

Nucleation and arrest of aseismic fault slip, during and after fluid pressurization

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1) Motivations & goals

- What are the impacts of the stress criticality on the nucleation of aseismic fault slip due to fluid pressurization?
- How does the rupture front for aseismic slip evolve with respect to the pressurized zone?
- How long after pressurization does aseismic fault slip stop?
- When is it safe to resume fluid injection after a swarm of aseismic fault slip?

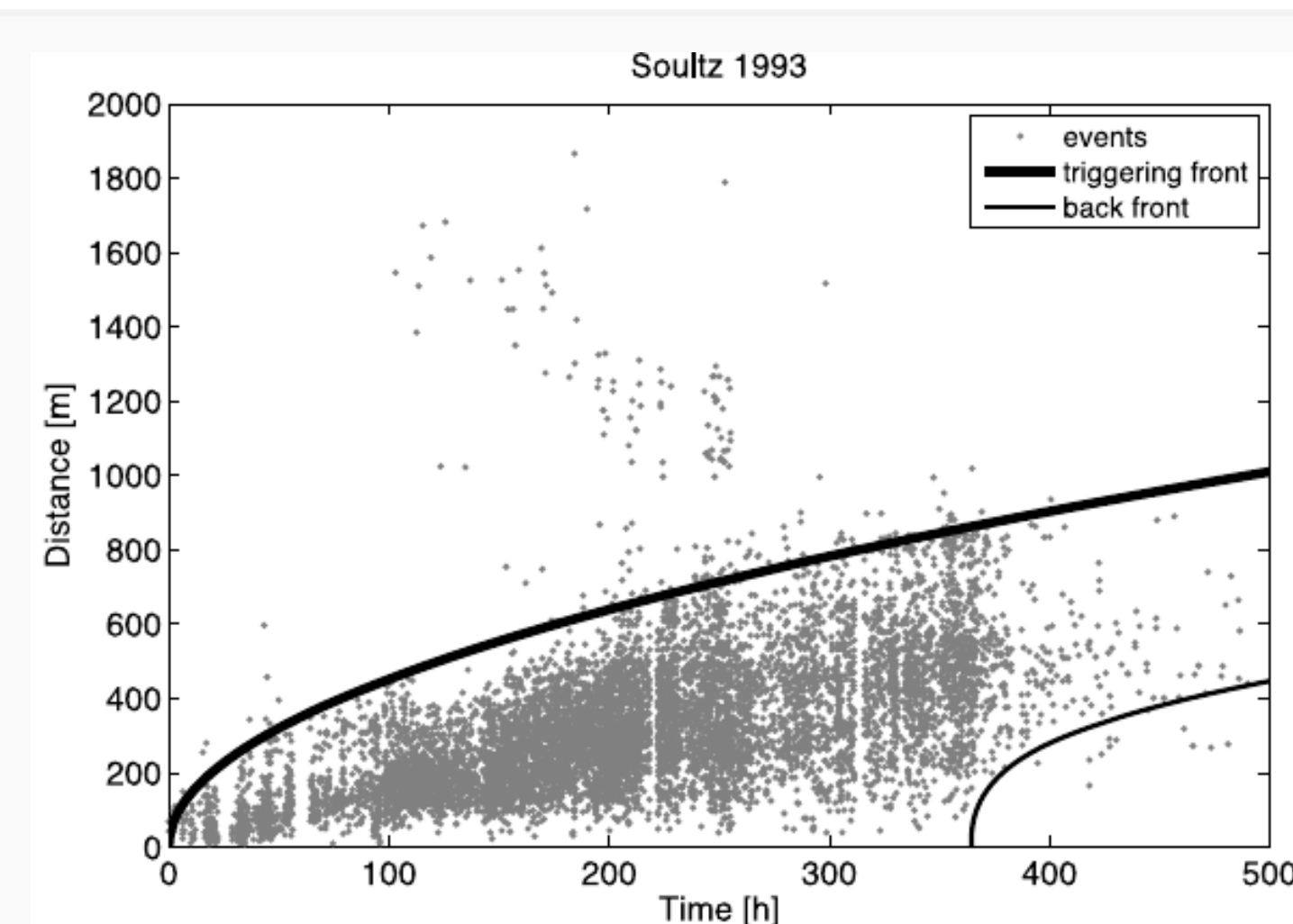


FIG. 1: Microseismicity induced by fluid injection in a borehole in Soultz, France. Figure from Shapiro and Dienske, (2009) [1].

