Extraction of fluids to mitigate the seismic risk associated with post-injection aseismic slip

Alexis Sáez[1], Brice Lecampion[1]

[1]École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland

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Why?

- Not rare that the **largest earthquakes** of injection-induced seismic sequences occur **after shut-in**

- Some examples:
  - 2006 $M_L > 3$ Basel earthquakes, Switzerland (EGS) **[shutdown]**
  - 2017 $M_W = 5.5$ Pohang earthquake, South Korea (EGS) **[shutdown]**

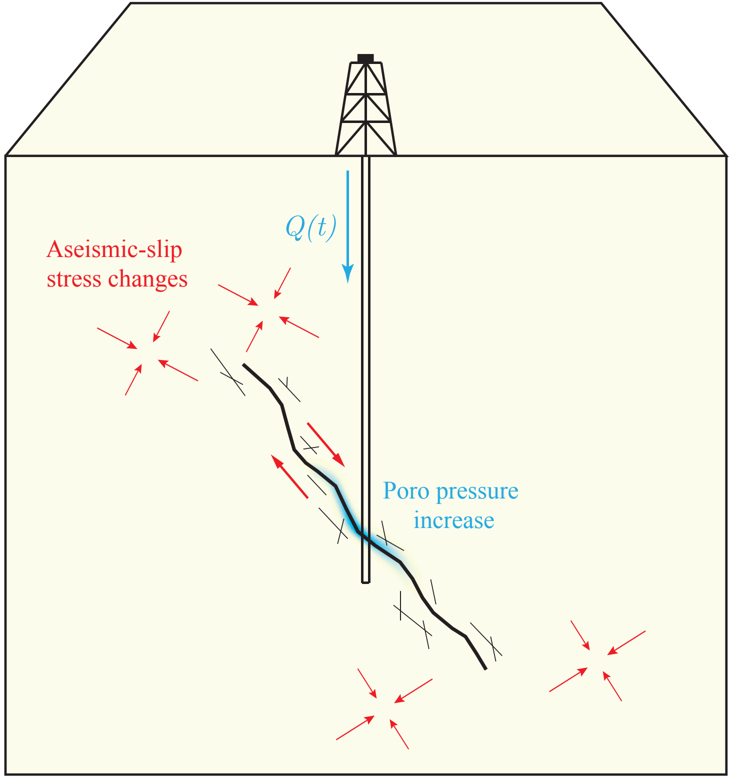
- Quite problematic since shutting off the well “is meant” to **decrease** the **seismicity potential**

Triggering mechanisms

$$\Delta CS = \Delta\tau - f \cdot (\Delta\sigma - \Delta p)$$

- Pore-pressure increase (e.g., Parotidis *et al*., GRL, 2004)
- Poroelastic stress changes (e.g., Segall and Lu, JGR, 2015)

Aseismic-slip stress transfer



Slip: mostly **aseismic**

[Cornet et al., 1994,1997;
Guglielmi et al., 2015; and many others]

Triggering mechanisms

$$\Delta CS = \Delta\tau - f\cdot(\Delta\sigma - \Delta p)$$

- Pore-pressure increase
- Poroelastic stress changes
- Aseismic-slip stress transfer

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Research

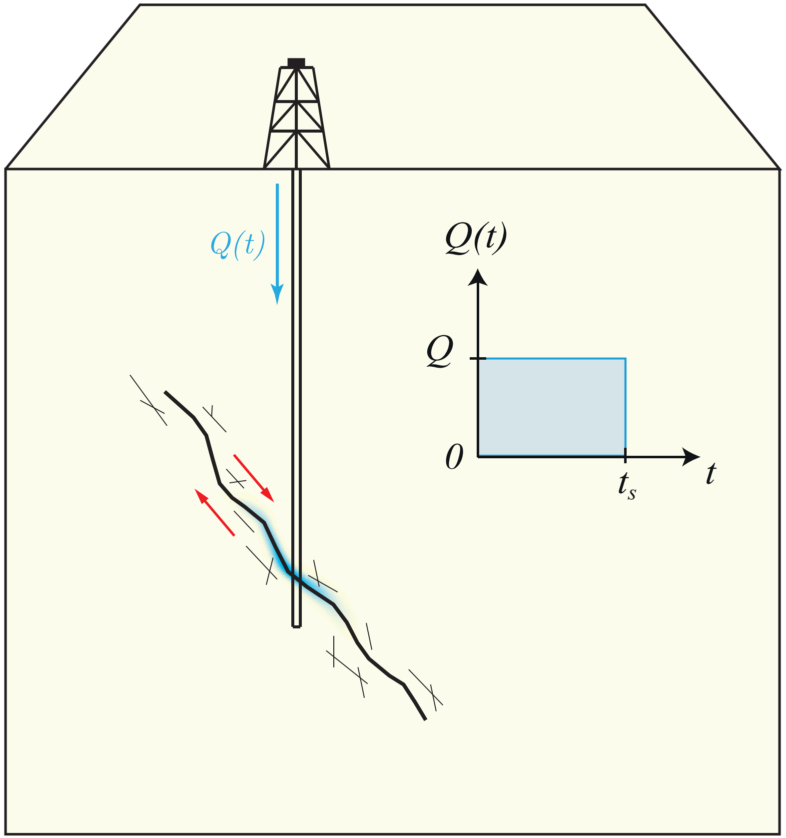
Check for updates

Post-injection aseismic slip as a mechanism for the delayed triggering of seismicity

