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Multiphase fluid flow and geomechanical analysis of the induced seismicity at the geothermal project in St. Gallen (Switzerland)

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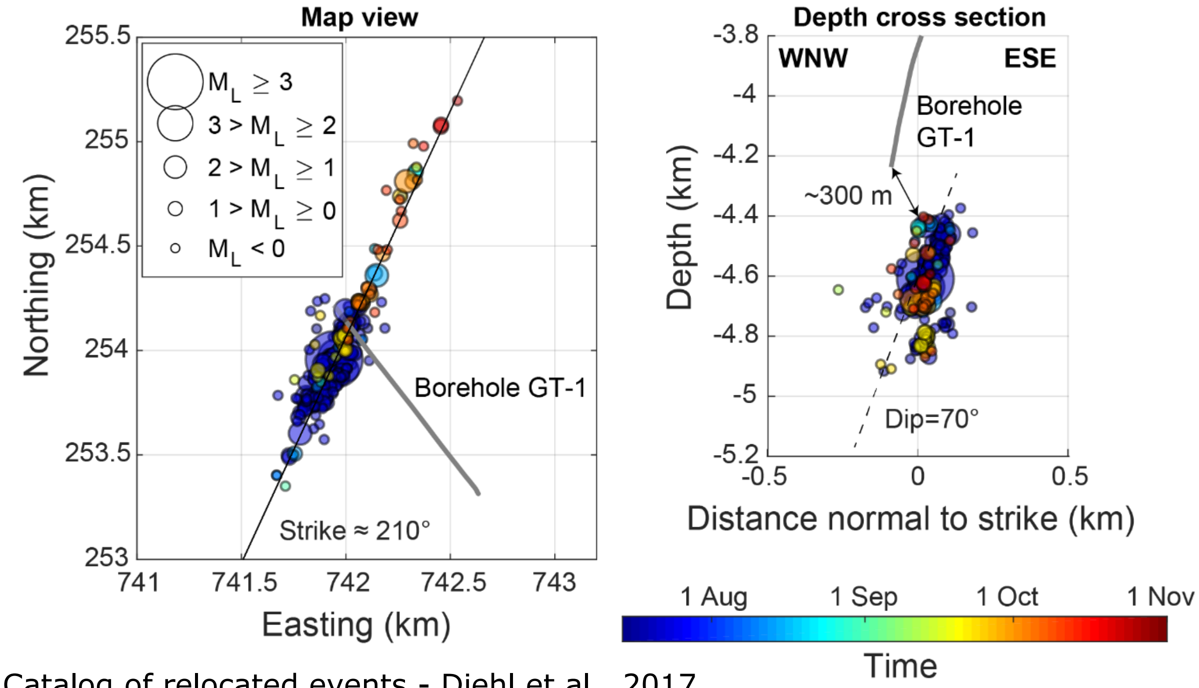
Photography encouraged

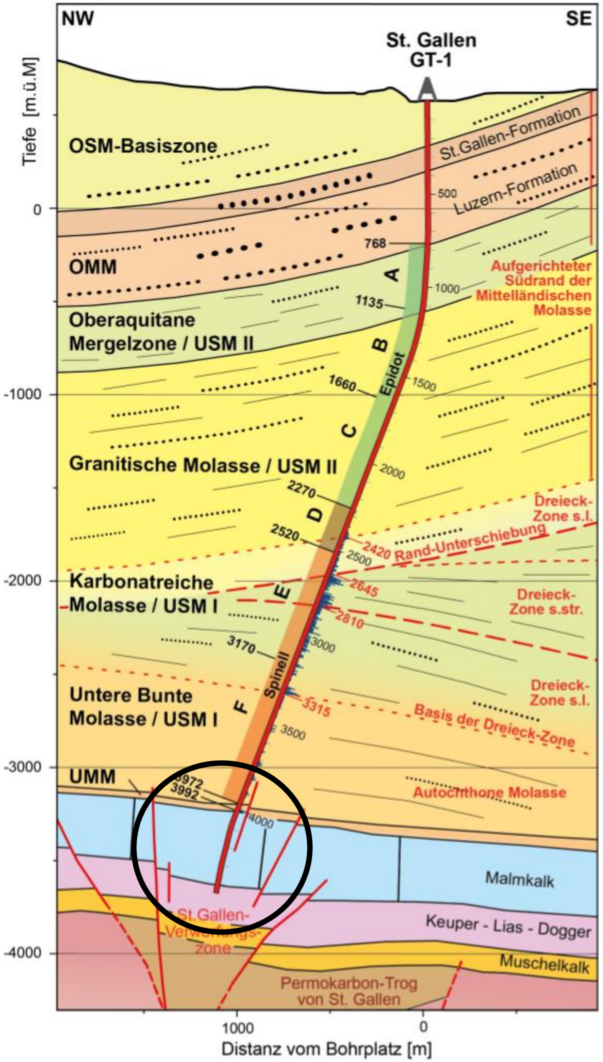
11 April, 2019

The St. Gallen deep geothermal project

Mar-Jul 2013	Borehole drilling into Malm (~4 km depth)
14-20 Jul 2013	Pre-stimulation phase
14-31 Jul 2013	~250 induced seismic events (relocated)
	ML 3.5 earthquake (20 July)



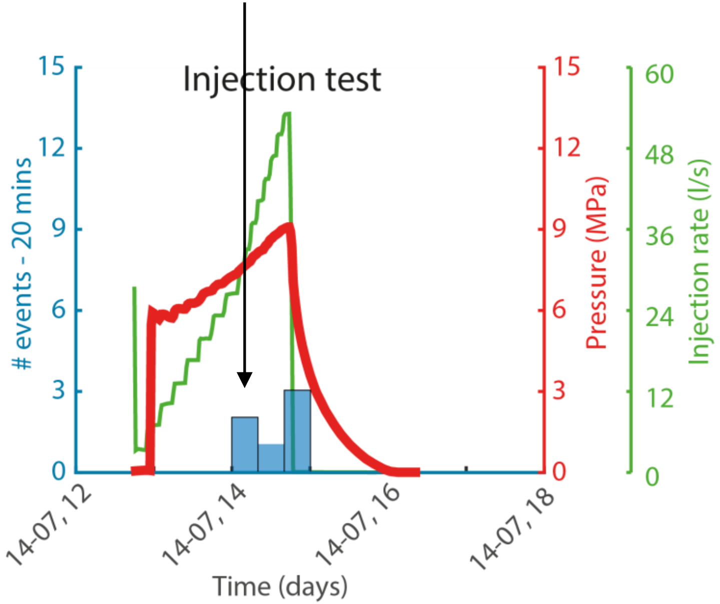
Catalog of relocated events - Diehl et al., 2017



