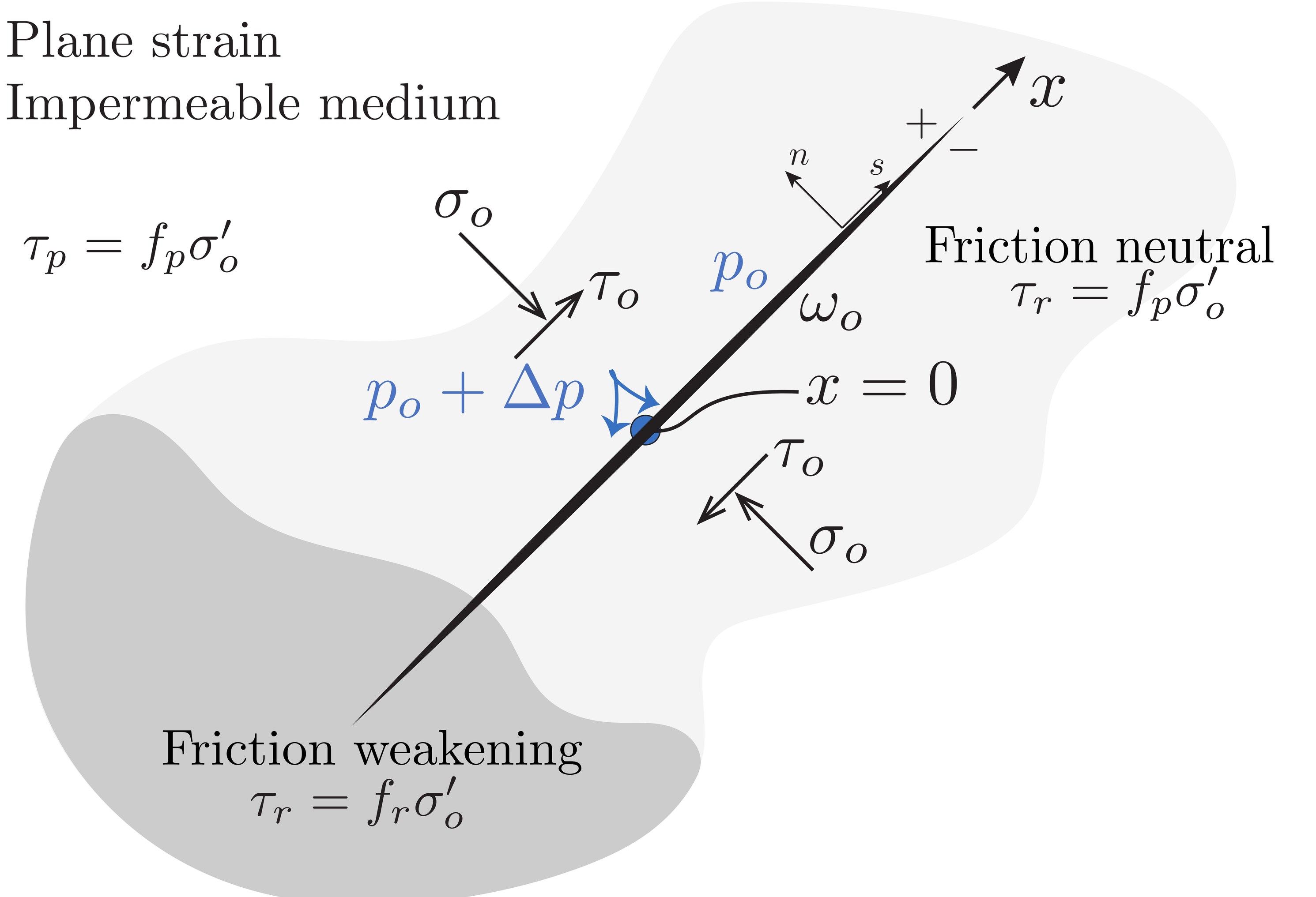
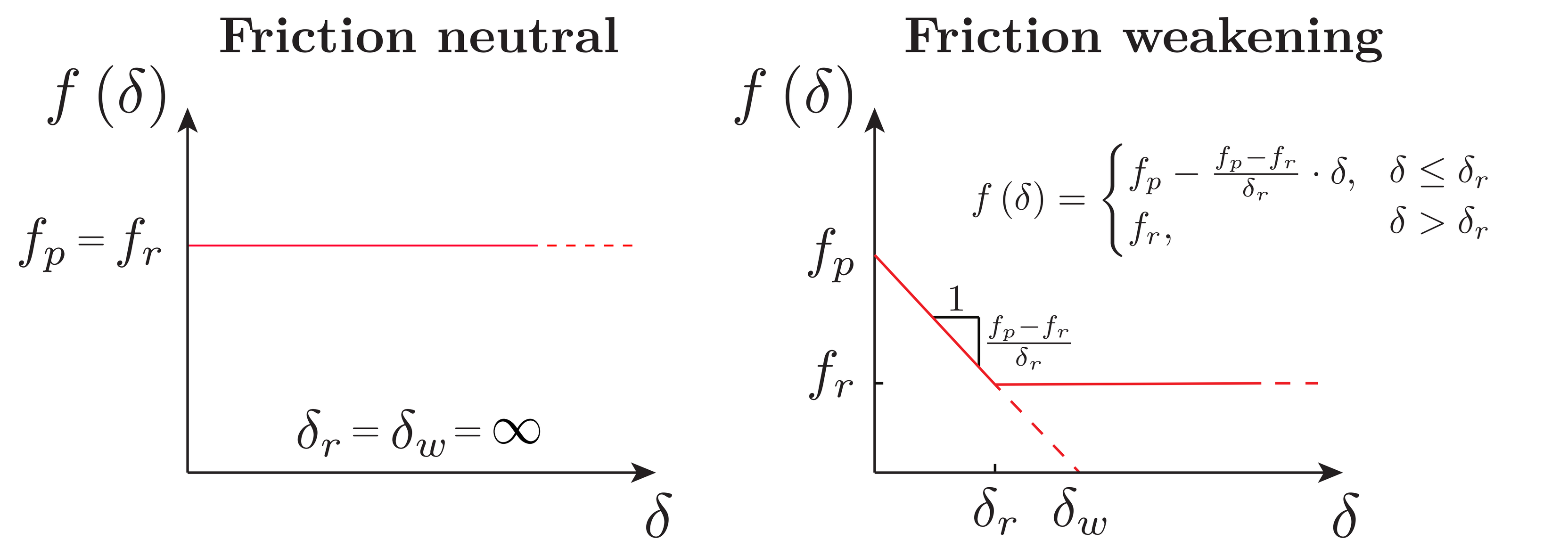
Fluid injection driven, a-seismic fracture growth with remote nucleation on heterogeneous fault

