Spatio-temporal patterns of fluid-driven aseismic slip transients: implications for seismic swarms

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GeoEnergyLab

This presentation participates in OSPP

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Outstanding Student & PhD candidate Presentation contest

Background - Motivation

- Common driving mechanisms:
  - Pore pressure diffusion

    (e.g., Parotidis *et al.*, *JGR*, 2005)
  - Aseismic slip

    (e.g., Lohman & McGuire, *JGR*, 2007)

- Evidence for coupled mechanism:

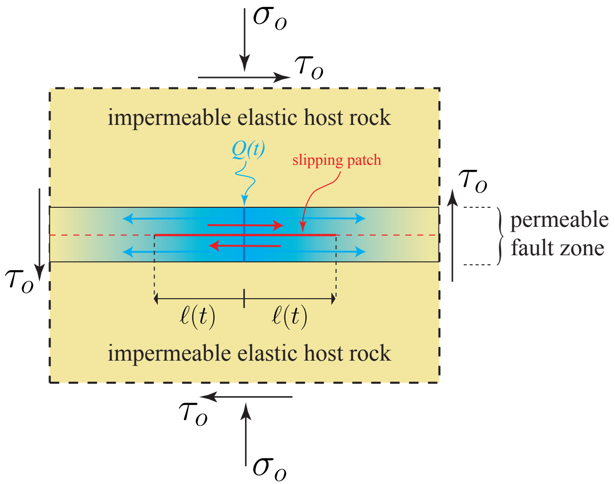
  Pore pressure → Aseismic slip → Seismicity

  (e.g., Bourouis & Bernard, GJI, 2007, Wei et al., EPSL, 2015; Guglielmi et al., *Science*, 2015; Yukutake et al., JGR, 2020)

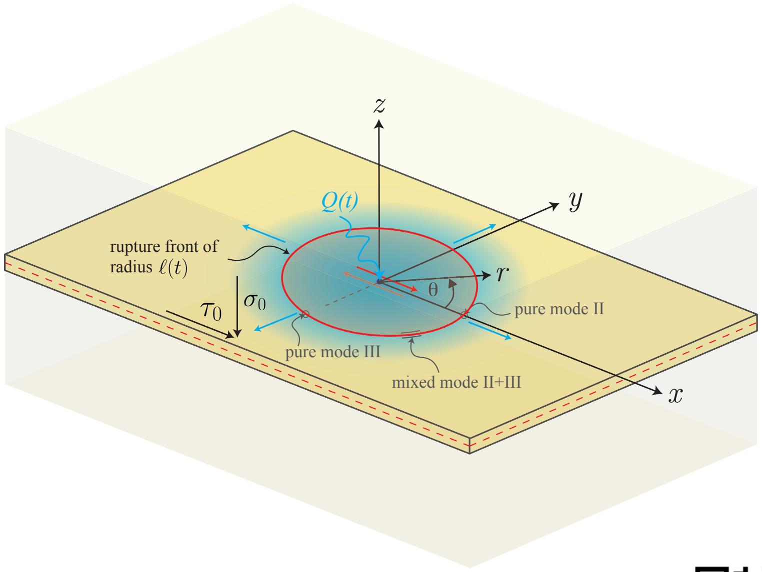
- Spatio-temporal patterns?

2D & 3D physics-based models

- **2D rupture**: Mode II or III shear crack



- **3D rupture**: Mixed-mode (II+III) circular crack



Assumptions:

