Towards improving laboratory determination of rate-and-state friction parameters

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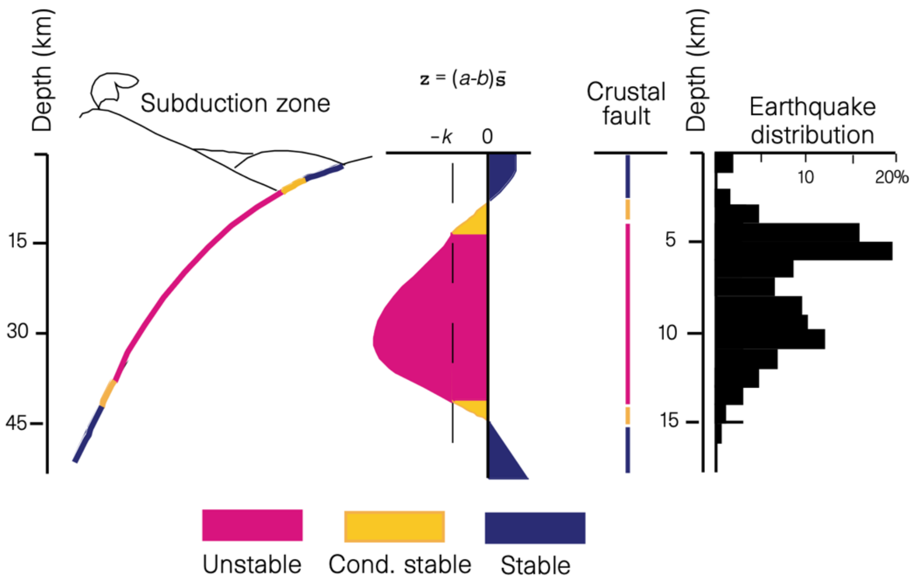
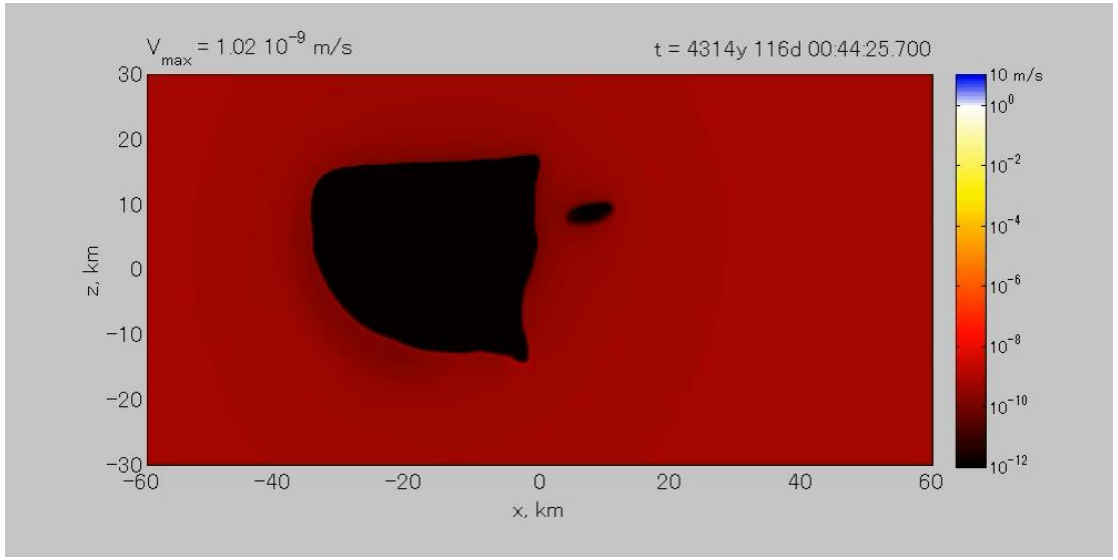
Importance of RS friction for understanding fault mechanics

