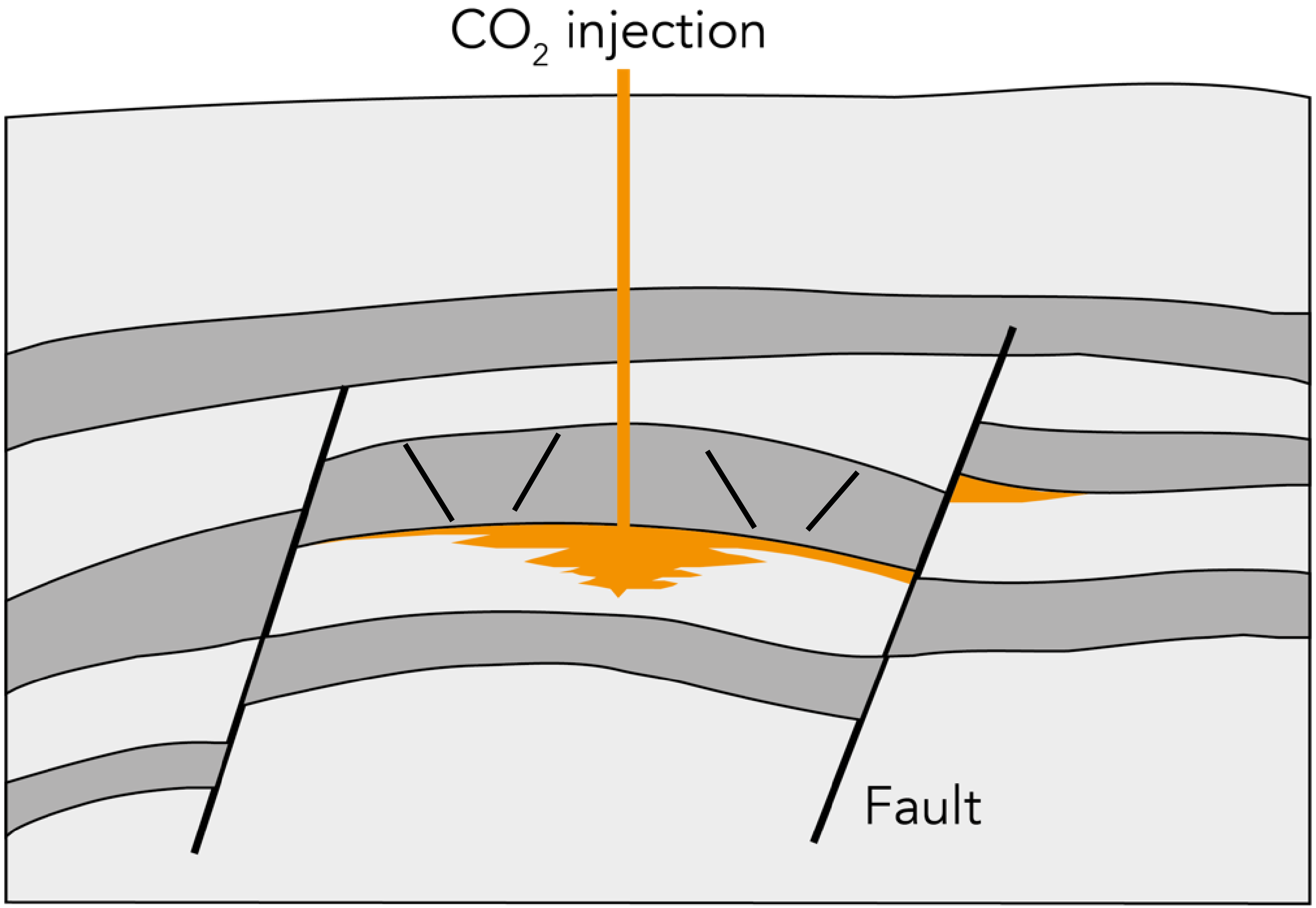
From quartz to clay rich faults: the role of fabric in permeability and fault stability with implications for induced seismicity and CO_2 leakage

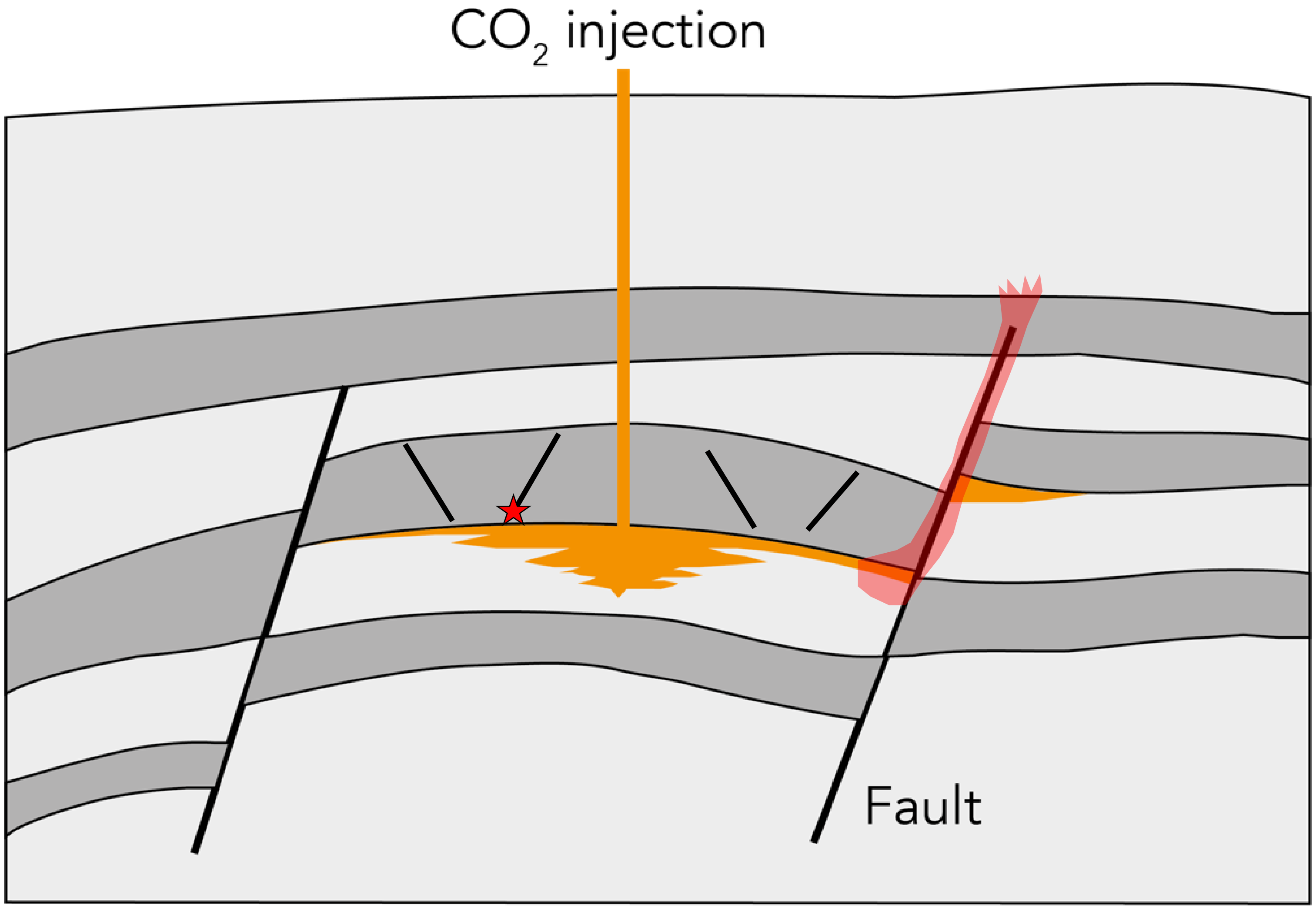
Collettini C. [1,2], Giorgetti C.[1,3], Coppola L. [1], Pozzi, G[2]., Scuderi, M.M.[1], Bourgeois, F.[4] and Wibberley, C.[4]

[1]Dipartimento di Scienze della Terra, Università di Roma La Sapienza, Rome, Italy
[2]Istituto Nazionale di Geofisica e Vulcanologia (INGV), Rome, Italy
[3]Laboratoire de Géologie de l'École normale Supérieure de Paris
[4]Total Geoenergies, Pau, France

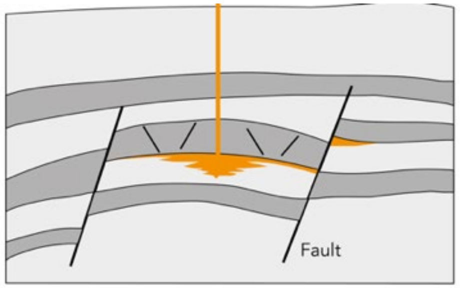
During underground CO_2 storage, the integrity of the trap often relies on how the faults bounding the trap, or contained within the topseal above, behave as pressure increases during injection.

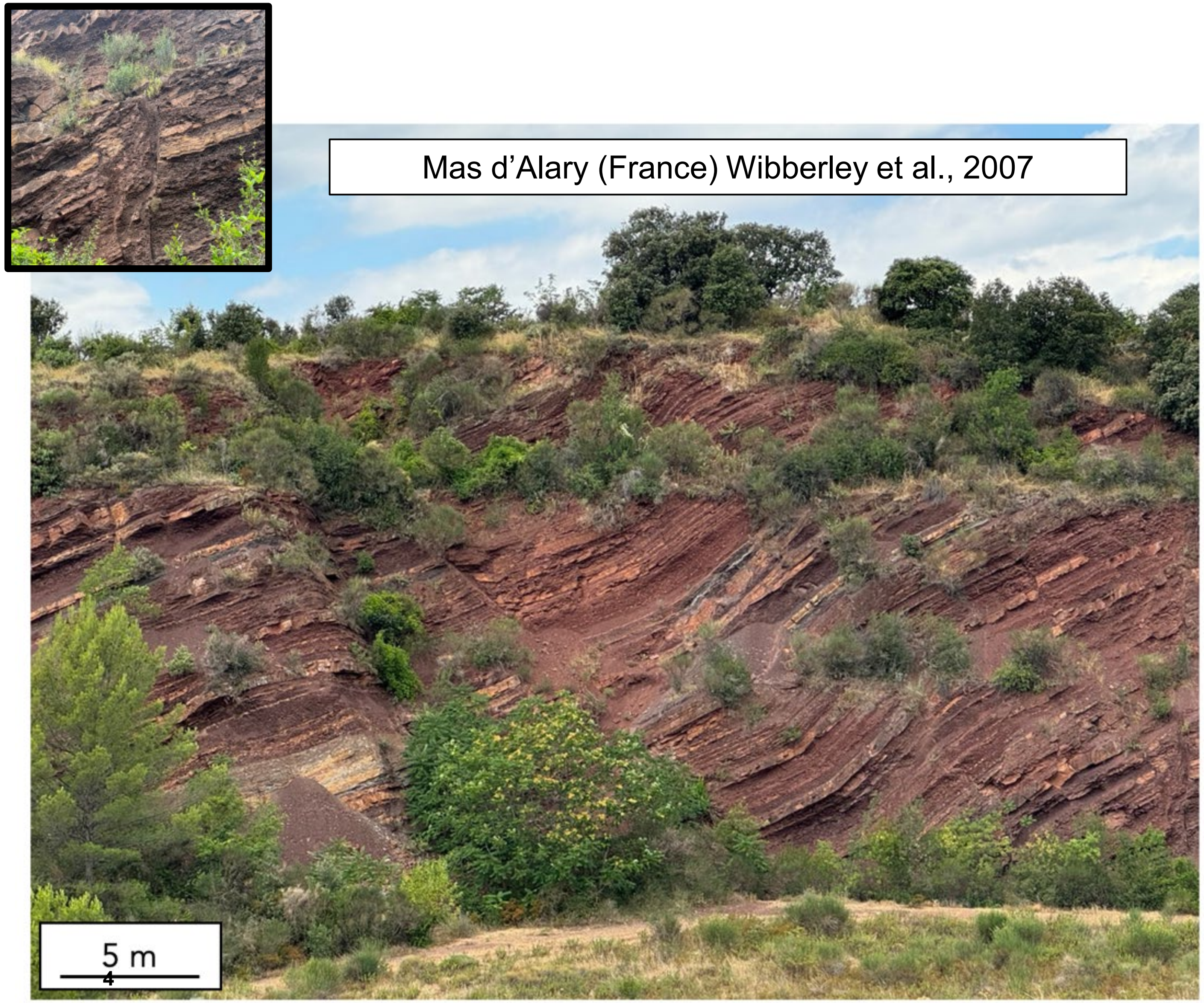


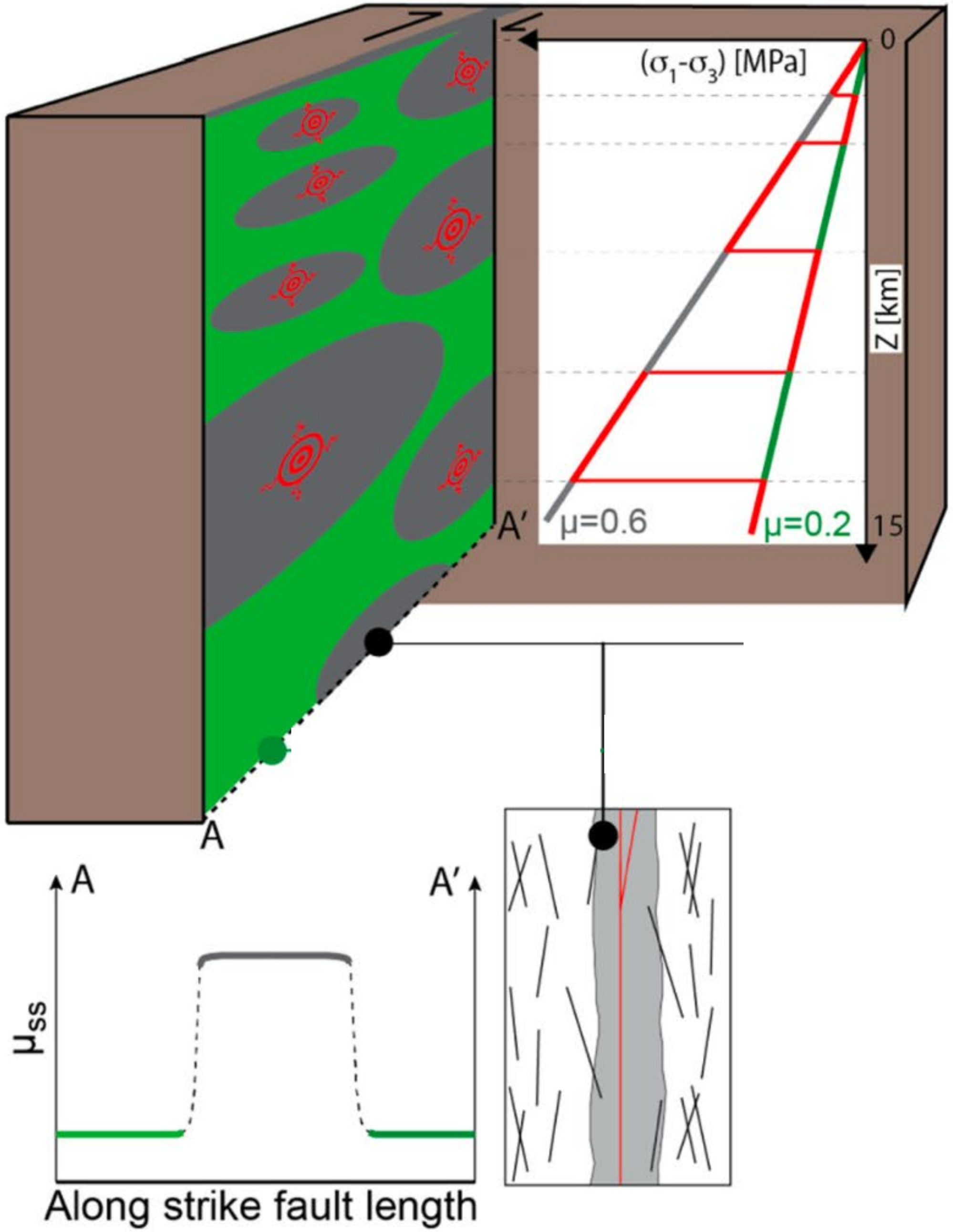
Fault leakages depend on the permeability properties of the faults.
Fault reactivation and induced seismicity are mainly controlled by fault frictional properties.
Frictional and fluid flow properties are coupled.

