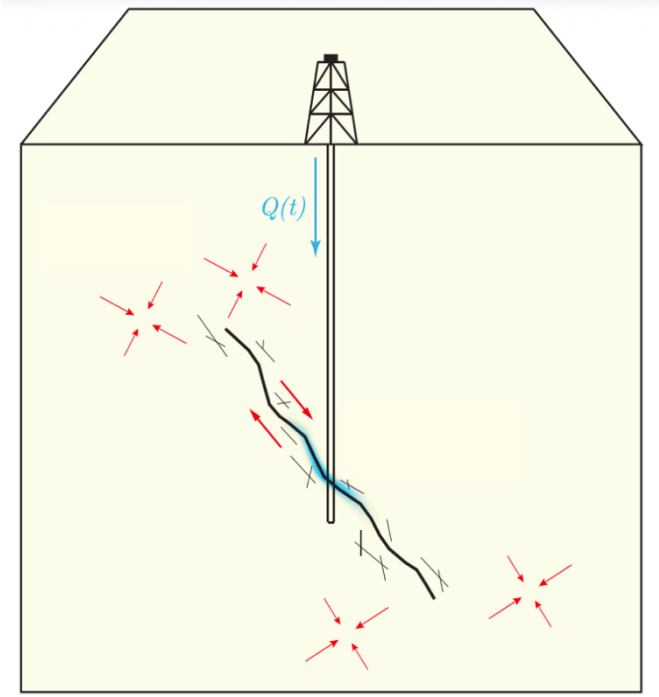


Simultaneous opening and slip of a fault during fluid injection

Brice Lecampion

Ankit Gupta* ,
Alexis Sáez**
A.Sarma, S. Brisson

Geo-Energy Lab

* Now at ENS Paris, ** now at Caltech

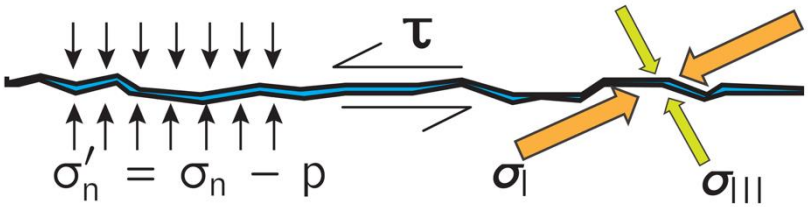
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

