The interplay between fault fabric and frictional healing in altered serpentinite-rich fault gouge

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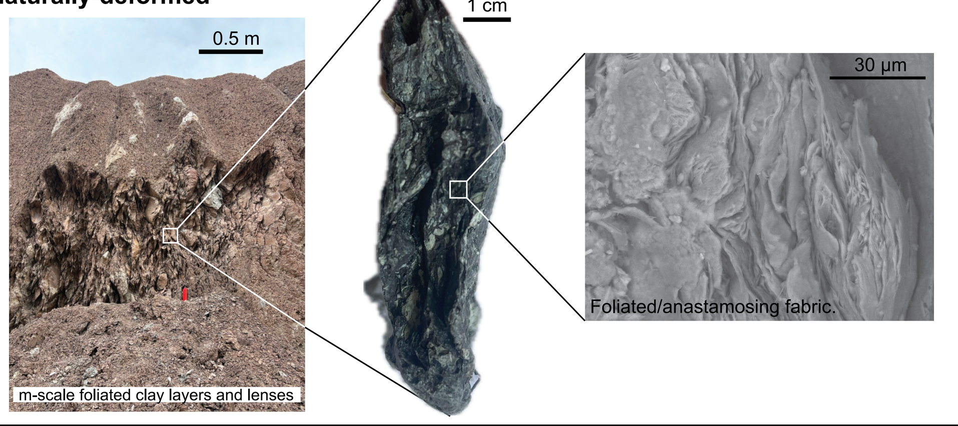
Motivation

- Creep modulates stress on faults and influences earthquake behavior.
- Fault creep may be controlled by frictional properties such as healing and/or fabric development.
- In the shallow portion of faults, fabric develops by mechanical breakdown and alignment of strong phases and oriented growth and/or alignment of weak phases.
- **How does fault fabric influence the ability to heal?**

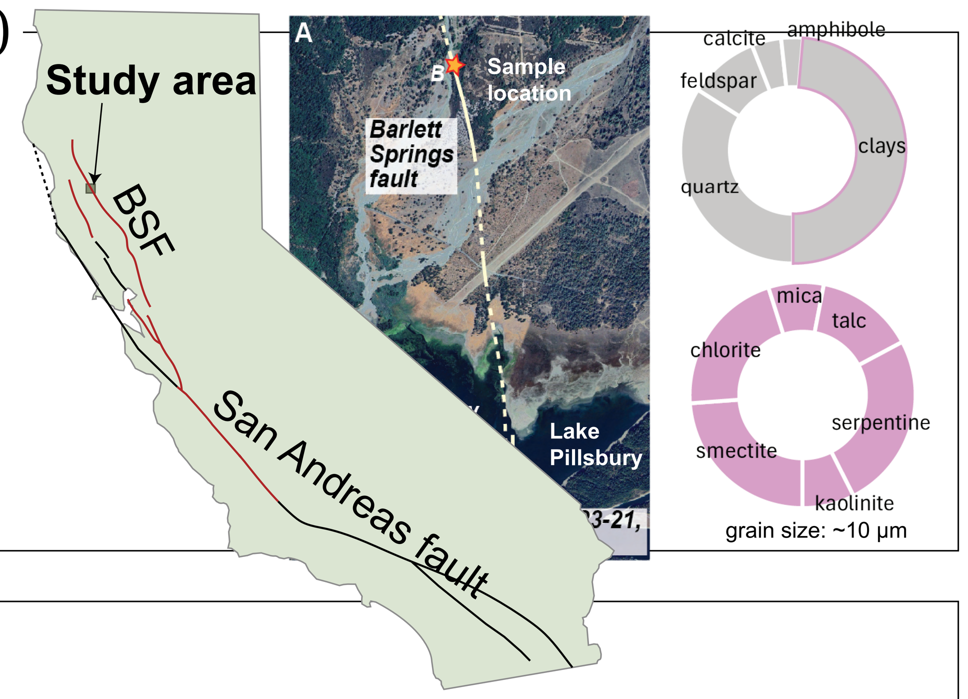
Fault fabric



- Fault fabric, or the preferred orientation minerals, is ubiquitous in phyllosilicate-rich faults.
- Fabric is observed on kilometer-scales (i.e., faults) to micro scales (i.e., individual mineral grains).
- Progressively develops with increasing slip, or fault maturity.

