Poroelastic Control of Shear Localization in Fluid-Saturated Fault Zones

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Cross-scale Fault Slip and Localization

Fault slip initiates in two extremely different scales:

(1) Up to meters and **kilometers** in fault length scale.

(2) Down to a few **millimeters** across the shear zone.

Q1: How to **bridge** the two distinct scales when modelling?

Q2: What is the role of **poroelasticity** during the process?

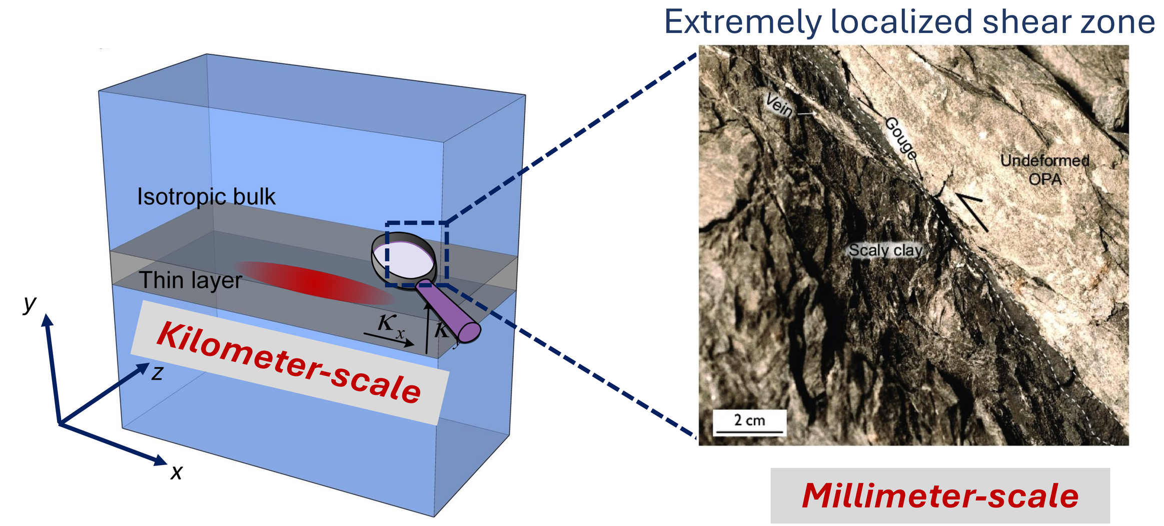


Figure 1: Ruture (red patch) in kilometer and millimeter scales.

