Understanding and preventing seismicity induced by fluid injection in Enhanced Geothermal Systems

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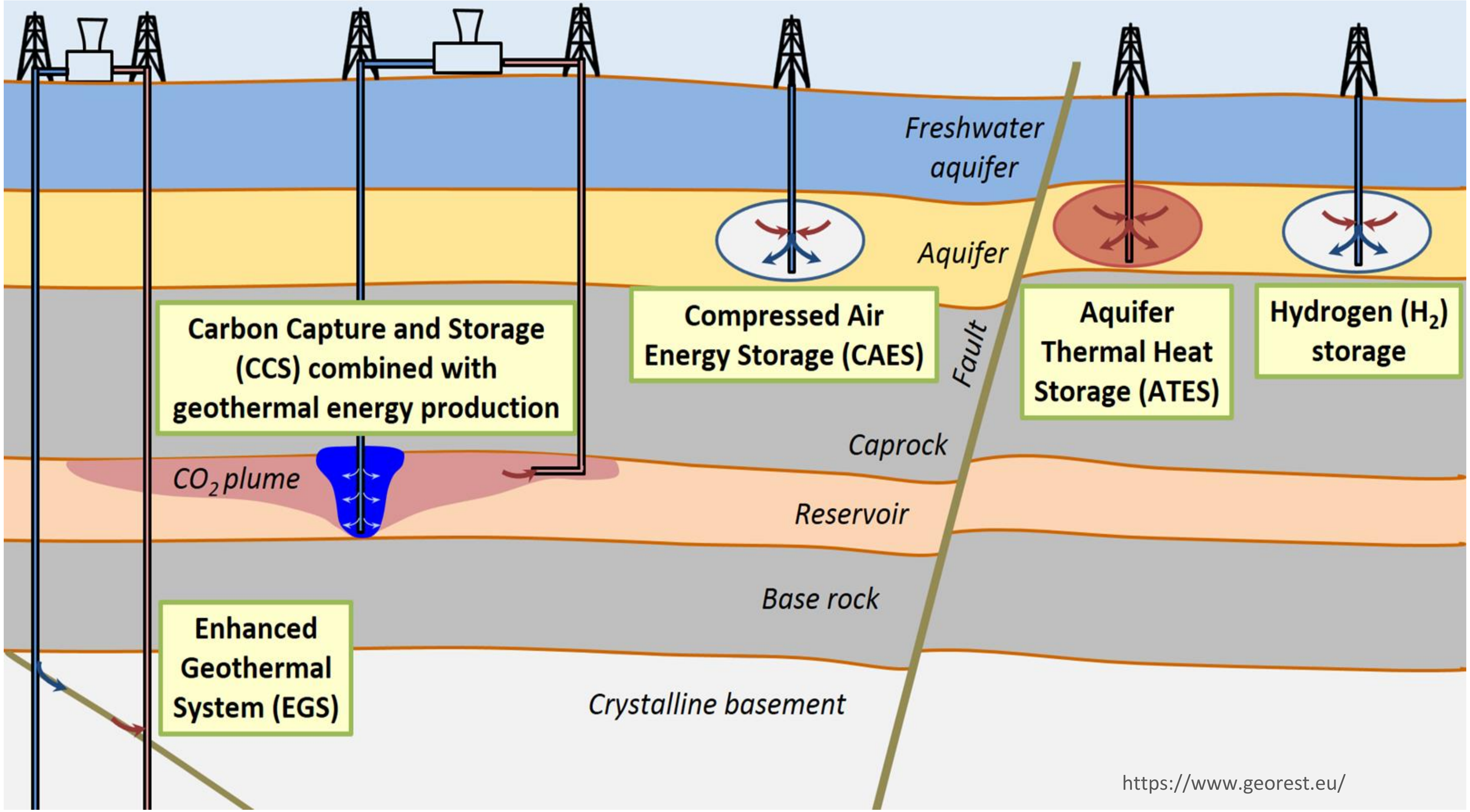
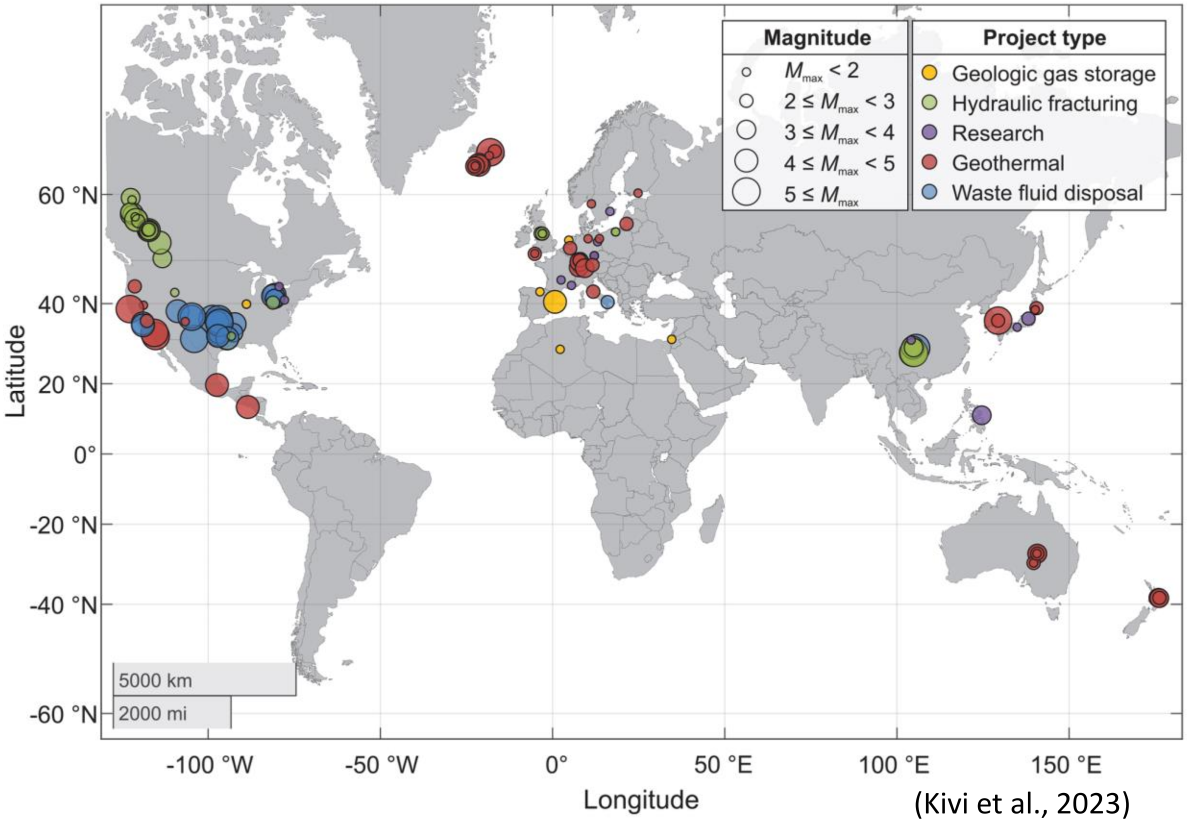
Geo-energy applications are major solutions for the energetic transition, but fluid injection may induce seismicity in the different applications

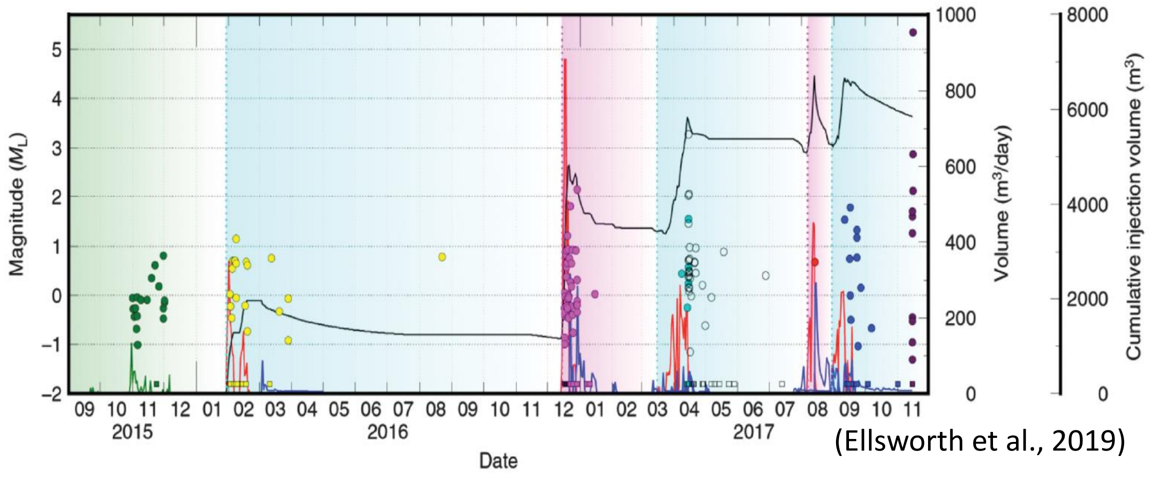


Induced seismicity is an inherent hurdle to geo-energy applications and European energetic transition decisions increase the risks of induced seismicity