Bartlett Springs fault (BSF)

- Exhumed, altered, serpentine-rich fault gouge (~2.5 m wide) exposed amongst Pleistocene gravels.
- BSF surface creep rate: ~3.5 mm/yr (~1x10^{-4} µm/s) (McFarland et al., 2017).
- Capable of hosting earthquakes up to M7.5 (M5 in 2016).
- >20% creeping fault (Lienkaemper et al., 2014).
- Contains 47% phyllosilicate minerals.



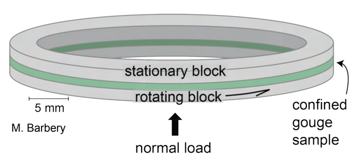
Experimental design: healing in lab-foliated gouge

We compared healing rates using slide-hold-slide (SHS) tests for samples with no foliation to strong foliation.

Tullis Rotary Shear, *Brown University Rock Mechanics Lab*

Ema with the TRS

The TRS permits infinite displacement, thus we develop artificial foliation with up to 2.5 m of pre-slip and conduct SHS tests to compare their healing rates to non-foliated samples.



Simplified schematic of Tullis Rotary Shear

Pre-experiment sample assembly prior to gouge placement

Post-experiment sample with foliation

Experiment design	Degree of foliation	Color code and total pre-slip distance (m)		
no pre-slip --> SHS and VS	no foliation	0	0	0
medium pre-slip --> SHS and VS	↕	0.5	0.5	0.5
long pre-slip --> SHS with fast slides VS		1	1.5	1
longer pre-slip --> SHS with fast slides VS	strong foliation		2.5	

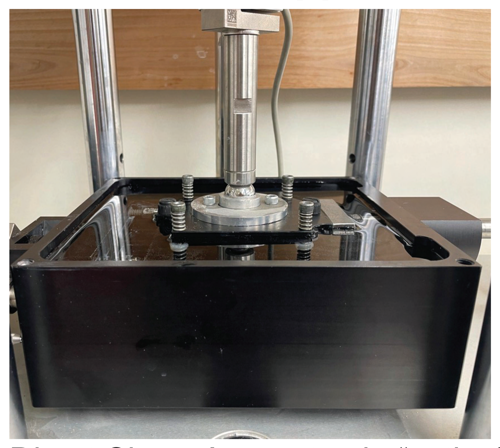
Lab conditions
- 10 MPa effective normal stress
- DI water-saturated
- Room temperature

Standard protocol
- 5 mm run-in
- SHS: holds from 10 s to 10,000 s, 0.001 mm/s or 0.01 mm/s
- velocity steps (VS): 0.0002 mm/s to 0.6 mm/s

Experimental design: healing in naturally-foliated gouge

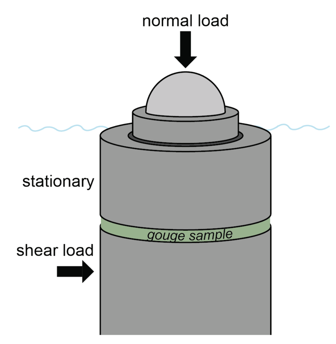
Naturally-foliated fault rock has orders of magnitude more slip than is produced in the TRS. We compared the healing rates using SHS tests in intact, naturally-foliated samples and powdered samples of the same material.

Direct Shear Apparatus, *USU Rock Deformation and Earthquake Mechanics Lab*



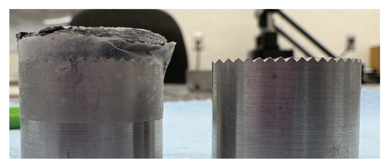
Direct Shear Apparatus in "action"

The Direct Shear Apparatus is ideal for characterizing the frictional behavior of samples in a creeping fault in the upper 1 km (up to 10 µm/s, 10 MPa, and fluid-saturated conditions).