Fault-Fluid Interactions and Model Setup

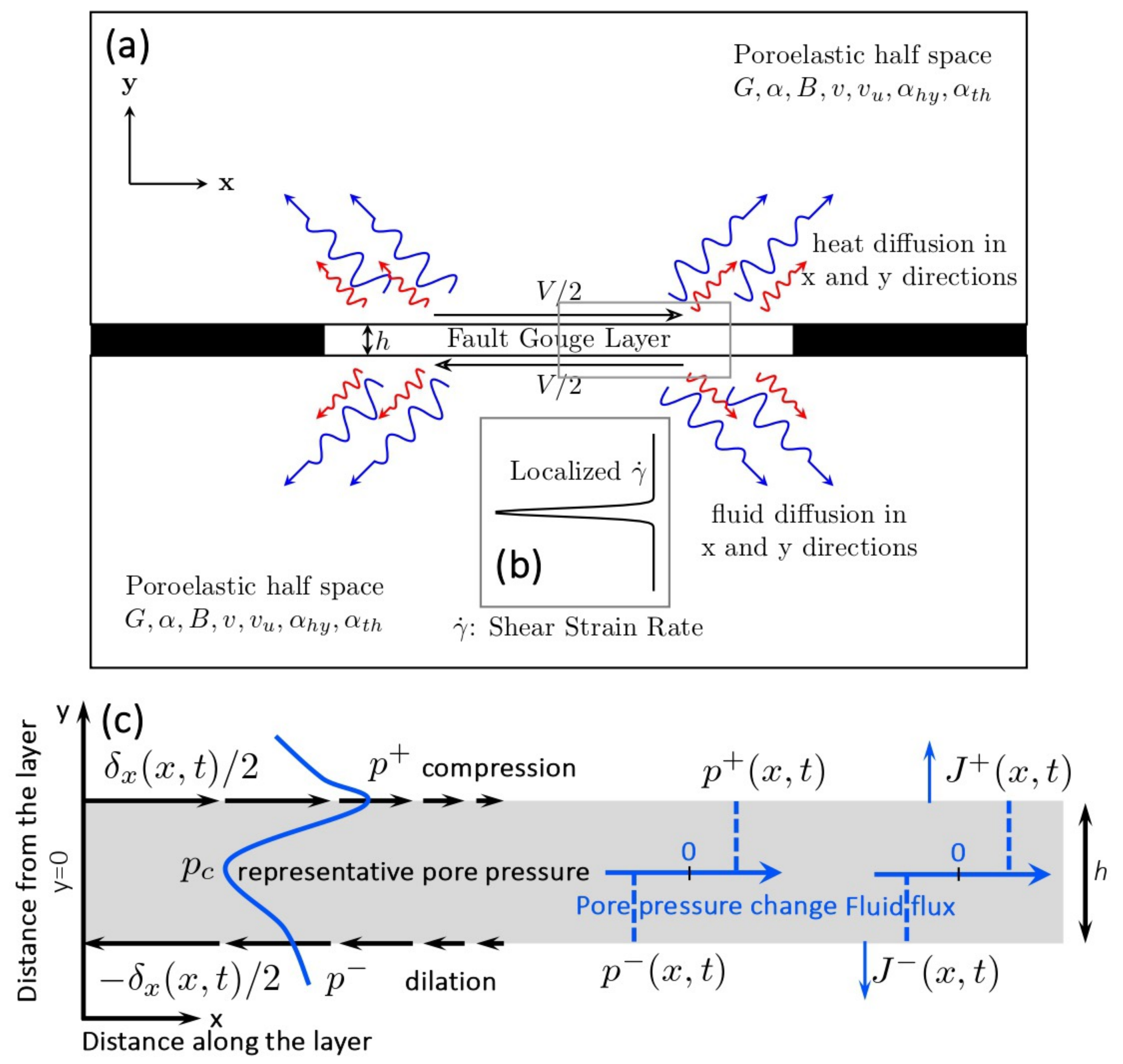


Figure 2: (a) Problem paradigm, (b) Localized strain rate, and (c) shear zone.

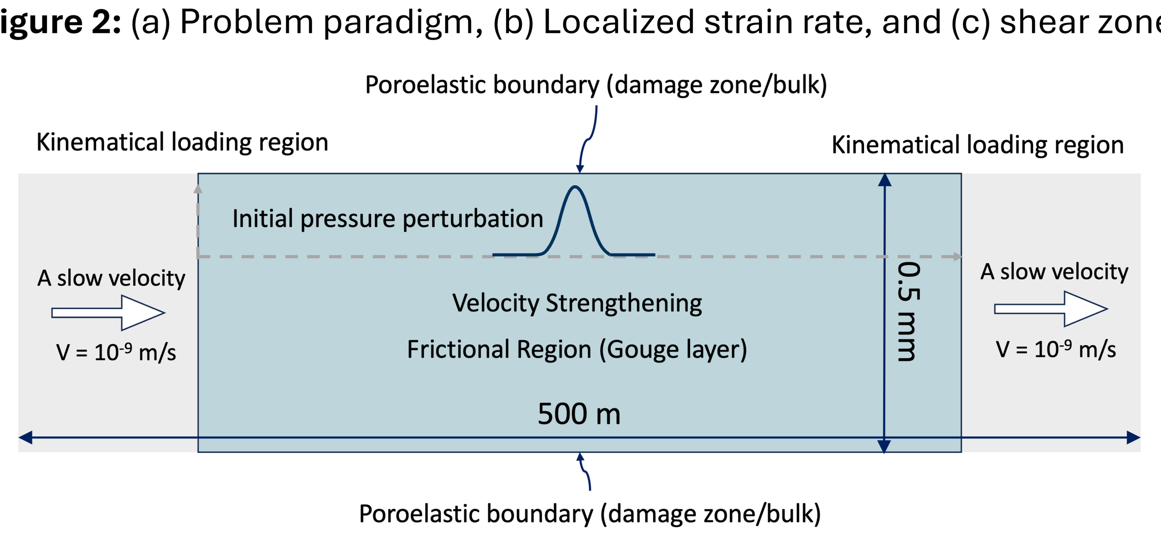


Figure 3: Model setup. The rupture is triggered by the initial pressure bump.