Naef and Schlanke (geosfer ag), 2014

July 2013 – injection test

First few microseismic events ~80 minutes after the start of injection



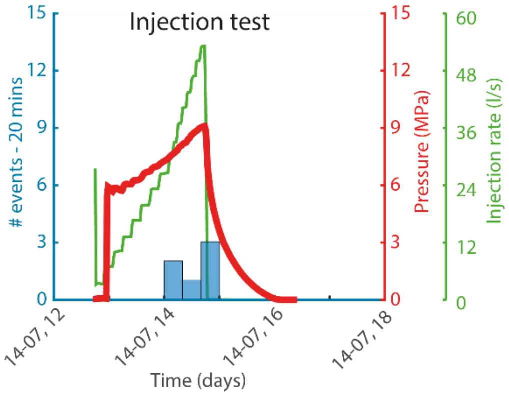
14 July

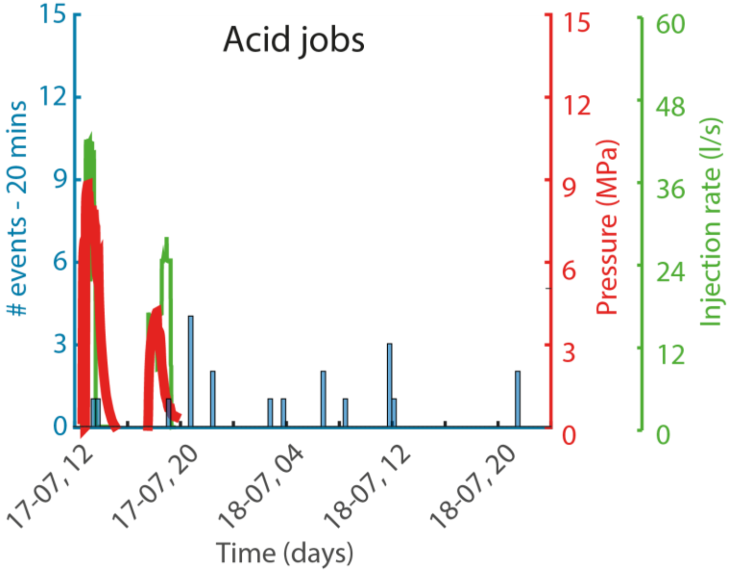
Injection test (175 m^3)

Time

Catalog of relocated events - Diehl et al., 2017
Pressures and injection rates - Wolfgramm (GTN), 2014

July 2013 – acid jobs





14 July

Injection test (175 m^3)

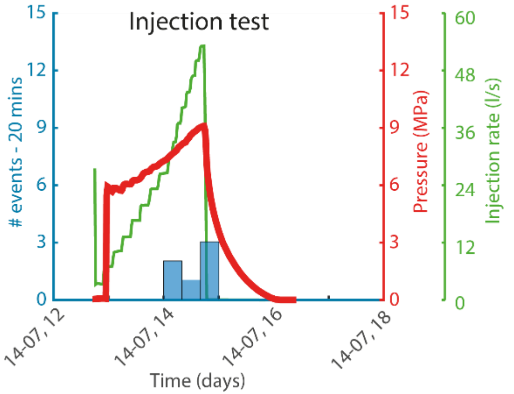
17 July

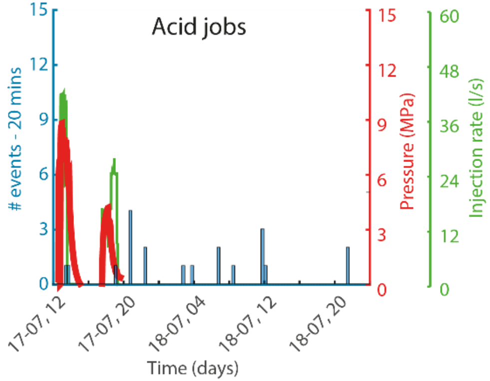
Acid stimulations (290 m^3)

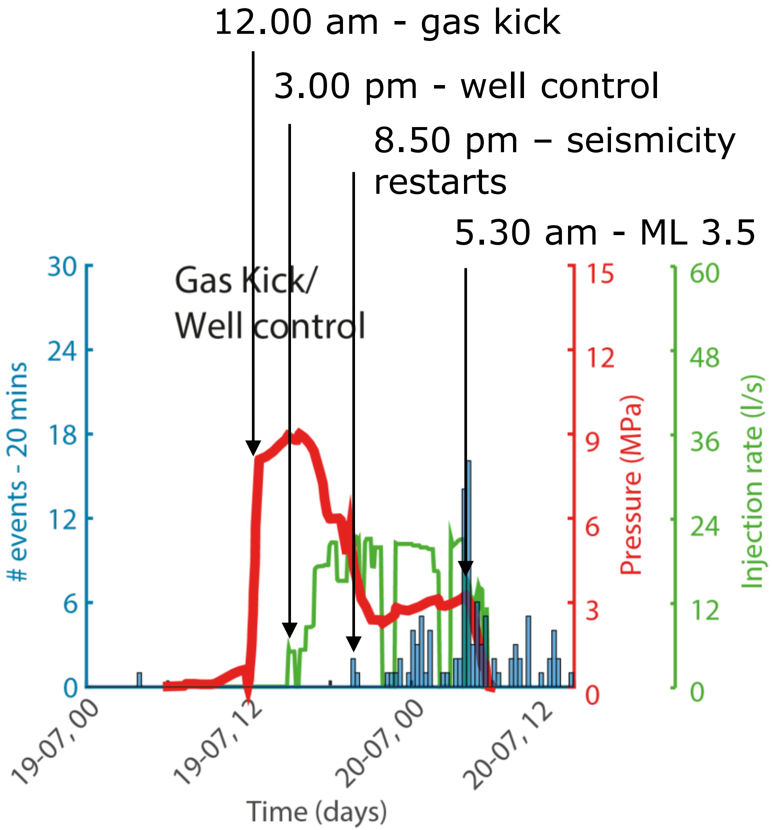
Time

Catalog of relocated events - Diehl et al., 2017
Pressures and injection rates - Wolfgramm (GTN), 2014

July 2013 – gas kick and well control







14 July

Injection test (175 m^3)

17 July

Acid stimulations (290 m^3)

19/20 July

Gas kick and well control measures (700 m^3)

Time

Catalog of relocated events - Diehl et al., 2017
Pressures and injection rates - Wolfgramm (GTN), 2014

Motivation and outline

Part I

Understanding possible physical mechanisms that led to the induced seismicity

- Single-phase hydro-mechanical model (TOUGH-FLAC – Rutqvist, 2011) with two scenarios: hydraulic connection (fracture zone) vs. poroelasticity (mini-fracture)

Part II

Understanding the potential influence of the gas on the induced seismicity

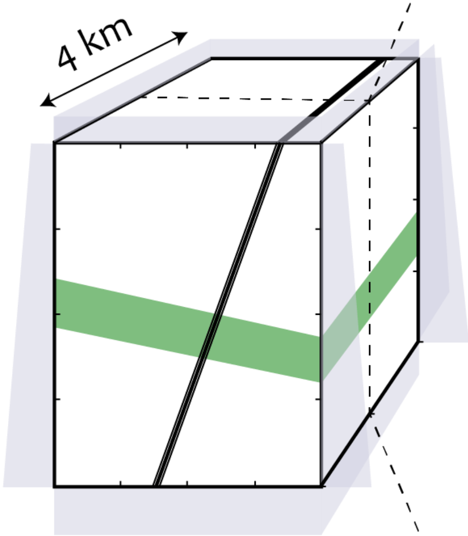
- Multi-phase fluid flow model coupled with a stochastic-geomechanical model (TOUGH2-Seed – Rinaldi and Nespoli, 2017)
- Hydraulic connection is used to simulate gas kick, well control measures and evolution of induced seismicity during the main sequence