Simplified schematic of Direct Shear Apparatus

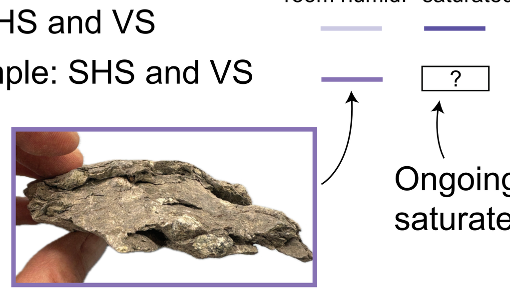
Preparing naturally-foliated sample



Pre-experiment, naturally-foliated sample in sample holder

Experiment design
powdered sample: SHS and VS
naturally-foliated sample: SHS and VS (intact)

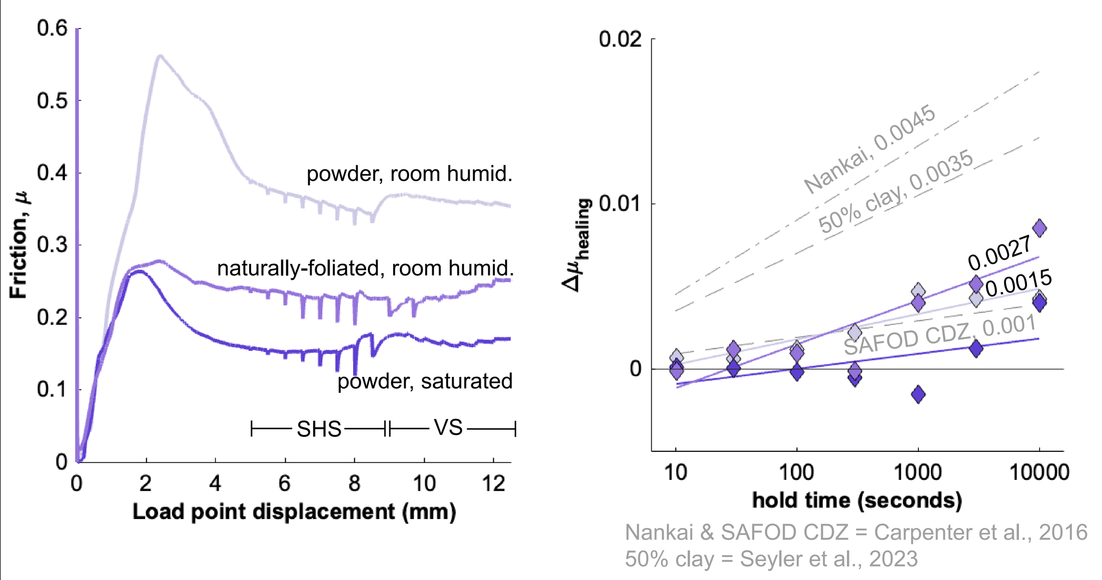
Color code
room humid. saturated



Ongoing work: how will a saturated intact sample heal?