Results - Quasi-dynamic Rupture Embedded in Poroelastic and Thermo-diffusive bulks

Spectrums of Fluid Pressure in Bulk and Slip Rate:

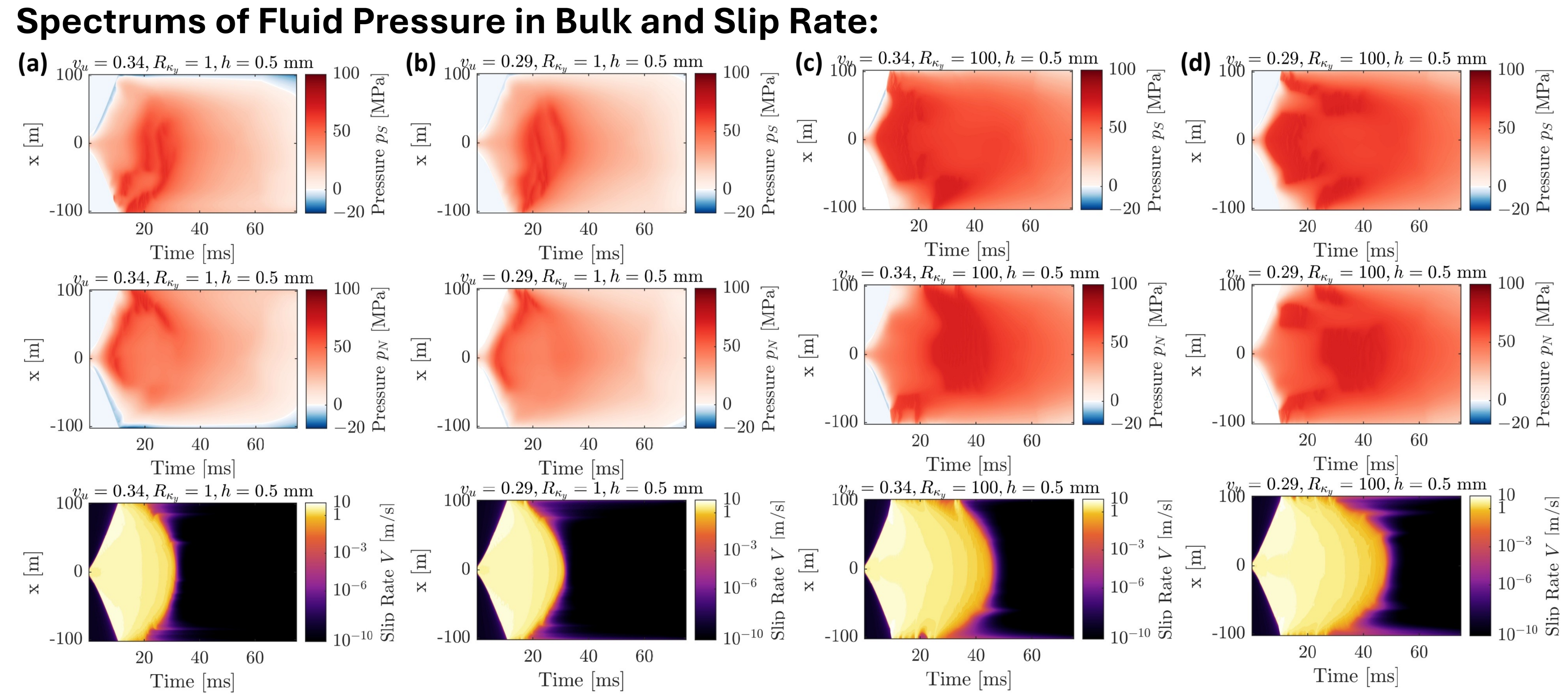


Figure 4: Spectra with various undrained Poisson's ratios and bulk permeabilities.

