S25C-0243: A Scaling Relation Between the Moment Release due to Aseismic Motion and the Injected Volume of Fluid

EPFL

Alexis Sáez[1], Brice Lecampion[1]

GeoEnergyLab

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

[1]Geo-Energy Laboratory-Gaznat Chair on Geo-Energy, Ecole Polytechique Fédérale de Lausanne (EPFL), Switzerland.

1. Motivation

Constraining the moment release associated with injection-induced fault slip is of first importance to assess the seismic hazard of subsurface fluid injections in the geo-energy industry. Experimental and observational studies suggest that a significant part of the moment release during injections may be due to aseismic motion. Current models of injection-induced aseismic moment do not incorporate fault rupture mechanics. Here, we derive a physics-based scaling relation between the aseismic moment M_0 and a key operational parameter, the injected volume of fluid V.

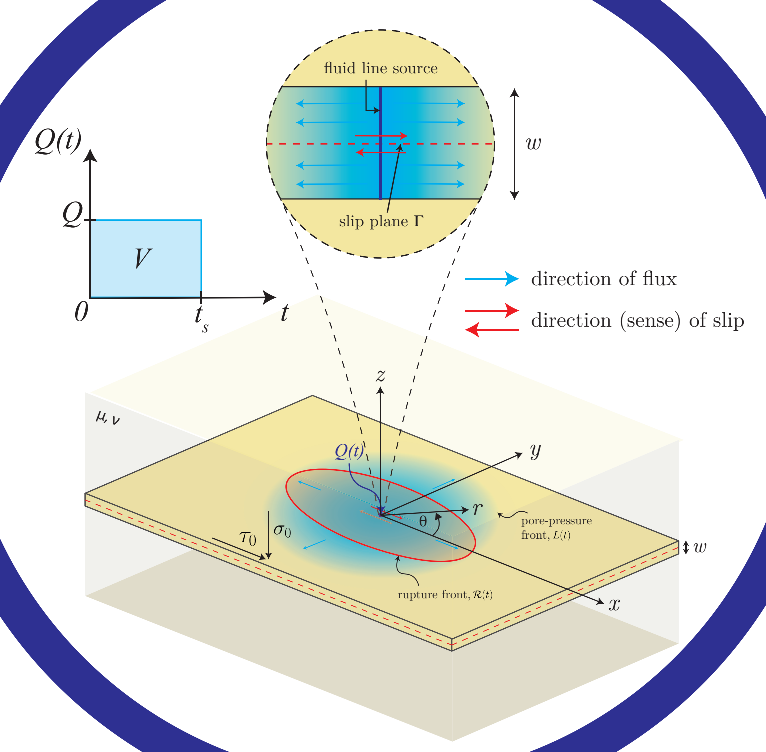
2. Model

We consider the nucleation, propagation and arrest of a quasi-static stable frictional shear crack (modes II+III) driven by a pulse of injection.

Our model has the following **assumptions**:

- Planar fault in an unbounded linearly elastic solid.
- Slip plane slides with a constant friction coefficient.
- Fault zone has a constant permeability and no leak-off.
- Line-fluid source at constant injection rate followed by shut-in.
- Uniform in-situ stress tensor and pore pressure field.

We solve the problem via a fully-implicit boundary-element-based method with elasto-plastic-like interfacial constitutive law.



3. Stress-injection parameter

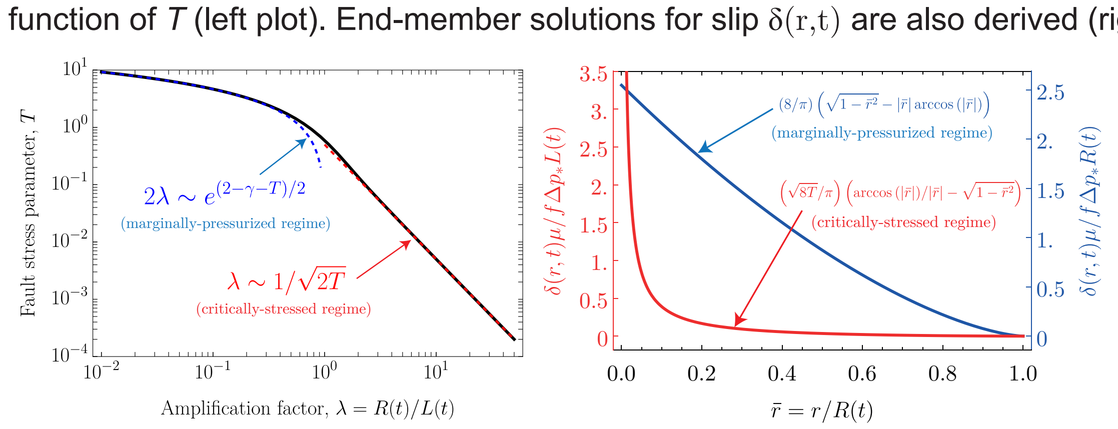
Our model is governed by essentially one non-dimensional parameter:

$$T = \frac{f\sigma_0' - \tau_0}{f\Delta p_*} \text{, with } \Delta p_* = \frac{Q\eta}{4\pi kw}$$

where $f\sigma_0' - \tau_0$ is the the "distance" to failure under ambient conditions (initial shear strength minus initial shear stress), and $f\Delta p_*$ is the strength of the injection, with Q the injection rate, η the fluid dynamic viscosity, and kw the fault hydraulic transmissivity.

