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Induced seismicity during the St. Gallen deep geothermal project, Switzerland: insights from numerical modeling

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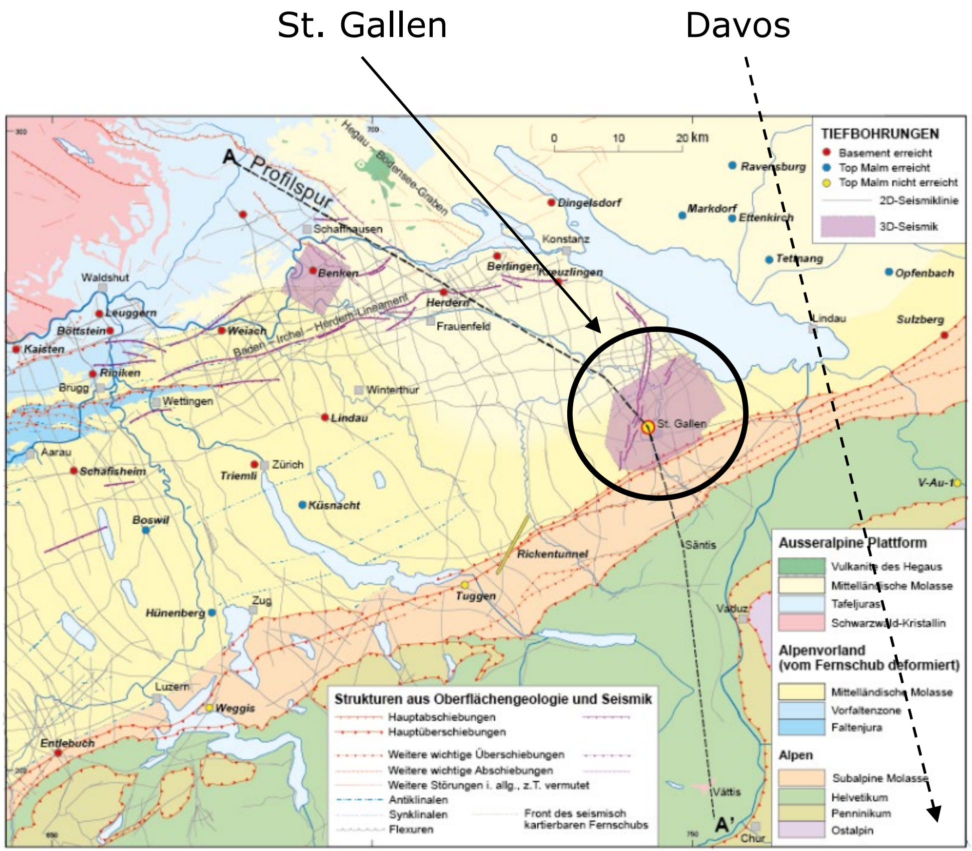
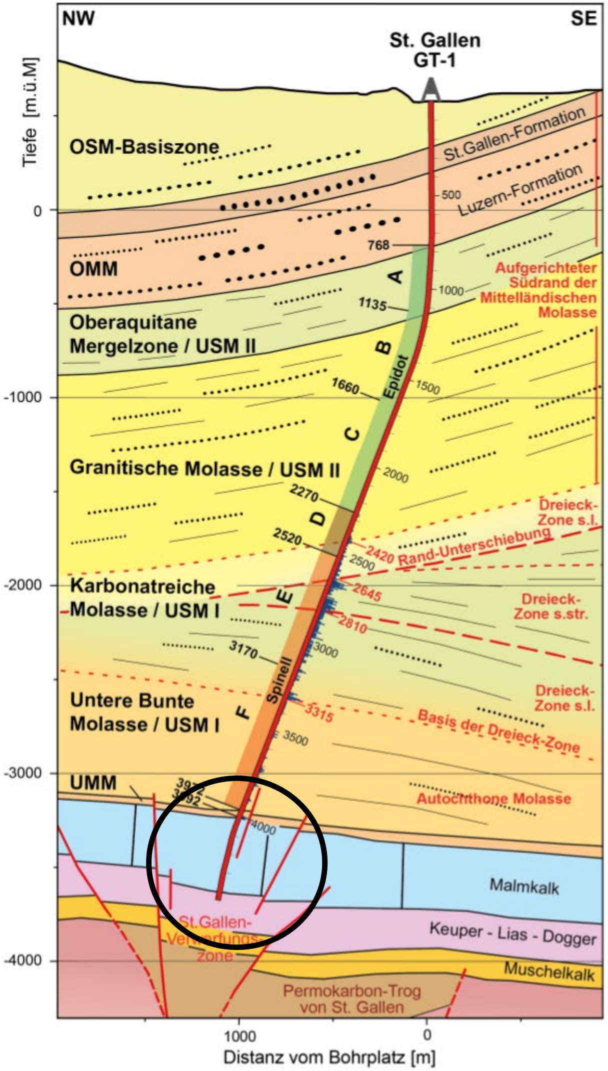
Swiss Seismological Service, ETH Zurich