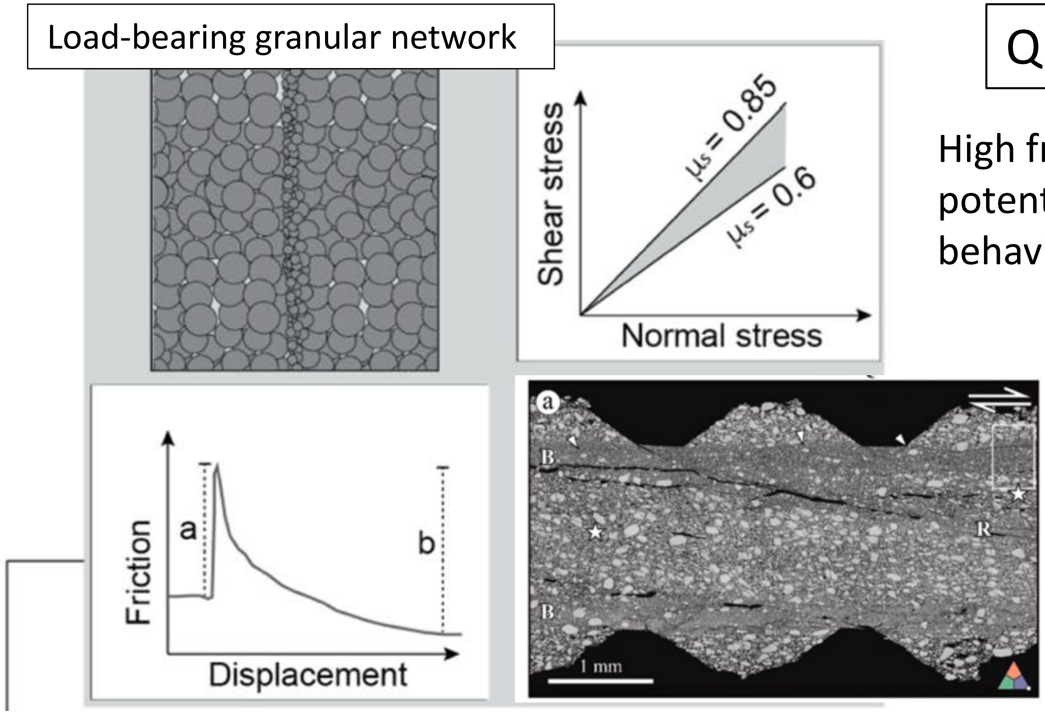


Faults contained in the geo-reservoirs occur within interbedded shales and sandstones/carbonates and are generally heterogenous









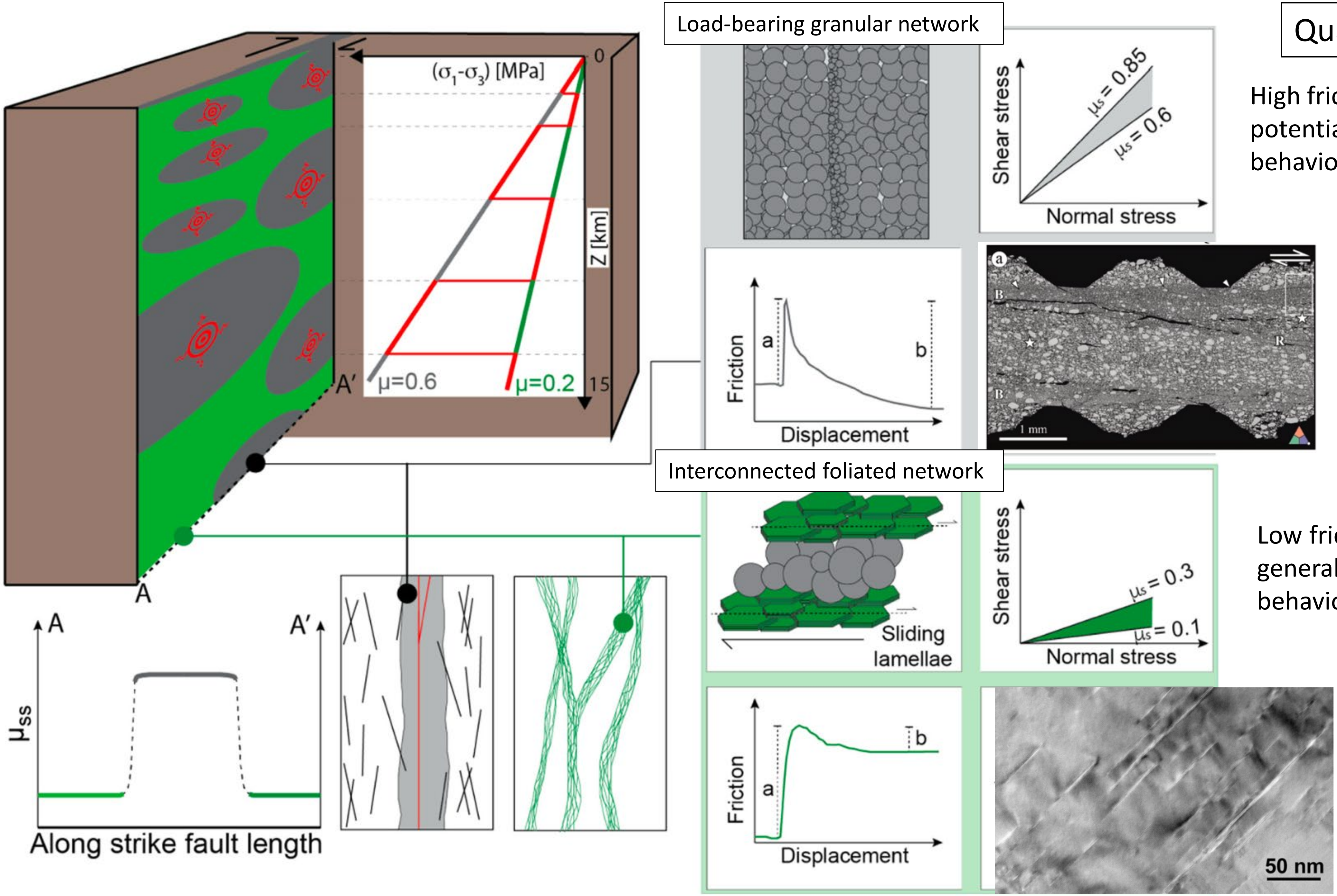
Quartz & carbonates

High friction, potentially unstable slip behaviour.

Collettini et al., EPSL 2019

Quartz & carbonates

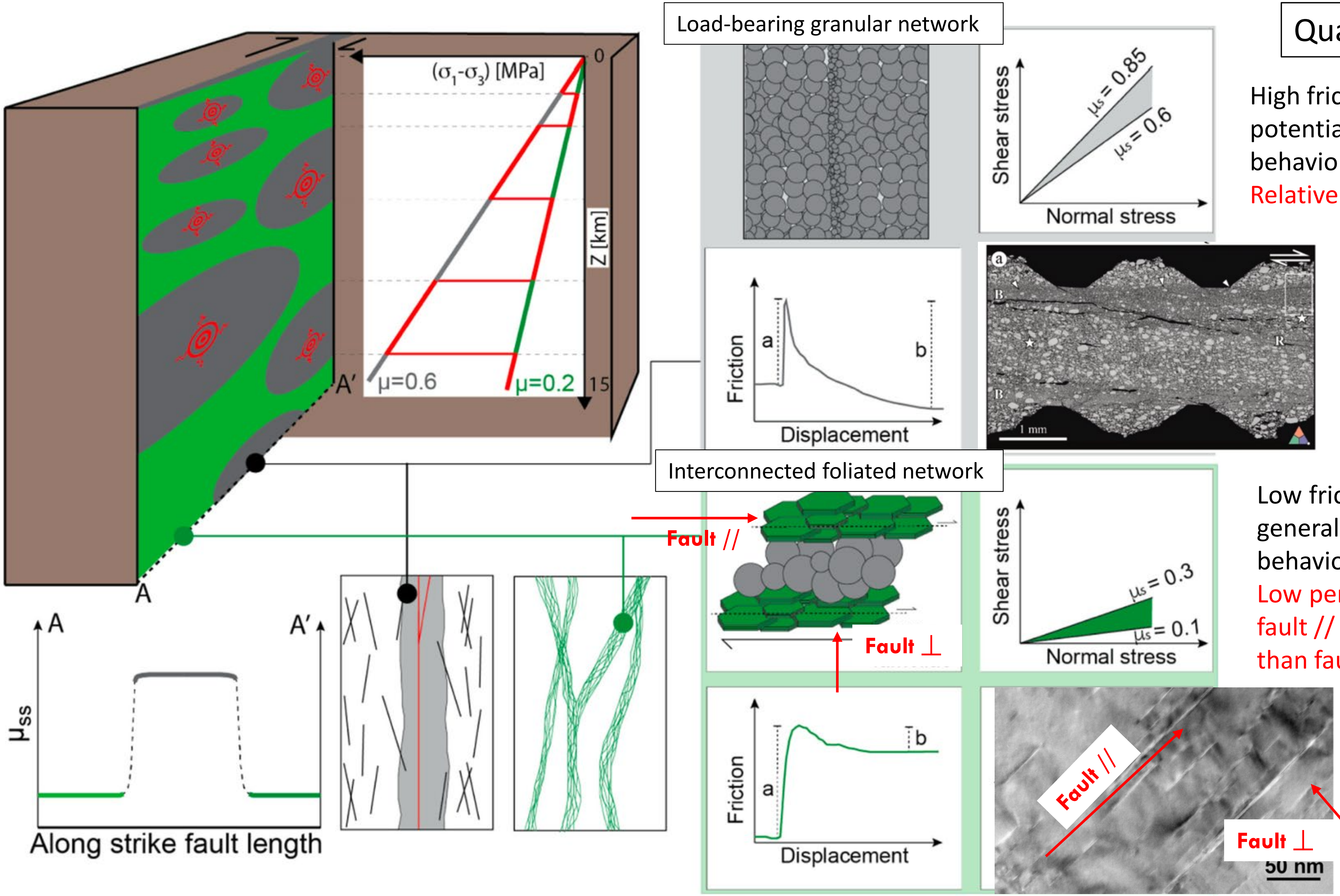
High friction,
potentially unstable slip behaviour.



Phyllosilicates

Low friction,
generally stable slip
behaviour.

Collettini et al., EPSL 2019

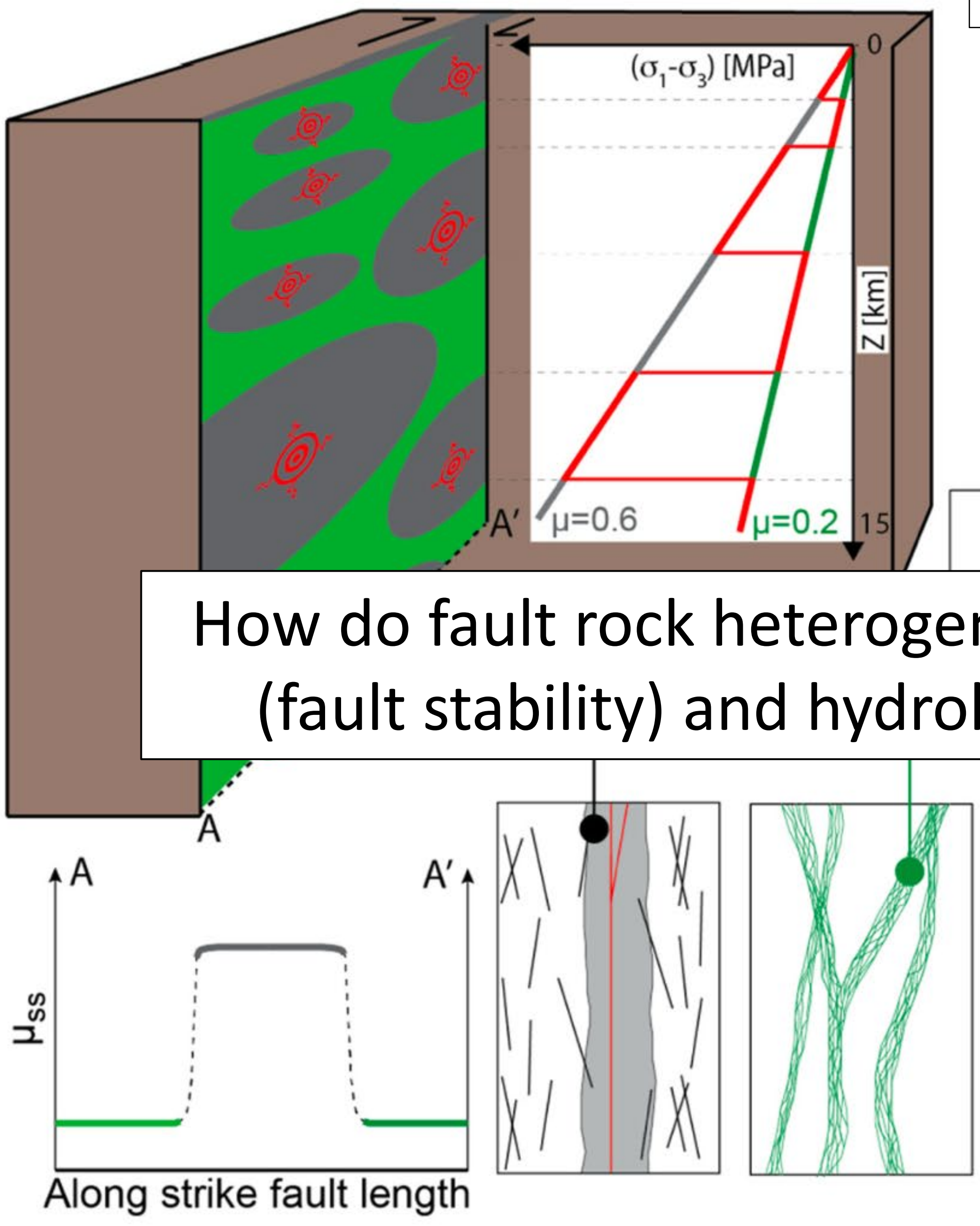


Quartz & carbonates

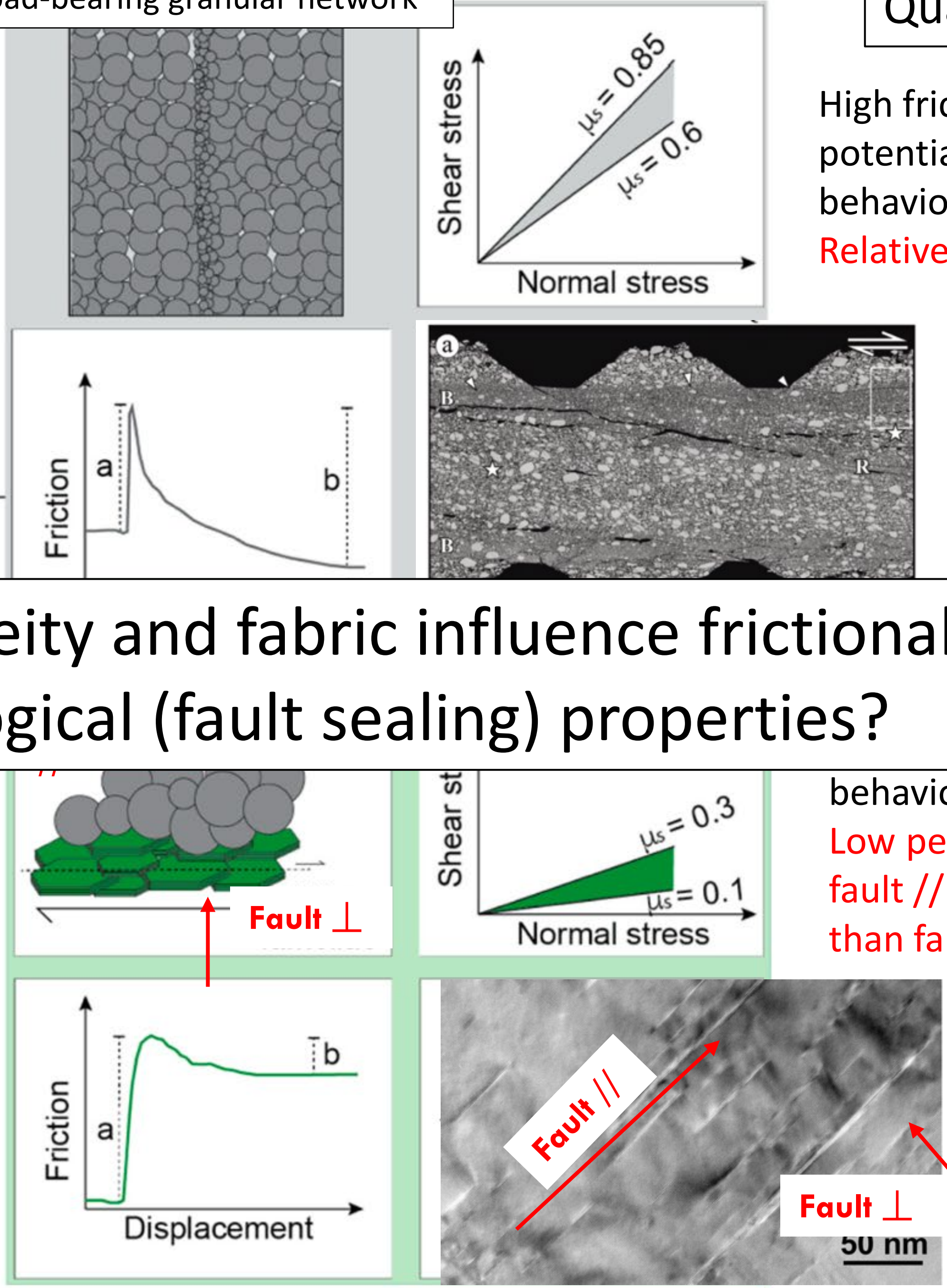
High friction, potentially unstable slip behaviour.
Relatively high permeability.