Andreas Möri, Brice Lecampion* and Federico Ciardo
Geo-Energy Laboratory - Gaznat chair on Geo-energy, EPFL, Lausanne, Switzerland
*Contact: brice.lecampion@epfl.ch

1. Model and problem formulation

Plane strain
Impermeable medium





- Linear quasi-static elasticity

$$t_i(x,t) = t_i^o(x) + \int_{-a}^{a} K_{ij}(\xi, x) \cdot d_j(\xi, t) \mathrm{d}\xi, \quad \text{for } i,j = n,s \qquad (1)$$

- Constant pressure injection condition / constant fault permeability case

$$p = p_o + \Delta p \qquad (2)$$

We assume $p_o + \Delta p$ remains below fault opening pressure (σ^o).

2. Numerics

- Displacement discontinuity method for elasticity (BEM)
- Finite volume scheme for fluid flow
- Fully coupled implicit solver (HFPx2D) developed at EPFL
- Adaptive time stepping based on current crack velocity

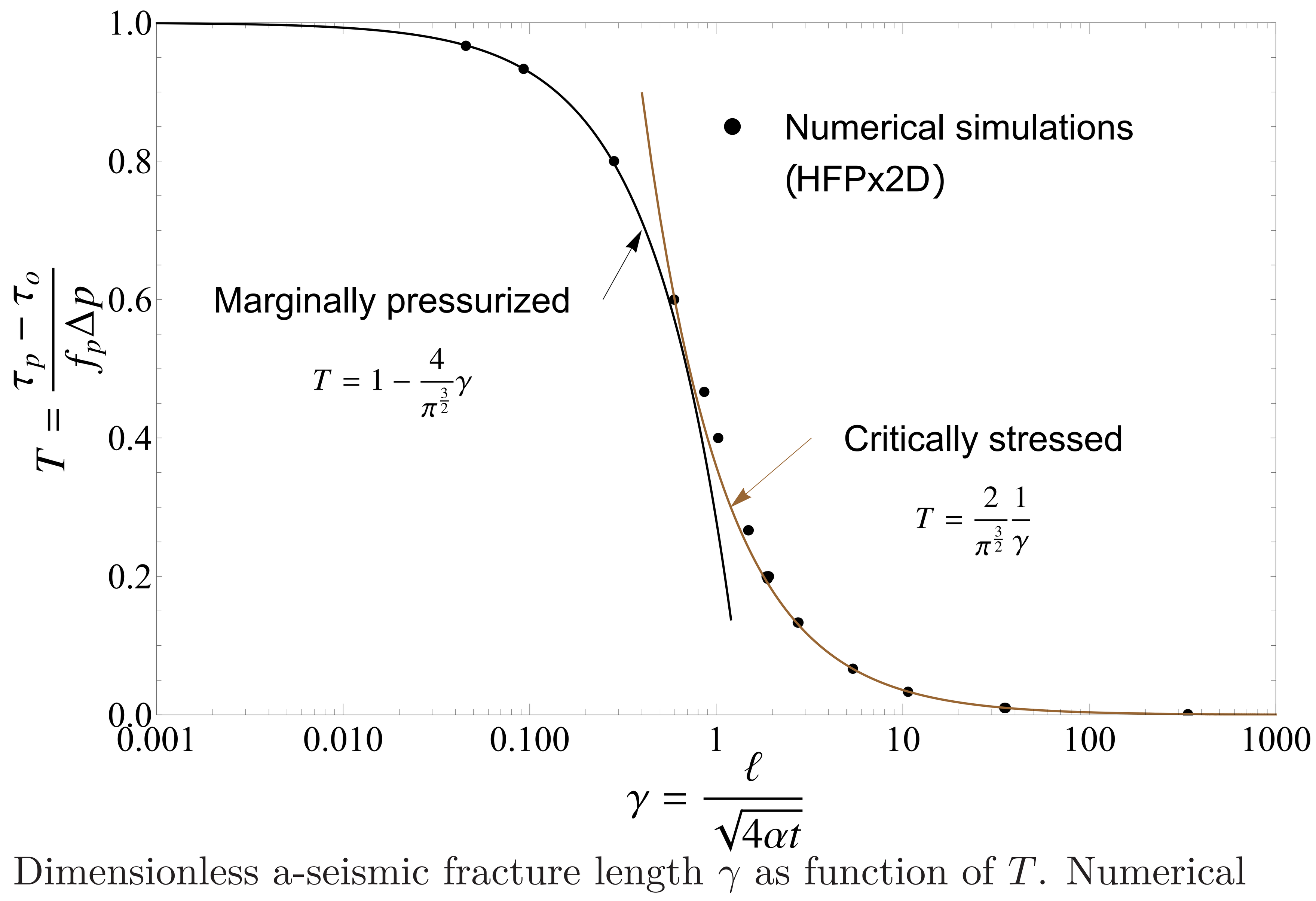
3. Theoretical developments

A linear relation between the crack half length and the position of the fluid pressure front due to pore pressure diffusion along the fault exists. Defining the dimensionless half-crack length $\gamma = \ell / \sqrt{4\alpha t}$ (with α the fault diffusivity), using the solution for 1D diffusion and stating that $\tau(\xi) = \tau_p$ inside the crack, the elasticity equation reduce for a planar fault to:

$$\frac{\tau(\xi) - \tau_o}{f_p \Delta p} \overset{\tau(\xi)=\tau_p}{\overbrace{=}} \underbrace{\frac{\tau_p - \tau_o}{f_p \Delta p}}_{T} = \mathrm{Erfc}|\gamma\xi| - \frac{1}{2\pi} \int_{-1}^{+1} \frac{\mathrm{d}\bar{\delta}}{\mathrm{d}\eta} \frac{\mathrm{d}\eta}{\xi - \eta} \qquad (3)$$