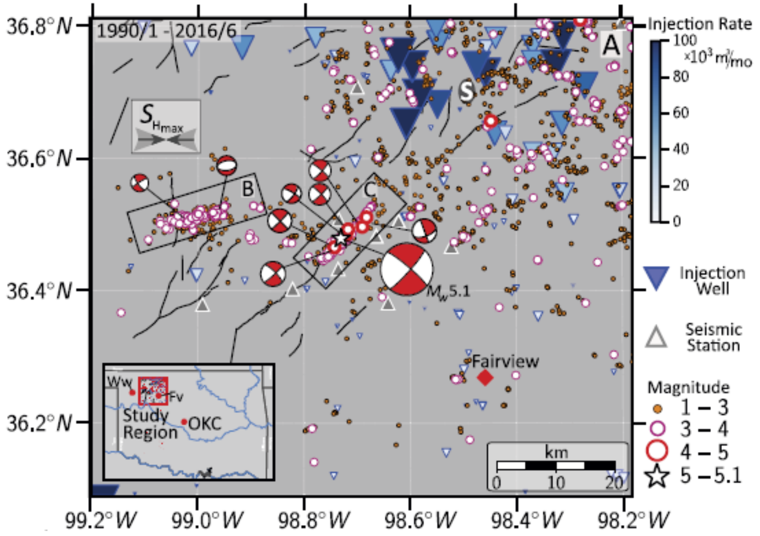
(Kivi et al., 2023)

Pohang EGS, Korean Republic – 2 months of delay



(Ellsworth et al., 2019)

Oklahoma WWD, USA



(Goebel et al., 2018)

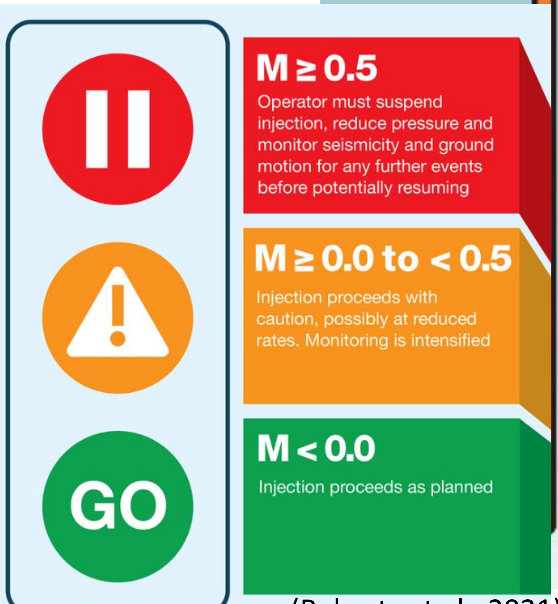
Enhanced Geothermal Systems (EGS) aim to produce electricity using the thermal energy of the subsurface

Fluid circulation is limited due to the low permeability of the deep crystalline rock

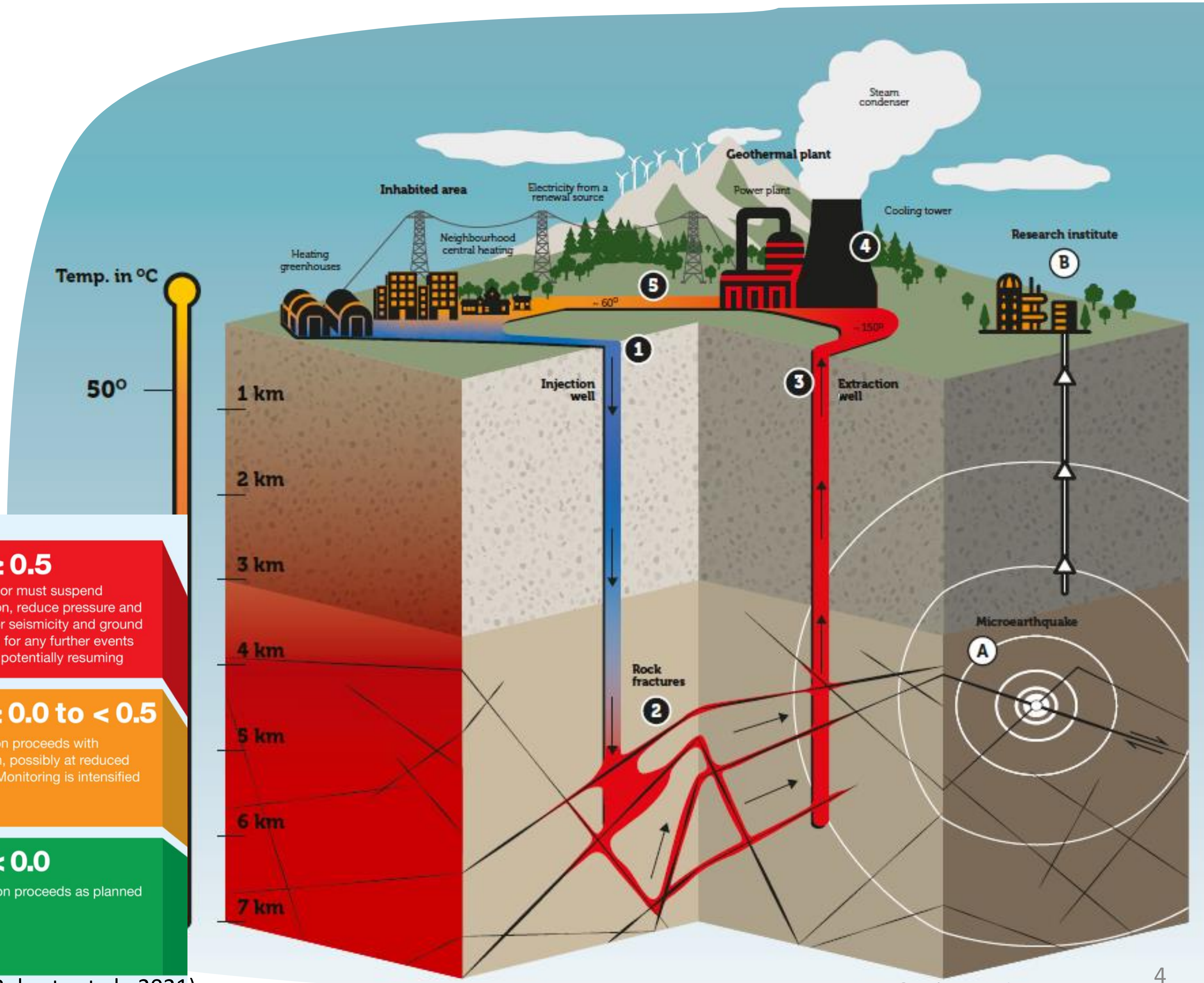
↳ Hydraulic stimulation enhances the permeability of the faults and initiates the propagation of a new fracture network

Felt earthquakes question the viability of these projects

Traffic light systems should prevent induced seismicity



(Roberts et al., 2021)



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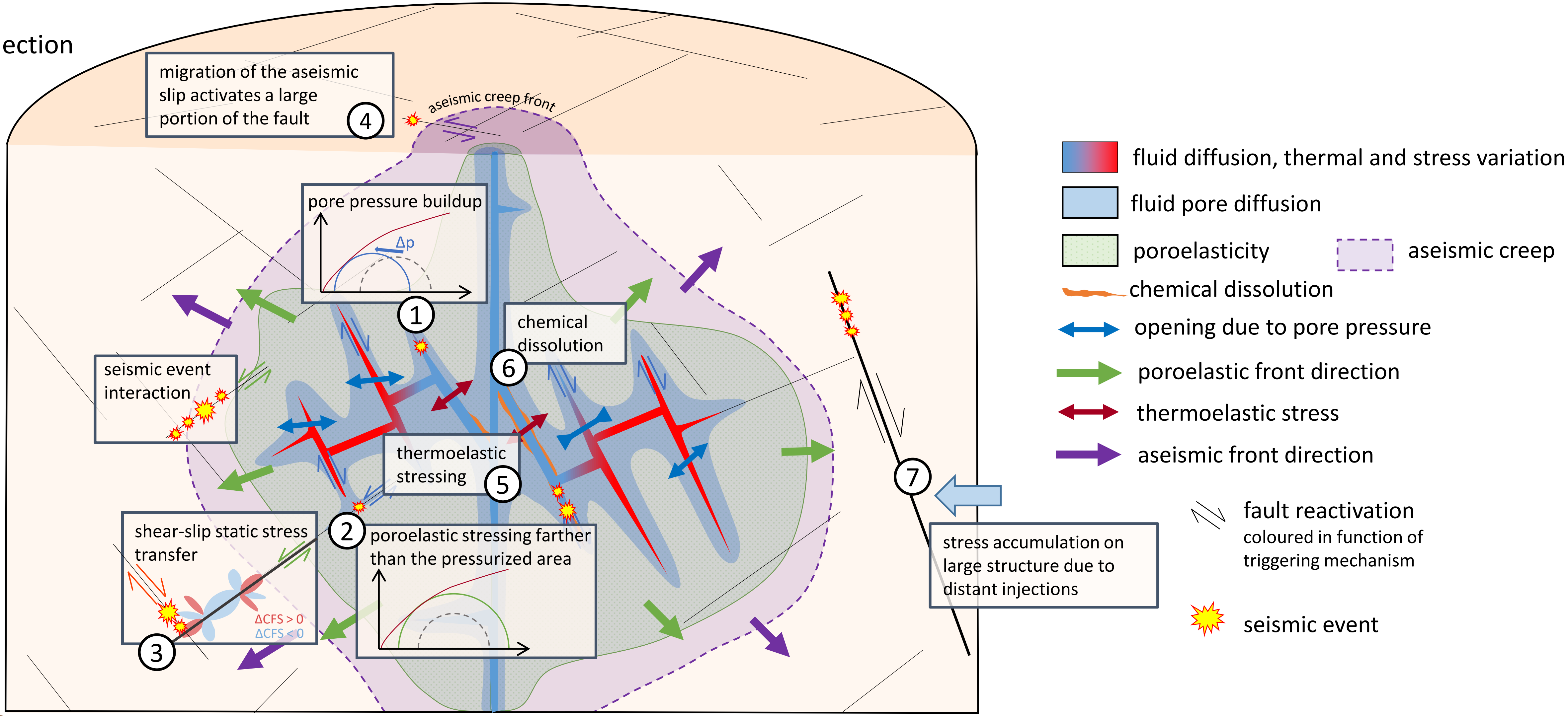
Fluid injection redistributes pressure and stress along the fractured reservoir