Phyllosilicates

Low friction, generally stable slip behaviour.
Low permeability (k) but fault // k might be higher than fault ⊥ k.



Load-bearing granular network



Quartz & carbonates

High friction,
potentially unstable slip
behaviour.
Relatively high permeability.

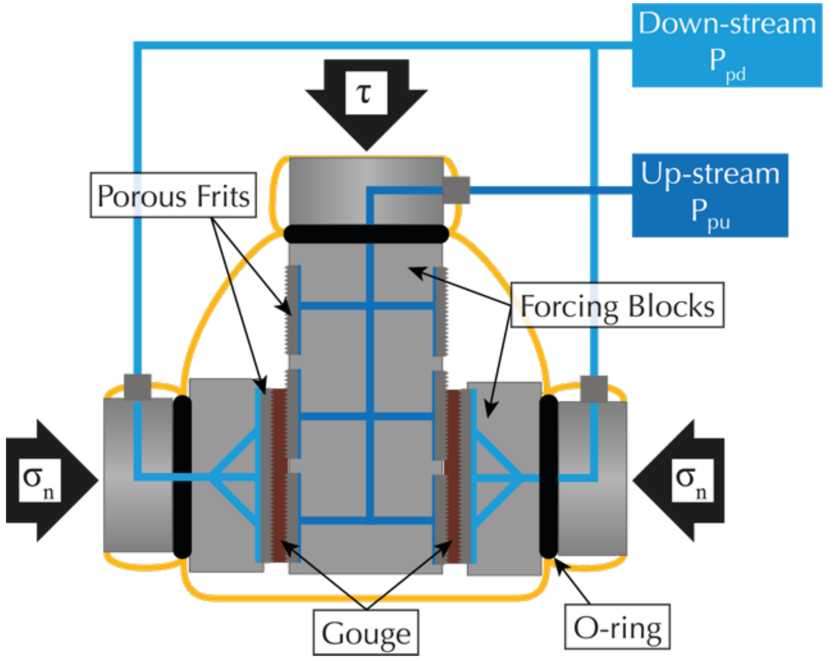
How do fault rock heterogeneity and fabric influence frictional (fault stability) and hydrological (fault sealing) properties?

Phyllosilicates

n,
table slip
behaviour.
Low permeability (k) but
fault // k might be higher
than fault ⊥ k.

Methods: characterization of frictional and fluid flow properties of heterogenous fault rocks.

Fault perpendicular ⊥ permeability



- **100% quartz**
- 75% quartz + 25% Rochester shale
- 50% quartz + 50% Rochester shale
- 25% quartz + 75% Rochester shale
- **100% Rochester shale**

0%
clay content
68%

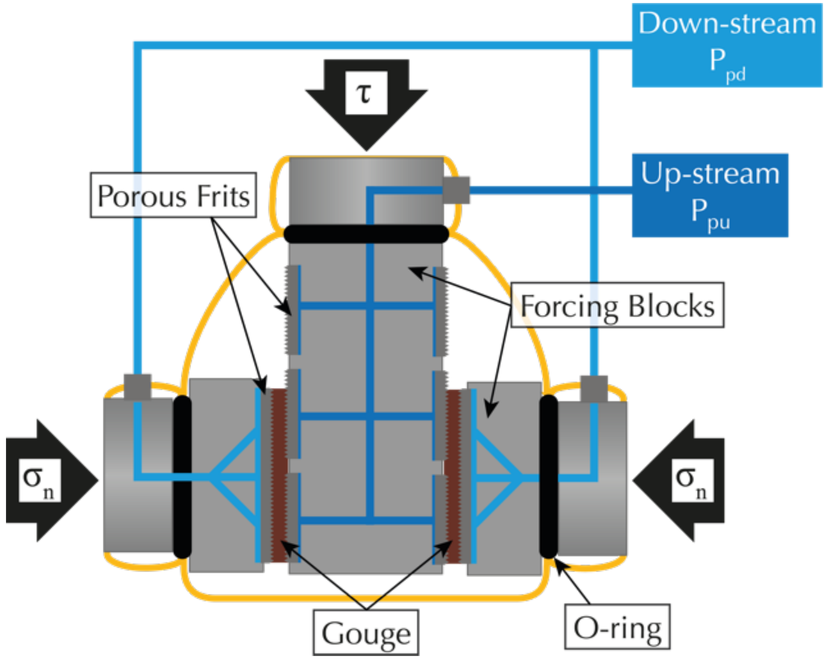
Stress boundary conditions:

σ'_n = 7MPa (λ=0.4)
σ'_n = 10MPa (λ=0.7)
σ'_n = 20MPa (λ=0.4)

$$\lambda = \frac{P_f}{\sigma_n}$$

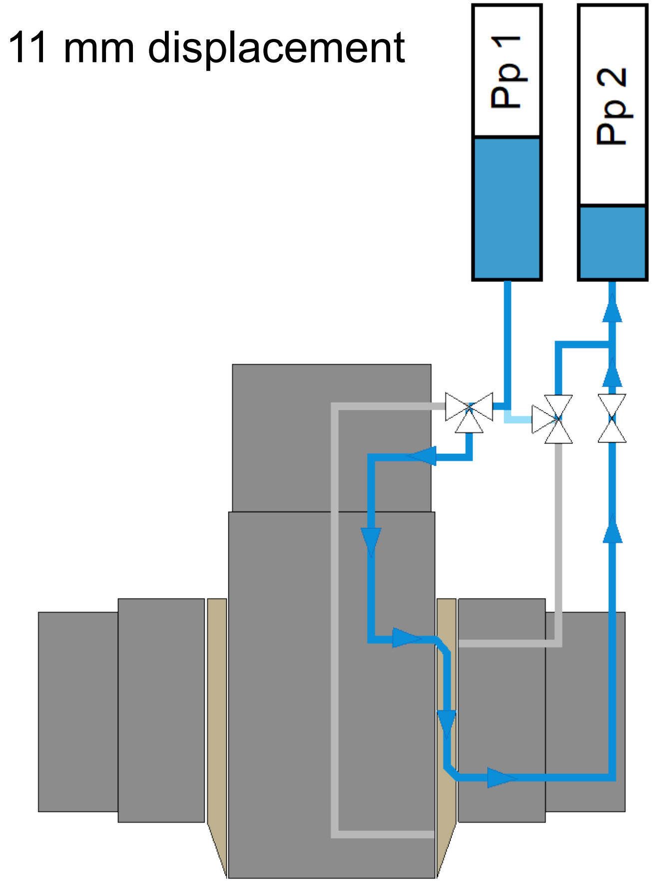
Methods: characterization of frictional and fluid flow properties of heterogenous fault rocks.

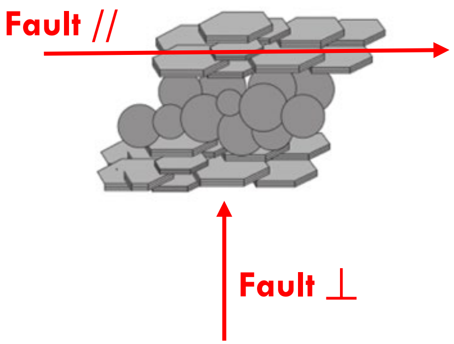
Fault perpendicular ⊥ permeability



Fault parallel // permeability

For simplicity pore fluid lines are sketched only on one side block.
Pore pressure lines are symmetric.

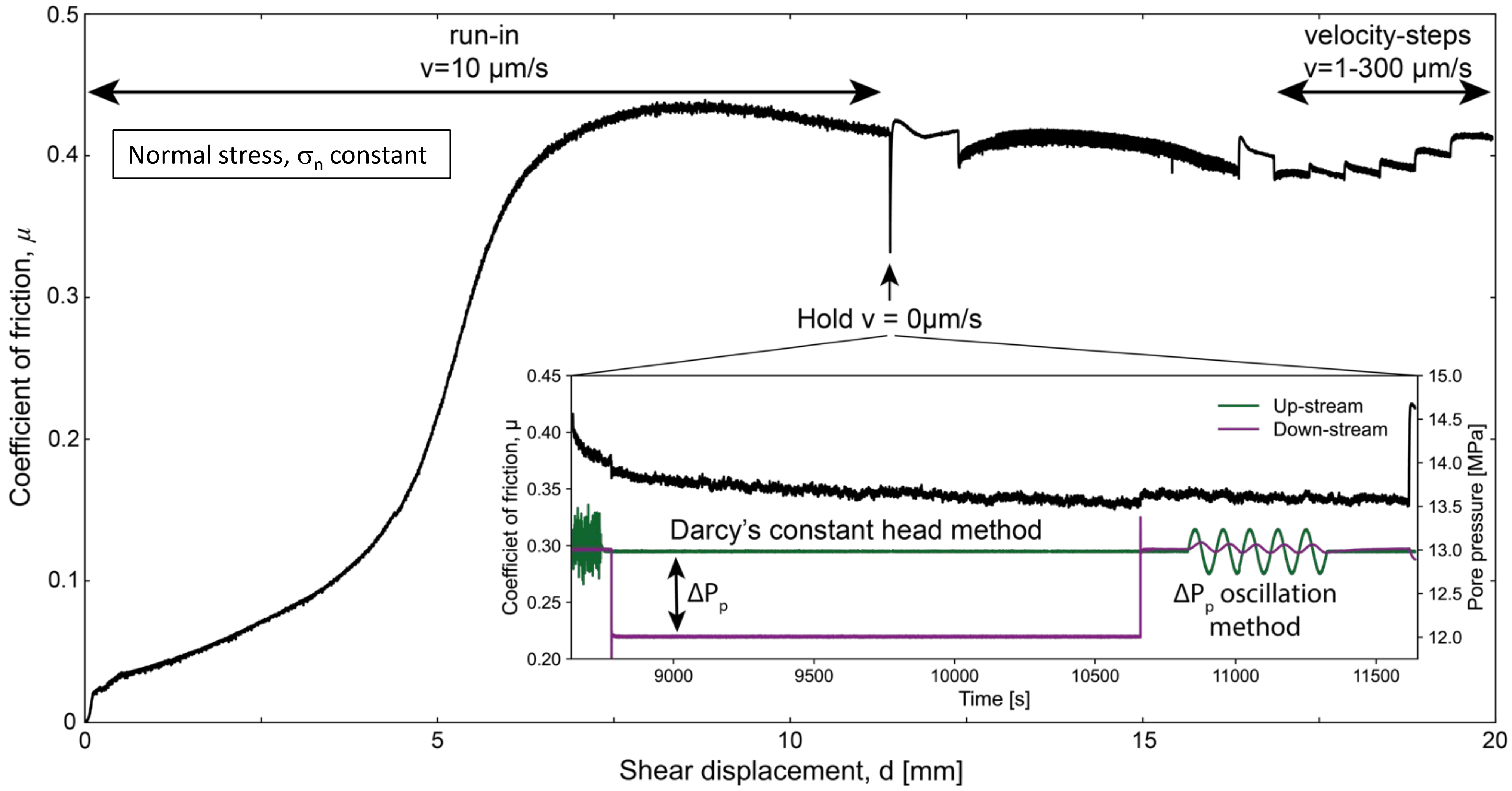




Giorgetti et al., in prep.

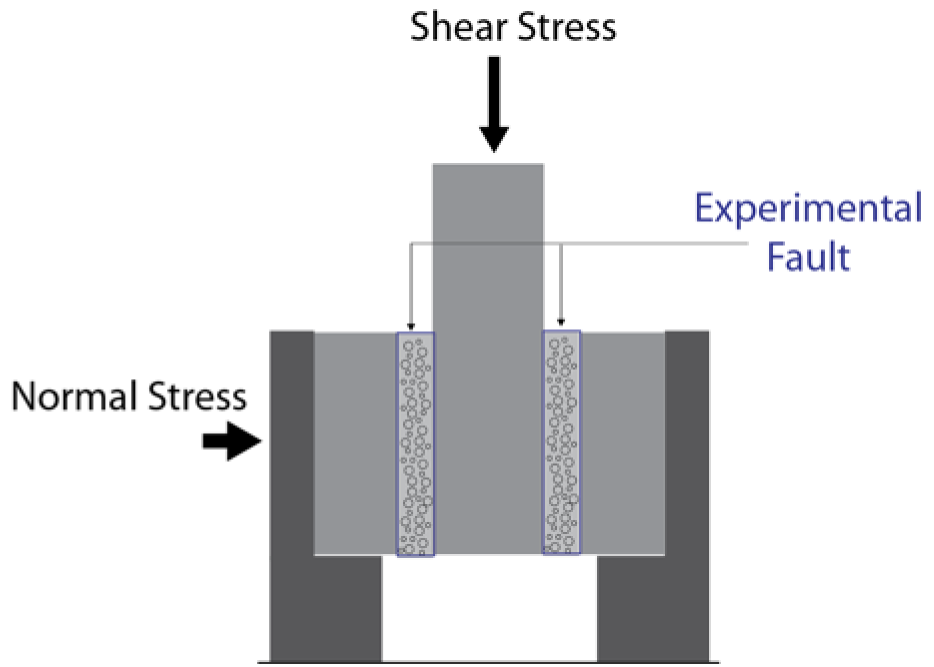
Methods

Coefficient of friction = shear stress divided by normal stress point by point $\mu = \dfrac{\tau}{(\sigma_n - P_f)}$



Methods

Seismic vs. aseismic slip via Rate & State friction (Dieterich 1979; Marone, 1998).