4. Solution before shut-in

Here, fault slip is self-similar (and diffusive). The rupture radius evolves as $R(t) = \lambda L(t)$ where $L(t) = \sqrt{4\alpha t}$ is the nominal position of the pore-pressure front (with α the fault hydraulic diffusivity) and λ is the so-called amplification factor, known analytically as function of T (left plot). End-member solutions for slip δ(r,t) are also derived (right plot).



Main Findings:

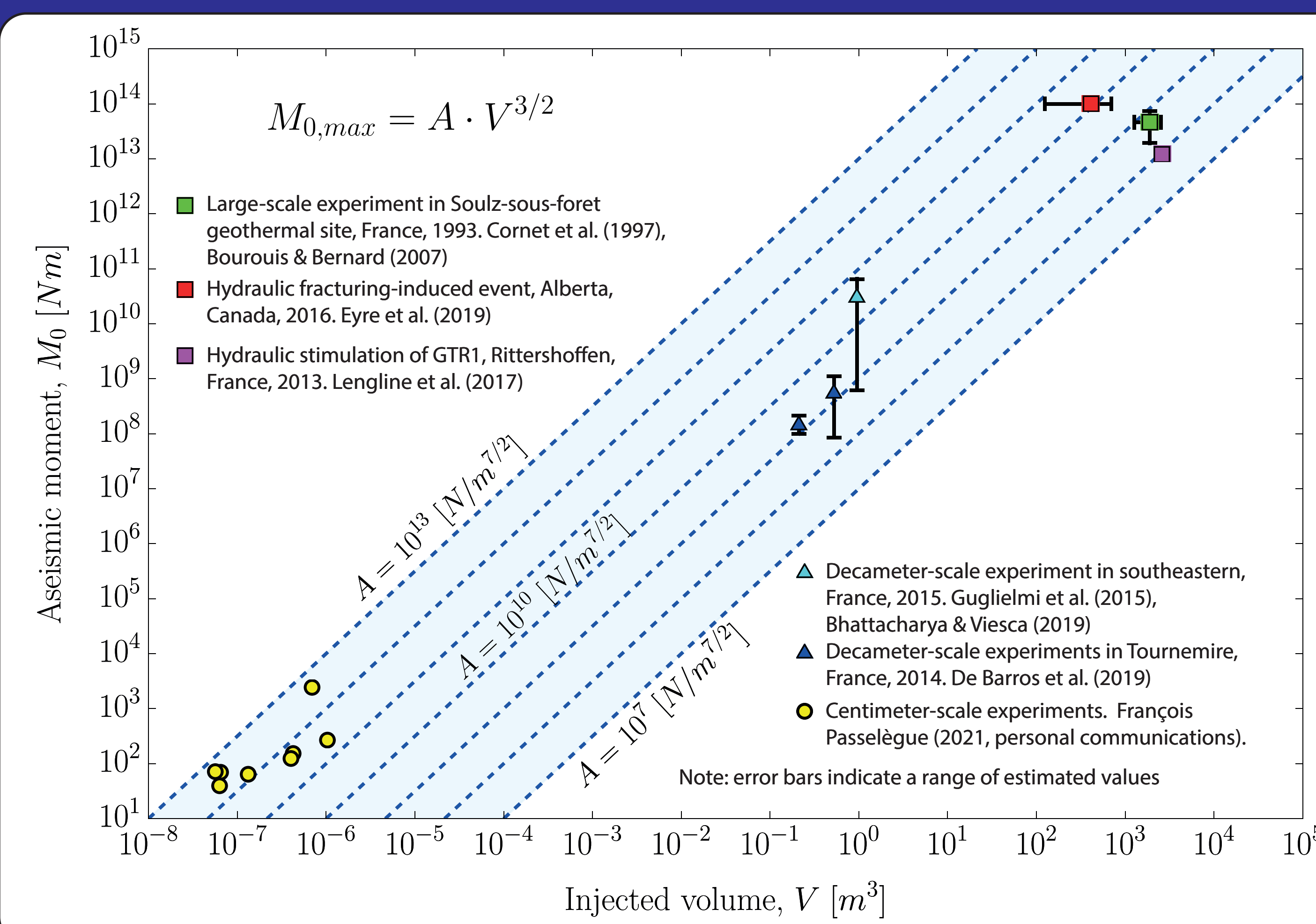
- Physics-based estimate of the radius at arrest of injection-induced aseismic ruptures.
- Upper bound for the aseismic moment:

$$M_{0,max} = A \cdot V^{3/2}$$

the pre-factor A depends mainly on the pre-injection stress state and fault hydraulic properties.

