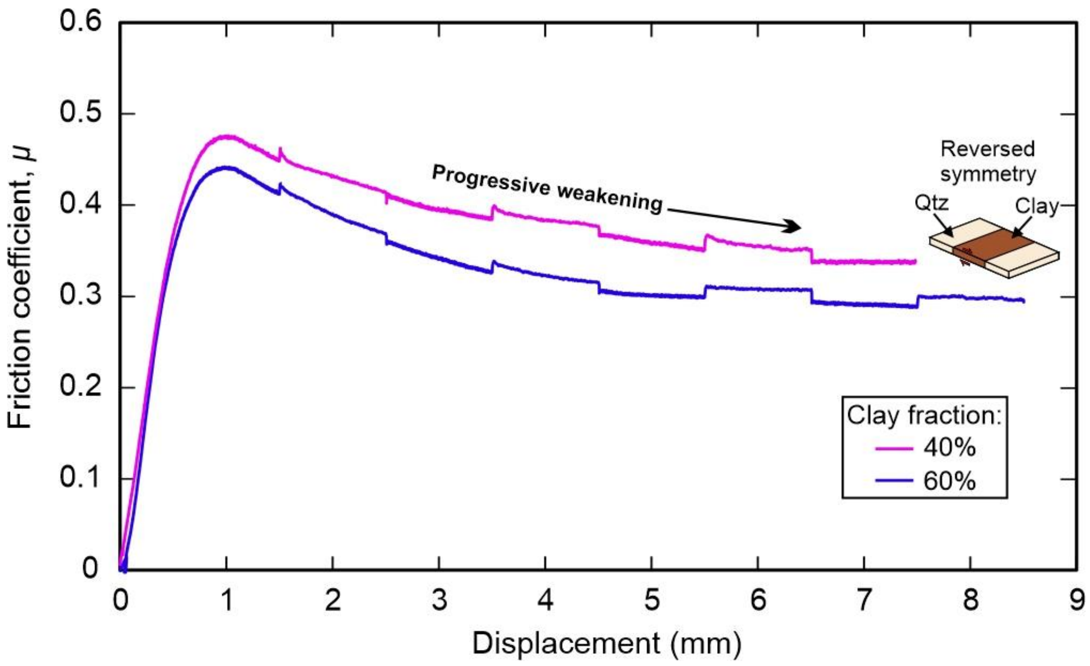
Sliding area: 50 mm long, 20 mm wide, 1 mm thick

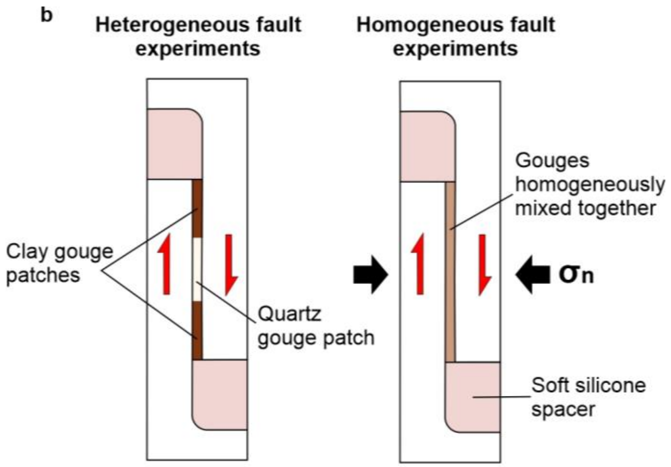
Results: Frictional strength evolution



Bedford et al., (2022), Nat. Comms.

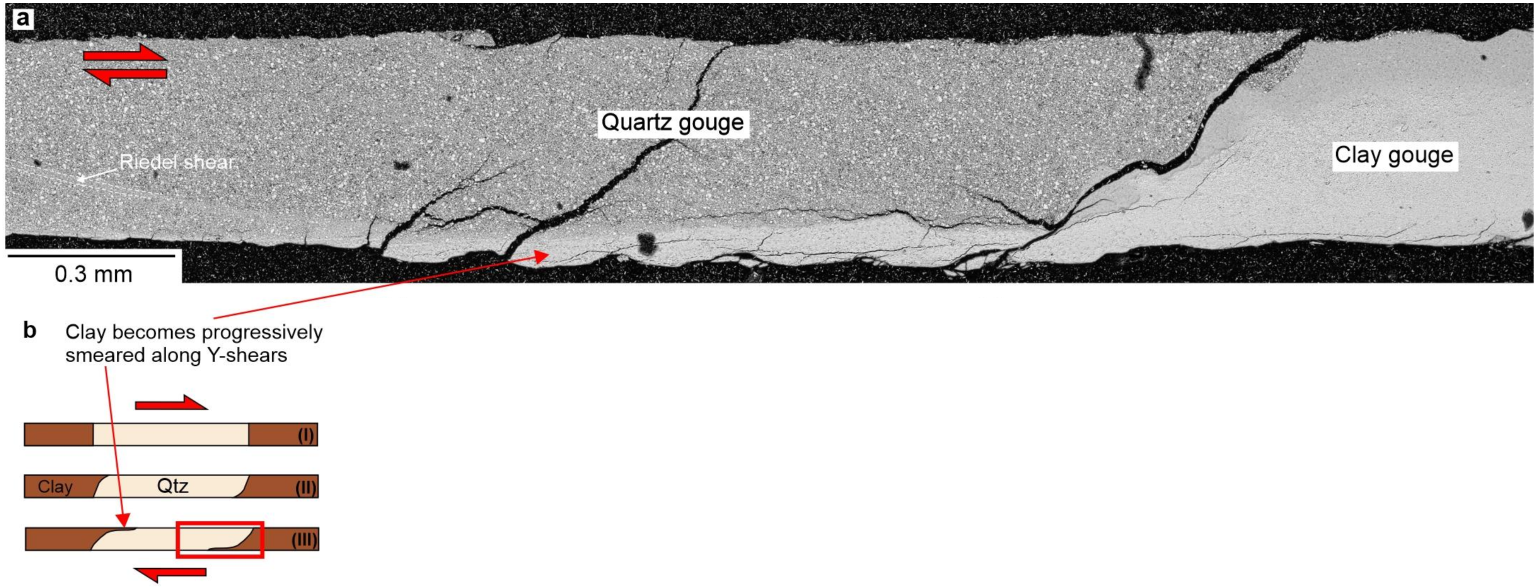
Results: Frictional strength evolution





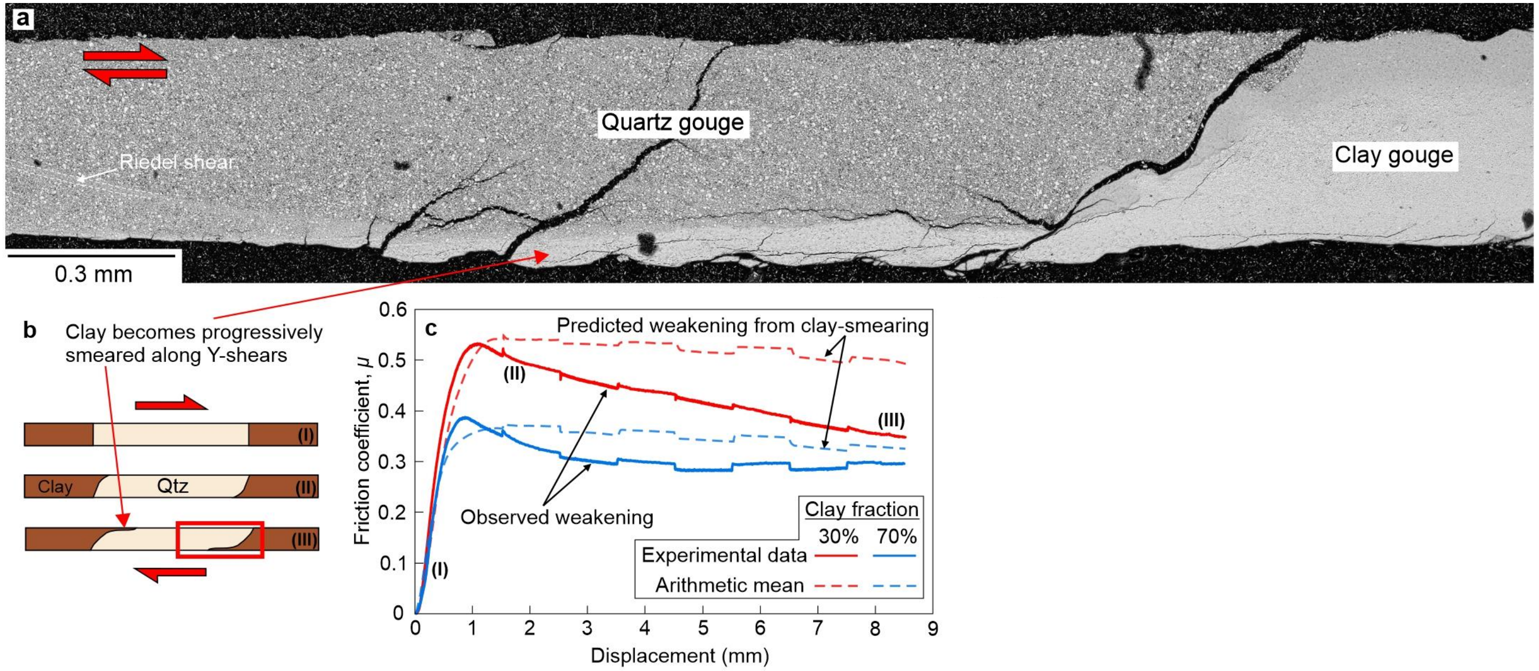
Bedford et al., (2022), Nat. Comms.

Results: Microstructure and heterogeneity-induced weakening



Bedford et al., (2022), Nat. Comms.

Results: Microstructure and heterogeneity-induced weakening



<u>Causes of the observed weakening:</u>

Clay-smearing

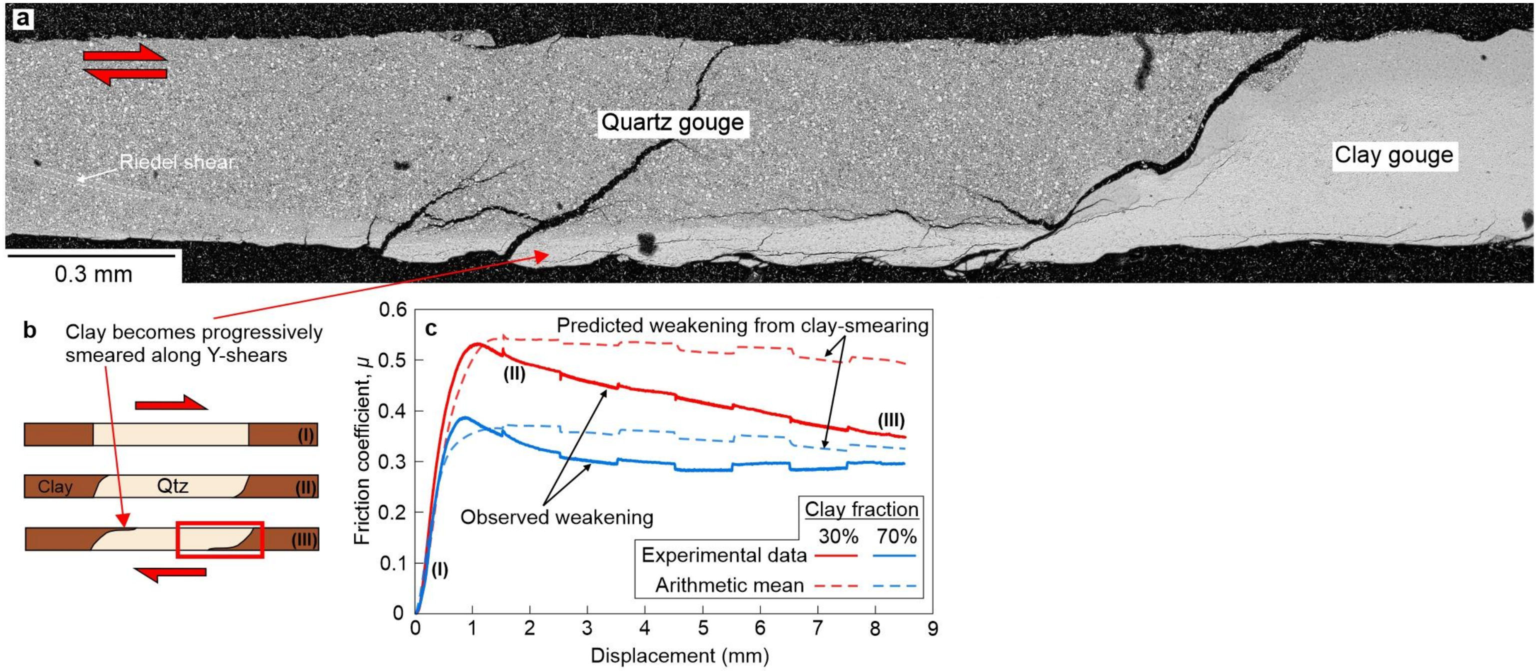
- Leads to a growing fraction of the shearing surface being hosted in the weaker clay gouge?