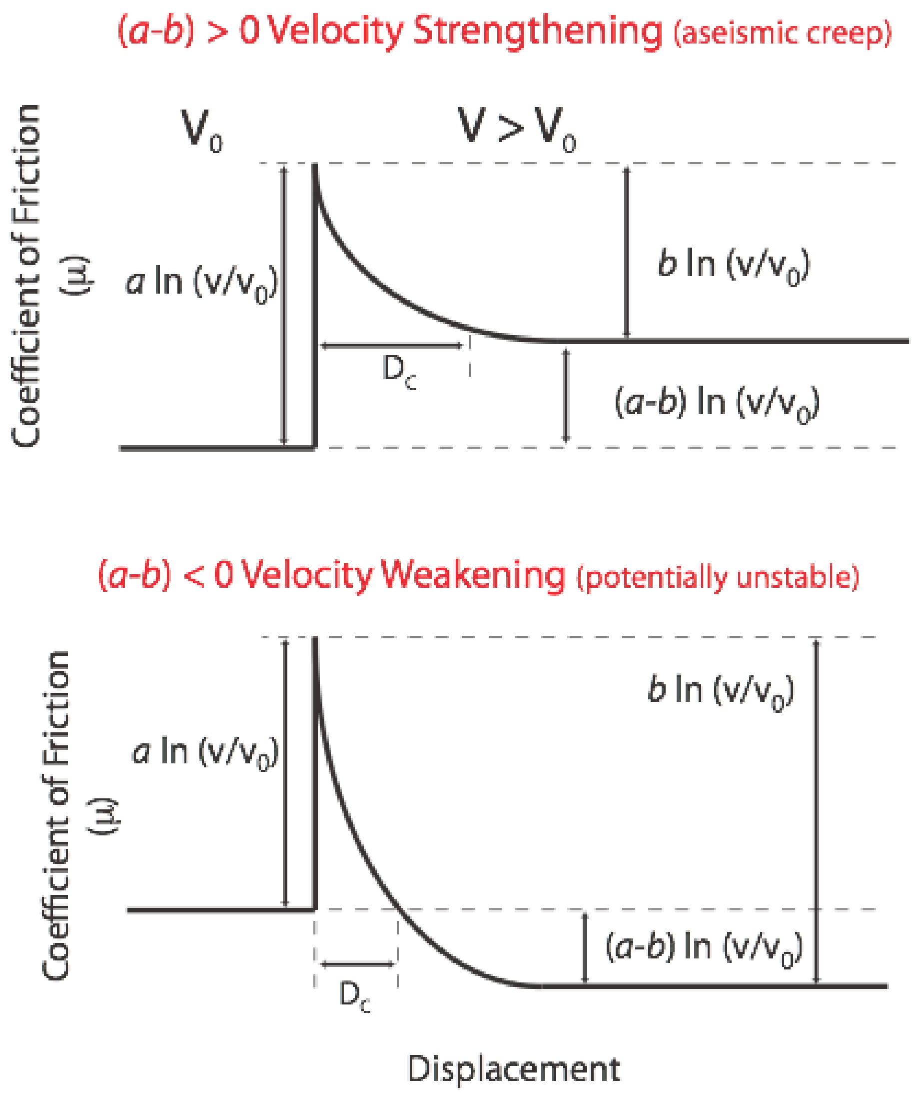


Rate & State friction equations

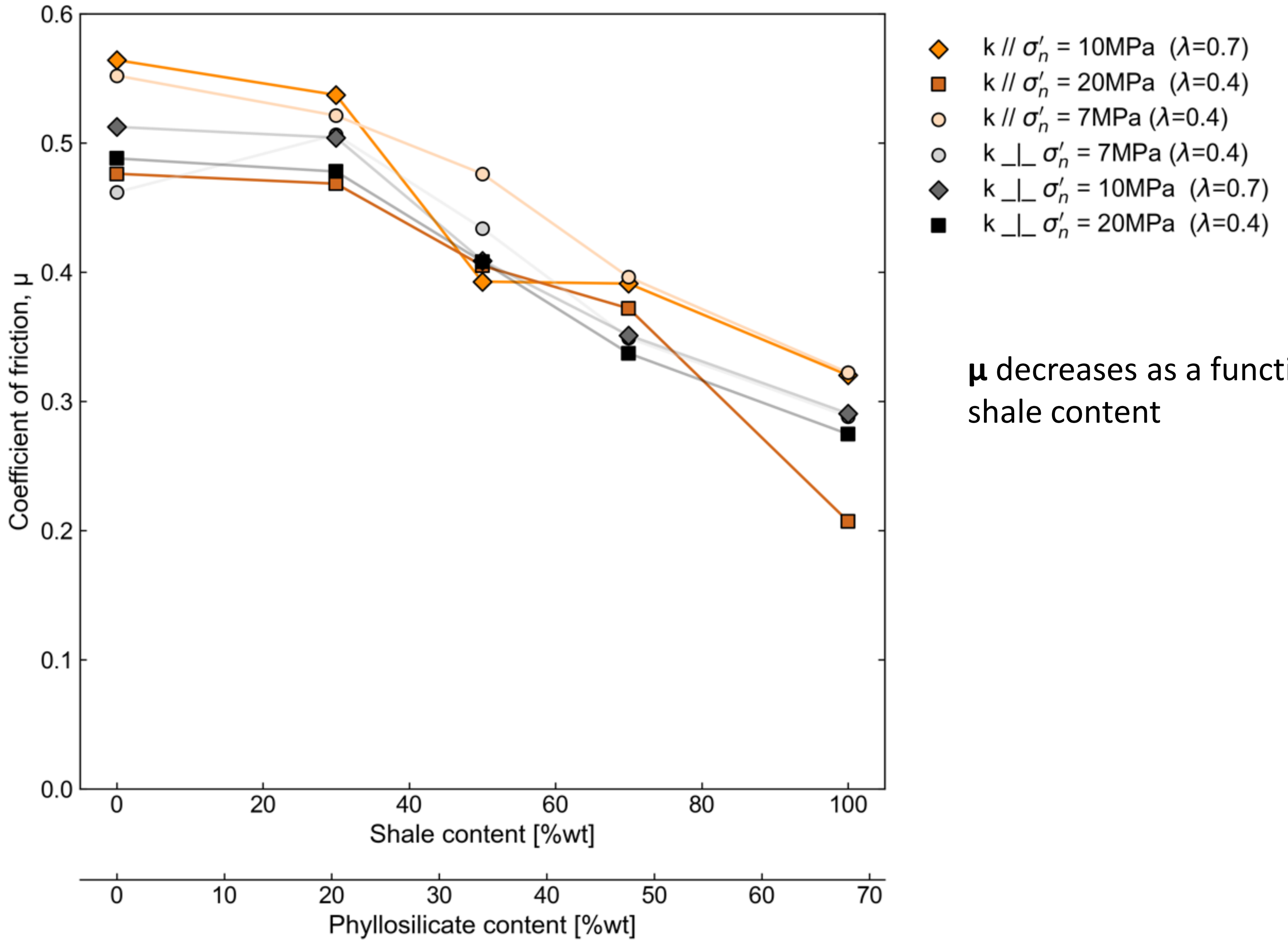
$$\frac{\tau(\theta, v)}{\sigma_n} = \mu_o + a\, ln\left(\frac{v}{v_o}\right) + b\, ln\left(\frac{v_o\theta}{D_c}\right)$$

$$\frac{d\theta}{dt} = 1 - \frac{v\theta}{D_c}$$

$$\frac{d\mu}{dt} = K(V_{lp} - V)$$



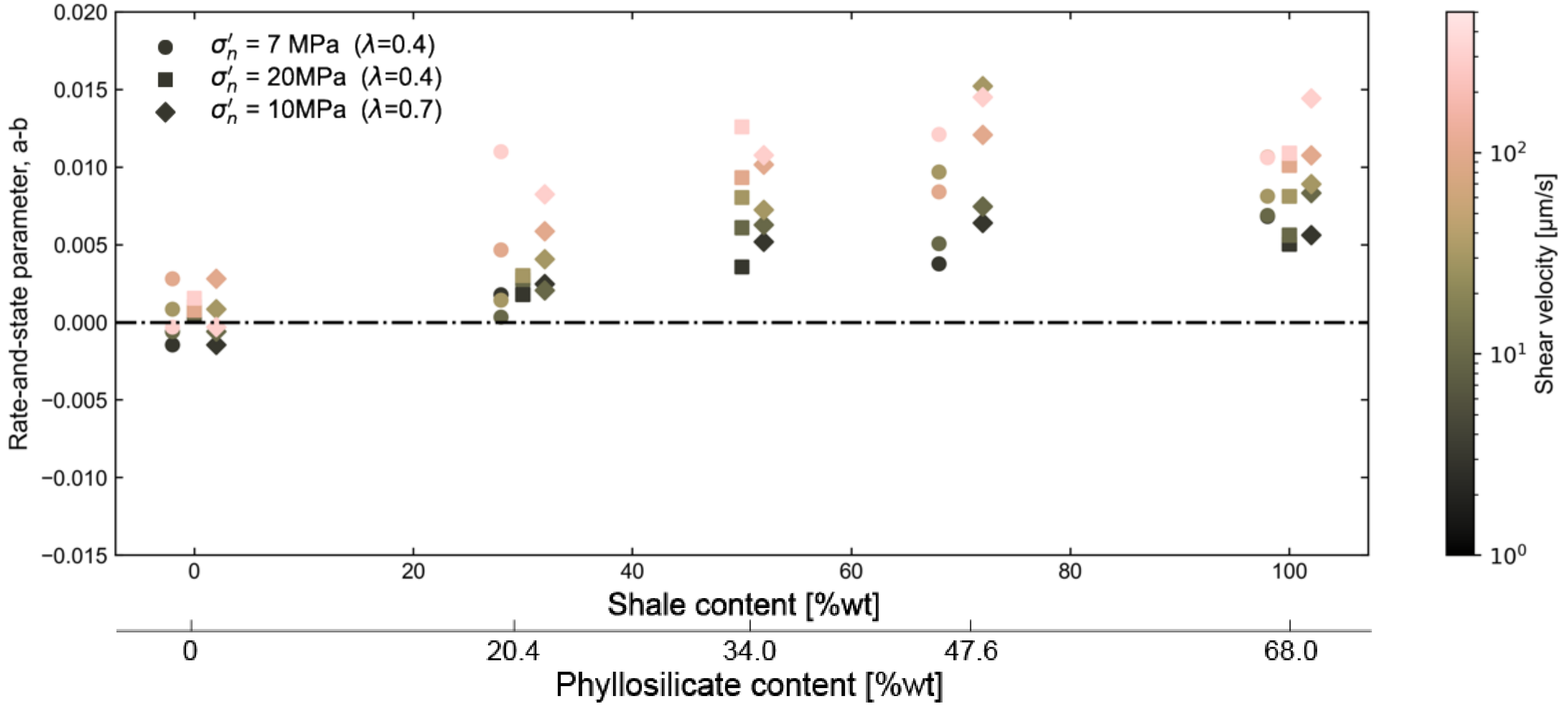
Results: friction



μ decreases as a function of shale content

Giorgetti et al., in prep.

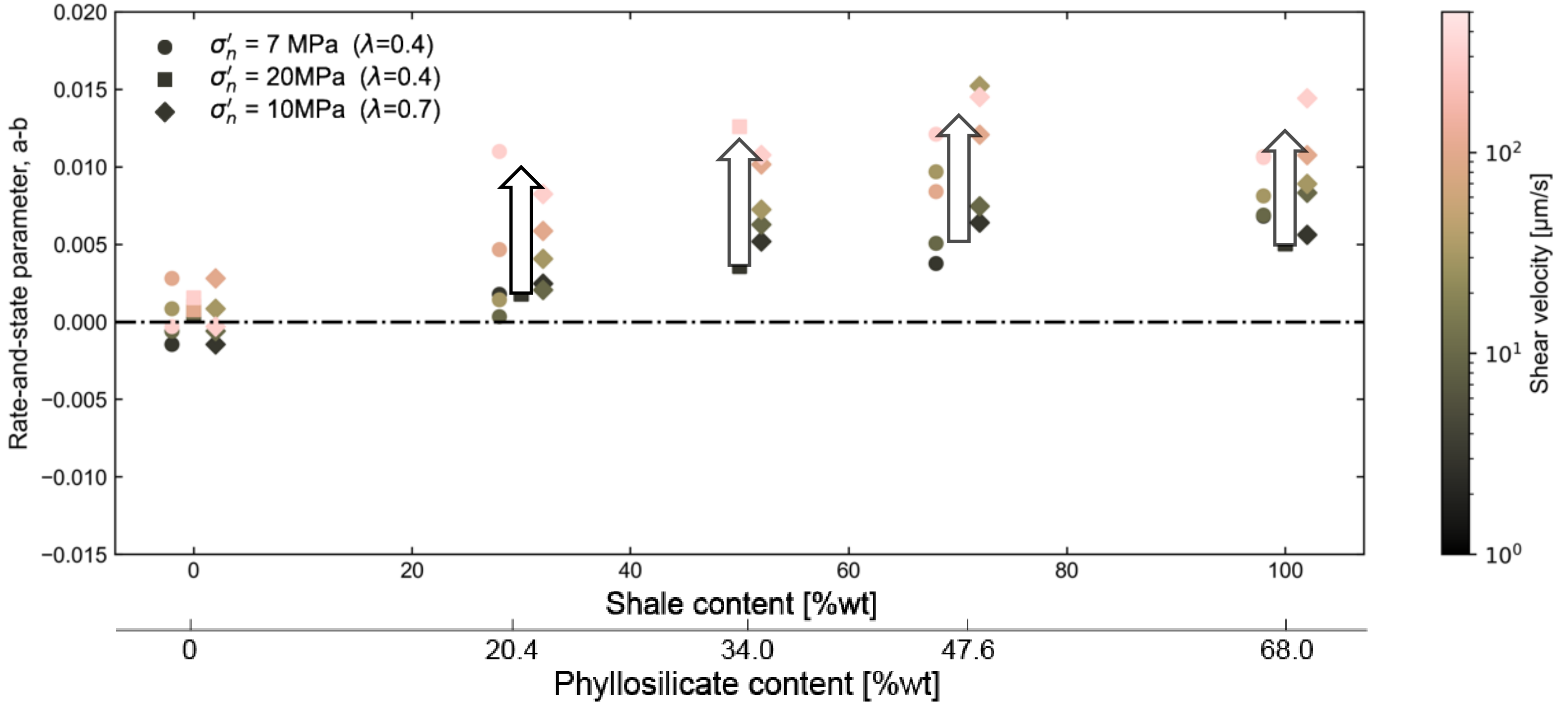
Results: frictional stability – seismic or aseismic behaviour?



(a-b) increases as a function of shale content

Giorgetti et al., in prep.

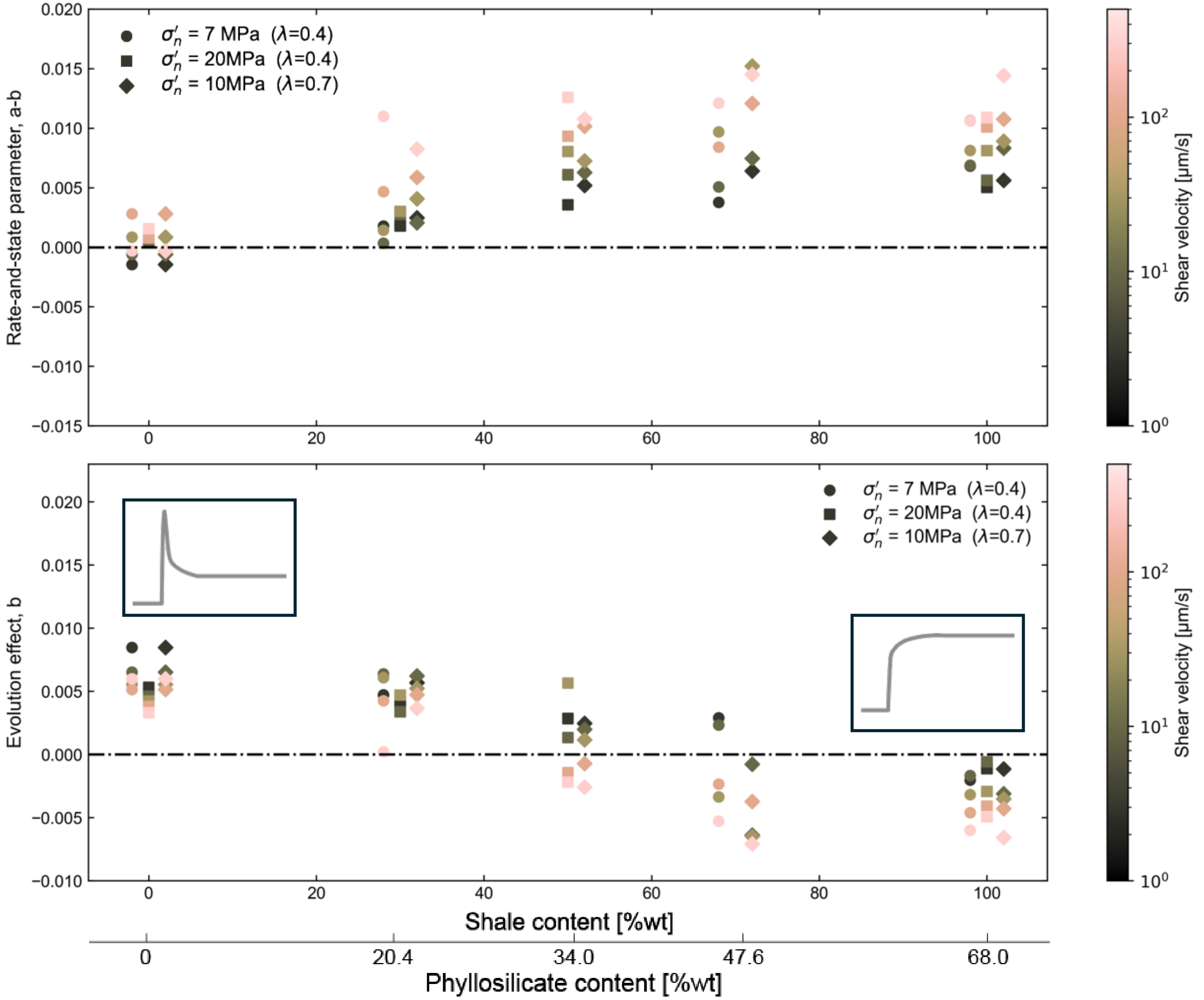
Results: frictional stability – seismic or aseismic behaviour?