Post-experiment sample

Healing rate of naturally-foliated samples

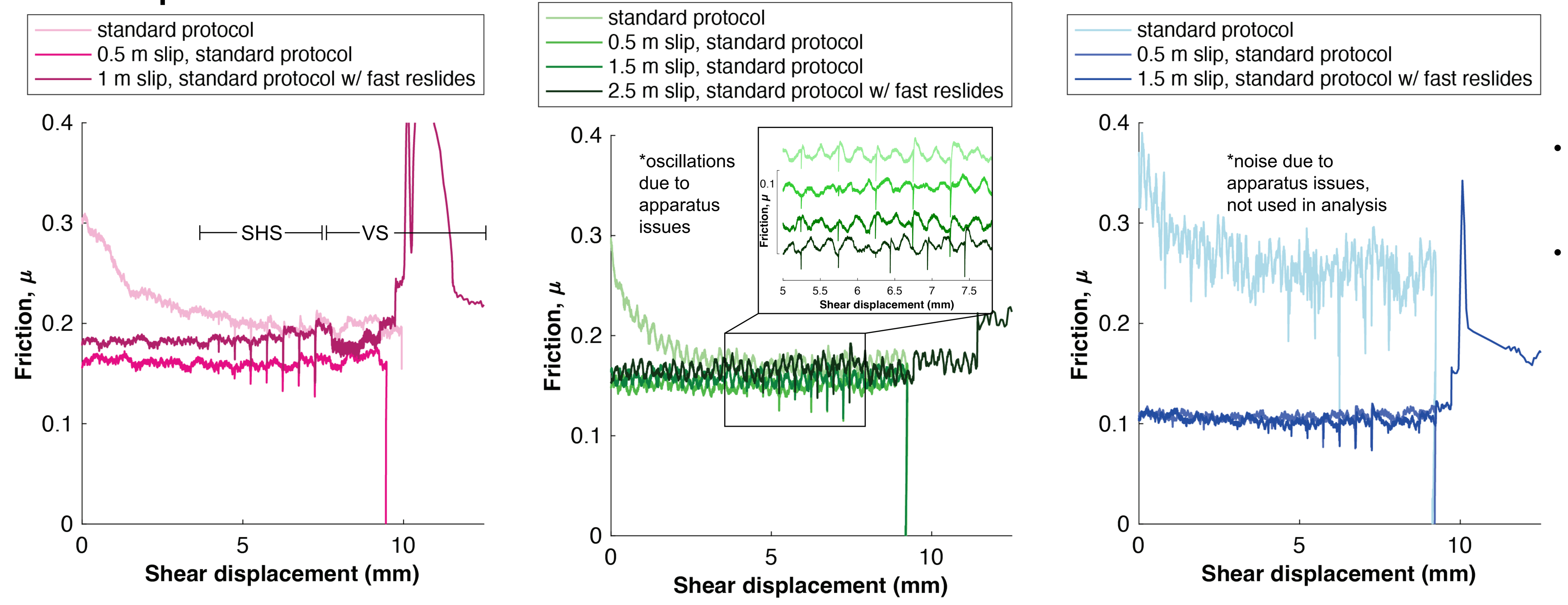


Nankai & SAFOD CDZ = Carpenter et al., 2016
50% clay = Seyler et al., 2023

- μ_{ss} is lower for naturally-foliated sample than the powdered sample (commensurate with TRS data above and Collettini et al., 2009).
- Naturally-foliated sample has higher healing rates than the powdered sample and rates are similar to those observed in lab-foliated samples.
- We expect saturated, naturally-foliated samples to have lower healing rates than saturated, powdered samples.
- Intact samples may be a proxy for the highest degree of foliation, suggesting that healing rate increases again as a fault becomes extremely foliated.

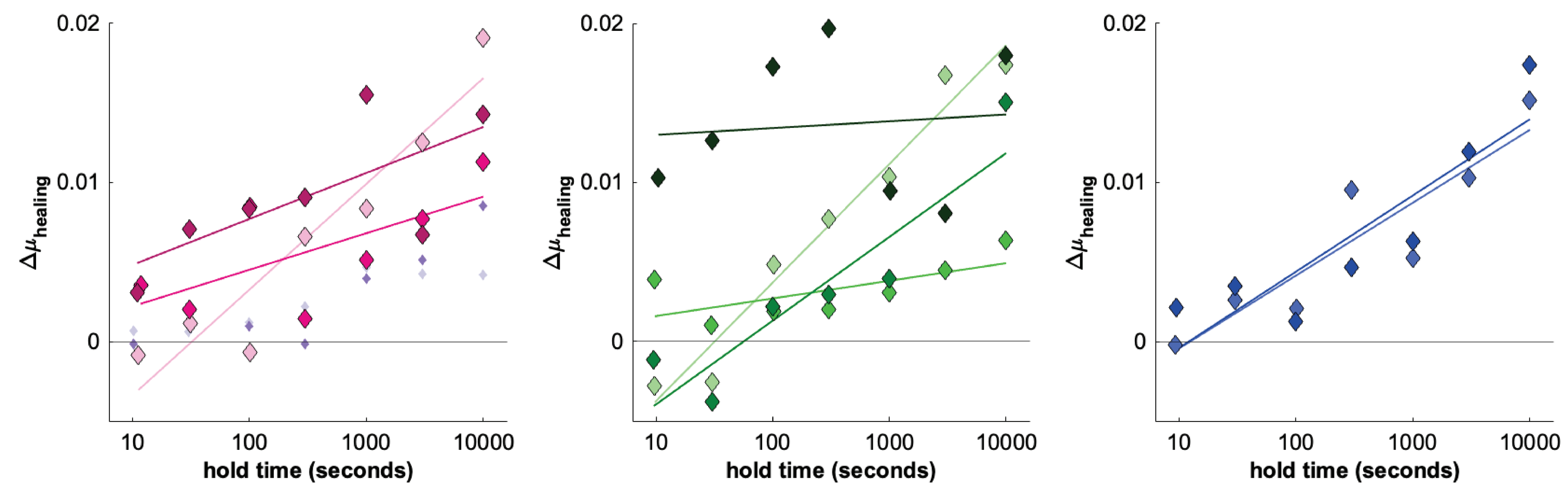
Healing rate variations due to lab foliation

