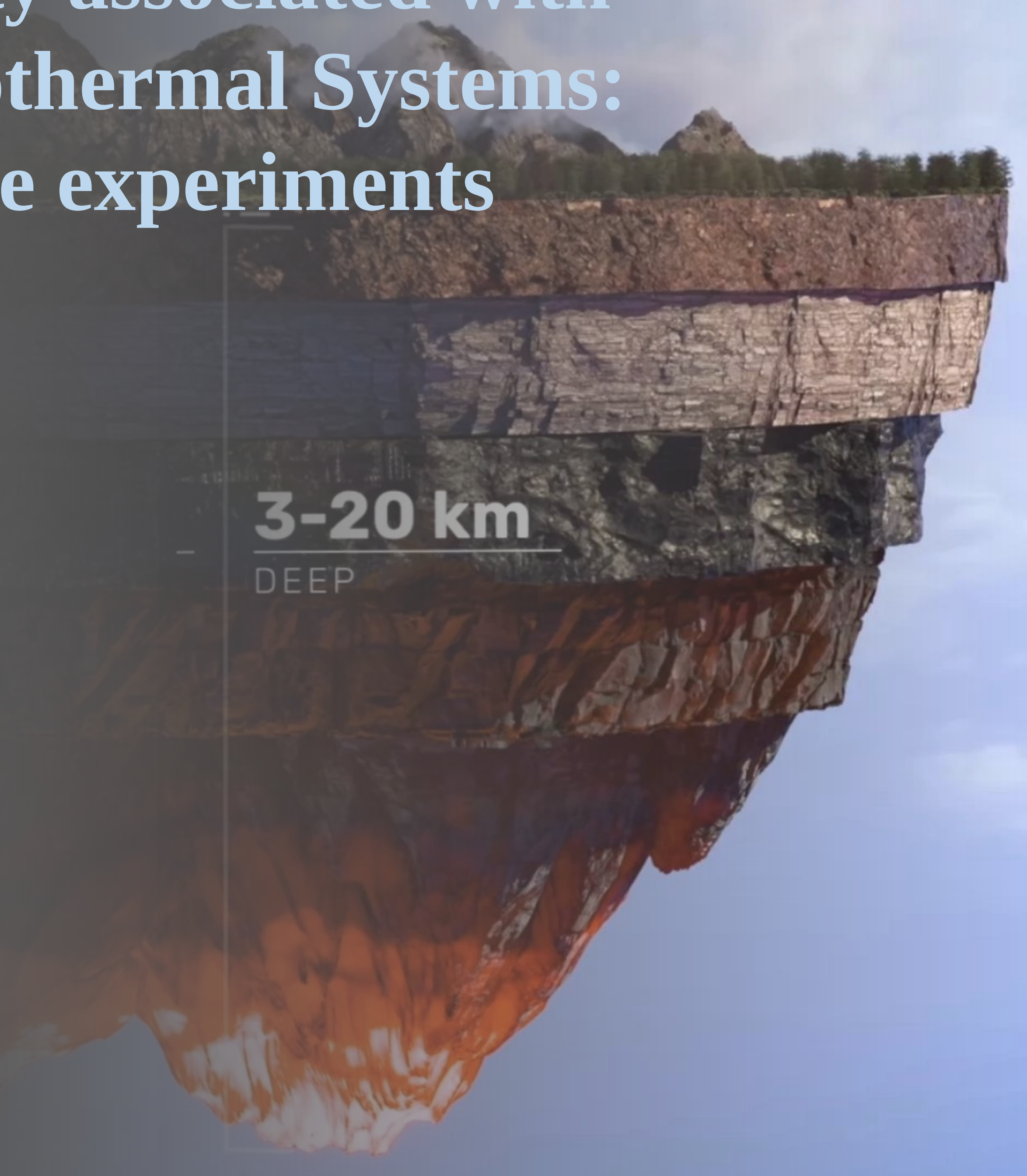
# Mitigated post-injection seismicity associated with fluid extraction in Enhanced Geothermal Systems: Evidence from lab- and field-scale experiments

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# Mitigated post-injection seismicity associated with fluid extraction in Enhanced Geothermal Systems: Evidence from lab- and field-scale experiments

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# Outline

## Introduction:

- Post-injection induced seismicity; plausible mechanisms; objectives

## Methods:

- Laboratory-scale experiments and field-scale modelling (Pohang EGS).

## Results:

- Changes of hydromechanical parameters in laboratory-scale experiments;
- Cross-scale pore pressure change contours;
- Cross-scale temporal change of pore pressure and Coulomb stress;
- The 2017 $M_w$ 5.5 Pohang earthquake could have been mitigated.

## Conclusion and Discussion:

- Immediate fluid extraction after fluid injection is recommended in most EGS.

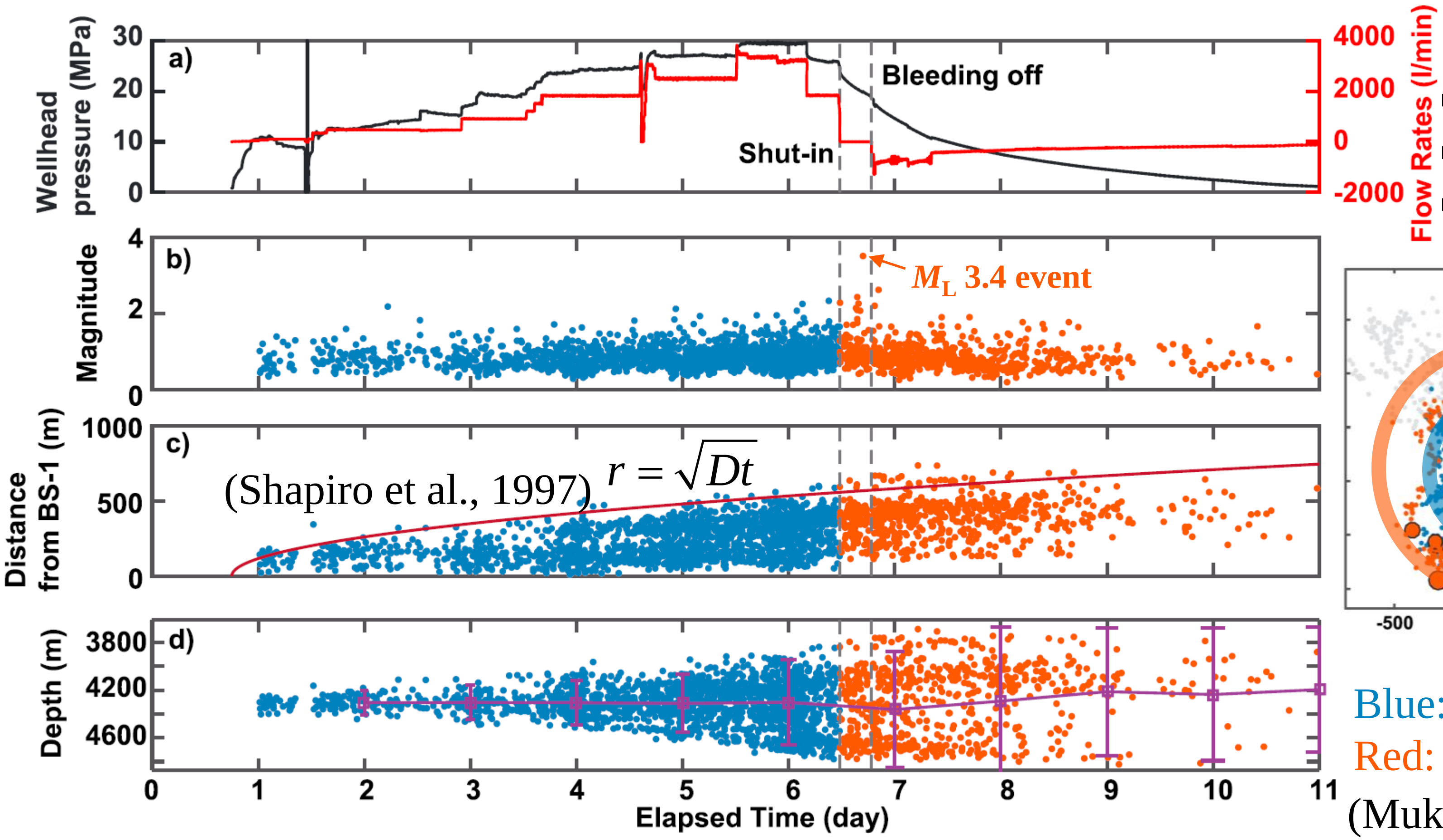
# Introduction: Frequent large magnitude earthquakes after injection in EGS

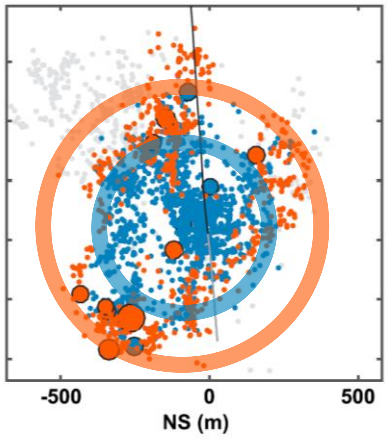
| NO. | Project site | Country | Type[b] | Year of occurrence | Hypocenter depth | Maximum wellhead pressure | Maximum bottomhole pressure[f] | Magnitude[c] | Time after injection | Distance from the injection well |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Soultz-sous-Forêts(Charléty et al., 2007) | France | EGS | 2003 | ~5.00 km | 19 MPa | ~68 MPa | M 2.9 | 85 h | - |
| 2 | Berlín Hot Fractured Rock(Bommer et al., 2006; Kwiatek et al., 2014) | El Salvador | EGS | 2003 | ~1.30 km | 159 MPa | ~172 MPa | $M_w$ 3.7 | 2 weeks | 3 km |
| 3 | Cooper Basin(Asanuma et al., 2005; Zang et al., 2014) | Australia | EGS | 2003 | ~4.42 km | 68 MPa | ~111 MPa | $M_w$ 3.7 | 1 day | ~0.4 km |
| 4 | Basel(Häring et al., 2008; Mukuhira et al., 2013) | Switzerland | EGS | 2006 | ~4.70 km | 30 MPa | 74 MPa | $M_w$ 2.68 | < 1 day | > 0.1 km |
| 5 | Pohang(Kim et al., 2018; Yeo et al., 2020) | South Korea | EGS | 2017 | ~4.30 km | 88 MPa | ~130 MPa | $M_w$ 3.2[d] | 14 hours | - |
| 6 | Pohang(Kim et al., 2018; Yeo et al., 2020) | South Korea | EGS | 2017 | ~4.30 km | 88 MPa | ~130 MPa | $M_w$ 5.5[d] | 2 months | 0.51 km |
| 7 | St1 Deep Heat(Leonhardt et al., 2021) | Finland | EGS | 2018 | 4.50-7.00 km | 97 MPa | ~150 MPa | $M_w$ 1.6 | 17 days | ~0.6 km |
| 8 | Vendenheim (Lengliné et al., 2023; | France | EGS | 2021 | ~4.30 km | >10 MPa | >52 MPa | $M_{Lv}$ 3.9 | > 6 months | ~1.9 km |

