3D Modeling of fluid-induced seismicity on fault with heterogeneous frictional asperities

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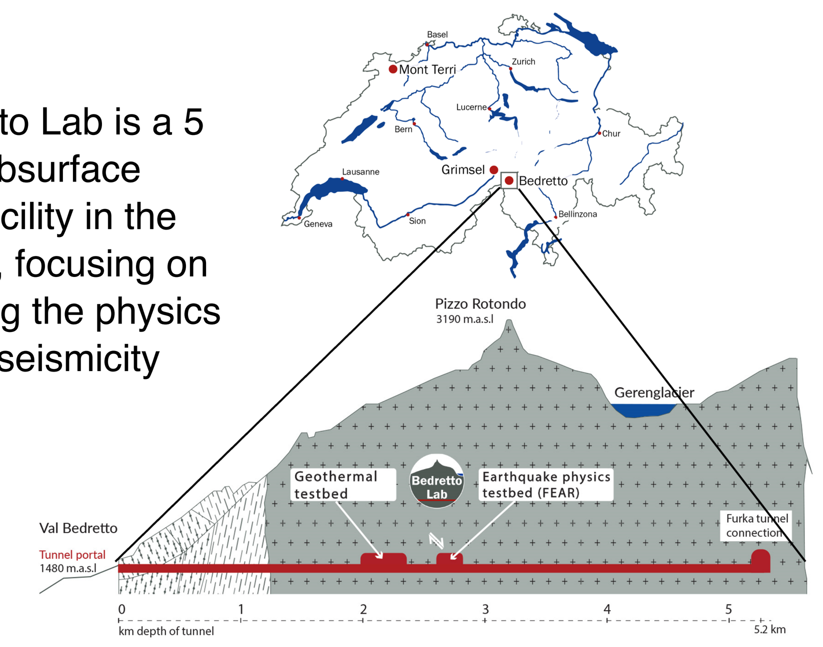
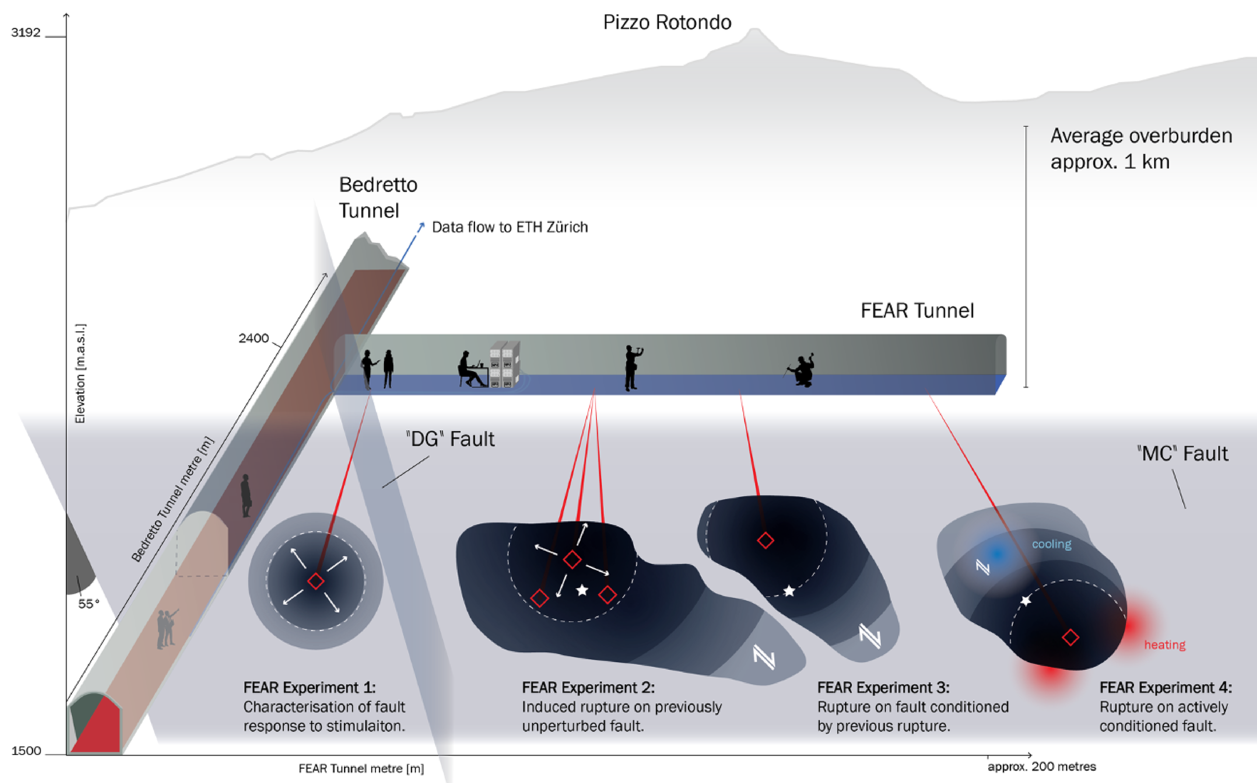
Introduction