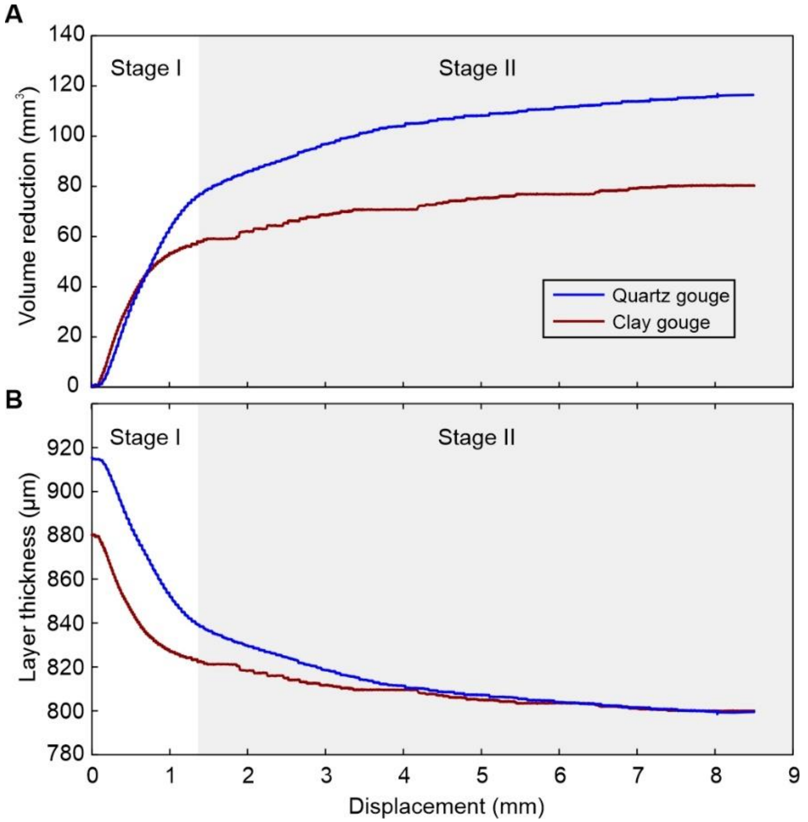
Stress concentrations

- Produced by the propagating localized Y-shear bands allowing the strong quartz patch to slip at a lower shear stress?

Bedford et al., (2022), Nat. Comms.

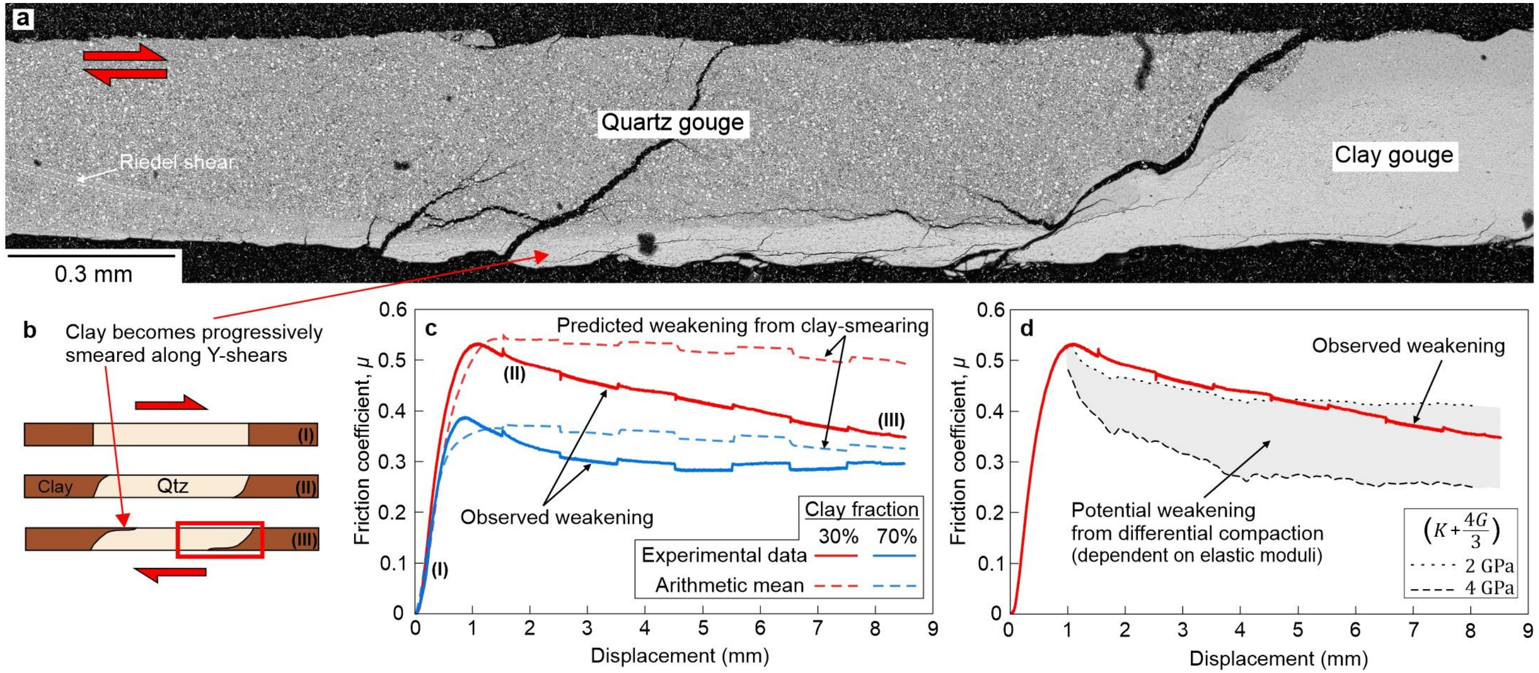
Results: Microstructure and heterogeneity-induced weakening





Bedford et al., (2022), Nat. Comms.

Results: Microstructure and heterogeneity-induced weakening



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Stress concentrations

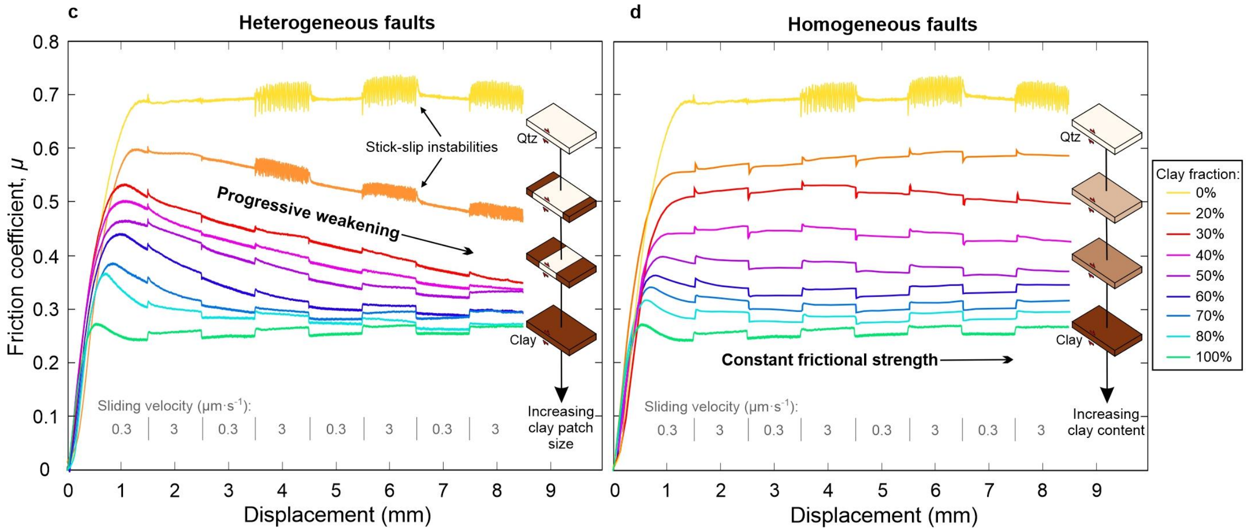
- Produced by the propagating localized Y-shear bands allowing the strong quartz patch to slip at a lower shear stress?

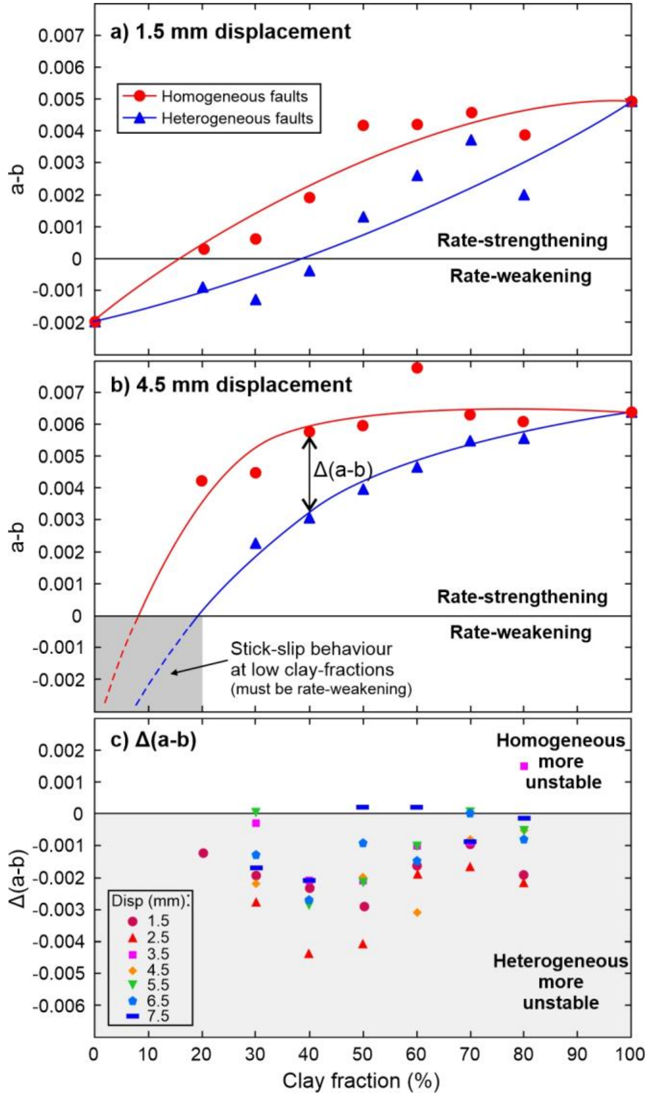
Differential compaction

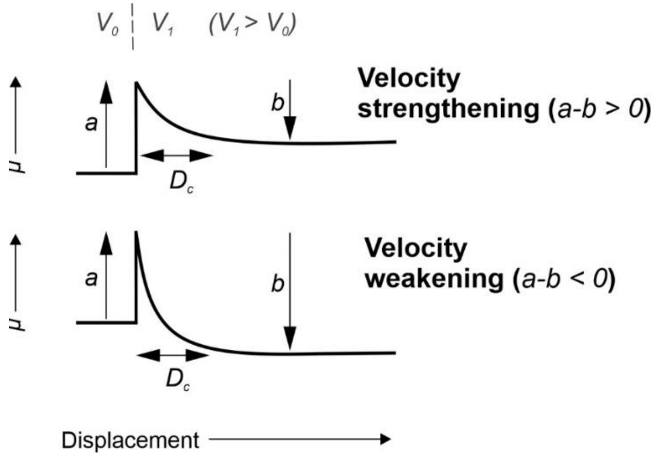
- Redistributing the normal stress leading to a weakening effect?

Bedford et al., (2022), Nat. Comms.