- Matching observed behaviour
- Earthquake cycle models

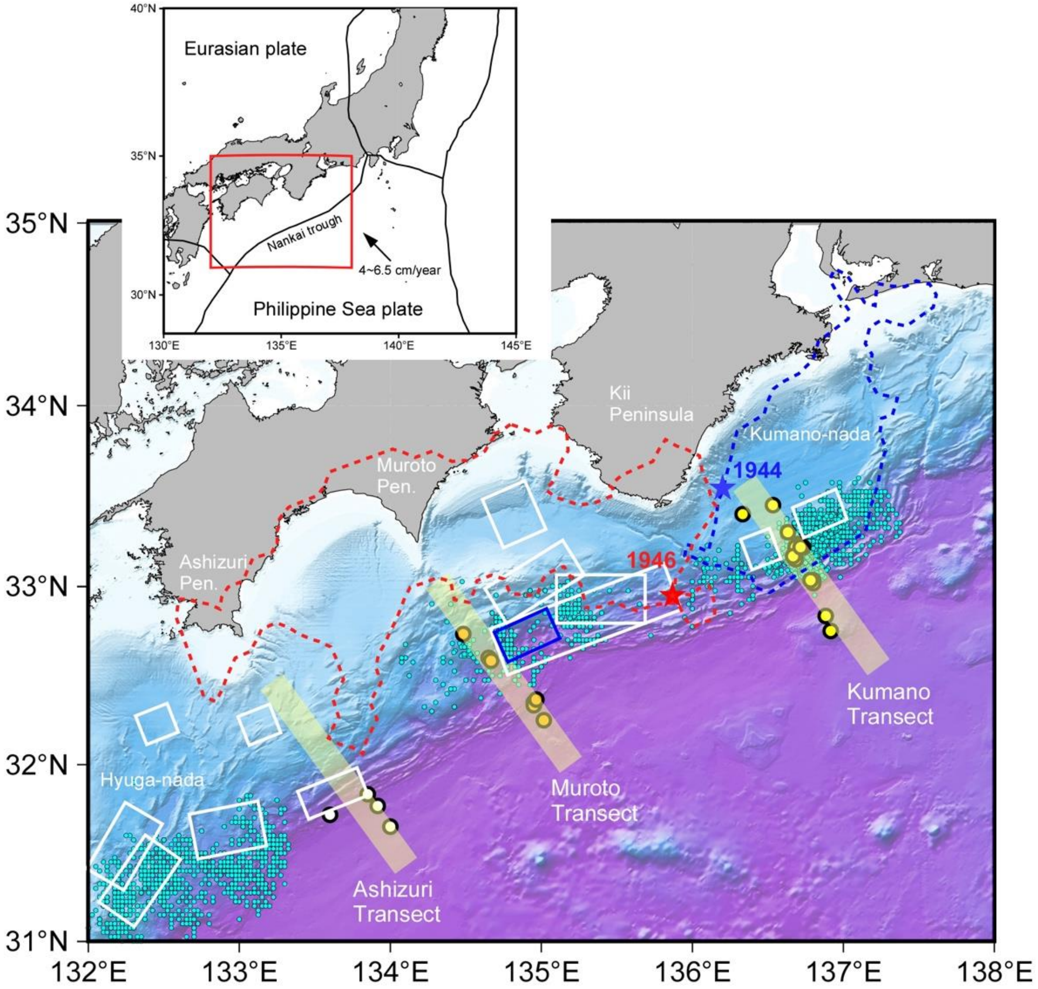


Scholz 1998



Noda and Lapusta 2013

Nankai Trough friction data

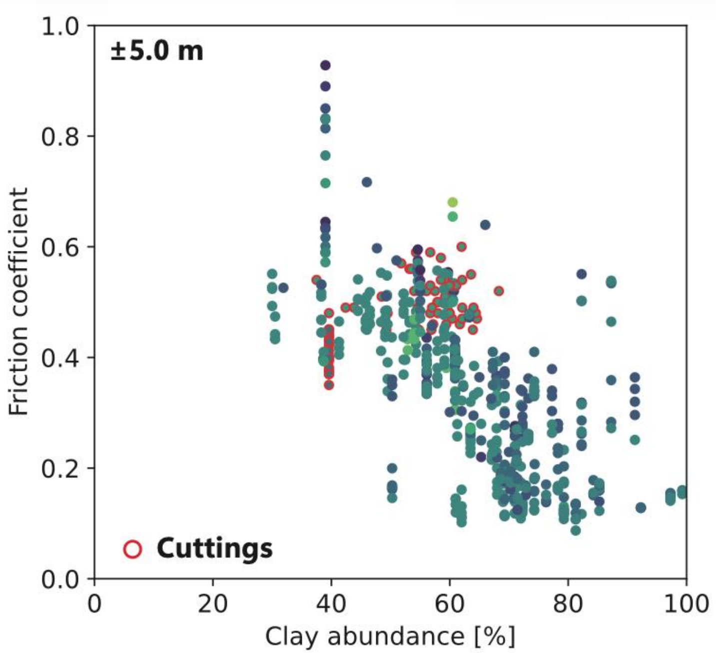


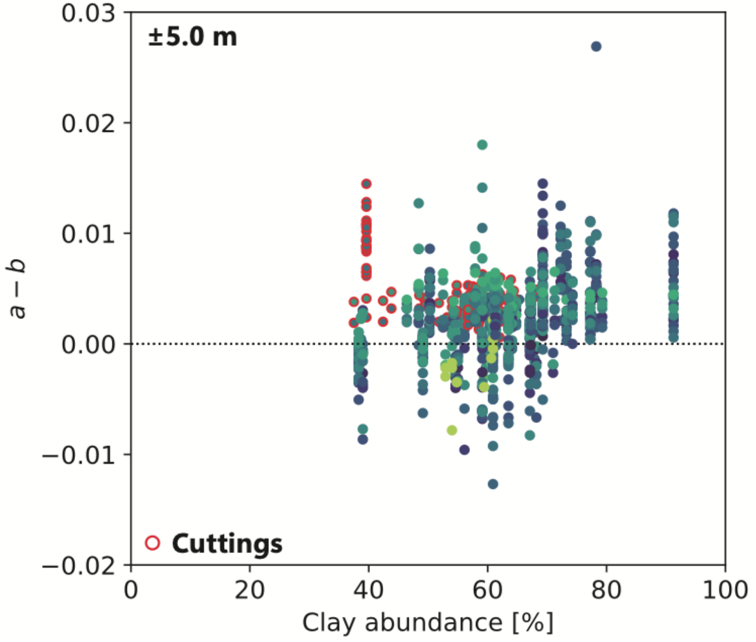
Drilling from 1980s, NanTroSEIZE 2007-2018

~30 laboratory friction studies published

What is true variability versus artefact?

Faulkner, Zhang, Okuda, Bedford, Ikari, Schleicher, Hirose, 2025, JGR





Rate-and-state friction parameter determination

- Fitting laboratory data
  - Choosing steady-state
  - Logarithmic searching for D_{RS}
  - Stiffness as a fitting parameter
- Avoiding pore-fluid pressure effects
  - Strength
  - Rate-and-state parameter determination

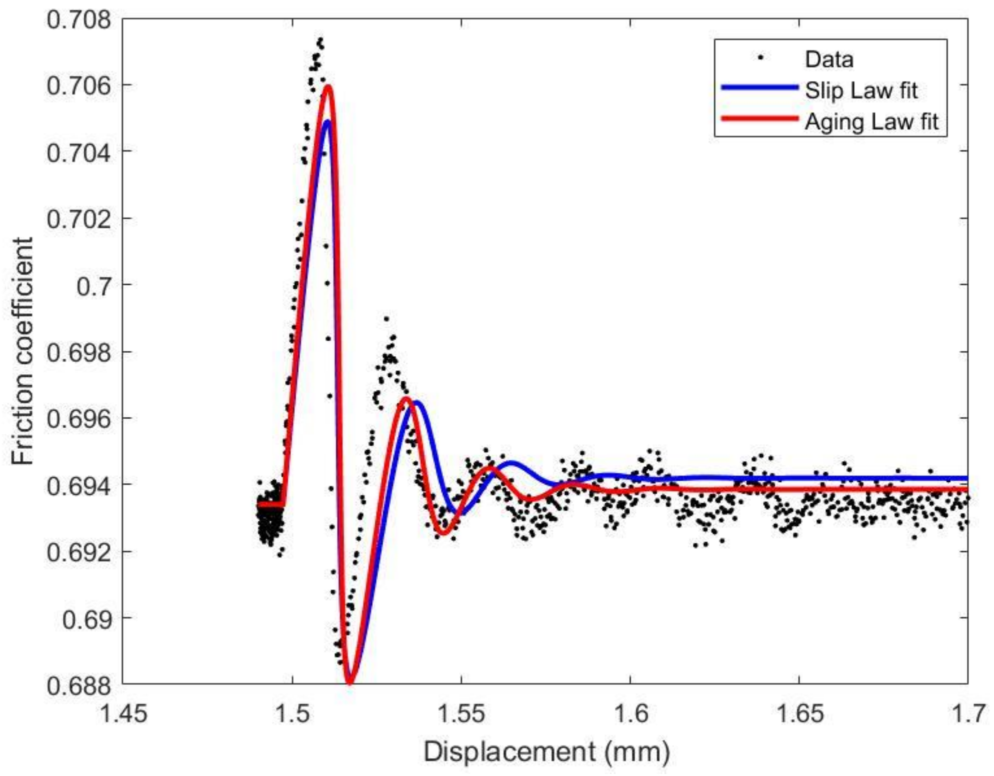
$$\tau = (\sigma_n - p)\left[\mu_0 + a ln\frac{V}{V_0} + b ln\frac{V\theta}{D_{RS}}\right]$$

ageing law; $$\frac{d\theta}{dt} = 1 - \frac{V\theta}{D_{RS}}$$

slip law; $$\frac{d\theta}{dt} = -\frac{V\theta}{D_{RS}} ln\frac{V\theta}{D_{RS}}$$