Off-fault Leakage Matters:

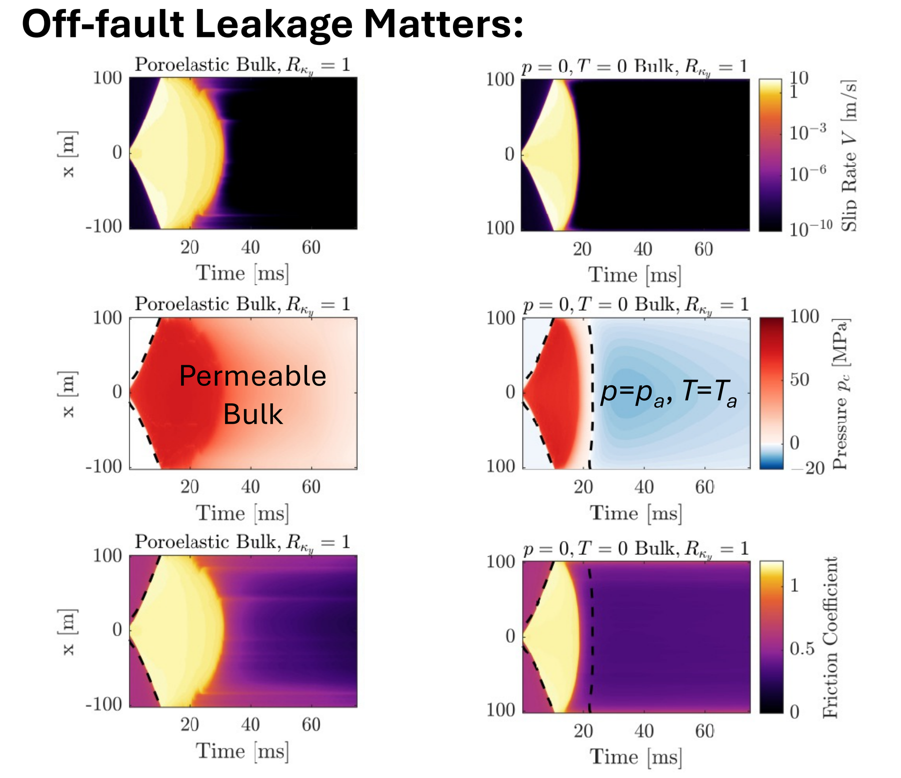


Figure 5: Comparison of spectrums with and without permeable bulks.

Fundamental Problem: Challenge of the Effective Stress Principle:

*Which Pressure is **Representative** within the Shear Zone?*

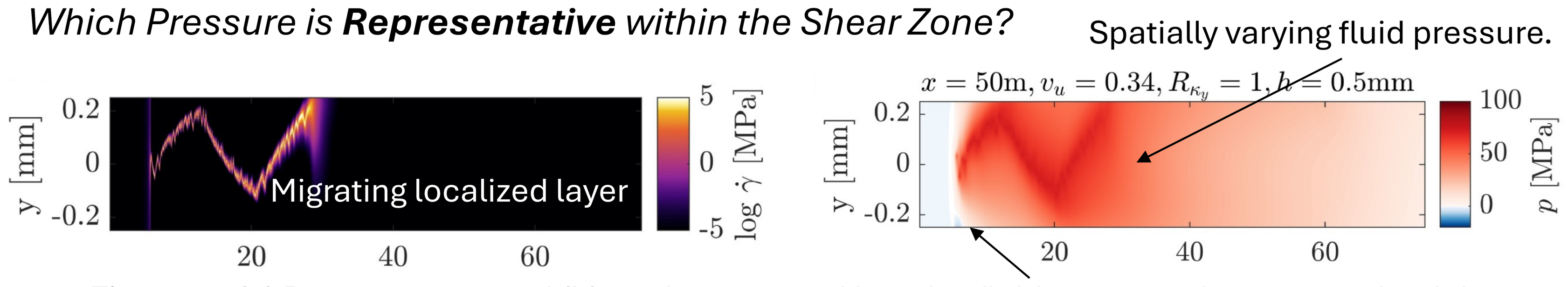


Figure 6: (a) Pore pressure and (b) strain rate.