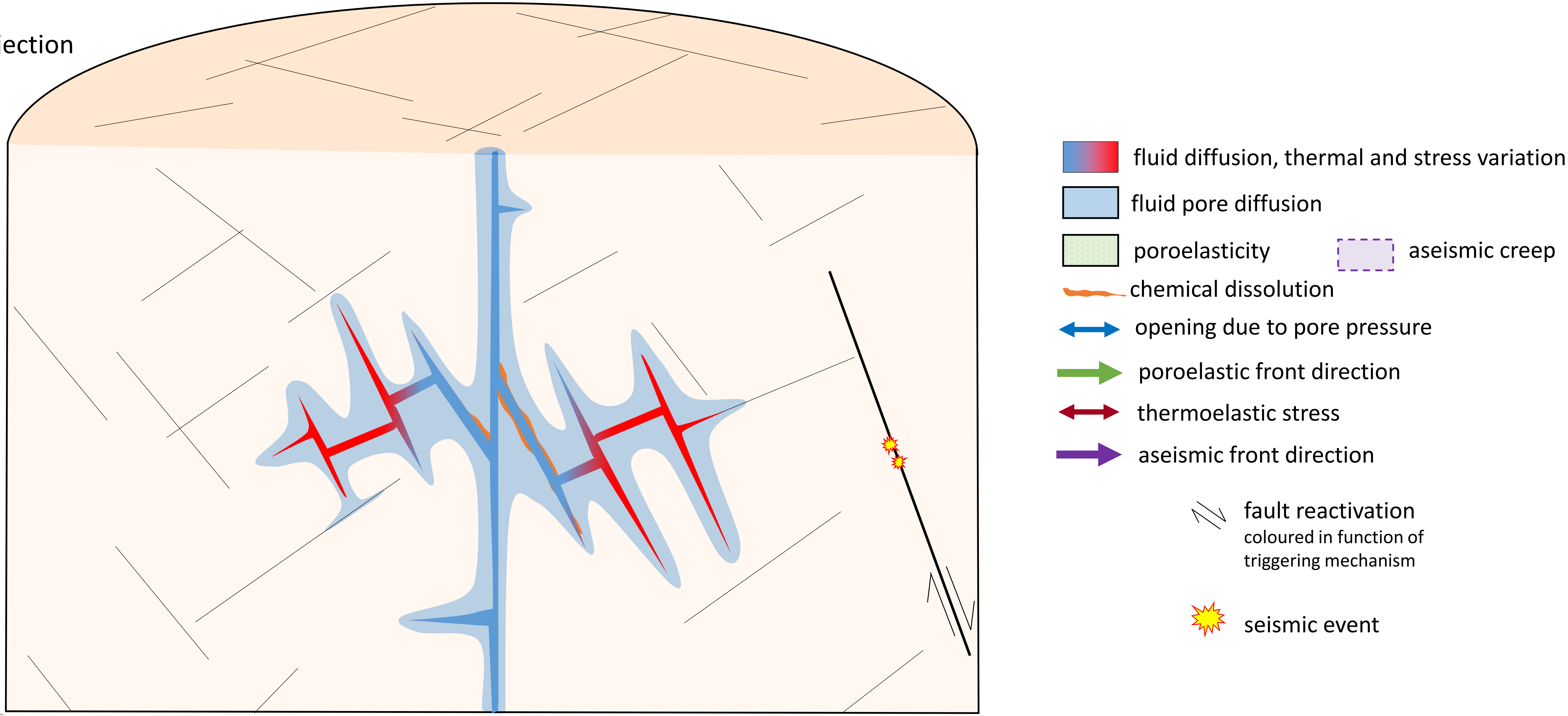
during injection



(Boyet et al., 2025)

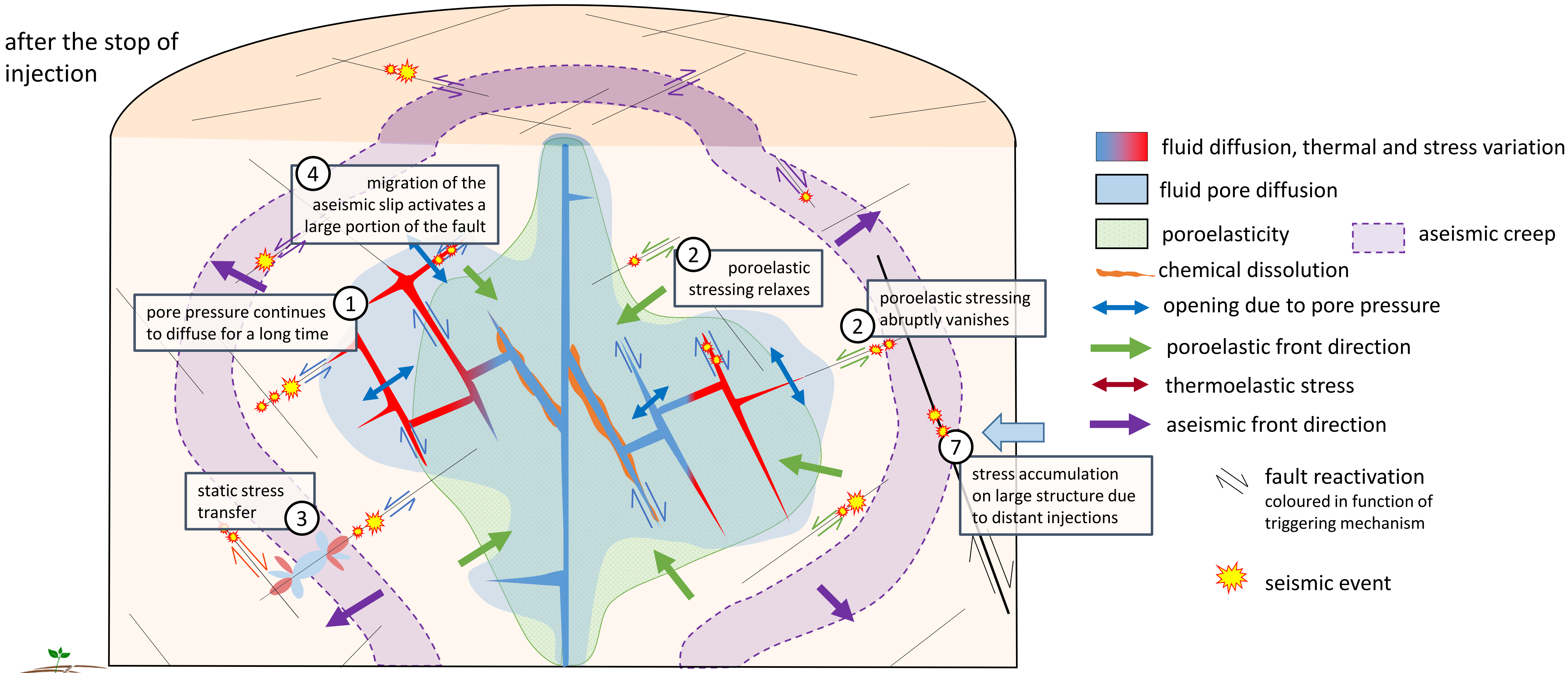
Fluid injection redistributes pressure and stress along the fractured reservoir

