How fluid-induced ruptures start

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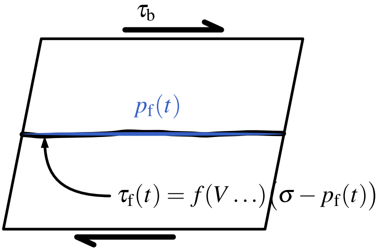
Injection-induced slip



"0D": preloaded fault slips when $\tau = \tau_f$. Dynamics follow from $f(V\ldots)$ (e.g., Rudnicki, *JGR* 2023).

3D: elastic stress transfer modifies $\tau(x,t)$. Coupled fracture problem (e.g., Garagash & Germanovich, *JGR* 2012; Sàez et al., *JMPS* 2022).

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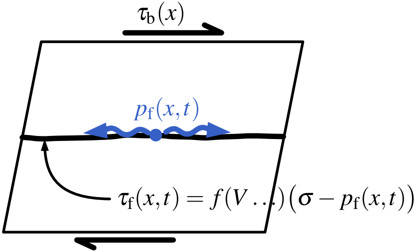

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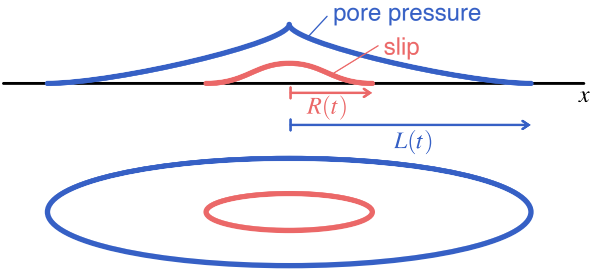
Fluid diffusion vs. rupture propagation



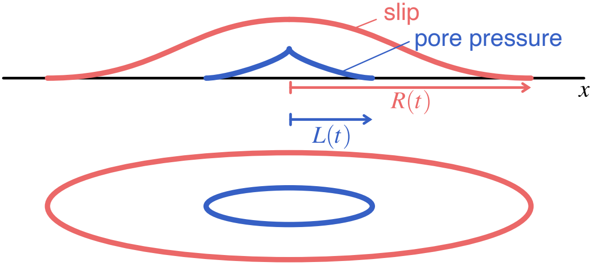
$$\lambda = R/L \ll 1$$

Two end-member scenarios (e.g., Garagash & Germanovich, *JGR* 2012):

Marginally pressurised fault: rupture remains confined well withing pressurised region (initial stress far from strength).

Critically stressed fault: rupture outpaces pressurised region (initial stress close to strength). See Battacharya & Viesca, *Science* 2019.

Fluid diffusion vs. rupture propagation



$$\lambda = R/L \gg 1$$

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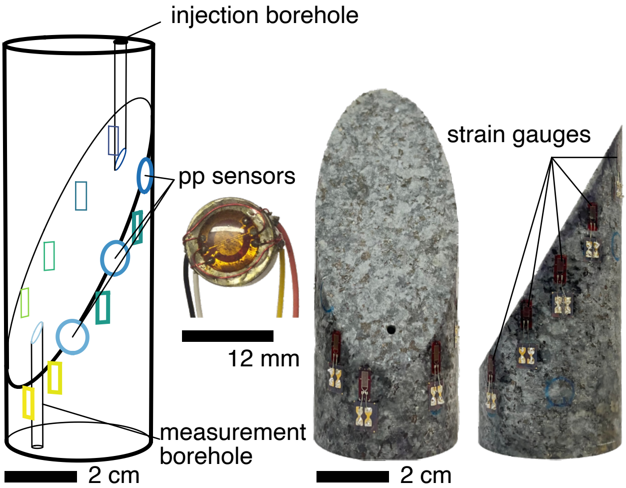
Motivation

Theory based on fracture mechanics predicts $\lambda \gg 1$ when injection rate is large (compared to diffusion time; e.g., Sàez et al., *JMPS* 2022). **Theory needs testing under realistic conditions.**

Methods

- Laboratory tests with faulted granite,
- Controlled prestress and injection rate,
- Instrumentation to detect R and L.

Setup and instrumentation



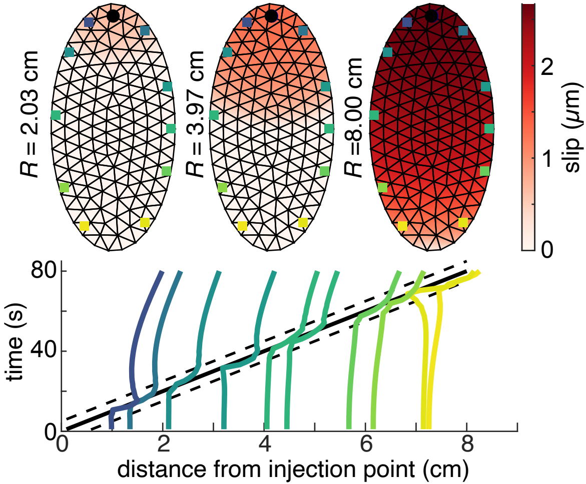
Impose prestress τ_b, lock piston. Inject at constant pressure rate c. Measure stress, shortening, pp in boreholes + 3 pp sensors, 10 strain gauges.