Bedretto Underground Laboratory for Geosciences and Geoenergies

The Bedretto Lab is a 5 km-long subsurface research facility in the Swiss Alps, focusing on investigating the physics of induced seismicity





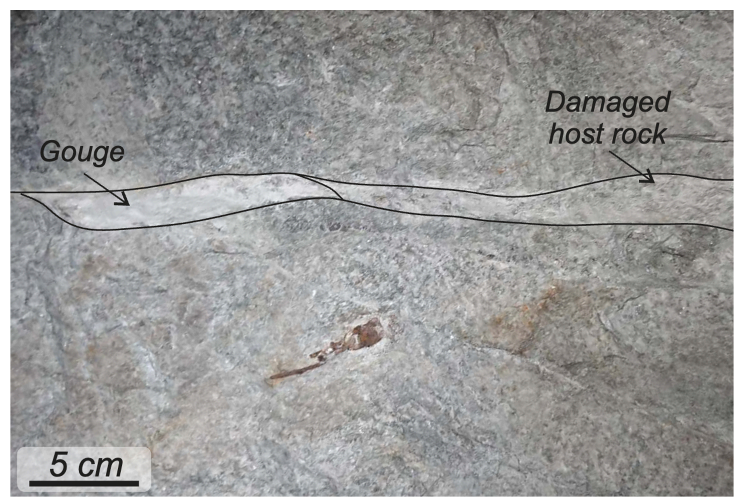
Earthquake physics testbed (FEAR)[1]

- **Objective:** Conduct controlled rupture experiments on ~50 m fault surfaces, generating events in the magnitude range M_w −2 to 1. This scale bridges laboratory studies, previous deep experiments, and natural earthquakes
- **Monitoring:** Deploy multi-disciplinary, next-generation sensors in boreholes very near the future rupture planes
- **Simulation:** Precondition the stress state on the target fault
- **Outcome:** Establish a data stream to ETH, including dense-seismicity, fluid flow measurement, and deformation data

Geometry of the target "MC" fault[1]

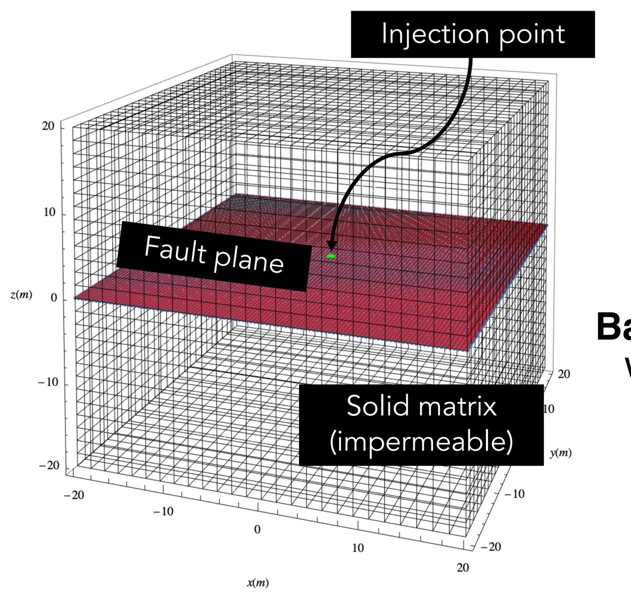
Gouge
Velocity-strengthening (VS) friction

