Hydro-mechanical modelling of induced seismicity during the deep geothermal project in St. Gallen, Switzerland

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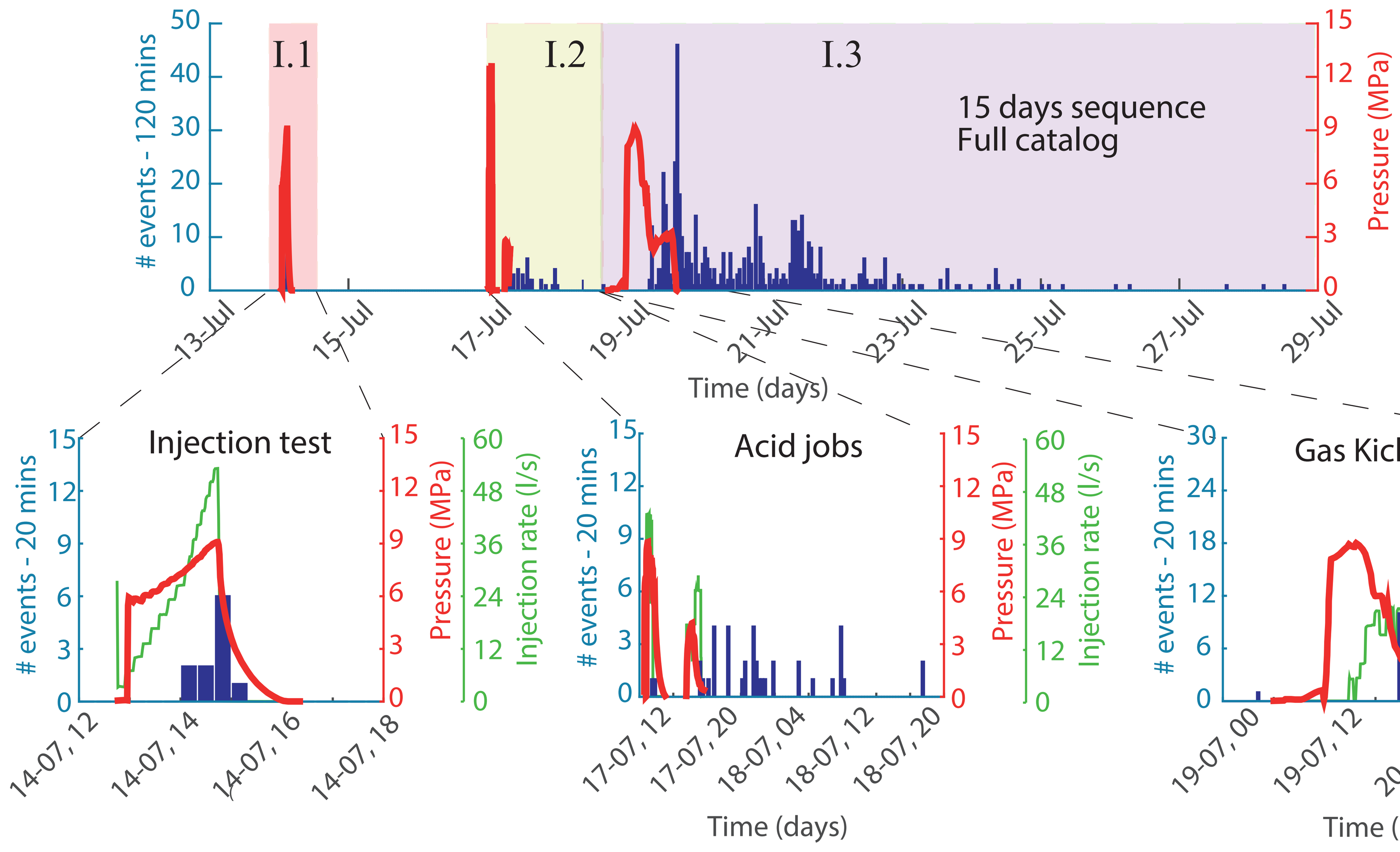
1 Introduction

The deep geothermal project in St. Gallen in 2013 was the second large geothermal project in Switzerland after the enhanced geothermal system (EGS) in Basel in 2006. In St. Gallen, after an injectivity test and two acid stimulations to estimate the properties of the reservoir, gas entered the borehole from an unknown source, which caused the operators to inject drilling mud to fight the gas kick. These measures lead to several seismic events, the largest one having a local magnitude of 3.5 [1]. The project was later halted because the geothermal reservoir was not as permeable as expected. The St. Gallen project shows that is crucial to understand the fluid-rock interaction at depth to more accurately determine the seismic hazard for such projects. In this study, we perform hydro-mechanical simulations to better determine the reasons for the induced seismicity in St. Gallen. Here, we show the conceptual model and some preliminary simulations to support our idea.