during injection



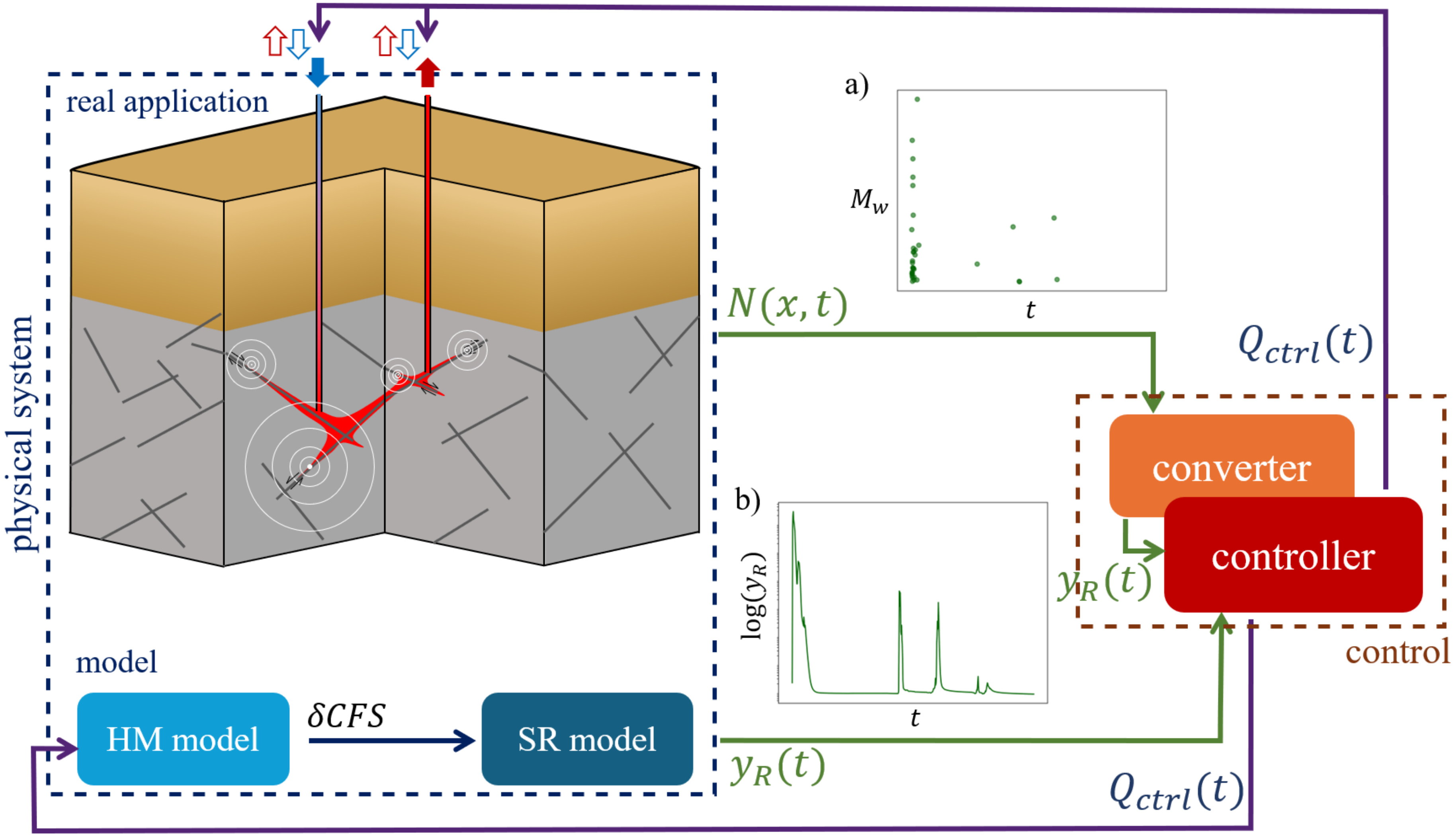
(Boyet et al., 2025)

After the stop of injection, the mechanisms continues to affect the stability of the pre-existing faulting network

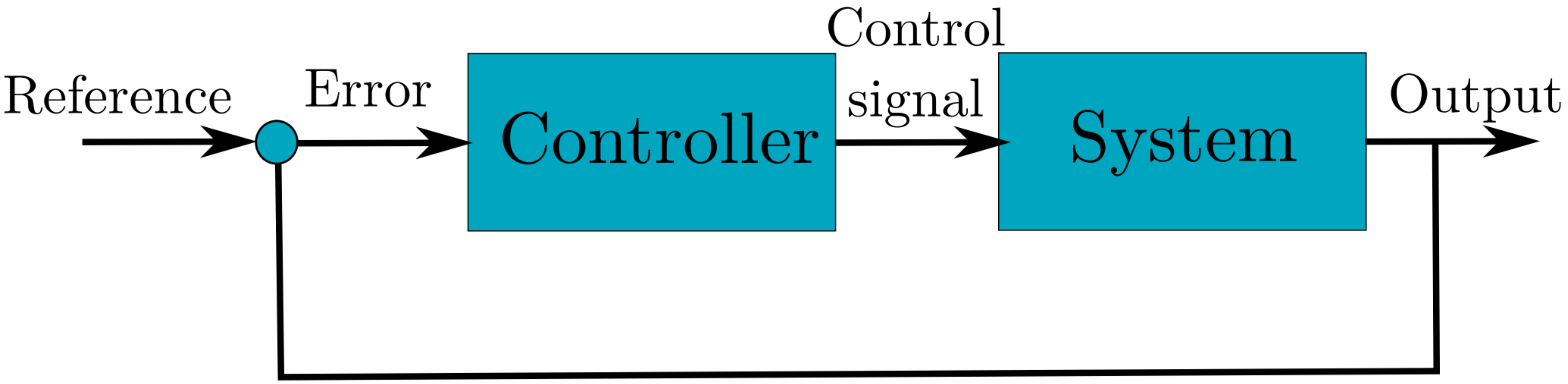


(Boyet et al., 2025)

Control theory brings a new paradigm for the prevention and mitigation of induced seismicity in geo-energy applications



Control theory is an automated closed-loop dynamic system set to force the system to achieve a desired reference or behaviour



Nonlinear proportional–integral controller:

- continuously adjusts a system's input to reach and maintain a desired target.

It combines three actions:

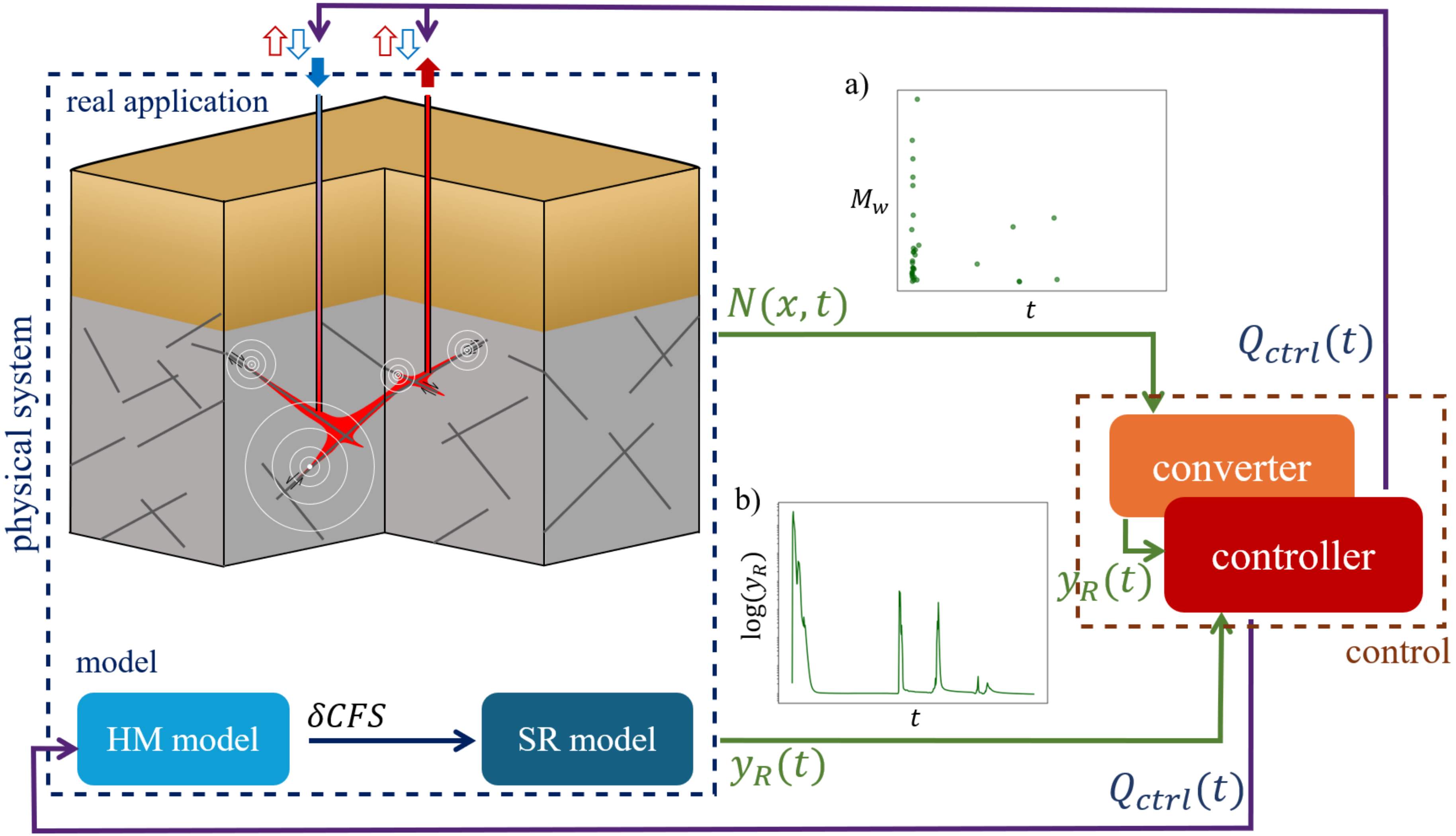
(a) the **Proportional** term reacts to the current error