Results: Frictional stability





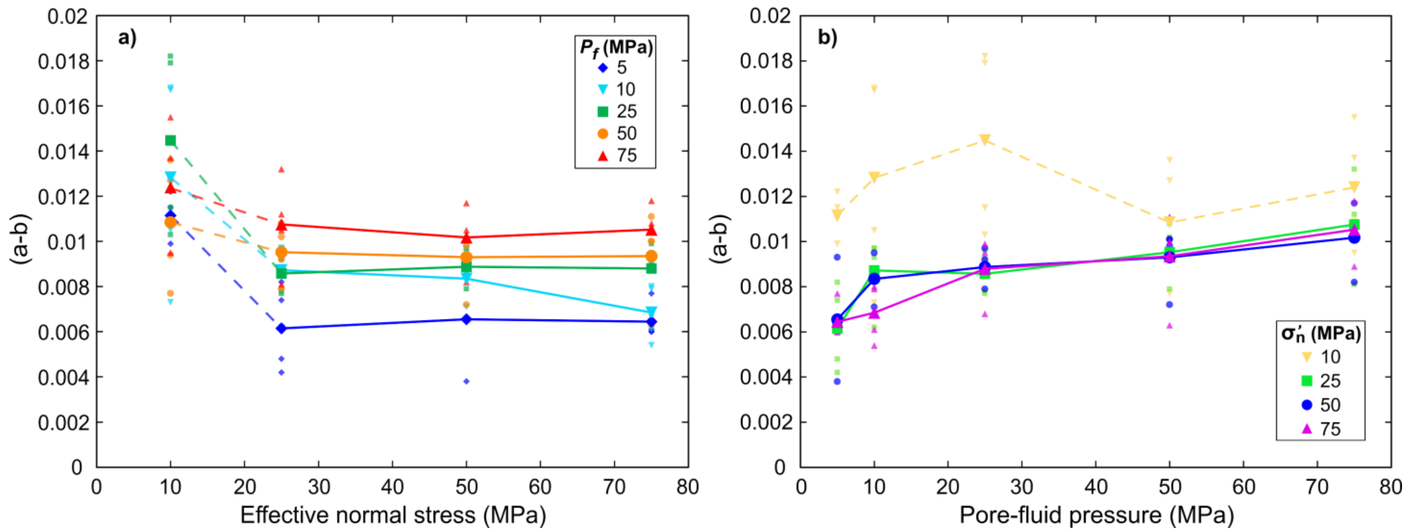


Heterogeneous faults have consistently lower a-b values than their equivalent homogeneous fault

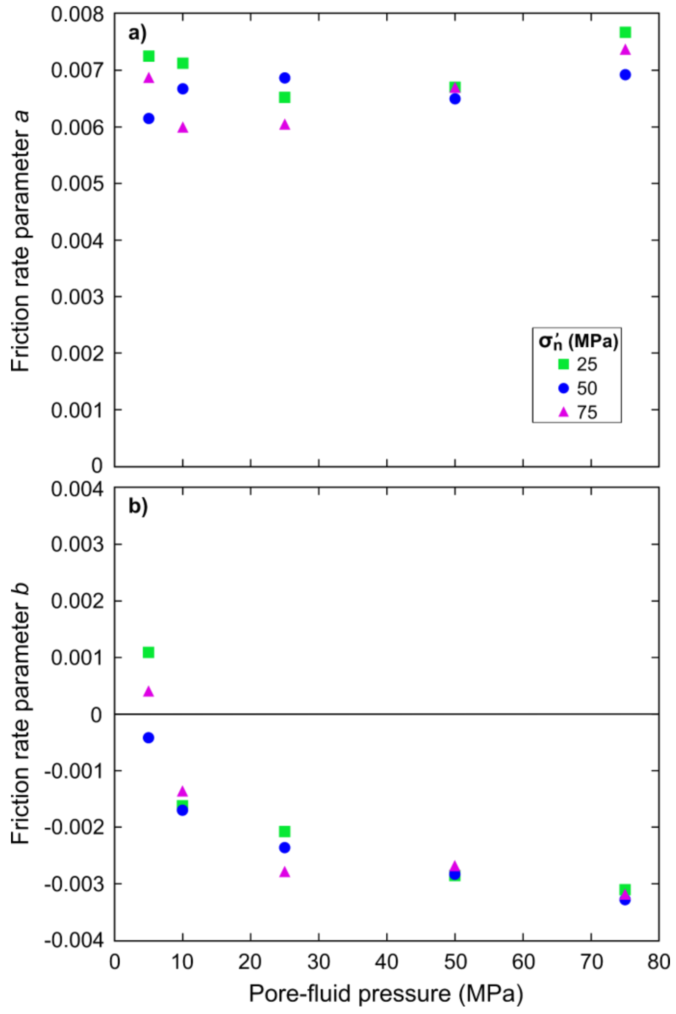
Bedford et al., (2022), Nat. Comms.

Other controls on frictional stability

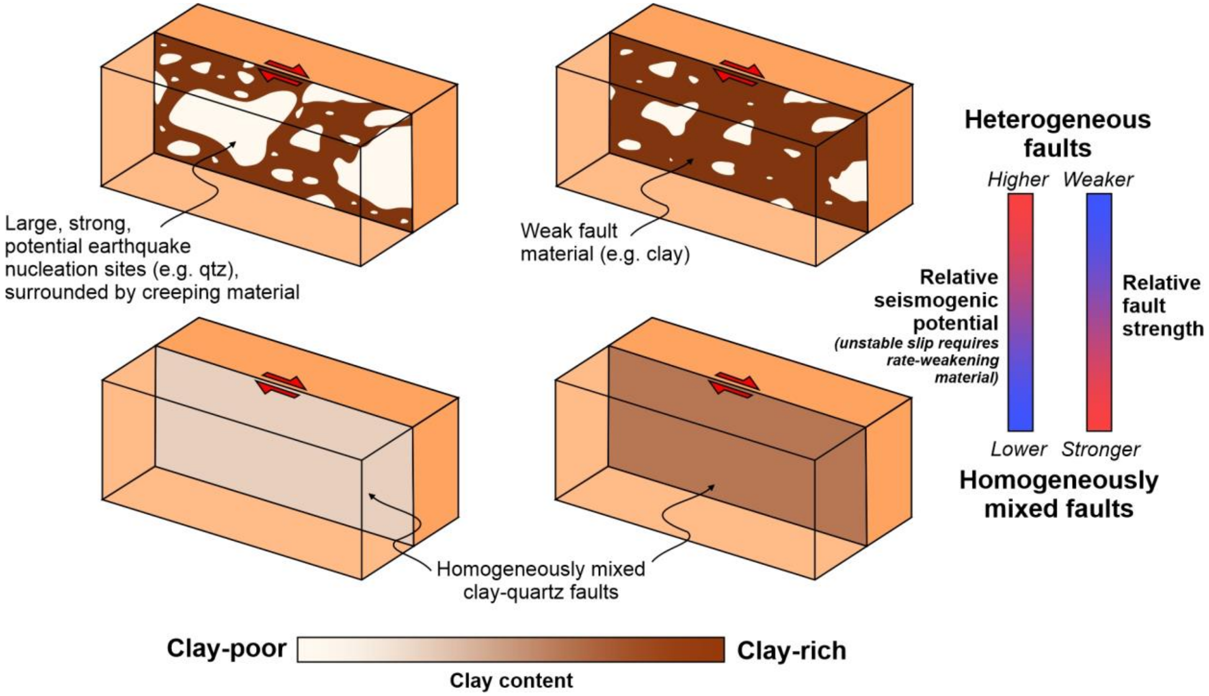
Velocity-step friction experiments on gouges from the Nankai Trough subduction zone (SW Japan).



Bedford et al., (2021), EPSL.



Summary (Part I)



Bedford et al., (2022), Nat. Comms.

Heterogeneous faults are weaker and more unstable than equivalent homogeneous faults.

- Could explain weak faults in nature?

The weakening effect is linked caused by a combination of processes:

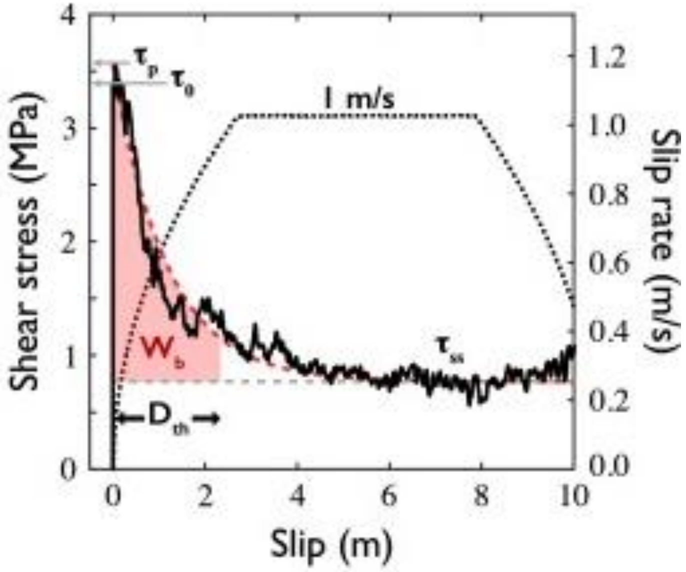
- Clay smearing
- Stress concentrations
- Differential compaction

The interplay between the scale of heterogeneity and fault structure will likely control the seismogenic potential of the fault.

Part II: Fault strength recovery after an earthquake

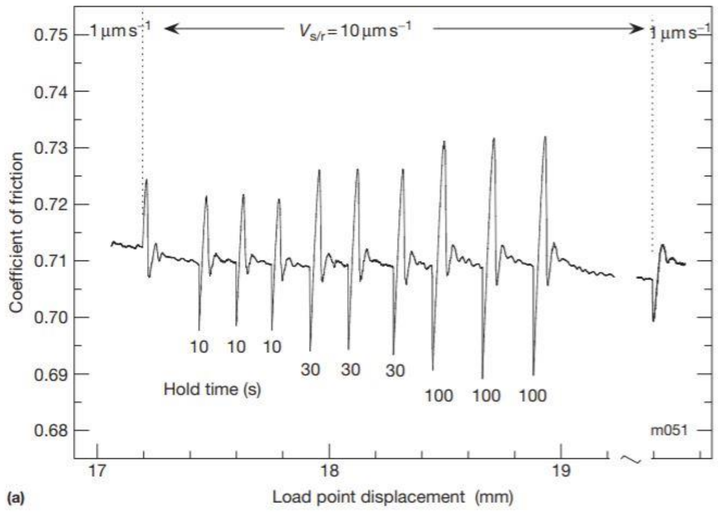
Fault weakening and restrengthening

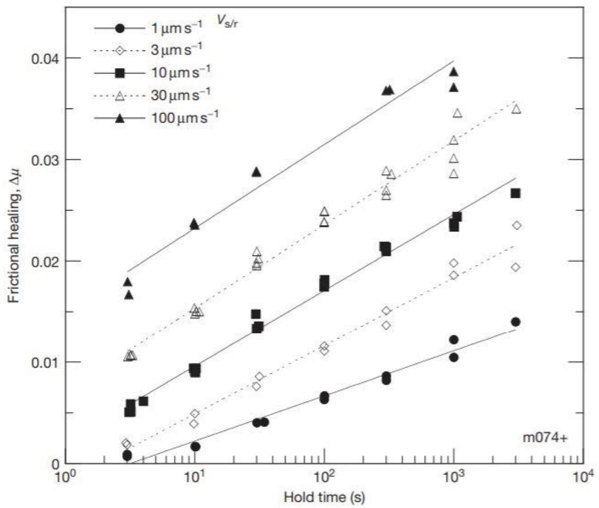
Dynamic fault weakening



Seyler et al., (2020), EPSL.

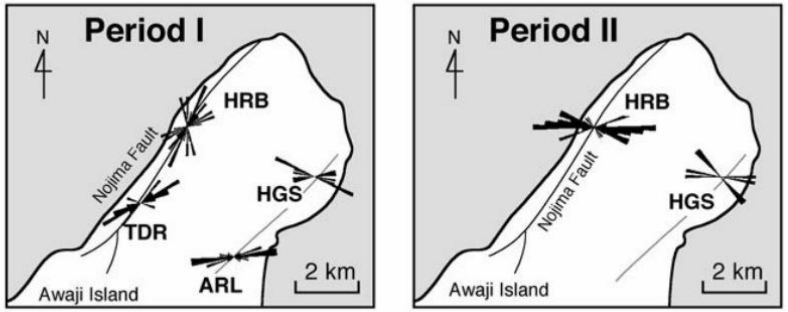
Fault restrengthening (healing)





Marone and Saffer (2015), Treatise on Geophys.

