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Effect of pore fluid properties on dynamic slip of sandstone-derived fault gouges

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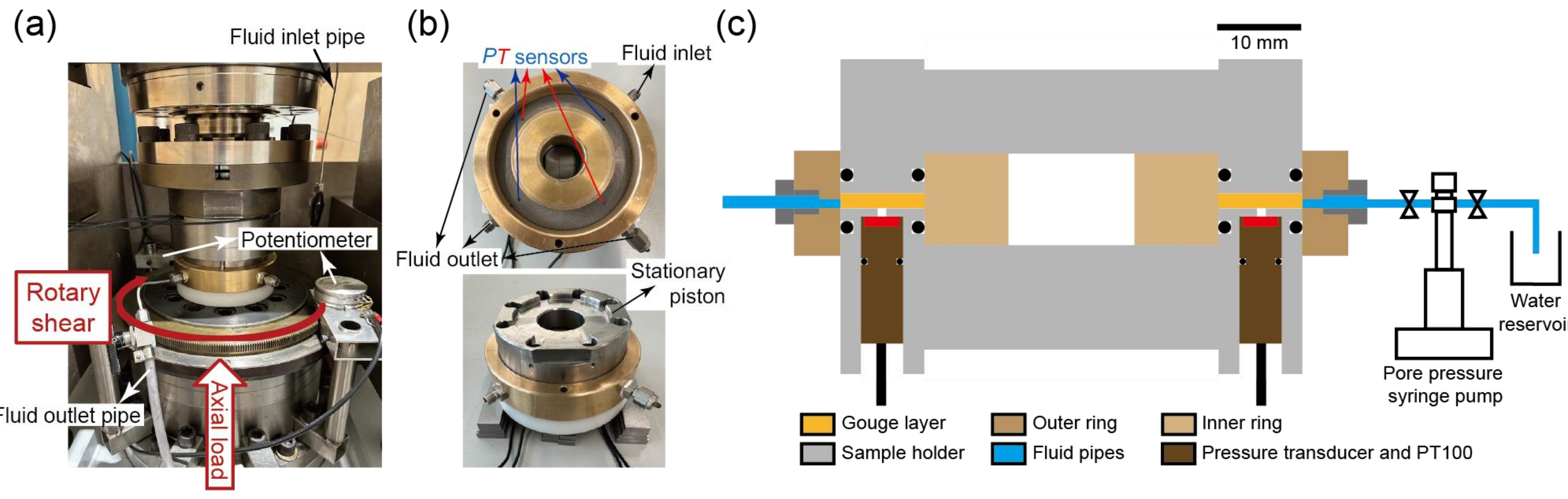
Introduction & Motivation

The thermal (e.g., expansivity) and hydraulic (e.g., viscosity) properties of pore fluid within the fault core significantly influence the slip behavior of faults as thermal pressurization by frictional heating is controlled by these parameters. Wet faults (water as pore fluid) in Groningen gas field lithologies has been reported to weaken significantly in a short seismic slip pulse (Hunfeld et al., 2021; Chen et al., 2023). However, the in-situ pore fluid in the gas reservoir is much more complex, consisting of a mixture of brine and methane, which have different viscosity η and thermal pressurization factor Λ. To investigate and predict the potential slip behavior of faults in the gas reservoir, we conducted seismic slip-pulse rotary-shear friction experiments on Slochteren sandstone gouges with different types of pore fluid at various pore fluid pressures. We then validated the experimental observations using analytical solutions. Our results indicate that thermal pressurization is the primary weakening mechanism for all types of fluid investigated. In addition, the variation in the friction, pore pressure and temperature between the measured data and the prediction suggests that the localization of slip in the gouge layer might differ between fluid. Once the experimental observation can be systematically predicted by analytical and numerical models, we can better constrain the fault behavior and weakening for the induced seismic in the Groningen gas reservoir.

Methodology: Rotary-shear friction experiment



- Starting material: **Slochteren sandstone gouge** (~75 wt% quartz, ~12 wt% feldspar, ~5 wt% clay, and ~5 wt% carbonate)
- Applied normal stress: **12 MPa**
- Pore fluid: **DI water**, **brine**, and **silicone oil** (1 cSt and 5 cSt)
- Pore fluid pressure: **1** and **2 MPa**
- Slip velocity: **5 cm/s**

Figure 1

(a) Photography of the pressurized gouge setup installed in the RAP. (b) Photography of the sample holder with an inner and an outer confining brass ring together with steel pistons. (c) Schematic plot of the pressurized gouge setup for RAP.