Take home message

- Rupture front still propagates after stopping pressurization.
- Decay of the maximum slip rate after pressurization scales with the pressurization duration.
- Arrest time of aseismic fault slip is proportional to pressurization time.
- Aseismic fault slip can take several orders of magnitude longer to stop after pressurization on critically stressed faults.

2) Problem description

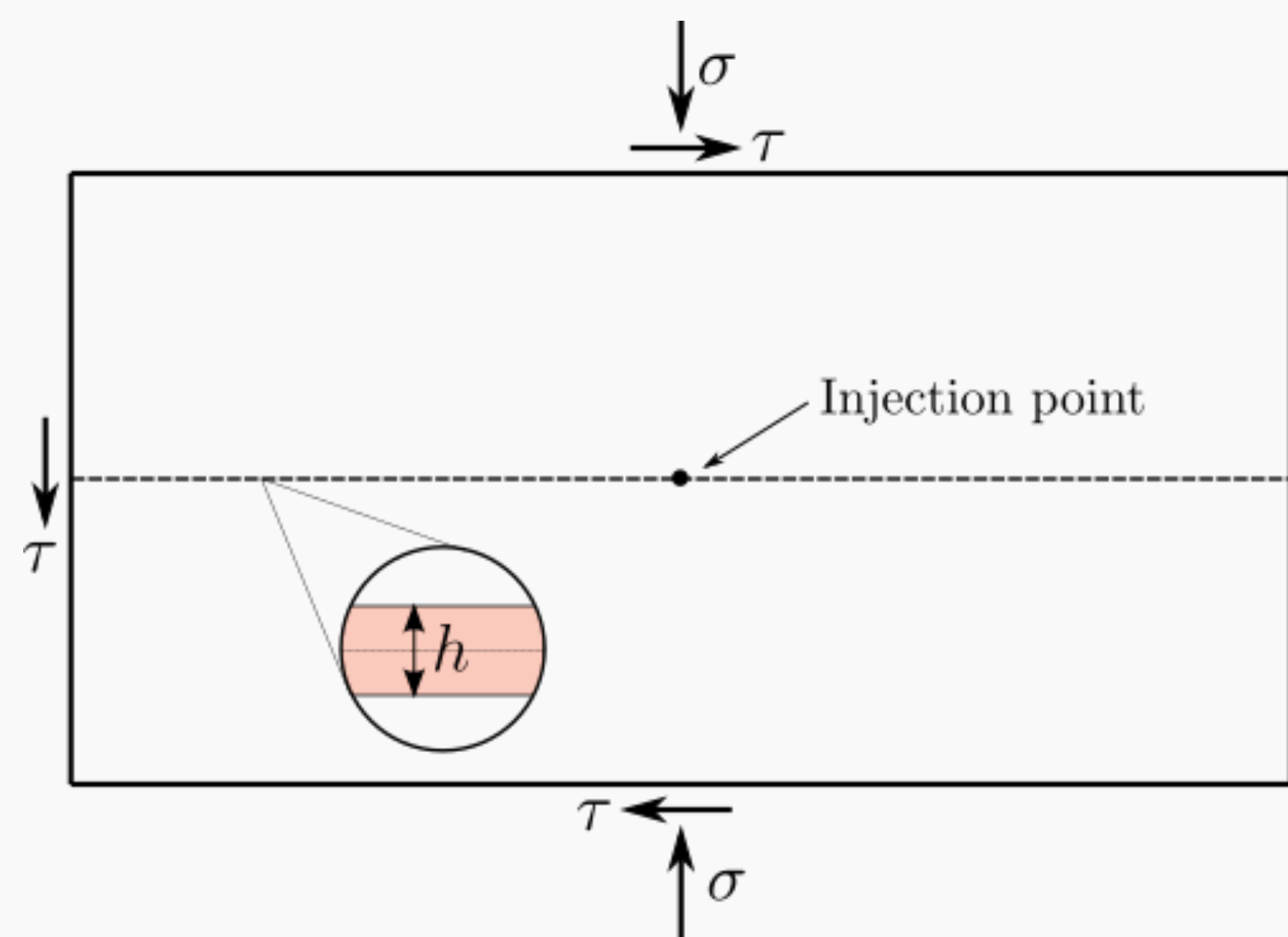


FIG. 2: Unbounded elastic body containing a fault, subject to a background stress field. Injected fluid diffuses along the fault line over time.