Friction response

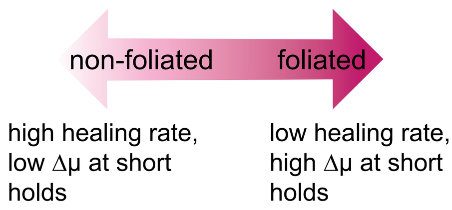


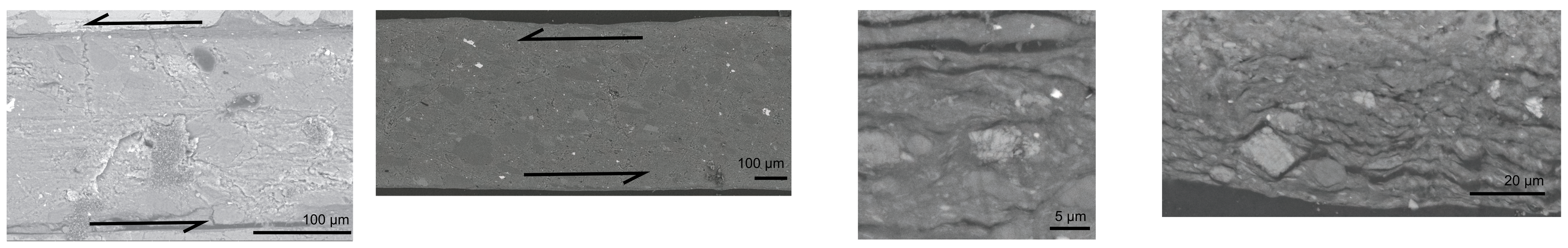
- For most experiments, μ_{ss} is consistent with that from DSA (see bottom left section).
- Within each experiment, μ_{ss} decreases slightly after 0.5 m pre-slip, suggesting foliation decreases μ_{ss} (consistent with Collettini et al., 2009).

Healing rate



- At short hold times, strongly foliated samples have higher Δµ (especially in pink experiment).
- At long hold times, strongly foliated samples have a lower Δµ, and thus a lower healing rate than non-foliated samples.