Fault healing in nature

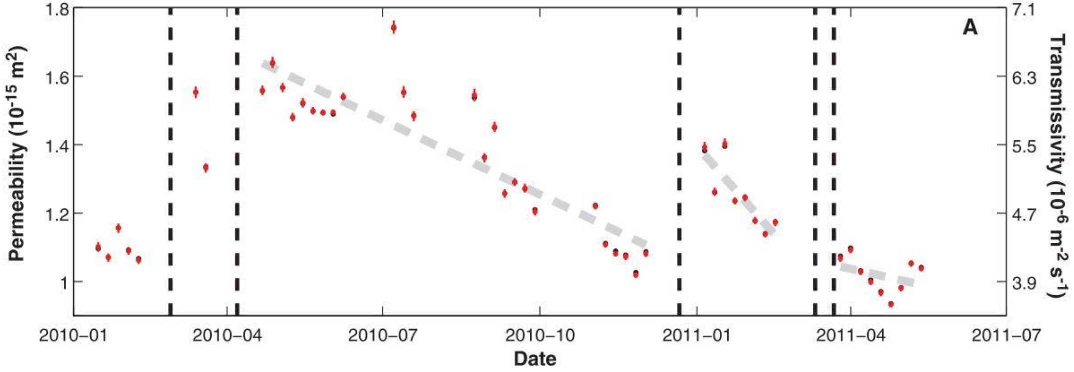


Tadokoro and Ando (2002), GRL

S-wave splitting measurements after the 1995 Kobe earthquake.

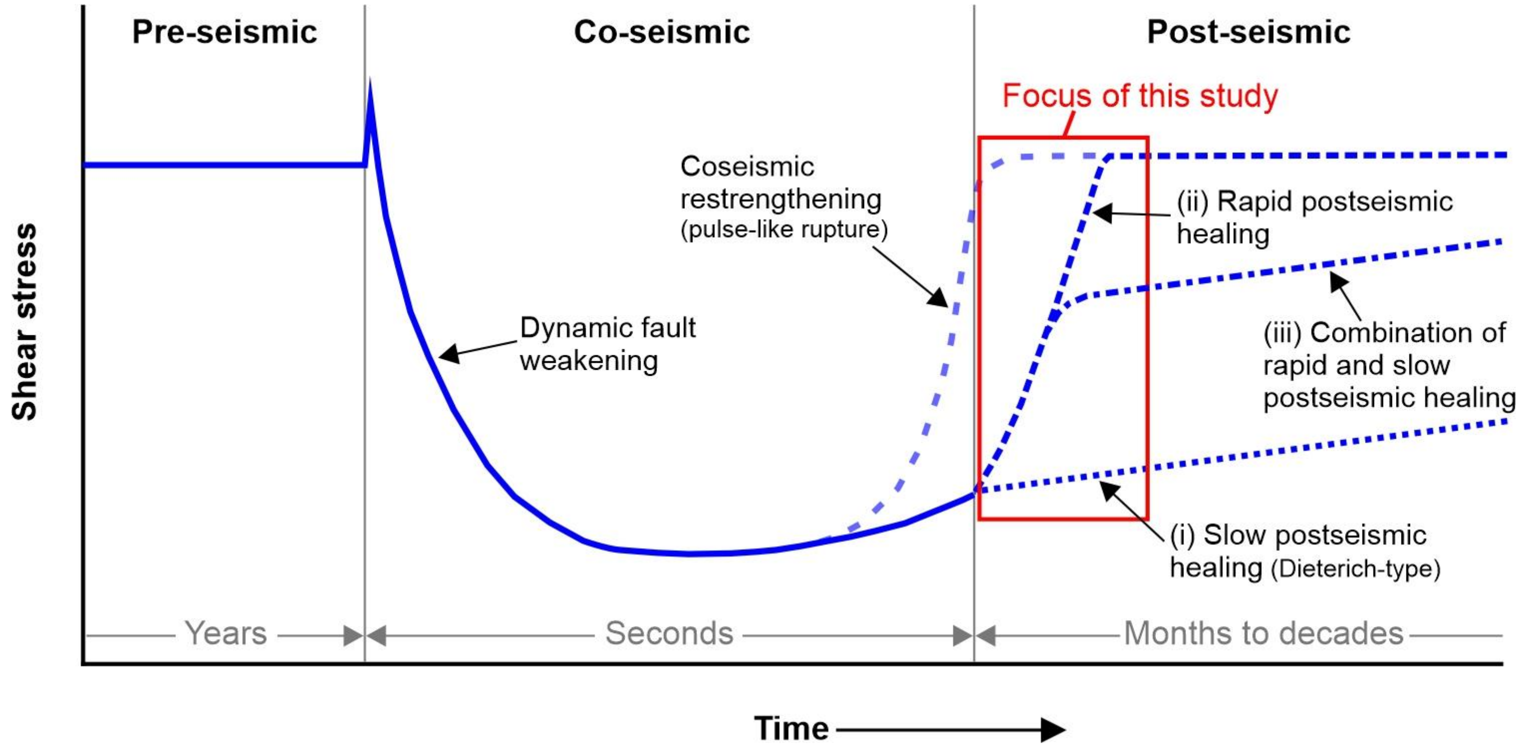
Fault healed after 33 months (recurrence interval ≈ 2000 yr).

Xue et al., (2013), Science



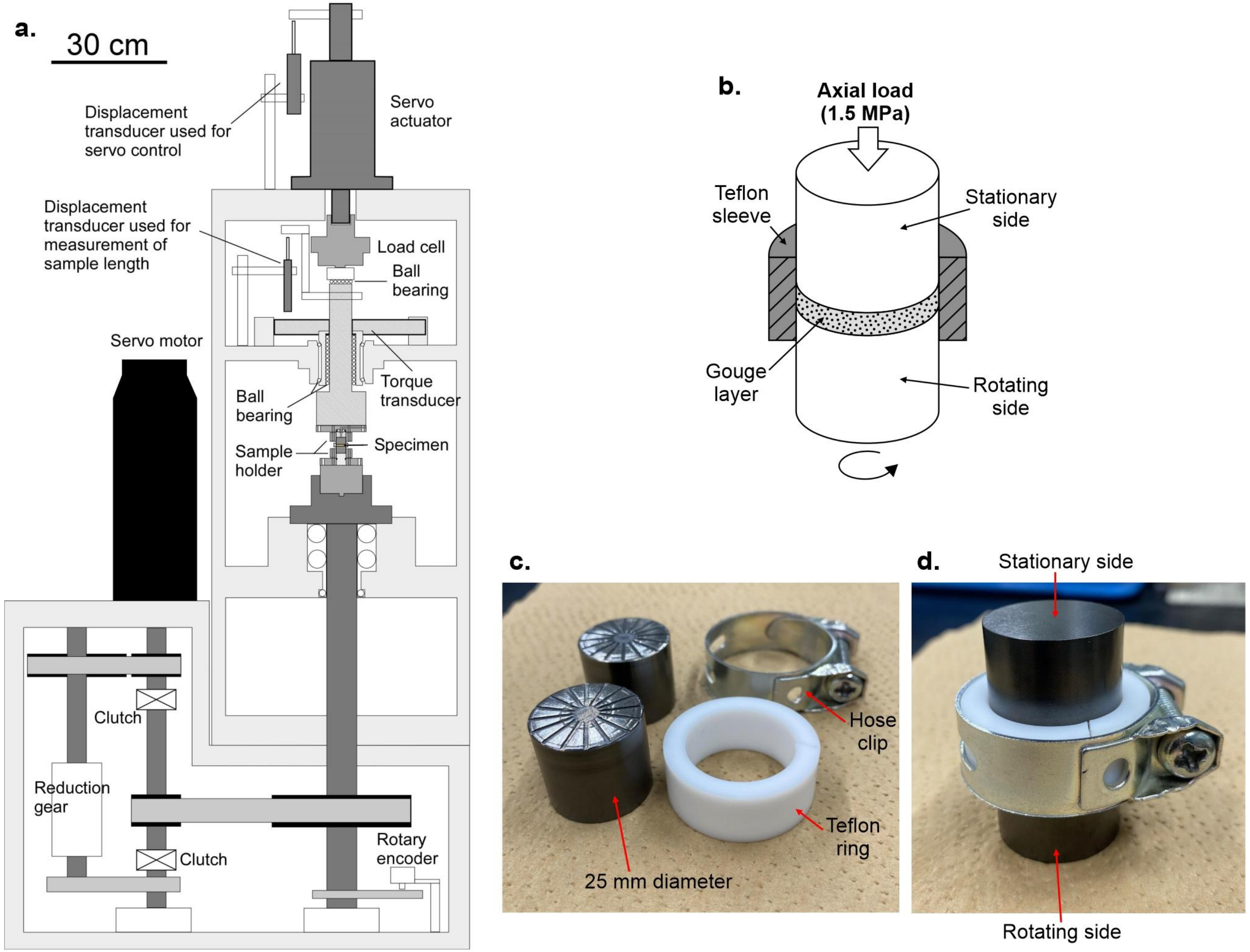
Borehole permeability measurements after 2008 Wenchuan earthquake (M_w 7.9). **Fault healed within 0.6–2.5 years.**

Fault weakening and restrengthening



Bedford et al., (preprint), EarthArXiv

Experimental setup



Bedford et al., (preprint), EarthArXiv

Gouge layer (1.5 mm initial thickness) placed between steel sample holders.

Tested 2 types of gouge: gabbro and granite (both 63-125 µm grain size).

No pore-fluid pressure (atmospheric humidity conditions).

Normal stress = 1.5 MPa

Equivalent slip velocity = 0.57 m/s (650 rpm)

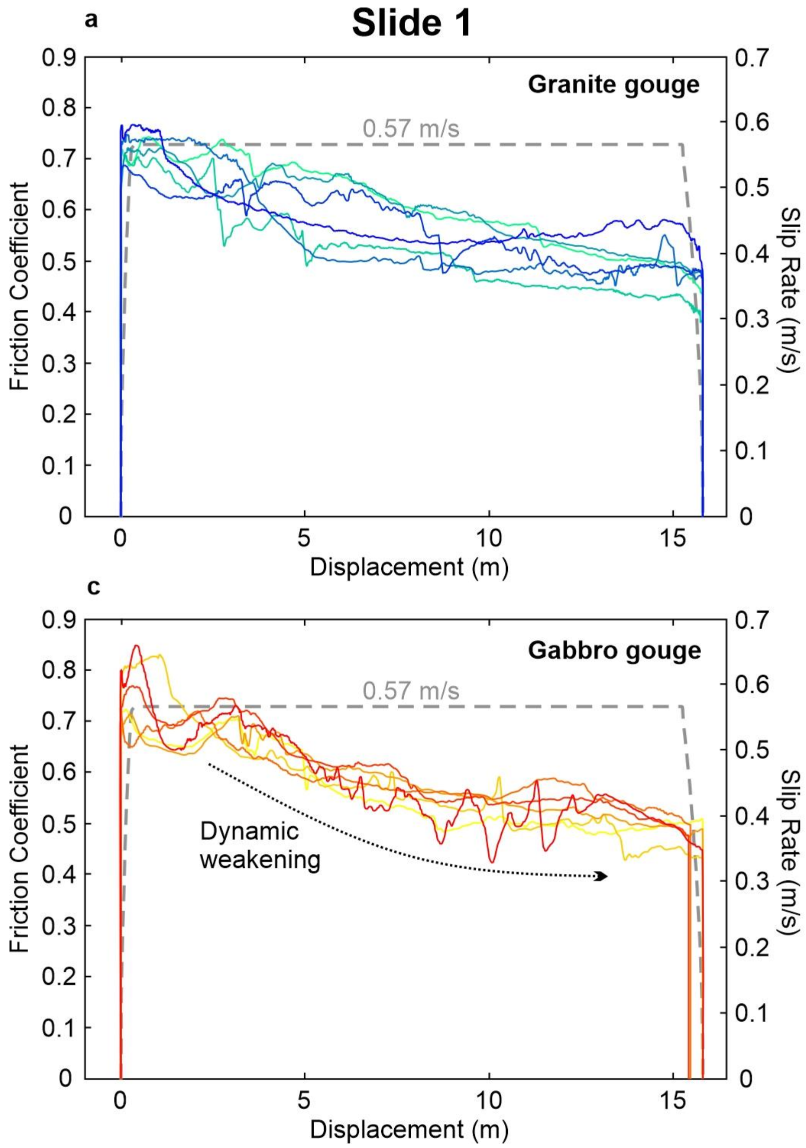
Slide-hold-slide experiments:

- 15 m displacement during each slide.
- Hold time varied.