Alexis Sáez and Brice Lecampion

Accepted for publication

3D Physical model



<u>Coupled (solid-fluid) initial boundary value problem</u>

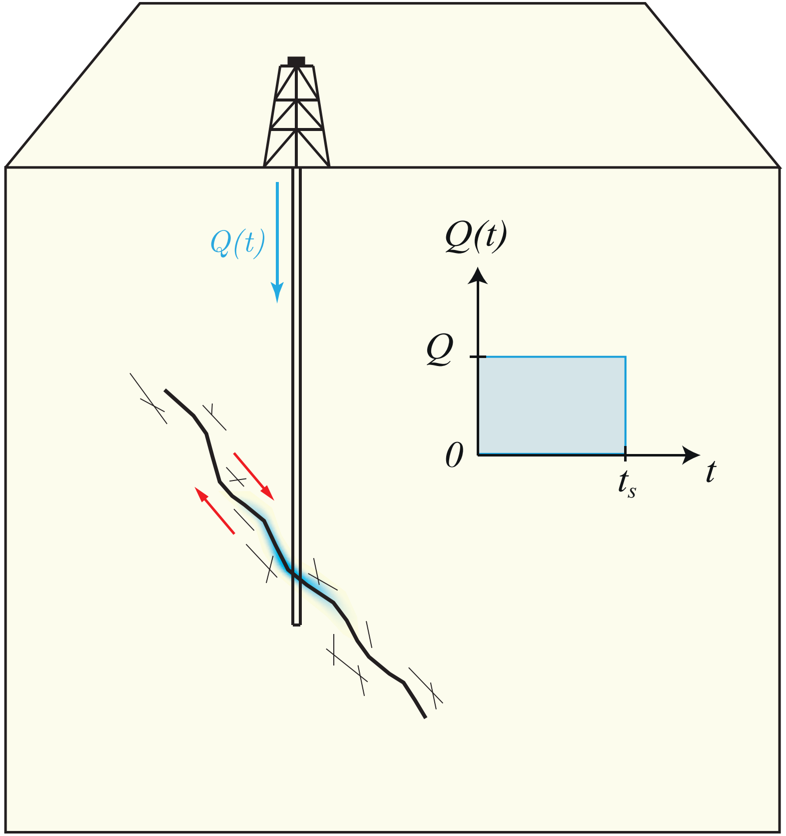
$$\tau(x,y,t) = \tau_0 + \int_\Gamma K(x-\xi, y-\zeta; \mu, \nu)\delta(x,y,t)\mathrm{d}\xi\mathrm{d}\zeta$$

$$|\tau(x,y,t)| \leq \tau_{strength} = f\left(\sigma_0' - \Delta p(r,t)\right)$$

$$\frac{\partial p(r,t)}{\partial t} - \alpha \nabla^2 p(r,t) = 0 \qquad \lim_{r\to 0} 2\pi r \frac{k}{\eta} w \frac{\partial p}{\partial r} = -Q(t)$$

$$\lim_{r\to\infty} p(r,t) = p_0$$

3D Physical model



Coupled (solid-fluid) initial boundary value problem

- Quasi-static elasticity
- Coulomb's friction
- Mass conservation + Darcy's law along the fracture/fault

During-injection versus after-injection response

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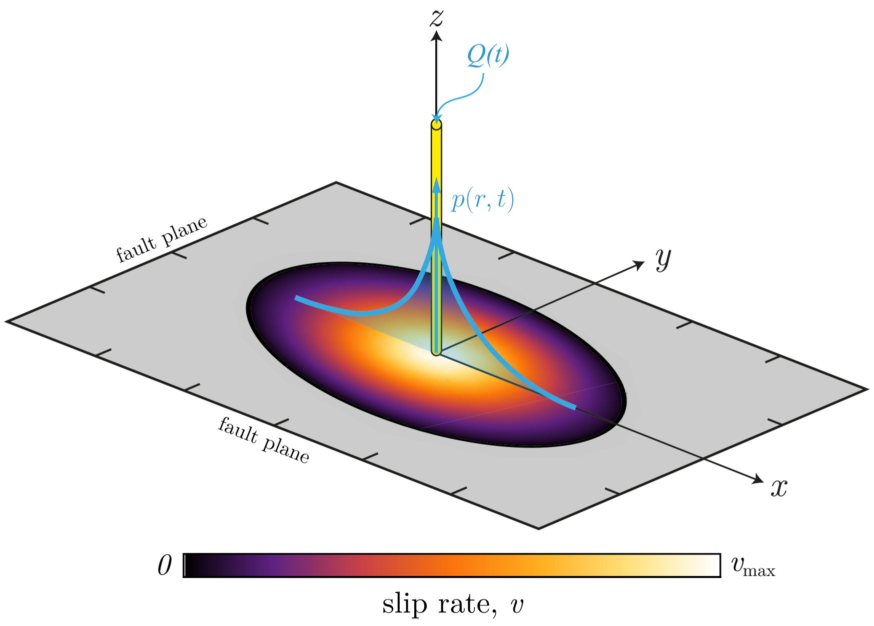
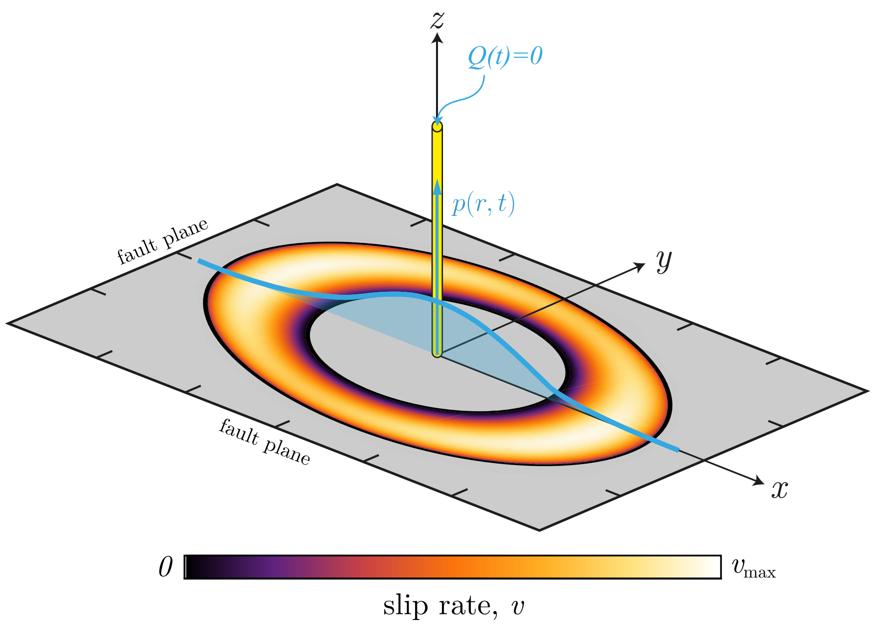
During injection – Crack-like