2013, Stadt St.Gallen / St.Galler Stadtwerke

Part I: TOUGH-FLAC model

Full model domain

1.4 km x 4 km x 1.8 km



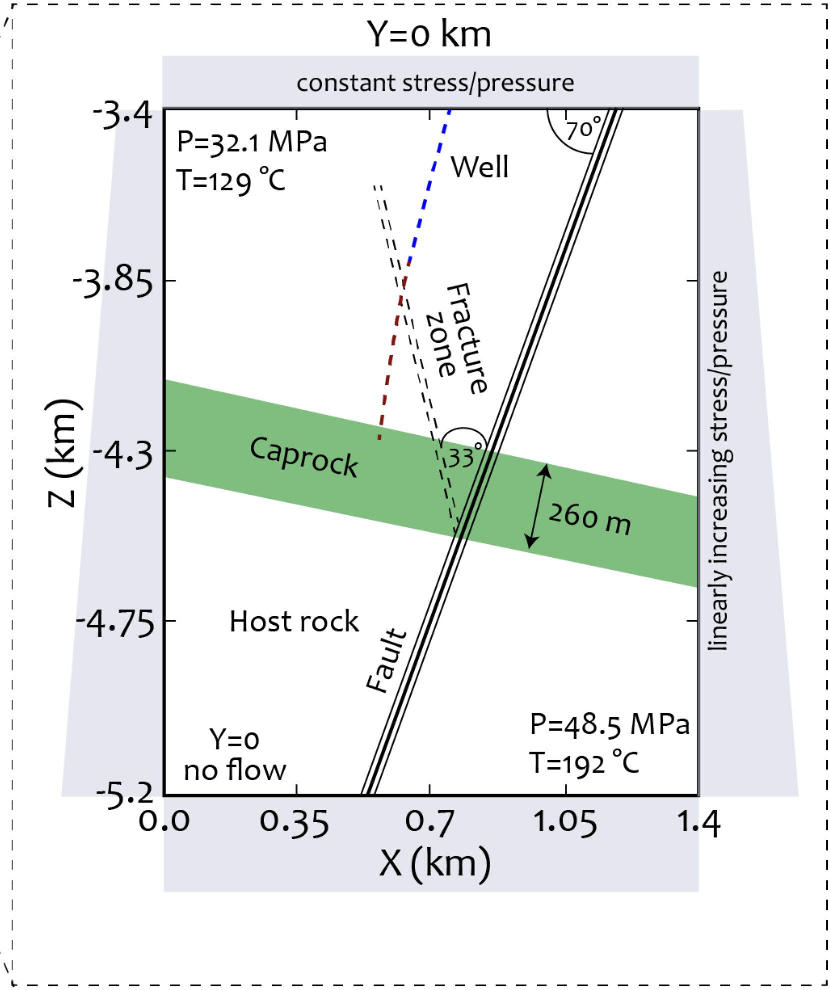
Scenarios

Mini fracture:

20 m x 250 m x 115 m

Full fracture:

20 m x 500 m x 920 m



Initial state of stress

S1 = 1.02 S_v; S2 = S_v = 85.3 MPa (3.4 km depth);

S3 = 0.53 S_v (minimum values of Moeck, 2016)

S1 parallel to fracture zone (optimal for normal opening)

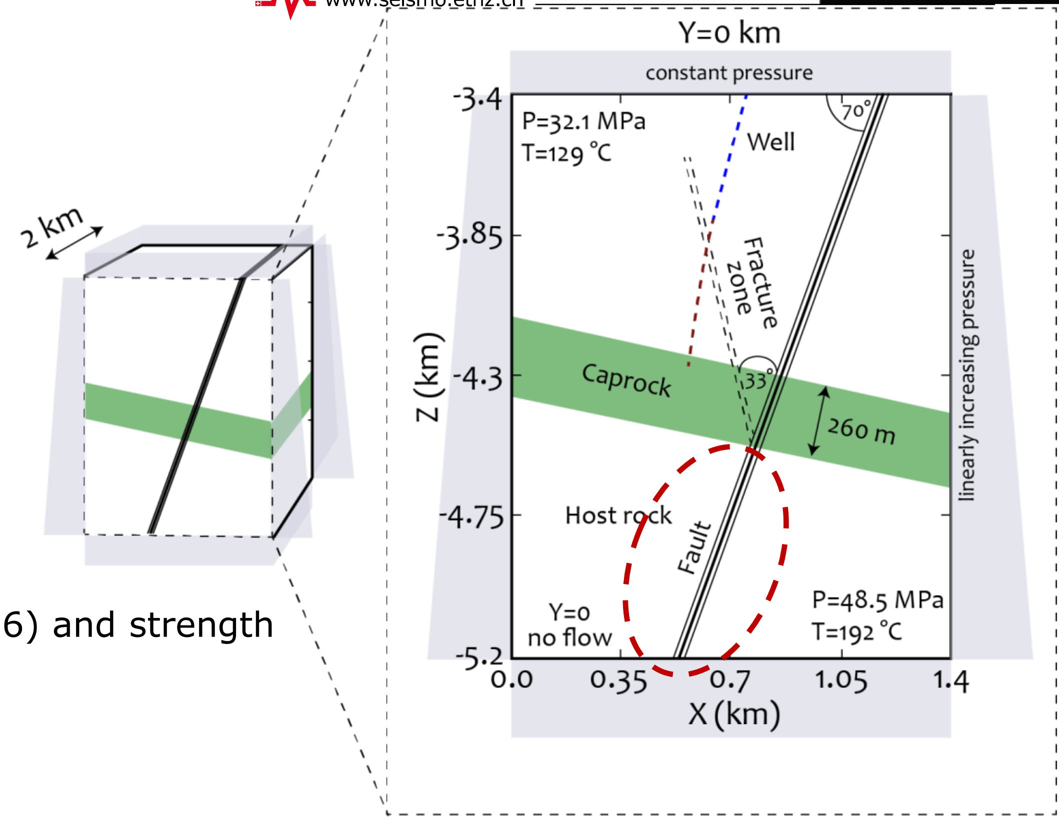
Part II: TOUGH2-Seed

Half model domain

1.4 km x 2 km x 1.8 km

Scenario

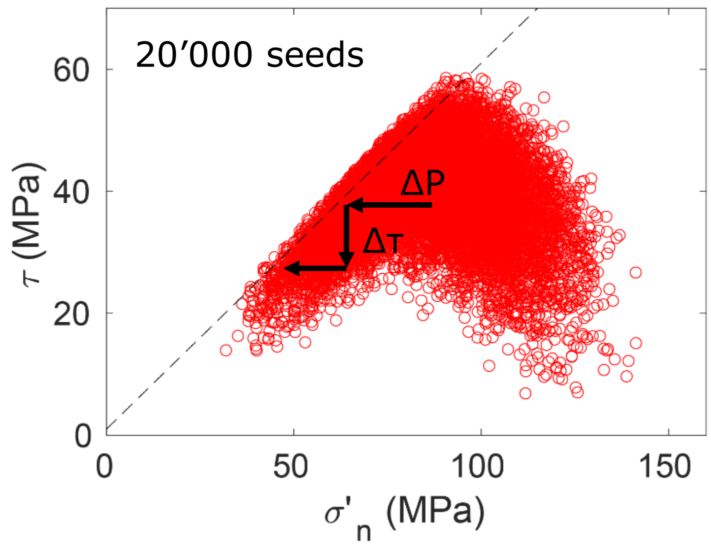
Full fracture: 20 m x 250 m x 920 m



Seed model

Randomly distributed potential failure points

with normally distributed stress (Moeck, 2016) and strength



Friction: μ=0.6 ± 0.05

Cohesion: 1 MPa

Stress drop: 5 % of σ'_N (~3 MPa - Edwards et al., 2015)