Strain-rate-based friction law :

$$f = f_0 + (a-b)\sinh^{-1}[\frac{\dot\gamma}{2\dot\gamma_0}e^{f_0/(a-b)}]$$

Coulomb's law in question:

$$f_c = \frac{\tau_f}{\sigma_e} = \frac{\tau_f}{\sigma_n + \sigma_{yy} - p_a - p_c}$$

Connecting strain rate with slip rate:

$$V = \int_{-h/2}^{h/2} \dot\gamma dy = \int_{-h/2}^{h/2} \frac{\partial \dot\delta_x}{\partial y} dy$$

Slip-rate-based friction law:

$$f_c = f_0 + (a-b)\log\left(\frac{V}{V_0}\right)$$

Characteristic pore pressure:

$$p_c = \sigma_n + \sigma_{yy} - p_a - \frac{\tau_f}{f_0 + (a-b)\log\left(\frac{V}{V_0}\right)}$$

➢ *Within one slice across the shear zone, we have a single p_c value.*

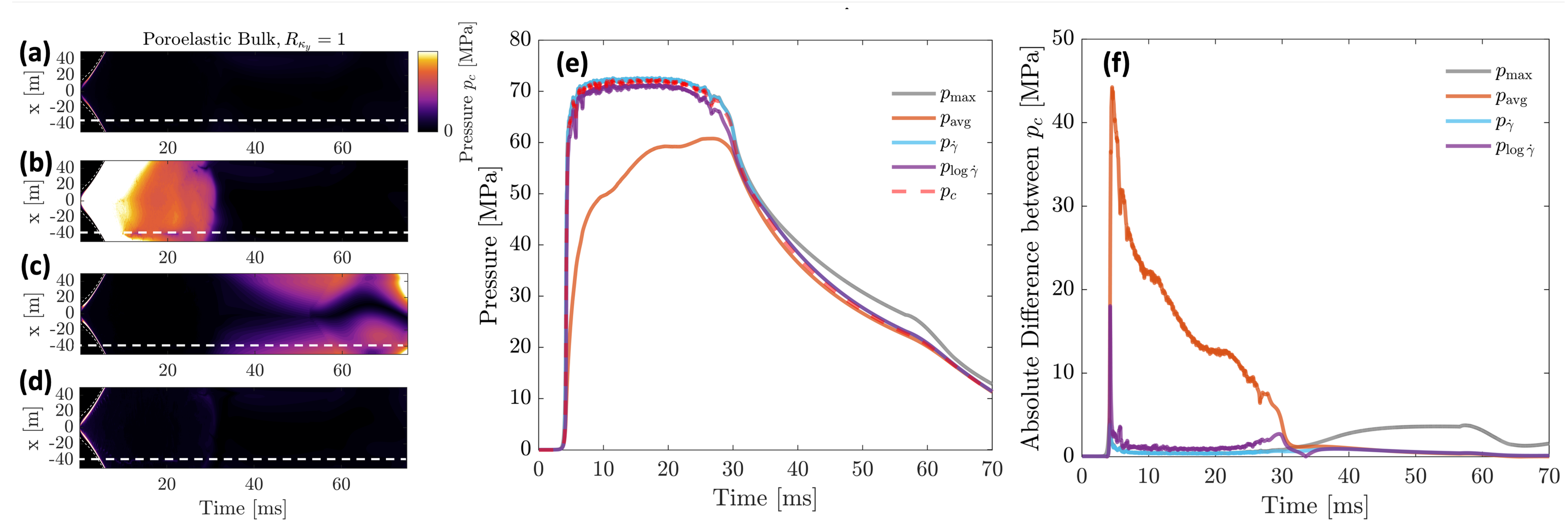


Figure 8: (a)-(d) Spatiotemporal spectrums of absolute error by different definitions of p_c. (e) and (f) Slices taken from the dashed white line in the left panels.

Characteristic Pore Pressure by Definition:

Clearly, neither $\boldsymbol{p_{max}}$ nor $\boldsymbol{p_{avg}}$ represents $\boldsymbol{p_c}$...