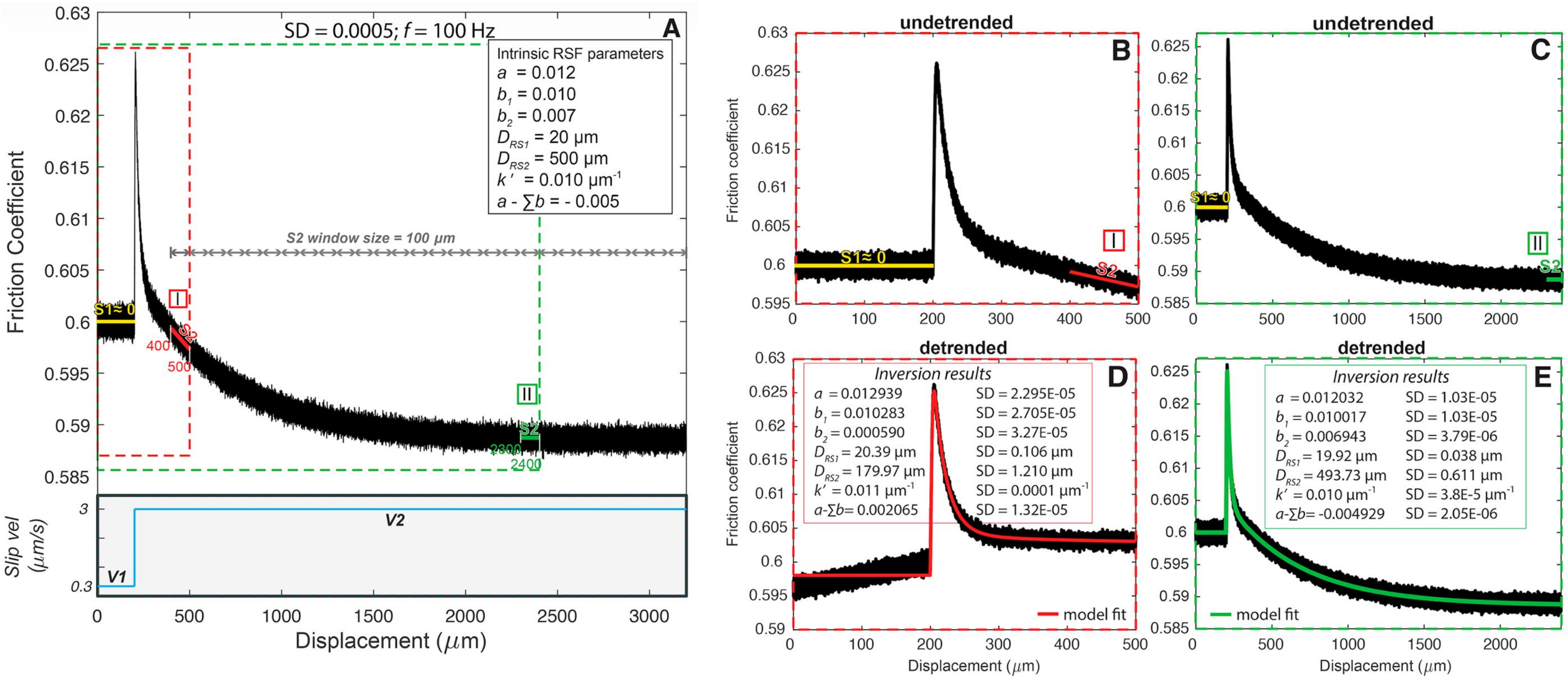
Need to determine μ_0, a, b, D_{RS} (and stiffness?)

Rate-and-state friction parameter fitting



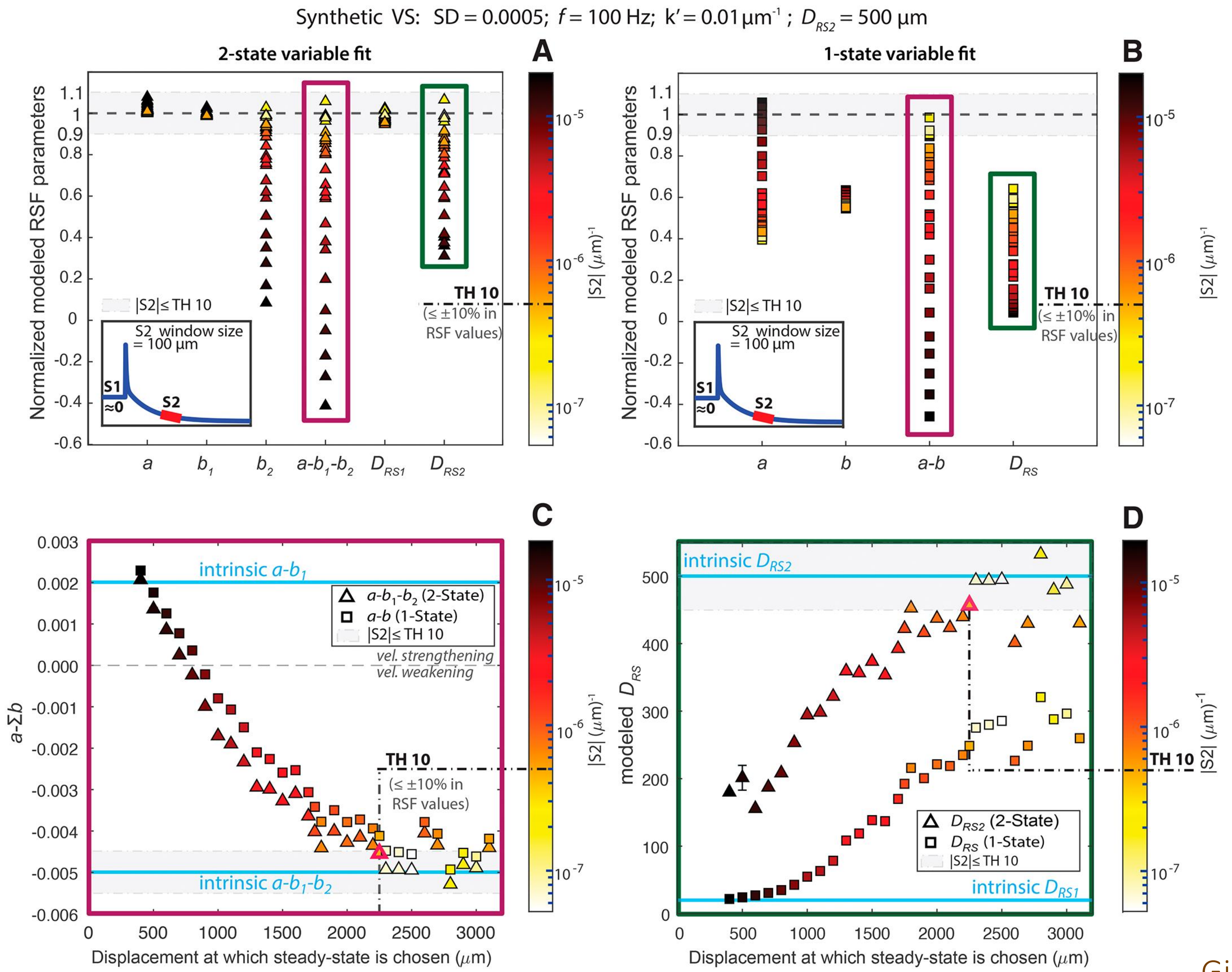
- Non-linear least squares fitting of the parameters
  - Reinen and Weeks 1993
  - Noda and Shimamoto 2009
  - Skarbek and Savage 2019
- Bayesian inversion (Markov Chain Monte Carlo)
  - Kim et al. 2026 (in review)