Constant hydraulic properties, self-similar pore pressure diffusion

EPFL

Energy balance at the rupture front

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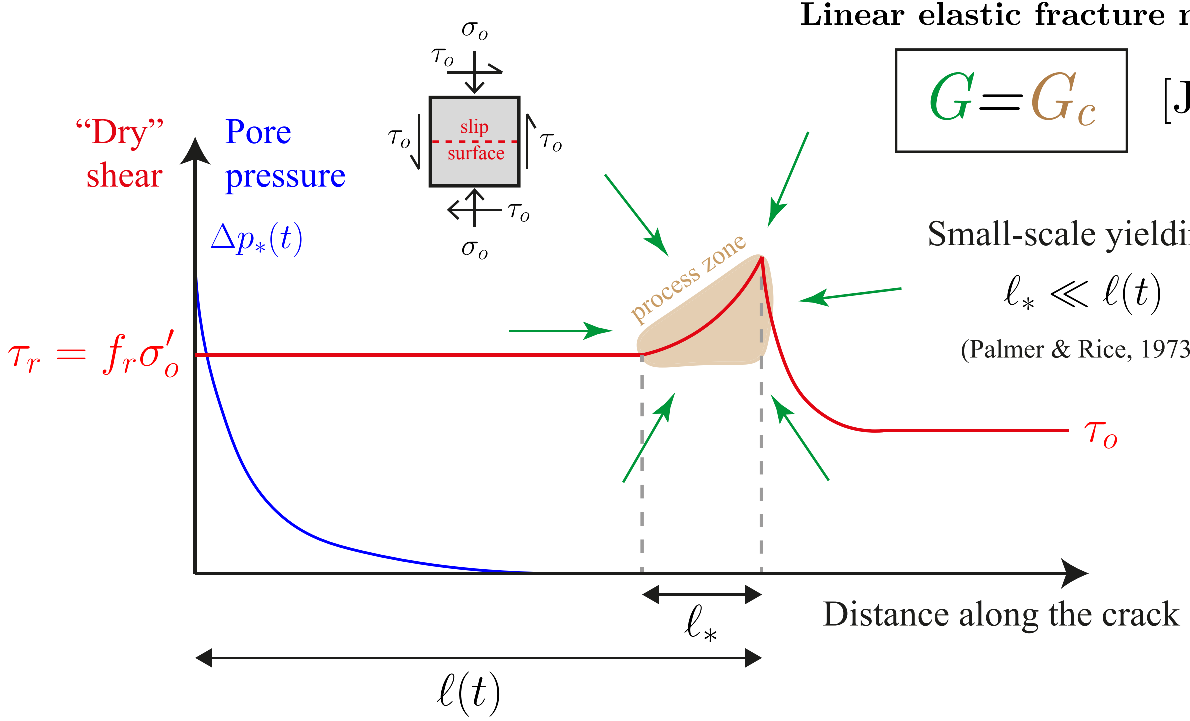

Linear elastic fracture mechanics

$$G = G_c \quad [\mathrm{J/m^2}]$$

Small-scale yielding:

$$\ell_* \ll \ell(t)$$

(Palmer & Rice, 1973)

Assumptions:

Constant frictional fracture energy G_c, constant residual friction

Energy balance at the rupture front

Ultimate regime

$G = G_c \Rightarrow$

Fracture energy term is ultimately **negligible** when:

$t \rightarrow \infty$ and $\ell \rightarrow \infty$

$$f_r \Delta p_* (t) \sqrt{\ell(t)} \int_0^1 \frac{\Pi\left(\ell(t)\eta/\sqrt{4\alpha t}\right)}{\sqrt{1-\eta^2}} \eta^\gamma \mathrm{d}\eta = \delta\left(f_r \sigma'_o - \tau_o\right)\sqrt{\ell(t)} + \frac{\sqrt{\pi}}{2} K_c^*$$

Fluid injection

Pre-stress & residual friction

~~Fracture energy~~

Equation for $\ell(t)$:

$$\int_0^1 \frac{\Pi\left(\frac{\ell(t)}{\sqrt{4\alpha t}}\eta\right)}{\sqrt{1-\eta^2}}\eta^\gamma \mathrm{d}\eta = \delta\frac{(f_r\sigma_0' - \tau_0)}{f_r\Delta p_*(t)}$$

$$\Longrightarrow F(\ell, t; p_1, \dots) = 0$$

Family of solutions

Table 1: Temporal patterns of $\ell(t)$ for different modes of propagation and types of fluid source.