Results

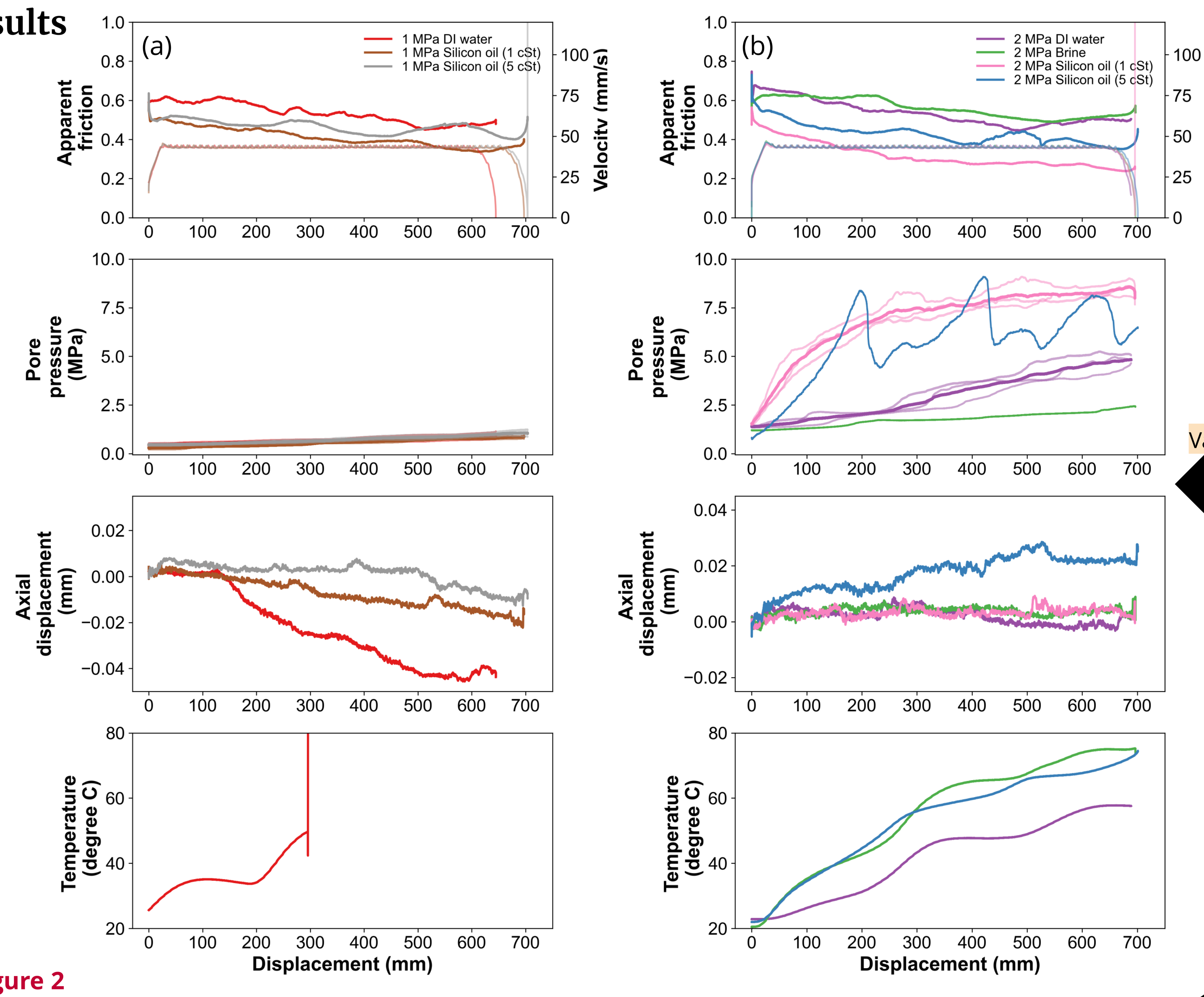


Figure 2

Results of the seismic slip-pulse experiments with different types of pore fluid at applied normal stress of 12 MPa and 5 cm/s. (a) P_0 = 1MPa. (b) P_0 = 2MPa.