2 Induced seismicity in St. Gallen during the geothermal

The injectivity test and the two acid stimulations caused several small earthquakes with $M_L < 1$. Most of the seismicity occurred during and after the well control measures after July 19 (including the main event (M_L 3.5)).



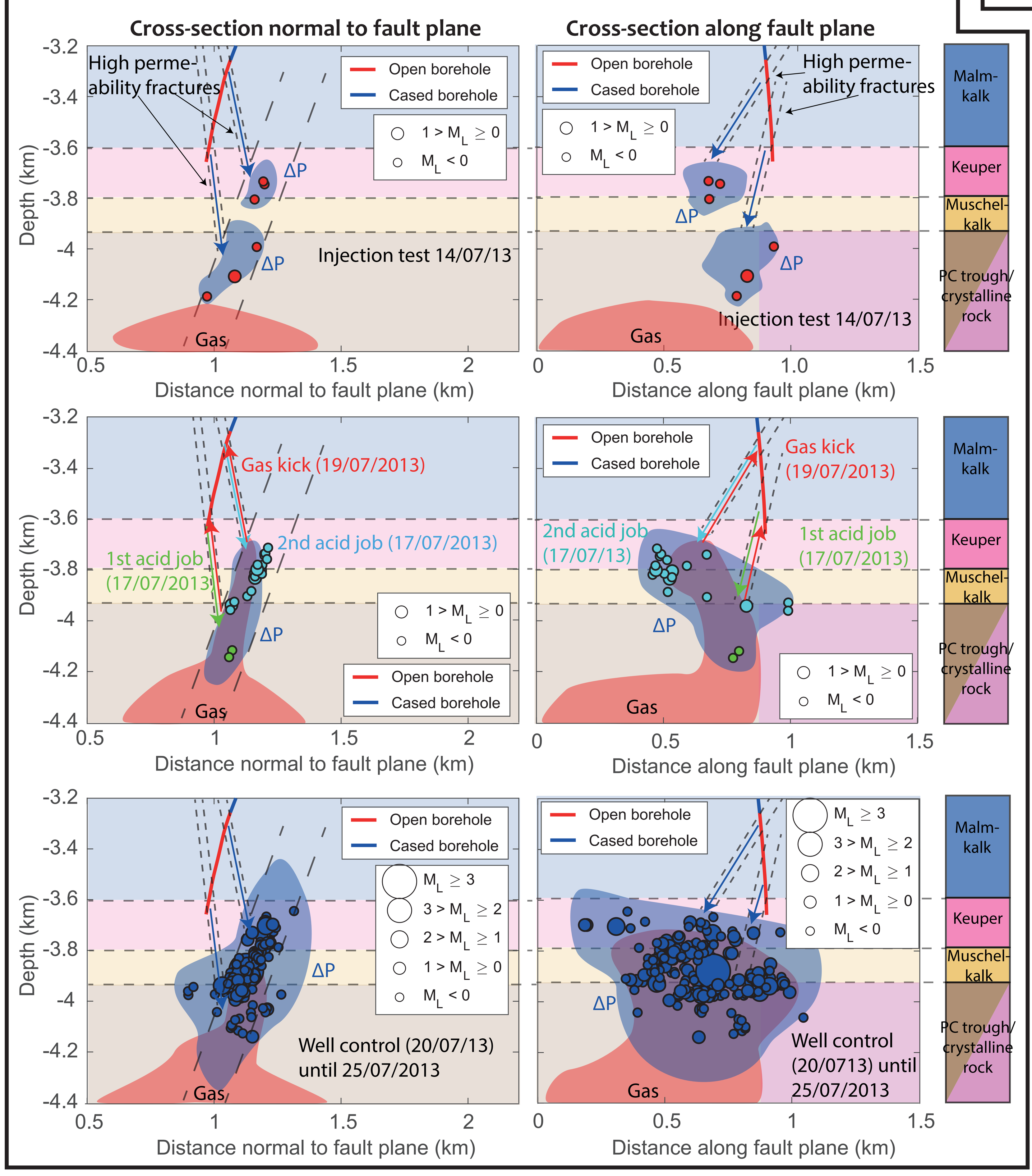
Number of detected seismic events [2], injection rates and well head pressure [3] for injectivity test, acid stimulations and well control measures.