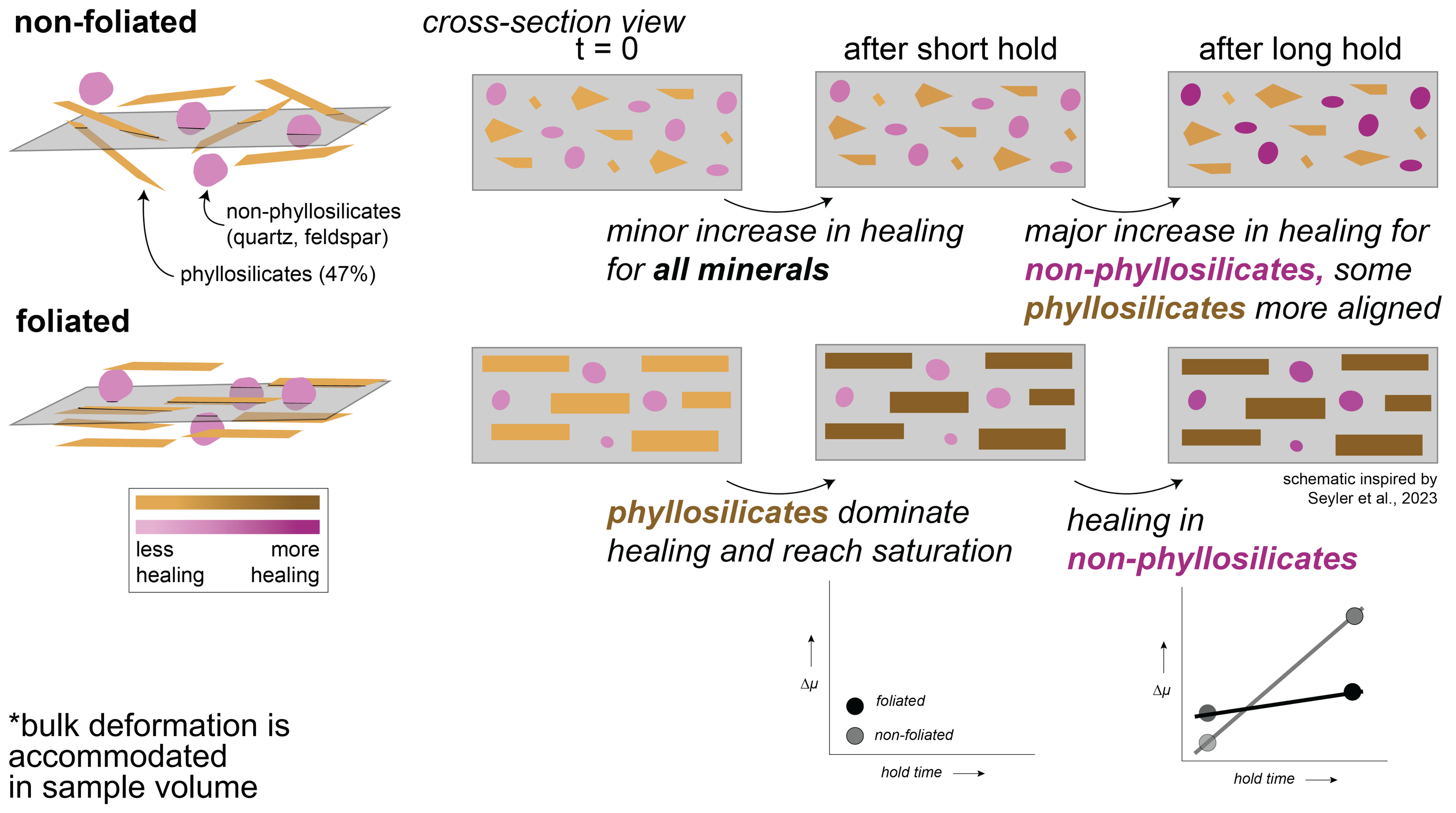


Volumetric deformation in bulk sample (limited slip localization in gouge).

Comminuted clast.

Clay particles 'roll over'/anastamose around more competent clasts.

Impacts of foliation in frictional healing for lab-foliated samples



*bulk deformation is accommodated in sample volume

- On short timescales, randomly-oriented materials do not exhibit much healing, but both phyllosilicates and non-phyllosilicates continue to heal with increased time.
- On short timescales, foliated phyllosilicates play an outsized role in healing; healing efficiency must be high. The amount of healing saturates during the 10s hold, limiting long-term healing of foliated phyllosilicates.
- Although non-phyllosilicates continue to heal over longer timescales (we do see a minor increase in Δµ), it is limited because grains are physically blocked by platy phyllosilicates.
- We cannot identify from this work whether healing in foliated or non-foliated phyllosilicates is due to an increase in contact quality or quantity.
- Limited normal displacement during SHS tests suggest healing is not related to compaction and dilation, but rather atomic-scale physiochemical processes, such as Si-O bonds.

Implications for foliated phyllosilicate-rich faults

Slightly higher Δµ at short holds suggests healing in aligned clays is a nearly instantaneous process. Rapid initial healing could promote locked behavior immediately after a slip event.

Low healing rates suggest foliated, phyllosilicate-rich faults are persistently weak over long timescales, promoting creep.

Increased foliation and higher clay content are assoicated with more mature faults. Because the healing behavior of of faults evolves with degree of foliation, healing behavior will evolve with fault maturity.

As non-foliated clasts and wall-rock become entrained in the fault, they may alter the healing behavior of portions of the fault. This may poses an explanation to the paradoxical creeping yet earthquake-hosting behavior of the BSF.

Persistent questions:
How do phyllosilicates heal?
What are the microphysical interactions occuring at clay-clay boundaries?
Let's talk about it!