Bare rock: granite
Velocity-weakening (VW) friction



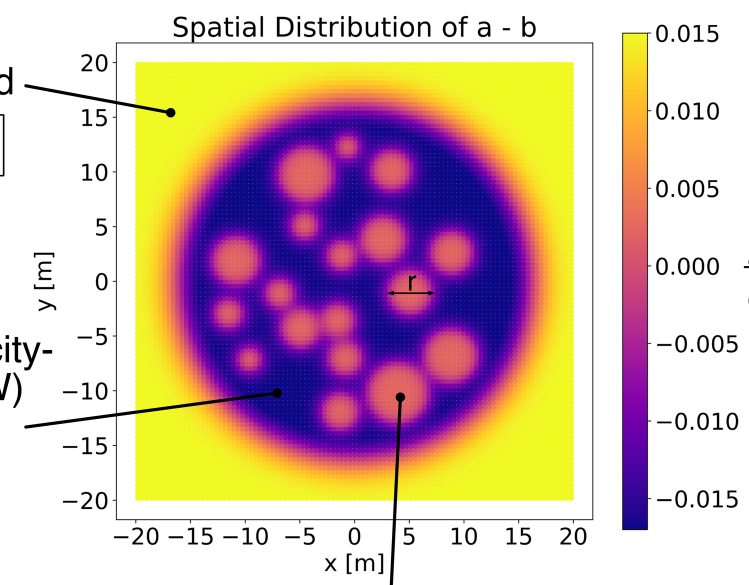
Model setup

We use numerical code **HydroMech3D**[2], a quasi-dynamic fluid-injection model, which incorporates a Boundary Element Method (BEM) and invariant rate-and-state-friction law.



VS background
a_{vs}, b_{vs}, l_{vs}

Bare rock: velocity-weakening (VW) region
a_{vw}, b_{vw}, l_{vw}



Gouge: velocity-strengthening (VS) patch
a_{patch}, b_{patch}, l_{patch}, r_{patch}, A_{patch}

Parameter	Symbol	Value
Length in x direction	L_x	20 m
Length in y direction	L_y	20 m
Resolution in x direction	d_x	0.2 m
Resolution in y direction	d_y	0.2 m
Shear modulus	μ	30 GPa
Total pressure (normal stress)	σ	22 MPa
Fluid pressure	p^f	6.8 MPa
Effective normal stress	σ_{eff}	15.2 MPa
Solid density	ρ^s	3000 kg/m^3
Fluid density	ρ^f	1000 kg/m^3
Solid compressibility	β^s	2.5×10^{-11} Pa^{-1}
Fluid compressibility	β^f	4×10^{-10} Pa^{-1}
Solid viscosity	η^s	10^{25} Pa·s
Fluid viscosity	η^f	10^{-3} Pa·s
Porosity	ϕ	1%
Initial reference permeability	k^*	10^{-14} m^2
RSF Direct parameter	$a_{vw}, a_{vs}, a_{patch}$	0.001, 0.025. 0.01
RSF Evolutionary parameter	$b_{vw}, b_{vs}, b_{patch}$	0.018, 0.01, 0.0075
RSF weakening slip parameter	$l_{vw}, l_{vs}, l_{patch}$	2e-5, 1e-5, 5e-5
State variable	Θ	1e5
Reference friction	f_0	0.6
Injection rate	Q	0.2 kg/s

Rate and state friction

$$\tau_s = f\,\sigma_{\text{eff}} = \left[f_0 + a\,ln\left(\frac{V}{V_0}\right) + b\,ln\left(\frac{\Theta V_0}{L}\right) \right] (\sigma - p^f)$$

Fluid mass conservation

$$\dot{p} = \frac{k}{\eta\beta}\nabla^2 p + \frac{Q}{b\beta}$$

The model geometry is based on the target MC fault, where patches of fault gouge (velocity-strengthening, VS) are embedded within a granite host rock (velocity-weakening, VW). All fault parameters used in this study—including frictional properties, in-situ stress state, and hydraulic parameters—are directly constrained by measurements on the MC fault.