Type of fluid source	2D - Mode II or III	3D - Mixed mode II+III
Constant injection rate	$\ell(t) \propto (t - \sqrt{t})$ at early times (1) $\ell(t) \propto t$ at large times (1)	$\ell(t) \propto \sqrt{t}$ (1)
Linearly increasing rate	$\ell(t) \propto (t^{3/2} - 1)/t$ at early times (2) $\ell(t) \propto t^2$ at large times (2)	$\ell(t) \propto \sqrt{t}e^{-t}$ at early times (2) $\ell(t) \propto t$ at large times (2)
Constant pressure	$\ell(t) \propto \sqrt{t}$ (3)	$\ell(t) \propto t^\beta$ (1)(4)

Notes: Derived in (1) Sáez, Lecampion, Bhattacharya & Viesca, *JMPS*, 2022.
(2) Sáez & Lecampion (in preparation). (3) Bhattacharya & Viesca, *Science*, 2019.
(4) β between 0 and 1/2.

EPFL

Example of application – Borehole fluid injection

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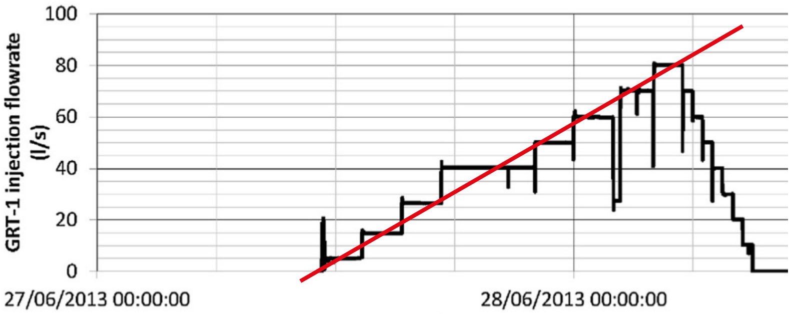
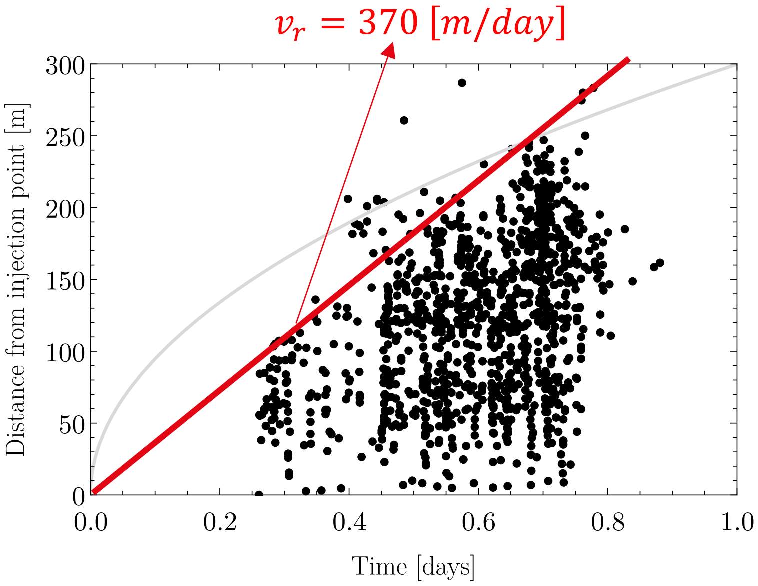
$$\ell(t) = v_r t, \text{ with } v_r = \sqrt{\frac{f_r \alpha \dot{Q} \eta / 4\pi k w}{f_r \sigma'_0 - \tau_0}}$$