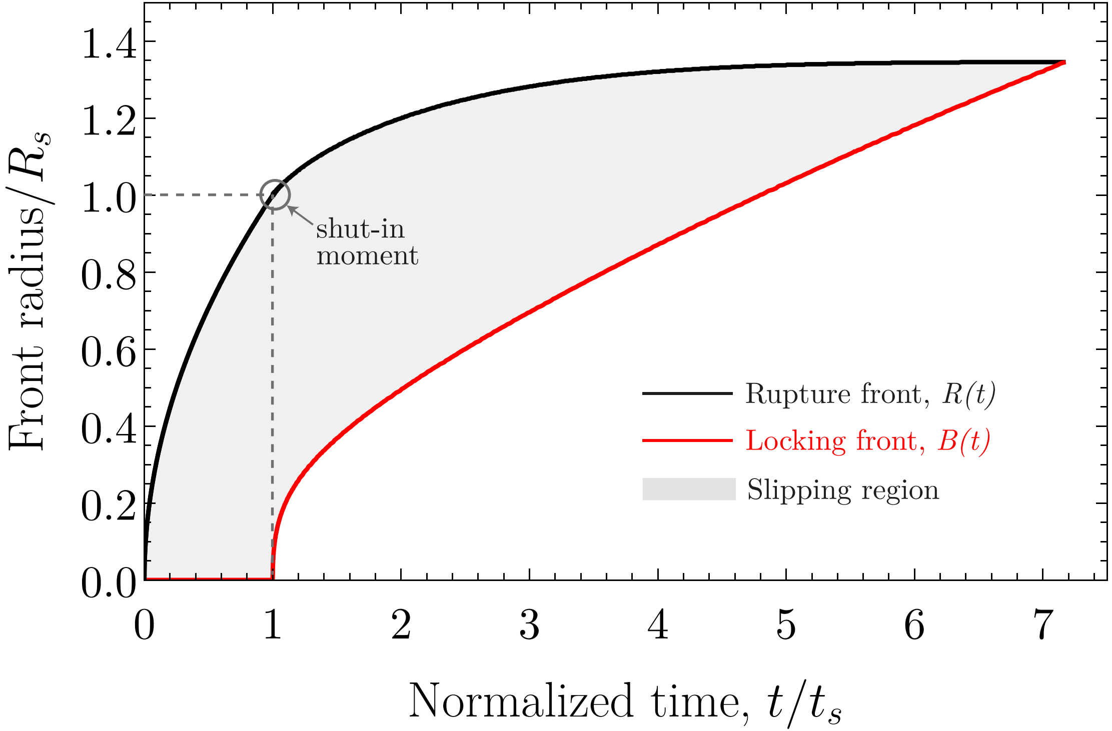
Sáez *et al.*, 2022, JMPS

After injection – Pulse-like

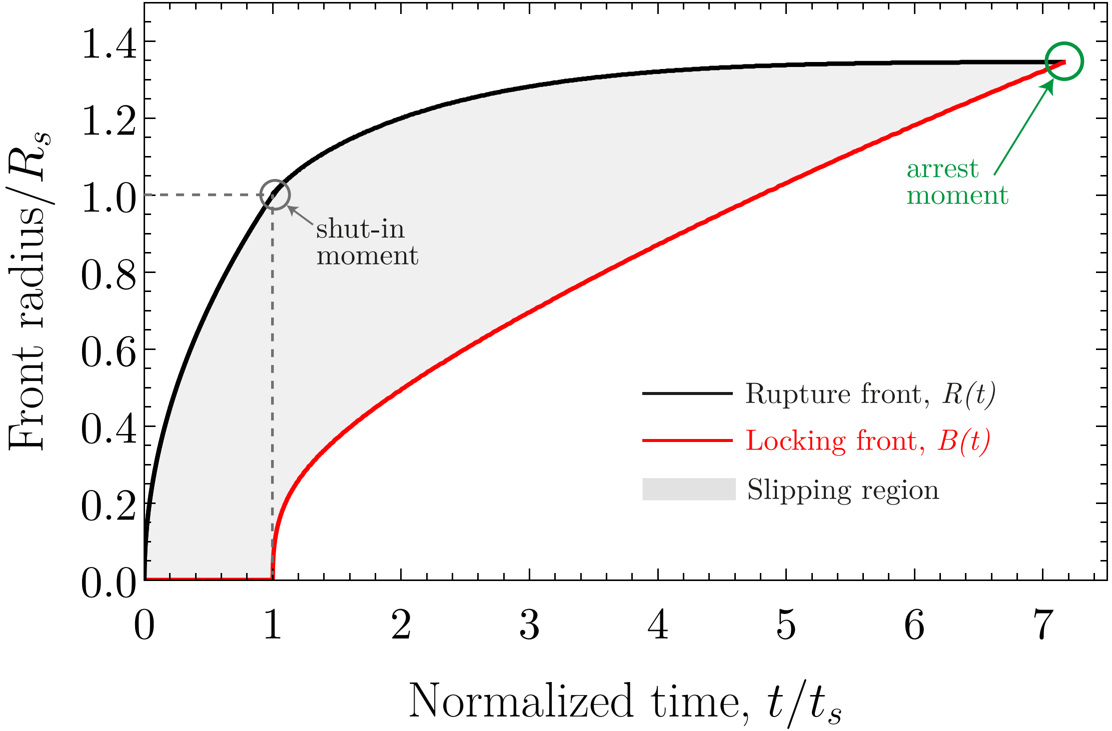


Sáez and Lecampion, 2023, PRSA.