No static stress transfer

Model calibration

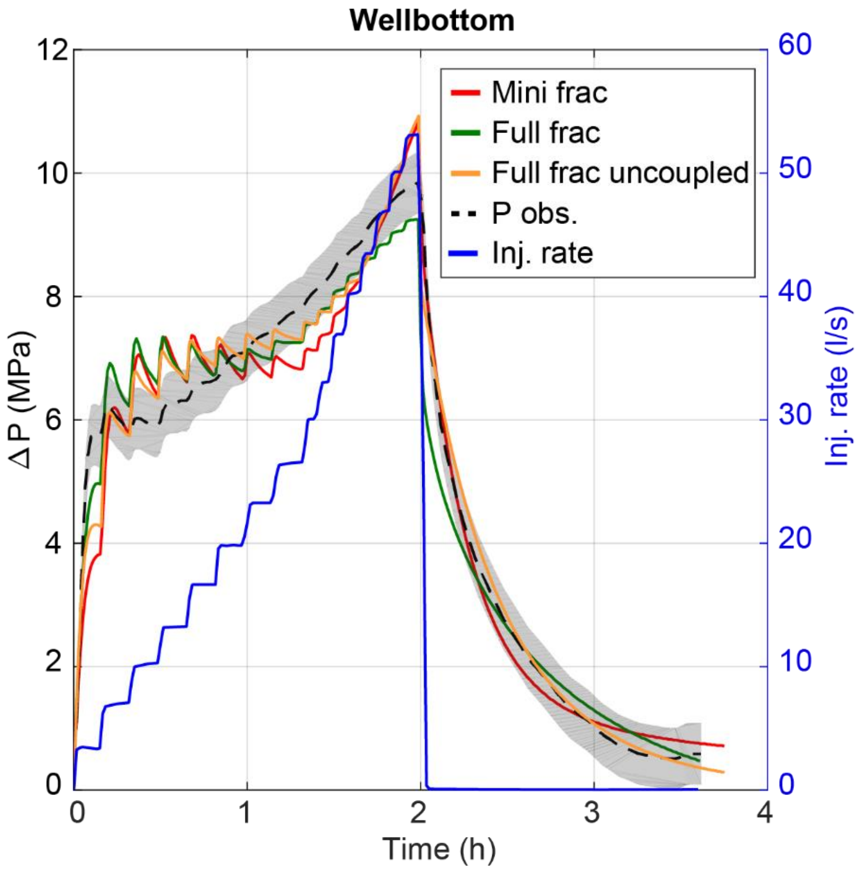
Data inversion with iTOUGH-PEST

(Finsterle and Zhang, 2011)

Well pressure of injection test as data

Inverted model parameters: coupled - uncoupled

- Fracture aperture - permeability
- Host rock permeability
- Fracture zone Young's modulus - compressibility
- Host rock Young's modulus - compressibility



Pressure and injection rates from Wolfgramm (GTN), 2014

Stress/pressure-dependent fracture zone permeability

Coupled

$$b = \mathrm{f}(\sigma'_N) \qquad \kappa_{hm} = \frac{b^3}{12 s_f}$$

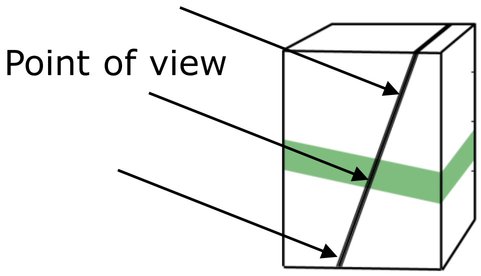
(e.g. Rinaldi and Rutqvist, 2019) (Cubic law)

Uncoupled

$$\kappa = f(\Delta P)$$

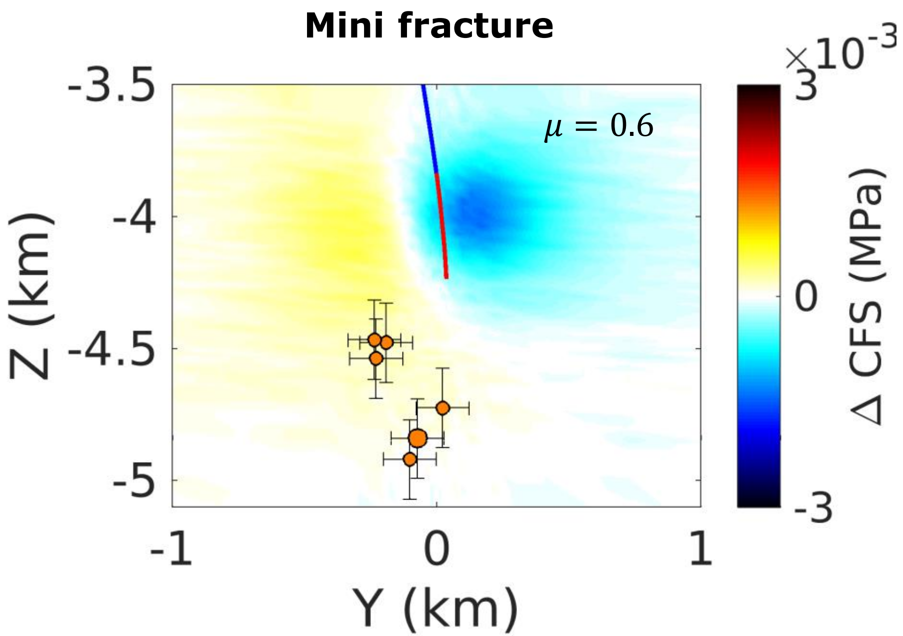
(e.g. Rinaldi and Nespoli, 2017)

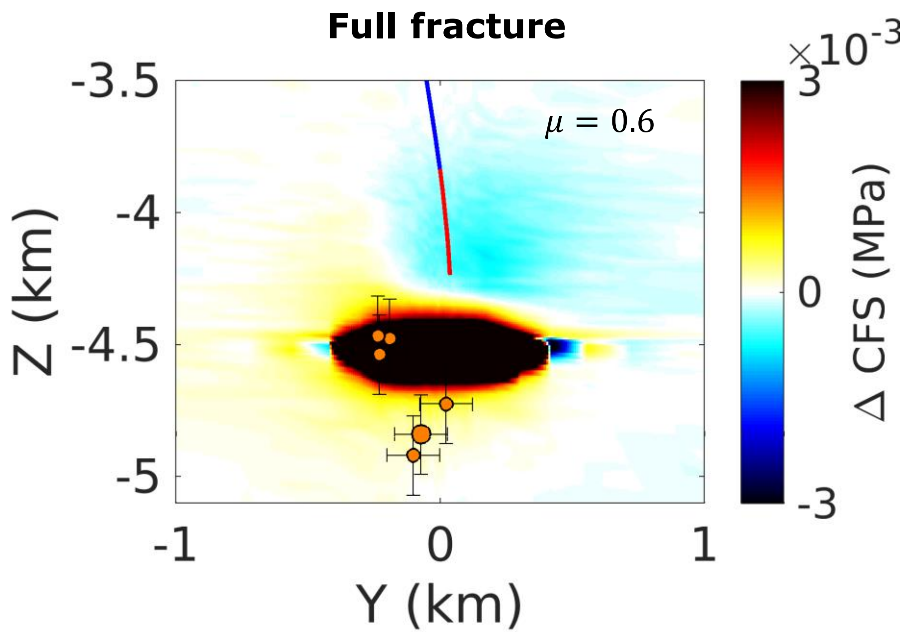
Mini fracture vs. full fracture



Stress change on the fault after 2 hours (shut-in)