7 March, 2019

Project overview

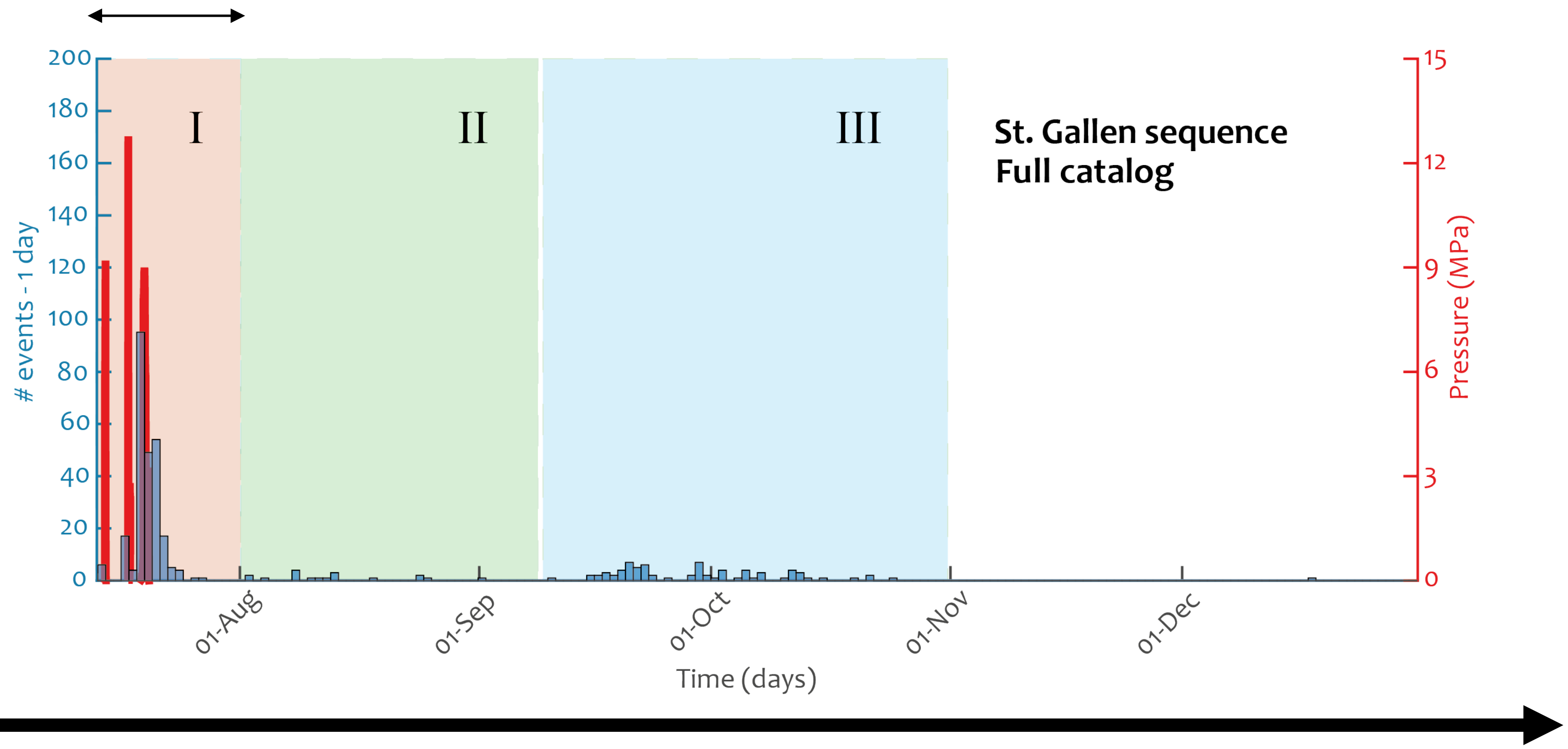




Naef and Schlanke (geosfer ag), 2014

July – December 2013

Injection period: 14 - 20 July 2013

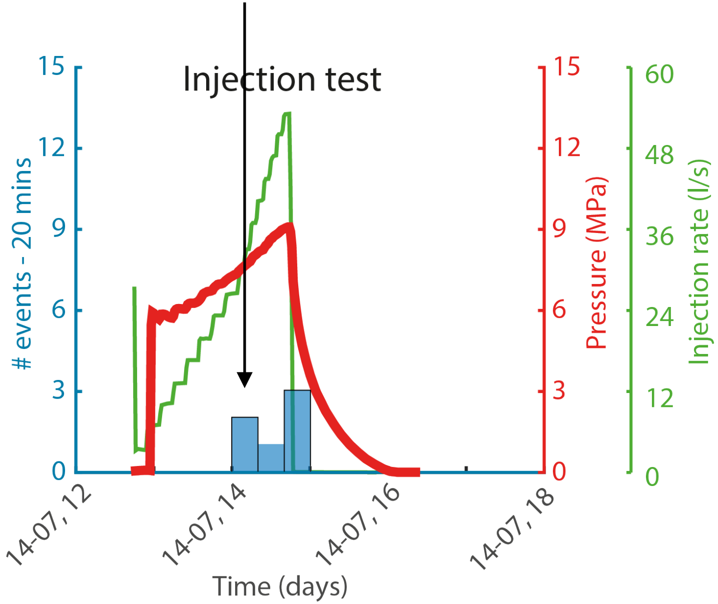


Time

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