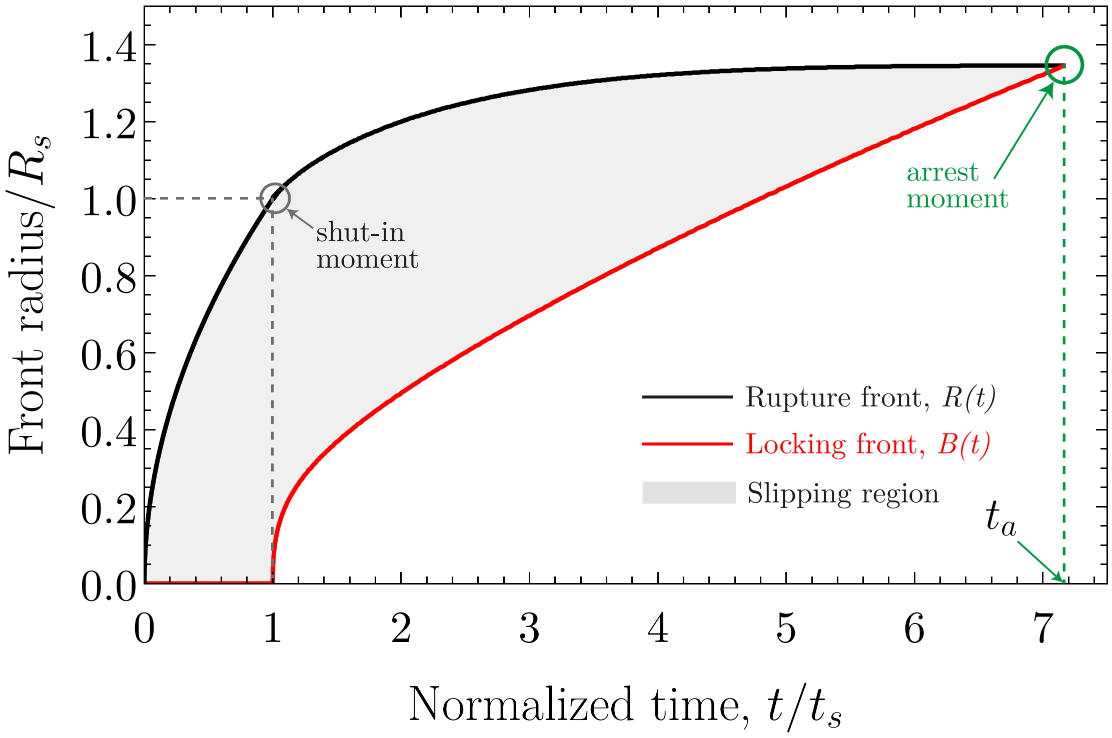
Propagation and arrest of aseismic slip



Propagation and arrest of aseismic slip



Propagation and arrest of aseismic slip



Propagation and arrest of aseismic slip

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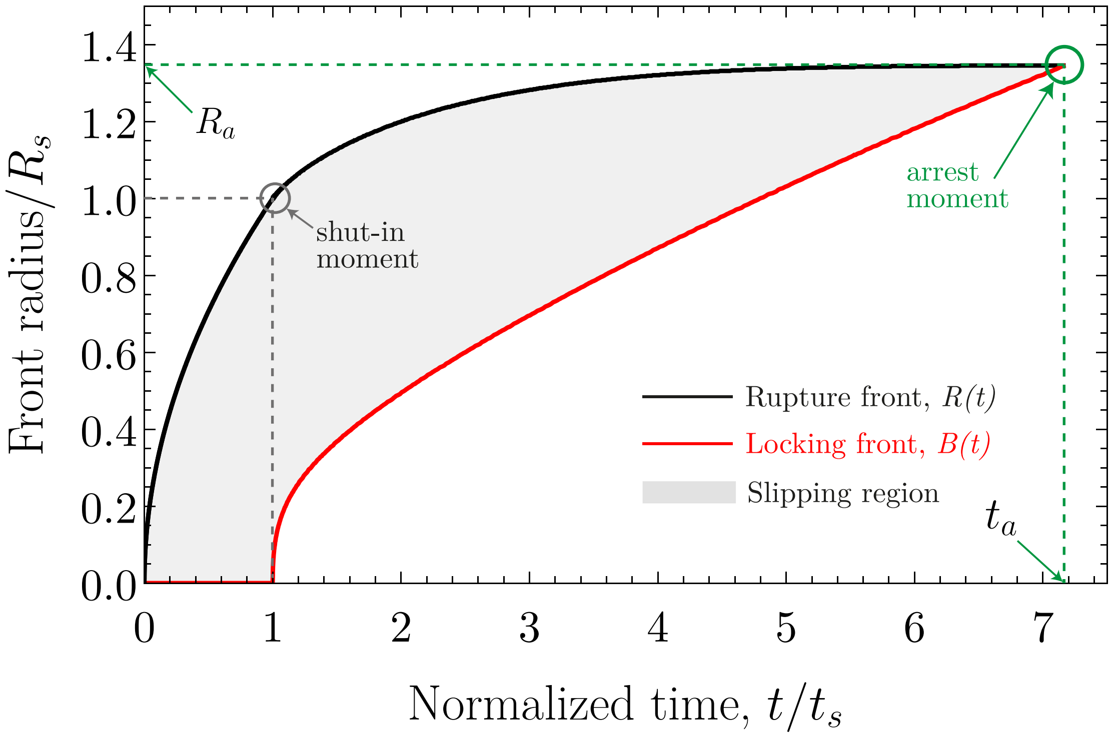

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Arrest time and maximum run-out distance

$$\frac{t_a}{t_s} = g(T)$$

$$\frac{R_a}{R_s} = h(T)$$

Stress-injection parameter T:

(Bhattacharya & Viesca, 2019; Sáez *et al*., 2022)

$$T = \frac{f\sigma_0' - \tau_0}{f\Delta p_*} \equiv \frac{\text{Closeness to failure}}{\propto \text{intensity of fluid injection}}$$

$T \to 0$ — $T \sim 10$

Critically-stressed regime — **Marginally-pressurized** regime

(regimes found first by Garagash & Germanovich, 2012)