# Introduction: Plausible mechanisms for post-injection earthquakes

**1. Pore pressure diffusion** 2. Poroelastic stress 3. Coulomb static stress transfer

## Basel EGS, $M_L$ 3.4, 5 hours after injection




- Expansion due to further pressure diffusion
- More suitable for seismicity before injection
- Other mechanisms may also involve in shut-in

Blue: before shut-in
Red: after shut-in
(Mukuhira et al., 2017)

# Introduction: Plausible mechanisms for post-injection earthquakes

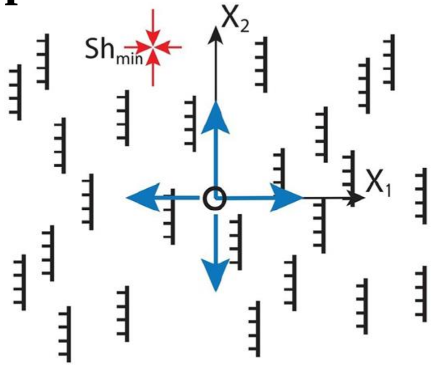
1. Pore pressure diffusion | **2. Poroelastic stress** | 3. Coulomb static stress transfer

**2D analytical modelling of seismicity induced by fluid injection to porous media**

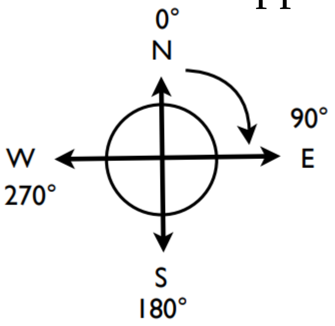
**Biot coefficient for coupling**

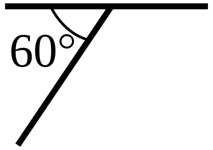
$$\alpha = 1 - \frac{K \text{ (Bulk modulus)}}{K_s \text{ (Grain modulus)}}$$

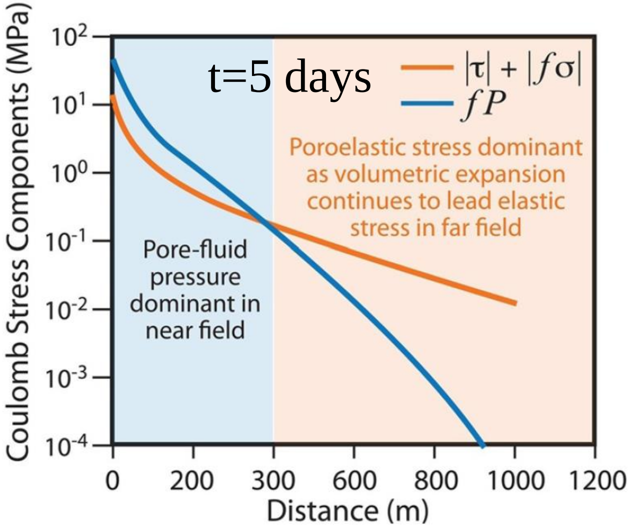
**Map view:** N-S Normal faults

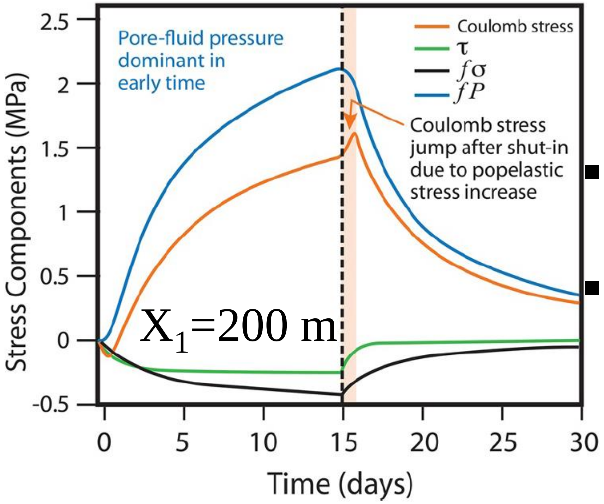


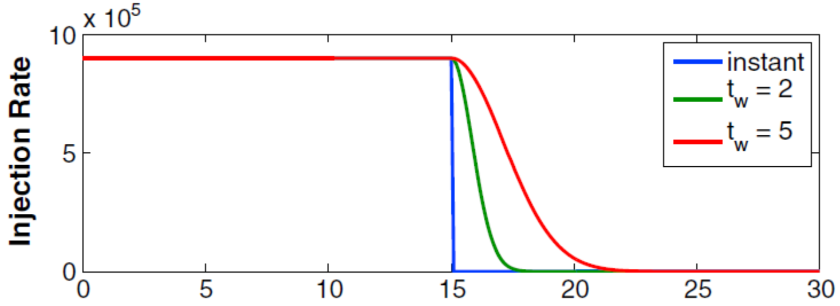

**Profile view:** dipping 60° to the west

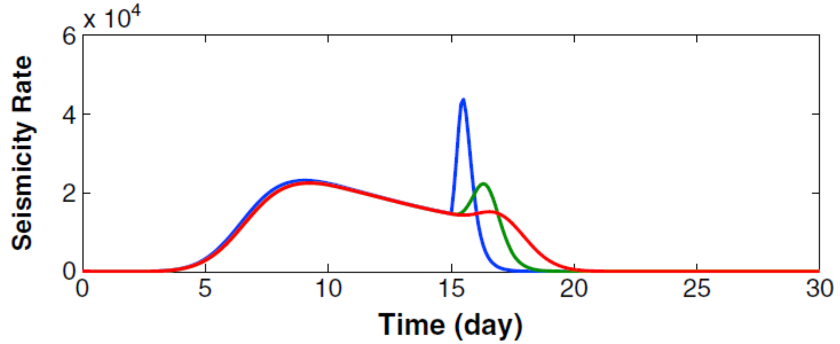


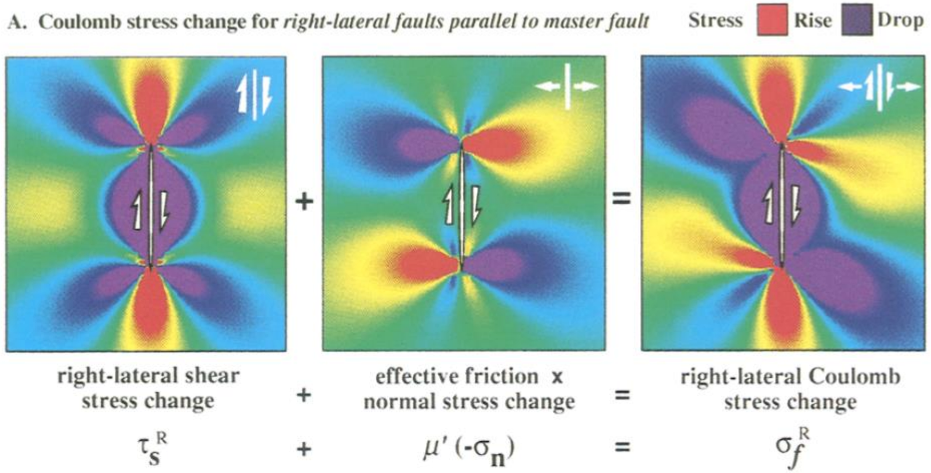

- If poroelastic stresses inhibit slip during injection, abrupt shut-in can lead to post shut-in spikes in seismicity rate.
- Tapering the injection rate mitigates the post shut-in spike in seismicity.

(Segall and Lu, 2016; Ge and Saar, 2021)

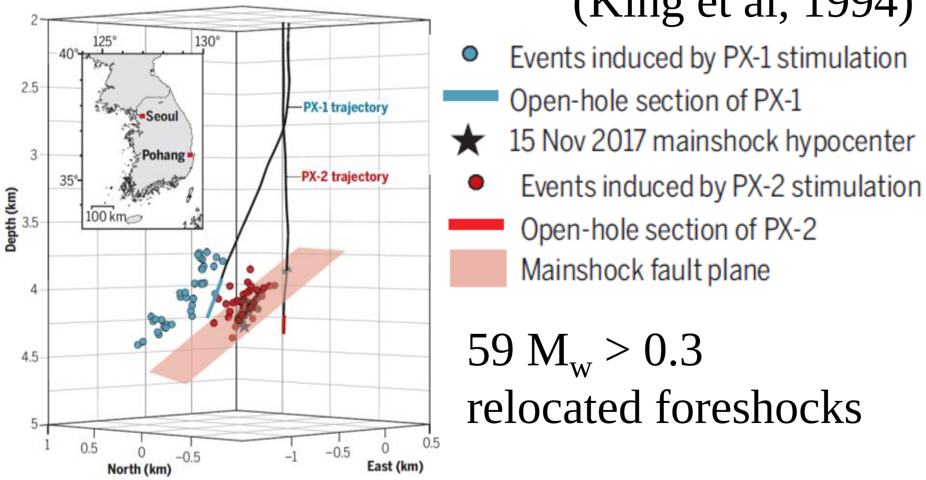
# Introduction: Plausible mechanisms for post-injection earthquakes