Hypothesis 1: $$p_{\dot\gamma} = \frac{\int_{-h/2}^{h/2} p(y)\dot\gamma(y)dy}{\int_{-h/2}^{h/2} \dot\gamma(y)dy}$$

Hypothesis 2: $$p_{\log\dot\gamma} = \frac{\int_{-h/2}^{h/2} p(y)\log\dot\gamma(y)dy}{\int_{-h/2}^{h/2} \log\dot\gamma(y)dy}$$

Attempts to Define Characteristic Pore Pressure:

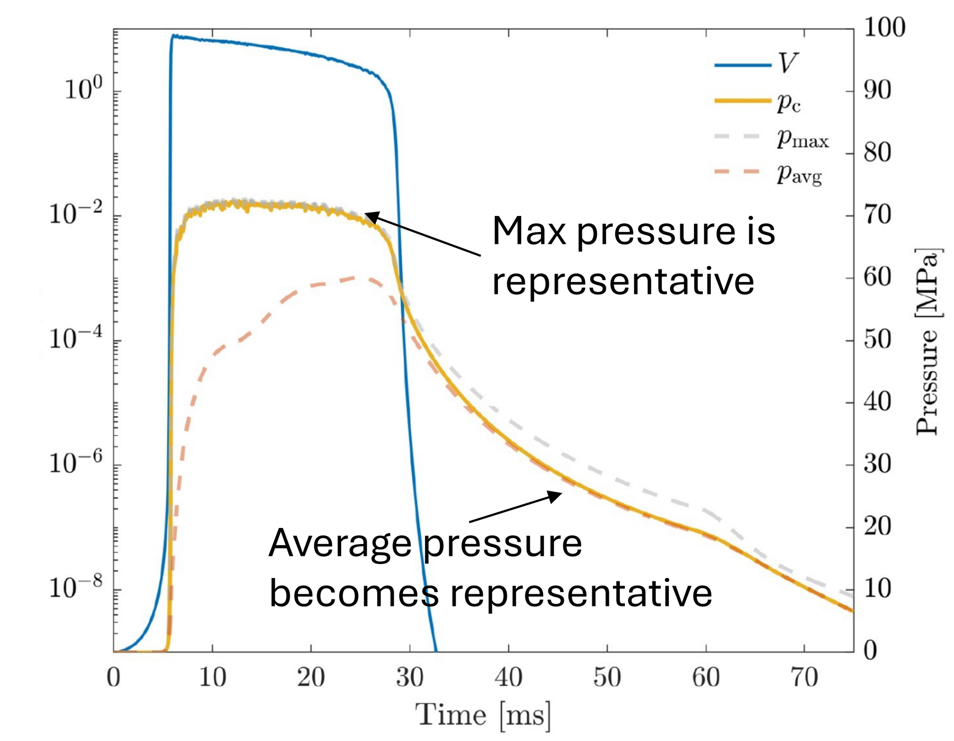
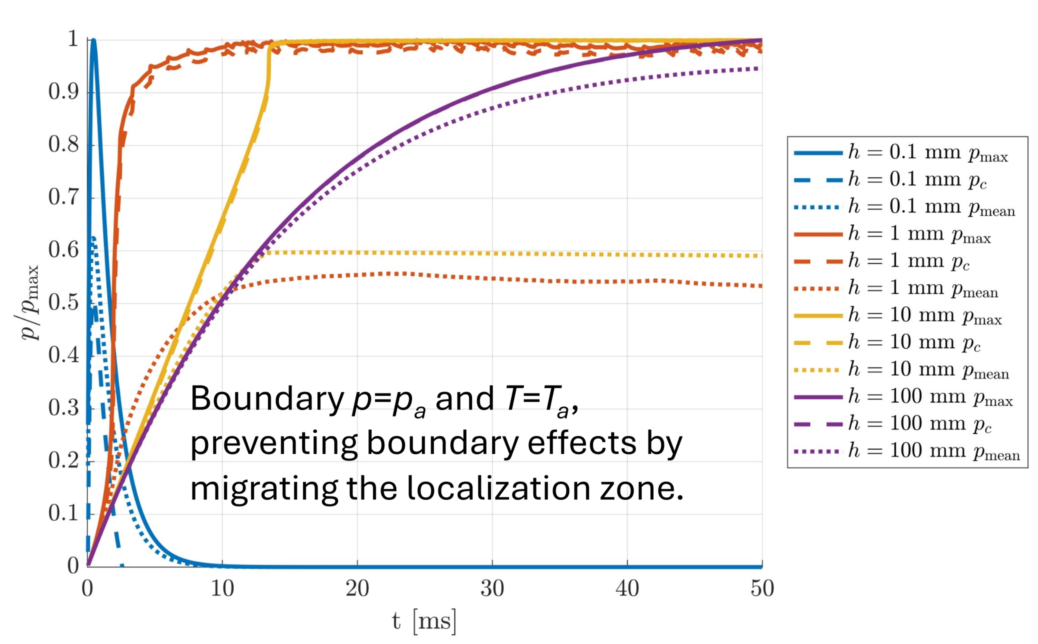