(b) the **Integral** term corrects accumulated past errors

Each one of them has gains, that need tunning to make the controller efficient and feasible in terms of technological limitations

Gutiérrez-Oribio and Stefanou (2026), arXiv:2412.06327

Control theory brings a new paradigm for the prevention and mitigation of induced seismicity in geo-energy applications



The governing equation couples the fluid diffusion and the volumetric deformation of the rocks following the Biot's theory (Biot, 1941):

$$\beta\dot{p}(x,t) + \alpha\dot{\mathrm{u}}_{i,i} = -q_{i,i}(x,t) + \sum_{i=1} B_i\,(x)Q_i(t) + \sum_{i=1}^{m} B_i^s(x)Q_i^s(t)\,,$$

$$0 = (\lambda(x) + G(x))_{,i}\mathrm{u}_{j,j}(x,t) + \left(G(x)\mathrm{u}_{j,j}(x,t\right)_{,j} + \alpha p_{,i}(x,t),$$

$$q_i(x,t) = -\frac{k(x)}{\eta(x)}p_{,i}(x,t),$$

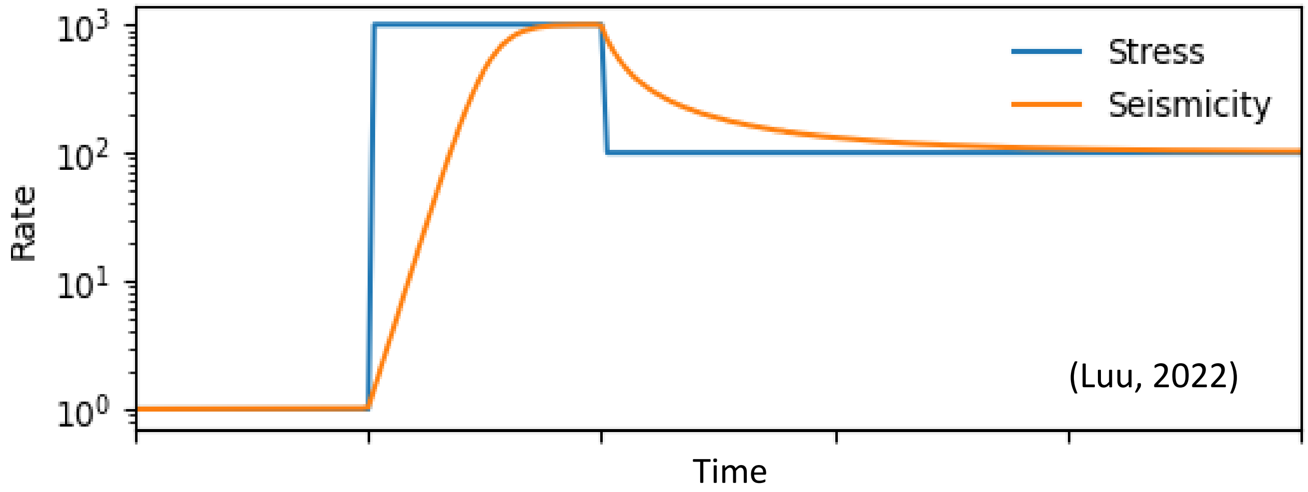
$$p(x,t) = u(x,t) = 0 \qquad \forall\, x \in \partial V,$$

$p(x,t)$ - change of the fluid pressure in the reservoir due to fluid injections
$u_i(x,t)$ - displacement
$k(x)$ - permeability of the host rock
$\eta(x)$ - dynamic viscosity of the fluid
β - mixture compressibility, i.e.,
$\lambda(x)$ and $G(x)$ - Lamé elastic parameters
α - Biot-Willis coefficient

The stress changes are converted into seismicity rate following the Rate-and-State friction model (Dieterich, 1994; Segall& Lu, 2015), defined by:

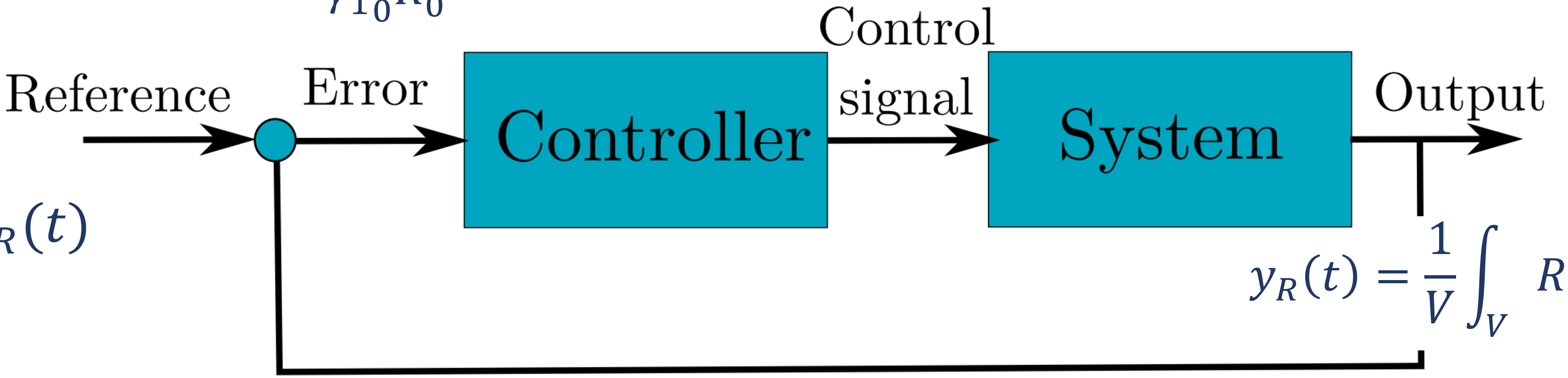
$$\dot{R}(x,t) = \frac{R(x,t)}{t_a}\left(\frac{\dot{CFS}(x,t)}{\dot{\tau}_0} - R(x,t)\right),$$

$\dot{CFS}(x,t)$ - Coulomb Failure Stressing rate
$\dot{\tau}_0$ - background stressing rate
t_a - characteristic decay time



The control-theoretical approach considers the seismicity rate of a region as the measurable output of the system and the background seismicity rate as the reference

$$\sigma(t) = \frac{1}{\gamma_{1_0} R_0^*} \left[y_R(t) - r_R(t) \right]$$



$r_R(t)$

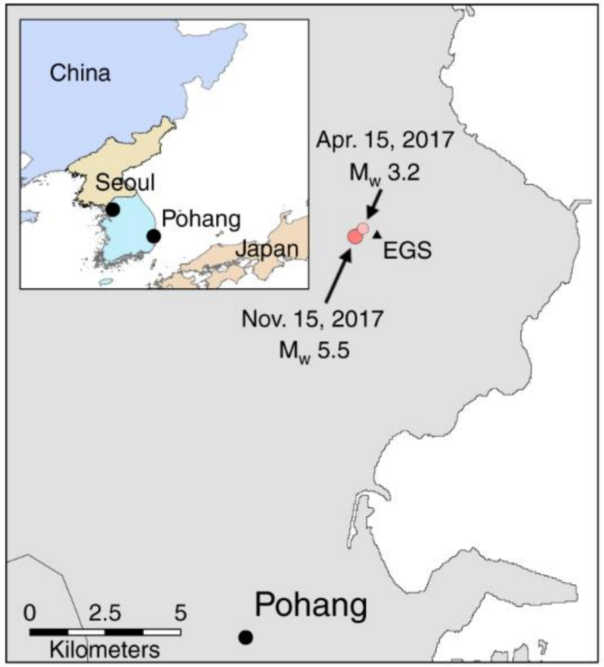
$$y_R(t) = \frac{1}{V} \int_V R(x,t) dV$$

$$Q_{ctrl}(t) = B_0^+ \left[-k_1 \phi_1\big(\sigma(t)\big) + v(t) \right]$$
$$\dot{v}(t) = -k_2\, \phi_2\big(\sigma(t)\big)$$