Arrest time and maximum run-out distance

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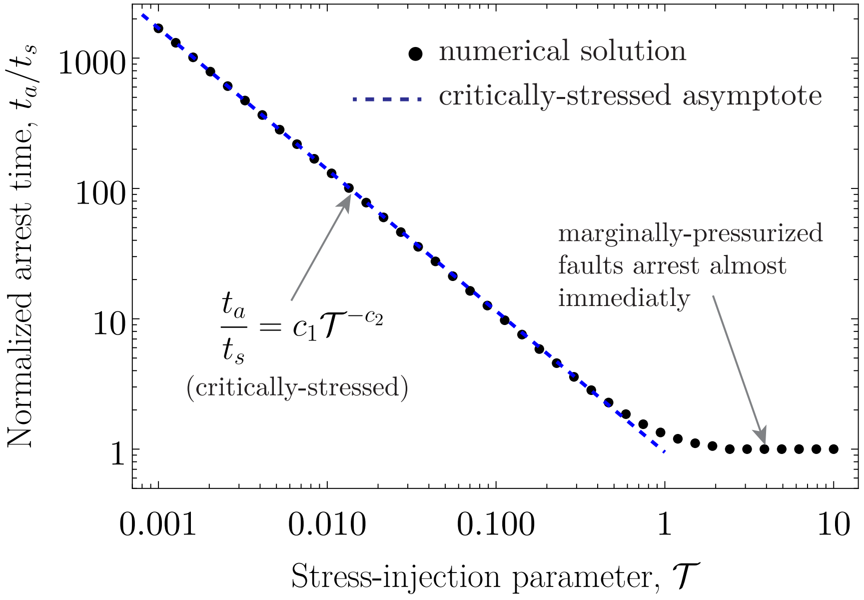
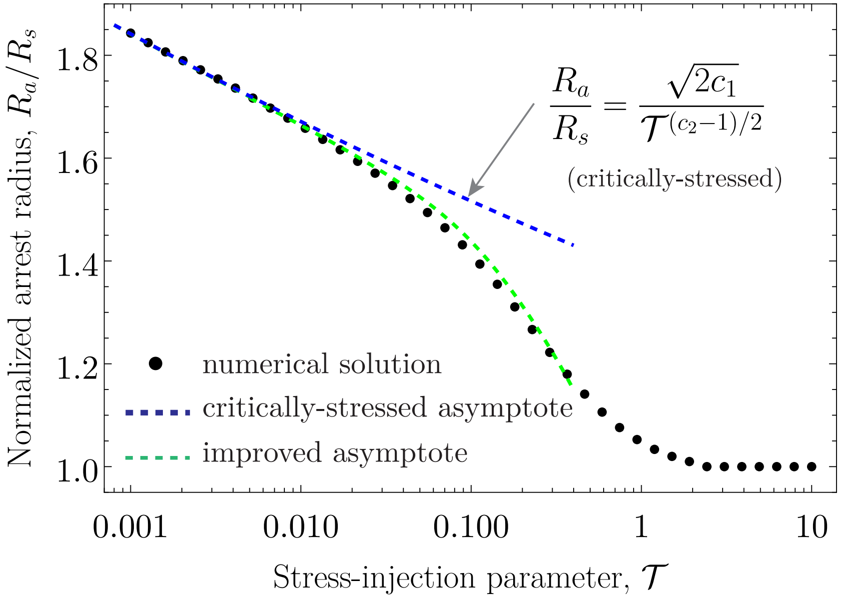
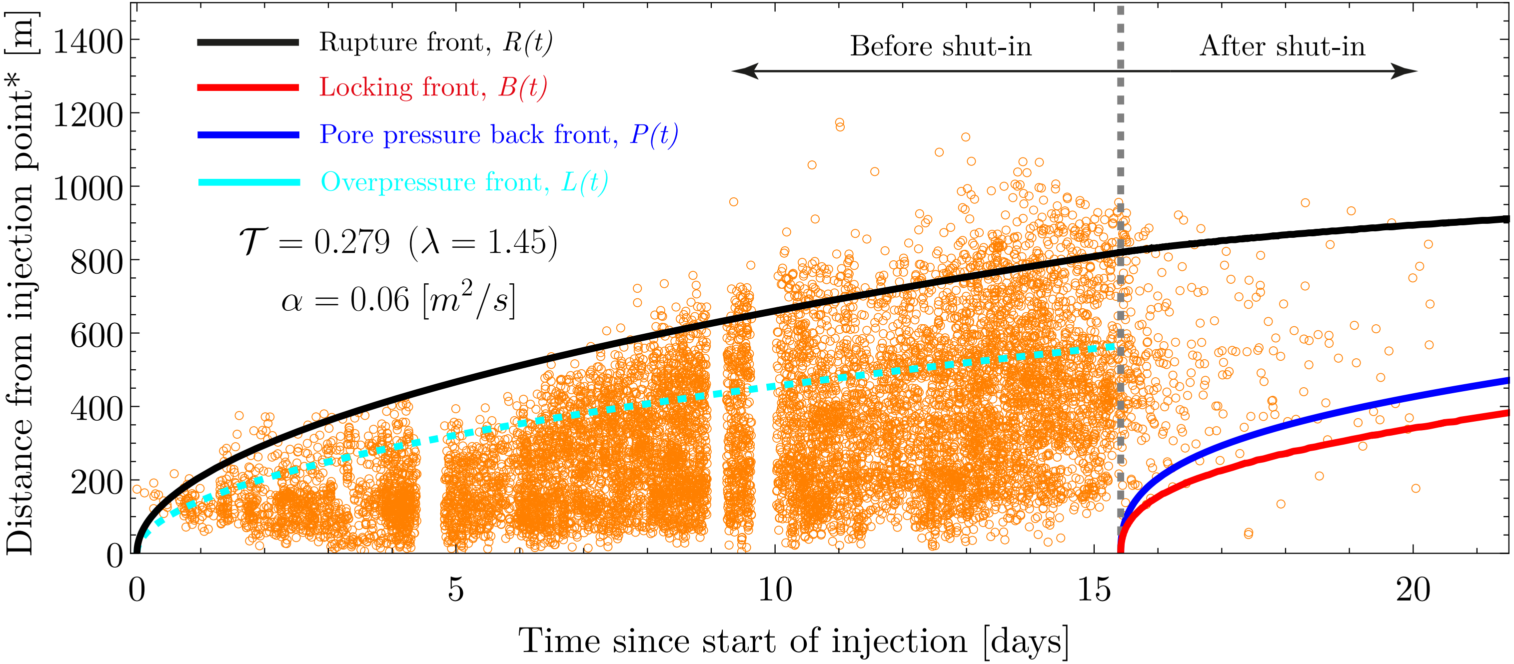