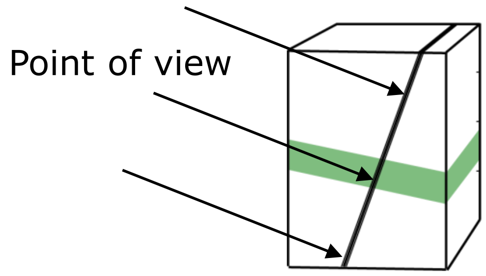
Coulomb stress change $\Delta CFS = \Delta\tau + \mu\Delta\sigma'_N$





Catalog of relocated events with absolute uncertainty
Diehl et al., 2017

Mini fracture vs. full fracture



Stress change on the fault after 2 hours (shut-in)

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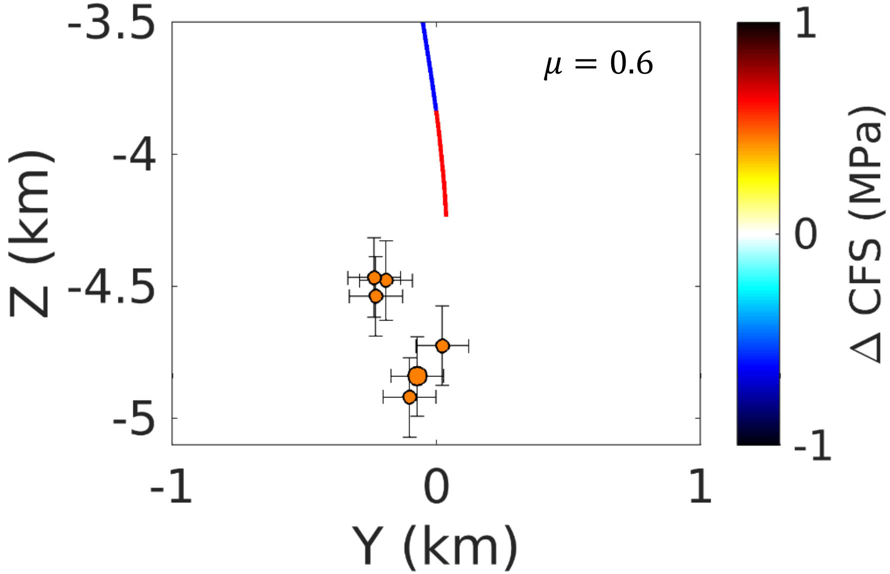
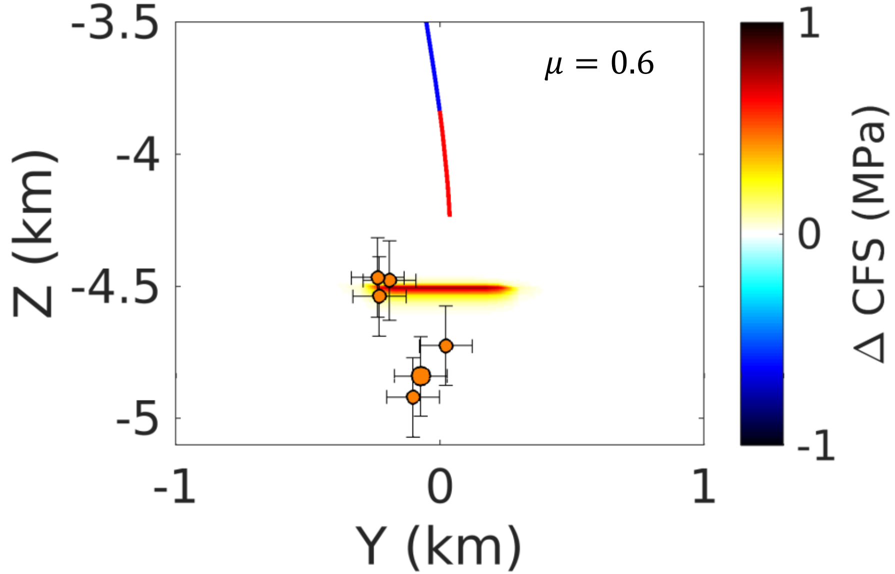
Mini fracture