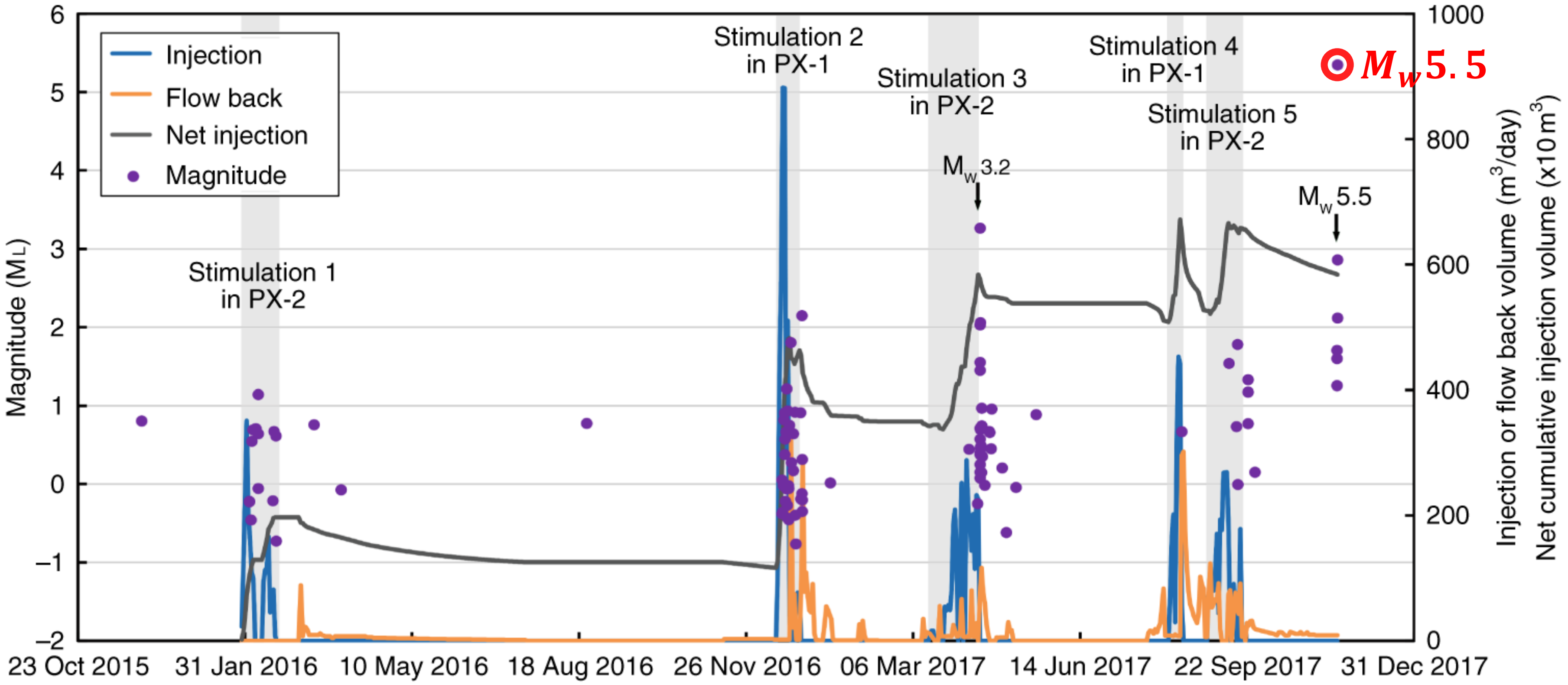
Gutiérrez-Oribio and Stefanou (2026), arXiv:2412.06327

$\phi_1(\sigma)$ $\phi_2(\sigma)$ - nonlinear functions of the error
k_1, k_2 - tuning parameters
B_0 - matrix with nominal values of the system

The Pohang EGS was initiated in 2016 and five hydraulic stimulations were operated over two years. A post-injection earthquake of magnitude $M_w 5.5$, occurred two months after the stop of the fifth stimulation.



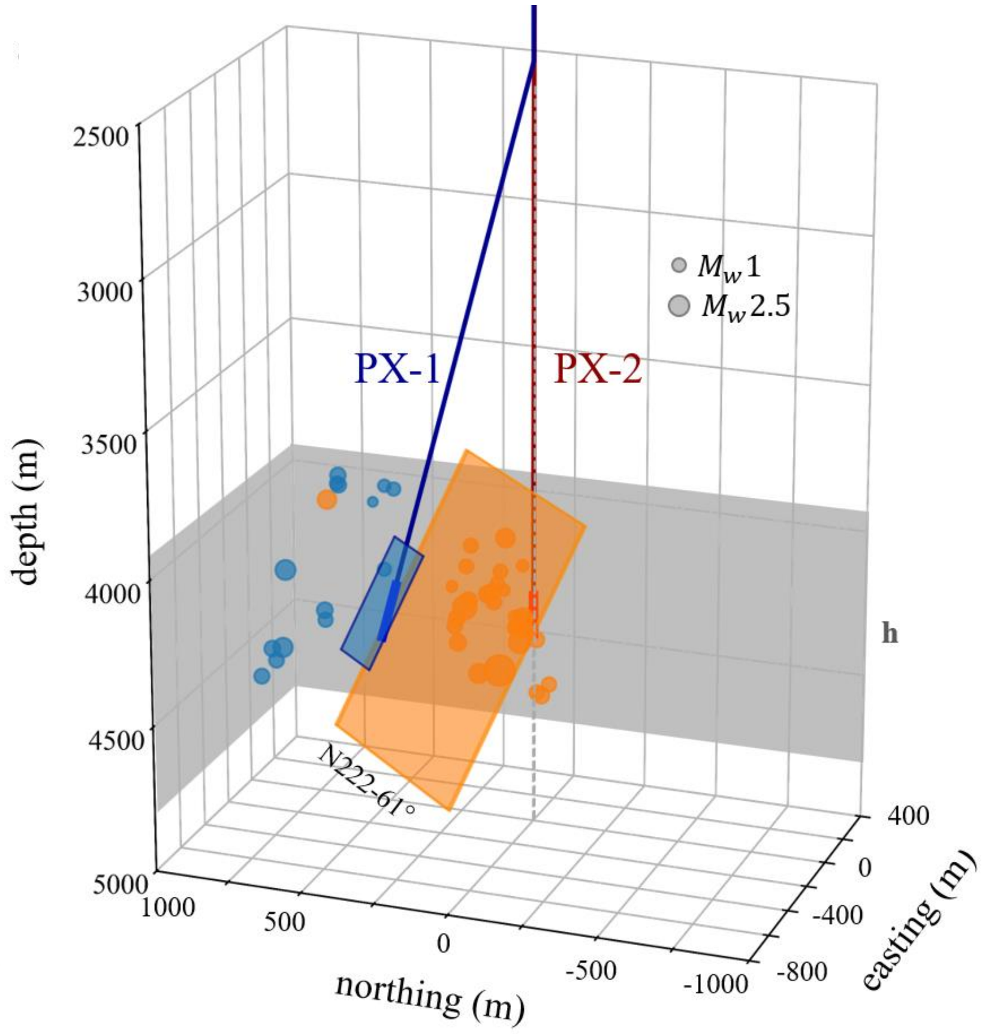
Injection and induced earthquakes during the two-year stimulations



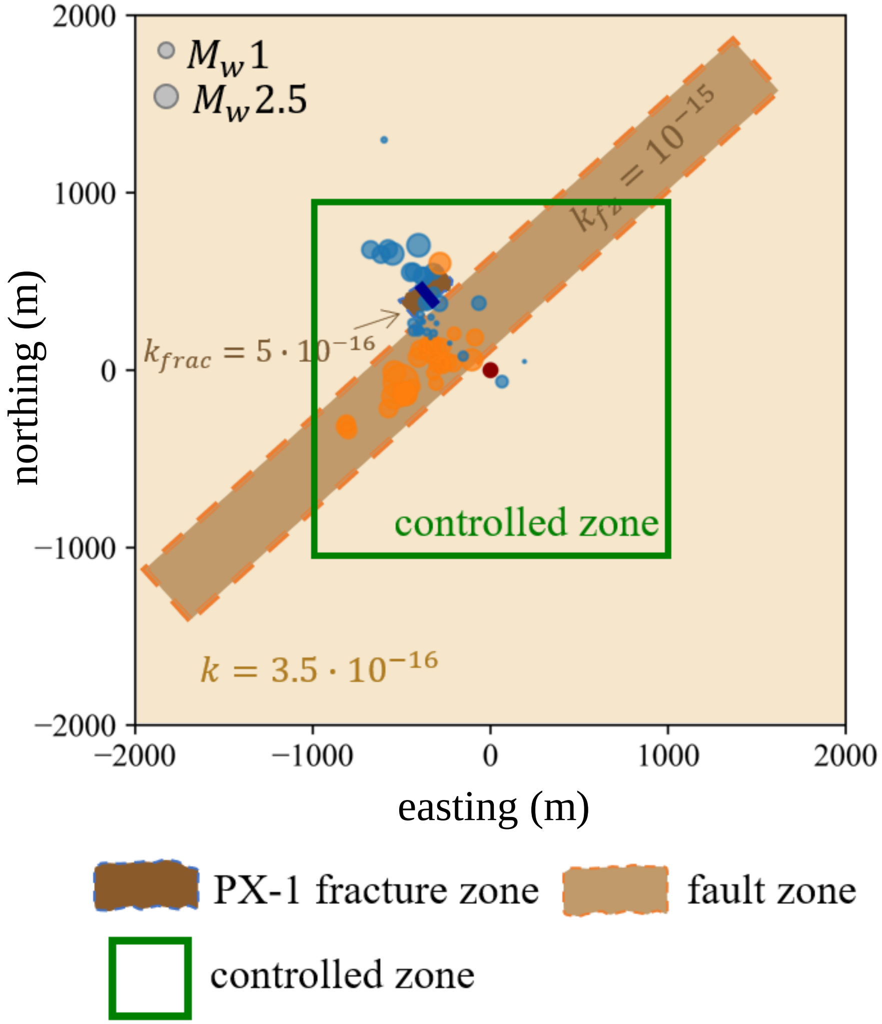
(Yeo et al., 2020)