Choosing steady state



Giacomel et al., 2024

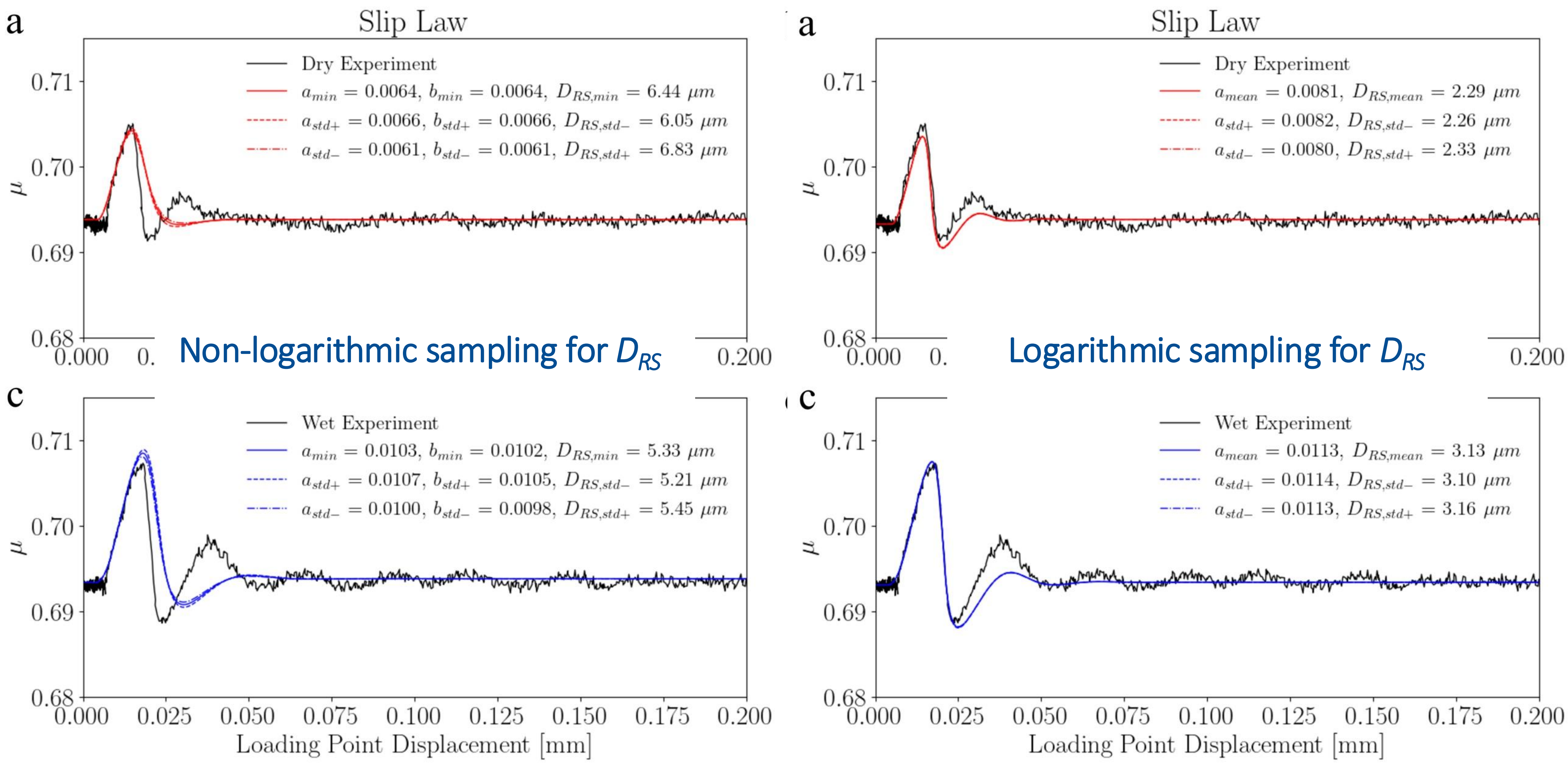
A two-state variable fit will always determine a, b_1 and D_{RS1} well, but for b_2 and D_{RS2} ss is needed.