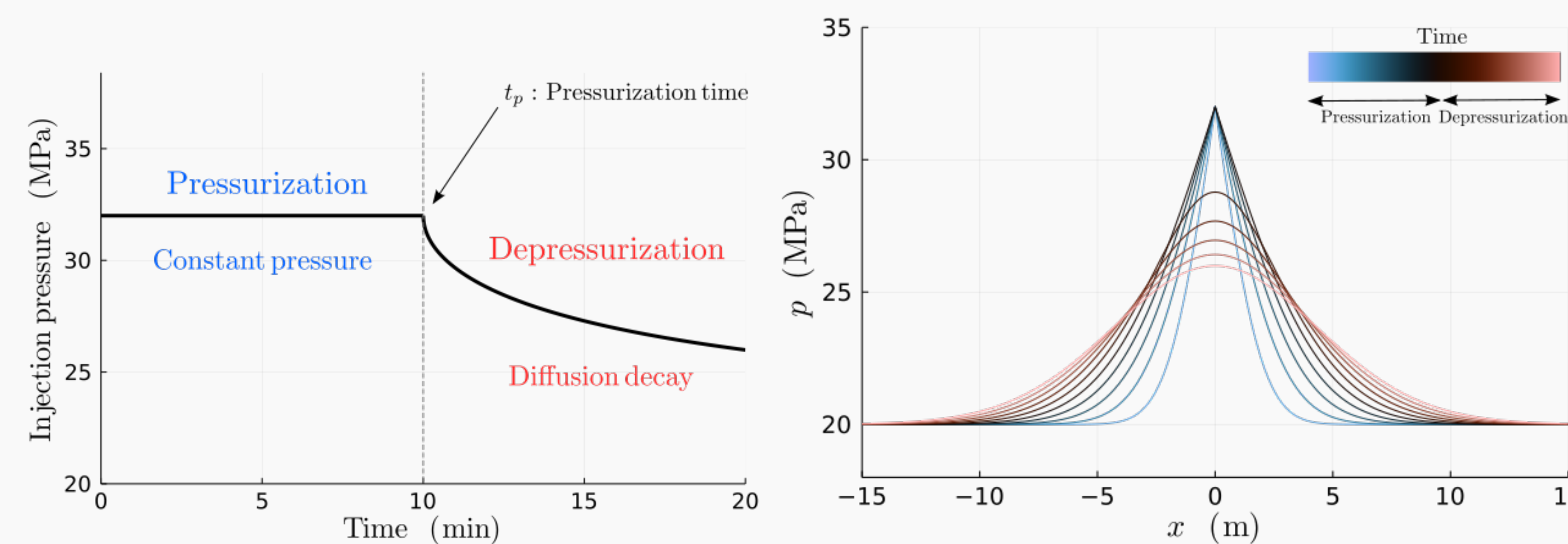


FIG. 3: Pressurization schedule. (left): Evolution over time of the pressure at the injection point. (right): Profiles of the fluid pressure during and after pressurization. During the pressurization phase, the fluid pressure is constant at the injection point. After pressurization, the fluid pressure is free to diffuse and decays over time.

3) Problem formulation and verification

Quasi-static stress equilibrium [2]:

$$\Delta\sigma(x) = \frac{\lambda'}{\pi} \int_{-a}^a \frac{\partial\epsilon}{\partial s} \frac{1}{s-x} ds.$$

$$\Delta\tau(x) = \frac{\mu'}{\pi} \int_{-a}^a \frac{\partial\delta}{\partial s} \frac{1}{s-x} ds$$

Fault frictional strength:

$$\tau - f(\sigma - p) = 0.$$

Local elasto-plastic relation:

$$\Delta\sigma = \frac{\lambda'}{h} \Delta\epsilon, \quad \Delta\tau = \frac{\mu'}{h} (\Delta\delta - \Delta\delta^p).$$

Fluid pressure diffusion:

$$\frac{\partial p}{\partial t} - \alpha \frac{\partial^2 p}{\partial x^2} = 0.$$