We model the Pohang EGS in a 2D depth-average coupled hydromechanical model simulating poroelasticity

Seismic data monitored during the PX-1 and the PX-2 stimulations



Model settings of the 2D modeling considering depth-average



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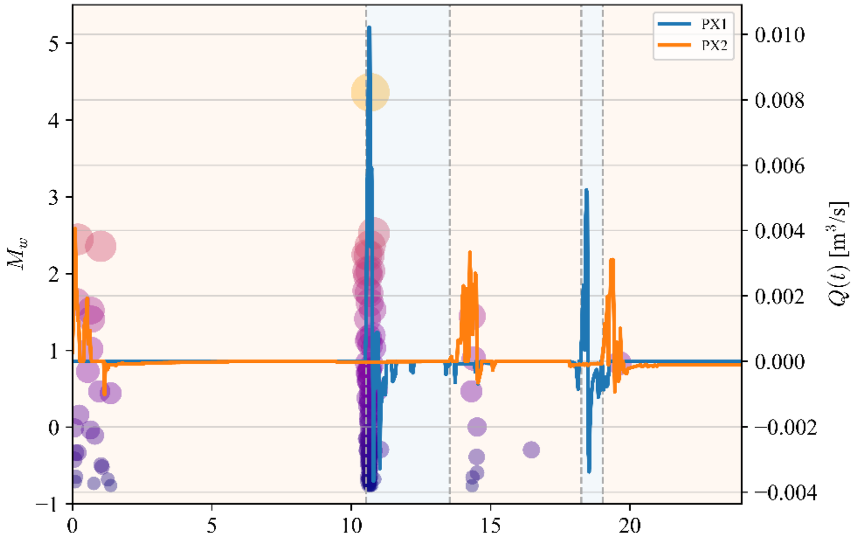
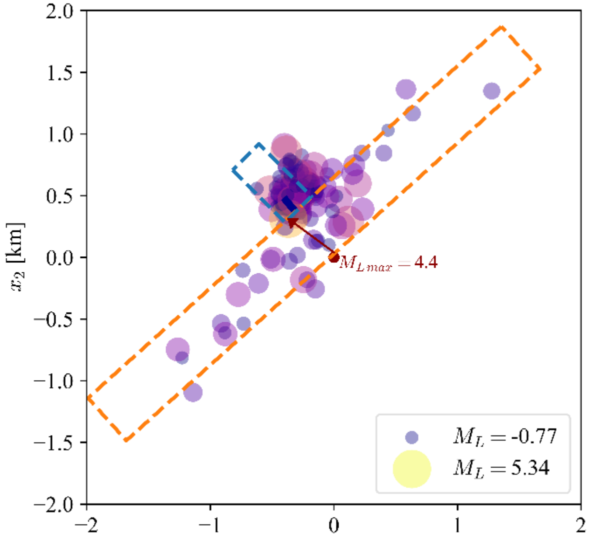
The controller is efficient for the case of induced discrete events (converted in seismicity rate) to prevent seismicity

Injection fluxes and magnitude of discrete seismic events

calibration



Discrete seismic events



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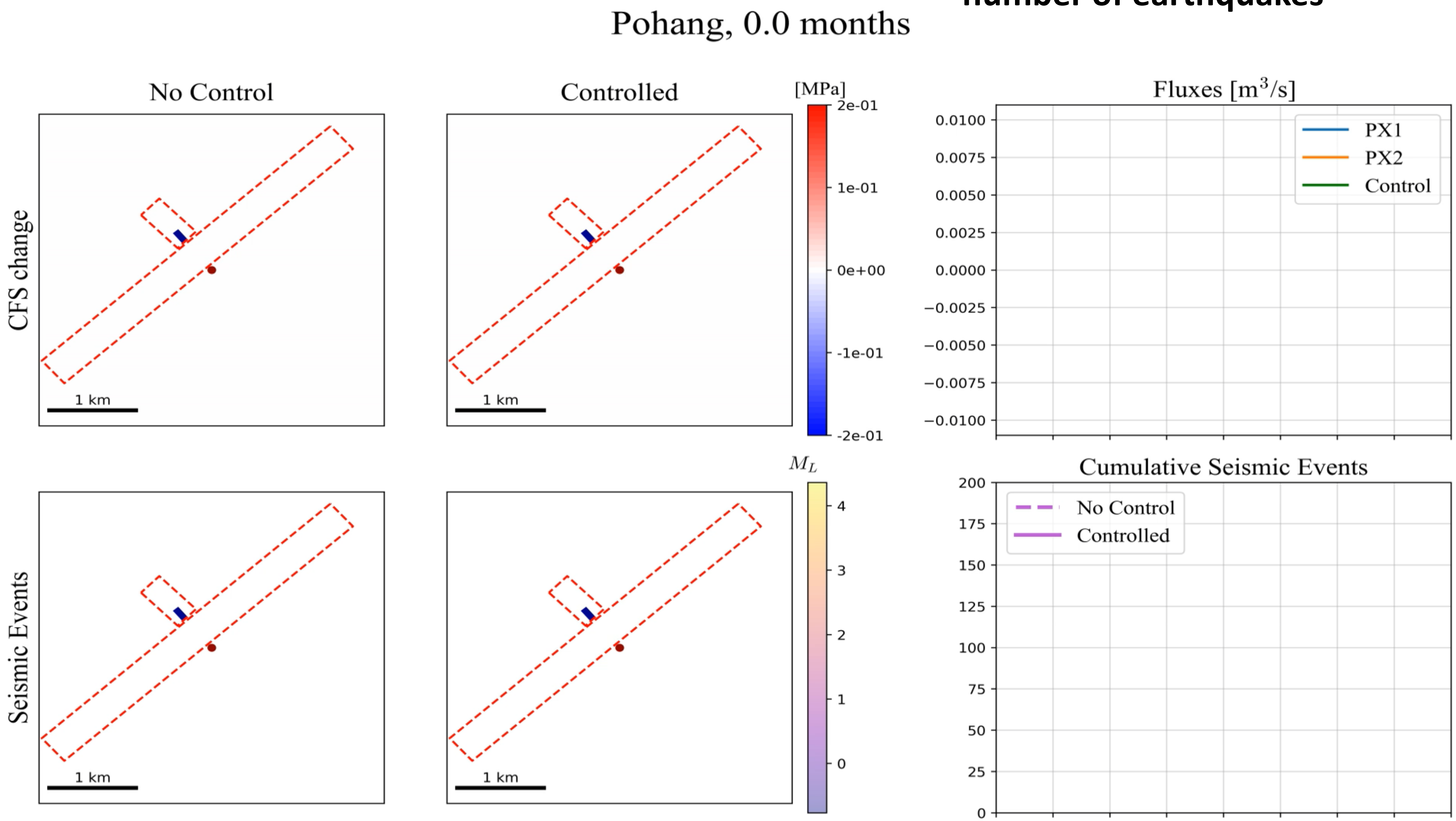
The controller, considering discrete events, is also efficient to prevent seismicity during the two-year stimulations

Discrete seismic events

Injection fluxes and cumulative number of earthquakes



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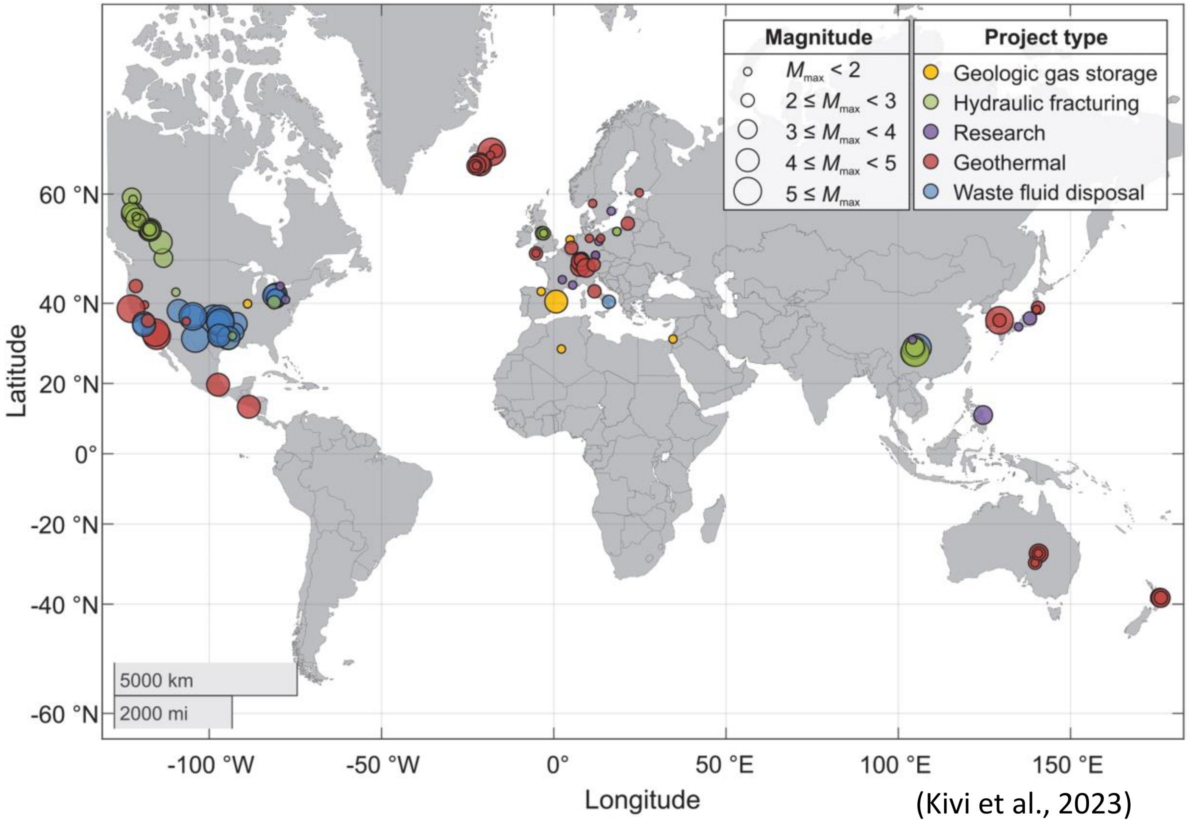
The control-theoretic approach has long path to be achievable in real application and development of models and controllers are necessary