For a one-state variable fit to two-state variable data, only (a-b) is reliable once ss is reached

Giacomel et al., 2024

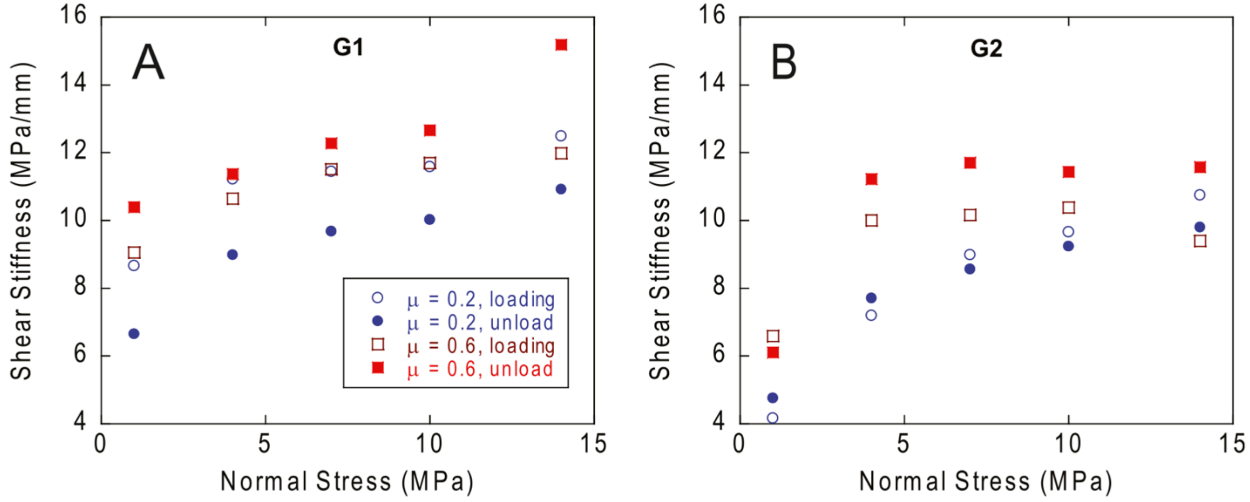
Logarithmic sampling of D_{RS}



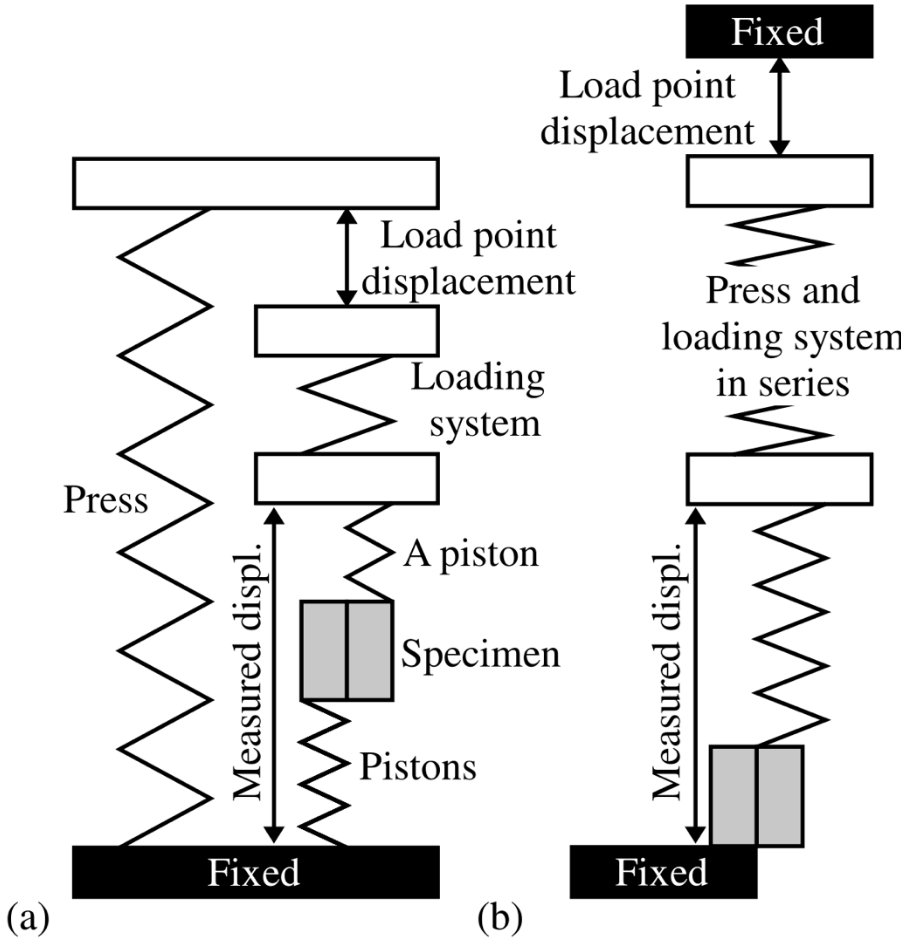
See also Bhattacharya et al. 2017

Kim et al., in review

Stiffness as a fitting parameter



Stiffness of some apparatus can vary with normal stress
Ikari and Haberkorn 2023

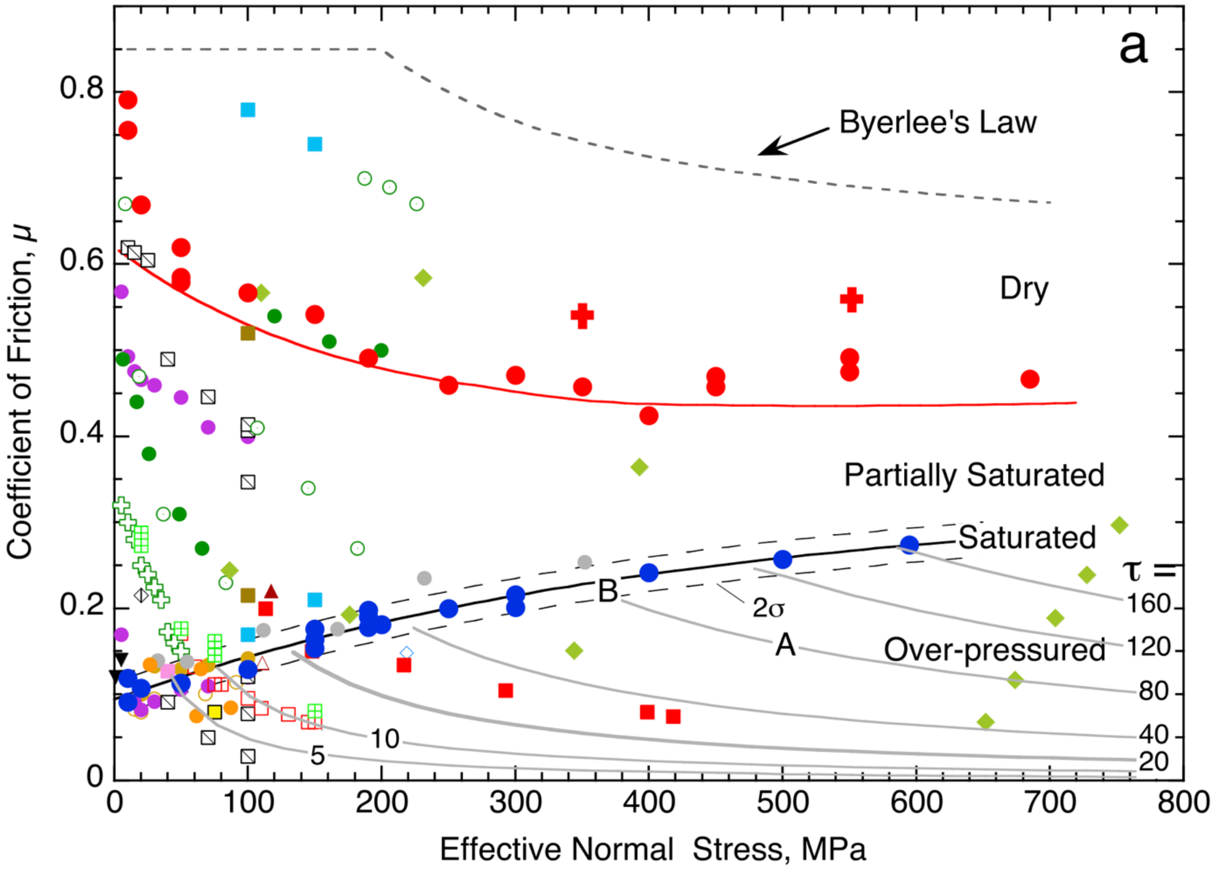


But fitting can put too much emphasis on stiffness (can a machine vary its stiffness by a factor of 2?) – fixing stiffness forces all variability into RS parameters