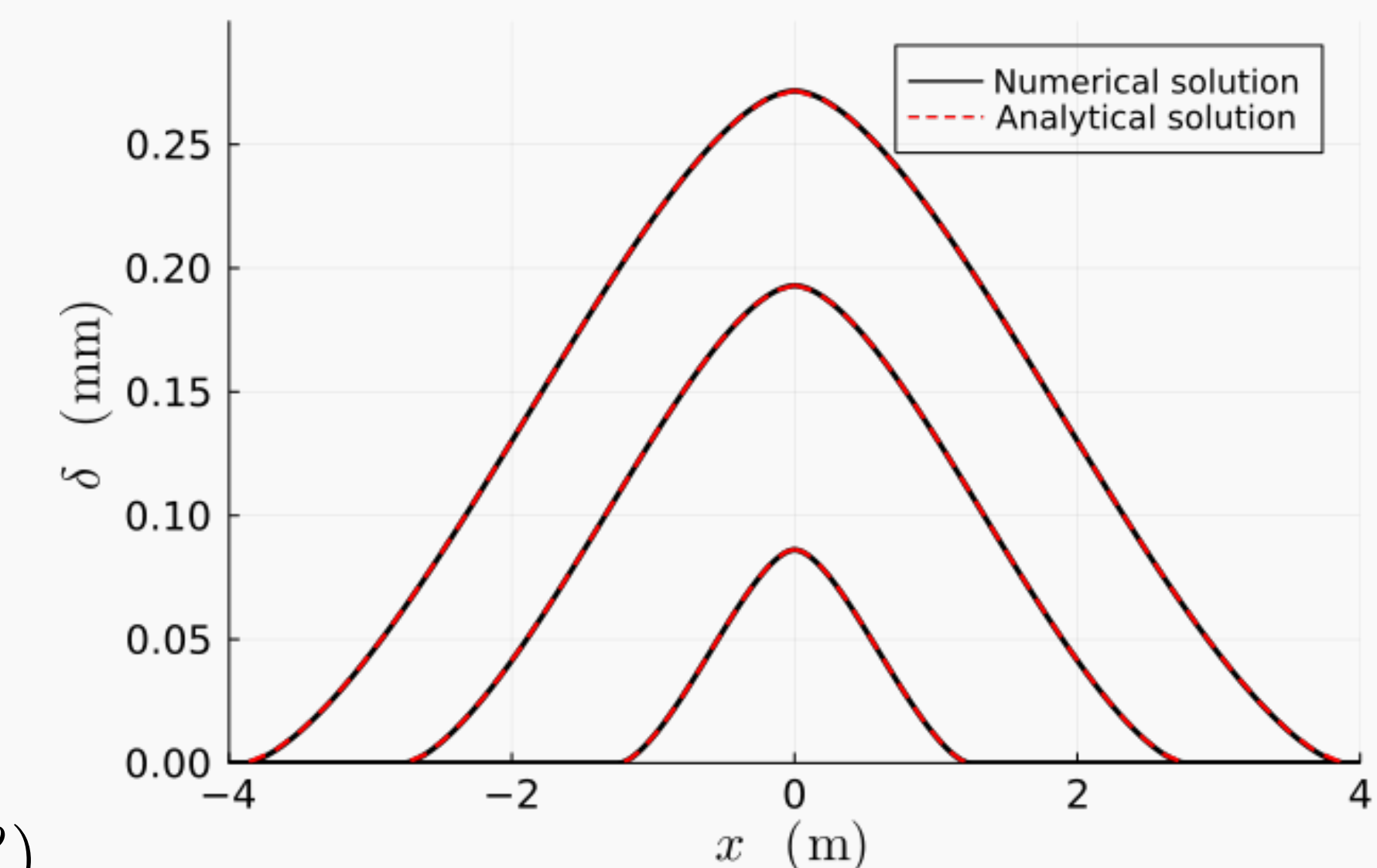


FIG. 4: Slip profiles after 1, 5, and 10 mins of pressurization.

Implementation using the boundary elements method (BEM) [3].