(a-b) increases as a function of shale content, and, for shale content >30%, as a function of shear velocity

Scuderi et al., in review

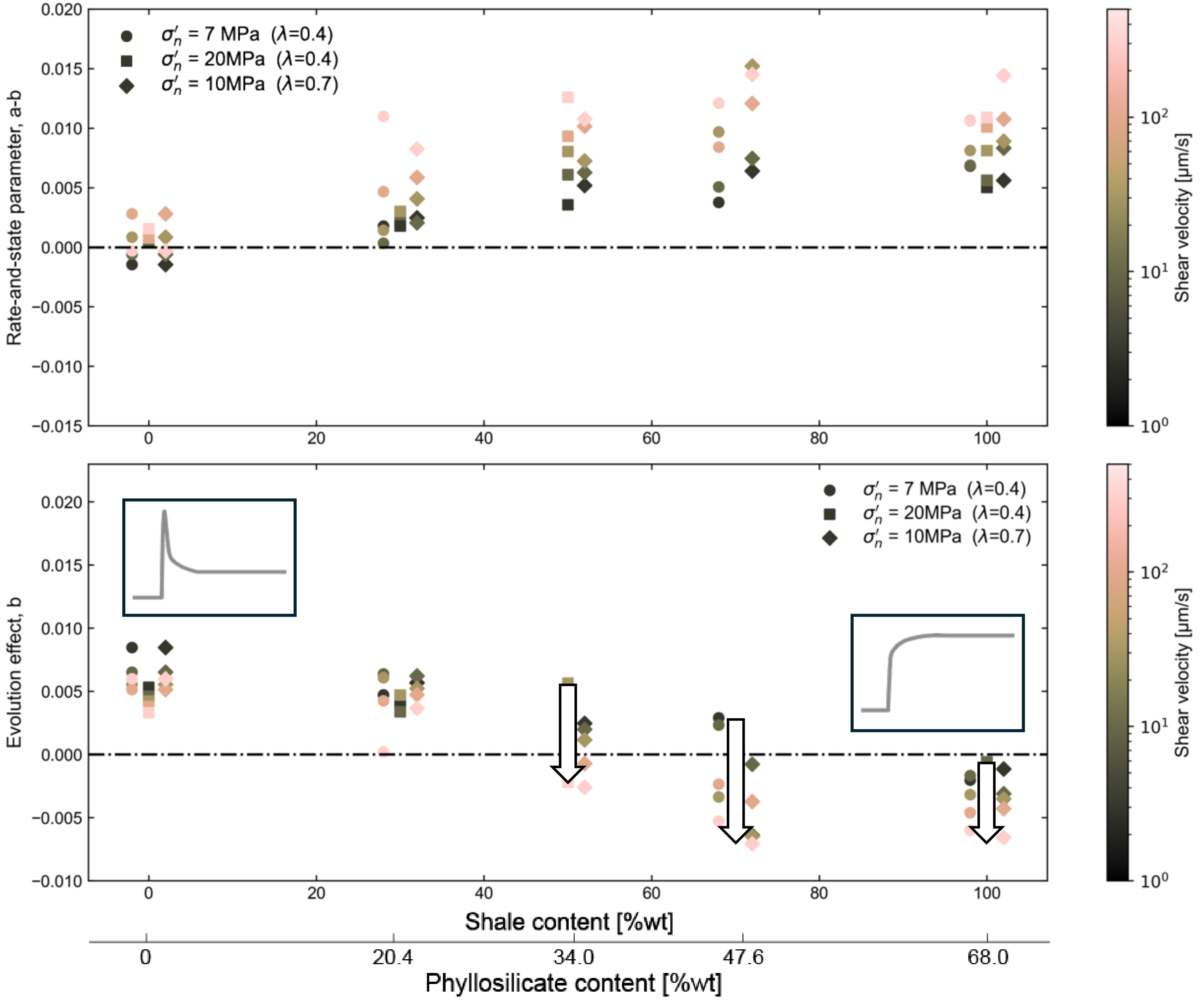
Results: frictional stability – seismic or aseismic behaviour?



Negative b values emerge for shale content >50%

Scuderi et al., in review

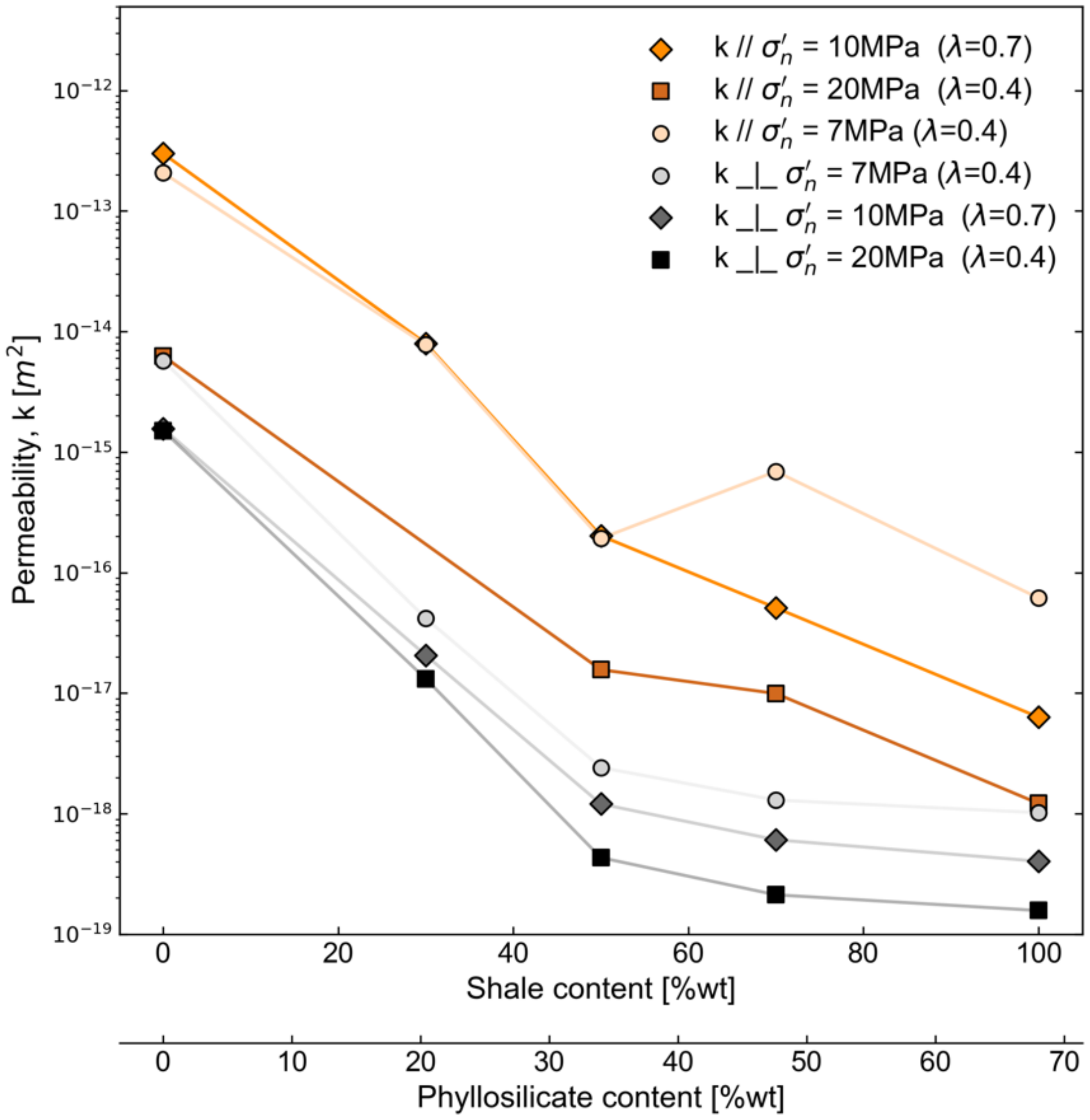
Results: frictional stability – seismic or aseismic behaviour?



Negative b values emerge for shale content >50% and high shear velocities

Scuderi et al., in review

Results: perpendicular ⊥ permeability versus parallel // permeability



k decreases with increasing shale content

k decreases with increasing normal stress

For the same shale %wt and σ'_n, **k//** always higher than **k⊥**

k// is up to 2 order of magnitude higher **k⊥**

Giorgetti et al., in prep.

Discussion: coupling of frictional and hydrological properties

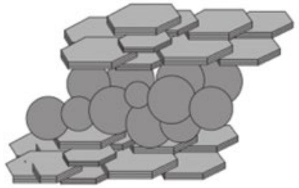
From Q to shale:

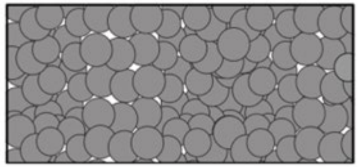
reduction in friction

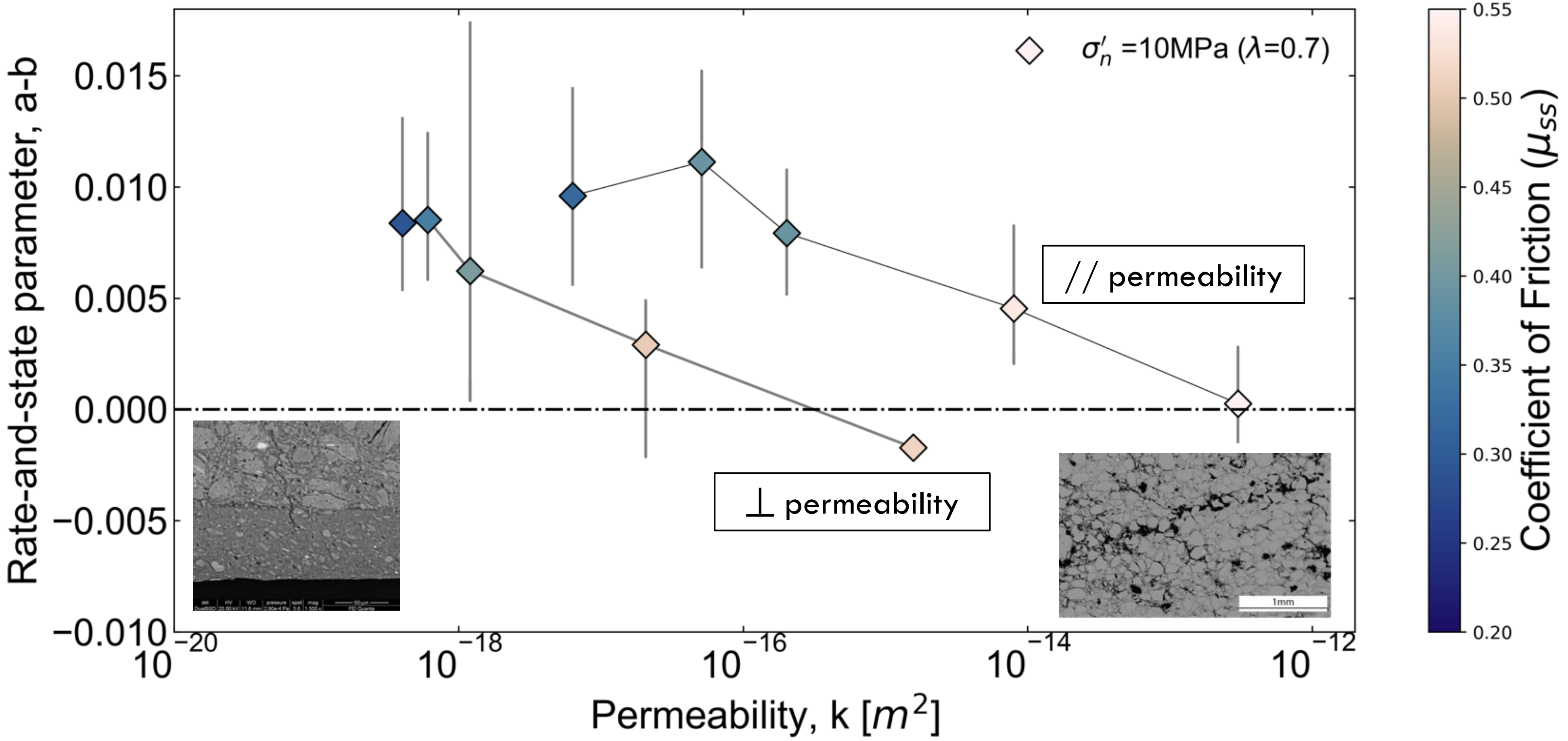
enhanced fault stability

reduction in permeability
but **k//** is higher **k⊥**

100% Shale ← 100% Quartz



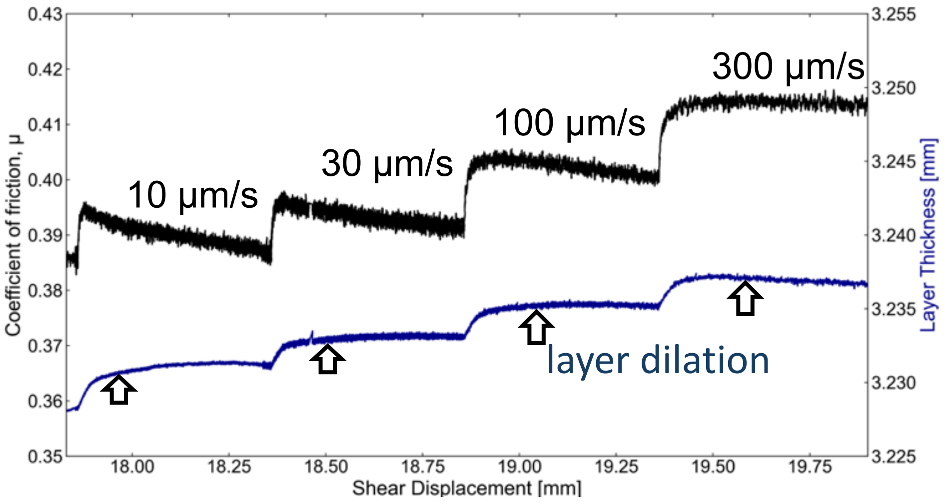


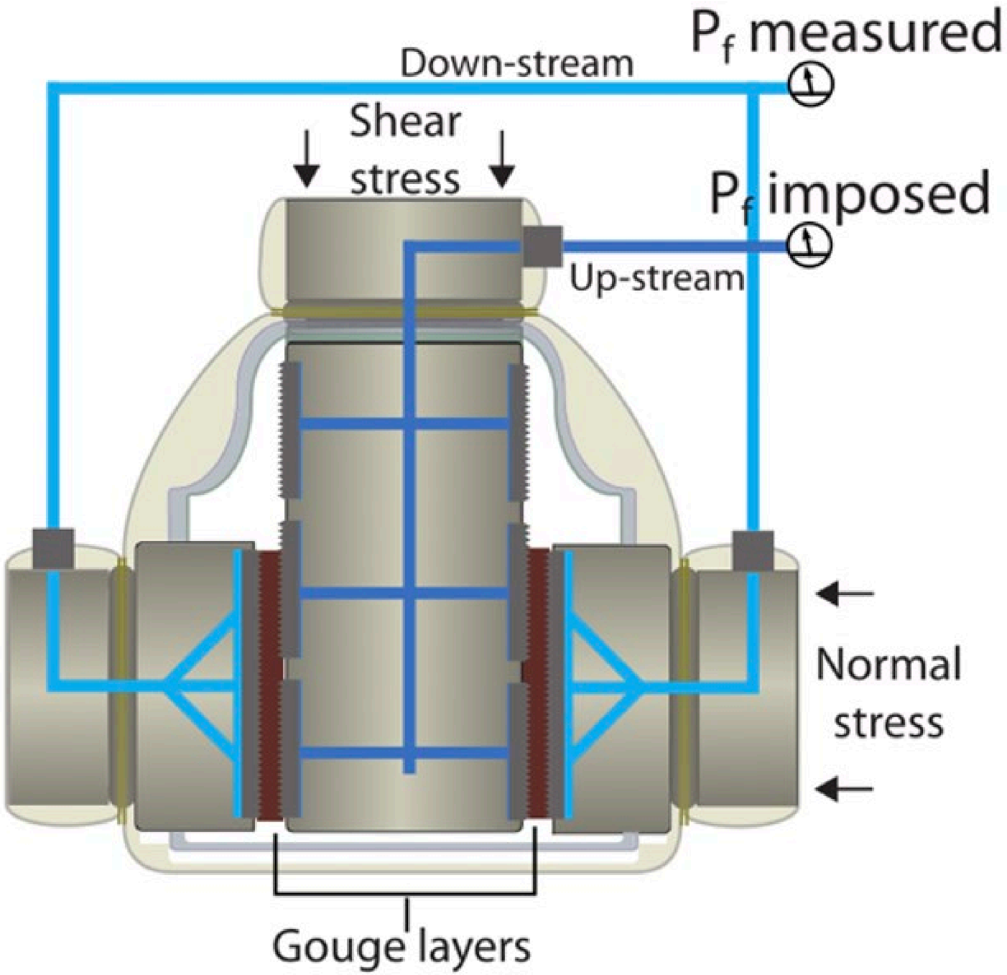


Giorgetti et al., in prep.