Friction data

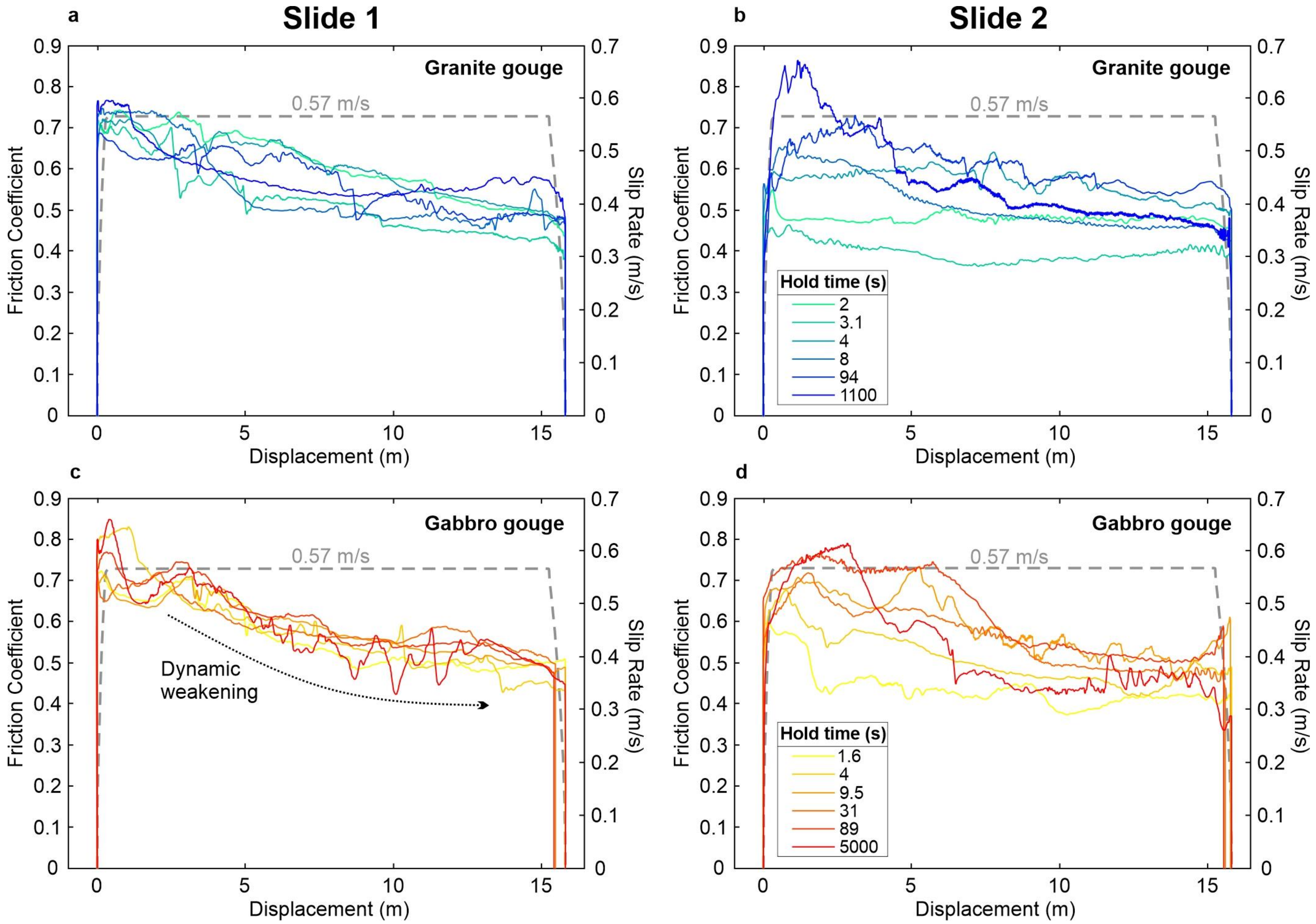
σ_n= 1.5 MPa

v = 0.57 m/s



Bedford et al., (preprint), EarthArXiv

Friction data



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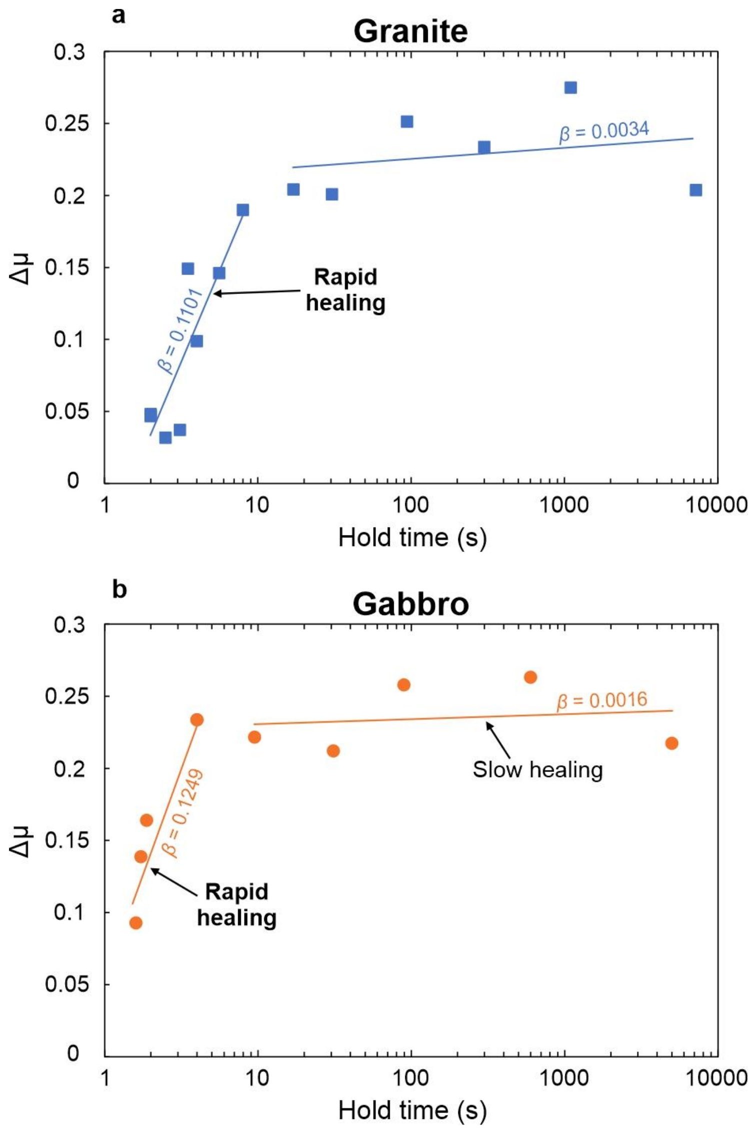
v = 0.57 m/s

Bedford et al., (preprint), EarthArXiv

Rapid frictional restrengthening



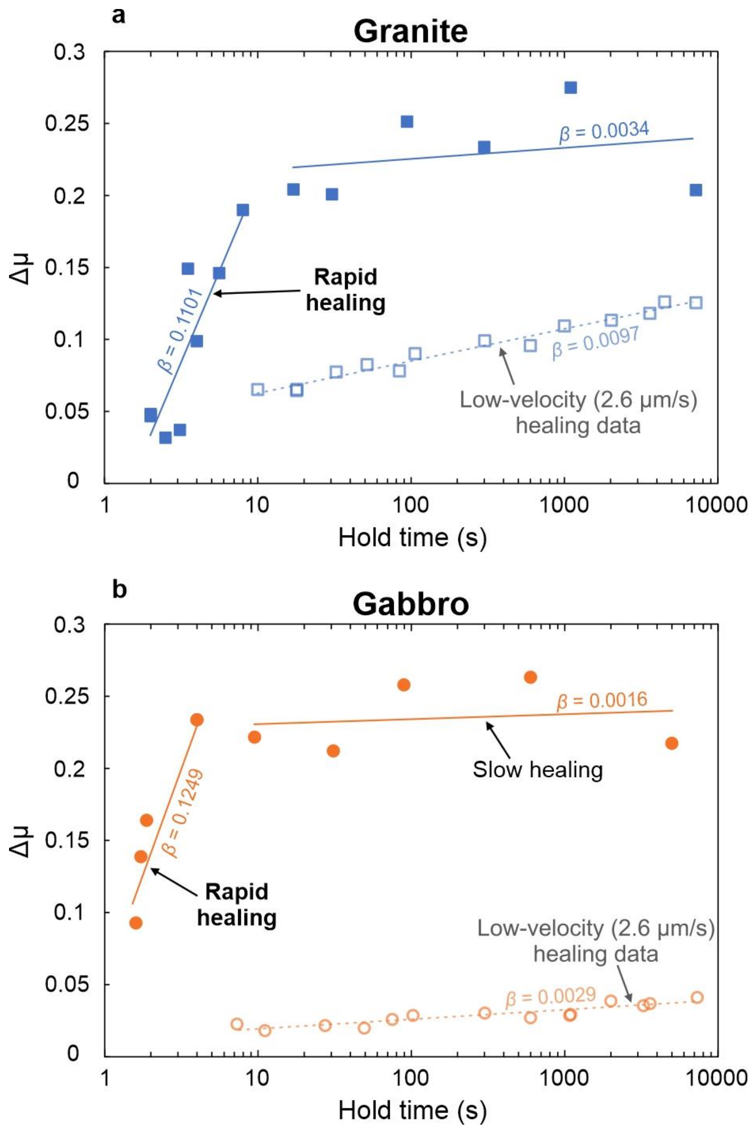
$$\Delta\mu = \mu_{p,2nd} - \mu_{f,1st}$$

<u>Healing rate (β):</u>

$$\beta = \frac{\Delta\mu}{log(t_h)}$$

Bedford et al., (preprint), EarthArXiv

Rapid frictional restrengthening



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Bedford et al., (preprint), EarthArXiv

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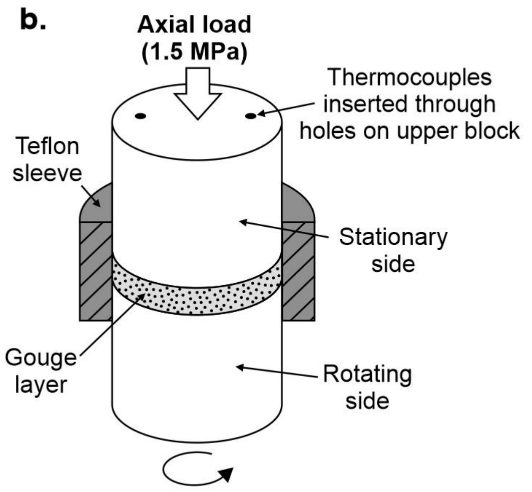