1. Pore pressure diffusion   2. Poroelastic stress   **3. Coulomb static stress transfer**

**Pohang EGS, $M_w$ 5.5, ~ 2 months after injection**

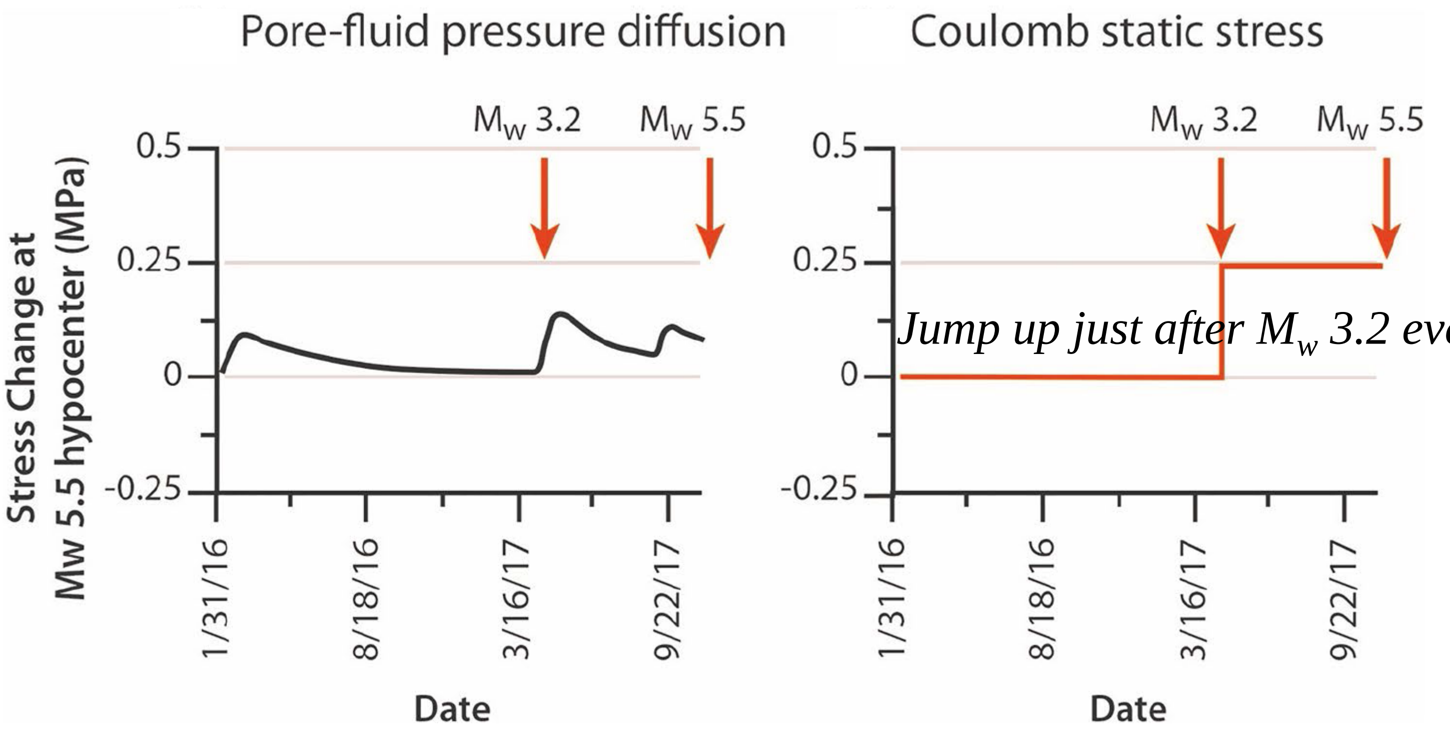



(King et al, 1994)




59 $M_w$ > 0.3
relocated foreshocks

(Lee et al., 2019; Yeo et al., 2020)



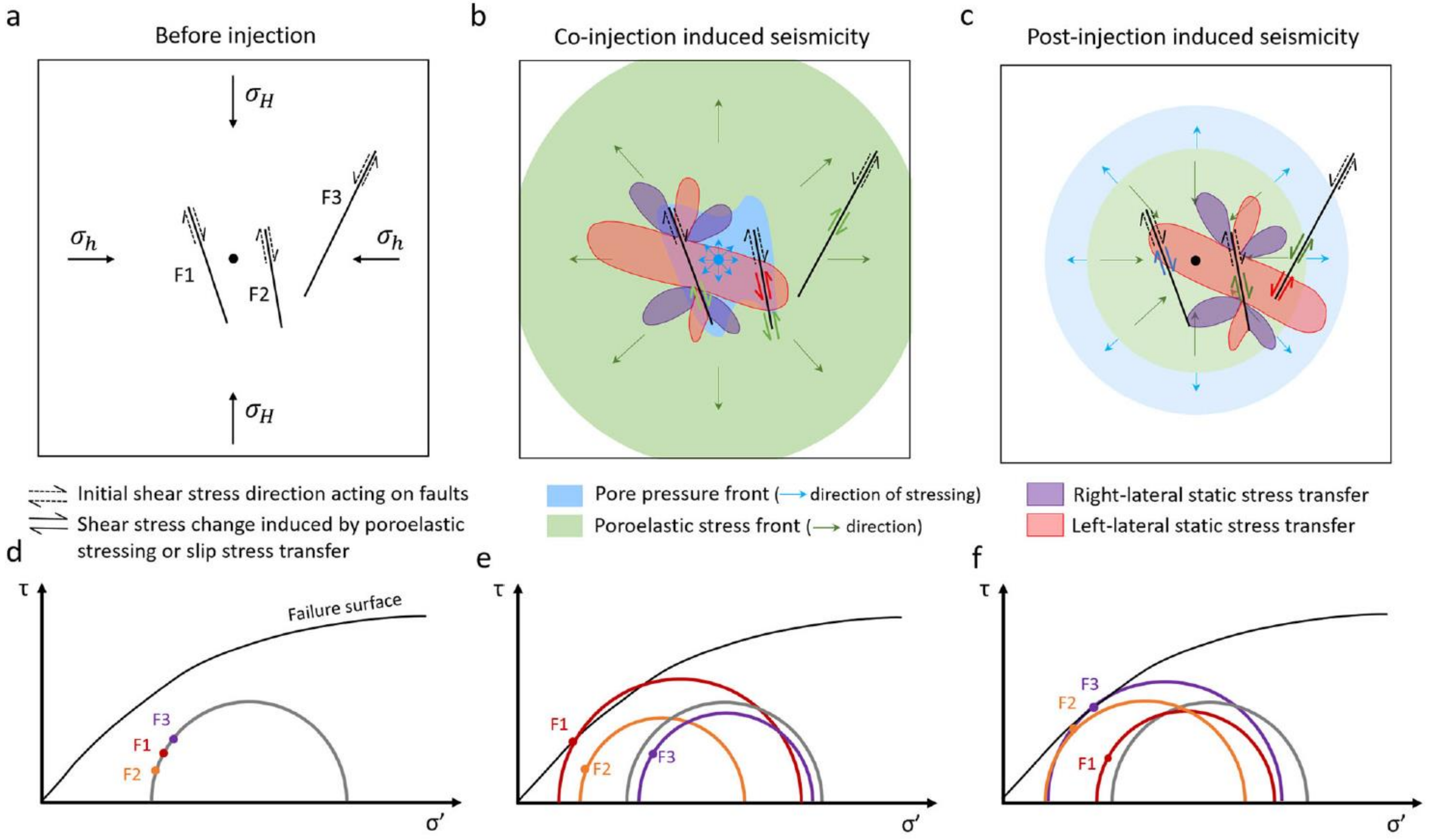

(Ge and Saar, 2021)

- $M_w$ 3.2 event is induced by pore pressure diffusion.
- Coulomb static stress transfer induced by $M_w$ 3.2 event triggered $M_w$ 5.5 earthquake.

# Introduction: Plausible mechanisms for post-injection earthquakes

**1. Pore pressure diffusion** **2. Poroelastic stress** **3. Coulomb static stress transfer**

**Conceptual model of Basel Enhanced Geothermal System (EGS)**
**($M_w$ 2.95, 5 hours after shut-in)**




(Boyet et al., 2023)

**F1: reactivated during fluid injection**
- pore pressure diffusion
- poroelastic stressing

**F2: reactivated during shut-in**
- pore pressure diffusion
- poroelastic relaxing

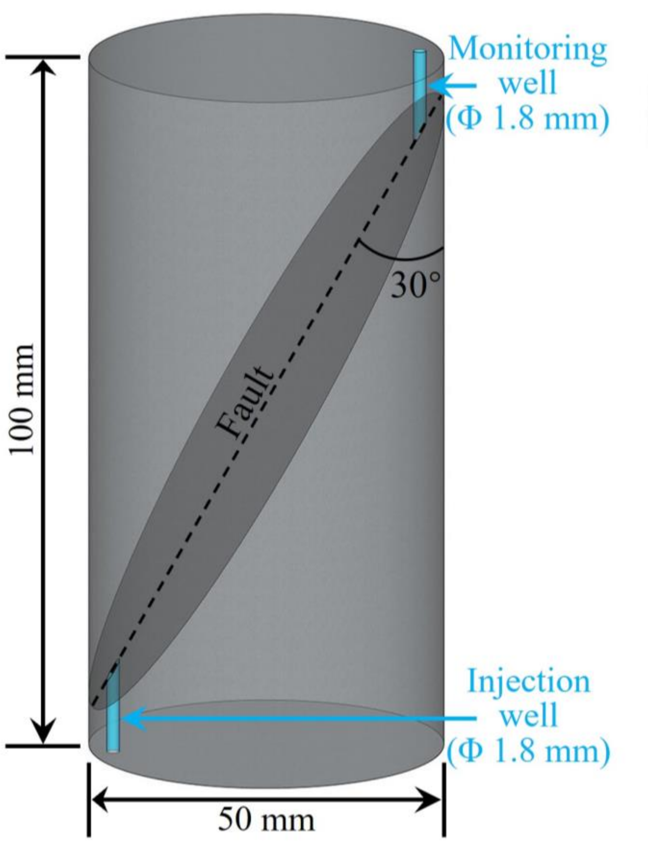
**F3: reactivated during shut-in**
- pore pressure diffusion
- poroelastic stressing
- Coulomb static stress transfer