3 Conceptual model

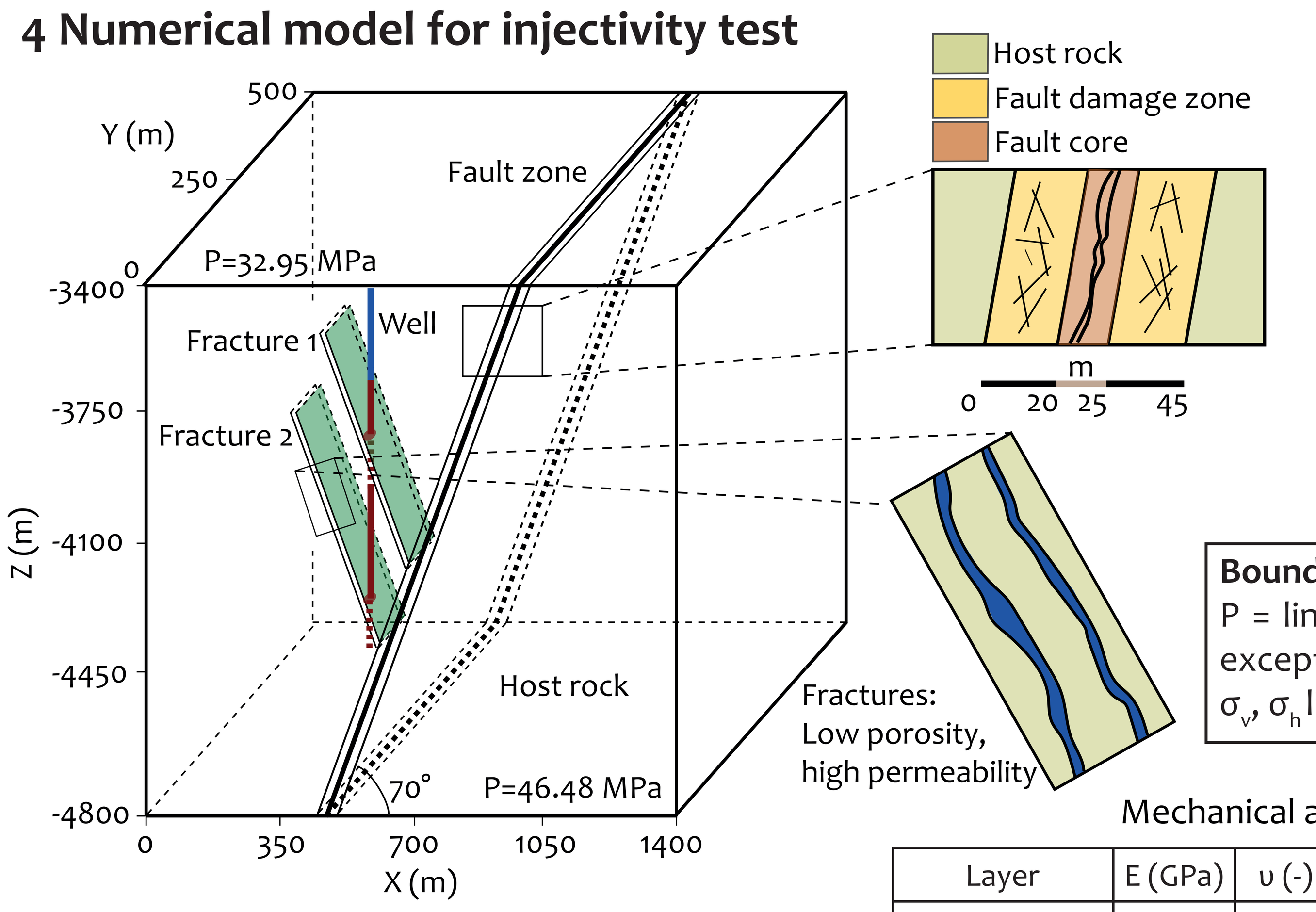
- Temperature, GR logs and analysis of well cuttings show evidence for at least **2 inflow zones** at open section of the well [3]
- Seismicity (located events) after injectivity test and acid stimulations starts to spread from 2 distinct areas [2]
- **2 major fractures connecting the borehole with the fault** might be present.