Fluid pressure tracking

Data assimilation procedure:

1. use local pore pressure data,
2. invert for fault diffusivity as a function of space, time,
3. use inverted model to interpolate data,
4. measure $L(t)$ using set p_{f} threshold.

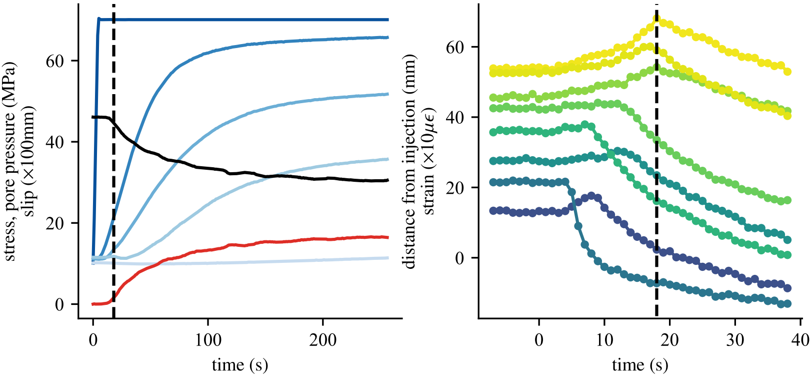
Rupture front tracking



Synthetic tests for strain field in circular crack expanding at constant speed.

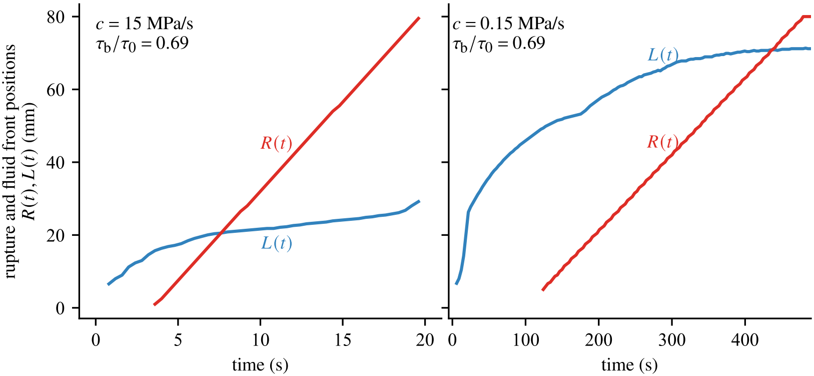
→ use strain gauges to detect rupture tip position $R(t)$.

Example



Injection at $c = 15$ MPa/s. Rupture speed ≈ 3.9 mm/s.

Ruptures outgrow fluid diffusion



Fast injection promotes $R/L > 1$.

Key controlling parameters

Idealised fracture mechanics model based on Sàez et al., *JMPS* 2022:

$$\text{Stress Intensity Factor} = K\left[R(t), p(x,t)\right] = K_{\mathrm{c}} \approx 0$$

Equivalent to

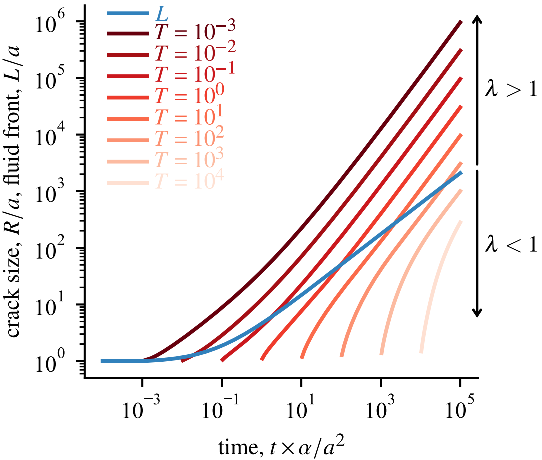
$$\frac{1}{R(t)} \int_0^{R(t)} \frac{\Delta p(x,t)/(t\Delta p^*)}{\sqrt{R^2 - x^2}} x dx = \frac{T}{t \times \alpha/a^2}.$$

where a is borehole radius, α is hydraulic diffusivity, Δp is the pore pressure perturbation, and

$$T = \frac{1 - \tau_{\mathrm{b}}/(f\sigma_0')}{ca^2/\alpha/\sigma_0'}$$

is the loading parameter. $T \gg 1$ at low injection rate, $T \ll 1$ as high injection rate. Rupture starts at $T = t \times \alpha/a^2$.