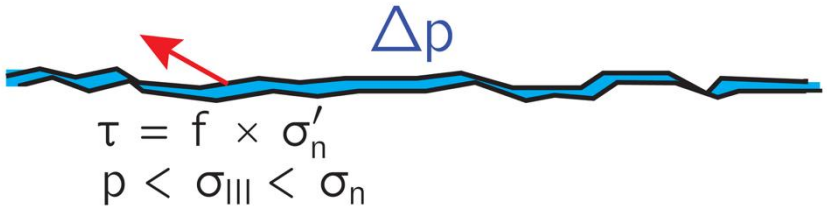
Office fédéral de l'énergie OFEN

Brice Lecampion

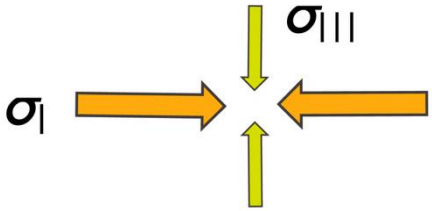
The 2 end-members

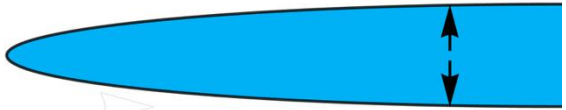
Fluid-driven frictional ruptures





Hydraulic Fractures



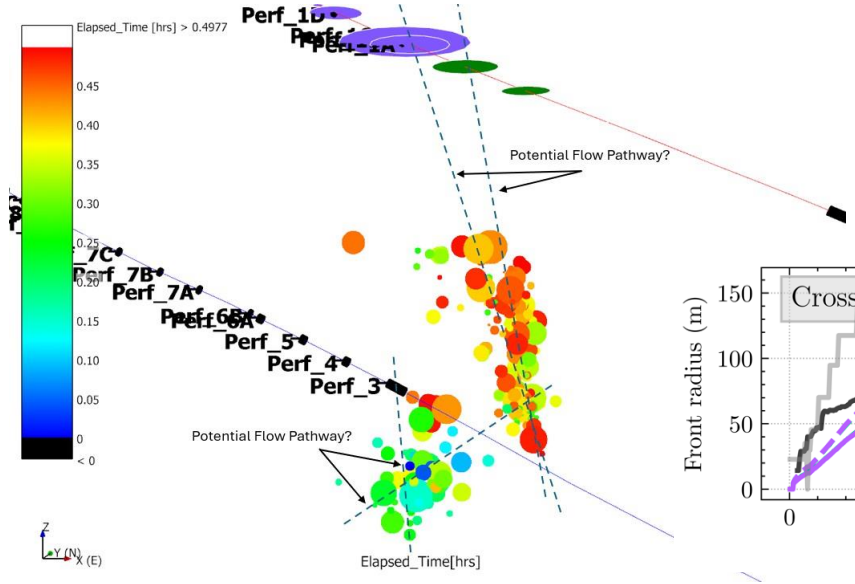


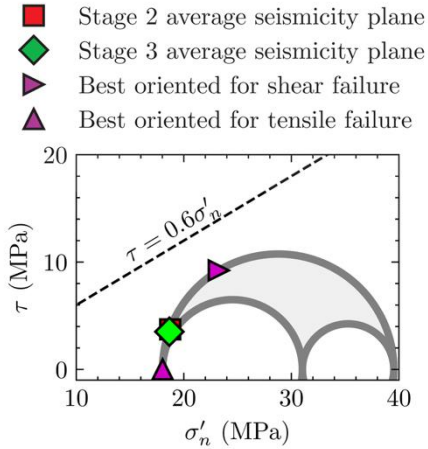
$p > \sigma_{III}$

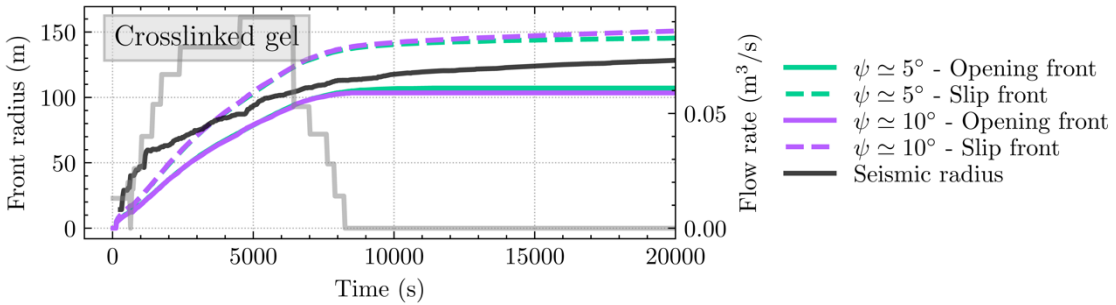


Example from Utah FORGE

2022 – Stage 3





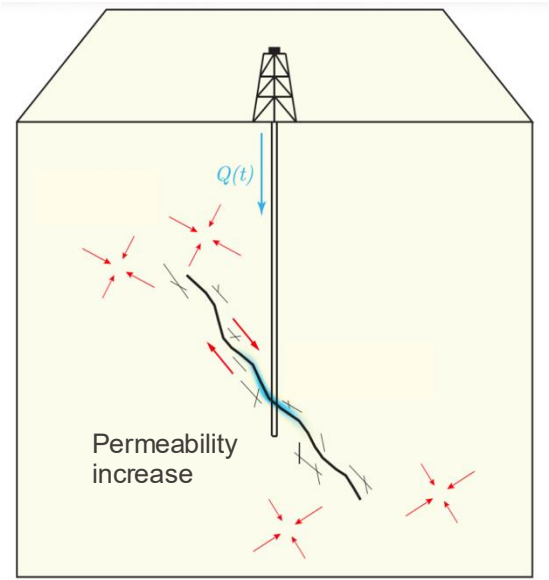


Brisson & Lecampion – RMRE 2027

From Finnila 2026 (Stanford Geothermal workshop)

Brice Lecampion

Motivations



- Understand the mechanics of the transition from hydro-shearing to opening (& its implication for fracture growth)
- Increasing permeability due to hydraulic opening and placing proppants not just relying on shear-induced dilation
- Hydraulic fracture intersecting pre-existing fracture / faults

… Eyre *et al.* (2019),
Weng (2024),
Brisson & Lecampion (2025)
Kim *et al* (2026)

Mechanics of hydroshearing

Theis solution for radial flow *(point source, flow in hydraulically conductive fracture)*

$$p_f(r,t) - p_o = \frac{\Delta p_c}{4\pi} E_1\left(\frac{r^2}{4\alpha t}\right)$$

$$\alpha = k/(\mu\, S_\epsilon)$$

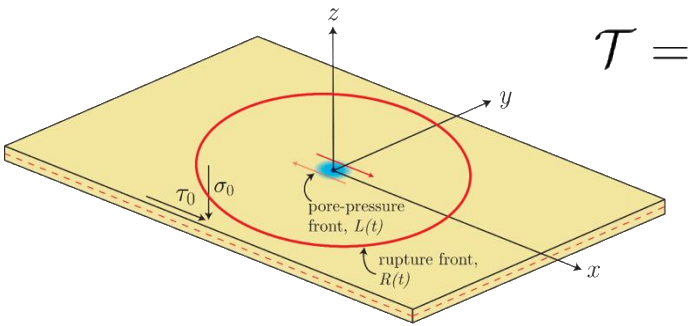
$$\Delta p_c = \frac{Q\mu}{k h_w}$$

Below the opening limit

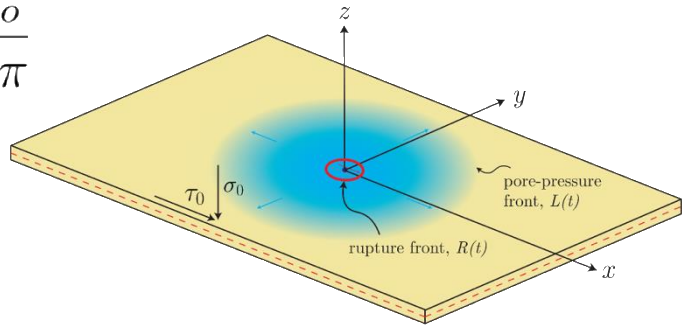
$$\Delta p_c < \sigma'_o$$

The *diffusion front* $\sqrt{4\alpha t}$ may lag or be ahead of the *shear rupture front*

$$\mathcal{T} = \frac{f\sigma'_o - \tau_o}{f\Delta p_c/4\pi}$$



Critically stressed regime



Marginally-pressurized regime

Sáez *et al* (2022), Sáez & Lecampion (2024, 25), Dunham (2024)

Mechanics of hydroshearing

Theis solution for radial flow *(point source, flow in hydraulically conductive fracture)*

$$p_f(r,t) - p_o = \frac{\Delta p_c}{4\pi} E_1\left(\frac{r^2}{4\alpha t}\right)$$

$$\alpha = k/(\mu\, S_\epsilon)$$

$$\Delta p_c = \frac{Q\mu}{k h_w}$$

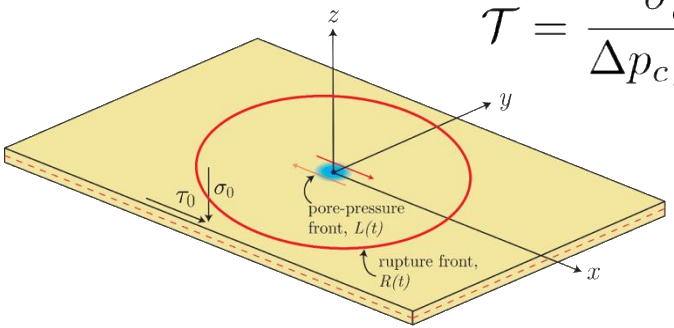
Below the opening limit

$$\Delta p_c < \sigma'_o$$

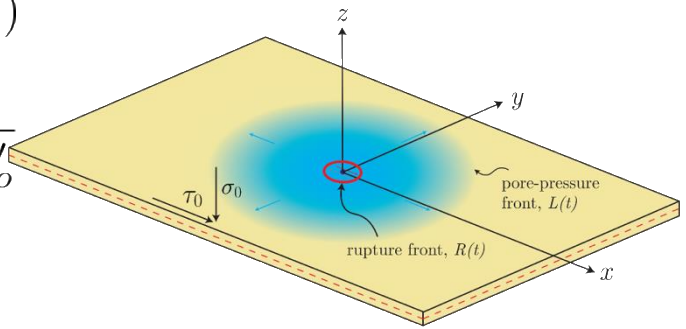
The *diffusion front* $\sqrt{4\alpha t}$ may lag or be ahead of the *shear rupture front*

$$\mathcal{T} = \frac{\sigma'_o}{\Delta p_c/4\pi}(1-\mathcal{S})$$

$$\mathcal{S} = \frac{\tau_o}{f\sigma'_o}$$



Critically stressed regime



Marginally-pressurized regime

Sáez *et al* (2022), Sáez & Lecampion (2024, 25), Dunham (2024)