4) Stress criticality and aseismic rupture front

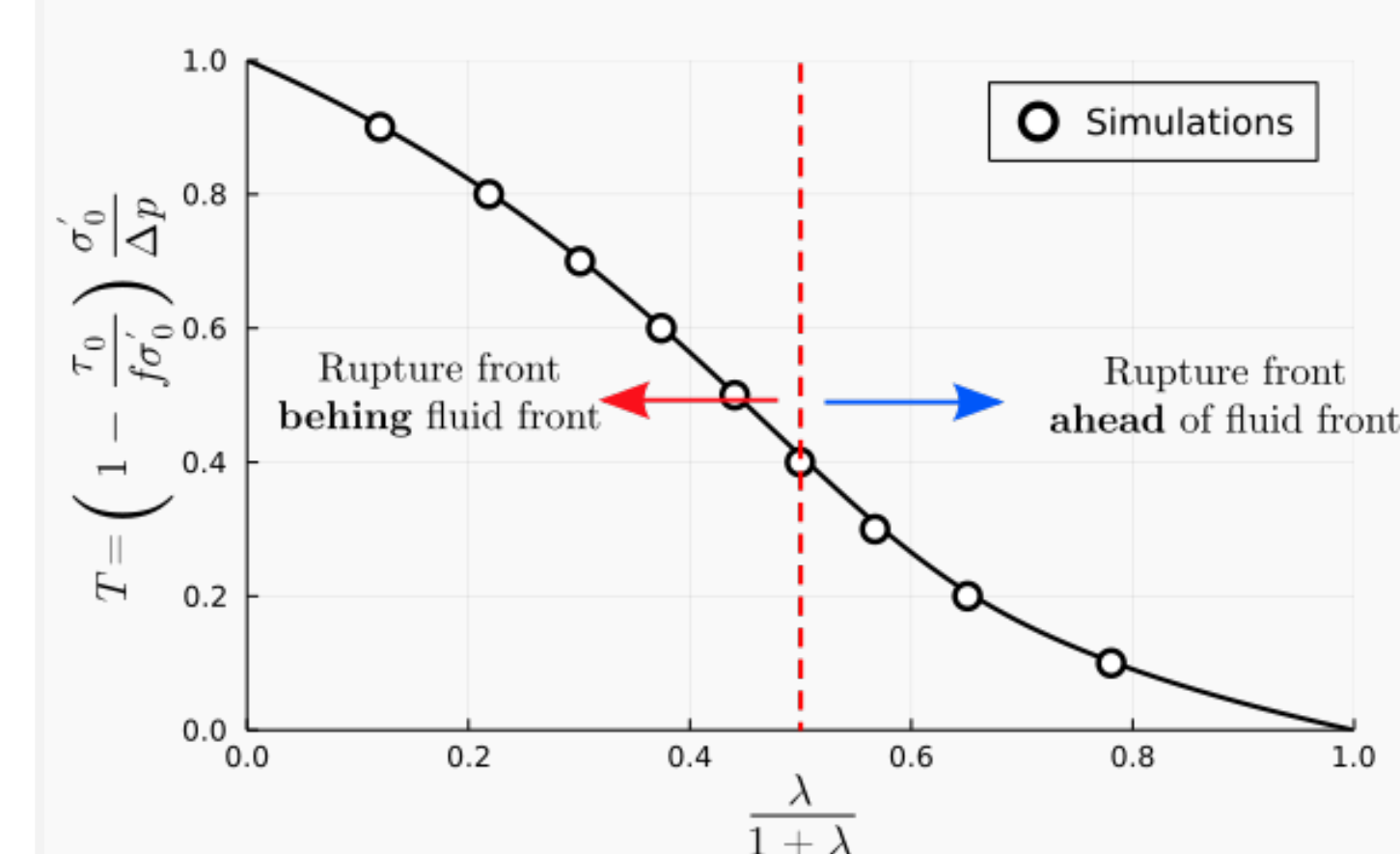


FIG. 5: Relation between stress parameter and the fronts ratio.

$$\lambda = \frac{a_t}{\sqrt{\alpha' t}} = \frac{\text{Rupture front}}{\text{Pressurization front}}.$$

$$T = \left(1 - \frac{\tau_0}{f\sigma'_0}\right) \frac{\sigma'_0}{\Delta p} = \frac{\text{Stress criticality}}{\text{Pressurization magnitude}}.$$

Rupture front can outpace fluid front during pressurization [4,5].