Role of injection rate



Correct intuition, using reasonable values of $0.6 < f < 0.75$. Note: Rupture and fluid diffusion more complex due to finite size effects, diffusivity variations and different boundary conditions.

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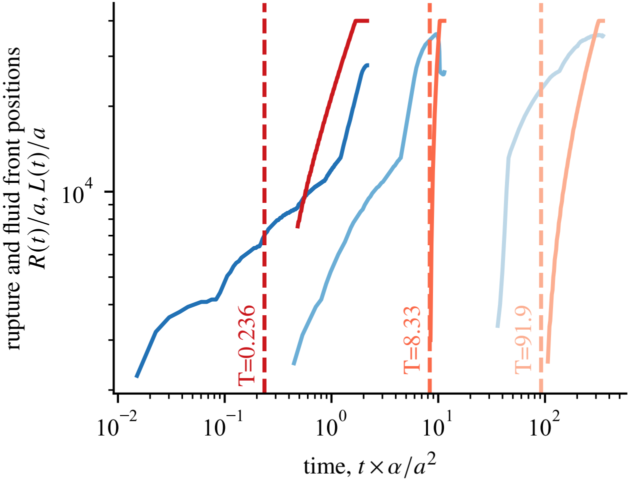

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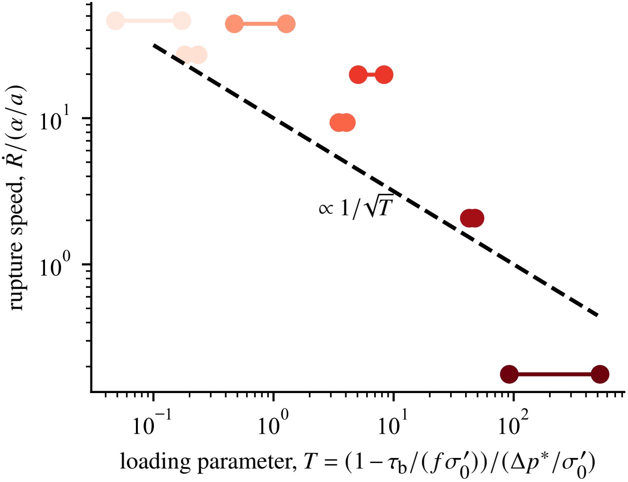
Rupture speed



Rupture speed decreases with increasing T (decreasing injection rate). Scales with $1/\sqrt{T}$, qualitatively similar to (simple) fracture mechanics model.

Main results

Experimental test documenting key controls on rupture initiation by fluid injection:

- Evidence of rupture front outpacing fluid pressure "front" (similar to field case analysed by Battacharay & Viesca, *Science* 2019),
- Rupture initiation controlled by loading parameter

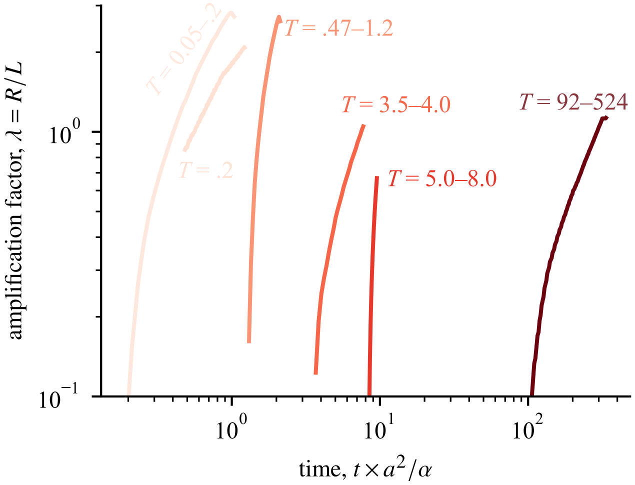
$$T = (1 - \tau_{\mathrm{b}}/(f\sigma_0'))/(ca^2/\alpha/\sigma_0'),$$

- Rupture speed scales (approximately) as $1/\sqrt{T}$.

Limitations:

- Data require pressure-dependent diffusivity: coupled problem,
- Uncertain friction coefficient at rupture initiation: RnS effects need to be accounted for (e.g., Garagash, *Phil. Trans. R. Soc. Lond.* 2021).

Amplification factor



Amplification $\lambda = R/L$ always increases with increasing time: consistent with theory at constant injection rate + role of finite system.