Radial model for combined hydraulic opening and shearing

- Quasi-static elasticity relates slip & opening to shear & normal tractions on the fracture
- Criteria related to opening

$$\sigma' \geq 0$$

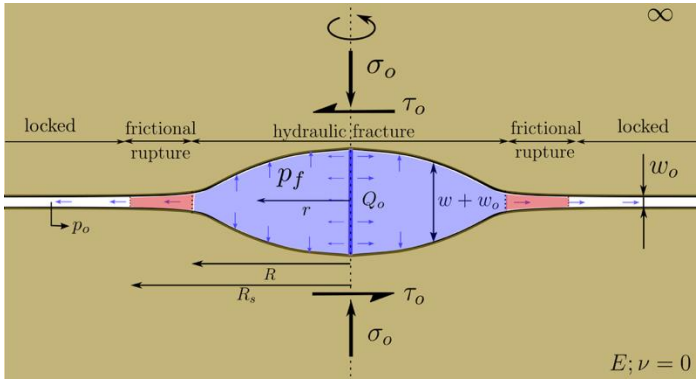
- Criteria for slip: constant Coulomb friction

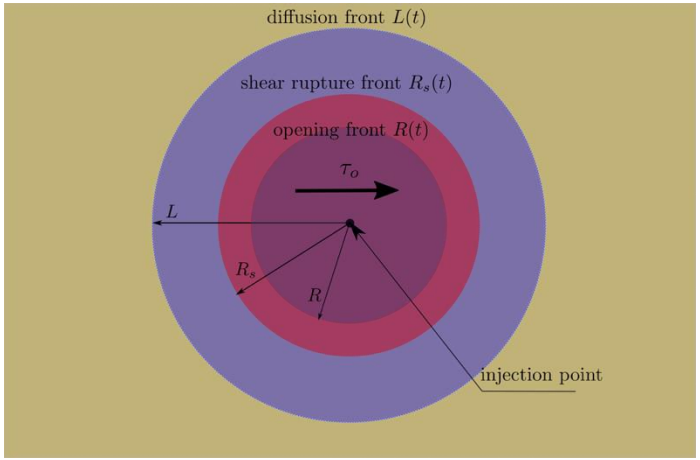
$$|\tau| \leq f\sigma'$$

For a planar fracture

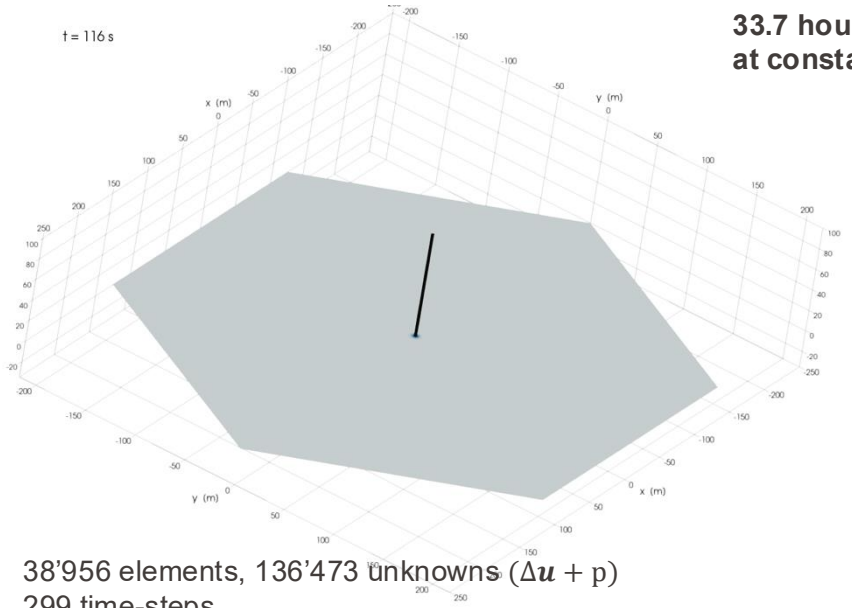
opening mode $\Rightarrow$ shear mode

shear mode $\not\Rightarrow$ opening mode



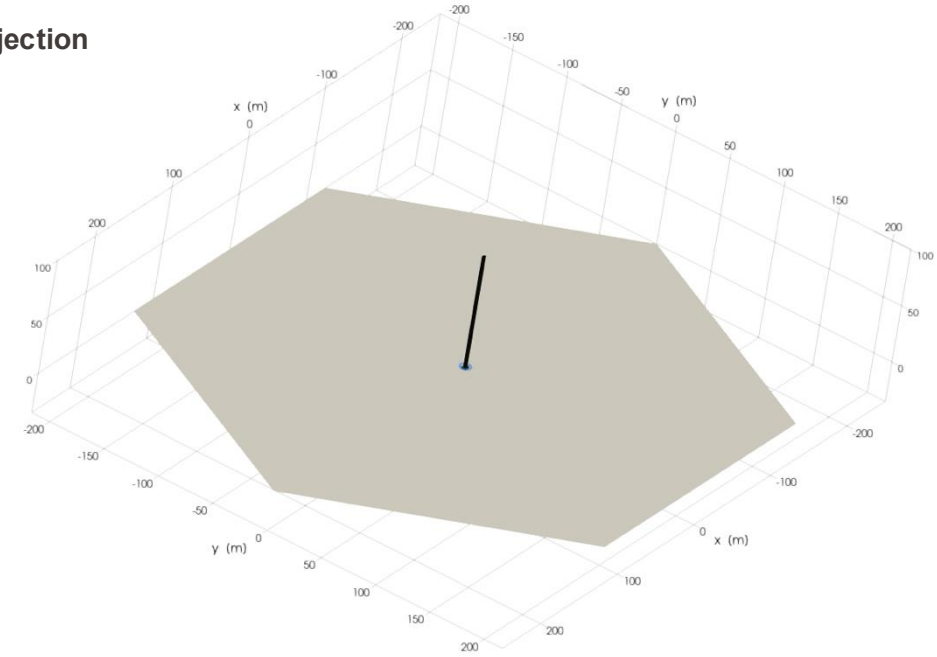


$$\frac{\Delta p_c}{\sigma'_o} = 6.28, S = \tau_o / f\sigma'_o = 0.5$$



33.7 hours of injection at constant rate





38’956 elements, 136’473 unknowns ($\Delta \boldsymbol{u} + \mathrm{p}$)
299 time-steps
54 minutes runtime on a single H100 GPU node