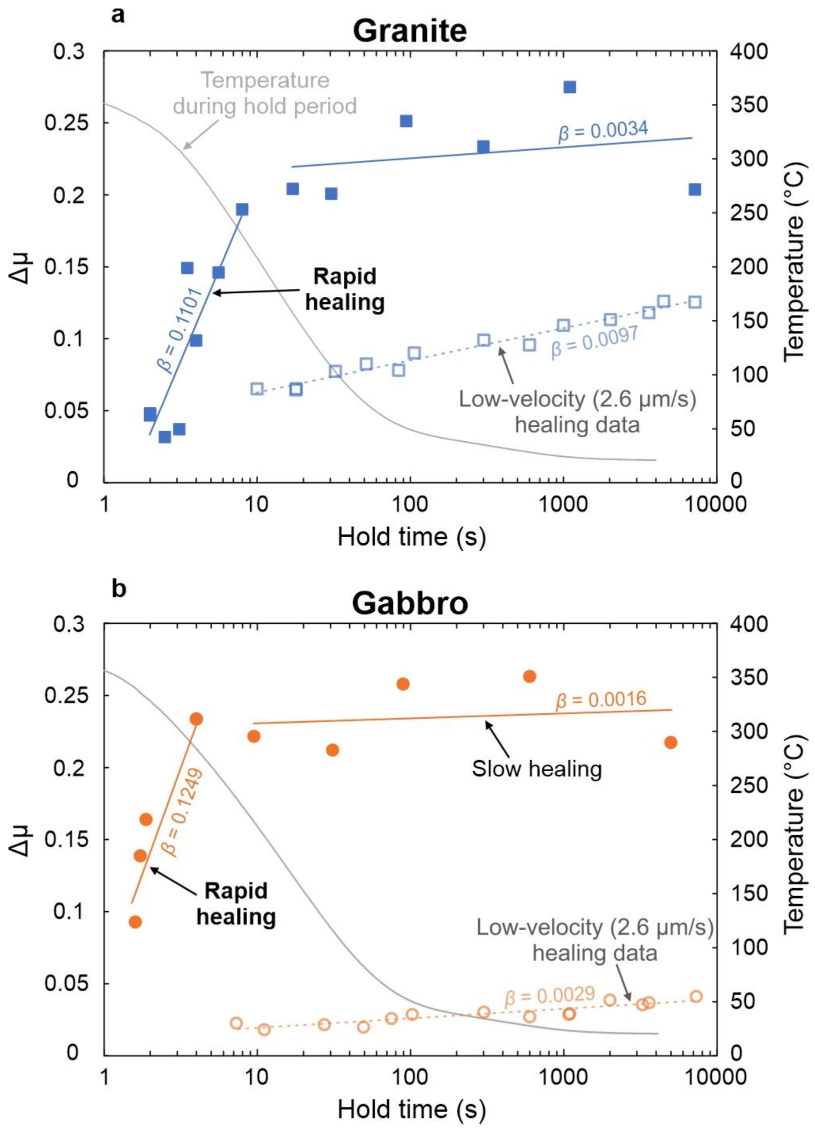

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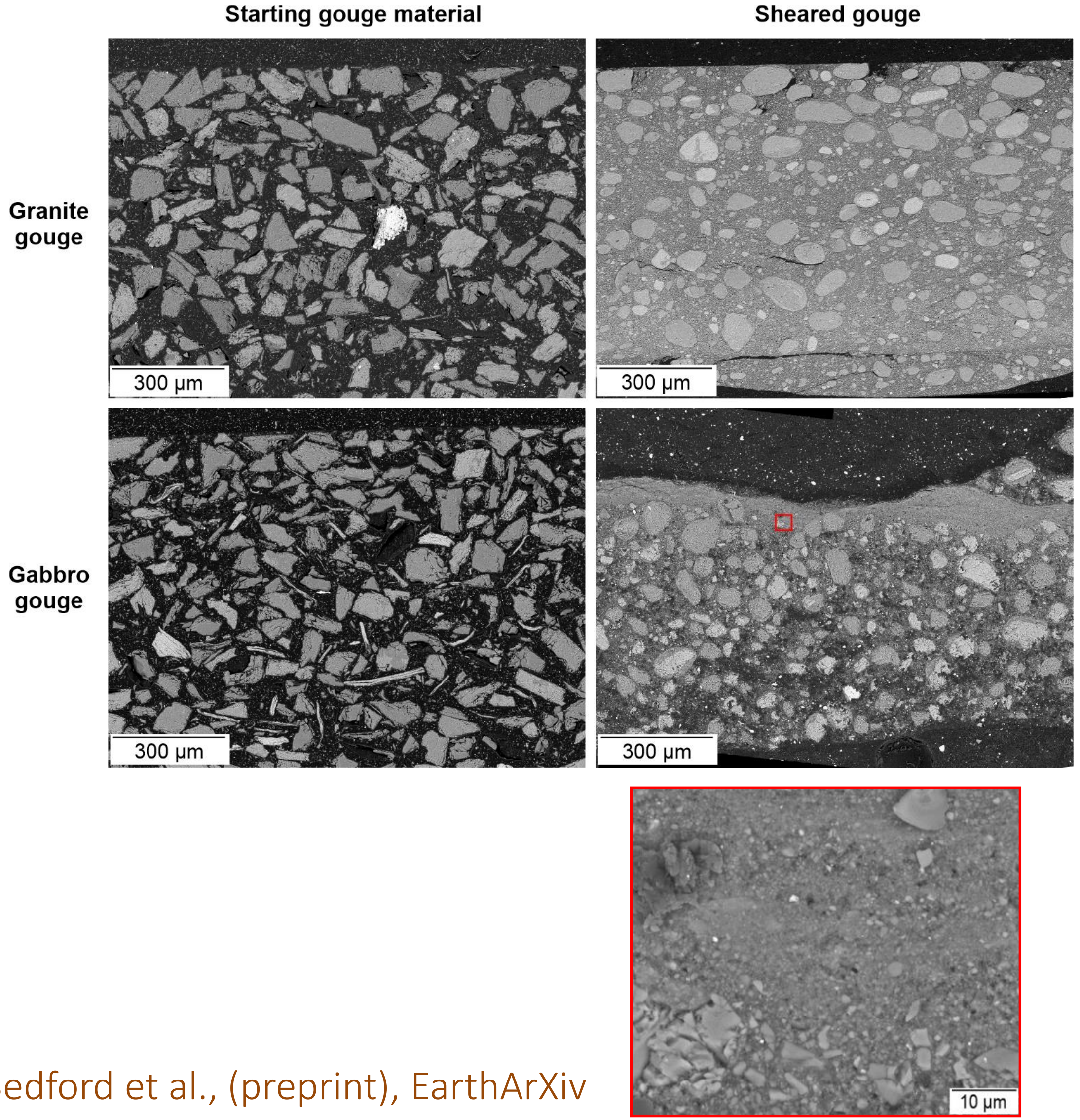
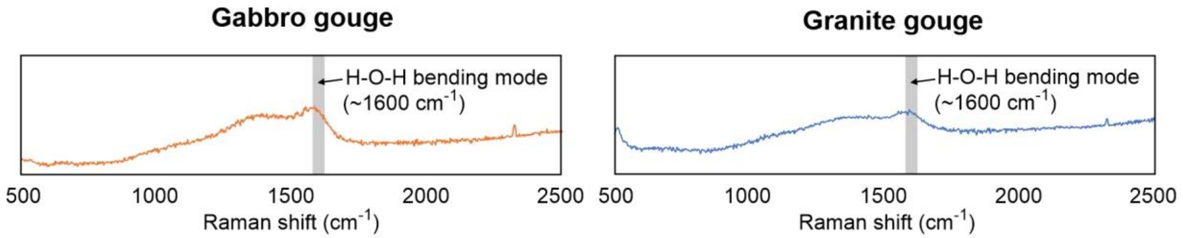
Bedford et al., (preprint), EarthArXiv

What is the restrengthening mechanism?



We analysed the surface of the sheared gouges using **Raman spectroscopy**:

- Provides information on the chemical bonding.



Bedford et al., (preprint), EarthArXiv

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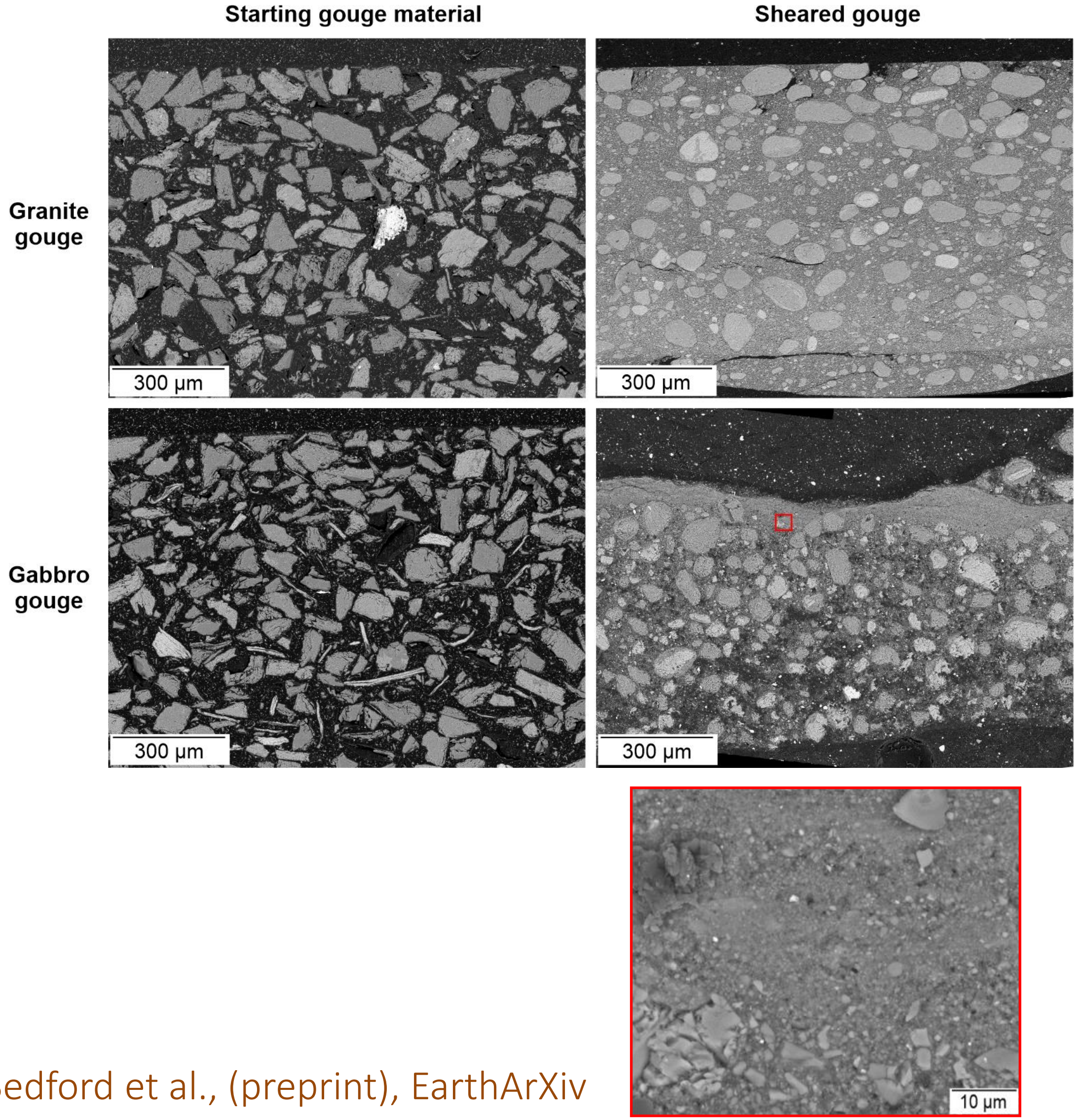

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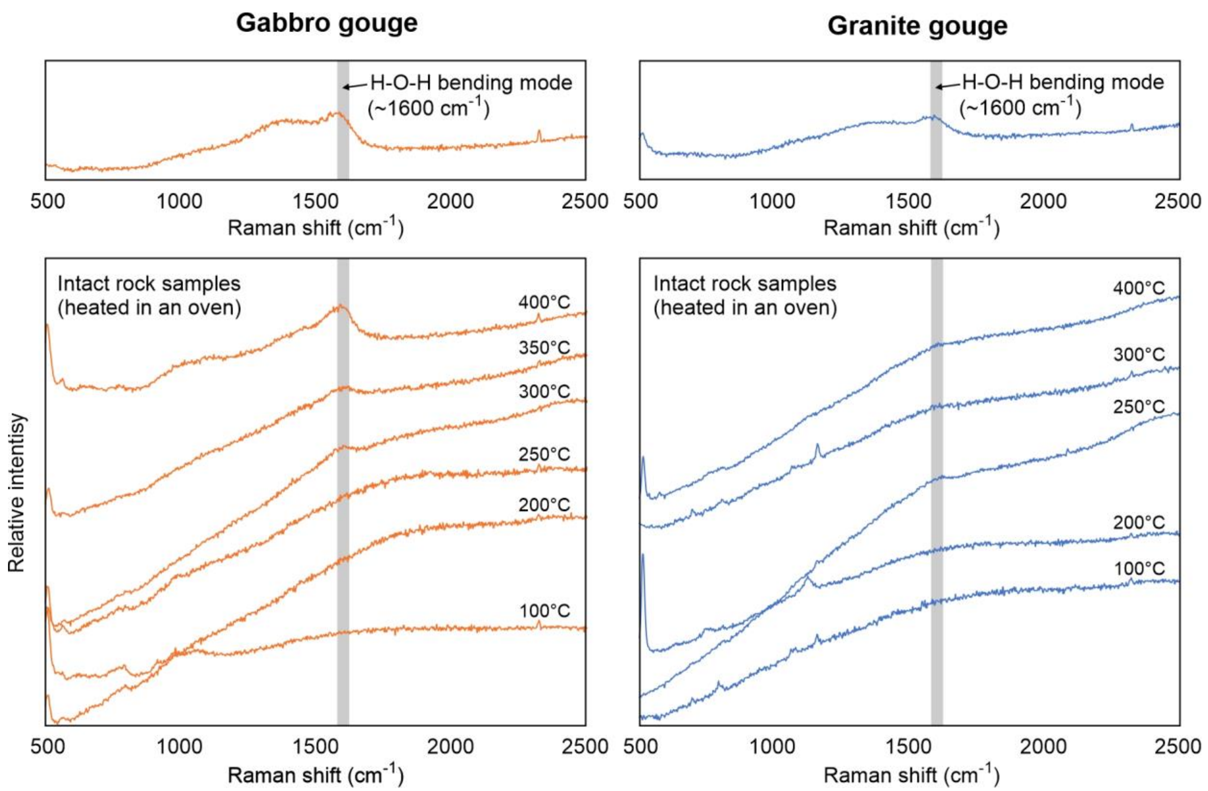