Prediction based on analytical solution (Rice, 2006)

Validate

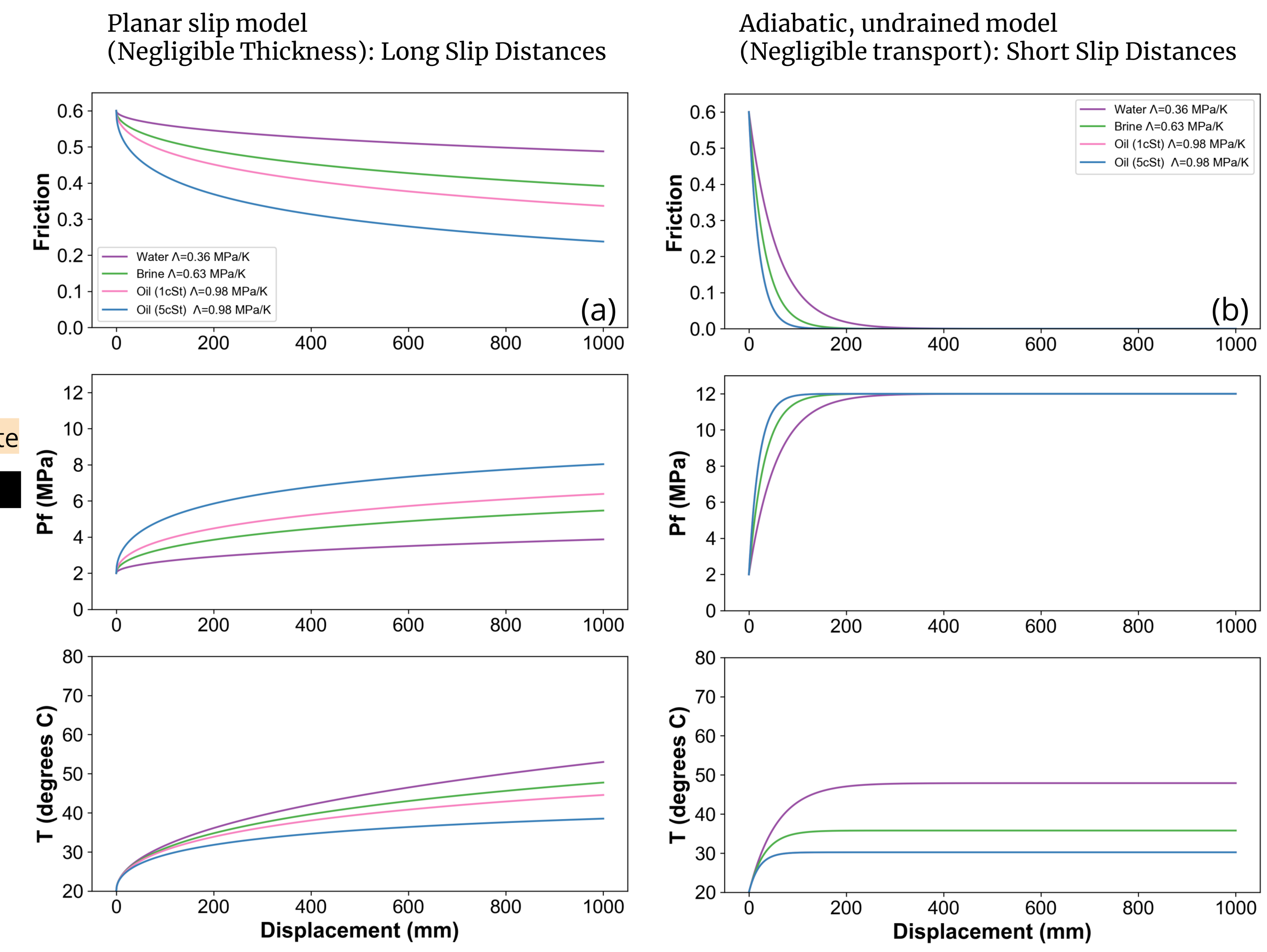


Figure 3

Prediction of friction, fluid pressure, and temperature versus slip based on the experimental conditions (left) for (a) planar slip model, valid for long slip distances, and (b) adiabatic and undrained conditions, valid for short slip distances.