B. Lecampion *et al* . Three dimensional simulation of fluid-driven frictional and tensile ruptures on existing discontinuities. *CMAME*, 463:119348, 2027.

Radial model for combined hydraulic opening and shearing

- Axisymmetric lubrication flow in the open part (with Poiseuille's law)

$$\frac{\partial[w(r,t)]}{\partial t} + c_f[w(r,t)+w_o]\frac{\partial[p_f(r,t)]}{\partial t} = -\frac{1}{r}\frac{\partial[r\,q(r,t)]}{\partial r}$$

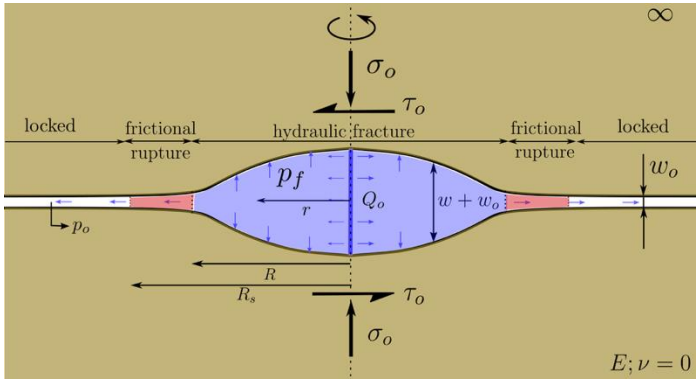
$$q(r,t) = -\frac{[w(r,t)+w_o]^3}{\mu'}\frac{\partial[p_f(r,t)]}{\partial r}$$

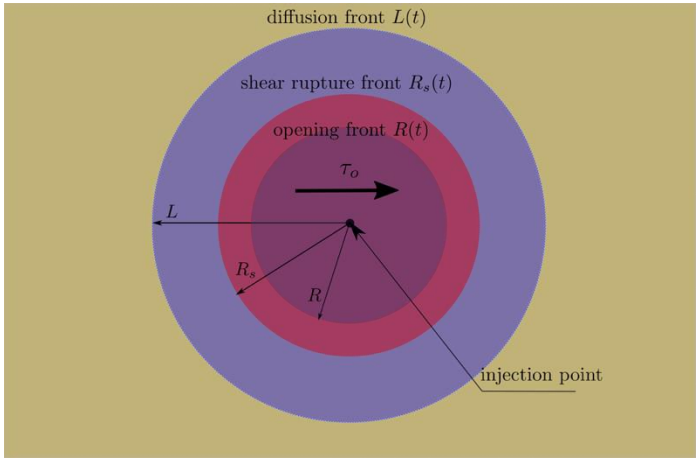
- Axisymmetric Darcy flow outside the open part

$$\frac{\partial[p_f(r,t)]}{\partial t} = \frac{w_o^2}{\mu' c_f}\frac{1}{r}\frac{\partial}{\partial r}\left[r\frac{\partial[p_f(r,t)]}{\partial r}\right]$$

- Constant injection rate from a point source

$$\lim_{r\to 0} 2\pi\, r\, q(r,t) = Q_o$$





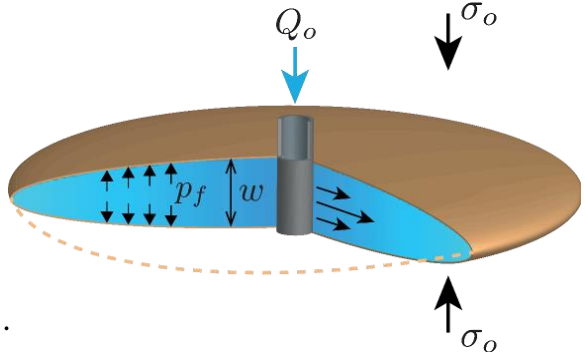
Gupta *et al.* (in preparation)

Brice Lecampion

Zero toughness radial hydraulic fracture (HF)

Global fluid volume balance for the HF

$$\frac{d}{dt}\left(2\pi\int_0^{R(t)} rw(r,t)dr\right) = Q_o - 2\pi R(t)q(R(t),t)$$



fluid flux at tip is zero

Fluid volume injected is same as volume of HF

$$\sigma - \sigma_o \sim P_m^{\text{net}}, \quad p_f - p_o \sim P_m^f, \quad w \sim W_m, \quad R \sim R_m.$$

$$R_m = \frac{E^{1/9}Q_o^{1/3}}{\mu'^{1/9}}t^{4/9}, \qquad P_m^{\text{net}} = E^{2/3}\mu'^{1/3}t^{-1/3}, \qquad W_m = \frac{\mu'^{2/9}Q_o^{1/3}}{E^{2/9}}t^{1/9}.$$

Savitski & Detournay (2002).