What could have happened in SG:

1. Fluid reaches fault plane through fractures
2. P increase on fault plane causes seismicity
3. P increase and seismicity enhances permeability
4. Gas enters fractures and borehole (gas kick)
5. Fluid and gas destabilises large area on fault leading to M_L 3.5 event



4 Numerical model for injectivity test



Well
- Cased section
- Open section
- Well cuts fractures

Initial conditions
Hydrostatic P
σ_3/σ_1=0.56

Boundary conditions
P = linearly increasing with z, except at y=0 (no flow)
σ_v, σ_h linearly increasing with z

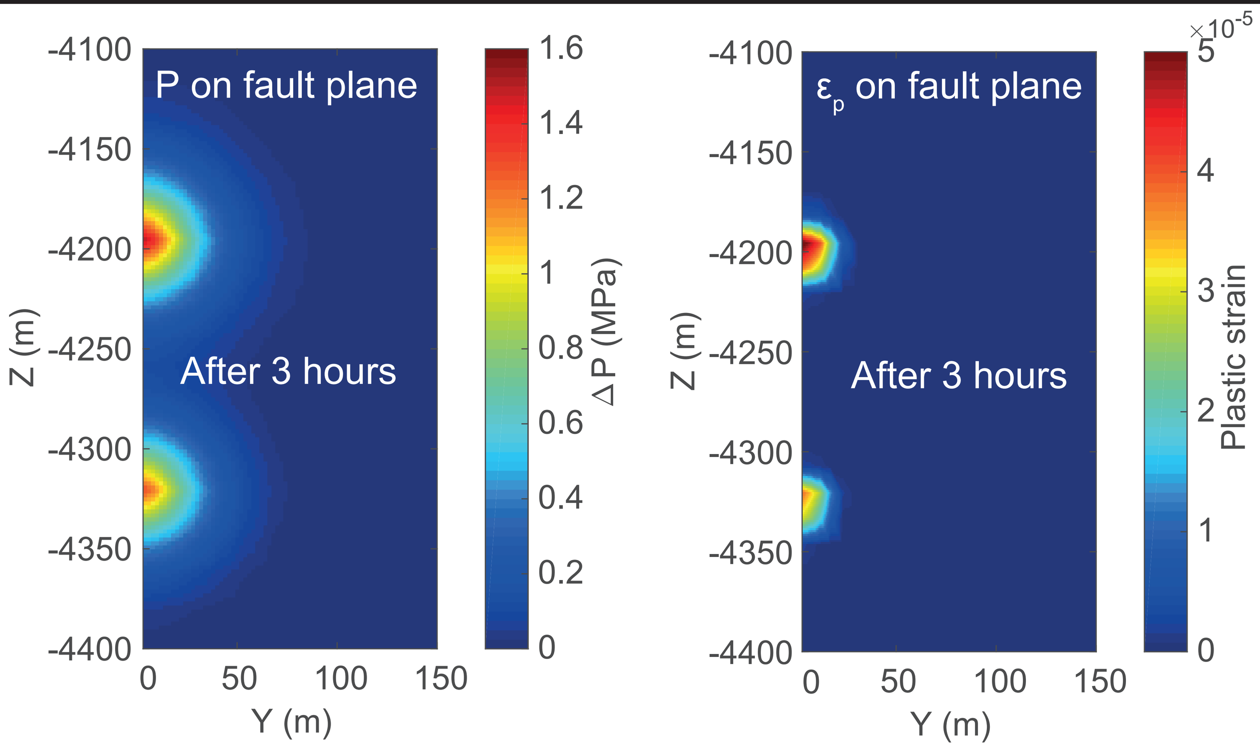
Mechanical and hydraulic parameters

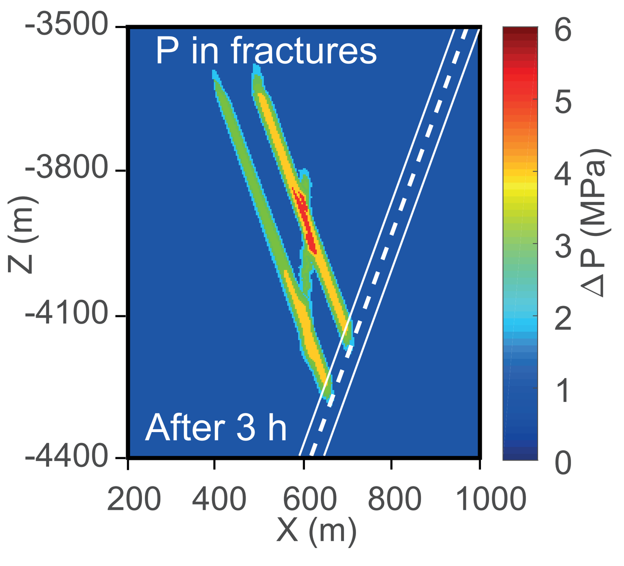
Layer	E (GPa)	υ (-)	ρ (kg/m³)	φ (%)	κ (m²)
Host rock	30	0.25	2650	8	10^{-17}
Fractures	30	0.25	2650	2	10^{-12}
Damage zone	30	0.25	2650	10	10^{-15}
Fault core	10	0.25	2650	10	10^{-17}