Applications

The 1993 hydraulic stimulation at Soultz, France



The 2013 hydraulic stimulation at Rittershoffen, France

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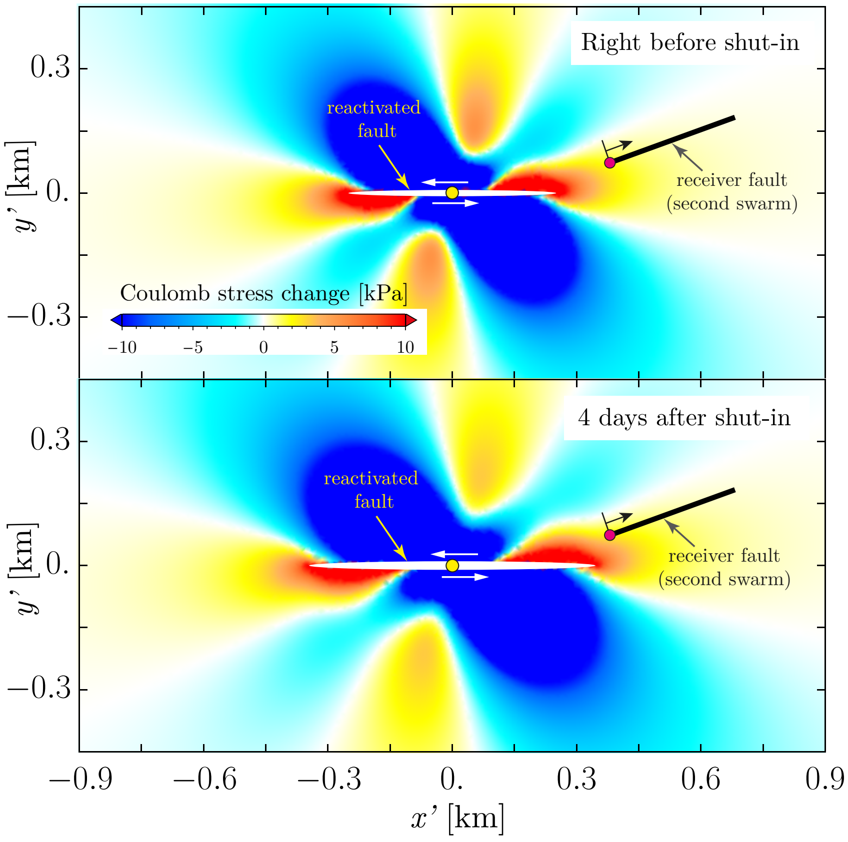

Extraction of fluids

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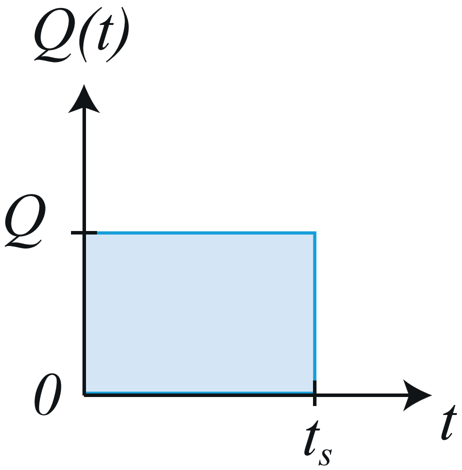
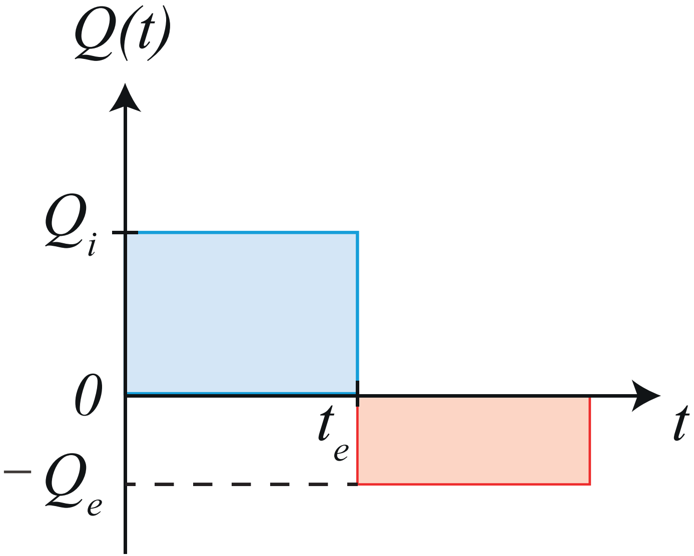


Extraction of fluids



Arrest time and maximum run-out distance

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$$\frac{t_a}{t_e} = g\left(T, \frac{Q_e}{Q_i}\right)$$