For opening to occur: $\sigma - p_f = \sigma' = 0$

$$P_m^f \sim \sigma'_o + P_m^{\text{net}}$$

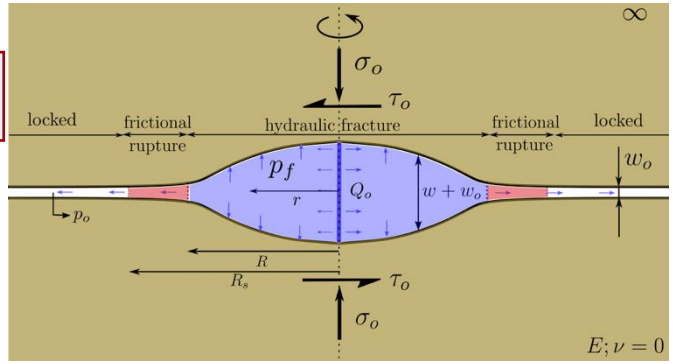
$$P_m^f \sim \sigma'_o, \quad \forall t \gg t_c = \frac{E'^2\mu'}{\sigma_o'^3}$$

Brice Lecampion

Hydraulic opening of an existing fracture

Global fluid volume balance for the open part

$$\frac{d}{dt}\left(2\pi\int_0^{R(t)} w(r,t)rdr\right) + 2\pi\int_0^{r(t)} c_f(w+w_o)\frac{\partial p_f}{\partial t}rdr = Q_o - 2\pi R(t)q(R(t),t)$$



We can show that for $t \gg t_c$

$$\int_0^{R(t)} c_f(w+w_o)\frac{\partial[p_f(r,t)]}{\partial t}\,r\,dr \ll Q_o \iff c_f\sigma_o' \ll 1$$

$$2\pi R(t)\,q(R(t),t) < Q_o \iff \frac{\Delta p_c}{\sigma_o'} > 1 \qquad \Delta p_c = \frac{Q_o\mu'}{w_o^3}$$

The volume of the open part is of the same order as injected volume & HF scaling holds

Characteristic time $t_c = \dfrac{E'^2\mu'}{\sigma_o'^3} \sim 10^{-2} - 100$ [sec]

Dimensionless numbers

$$c_f\sigma_o' \ll 1 \quad \sim \mathcal{O}(10^{-2})$$

$$\frac{\Delta p_c}{\sigma_o'} > 1 \quad \sim \mathcal{O}(1) - \mathcal{O}(10^6)$$

Brice Lecampion

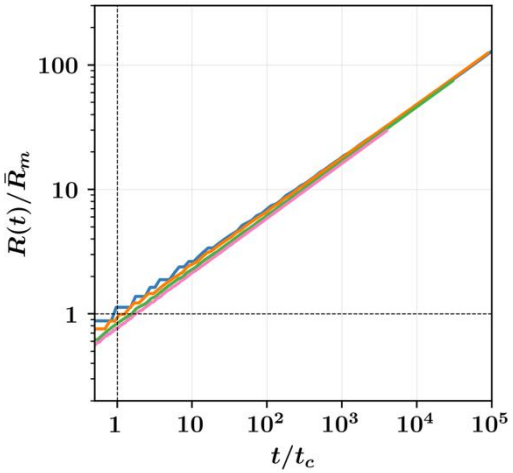
Numerical Results: zero shear stress

$$c_f \sigma_0' \approx 10^{-2}$$

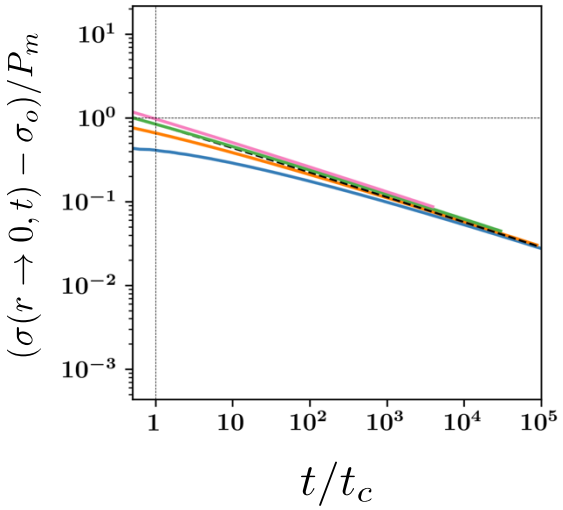
$$t_c \approx 10^{-2}\,[\text{sec}]$$

$\Delta p_c/\sigma_o' = 10^1$
$\Delta p_c/\sigma_o' = 10^2$
$\Delta p_c/\sigma_o' = 10^3$
$\Delta p_c/\sigma_o' = 10^4$

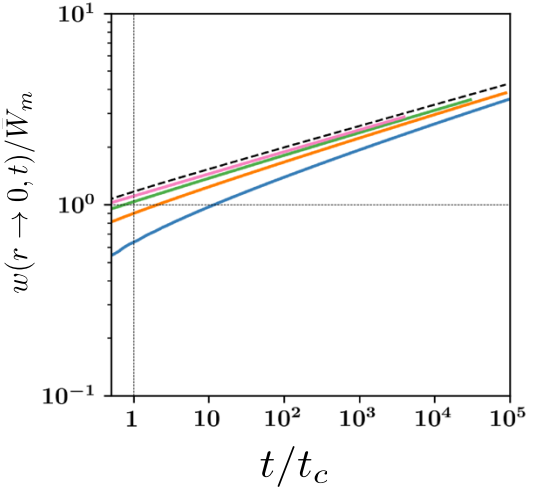
$$R_m(t_c) = \bar{R}_m = \frac{Q_o^{1/3}\,\mu'^{1/3}\,E'}{\sigma_o'^{4/3}}$$



$$P_m^{\text{net}}(t_c) = \bar{P}_m = \sigma_o'$$



$$W_m(t_c) = \bar{W}_m = \frac{Q_o^{1/3}\,\mu^{1/3}}{\sigma_o'^{1/3}}$$



Hydraulic opening of existing fracture follows the zero toughness HF scaling at late time

What happens ahead of the opening front ?

Diffusion equation ahead of the hydraulically open part:

$$\frac{\partial [p_f(r,t)]}{\partial t} = \frac{w_o^2}{\mu' c_f} \frac{1}{r} \frac{\partial}{\partial r} \left[r \frac{\partial [p_f(r,t)]}{\partial r} \right]$$

Competition between the pressure *diffusion front* and the *opening front propagation*

$$L(t) \sim \left(\sqrt{\frac{w_o^2}{\mu'\, c_f}} \right) t^{1/2}$$

$$R(t) \sim \left(\frac{E'^{1/9}\, Q_o^{1/3}}{\mu'^{1/9}} \right) t^{4/9}$$

At late time, the diffusion front overruns the opening front

Time dependent dimensionless diffusivity

$$D(t) = \frac{w_o^2\, t}{c_f\, \mu'\, R_m^2} = \frac{w_o^2\, t^{1/9}}{c_f\, E'^{2/9}\, \mu'^{7/9}\, Q_o^{2/3}} = \bar{D} \left(\frac{t}{t_c} \right)^{1/9}$$