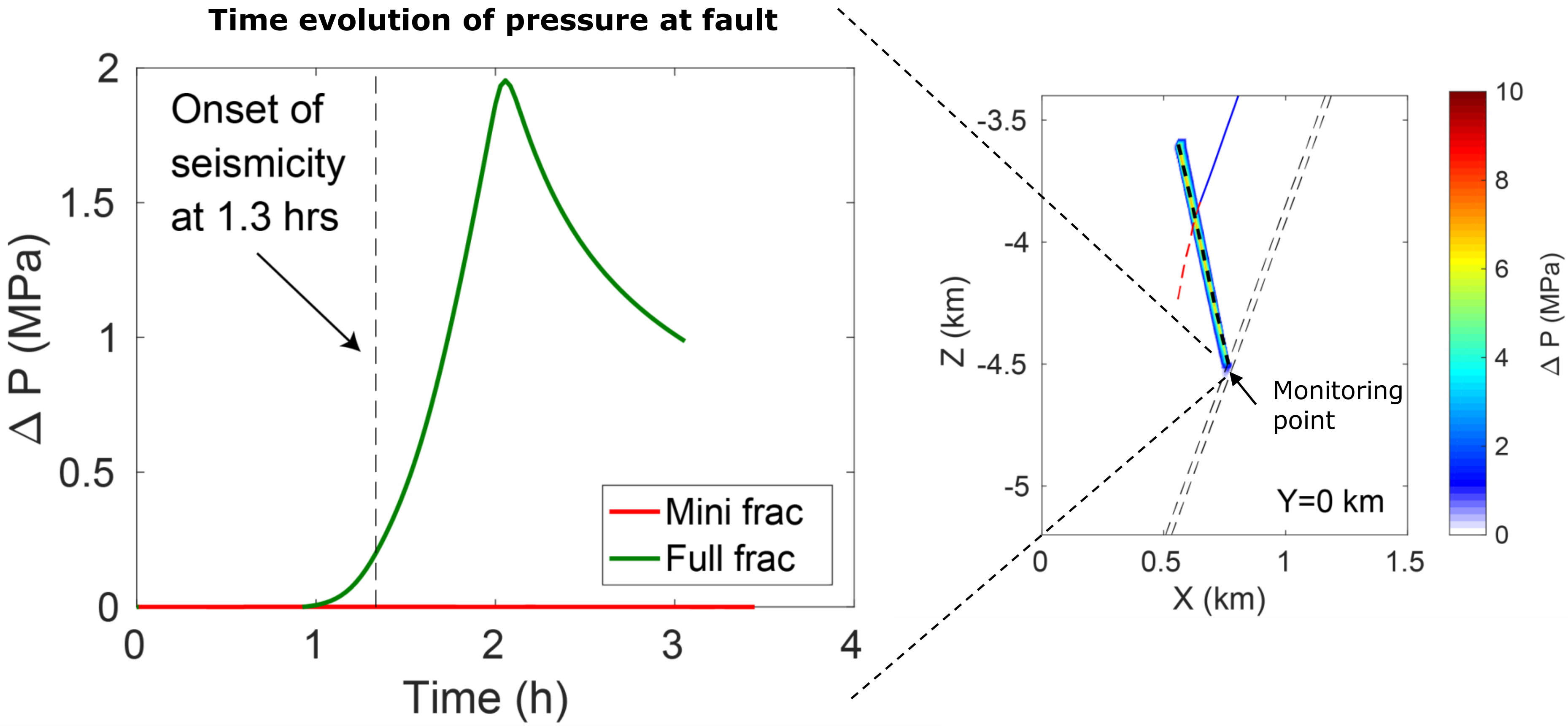


Full fracture



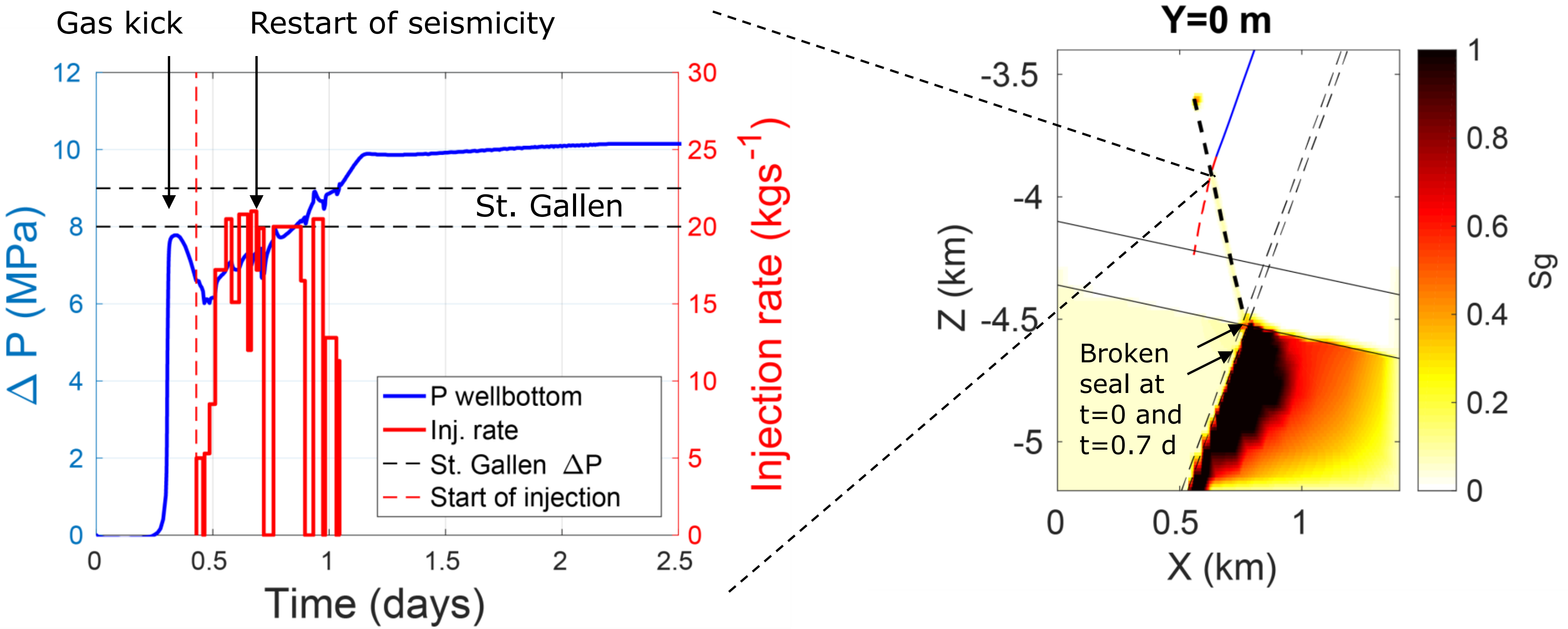
Catalog of relocated events with absolute uncertainty
Diehl et al., 2017

Full fracture (hydraulic connection)



Part II: Gas kick and well control simulation

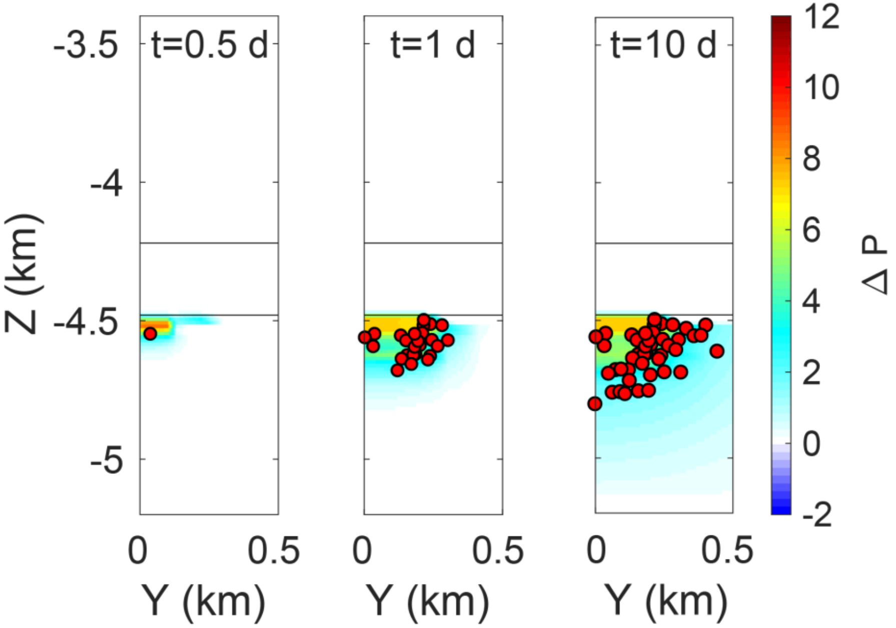
- Gas kick modeled assuming an overpressurized gas reservoir at depth (ΔP=13 MPa)
- Subsequent water injection (~700 m^3 for about 15 hours)
- Fault seal is forced to break at t=0 at -4.5 km (onset of gas kick) and at t=0.7 d at -4.6 km (restart of seismicity)