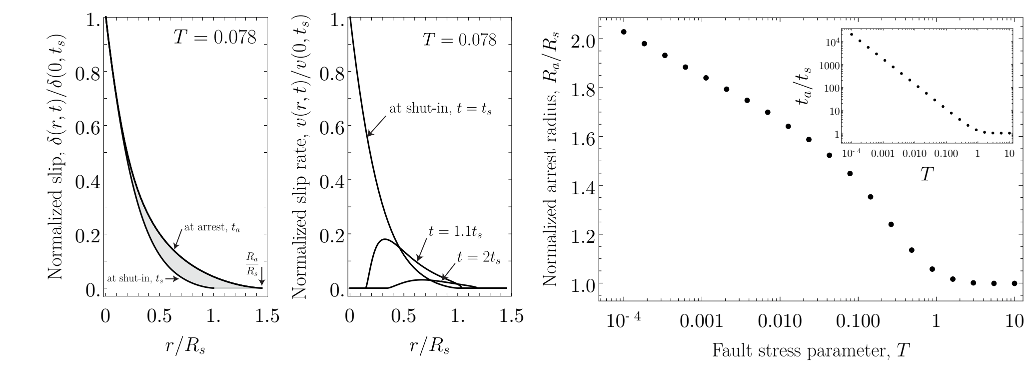
- Predictions are in good agreement with estimates of fluid injections from laboratory experiments to industrial applications.

Comparison to fluid injection cases



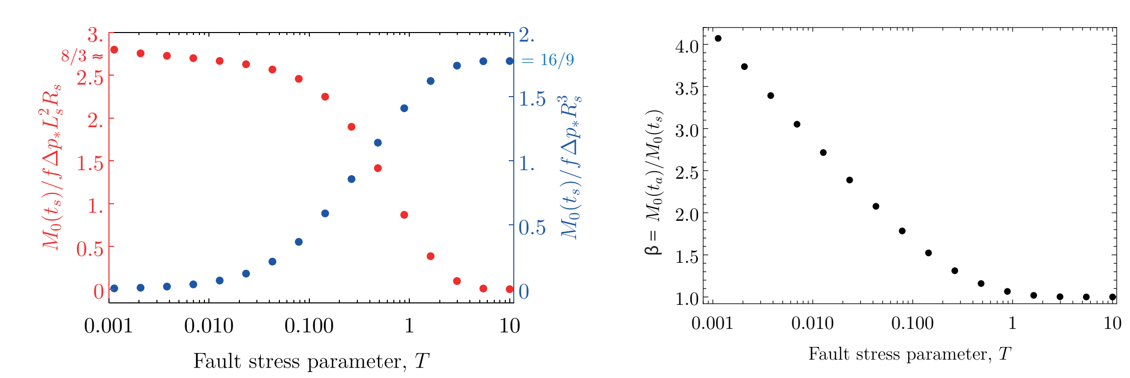
5. Solution after shut-in

After shut-in, self-similarity is broken. Moreover, fault slip undergoes a transition from crack-like to pulse-like rupture (left plots). The more critically stressed the fault is, the further the rupture propagates before arresting. We determine the arrest time t_a and the arrest radius of the rupture R_a, as function of the fault stress parameter T (right plot).



6. Aseismic moment

At the shut-in time, the moment release is calculated analytically for the limiting cases of critically-stressed (T small) and marginally-pressurized faults (T large), and numerically for intermediate cases (left plot). The contribution of the shut-in stage to the aseimic moment is computed numerically as function of T (right plot).



7. Pre-factor A

The pre-factor A is given by: $A = \frac{\beta\,(f\alpha\eta/kw)^{3/2}}{(f\sigma_0' - \tau_0)^{1/2}}$

where f is the constant friction coefficient, α is the fault hydraulic diffusivity, η is the fluid dynamic viscosity, kw is the fault hydraulic transmissivity, σ'_0 is the initial effective normal stress, τ_0 is the initial shear, and β is a factor of order one that quantifies the contribution of the shut-in stage (right plot, previous section).

References

Sáez, A., Lecampion, B., Bhattacharya, P., Viesca, R.C. (2021), Three-dimensional fluid-driven stable frictional ruptures. Manuscript submitted for publication.

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