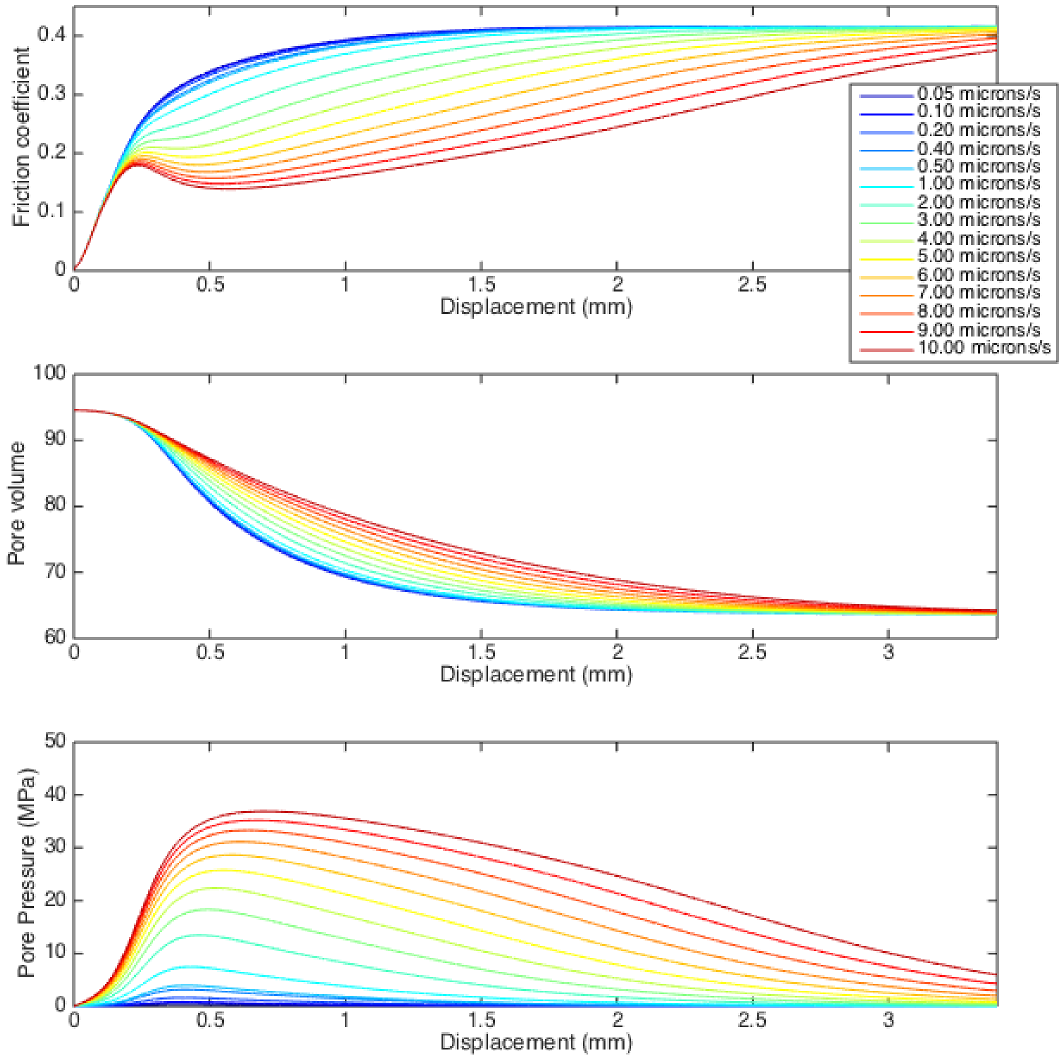
Noda and Shimamoto 2009

Development of pore-fluid pressure in low permeability gouge

Montmorillonite friction

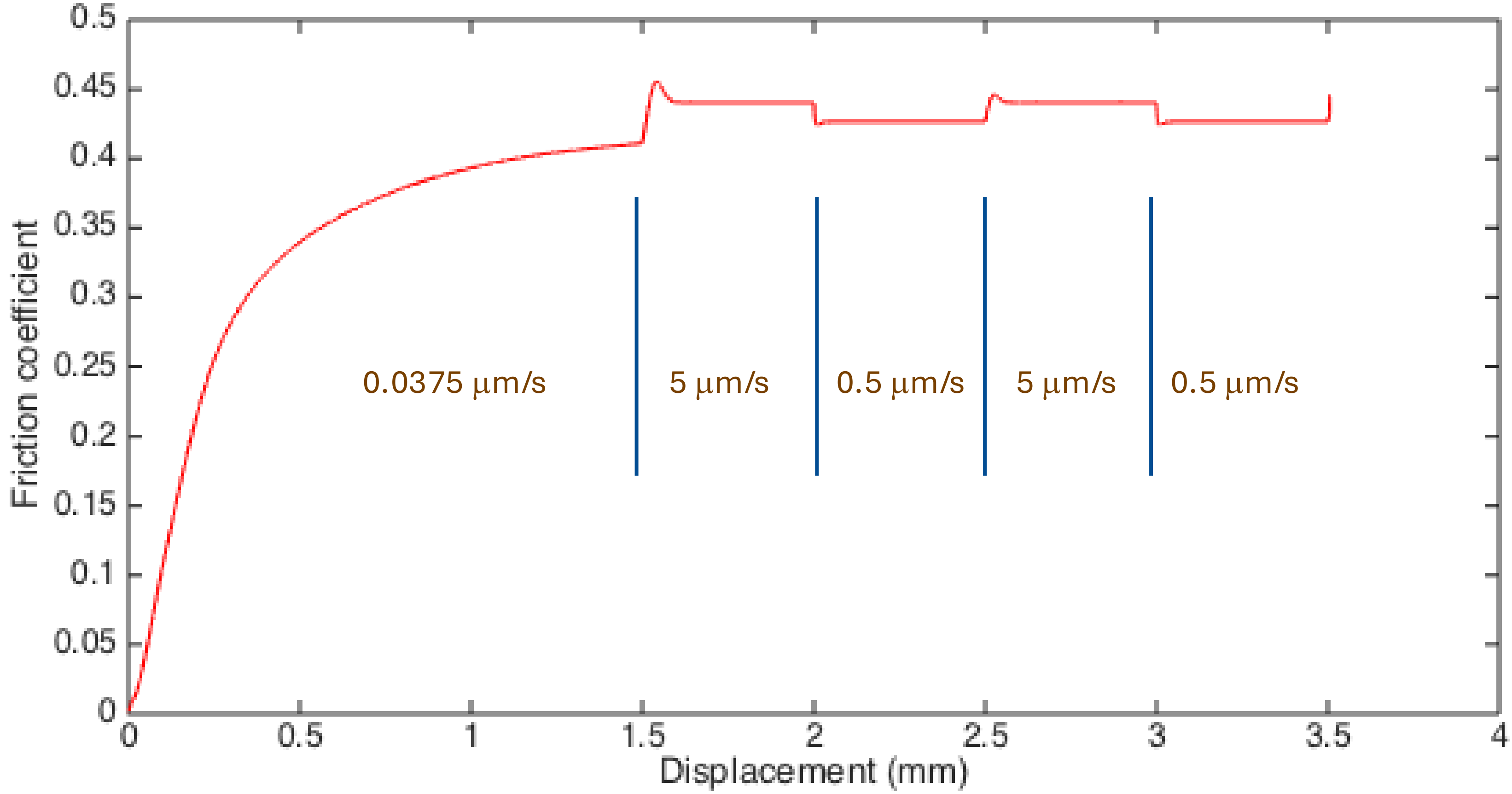


Morrow et al. (2017)



Faulkner et al. (2018)

Velocity stepping, without pore fluid pressure