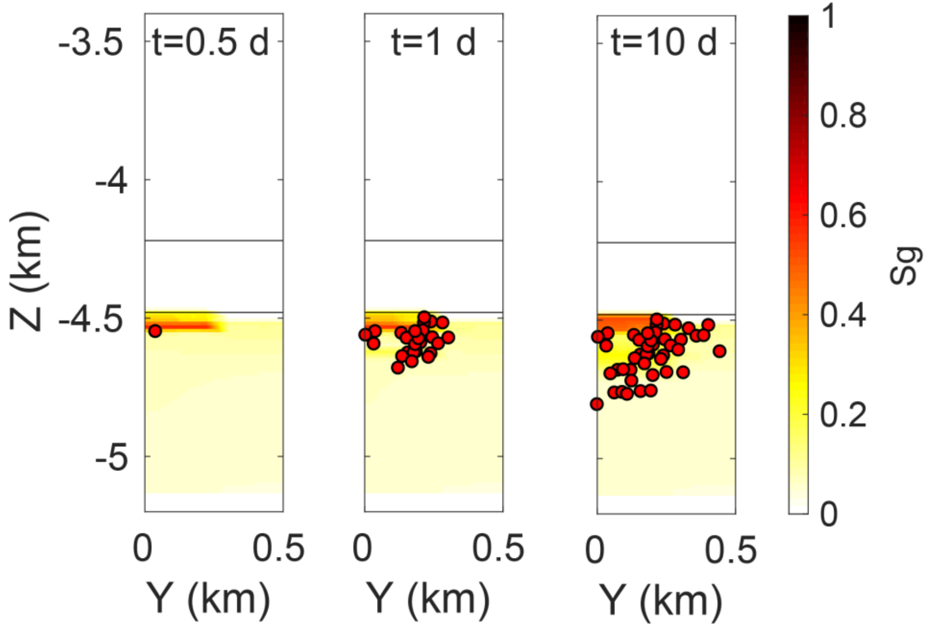
Simulation of induced events

- Single realization with 20’000 seeds
- Strong increase of seismicity between 0.5 and 1 day due to fault seal opening

Pressure change



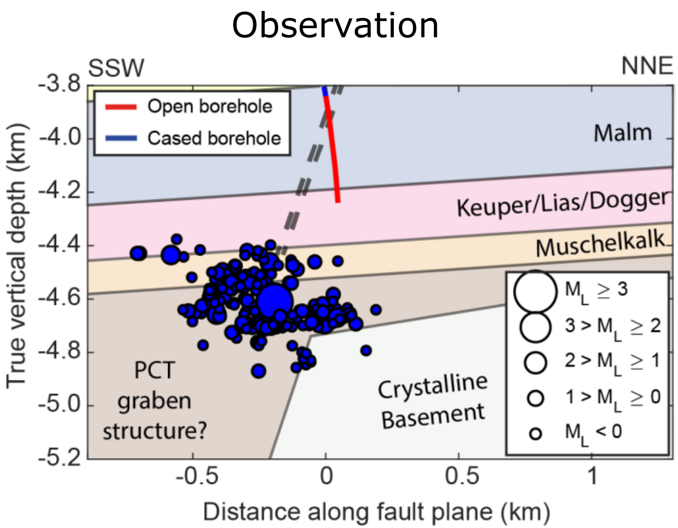
Gas saturation

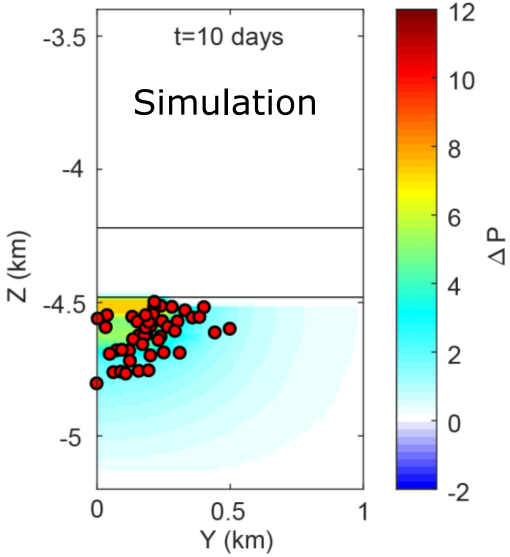


Spatial distribution

Along fault plane

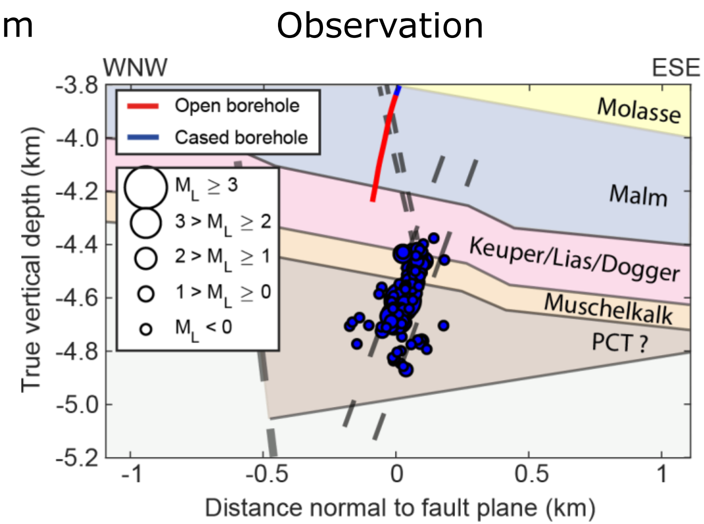
- Width of cloud: ~500 m
- Good agreement with observations

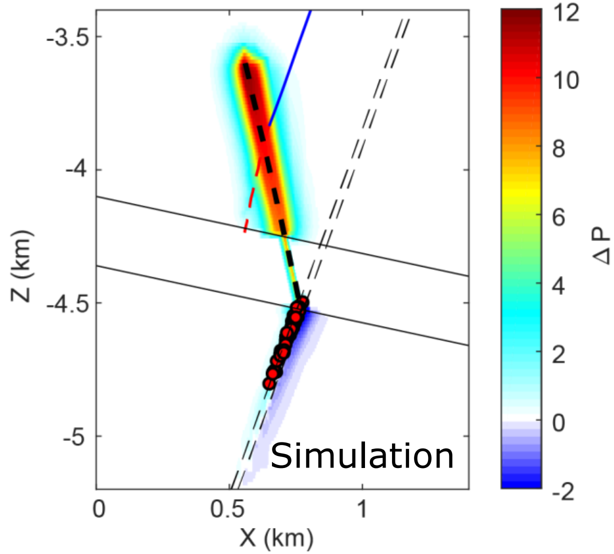




Along dip

- Extension of cloud: ~400 m
- Model produces slightly smaller and thinner cloud (no stress transfer)





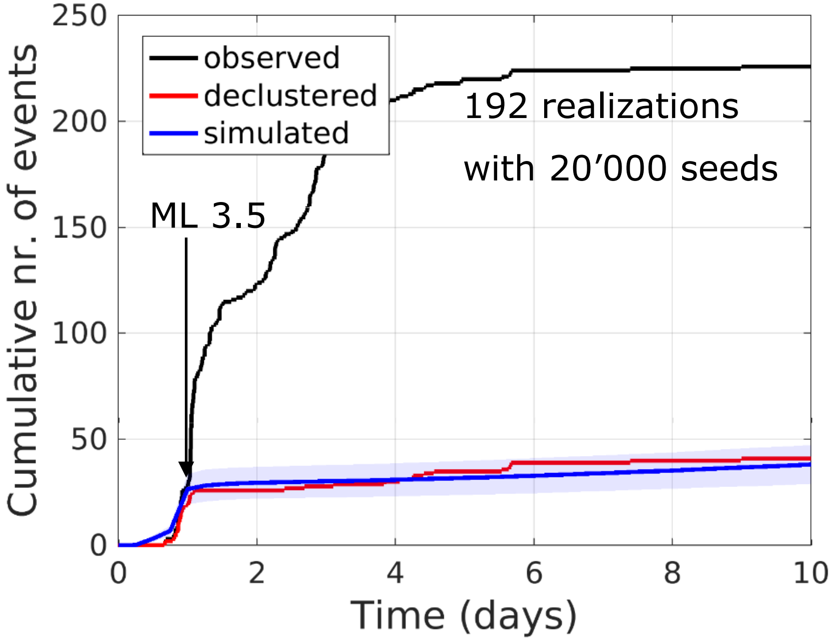
Catalog of relocated events - Diehl et al., 2017