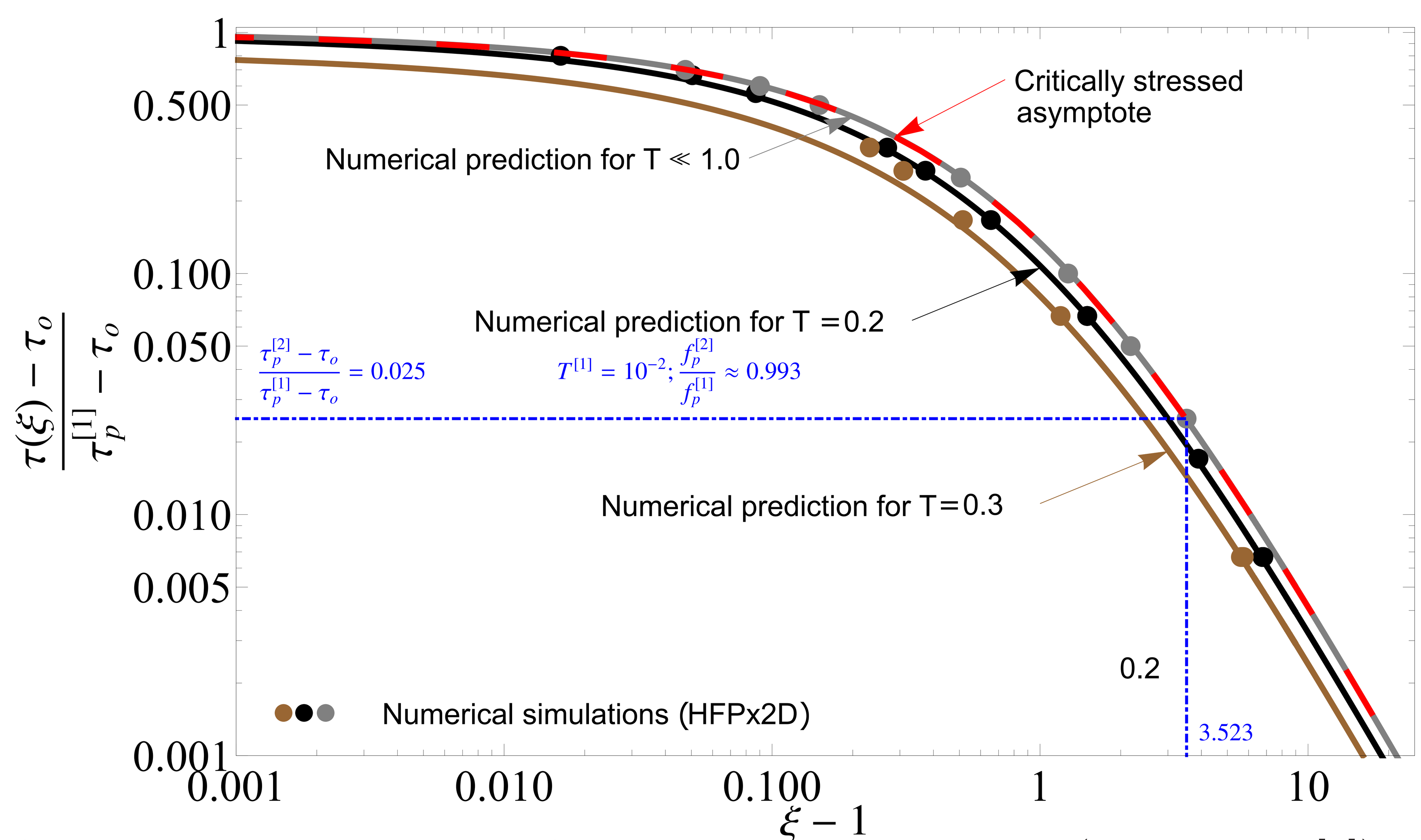
Dimensionless parameter T balances stress criticality (prior to the injection) and magnitude of the over-pressure. Asymptotic solution following [Viesca R., pers. comm., September 2018] serve as benchmark for the numerical solvers.