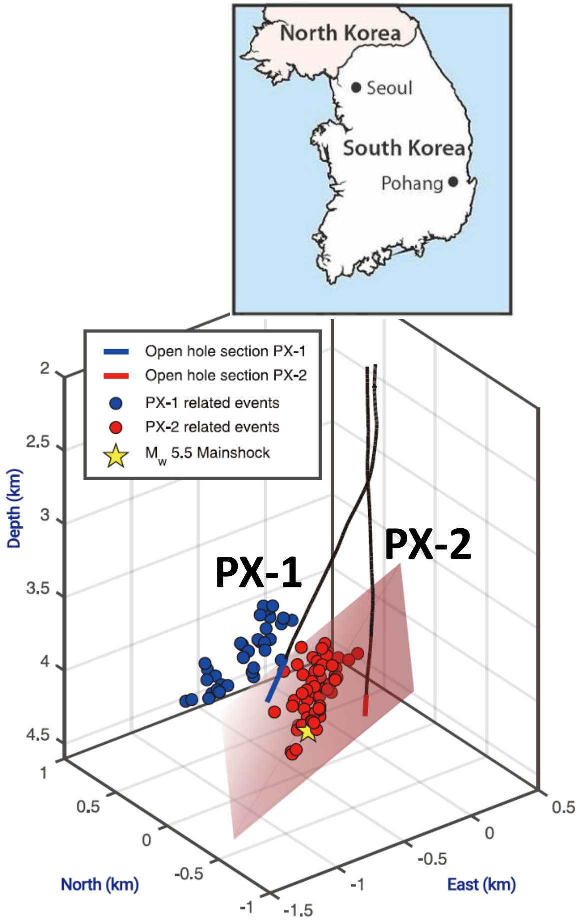
# Introduction: Objectives_cross-scale study on shut-in strategies

- Implement fluid extraction/tapering injection during shut-in in *lab-scale experiments on faults in representative deep geothermal reservoir rocks*.
- Execute fluid extraction/tapering injection during shut-in through *field-scale modelling of Pohang EGS*.
- Identify the *primary mechanisms* responsible for post-injection induced seismicity in EGS.
- Provide EGS operators with *recommendations for optimal shut-in strategies*.

# Methods: Laboratory-scale experiments and field-scale modelling

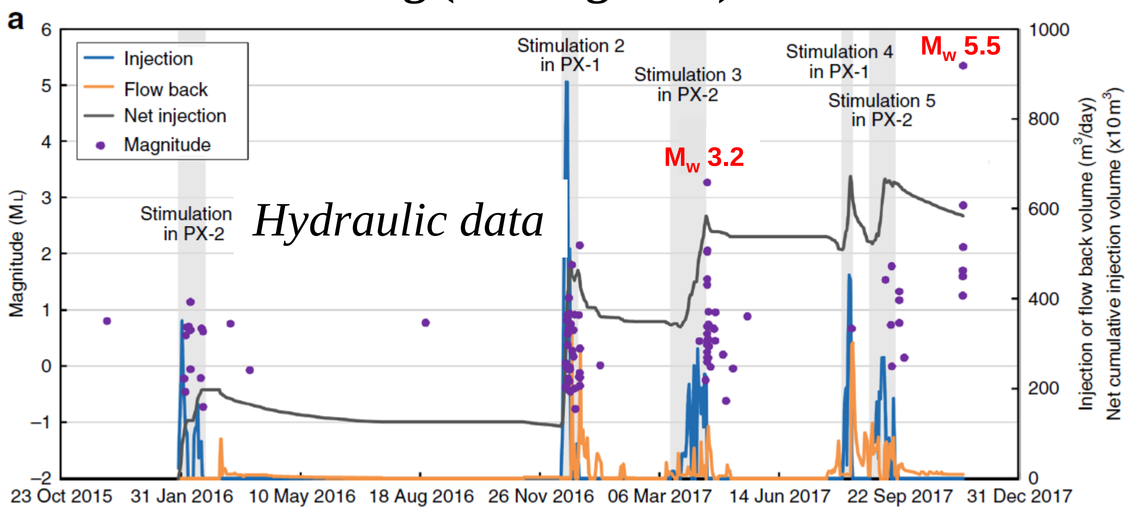
## Laboratory-scale experiments (granitic rocks)




- Well-controlled and monitored laboratory-scale experiments on faults in representative deep geothermal reservoir rocks.

## Field-scale modelling (Pohang EGS)



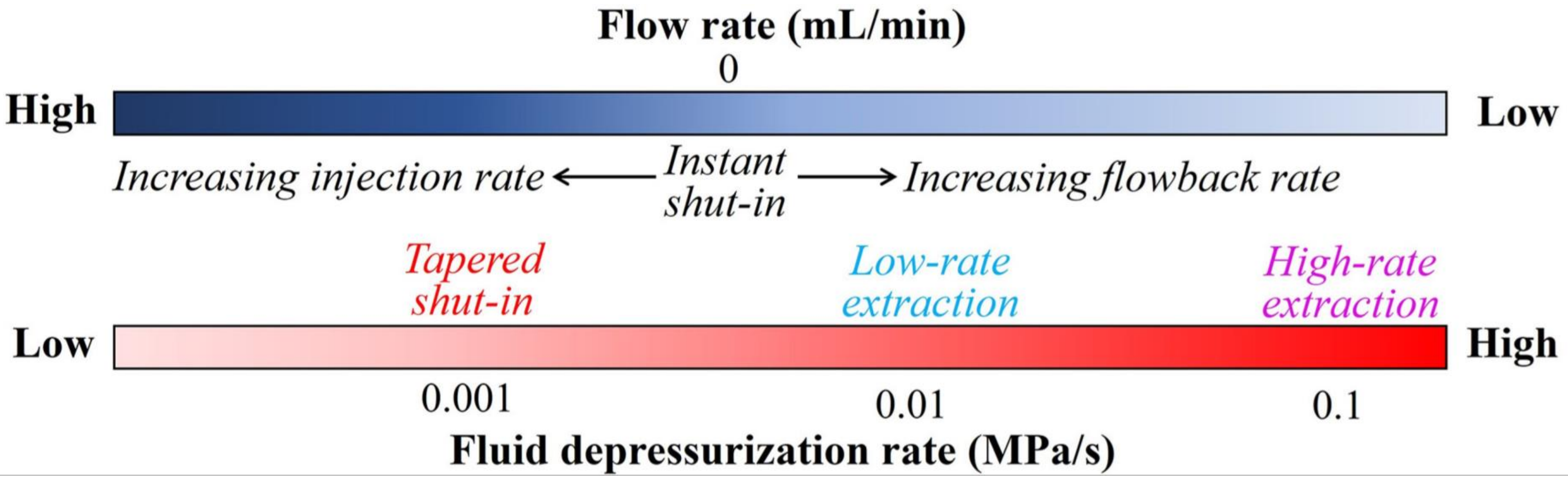

*Seismic events (not all shown here)*

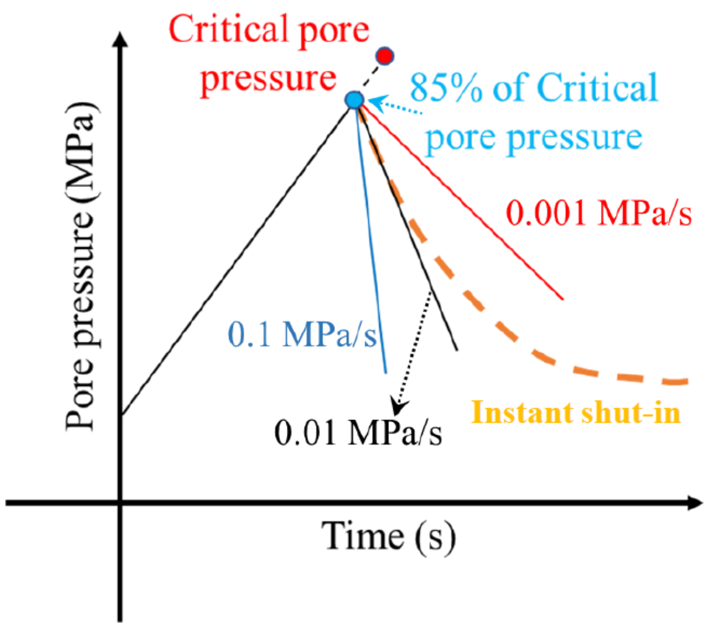
| Origin time (MM/DD/YY hh:mm:ss.sss) | Event Location | | | Magnitudes | | Focal Mechanism Nodal Plane Used | | | Coulomb Static Stress Results (Young's modulus = 80 GPa) | | | Coulomb Static Stress Results (Young's modulus = 50 GPa) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Latitude | Longitude | Depth (km) | Local Magnitude ($M_L$) | Moment Magnitude ($M_w$) | Strike | Dip | Rake | Coulomb Results at $M_w$ 3.2 Location (MPa) | Coulomb Results at $M_w$ 5.5 Location (MPa) | Coulomb Result at each event location (MPa) | Coulomb Results at $M_w$ 3.2 Location (MPa) | Coulomb Results at $M_w$ 5.5 Location (MPa) | Coulomb Result at each event location (MPa) |
| 11/30/2015 03:52:20.35 | 36.1091 | 129.3768 | 3.96 | 0.80 | 0.97 | 275.1 | 68.6 | 35.9 | NA | NA | NA | NA | NA | NA |
| 02/04/2016 03:55:45.64 | 36.1087 | 129.3757 | 4.09 | 0.55 | 0.94 | 206.5 | 56.0 | 94.7 | 1.13E-04 | 2.00E-05 | 5.14E-04 | 5.83E-05 | 1.25E-05 | 3.21E-04 |
| 02/04/2016 19:09:52.44 | 36.1088 | 129.3760 | 4.10 | 0.69 | 1.07 | 218.4 | 37.8 | 137.0 | 1.89E-04 | 3.82E-05 | 7.95E-03 | 1.18E-04 | 2.38E-05 | 4.97E-03 |
| 02/06/2016 05:11:31.03 | 36.1070 | 129.3759 | 4.06 | 0.70 | 1.17 | 219.5 | 38.3 | 139.8 | 3.77E-04 | 3.73E-05 | 1.09E-03 | 2.36E-04 | 2.33E-05 | 6.86E-04 |
| 02/06/2016 15:01:33.72 | 36.1087 | 129.3759 | 4.08 | 0.70 | 1.08 | 214.6 | 50.1 | 115.0 | 9.44E-04 | 7.90E-06 | 1.15E-01 | 5.90E-04 | 5.00E-06 | 7.17E-02 |
| 02/07/2016 22:04:12.28 | 36.1072 | 129.3750 | 4.11 | 1.14 | 1.62 | 207.9 | 57.8 | 156.4 | 1.14E-03 | 2.60E-05 | -1.90E-02 | 7.13E-04 | 1.62E-05 | -1.19E-02 |
| 02/07/2016 22:04:15.40 | 36.1071 | 129.3755 | 4.15 | 0.64 | 1.29 | 207.9 | 57.8 | 156.4 | 1.33E-02 | 2.84E-04 | -5.98E-02 | 8.33E-03 | 1.78E-04 | -3.74E-02 |
| 02/17/2016 07:43:44.02 | 36.1069 | 129.3752 | 4.07 | 0.67 | 1.09 | 212.8 | 53.1 | 151.9 | 1.84E-02 | 8.77E-05 | 1.02E-02 | 1.15E-02 | 5.48E-05 | 6.40E-03 |
| 02/18/2016 13:08:16.51 | 36.1083 | 129.3762 | 3.98 | 0.61 | 1.00 | 275.1 | 68.6 | 35.9 | 1.89E-02 | 8.27E-05 | 1.58E-03 | 1.18E-02 | 5.17E-05 | 9.89E-04 |
| 03/12/2016 07:25:46.75 | 36.1079 | 129.3752 | 4.03 | 0.76 | 1.17 | 344.7 | 34.5 | 93.8 | 1.91E-02 | 1.17E-04 | 3.85E-02 | 1.19E-02 | 7.32E-05 | 2.41E-02 |
| 08/22/2016 11:48:29.20 | 36.1083 | 129.3772 | 4.03 | 0.77 | 1.19 | 275.1 | 68.6 | 35.9 | 1.86E-02 | 1.27E-04 | -1.05E-02 | 1.16E-02 | 7.93E-05 | -6.58E-03 |
| 12/18/2016 18:43:44.36 | 36.1128 | 129.3718 | 4.27 | 0.82 | 1.47 | 234.0 | 54.2 | 150.6 | 1.85E-02 | 1.42E-04 | -1.59E-04 | 1.15E-02 | 8.88E-05 | -9.91E-05 |