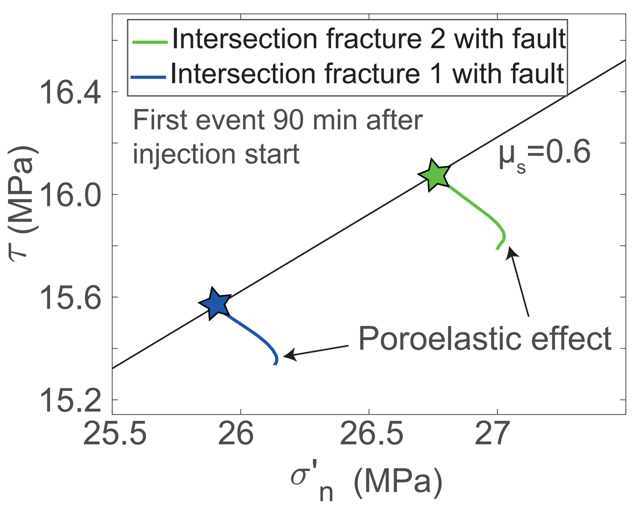
Fluid is injected into the well using the **rates from the injectivity test** [3]. The fault is initially highly stressed, in agreement with tectonic stress estimations in the St. Gallen area [4]. We use the coupled hydro-mechanical simulator TOUGH-FLAC [5] for the simulations.

The simulation with **fracture permeability of 10^{-12} m²** yields
i) ΔP = 9.7 MPa at open section of the well after 2 hours,
ii) ΔP = 1.6 MPa at intersection of fracture 1 and fault core after 3 hours,
iii) ΔP = 1.4 MPa at intersection of fracture 2 and fault core after 3 hours.

For a highly critically stressed fault, this pressure increase can **destabilise two patches of ~100 m² on average**. The pressure increase at the lower fracture is slightly less pronounced because injection occurs above the upper fracture.