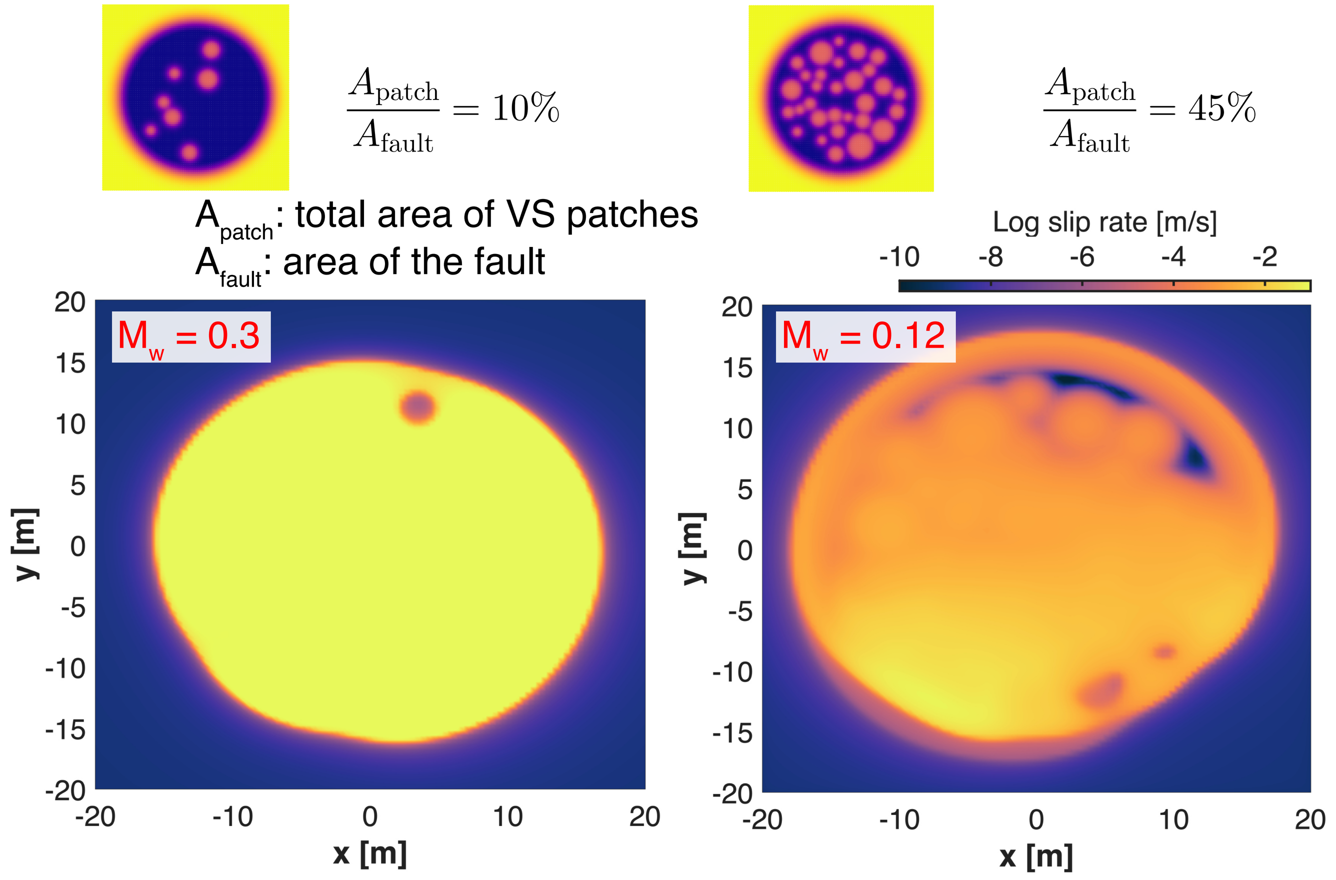
Results

Area of VS patches

$$\frac{A_{\text{patch}}}{A_{\text{fault}}} = 10\%$$

$$\frac{A_{\text{patch}}}{A_{\text{fault}}} = 45\%$$

A_{patch}: total area of VS patches