- Well-calibrated numerical model for pore pressure diffusion
- Well-documented seismicity sequence for Coulomb static stress calculation

(Yeo et al., 2020; Ge and Saar, 2021)

# Methods: Design of shut-in strategies in this study




- Fluid extraction by fluid depressurization rates at 0.1 and 0.01 MPa/s
- Instant shut-in by abruptly setting a zero injection rate
- Tapered shut-in by fluid depressurization rate at 0.001 MPa/s

Spontaneous reduction rate of injection pressure in instant shut-in:

- *~0.002 MPa/s in the laboratory-scale experiment*
- *~0.003 MPa/s in the field-scale Pohang EGS*

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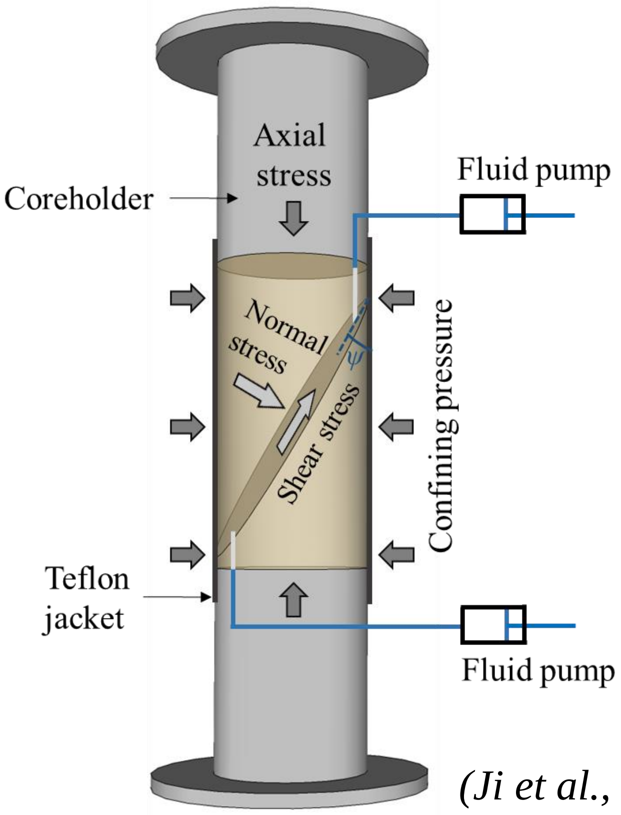
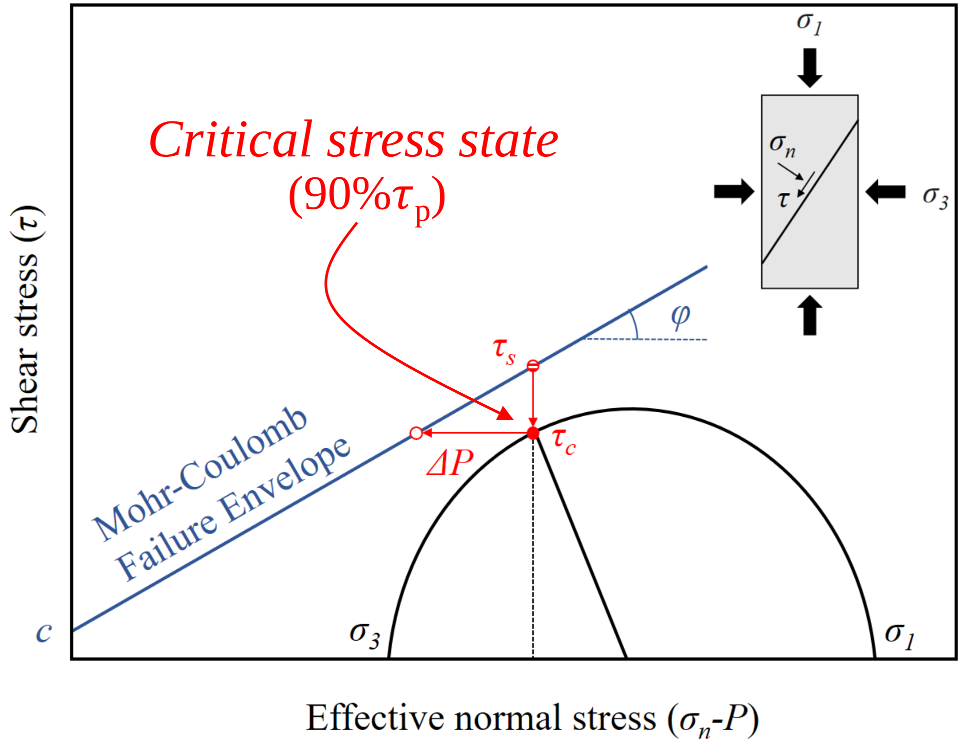
# Methods: Laboratory-scale experiments




(Ji et al., 2022)




**Matrix**

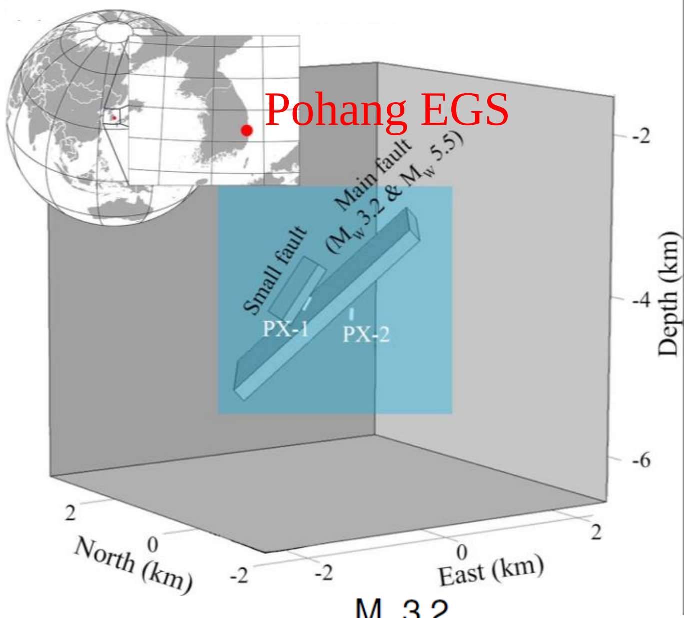
- **Rock type:** Odenwald granite in Germany, representative deep geothermal reservoir rock
- **Dimensions:** 50 mm diameter and 100 mm height

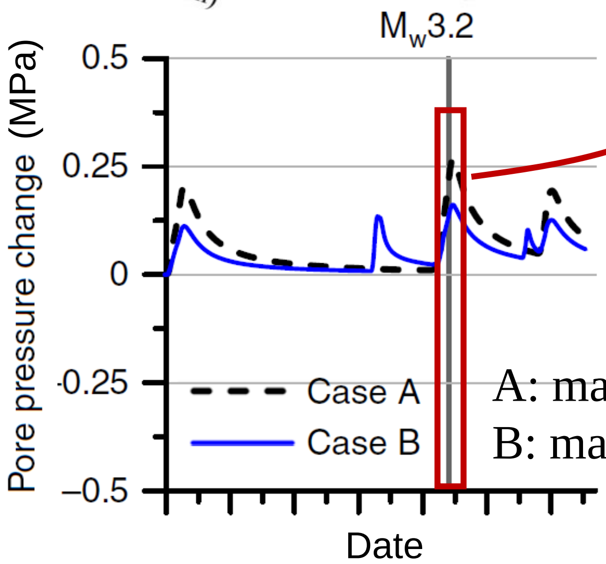
**Fault**

- **Inclination angle:** 30° to the sample axis
- **Roughness:** ground by sandpaper with a particle size of 30.2 $\mu$m