Bedford et al., (preprint), EarthArXiv

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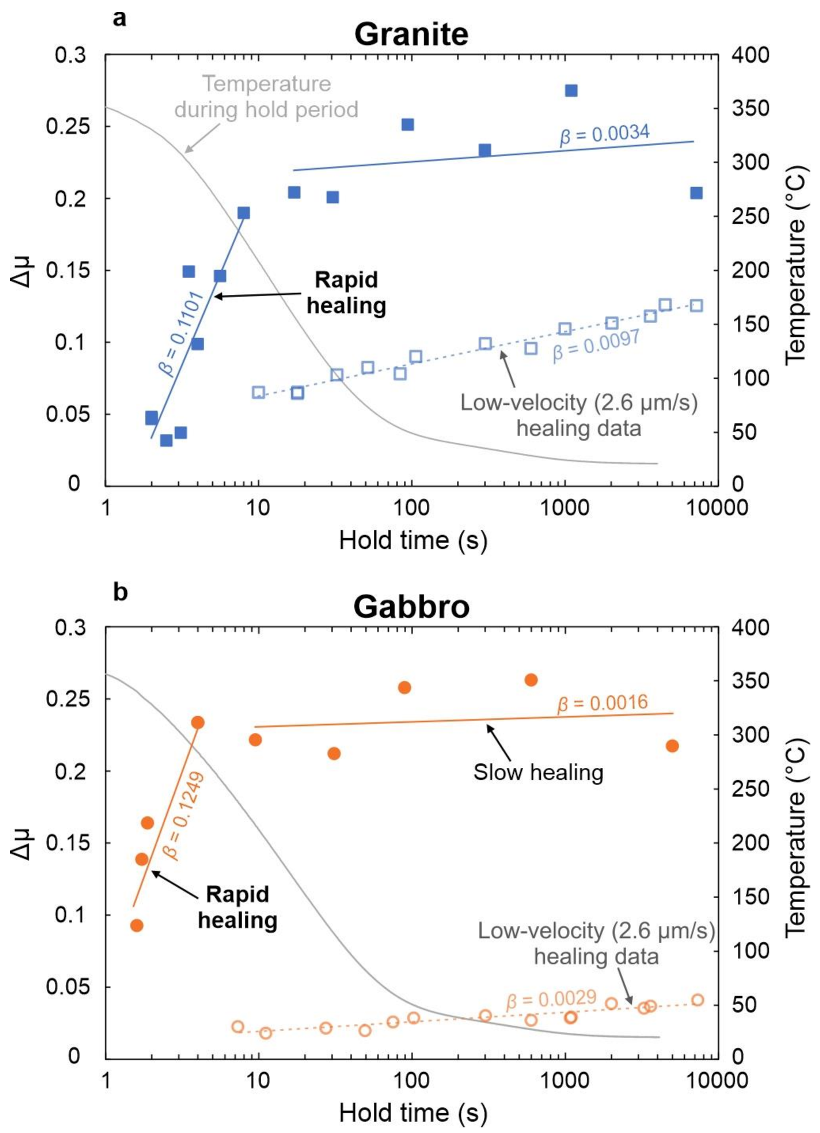

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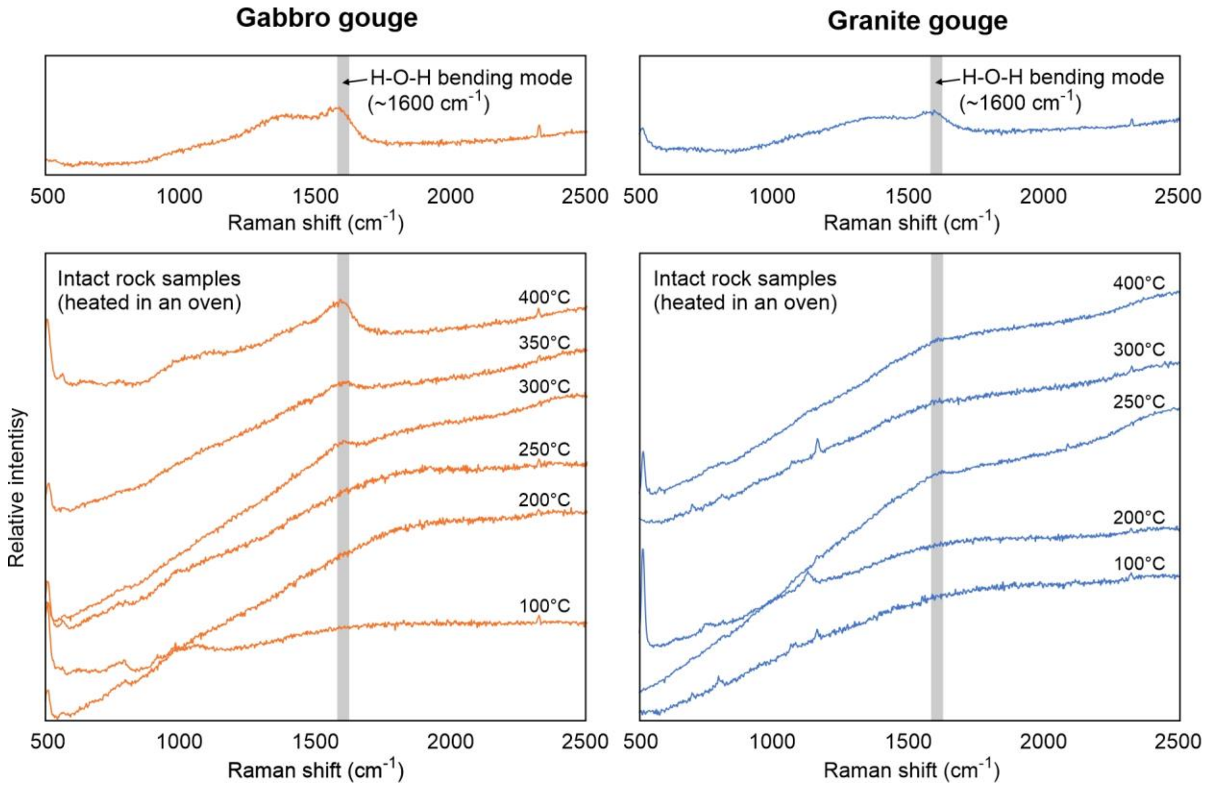

Bedford et al., (preprint), EarthArXiv

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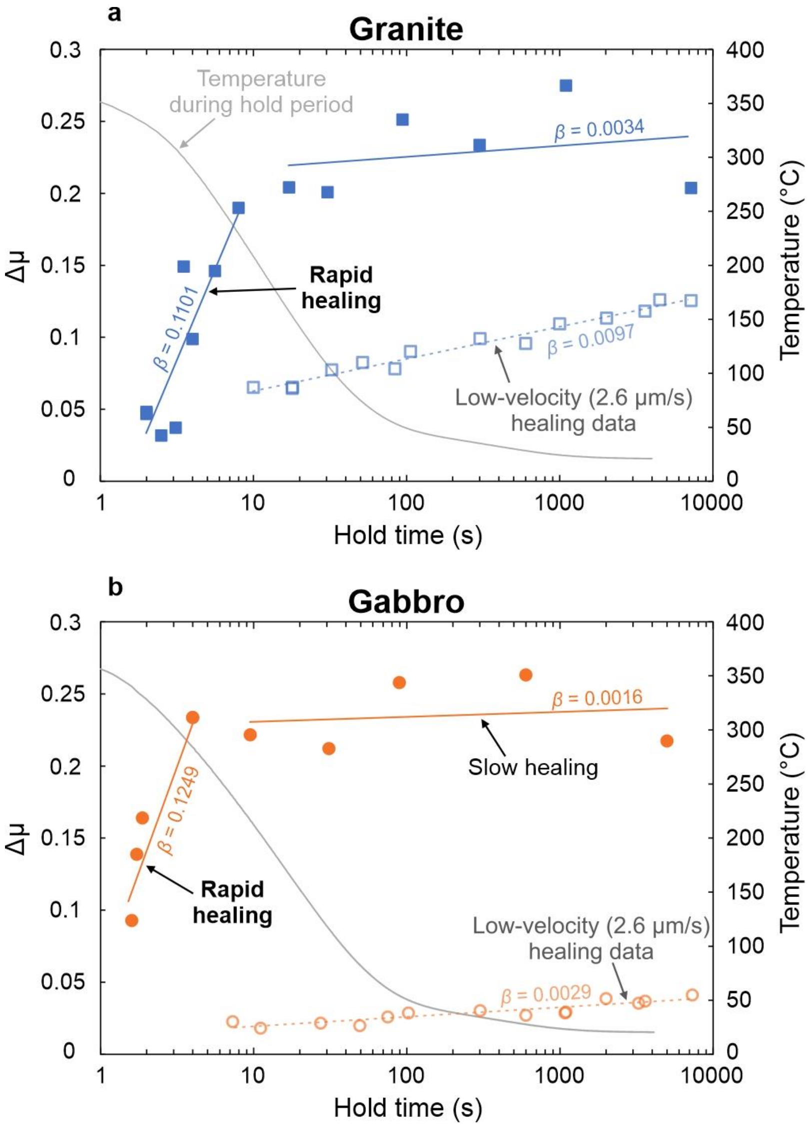
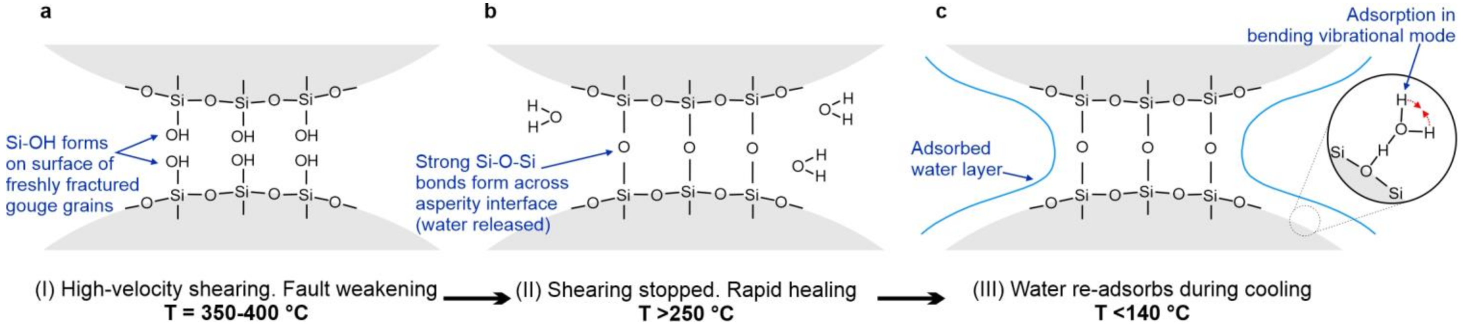
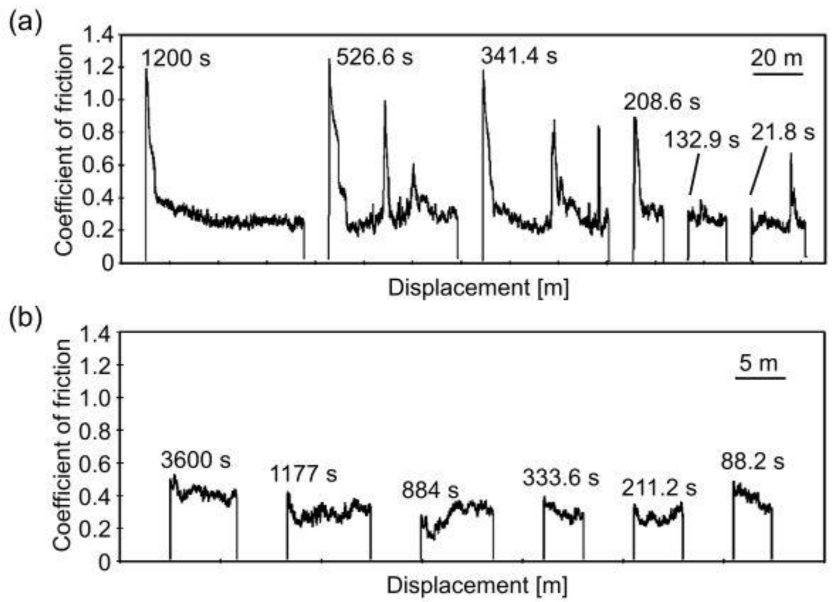


Rapid restrengthening potentially caused by enhanced hydrogen bonding at asperity contacts in the gouge?