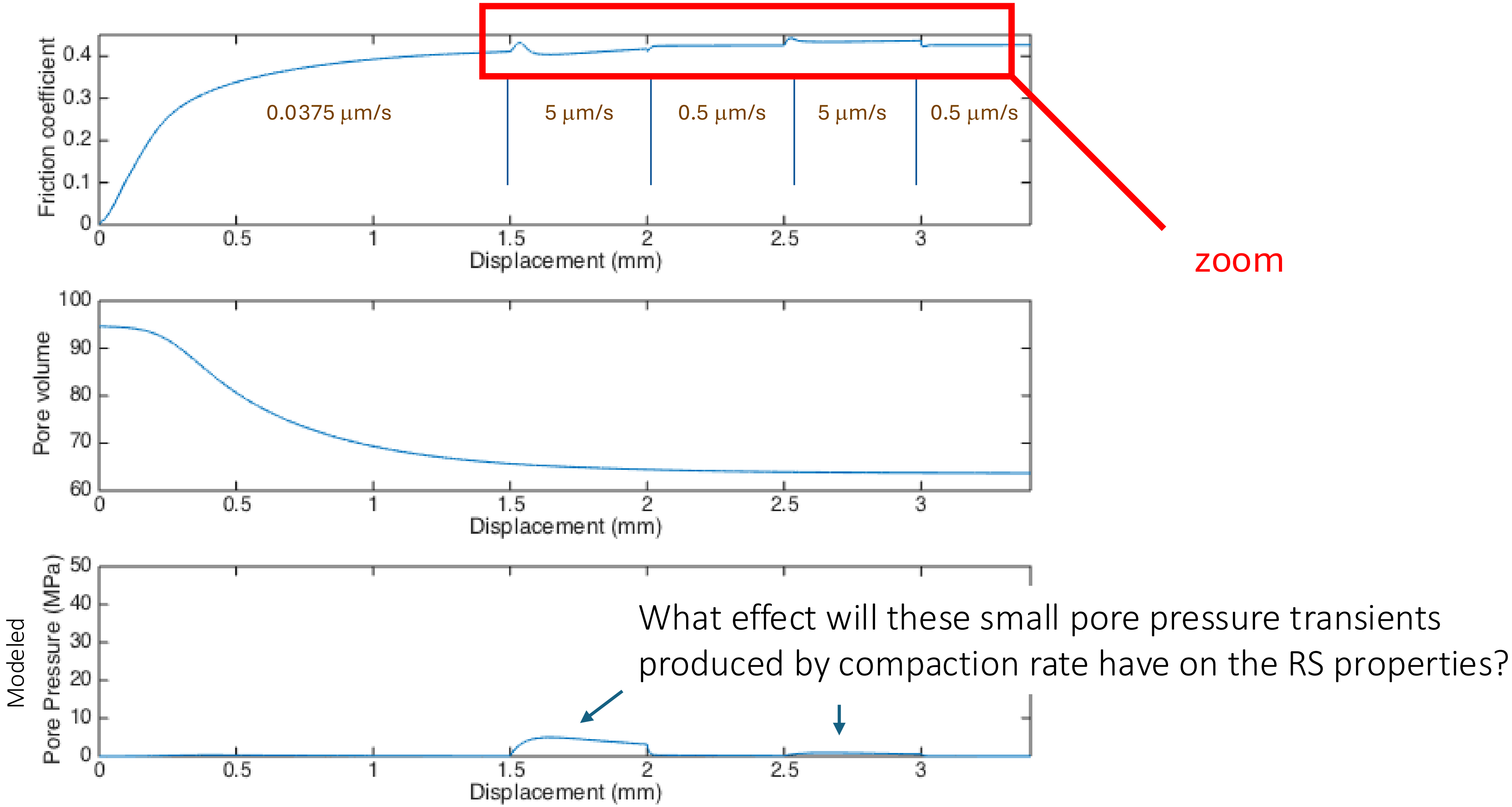
- a = 0.01; b = 0.004; D_c = 10 microns; *stiffness* = 1500 m^{-1} (friction units)

$$\tau = (\sigma_n - p)\left[\mu_0 + a ln\frac{V}{V_0} + b ln\frac{V\theta}{D_c}\right]$$

ageing law; $$\frac{d\theta}{dt} = 1 - \frac{V\theta}{D_c}$$

Faulkner et al. (2018)