Baujard et al., *Geothermics*, 2017



Data from Lengliné et al., *GJI*, 2017

Diffusive seismic swarms

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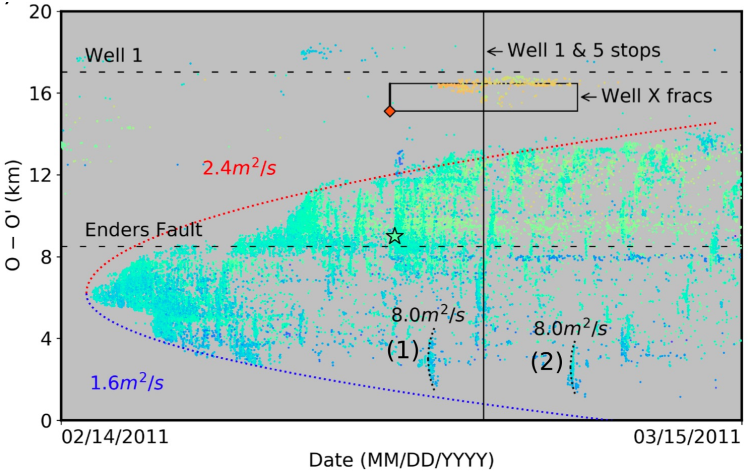

Park et al., *GRL*, 2020

$$\ell(t) = \sqrt{\alpha_{slip} t}$$

$$\boxed{\alpha_{slip} = \lambda^2 \alpha_h}$$

With $\lambda = \sqrt{\frac{1}{8\pi} \frac{f_r Q\eta/kw}{f_r\sigma_0' - \tau_0}} \gg 1$

(for critically-stressed faults)

Reconciling high diffusivities!

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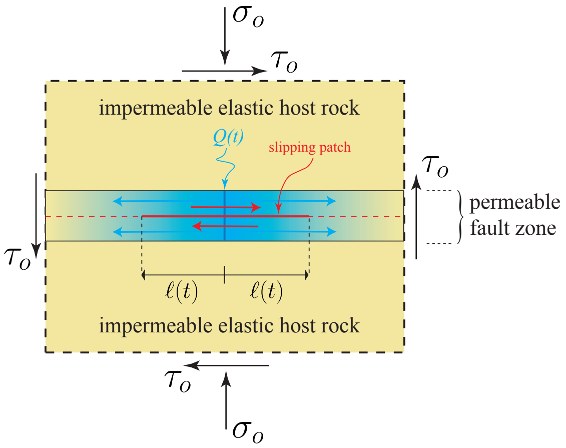
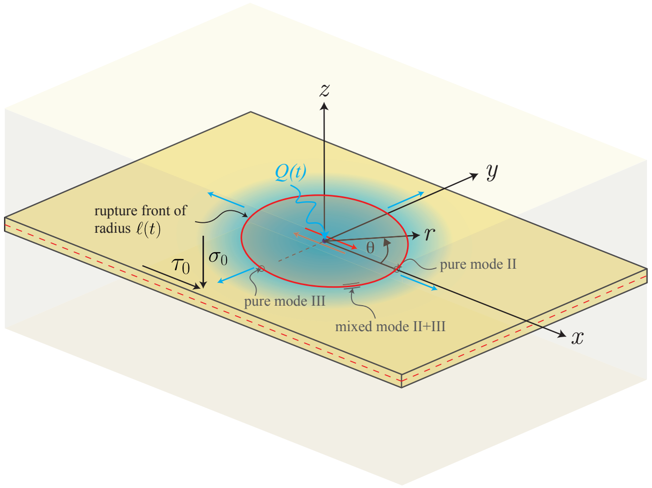
Summary

- Family of **physics-based solutions** for fluid-driven **aseismic slip** fronts $\ell(t)$
- Many **different** spatio-temporal **patterns** may occur depending on **fluid source** and **mode of sliding**, among others.
- For instance,
  - We used a seismic swarm of **known fluid source** to show under which **conditions** a swarm may be expected to migrate **linearly with time** if dominated by aseismic slip.
  - We speculate that some **diffusive seismic swarms** ($\sqrt{t}$) may be driven by **diffusive aseismic slip** in 3D, which **reconciles** relatively **high diffusivities** inferred in many cases ($\alpha_{slip} = \lambda^2 \alpha_h$, with $\lambda \gg 1$).
- Finally, we expect our solutions to provide a **simple means** to **interpret observations** of seismic swarms, in the framework of coupled fluid flow and aseismic slip processes.

Thank you!





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