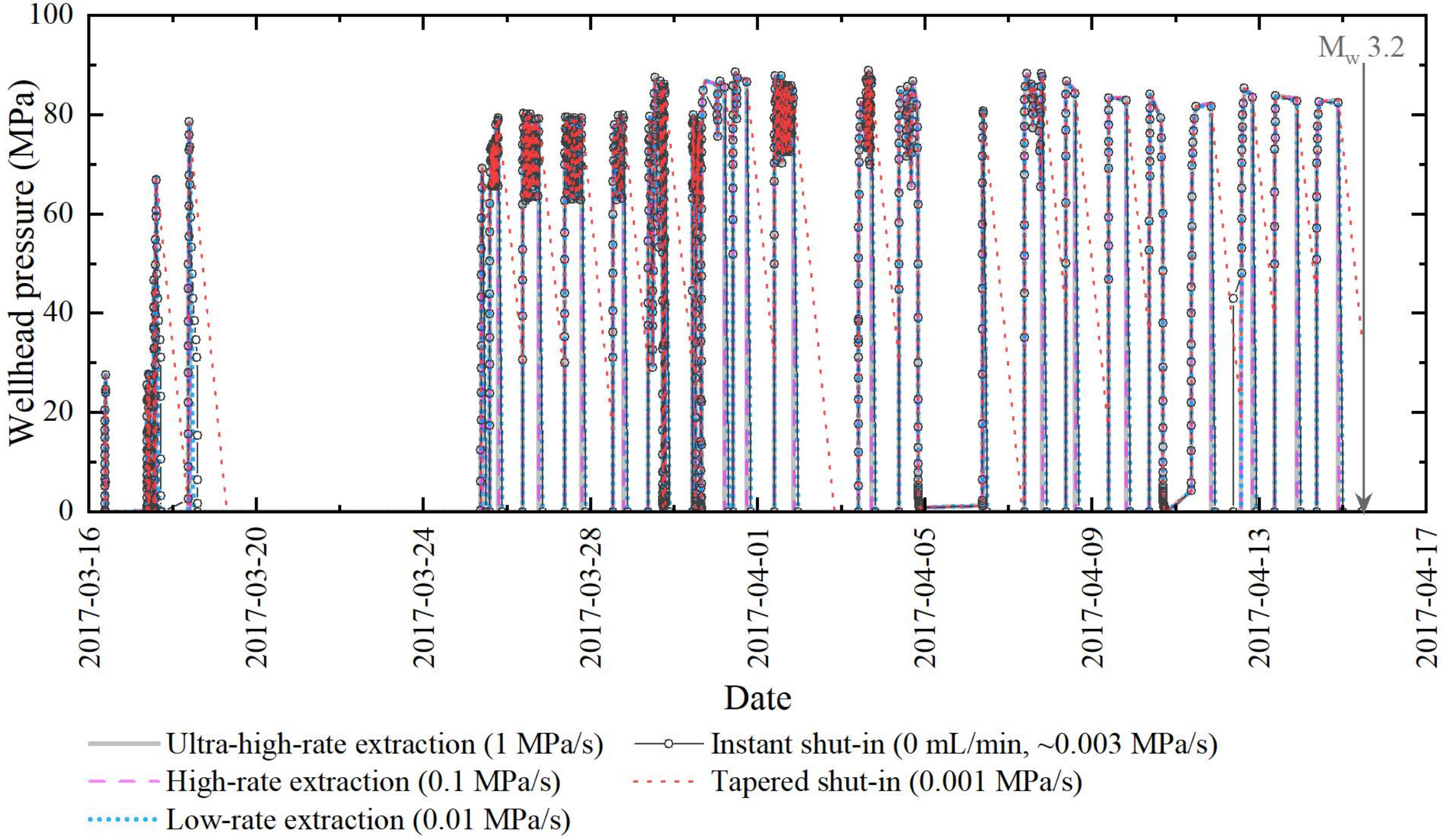
# Methods: Field-scale modelling

Well-calibrated 3D finite element model for pore pressure diffusion



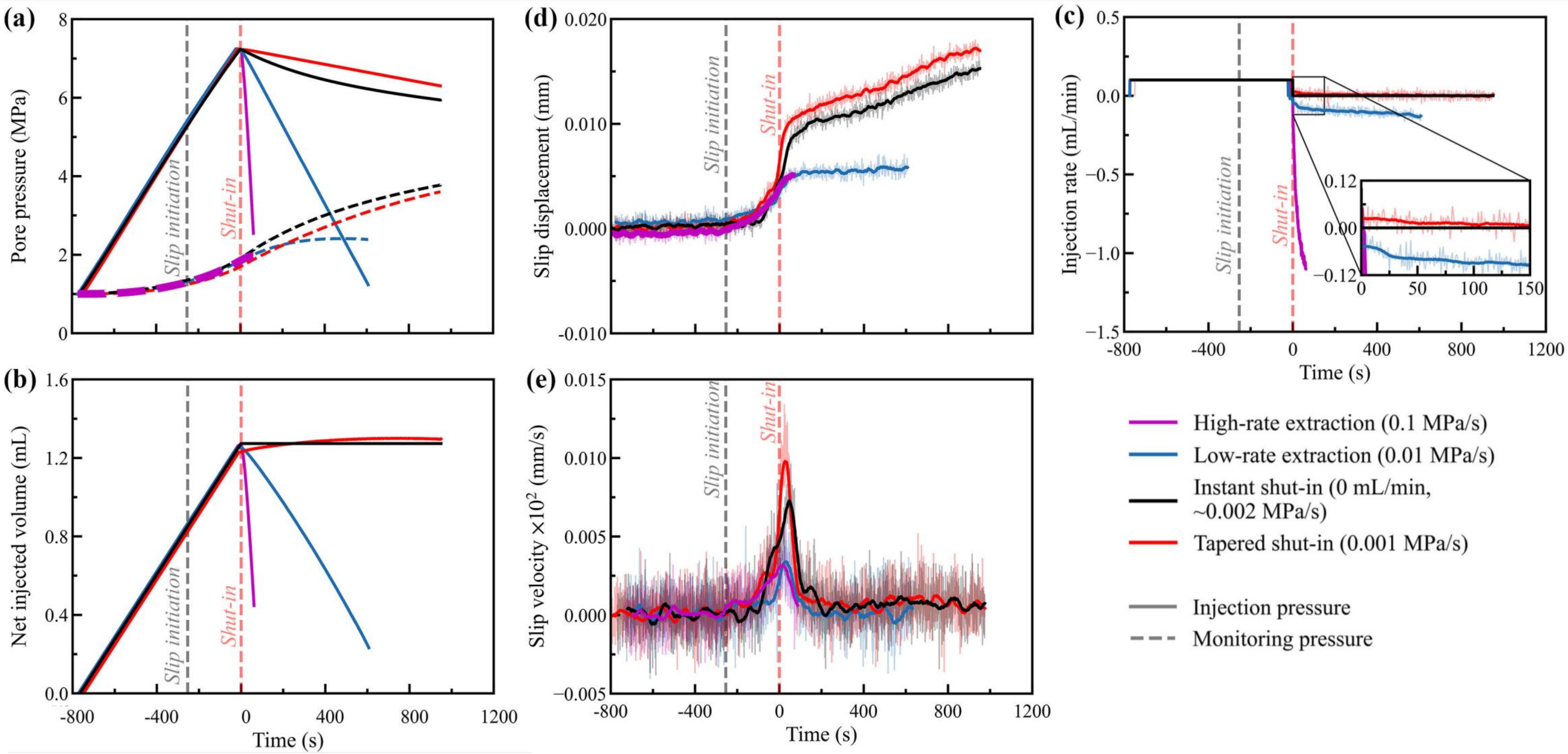

3rd Stimulation in PX-2




A: main fault with a low-permeability fault core
B: main fault without a low-permeability fault core

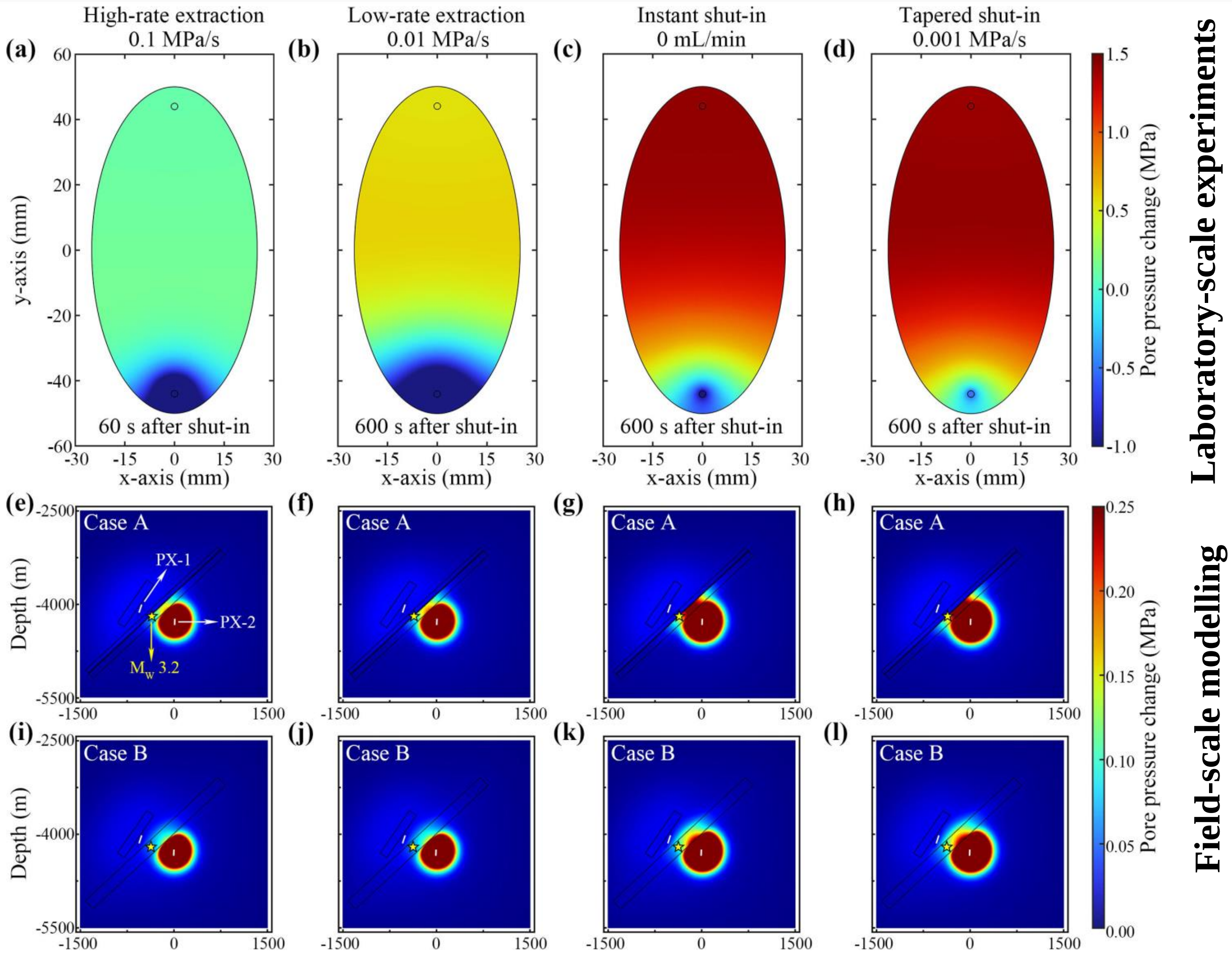
(Yeo et al., 2020)

# Results: Changes of hydromechanical parameters in laboratory-scale experiments




- Flowback (less net injected volume) tends to reduce the dynamic fault slip velocity and prevent aseismic slip.
- Tapered shut-in (more net injected volume) and instant shut-in further increase the fault slip velocity, and sustain aseismic slip.