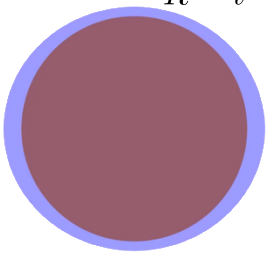
$$\bar{D} = D(t_c) = (c_f \sigma_o')^{-1} \left(\frac{\Delta p_c}{\sigma_o'} \right)^{-2/3} \sim O(10^{-2}) - O(10^{2})$$

Limiting regimes

Minimal diffusion

$L(t) >\sim R(t)$

$R \sim t^{4/9}$

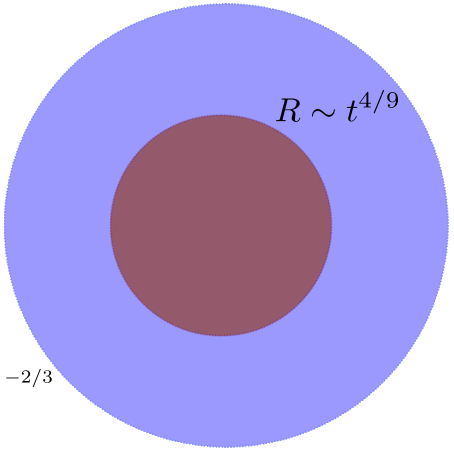


$\bar{D} \times (t/t_c)^{1/9}$

Transition time

Significant diffusion

$L(t) \gg R(t)$



$$\bar{D} = D(t_c) = (c_f \sigma'_o)^{-1} \left(\frac{\Delta p_c}{\sigma'_o} \right)^{-2/3}$$

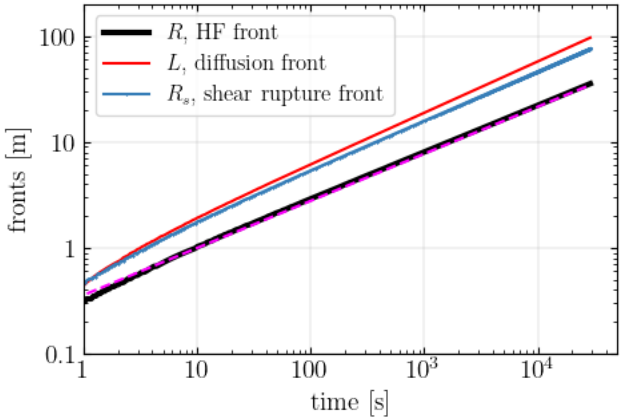
$\bar{D} < 1$: transition from minimal to significant diffusion regime possible

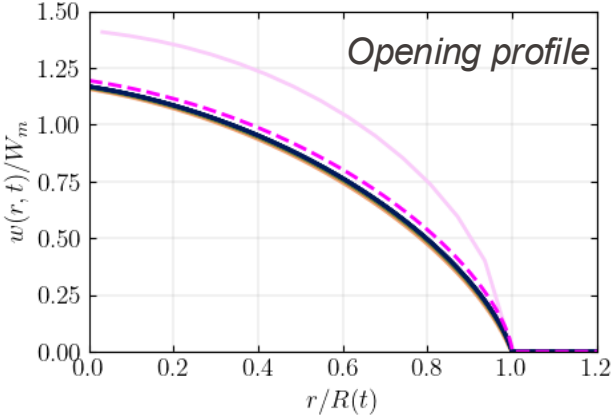
$\bar{D} > 1$: only the significant diffusion regime occurs

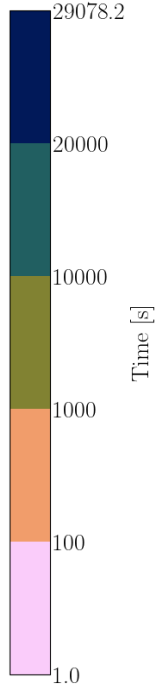
The shear rupture is controlled by $\bar{D}$ & the stress criticality $\mathcal{S} = \dfrac{\tau_o}{f\sigma'_o}$

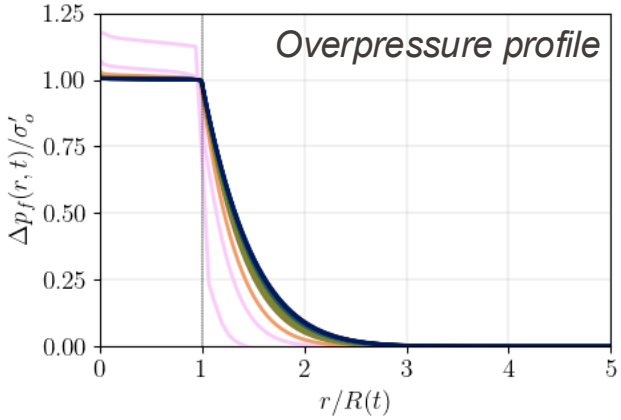
Results: Minimal diffusion regime

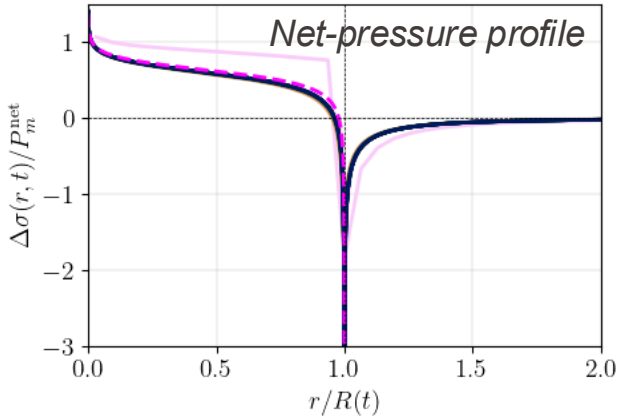
$\bar{D} = 0.0424 \quad \mathcal{S} = 0.7$