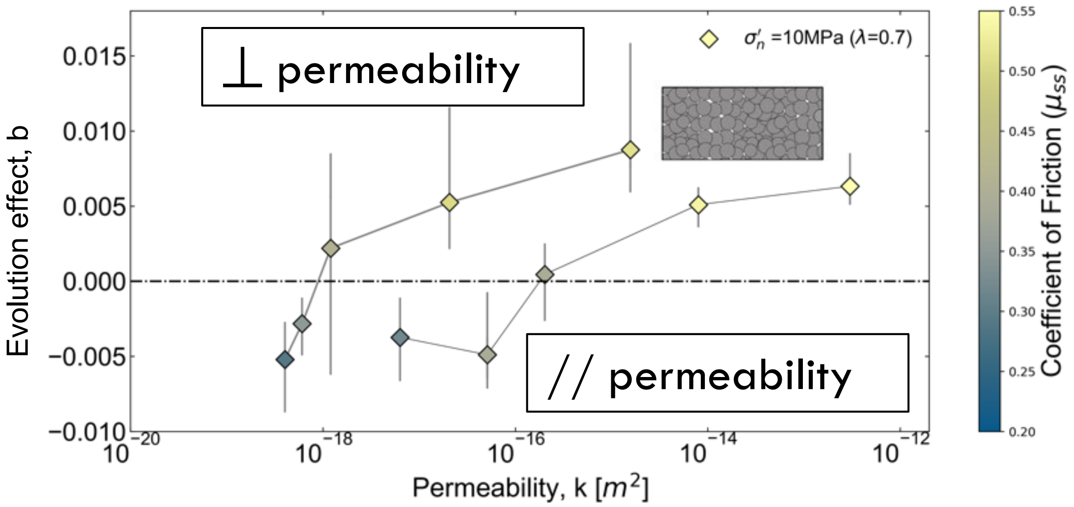
Hydromechanical coupling and frictional stability

To capture the hydromechanical coupling during velocity steps we:
1) imposed a constant Pf in the upstream and measured Pf in the downstream;
2) monitor the dilation (layer thickness) the fault experiences to dissipate the energy surplus.

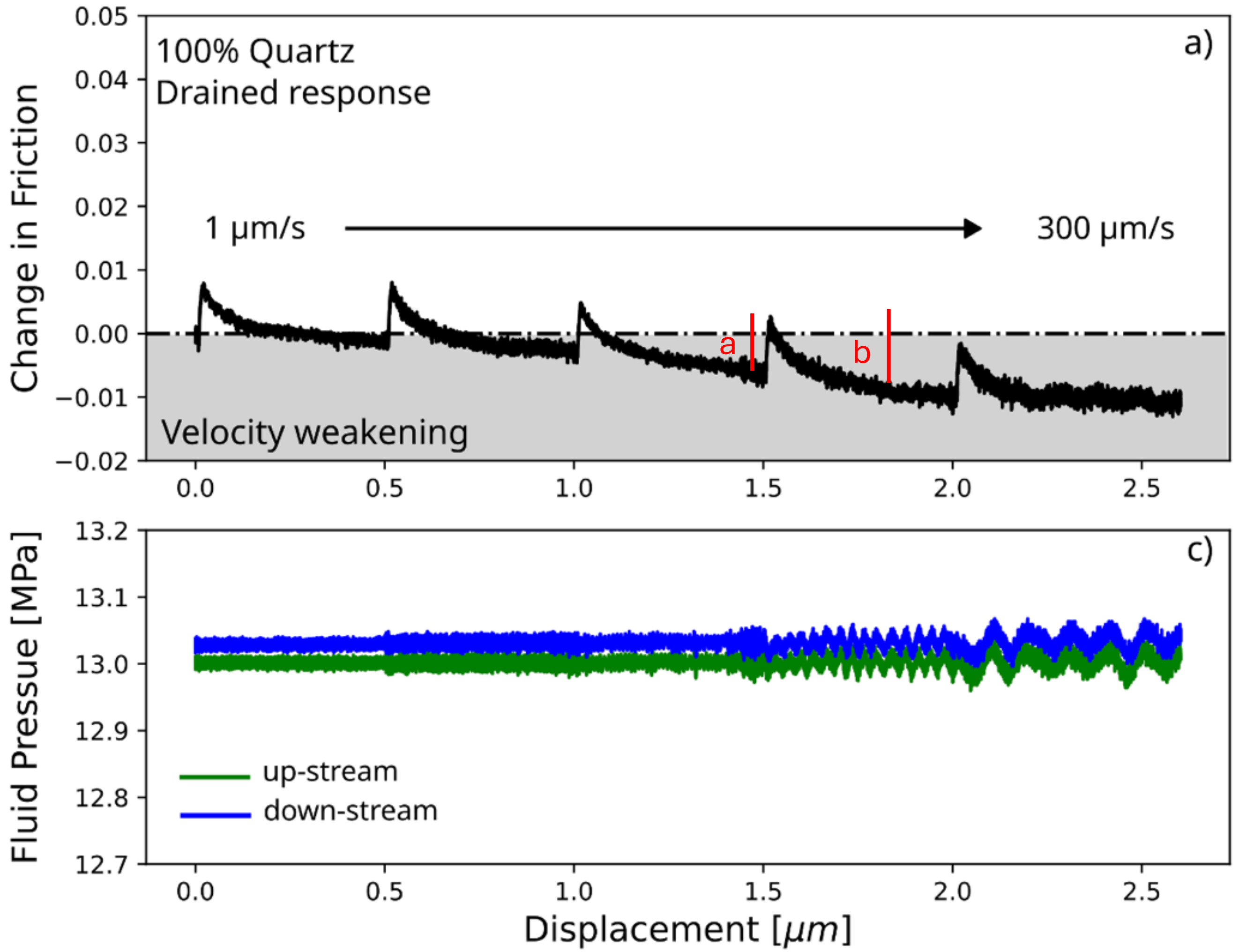




In Quartz we document VW with a well pronounced b parameter.



No pressure drop during the velocity steps in agreement with the high k of the fault.



Scuderi et al., in review

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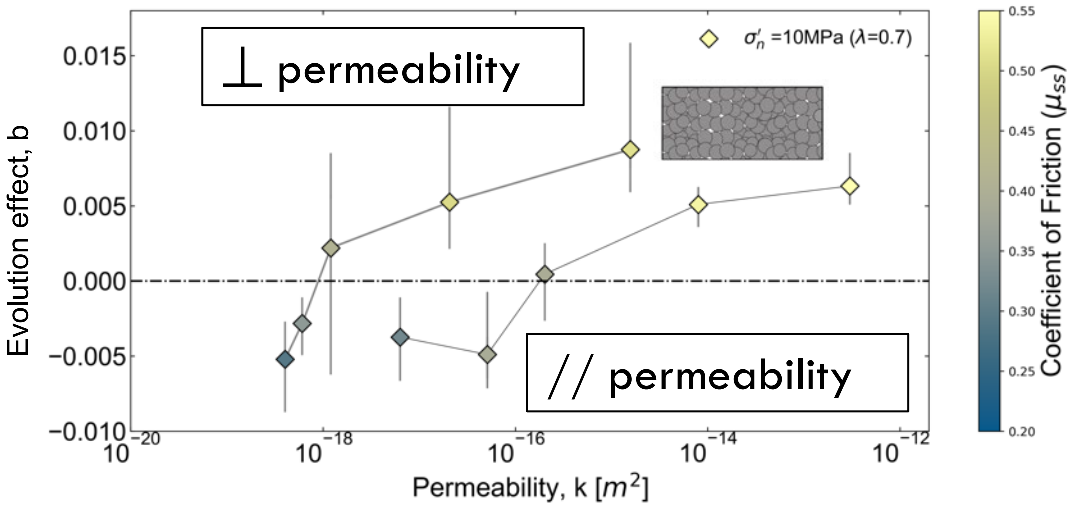
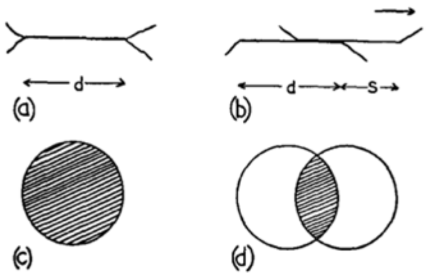
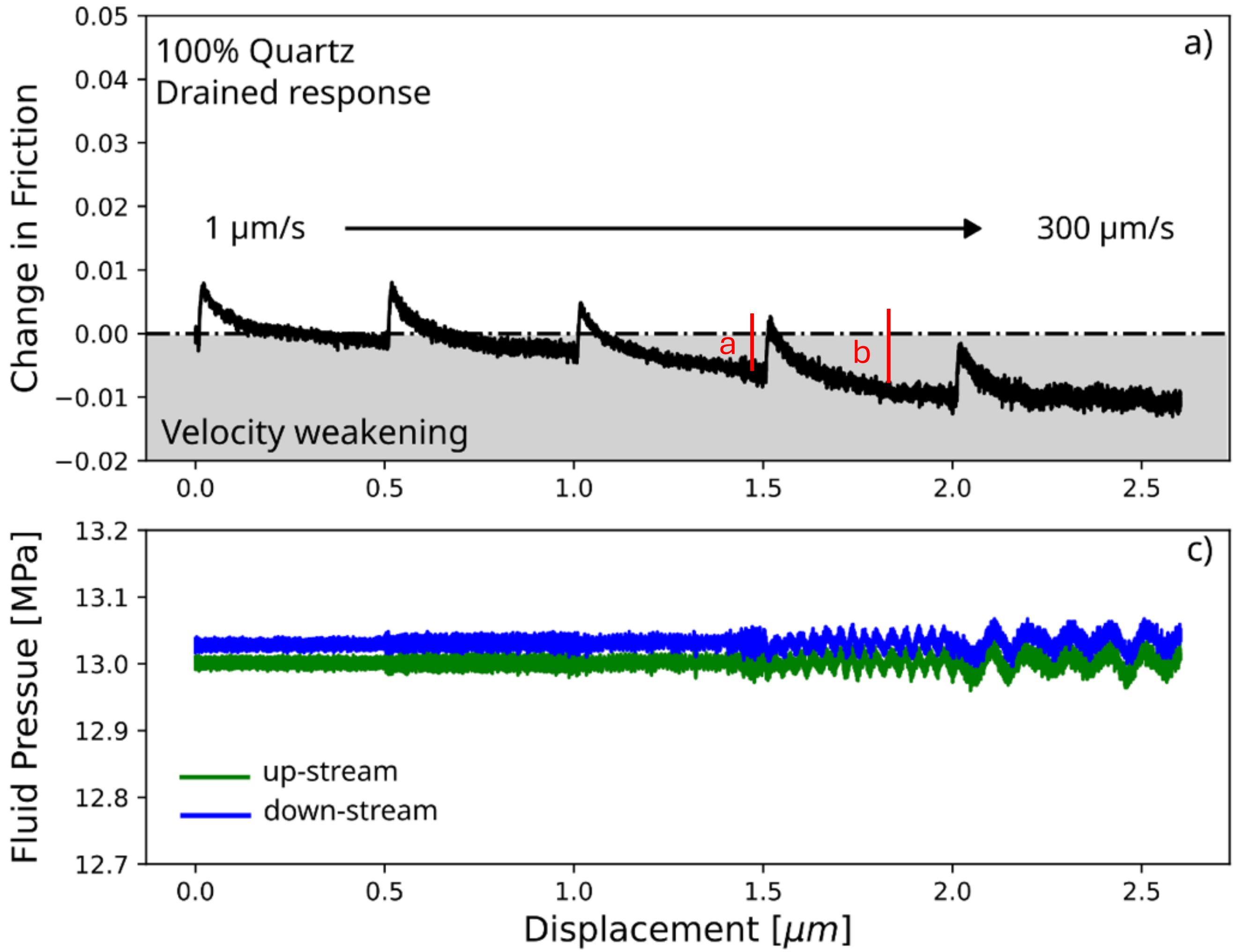


No pressure drop during the velocity steps in agreement with the high k of the fault.

The decrease in contact area promotes positive b and velocity weakening behaviour.

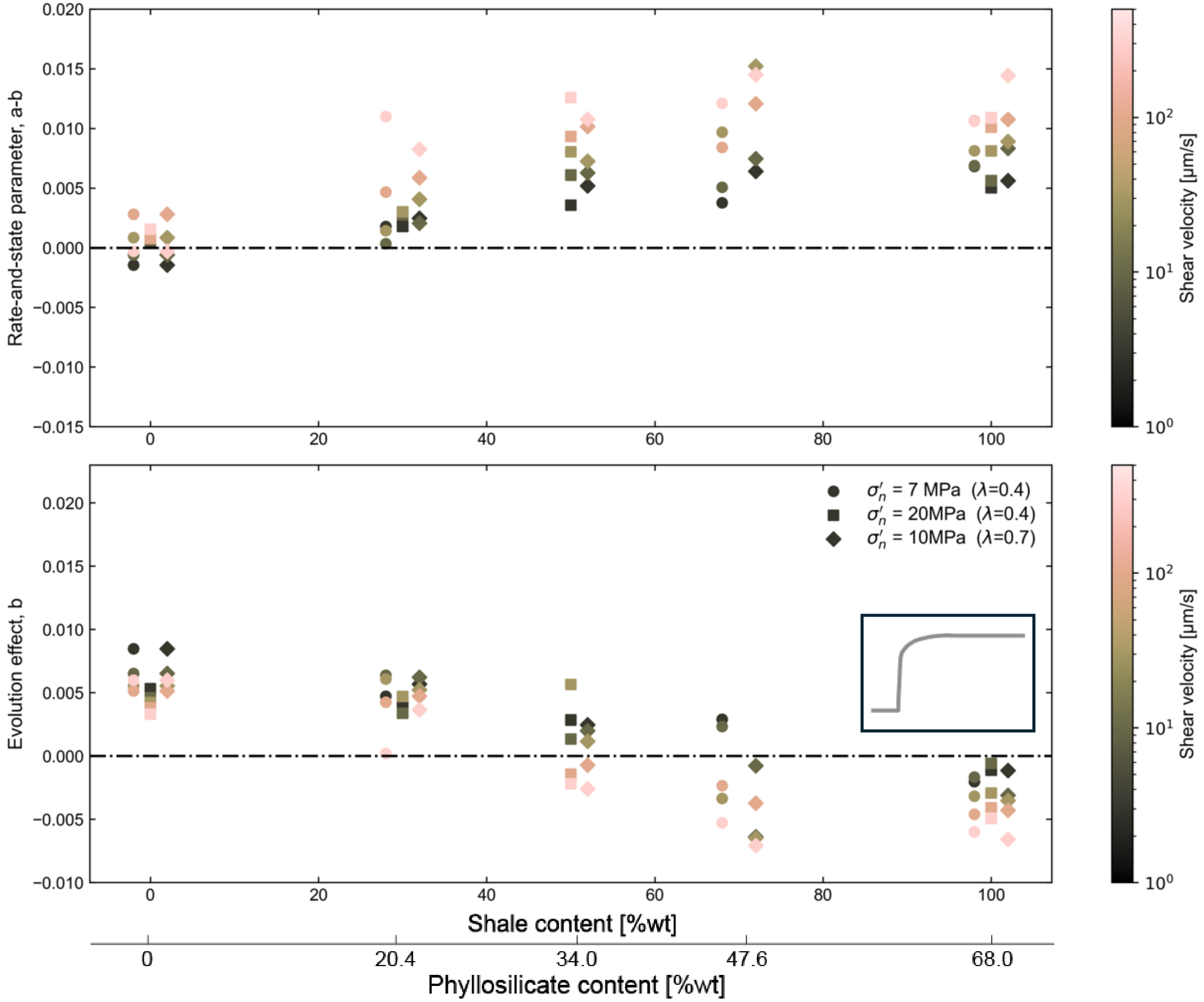


Rabinowicz, J. of Applied Physics 1951



Scuderi et al., in review

In shale we document VS and a negative b.