# Results: Cross-scale pore pressure change contours




A: main fault with a low-permeability fault core
B: main fault without a low-permeability fault core

**Laboratory-scale experiments**

- lab-scale pore pressure diffusion is modelled also by finite element modelling (Ji et al., 2020).
- same time after injection (60s in high-rate flowback)
- magnitude of pore pressure change is reduced by flowback while it is enhanced by tapered shut-in.

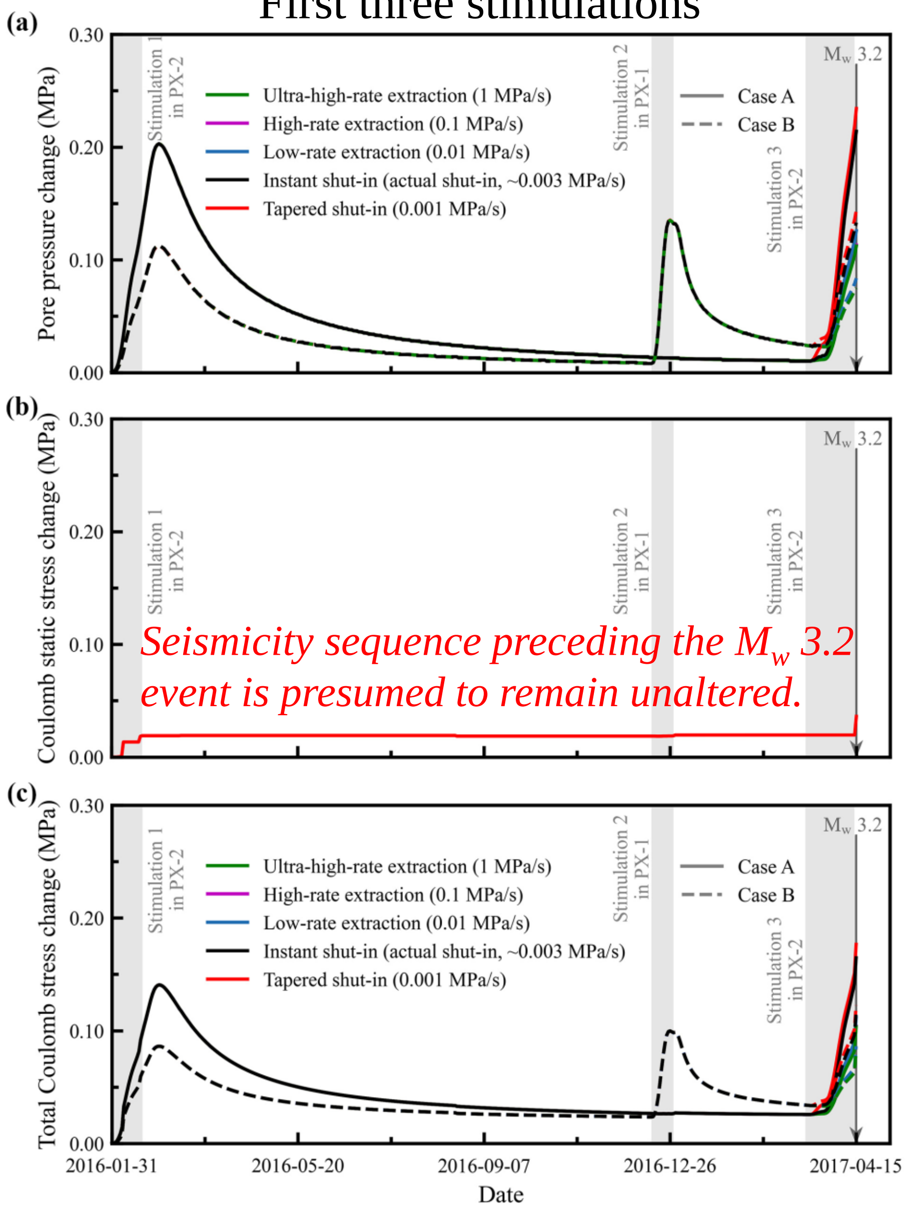
**Field-scale modelling**

- at the time of $M_w$ 3.2 event
- in Case A, the enhanced diffusion along the main fault is due to the low-permeability fault core.
- magnitude of pore pressure change is reduced by flowback while it is enhanced by tapered shut-in.

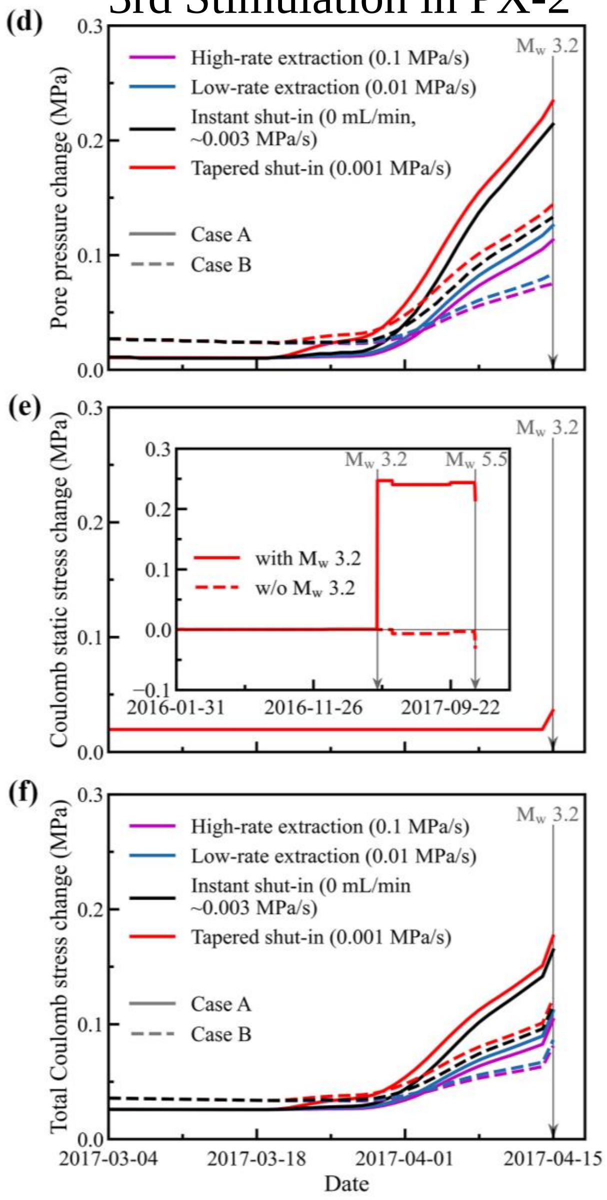
# Results: Cross-scale temporal change of pore pressure and Coulomb stress