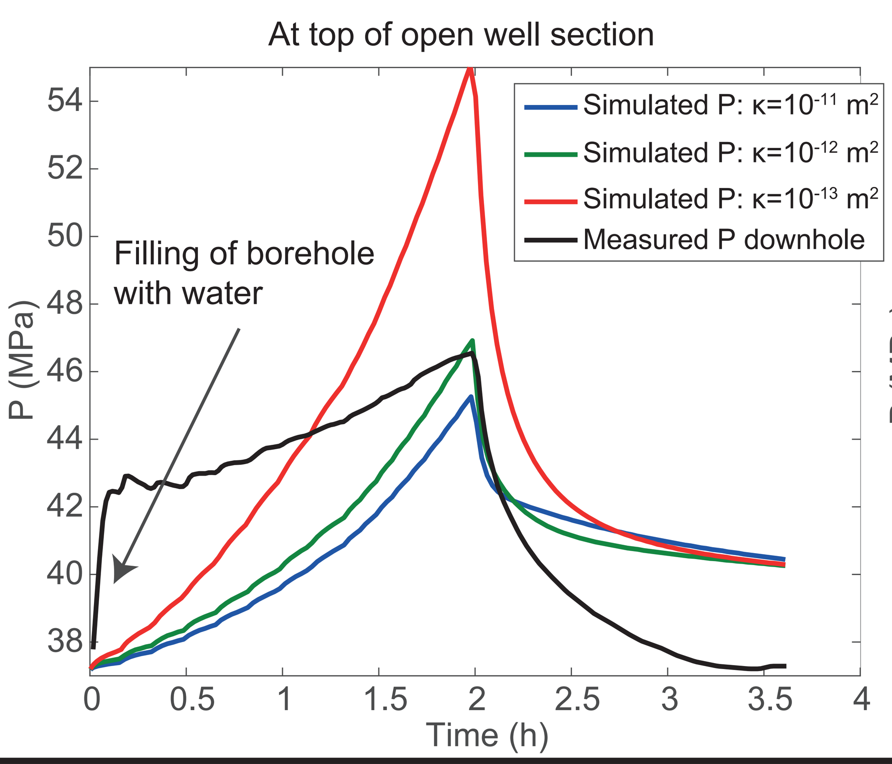


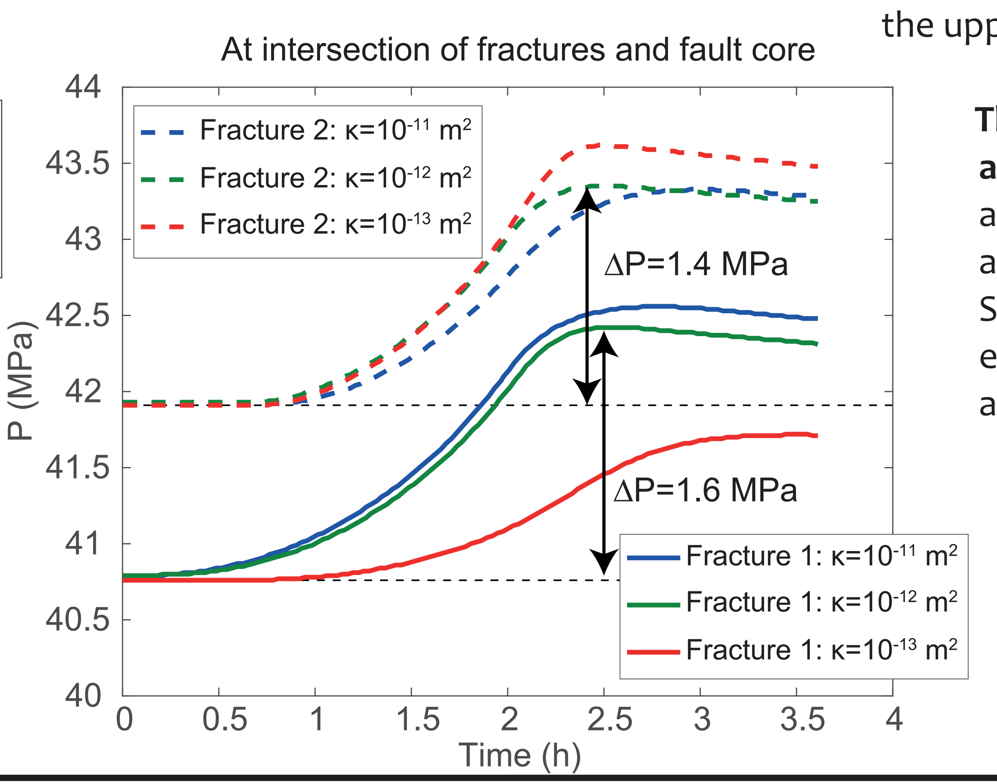


The first event occurs after 1.5 h, which agrees well with the actual seismicity in SG, where the first event was induced after ~80 min [2].

5 Preliminary results

- Fracture permeability κ_{frac} **of 10^{-12} m² yields the best ΔP** at the well compared to field data
- Highest P change at intersection of fracture 1 and fault plane with fracture permeability of 10^{-11} m²
- Highest P change at intersection of fracture 2 and fault plane with fracture permeability 10^{-13} m²





6 Conclusions and outlook

- Conceptual model explaining main features of induced seismicity sequence in St. Gallen after injectivity test, acid stimulations and well control measures
- Numerical model for injectivity test shows P increase on fault plane of ~1.5 MPa
- P increase **sufficient to induce seismicity** on highly stressed fault

Next steps:

i) Implement P dependent permeability of fractures and fault, ii) implement permeability dependence of fault on seismic events, iii) include gas (multi-phase fluid flow).

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