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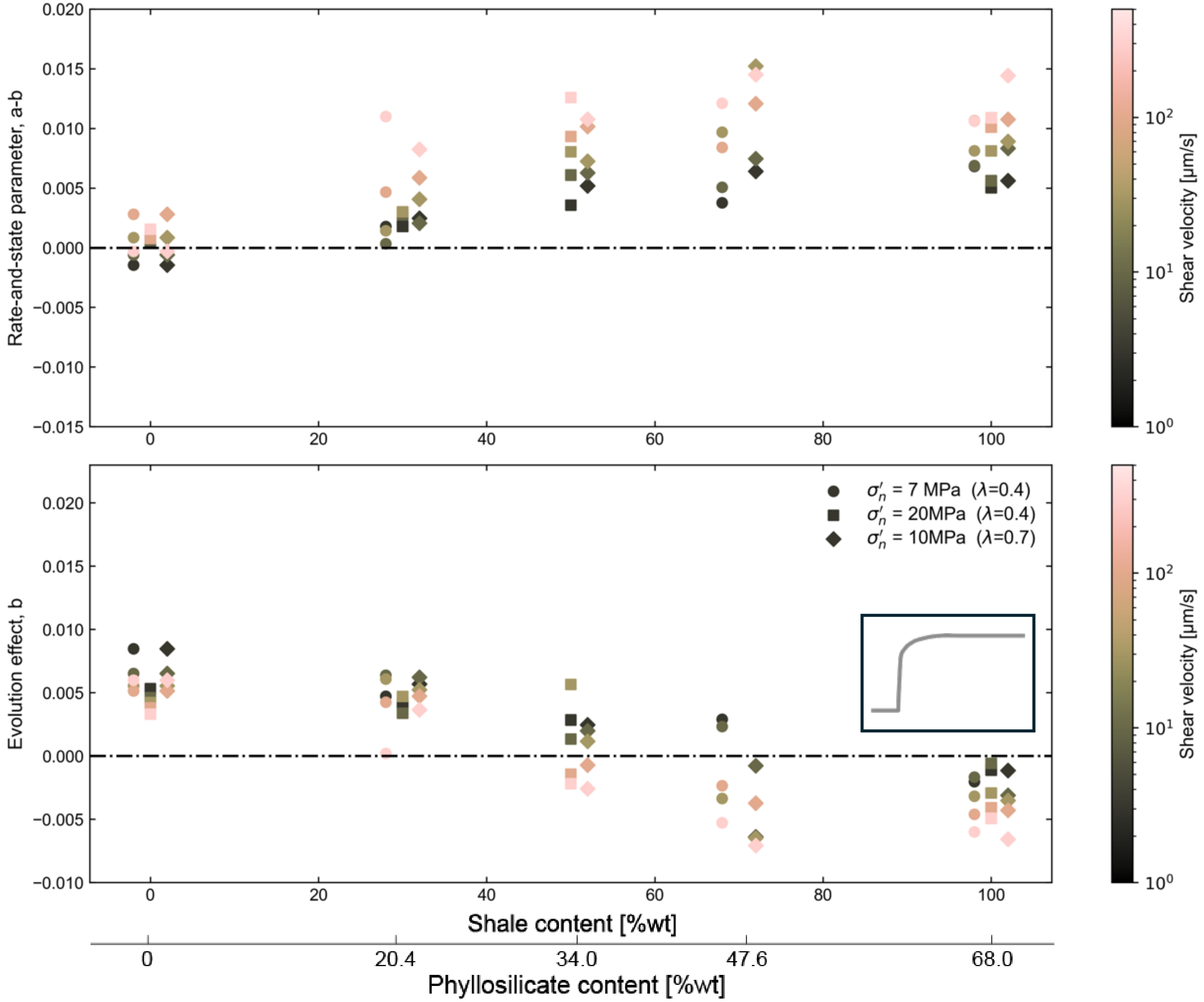
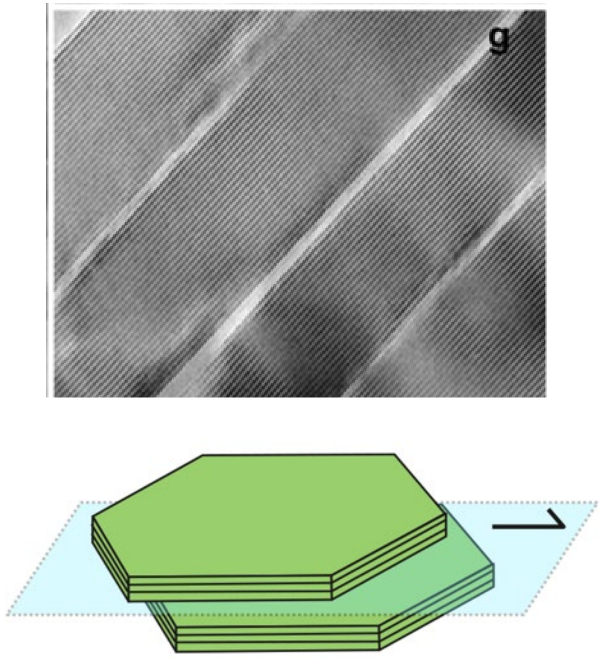
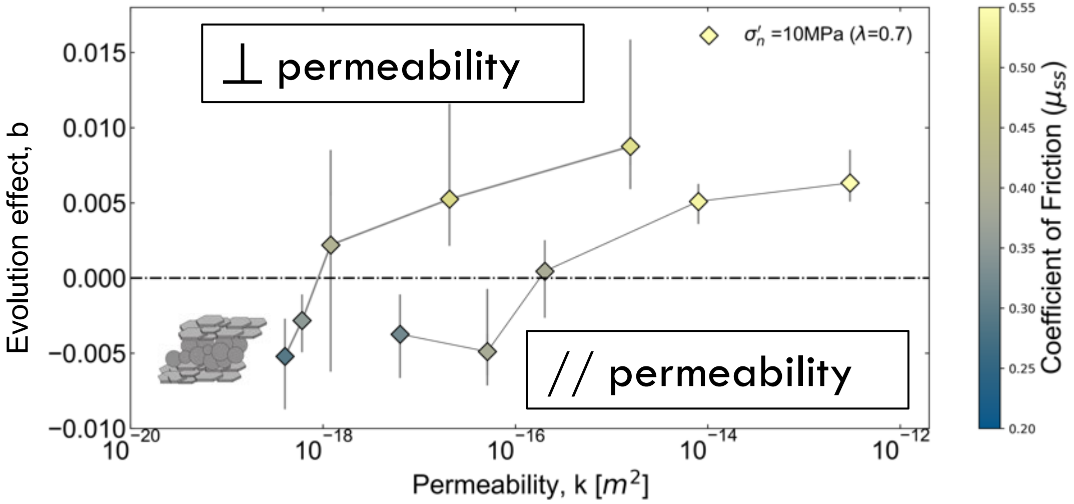


The enhanced fault stability in shale rich rocks can in part be due to saturation of the contact area resulting in no change in the real area of contact when the velocity is perturbed.



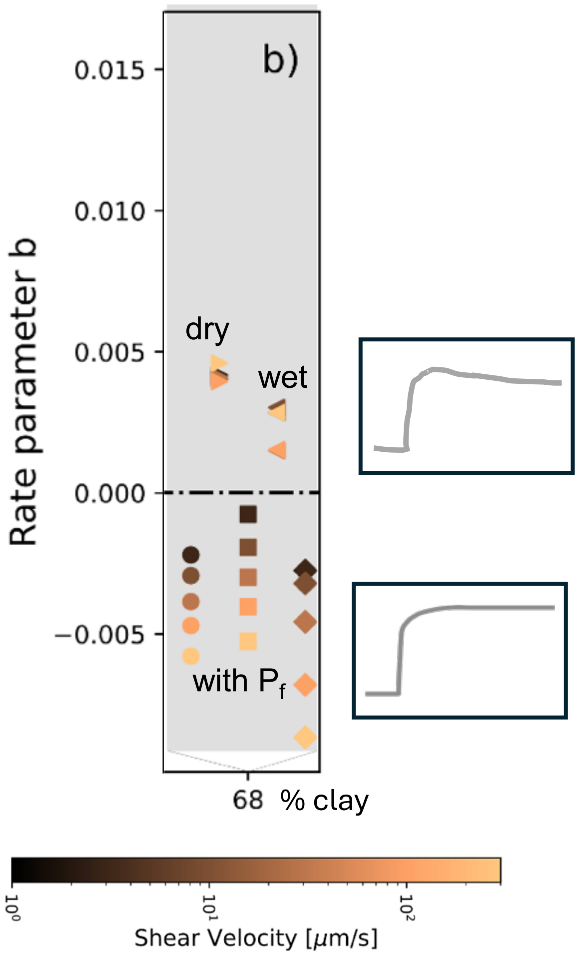
Scuderi et al., in review

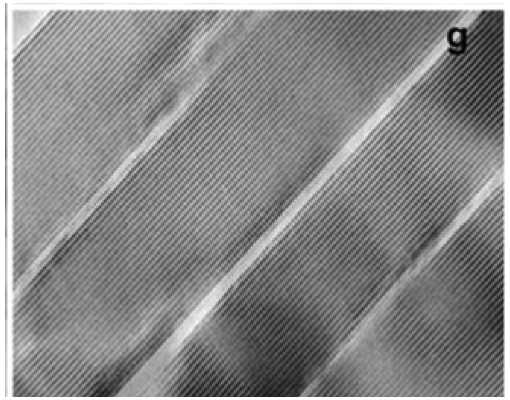
However, contact area saturation cannot explain the negative b.

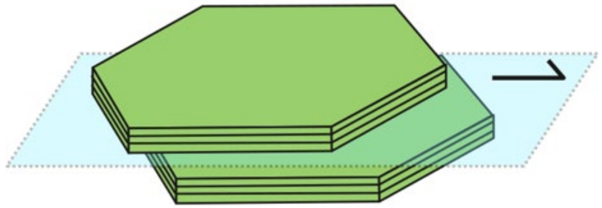


A systematic decrease in b values from dry, to wet, to Pf conditions.

With Pf, b becomes more negative with increasing shear velocity.

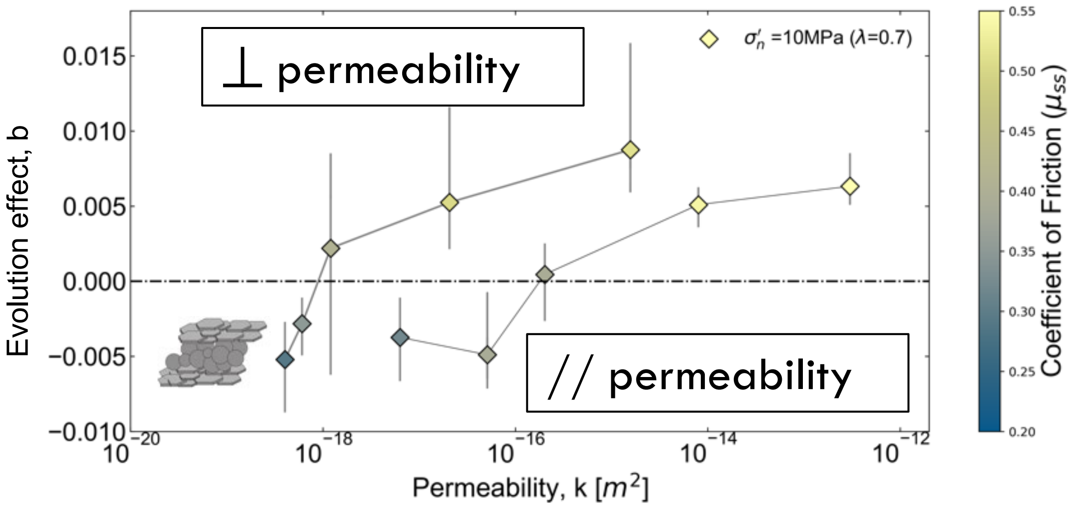






Scuderi et al., in review

In shale negative b: why?

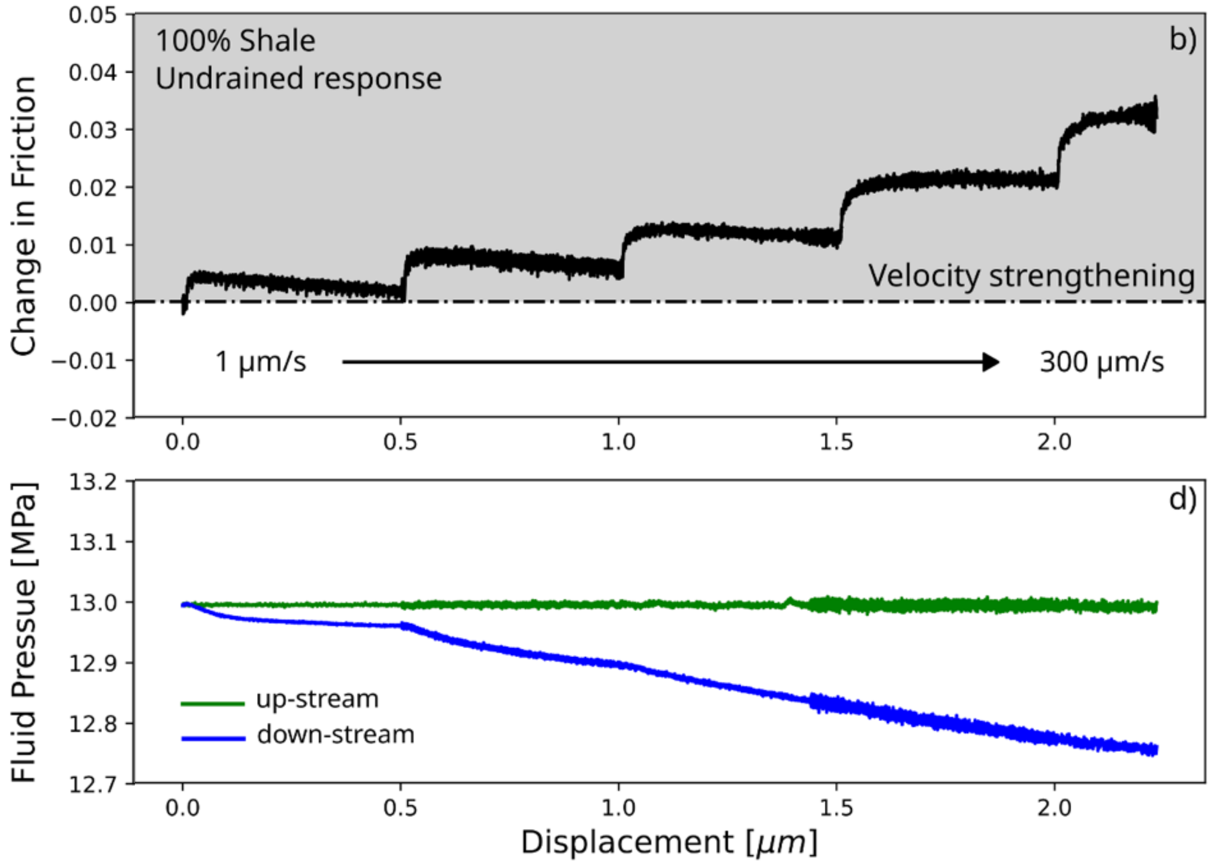


We suggest that the low k of clay generates a barrier for fluid diffusion across the fault.

With undrained boundary conditions, as shown by the pressure drop measured in the downstream.

dilation + low permeability → drop in Pf & increase in μ

$$\mu = \frac{\tau}{(\sigma_n - P_f)}$$



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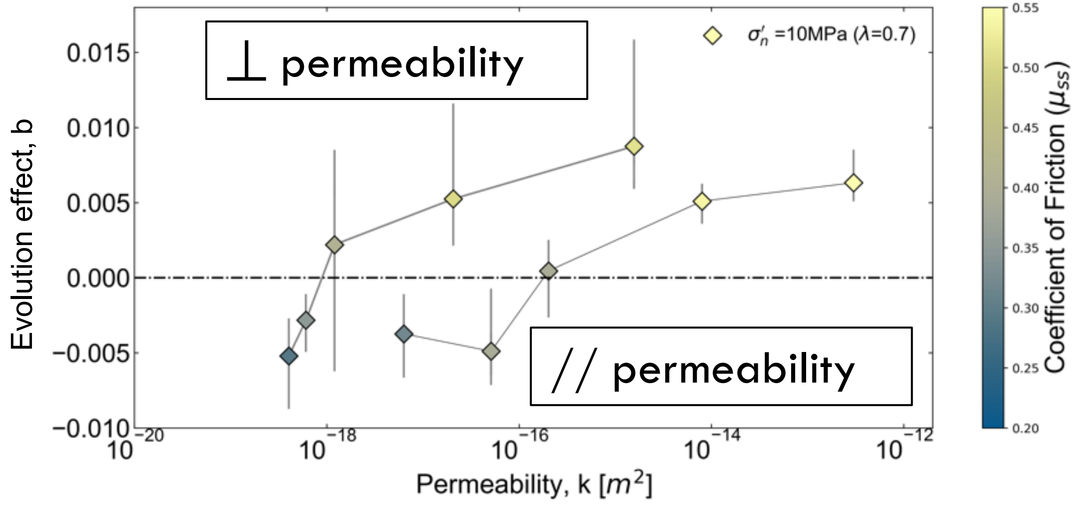
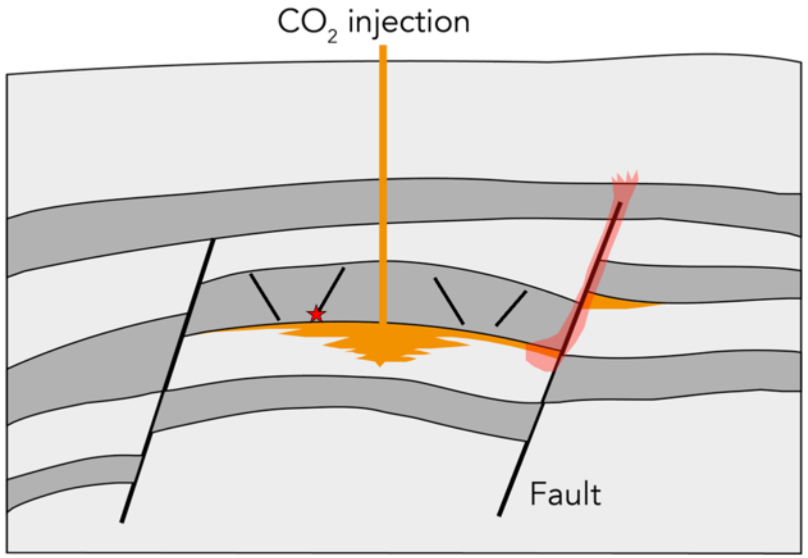
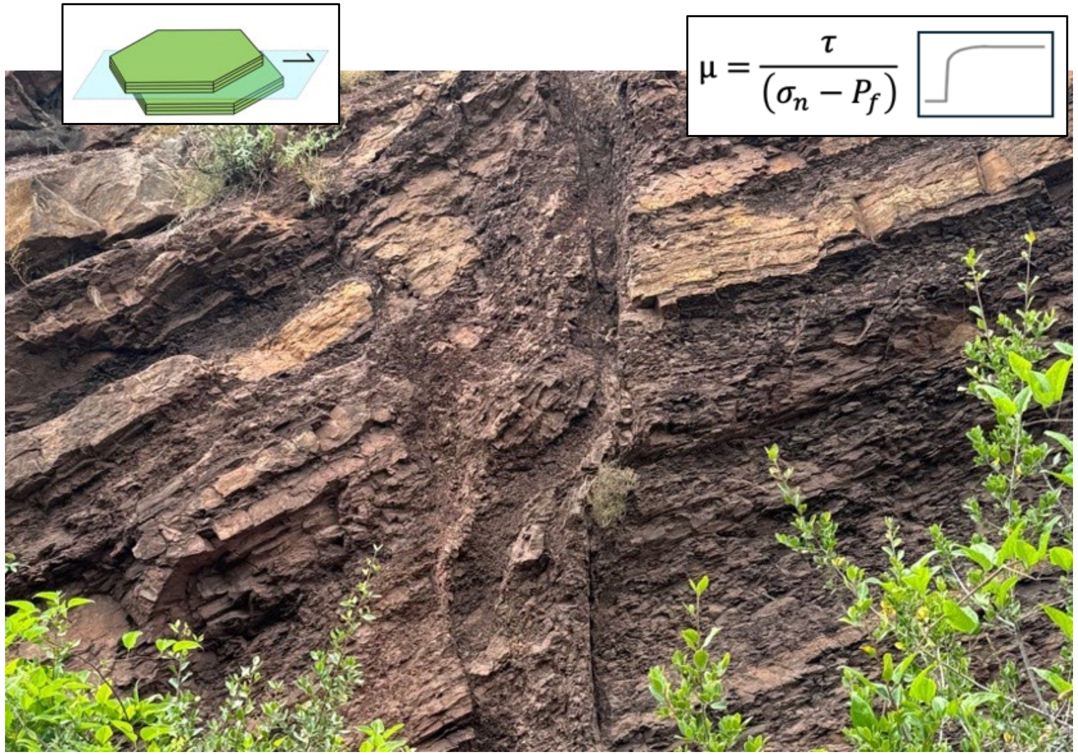
Take-home messages and potential implications