$$\frac{R_a}{R_e} = h\left(T, \frac{Q_e}{Q_i}\right)$$

Arrest time

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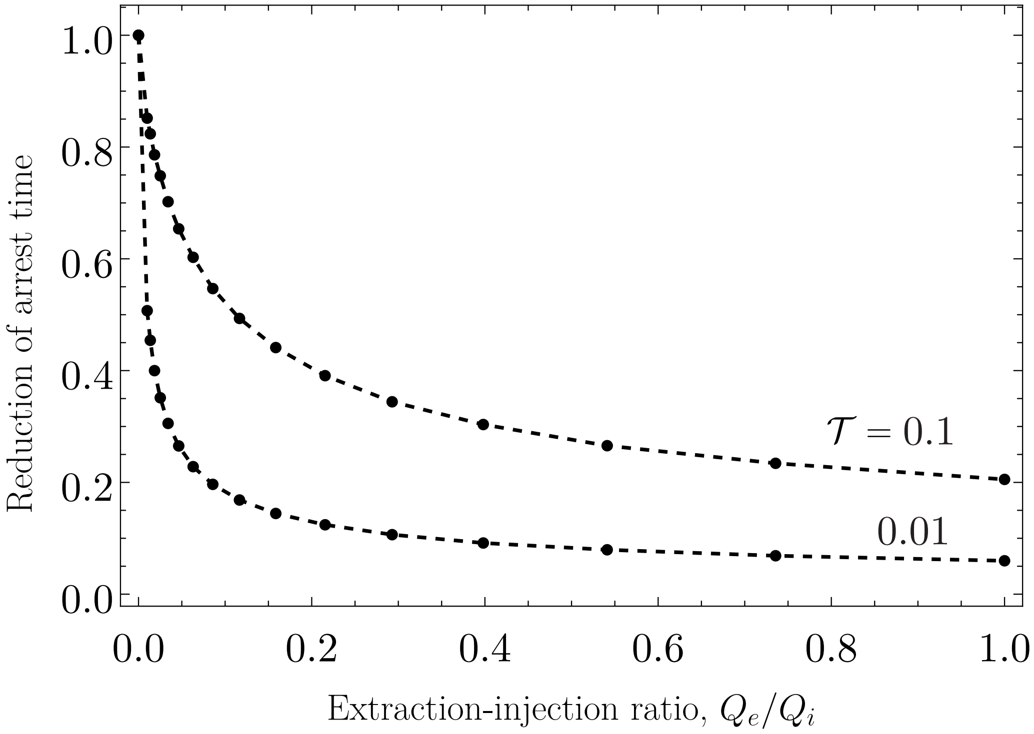
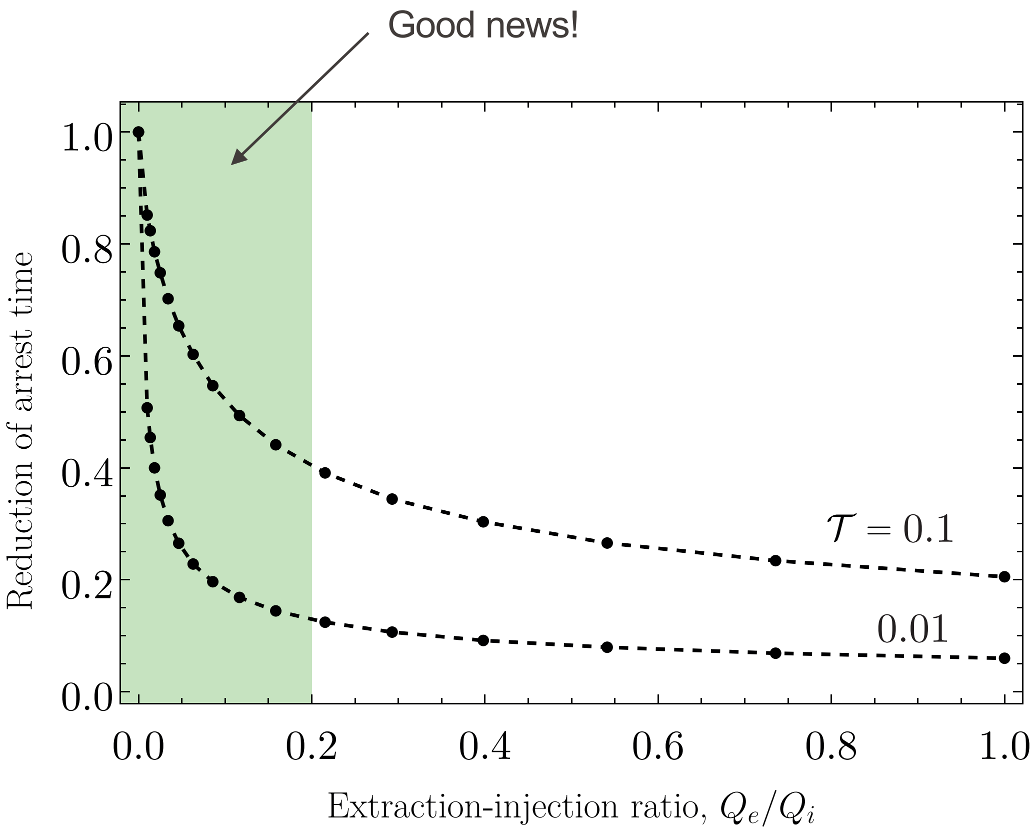
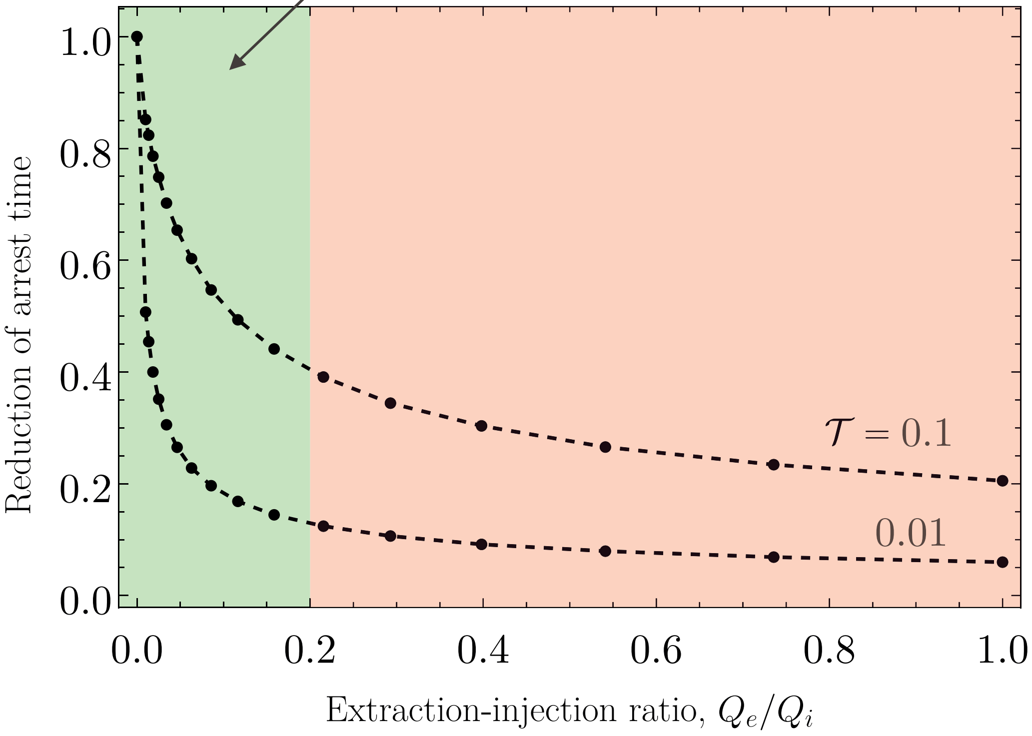


Arrest time


Good news!
1.0
0.8
0.6
0.4
0.2
0.0
Reduction of arrest time
$\mathcal{T} = 0.1$
0.01
0.0
0.2
0.4
0.6
0.8
1.0
Extraction-injection ratio, Q_e/Q_i

Arrest time

Good news!



