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

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Byerlee’s rule

Friction coefficient \( \mu = \frac{\text{Shear stress}}{\text{Normal stress}} \)

For most geological materials: \( 0.6 \leq \mu \leq 0.85 \)

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

How does heterogeneity influence fault strength and stability?
Methods: How does heterogeneity affect fault strength?

**Experimental conditions:**
- Confining pressure = 60 MPa
- Pore-fluid pressure = 20 MPa
- Effective normal stress = 40 MPa
- Velocity steps of 0.3 to 3 \( \mu \text{m} \cdot \text{s}^{-1} \) 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 \( \mu \text{m} \) grain size

Sliding area: 50 mm long, 20 mm wide, 1 mm thick
Results: Frictional strength evolution

Bedford et al., (2022), Nat. Comms.
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Bedford et al., (2022), Nat. Comms.
Results: Microstructure and heterogeneity-induced weakening

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Causes of the observed weakening:

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?

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**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)

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.

Bedford et al., (2022), Nat. Comms.
Part II: Fault strength recovery after an earthquake
Fault weakening and restrengthening

Dynamic fault weakening

Fault restrengthening (healing)

Seyler et al., (2020), EPSL.

Marone and Saffer (2015), Treatise on Geophys.
S-wave splitting measurements after the 1995 Kobe earthquake.
Fault healed after 33 months (recurrence interval $\approx$ 2000 yr).

Tadokoro and Ando (2002), GRL

Fault healing in nature

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

Xue et al., (2013), Science
Fault weakening and restrengthening

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

$\sigma_n = 1.5 \text{ MPa}$
$v = 0.57 \text{ m/s}$

Bedford et al., (preprint), EarthArXiv
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Rapid frictional restrengthening

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

**Healing rate (β):**

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

Bedford et al., (preprint), EarthArXiv
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**Healing rate (\(\beta\))**:

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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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Bedford et al., (preprint), EarthArXiv
What is the restrengthening mechanism?

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

Bedford et al., (preprint), EarthArXiv
What is the restrengthening mechanism?

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

Room humidity atmosphere
Nitrogen atmosphere
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