Geological model after Heuberger et al., 2016

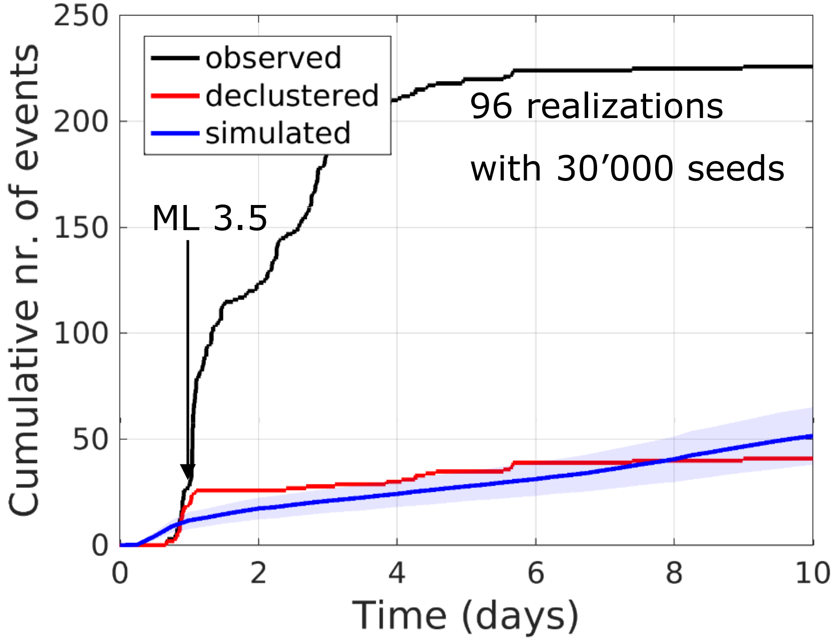
Temporal evolution

- The stochastic model cannot reproduce the aftershock sequence of the ML 3.5 event
- The model however fits the declustered sequence (window method - Gardner and Knopoff, 1974)
- Fault seal opening (permeability change) improves the fit between observation and simulation

with permeability increase due to seismicity



w/o permeability increase



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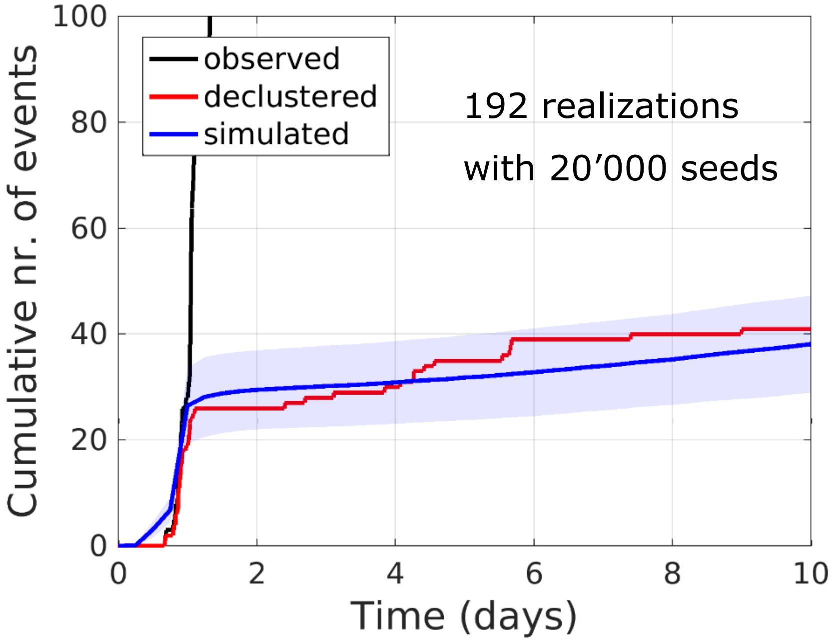

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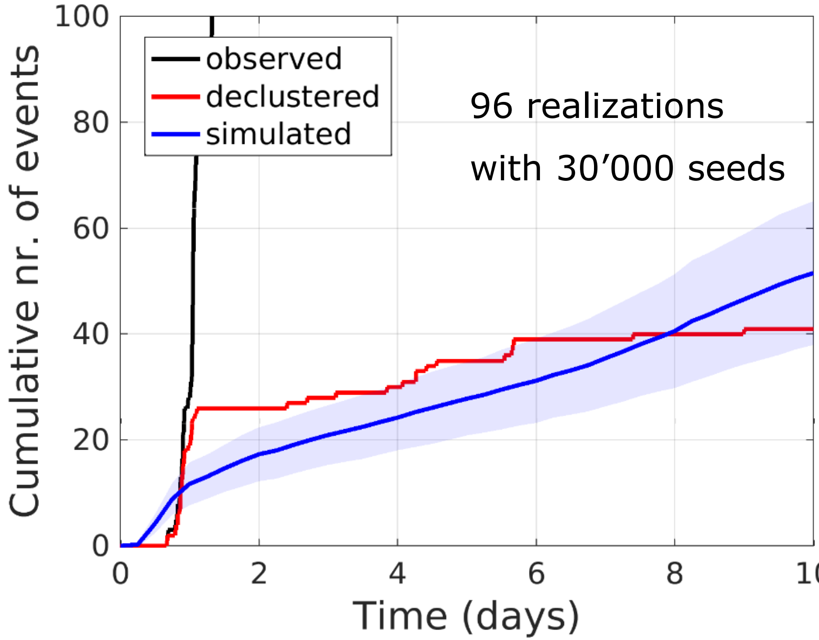
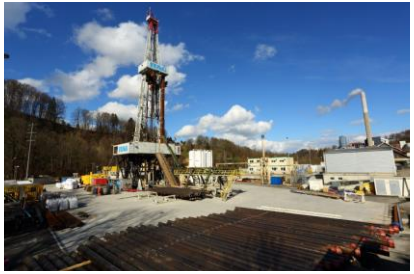


Conclusions

- In St. Gallen, **poroelastic effects may have induced the seismicity** on a remote fault
- However, a hydraulic connection could have led to Coulomb stress changes that are **about 3 orders of magnitude higher**
- The timing and strength of the **gas kick can be approximately reproduced using the same fracture** zone as a conduit
- The spatio-temporal evolution may be better reproduced by allowing **permeability changes within the fault seal** during the seismic sequence
- The model suggests that the **seismicity is mainly induced by the gas** – this is probably only one out of several possible models

Thank you for your attention



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2013, Stadt St.Gallen / St.Galler Stadtwerke