Figure 7: Slip rate versus time (the solid blue line). Respective temporal evolutions of characteristic pore pressure, maximal pore pressure, and average pore pressure within the shear zone.

Figure 9: Hypothesis test result. h is the shear-zone width



Next Step – Localization and Delocalization of Fault Gouge in Earthquake Cycles with a Strain-rate-and-state Friction Law

Spring slider coupled with finite fault gouge

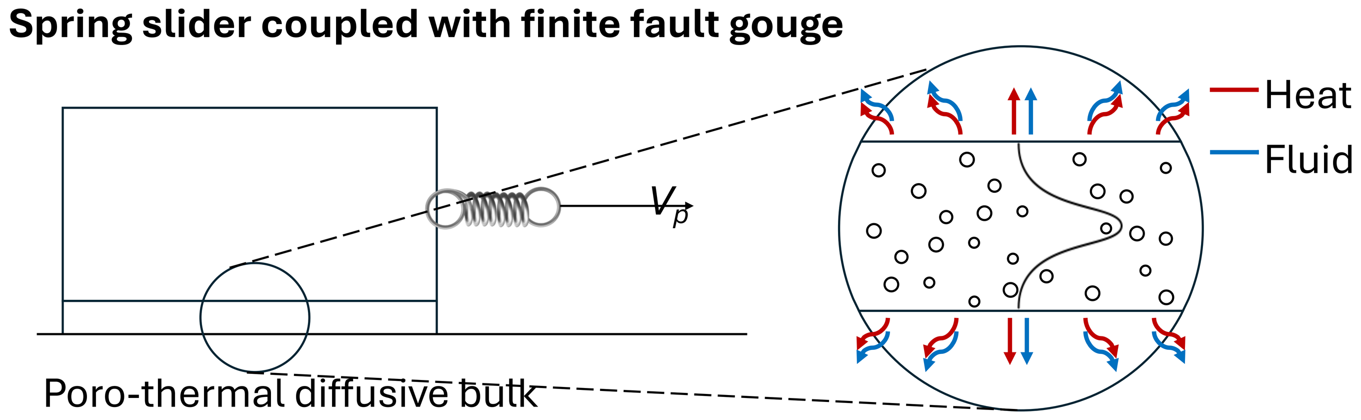


Figure 10: (a) Schematic of the spring–slider system, in which the fault gouge is sheared by a spring pulled at a constant tectonic slip rate, V_p.
(b) Finite fault gouge model under saturated conditions, incorporating fluid and heat exchange between the gouge and the surrounding bulk material.

➢ A finite fault gouge model with poro-thermal diffusive bulk boundaries and the reformulated strain-rate-and-state law.

$$S_c(\frac{\partial p}{\partial t} - \Lambda\frac{\partial T}{\partial t}) = \frac{\partial}{\partial y}(\frac{k_{fx}}{\eta}\frac{\partial p}{\partial y}) - \frac{\partial n_{pl}}{\partial t} \qquad \frac{\partial T}{\partial t} = \alpha_{th}\frac{\partial^2 T}{\partial y^2} + \tau\dot\gamma$$

$$\dot\gamma = 2\dot\gamma_0 \sinh\left(\frac{\tau}{a(\sigma - p)}\exp(-\frac{f_0 + b\log(\dot\gamma_0\theta/D'_{RS})}{a})\right)$$

$$D'_{RS} = \frac{D_{RS}}{h_{local}} \qquad \frac{d\theta}{dt} = 1 - \frac{\dot\gamma\theta}{D'_{RS}}$$

Note: a constant shear stress is assumed across the fault gouge.