**Field-scale modelling**

## First three stimulations

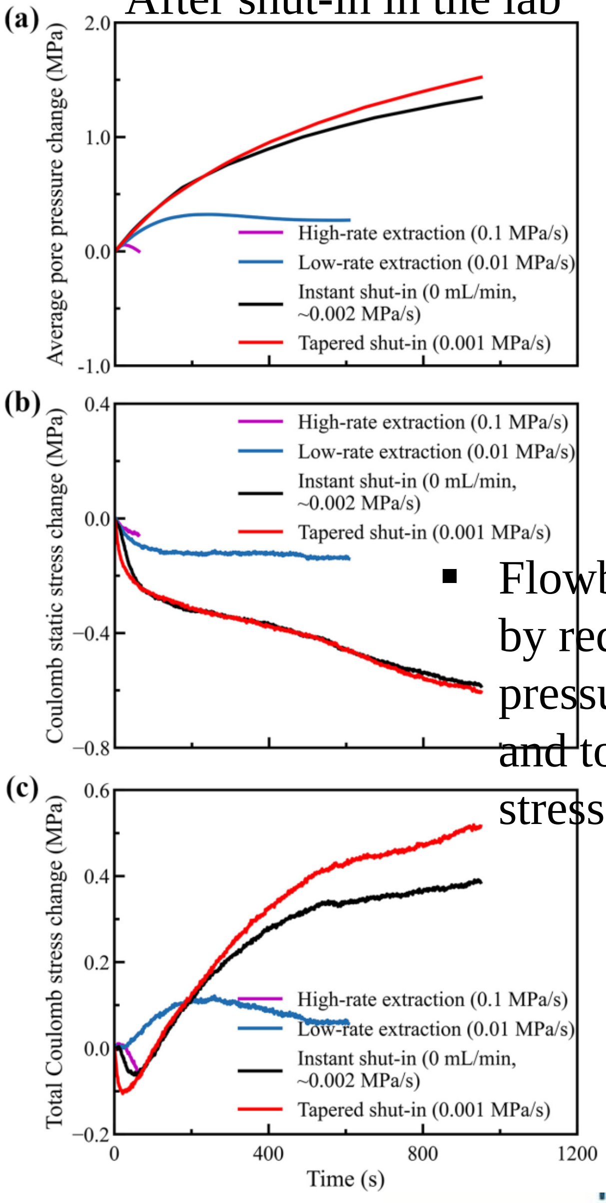



## 3rd Stimulation in PX-2



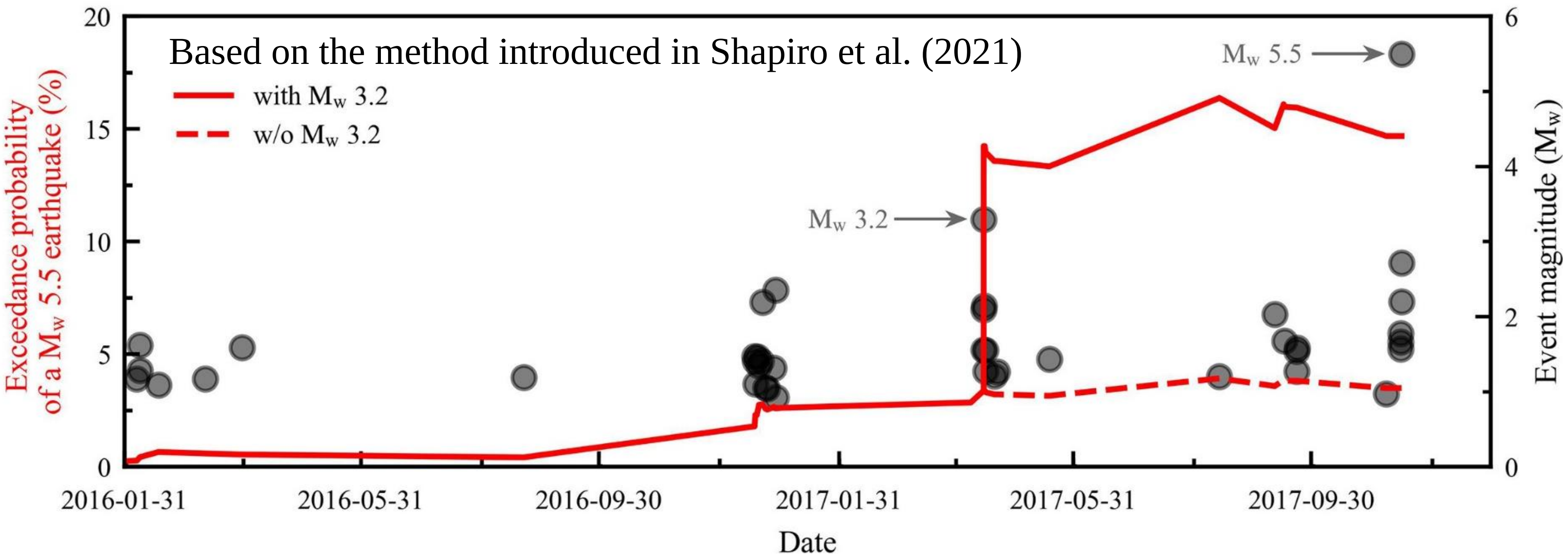

**Laboratory-scale experiments**

## After shut-in in the lab




- Flowback is safer by reducing pore pressure change, and total Coulomb stress change!

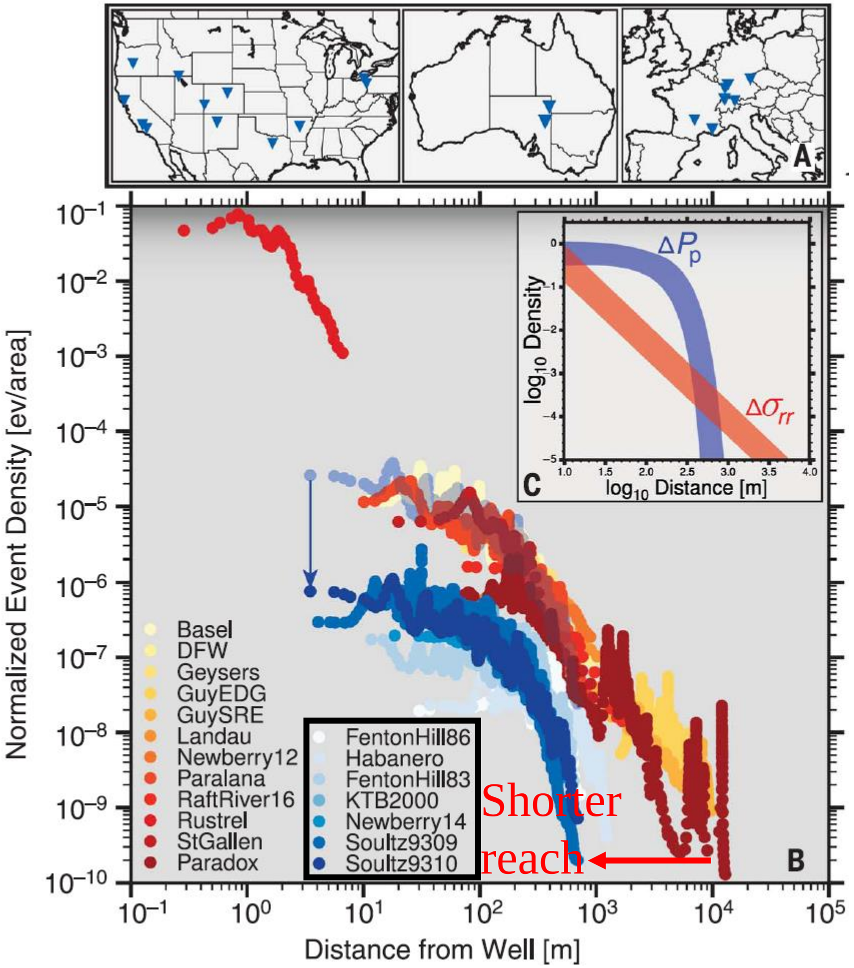
# Results: The 2017 $M_w$ 5.5 Pohang earthquake could have been mitigated

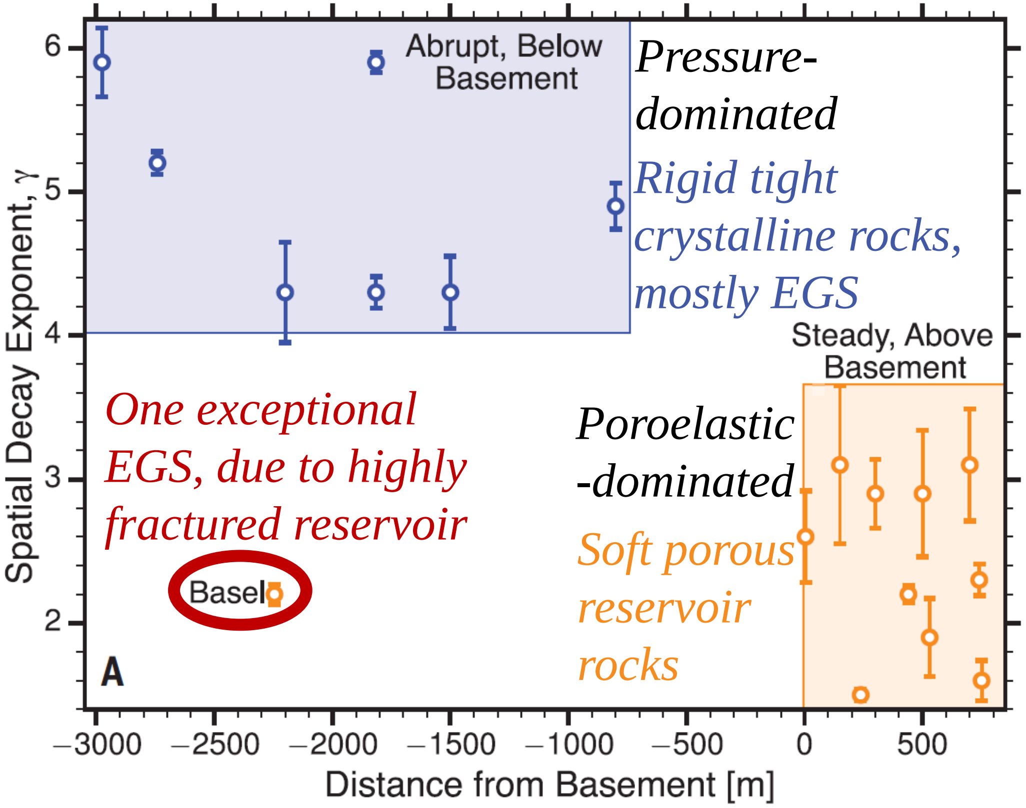



- ***Significantly reduced exceedance probability of a $M_w$ 5.5 earthquake!***

# Conclusion and Discussion

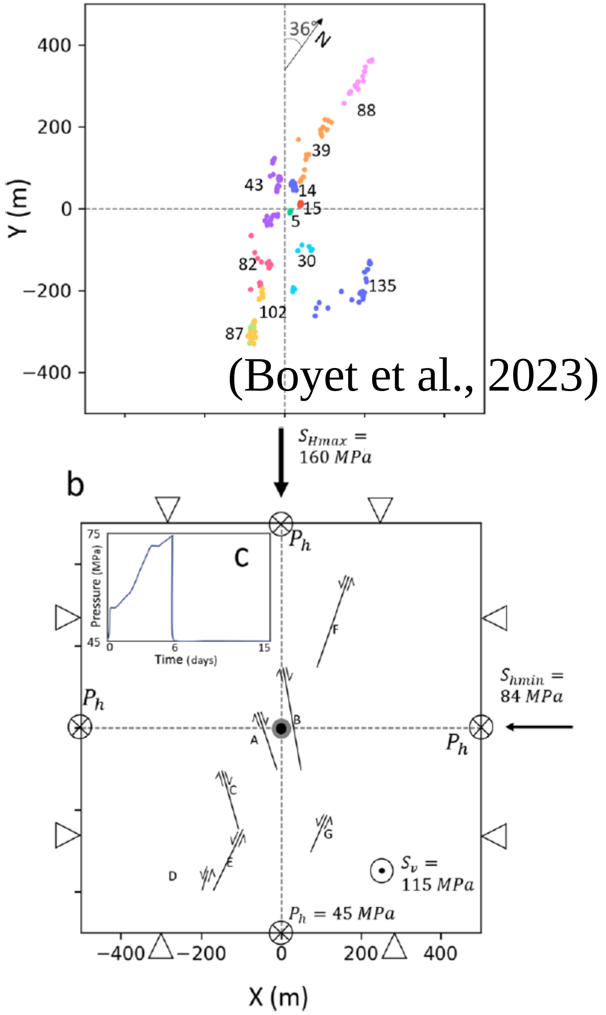
**Poroelastic effects is minimal in most EGSs**




(Goebel and Brodsky, 2018)

***Highly fractured Basel EGS with strong poroelastic effects***




- ***Immediate fluid extraction after injection could mitigate post-injection induced seismicity in EGS within low-permeability crystalline rocks.***