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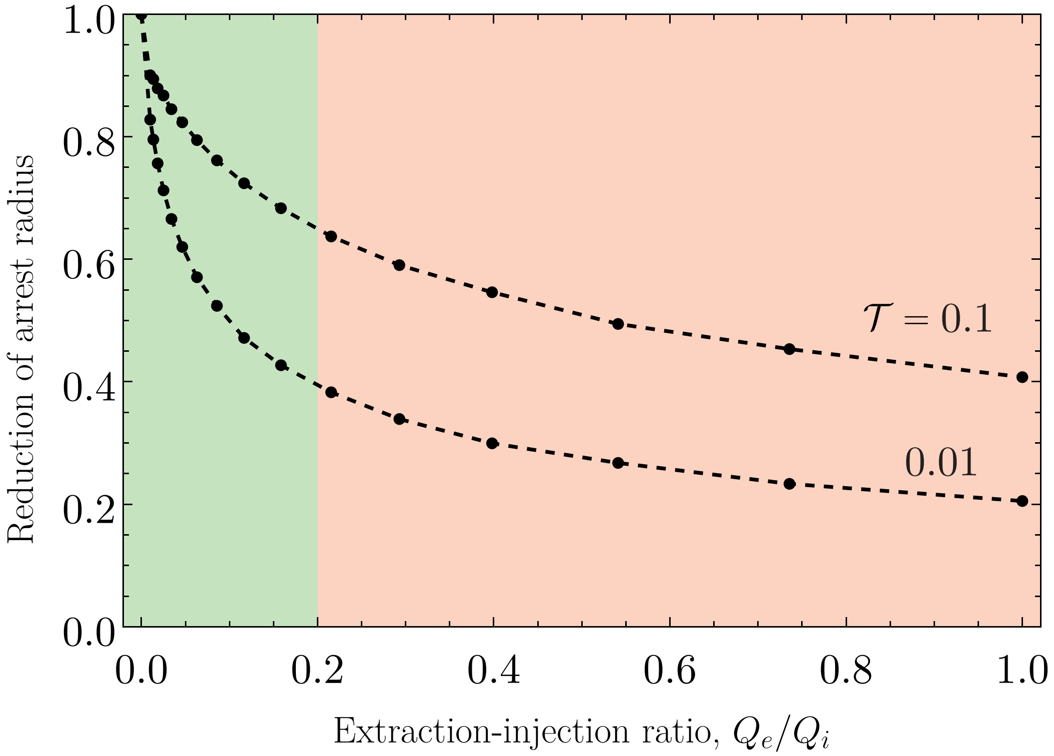
Maximum run-out distance



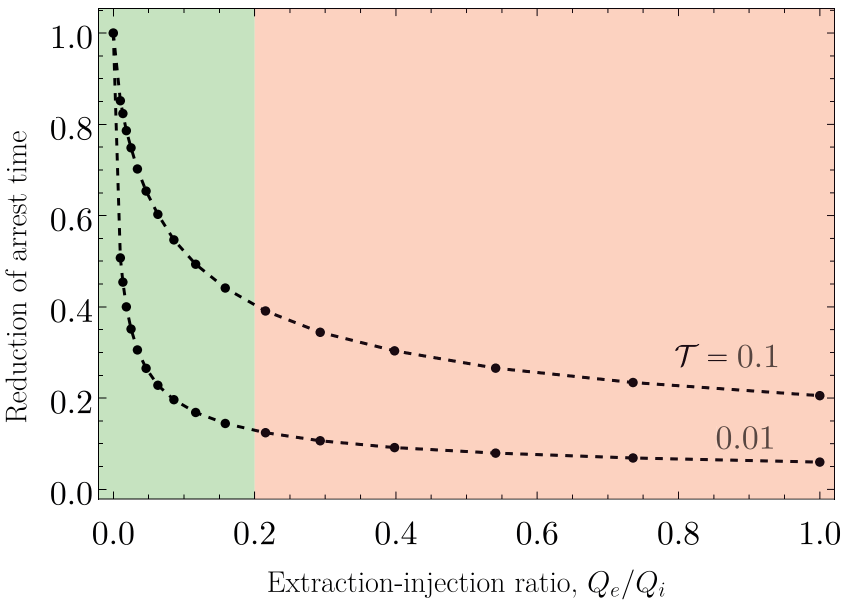
Summary

- A **slip pulse** propagates **after shut-in** and may keep triggering seismicity due to stress transfer.

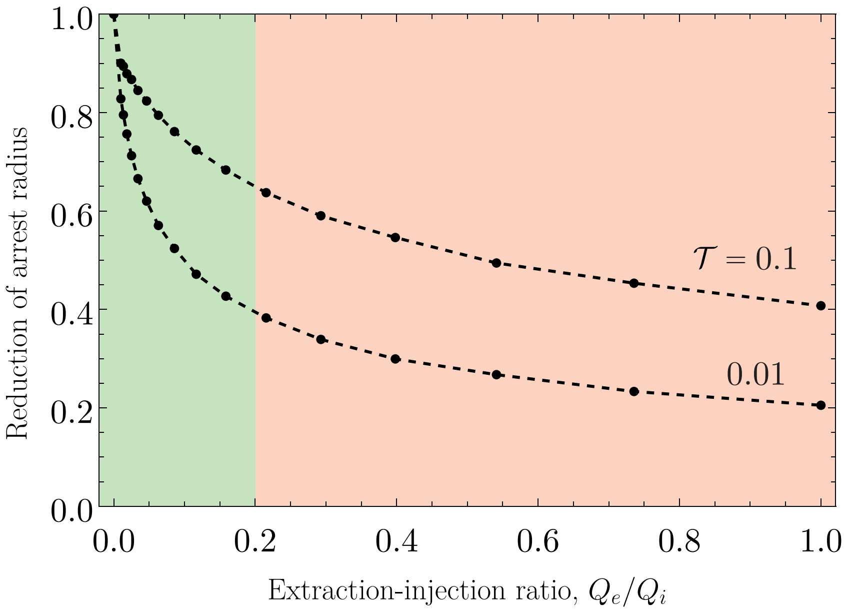
- A **small** amount of **extraction** significantly reduces the time and rock volume exposed to post-injection seismicity.

- There is a **remaining risk that cannot be avoided** even with large rates of extraction.

Thanks!



Reduction of arrest time
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
$\mathcal{T} = 0.1$
0.01
Extraction-injection ratio, Q_e/Q_i



Reduction of arrest radius
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
$\mathcal{T} = 0.1$
0.01
Extraction-injection ratio, Q_e/Q_i