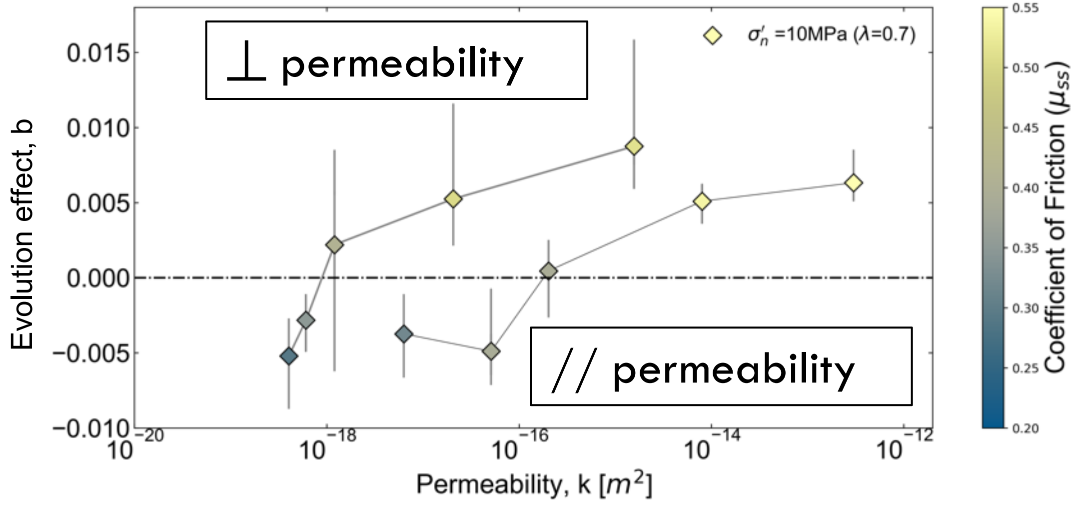


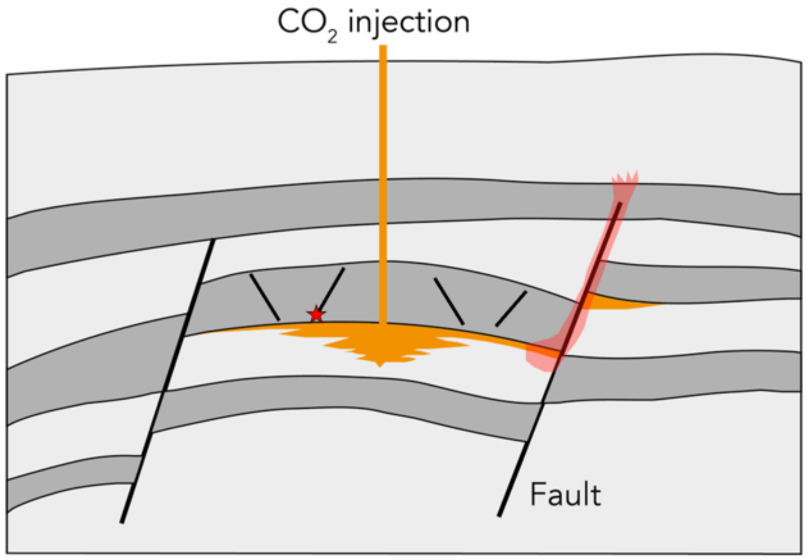




Contact area saturation plus dilation hardening stabilize shale-rich faults: accelerated slip prevails on induced seismicity

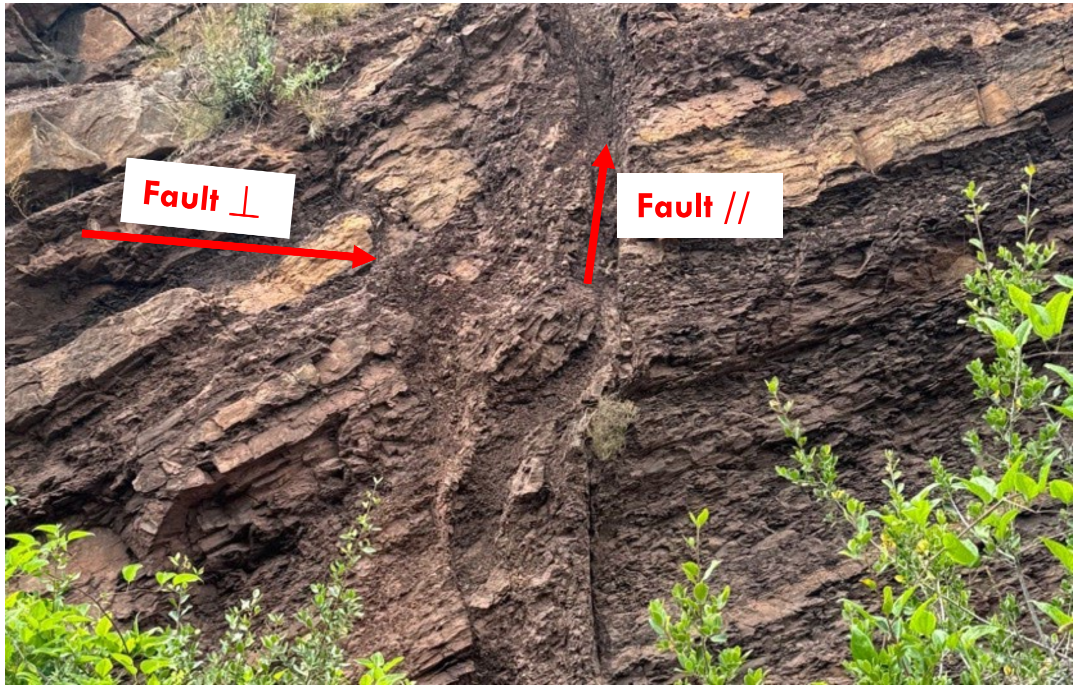
Take-home messages and potential implications



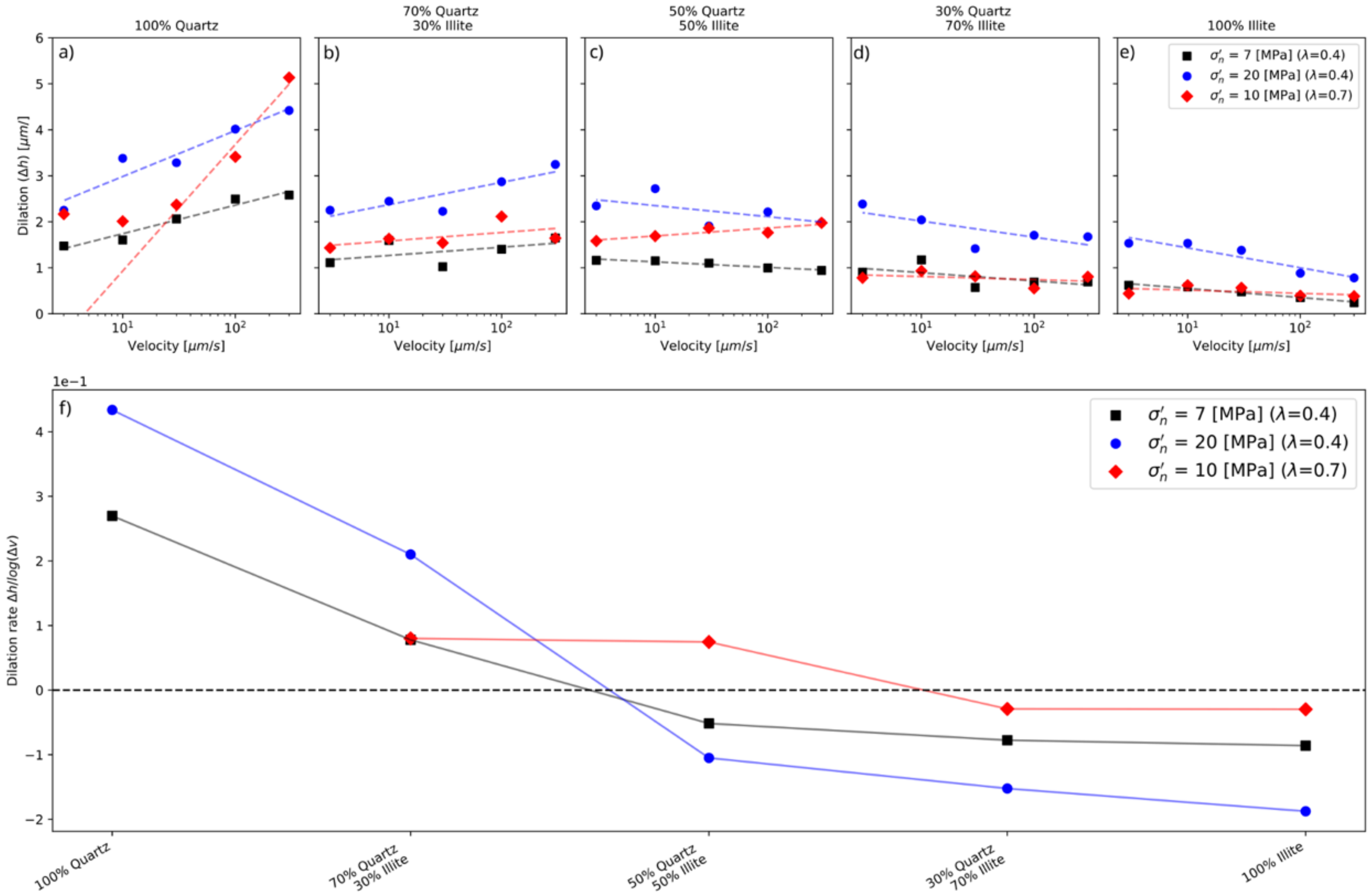


Contact area saturation plus dilation hardening stabilize shale-rich faults: accelerated slip prevails on induced seismicity

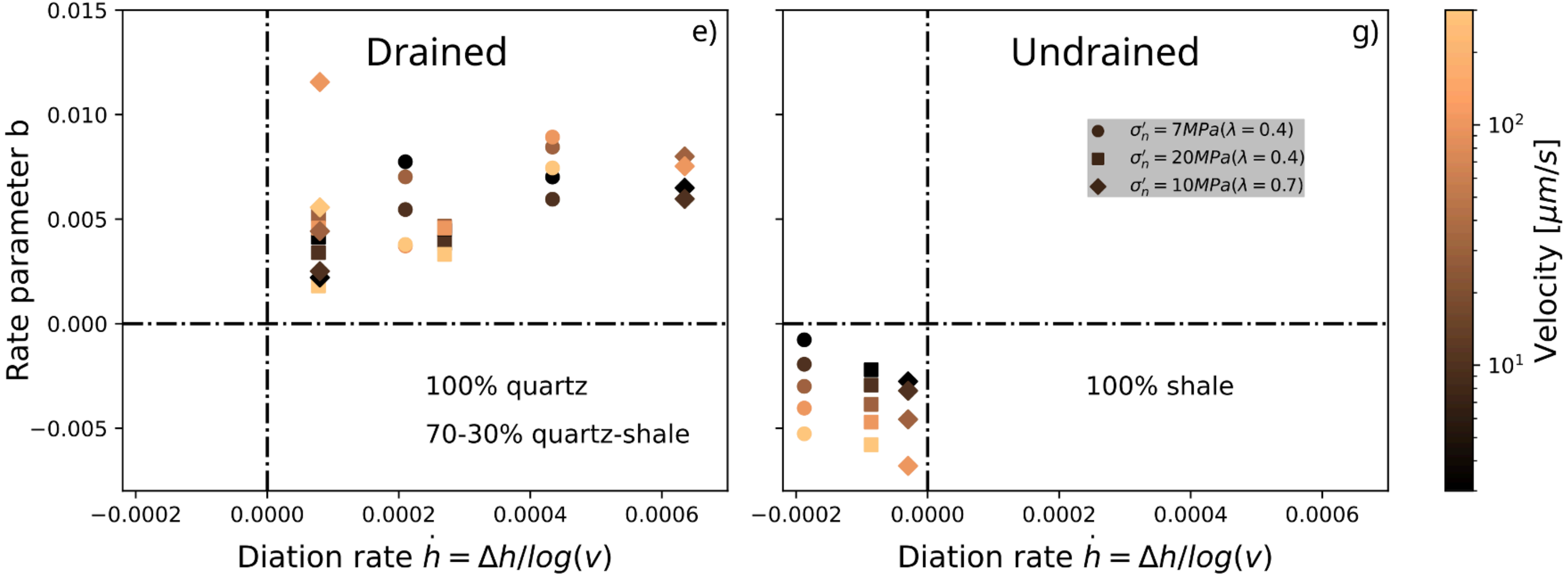
Permeability in fault parallel direction is higher than in fault perpendicular direction: potential fault parallel leak upon aseismic reactivation



Thank you



100% Quartz
70% Quartz
30% Illite
50% Quartz
50% Illite
30% Quartz
70% Illite
100% Illite
a)
b)
c)
d)
e)
Dilation (Δh) [μm]
Velocity [μm/s]
σ'n = 7 [MPa] (λ=0.4)
σ'n = 20 [MPa] (λ=0.4)
σ'n = 10 [MPa] (λ=0.7)
f)
1e−1
Dilation rate Δh/log(Δv)
100% Quartz
70% Quartz 30% Illite
50% Quartz 50% Illite
30% Quartz 70% Illite
100% Illite



Drained
e)
Undrained
g)
0.015
0.010
0.005
0.000
−0.005
Rate parameter b
100% quartz
70-30% quartz-shale
100% shale
$\sigma'_n = 7MPa(\lambda = 0.4)$
$\sigma'_n = 20MPa(\lambda = 0.4)$
$\sigma'_n = 10MPa(\lambda = 0.7)$
−0.0002
0.0000
0.0002
0.0004
0.0006
Diation rate $\dot{h} = \Delta h/log(v)$
Diation rate $\dot{h} = \Delta h/log(v)$
10^2
10^1
Velocity $[\mu m/s]$

Dimensionless dilation hardening parameter, Samuelson et al. (2009)

$$V_D = \frac{va^2\eta}{kKD_c}$$

V_D above 1 suggests dilation hardening, with dilation dominating on fluid pressure diffusion.

v is sliding velocity, a is the shear zone half width (1.5 mm), η is the fluid viscosity (η = 0.89 x 10^{-3} Pas), k is the permeability, K is the fluid modulus (2.2 GPa), and D_c is the critical slip distance.