Limitations and future works:

- The models are simplifications of the real triggering mechanisms and seismic phenomena,
- Fractures and faults need to be considered as discrete, with plastic behavior
- The actuators are not physically limited and can change sign



(Kivi et al., 2023)

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Control theory : a (small) introduction

Consider the simple system

$$\dot{x}_1 = x_2,$$
$$\dot{x}_2 = u.$$

x_1,x_2 - State variables (position and velocity)
u - Control input (force)

Objective: Design the input u to follow a **constant** reference r on the state x_1 (**regulation**).

Control theory : a (small) introduction

Introducing the error:

$$e_1 = x_1 - r \qquad e_2 = x_2 - \dot{r} = x_2$$

Error system:

$$\dot{e}_1 = e_2,$$
$$\dot{e}_2 = u.$$

Question: Are they the same system?

Difference: If t $e_1, e_2 \to 0$ ved the regulation problem!

Control theory : a (small) introduction

PID control:
$$u = -k_P e_1 - k_D e_2 - k_I \zeta,$$
$$\dot{\zeta} = e_1,$$

Closed-loop system:
$$\dot{e}_1 = e_2,$$
$$\dot{e}_2 = -k_P e_1 - k_D e_2 - k_I \zeta,$$
$$\dot{\zeta} = e_1.$$

How to chose the gains k_P, k_D, k_I **?**

Control theory : a (small) introduction

System matrix:

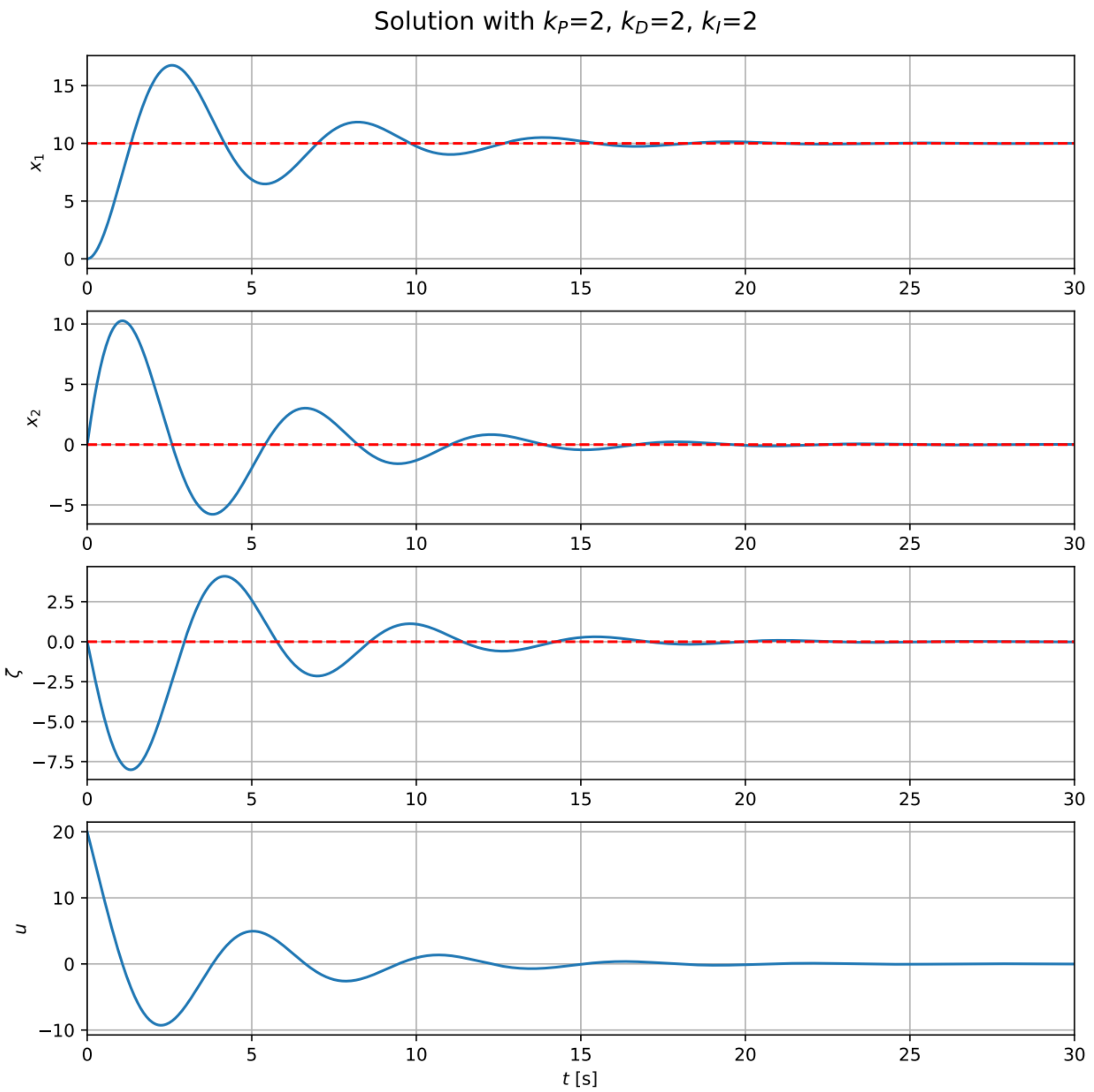
$$A = \begin{bmatrix} 0 & 1 & 0 \\ -k_P & -k_D & -k_I \\ 1 & 0 & 0 \end{bmatrix}$$

Characteristic equation:

$$s^3 + k_D s^2 + k_P s + k_I = 0$$

Exponentially stable if:

$$k_P > 0, \quad k_D > 0, \quad k_I < k_P k_D$$



Control theory : a robust control design

Output of the system:

$$y_R(t) = \frac{1}{V} \int_V R(x,t)\, dV$$

Reference for SR $r_R(t)$

Error variable:

$$\sigma(t) = \frac{1}{\gamma_{1_0} R_0^*} \left[y_R(t) - r_R(t) \right]$$

Control theory : a robust control design

$$Q_{ctrl}(t) = B_0^+ \Big[-k_1 \phi_1(\sigma(t)) + \nu(t) \Big],$$

$$\dot{\nu}(t) = -k_2 \phi_2(\sigma(t)),$$

$\phi_1(\sigma)$ $\phi_2(\sigma)$ - nonlinear functions of the error
k_1, k_2 - tuning parameters
B_0 - matrix with nominal values of the system

Analytic results:

- Exact tracking of the reference.
- Requires minimum information of the system.
- Agnostic against uncertainties and external perturbations.
- Finite-time or exponential convergence.

Control theory : Sketch of the proof

Closed-loop error dynamics :

$$\dot{\sigma} = [\mathbb{I}_m + \Delta B(t)] \left[-k_1 \phi_1(\sigma) + \sigma_I\right],$$
$$\dot{\sigma}_I = -k_2 \phi_2(\sigma) + \dot{\bar{\Psi}}(t).$$

The control *Q(t)* will work if:

$$\|\Delta B(t)\| \leq \delta_B < 1,$$
$$\|\dot{\bar{\Psi}}(t)\| \leq \delta,$$

Control theory : Sketch of the proof

Using Lyapunov theory, we can conclude :

$$||u(x,t)||_{L^2(V)} \leq \Gamma_u,$$

$$||u_t(x,t)||_{L^2(V)} \leq \Gamma_{u_t},$$

$$||R(x,t)||_{L^2(V)} \leq \Gamma_R,$$

$$||R_t(x,t)||_{L^2(V)} \leq \Gamma_{R_t},$$

Which ensures the existence of δ_B, δ