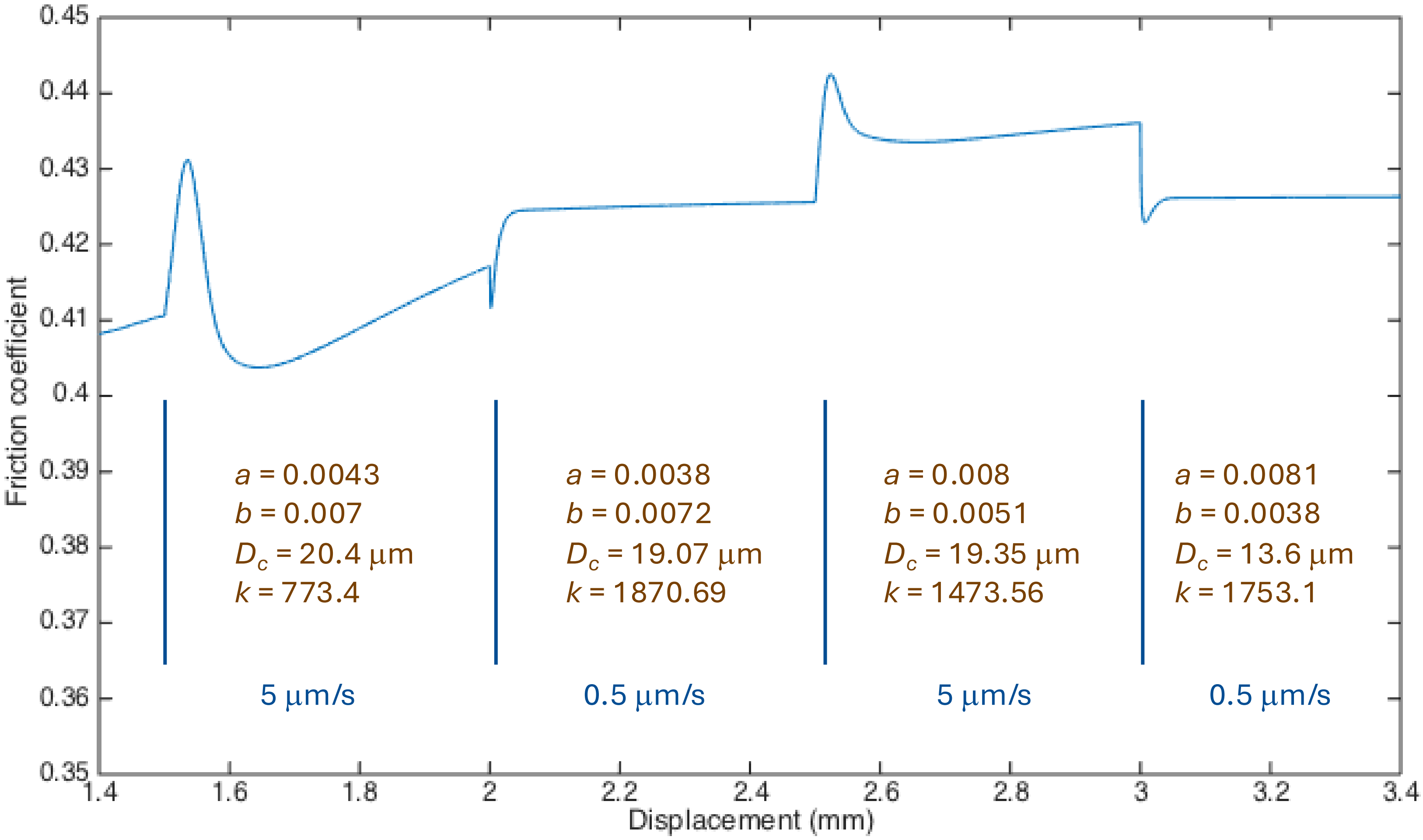
Velocity stepping, with pore fluid pressure



- a = 0.01; b = 0.004; D_c = 10 microns; *stiffness* = 1500 m^{-1} (friction units)
- 2 x 10^{-21} < k < 2 x 10^{-20} m^2

Faulkner et al. (2018)

Velocity stepping, with pore fluid pressure

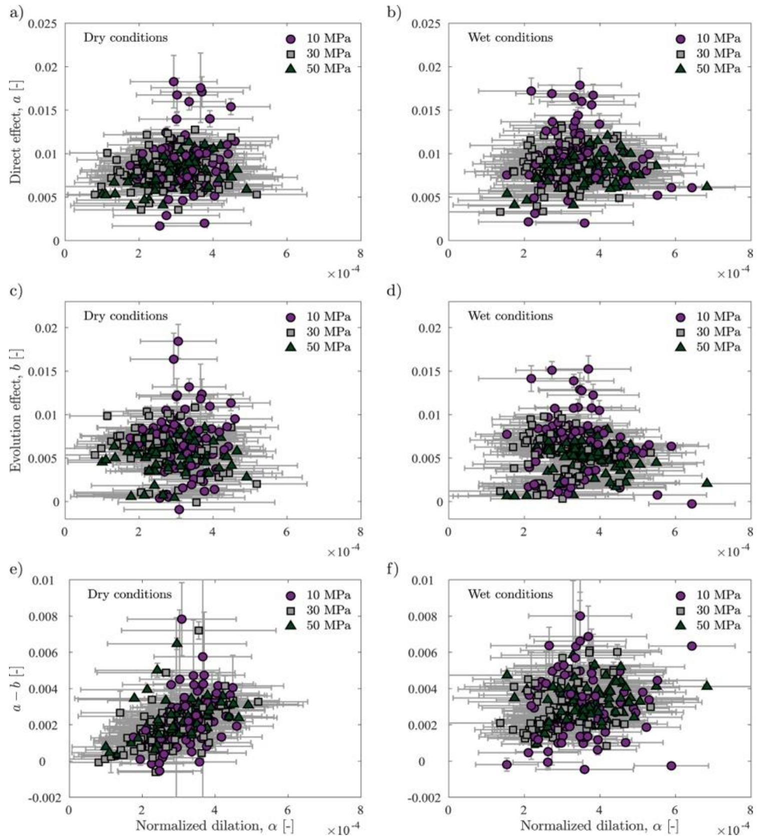


- a = 0.01; b = 0.004; D_c = 10 microns; *stiffness* = 1500 m^{-1} (friction units)

Faulkner et al. (2018)

Conclusions

- Fitting laboratory data
  - Compare steady state gradient before and after velocity steps
  - Use logarithmic searching for D_{RS}
  - Fix stiffness?
- Avoiding pore-fluid pressure effects
  - Use a slow 'run-in'
  - What is the characteristic time for fluid diffusion?
- Report uncertainty!



Fryer et al. (2025)