A_{fault}: area of the fault

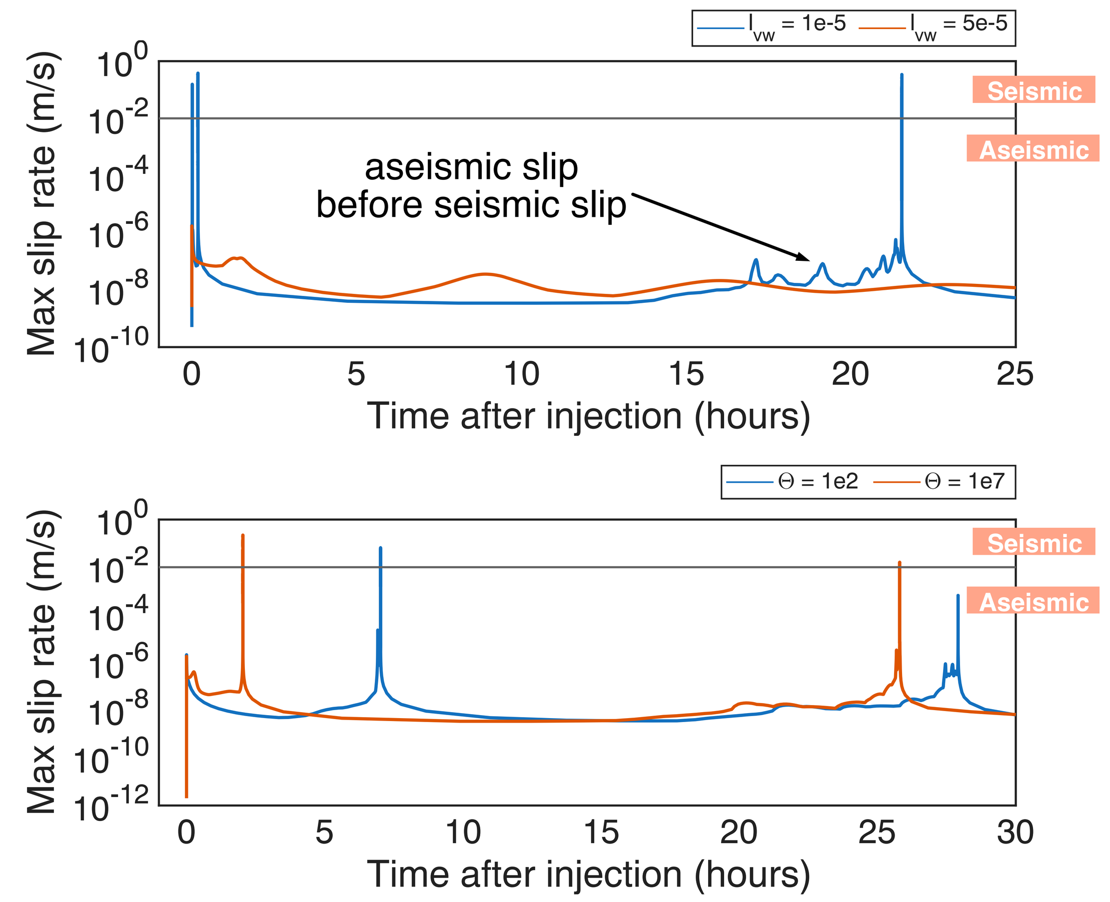


Higher percentage of VS patches leads to smaller magnitude (~0.12), and lower percentage results in larger magnitude (~0.3)

Nucleation size[3]