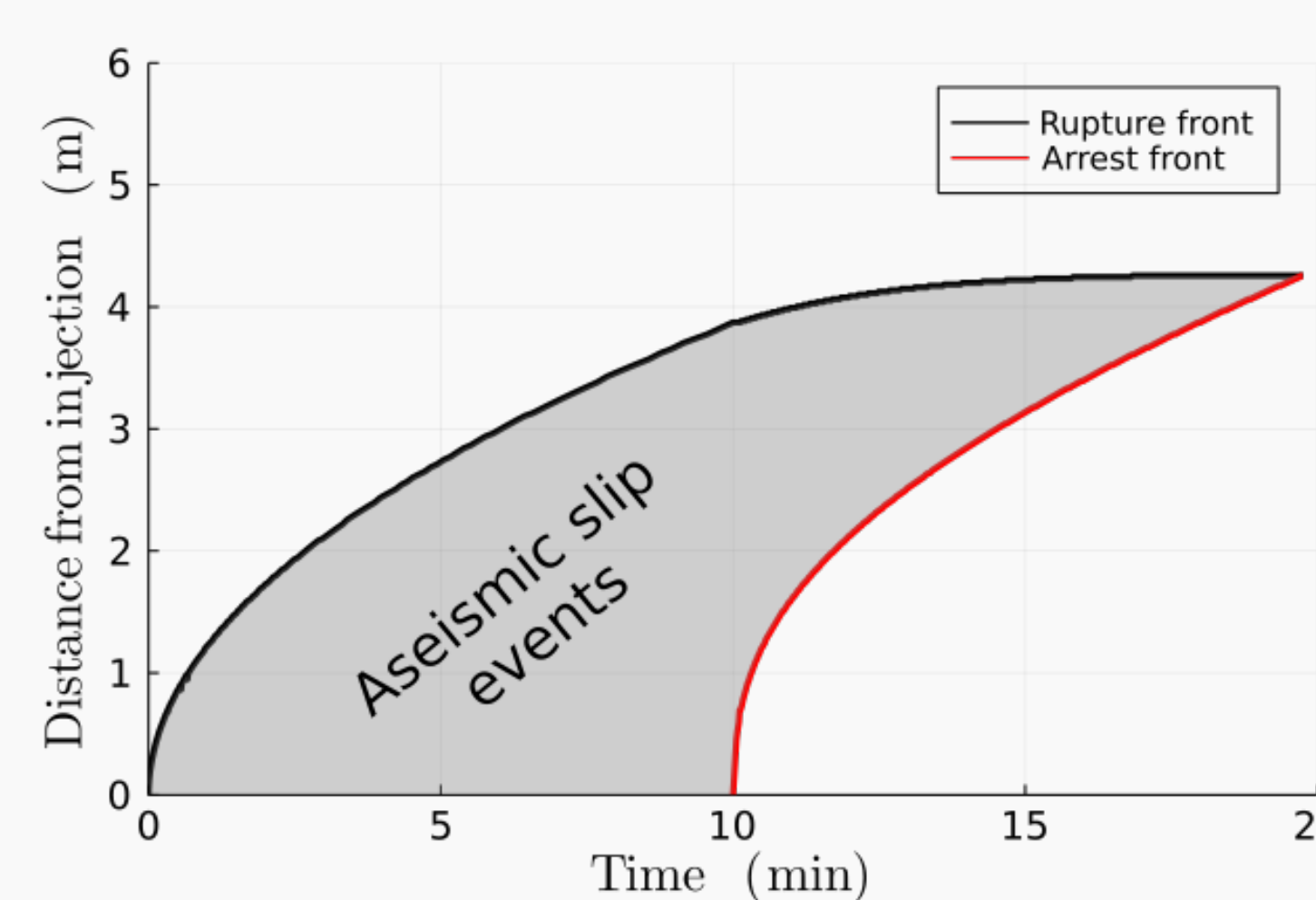


FIG. 6: Evolution of the rupture front and the arrest front during and after pressurization.

5) Next steps

- Extend frictional model to account for dilation and rate-dependent slip accumulation.
- Account for dilatant strengthening in the fluid pressure update .
- Describe the transition to seismic slip by considering thermal-activated dissipative slip.
- Investigate the impacts of different pressurization schedule on the onset and arrest of aseismic slip.
- Constrain model results with observations of fluid-induced aseismic and seismic slip.

References

- [1]: Shapiro S. A. and C. Dienske, Fluid-induced seismicity: Pressure diffusion and hydraulic fracturing, *Geophysical Prospecting*, (2009).
- [2]: Bilby B. A. and J. D. Eshelby, Dislocations and theory of fracture, in *Fracture, An Advanced Treatise*, (1968).
- [3]: Rice J.R. and K. Uenishi, Rupture nucleation on an interface with a power-law relation between stress and displacement discontinuity, *International Journal of Fracture*, (2010).
- [4]: Bhattacharya P. and R. C. Viesca, Fluid-induced aseismic fault slip outpaces pore-fluid migration, *Science* (2019).
- [5] Viesca R.C., Self-similar fault slip in response to fluid injection, *arXiv*, (2021).