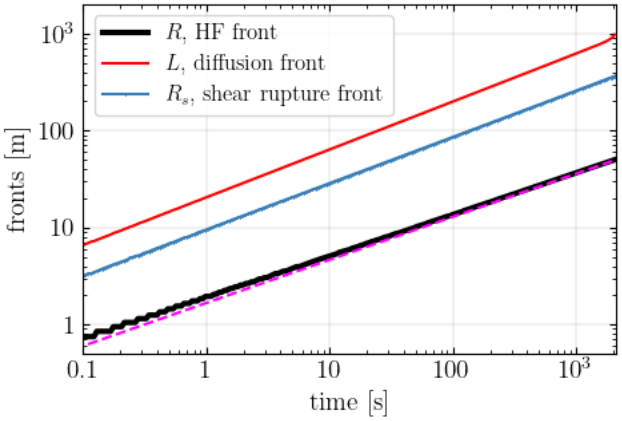


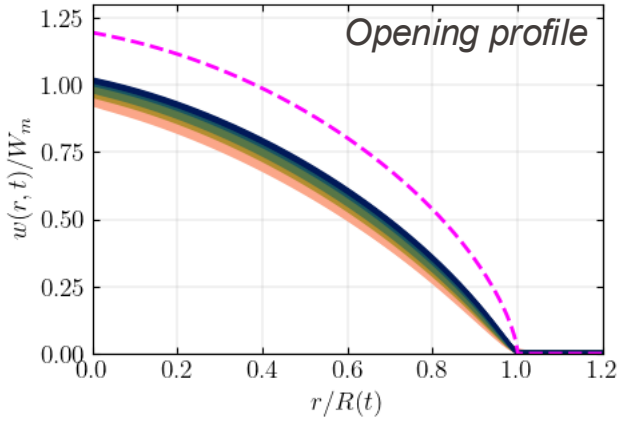


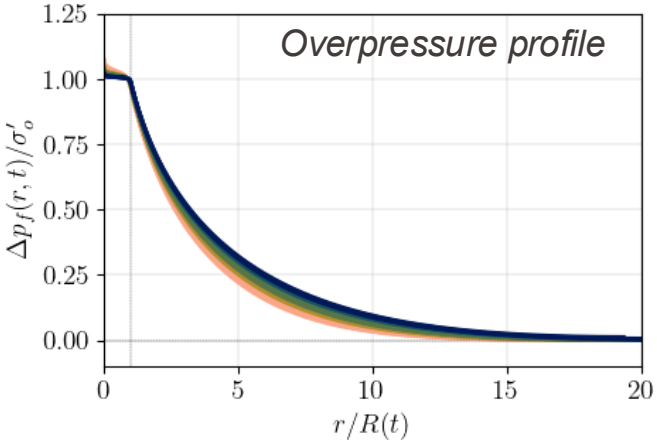


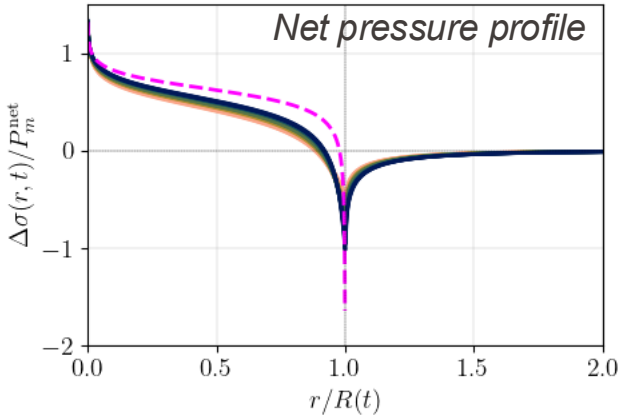
Results: Significant diffusion regime

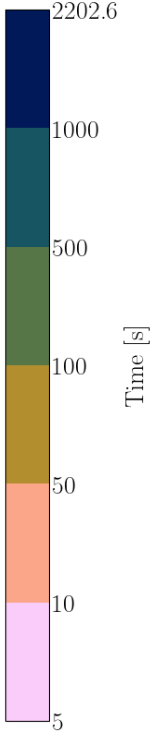
$\bar{D} = 4.24 \quad \mathcal{S} = 0.7$