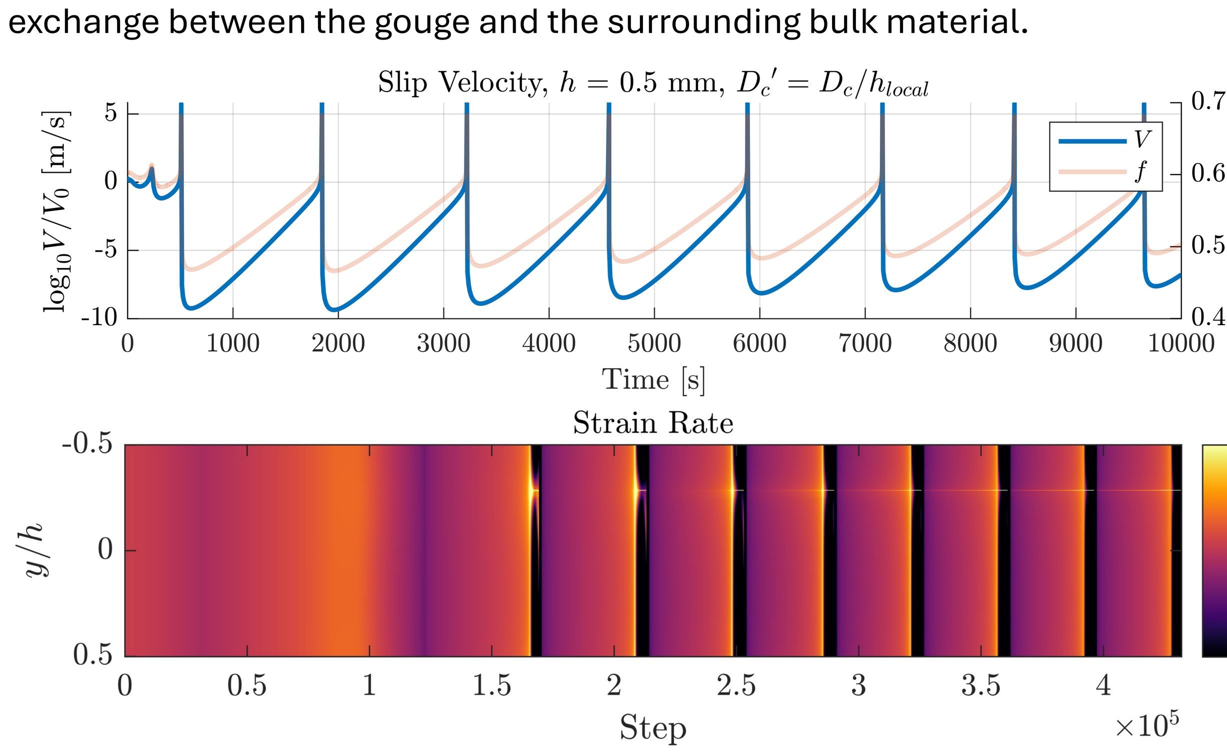


Figure 11: Slip rate/Friction versus time in earthquake cycles and respective evolution of strain rate.

Highlights and Conclusions

1. Poroelastic effects regulate shear zone evolution by modulating pore pressure in the surrounding bulk, which is further diffused into the shear zone.
2. Fluid leak-off from the shear zone is crucial. Off-fault fluid leakage reduces rupture persistence and slip magnitude by draining fluid from the shear zone.
3. Shear strength estimates should use maximum pore pressure during coseismic (localizing) stages and average pore pressure during aseismic (delocalizing) stages.
4. The strain-rate–and–state friction law reproduces both localization and delocalization, with localization possible even during aseismic slip.

References:

[1] Wang, Y., & Heimisson, E. R. (2024). A coupled finite difference-spectral boundary integral method with applications to fluid diffusion in fault structures. *International Journal for Numerical and Analytical Methods in Geomechanics*, *48*(10).

[2] Rice, J. R., Rudnicki, J. W., & Platt, J. D. (2014). Stability and localization of rapid shear in fluid-saturated fault gouge: 1. Linearized stability analysis. *Journal of Geophysical Research: Solid Earth*, 119(5).

[3] Barras, F., & Brantut, N. (2025). Shear localisation controls the dynamics of earthquakes. *Nature Communications*, 16(1).