$$h^* = \frac{2\,\mu\,b\,l}{\pi\,(b-a)^2\,p_{\text{eff}}}$$

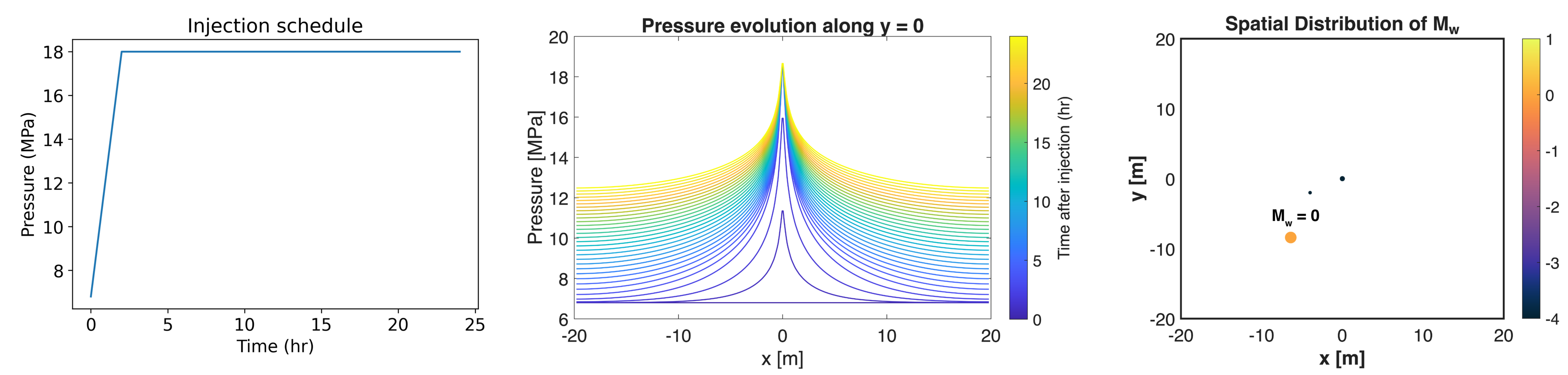
Frictional parameters



Small l_{vw} and large θ result in higher slip rate and generate more seismic slip

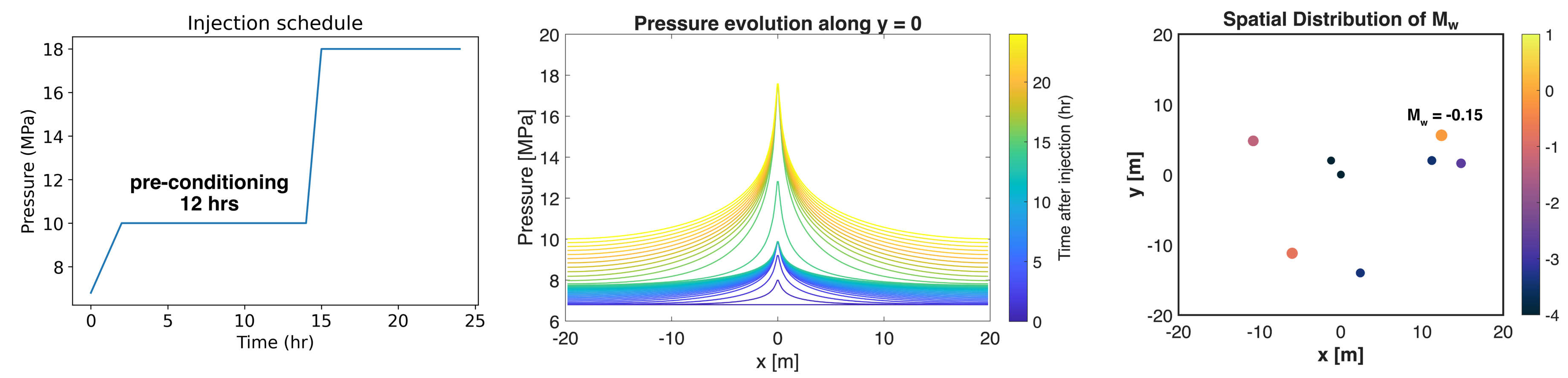
Injection protocols on seismicity magnitude

Gradual pressure increase 6.8 -> 18 MPa



Fault is partially activated through a single event, leading to less seismicity

Pre-conditioning at 10 MPa (12hrs)



Larger fault area is activated, potentially for larger magnitude

Conclusions

1. A higher proportion of velocity-strengthening (VS) patches results in smaller event magnitudes (~0.12), whereas a lower proportion leads to larger magnitudes (~0.3).
2. Frictional parameters—the characteristic slip distance (l_{vw}) and state variable (θ)—control slip rate and govern the partitioning between aseismic and seismic slip.
3. Compared to gradual pressure injection, stress preconditioning has a greater potential to activate a larger fault area and generate larger magnitude.

Reference:
1 Meier, M. A., Selvadurai, P., Gischig, V., Hertrich, M., Tinti, E., Rinaldi, A. P., ... & Giardini, D. (2026). Activating a Natural Fault Zone in the Swiss Alps. Seismica, 5(1).
2 Wang, Z., Dal Zilio, L., Ciardo, F., and Rinaldi, A.: HydroMech3D: physics-based earthquake-cycle modeling of fluid-driven fault slip with realistic fault geometry, EGU General Assembly 2026, Vienna, Austria, 3–8 May 2026, EGU26-8716, https://doi.org/10.5194/egusphere-egu26-8716, 2026.
3 Rubin, A. M., & Ampuero, J. P. (2005). Earthquake nucleation on (aging) rate and state faults. Journal of Geophysical Research: Solid Earth, 110(B11).