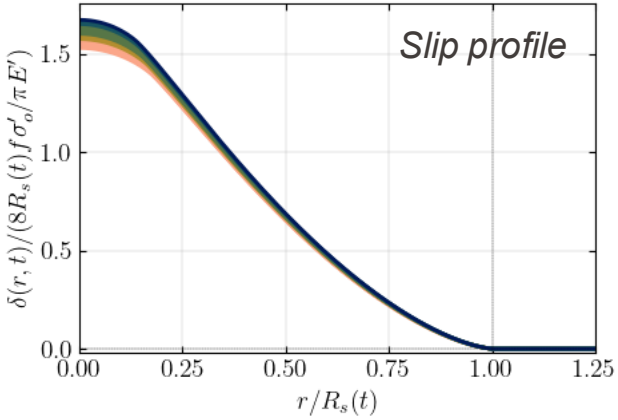


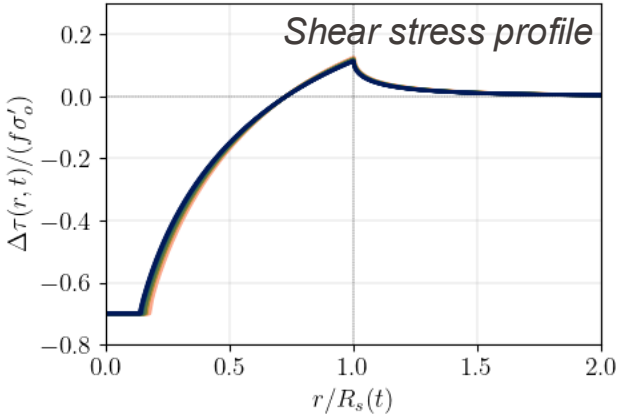
Brice Lecampion

Brice Lecampion

Results: Shear rupture

Significant diffusion regime

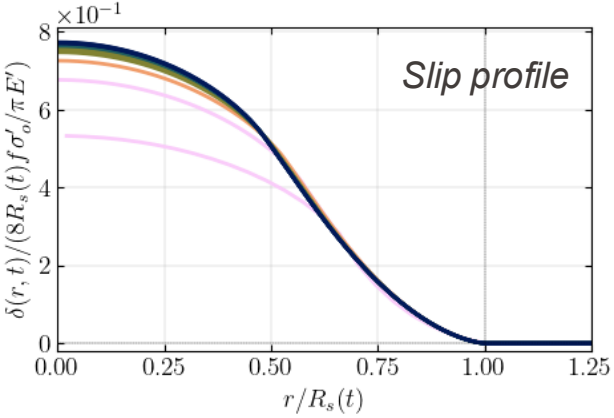


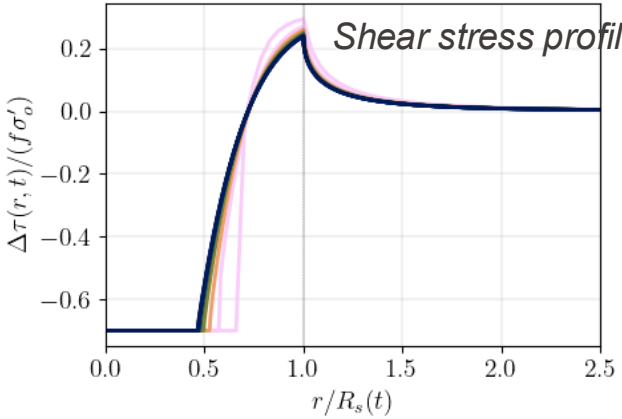


$\bar{D} = 4.24$

$\mathcal{S} = 0.7$

Minimal diffusion regime





$\bar{D} = 0.0424$

$\mathcal{S} = 0.7$

Brice Lecampion

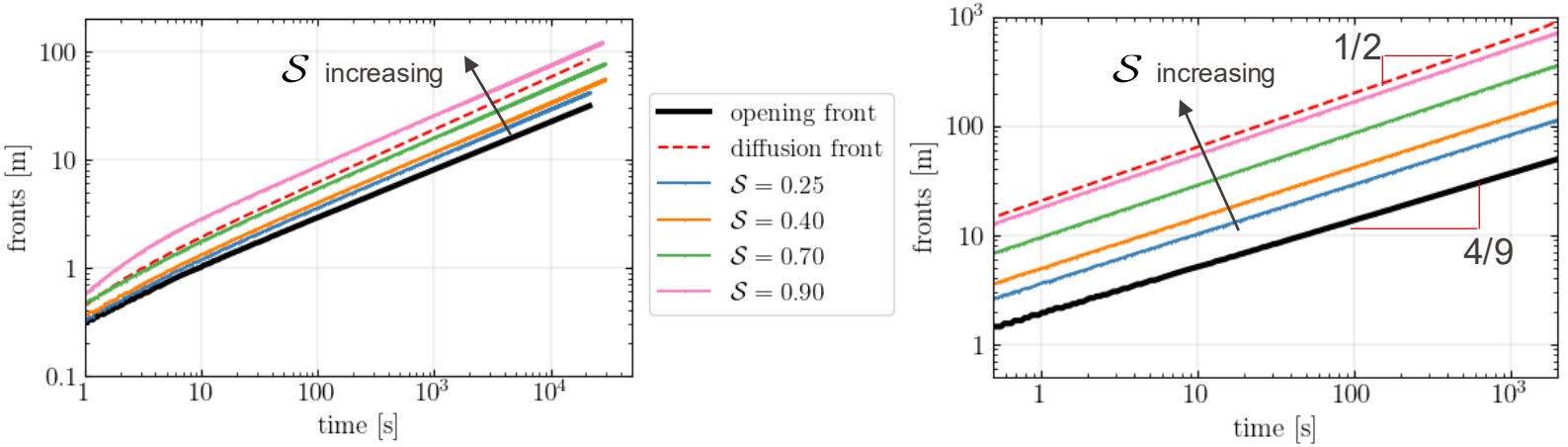
Results: Effect of stress criticality $S = \tau_o / f\sigma'_o$

Minimal diffusion regime

$\bar{D} = 0.0424$

Significant diffusion regime

$\bar{D} = 4.24$

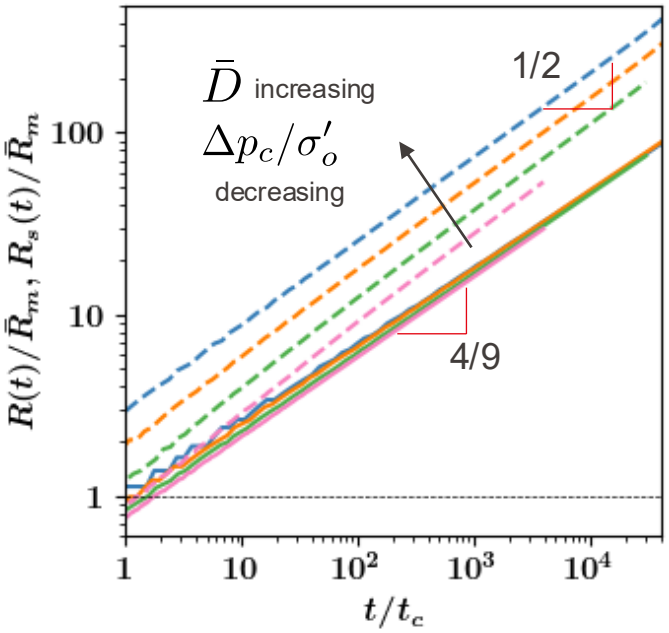


Diffusion ahead & stress criticality enhance slip patch size

Brice Lecampion

Results: Effect of Injection intensity on shear rupture

Rupture fronts growth



$\Delta p_c/\sigma'_o = 10^1$
$\Delta p_c/\sigma'_o = 10^2$
$\Delta p_c/\sigma'_o = 10^3$
$\Delta p_c/\sigma'_o = 10^4$

$$\bar{D} = D(t_c) = (c_f \sigma'_o)^{-1} \left(\frac{\Delta p_c}{\sigma'_o} \right)^{-2/3}$$

$$\mathcal{S} = \frac{\tau_o}{f \sigma'_o} = 0.4$$

$$c_f \sigma'_0 \approx 10^{-2}$$

$$t_c \approx 10^{-2} \, [\text{sec}]$$

$$R_m(t_c) = \bar{R}_m = \frac{Q_o^{1/3} \, \mu'^{1/3} \, E'}{\sigma'^{4/3}_o}$$

Conclusions

- Combined hydraulic opening & shearing of pre-existing fracture is likely common

- The zero-toughness HF scaling/solution holds for the open patch growth

- The pore-pressure diffusion along the fault eventually overruns the opening front, intensity of diffusion function of $\overline{D}$ (which is related to $\Delta p_c/\sigma_o'$)

- The extent of the shear rupture patch (ahead of the open part) is function of both dimensionless stress criticality & diffusion
- We have obtained semi-analytical expressions spanning the minimal and large diffusion regimes (not presented here).