4. Benchmark

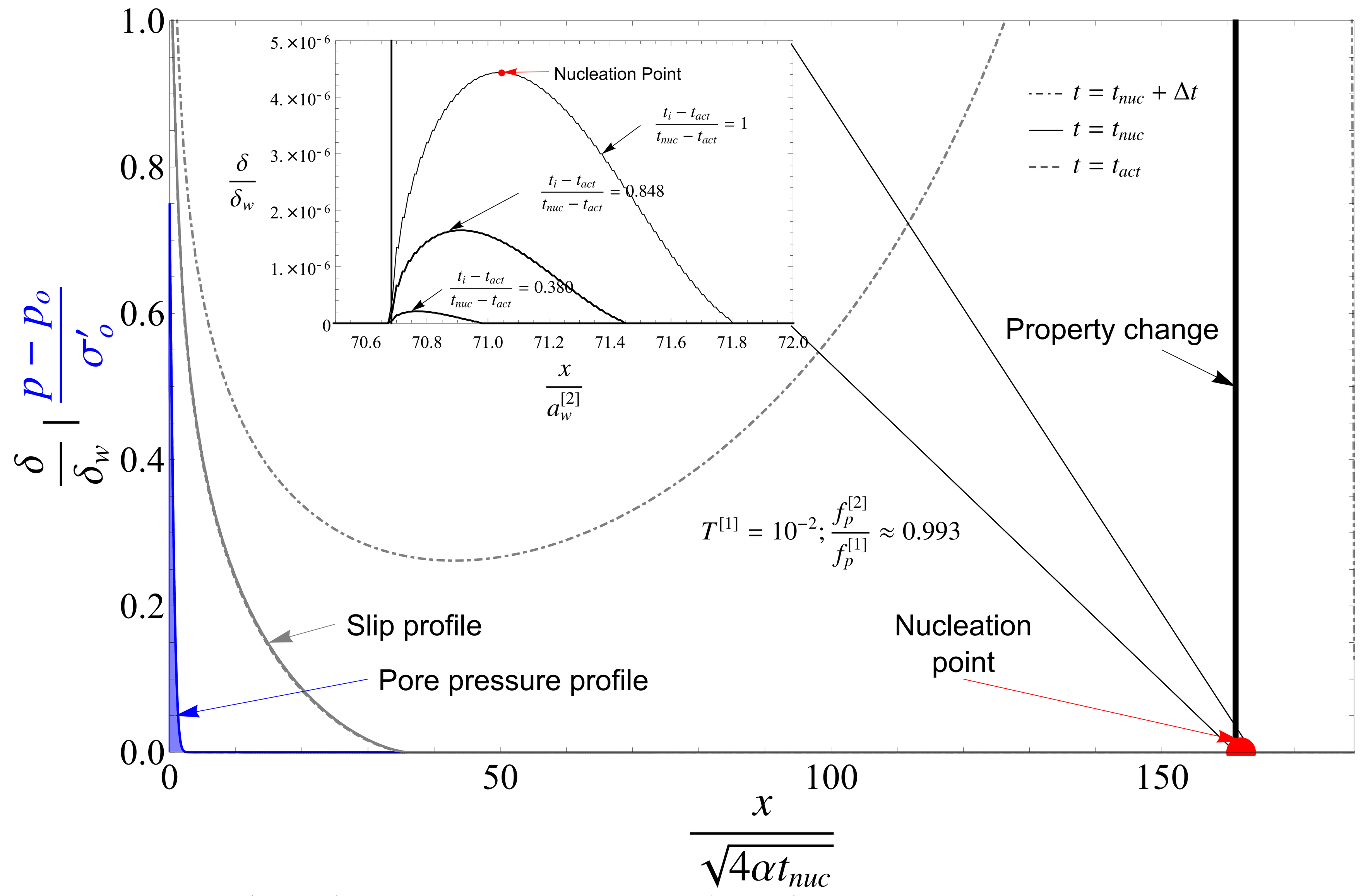


Dimensionless a-seismic fracture length γ as function of T. Numerical results are displayed as dots, analytical asymptotes for the marginally pressurized and critically stressed cases as continuous lines [Viesca, pers. comm., September 2018]

5. Remote activation on weaker part of fault



Stress perturbation ahead of aseismic mother crack tip (superscript [1]) for critically stressed cases, where $\xi = \frac{x}{\ell^{[1]}}$. This can lead to a remote activation of a daughter crack (superscript [2]), on a heterogeneity with lower strength, possibly nucleating dynamically (if frictional weakening occurs).



Slip profiles (gray) and pore pressure (blue) in function of normalized line coordinate. Inset shows slip evolution within the daughter crack. Nucleation in daughter crack scales with $a_w^{[2]}$.

- Friction neutral fault properties at injection
- Frictional weakening part with lower peak friction coefficient (i.e. $f_p^{[1]} > f_p^{[2]}$)
- Stress transfer dominated regime
- Remote activation of a-seismic slip with possible nucleation

6. Conclusions

- A-seismic crack tip and pore pressure front can significantly differ:
  - marginally pressurized (fluid pressure front ≫ aseismic crack front)
  - critically stressed (aseismic crack front ≫ fluid pressure front)
- Critically stressed faults with a weaker frictional weakening part can exhibit remote activation (far away from the pore-pressure disturbance), i.e. activation of a daughter crack with a possible subsequent nucleation of a dynamic rupture
- The dynamic nucleation lengthscale of the daughter crack scales as $a_w = \delta_w E' / (2\tau_p)$ following [Uenishi, K., and J.R. Rice (2003), Garagash, D. and Germanovich, L. (2012)] (linear frictional weakening).