Bedford et al., (preprint), EarthArXiv

What is the restrengthening mechanism?

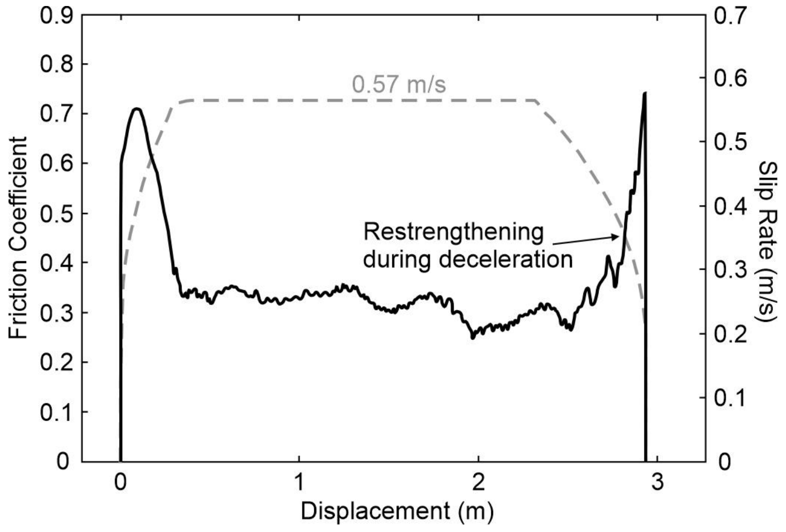


Room humidity atmosphere

Nitrogen atmosphere

SHS experiments run at subseismic slip velocities (85 mm/s) on bare surfaces of gabbro.

Mizoguchi et al., (2006), GRL.



Bedford et al., (preprint), EarthArXiv

Summary (Part II)

Granite and gabbro gouge faults regain their strength rapidly after seismic slip.

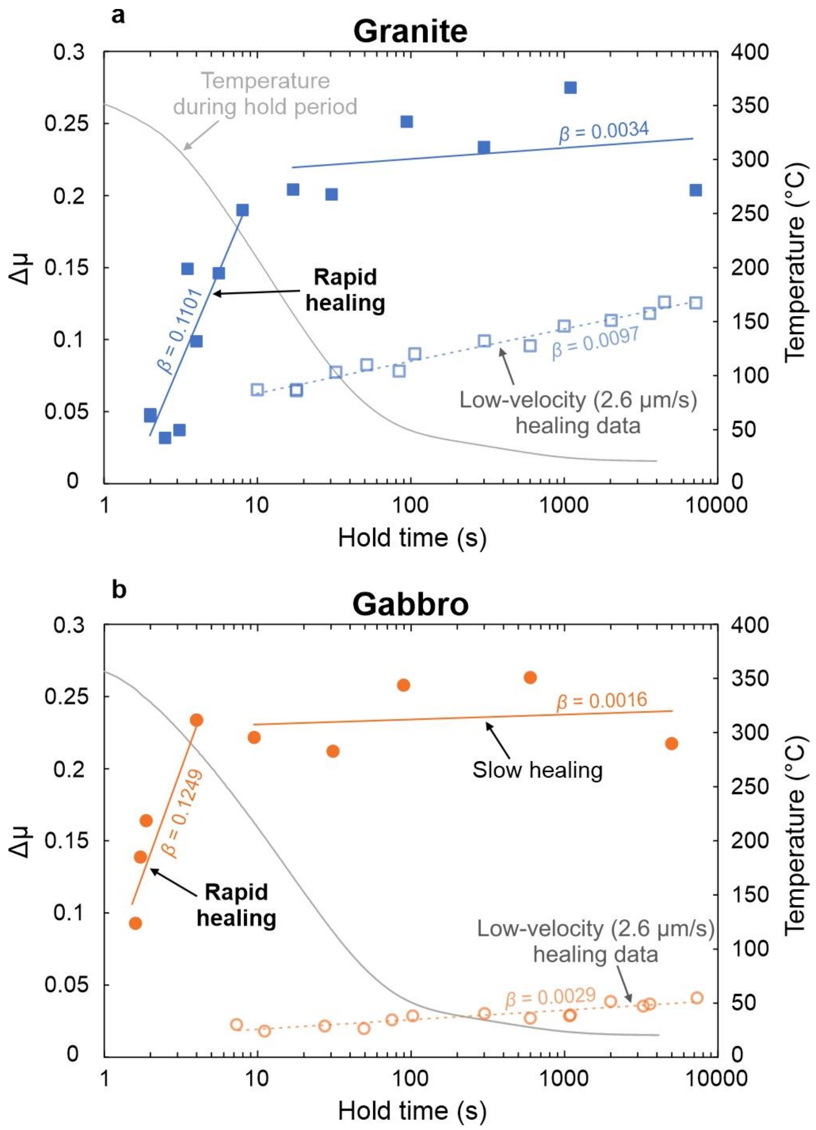
- Healing occurs at temperatures >250°C

The sheared gouges show a Raman peak associated with the H-O-H bending vibration mode.

- Potentially enhances chemical bonding at frictional contacts leading to rapid restrengthening.

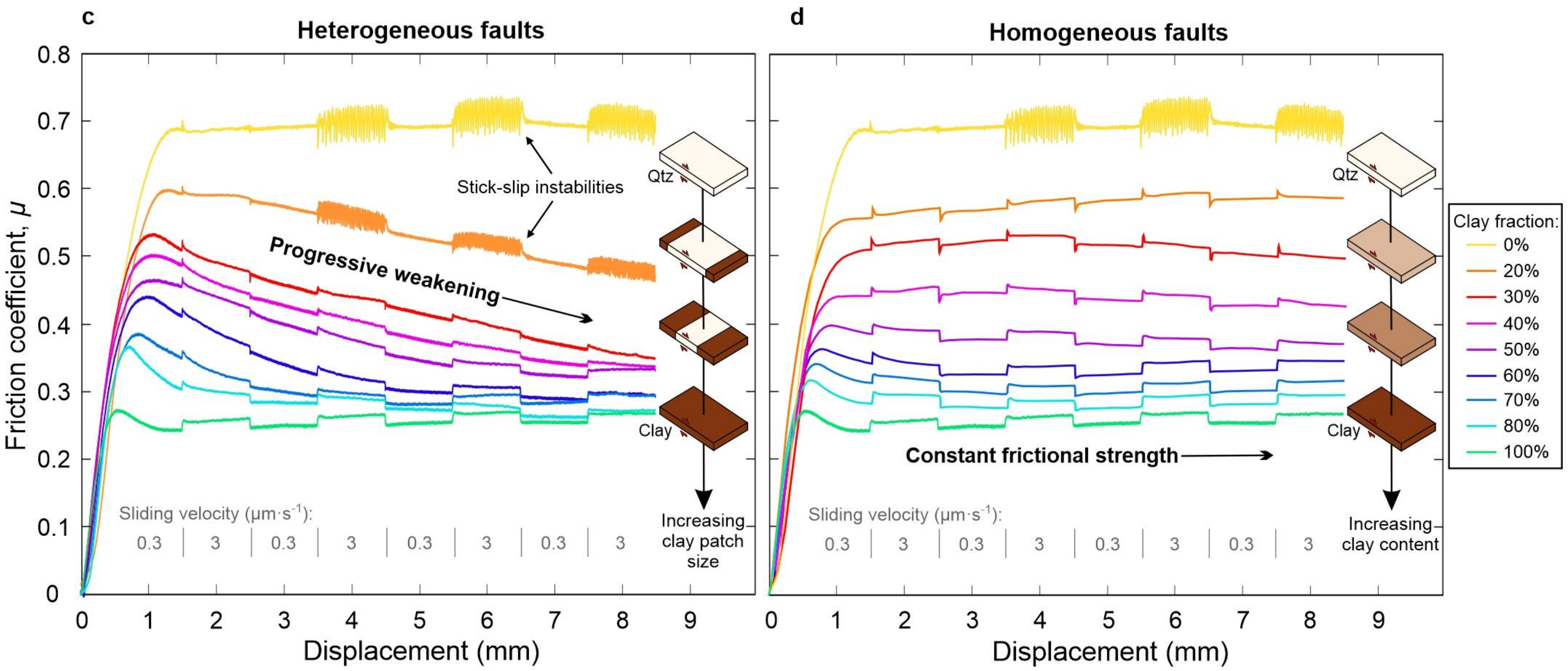
Our results suggest faults can heal rapidly after an earthquake

- Fast-acting healing mechanisms may also be important for the generation of pulse-like ruptures

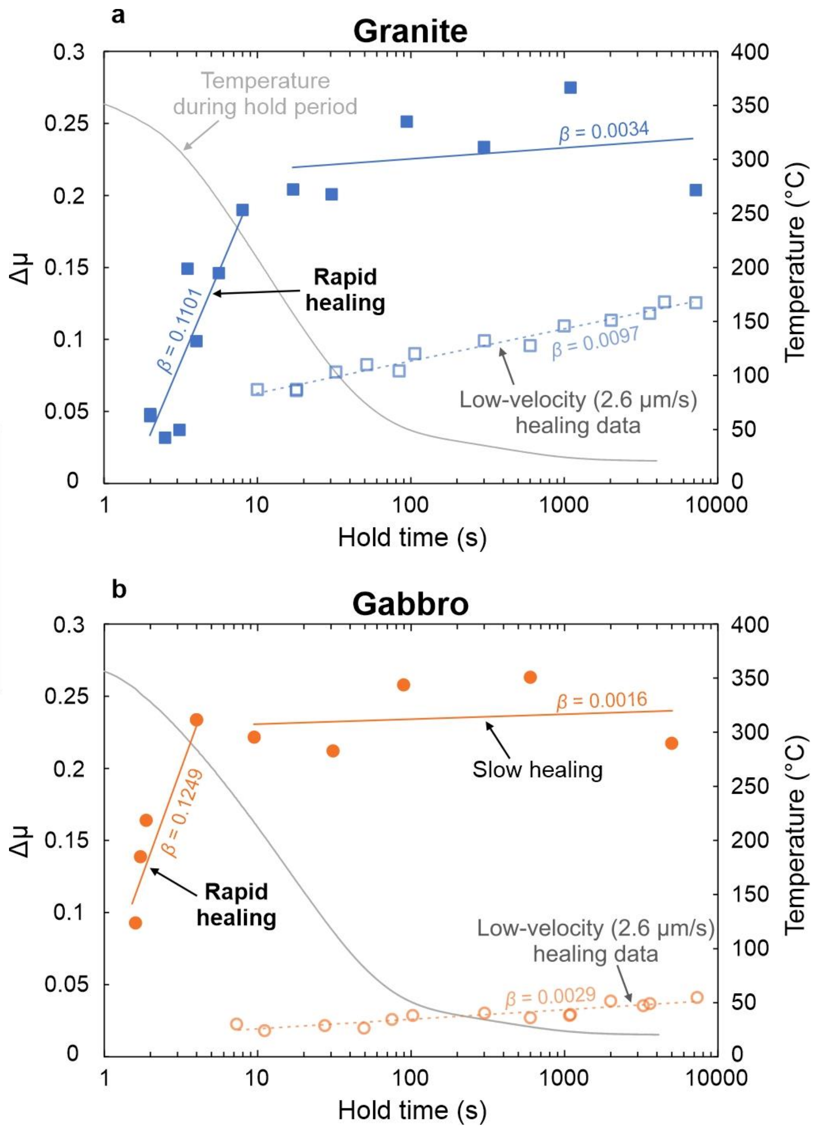


Bedford et al., (preprint), EarthArXiv

Summary



Bedford et al., (2022), Nat. Comms.



Bedford et al., (preprint), EarthArXiv