Predict Groningen fault behavior

Assumed reservoir and earthquake conditions for the planar slip model:

- Normal stress σ_n: 55 MPa
- Ambient pore pressure P_0: 15 MPa
- Ambient temperature T_0: 100 °C
- Pore fluid: Mixture of brine and methane
- Slip velocity V: 1 m/s
- Starting gouge porosity n: 0.15

Assumed material properties:

- Thermal diffusivity α_{th}: 0.77 mm^2 s^{-1}
- Fluid viscosity η (3.5 mol/kg): 4.36 × 10^{-4} Pa s (brine)
- Fluid thermal expansivity λ_f: 1.12 × 10^{-3} °C^{-1} *(Rice, 2006)*
- Pore space thermal expansivity λ_n: -0.19 × 10^{-3} °C^{-1} *(Rice, 2006)*
- Fluid compressibility β_f: 4 × 10^{-10} Pa^{-1} (brine)
- Pore space pressure expansivity β_n: 0.65 × 10^{-9} Pa^{-1} *(Rice, 2006)*
- Permeability k: 2 × 10^{-20} m^2

Resulting material properties:

- Pressurization factor Λ: 1.23 MPa °C^{-1}
- Hydraulic diffusivity α_{hy}: 0.29 mm s^{-1}
- Maximum temperature T_{max}: 152 °C

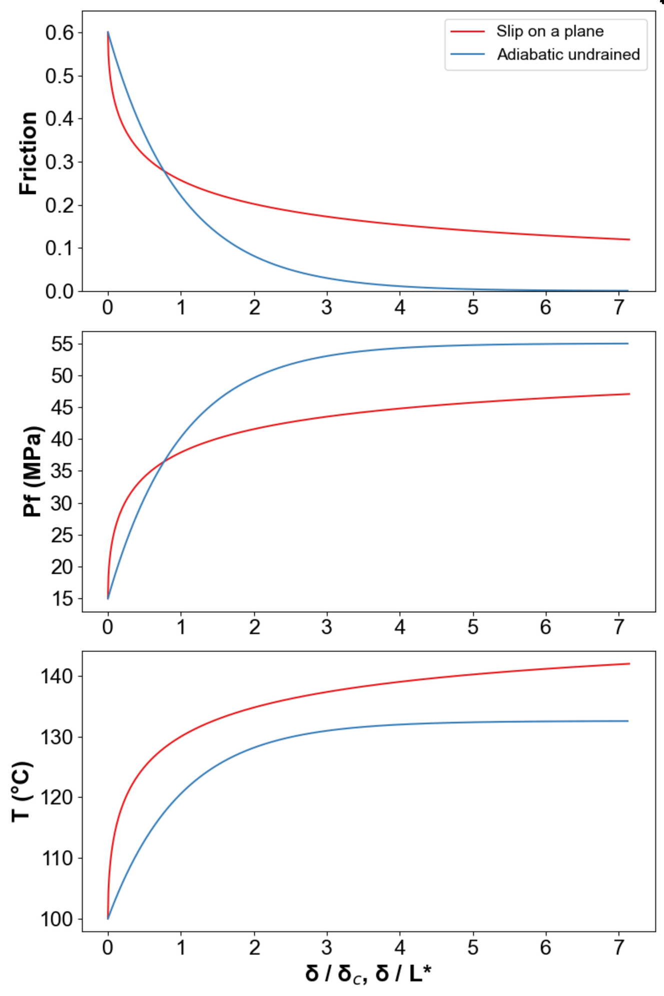


Figure 4

Prediction of friction, fluid pressure, and temperature as a function of scaled slip distance δ for both planar slip model (red curve) where the slip distance is scaled by $\delta_c = \rho Ch/(\Lambda f)$, as well as the undrained, adiabatic limit model where the slip distance is scaled by $L^* = (2\rho C(\Lambda f))^2(\sqrt{\alpha_{th}} + \sqrt{\alpha_{hy}})^2/V$.

Summary & Future work

- Independent of the pore fluid pressure and the types of pore fluid investigated, all wet gouges show weakening due to thermal pressurization which is significantly controlled by the fluid viscosity and the pressurization factor.
- Higher temperature rise but lower pore pressure increase in the brine experiment than in water experiment suggests that the localization of slip in the gouge layer might be varied between fluid.
- Numerical modeling is required to obtain a better prediction for the experimental observation and hence to predict the slip behavior of faults under Groningen reservoir conditions, if some in-situ fluid properties is known.

Reference

- Chen et al., 2023
- Hunfeld et al., 2021
- Rice, 2006