July 2013 – injection test

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



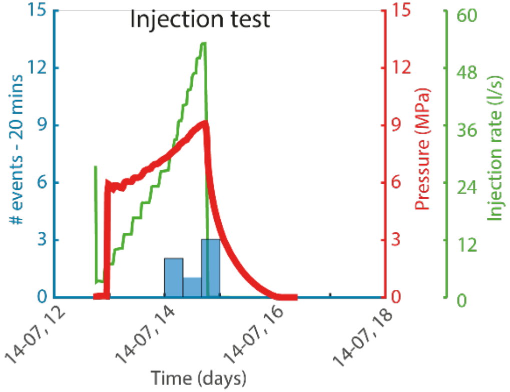
14 July

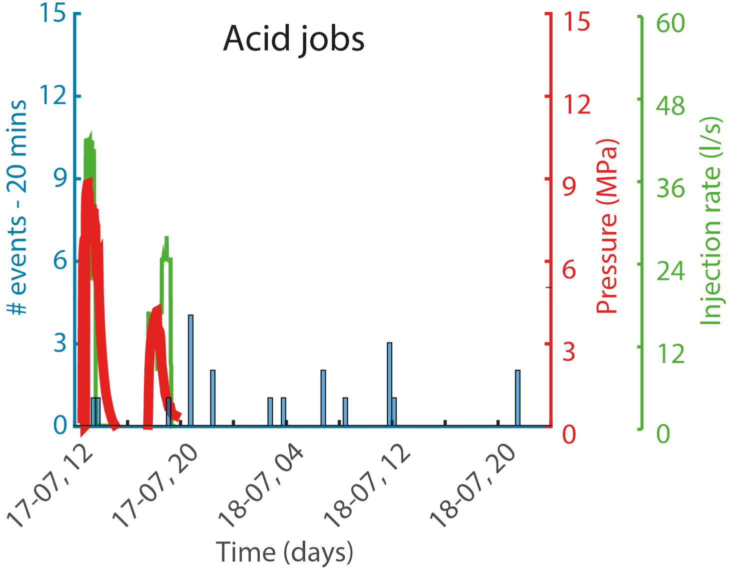
Injection test (175 m^3)

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)

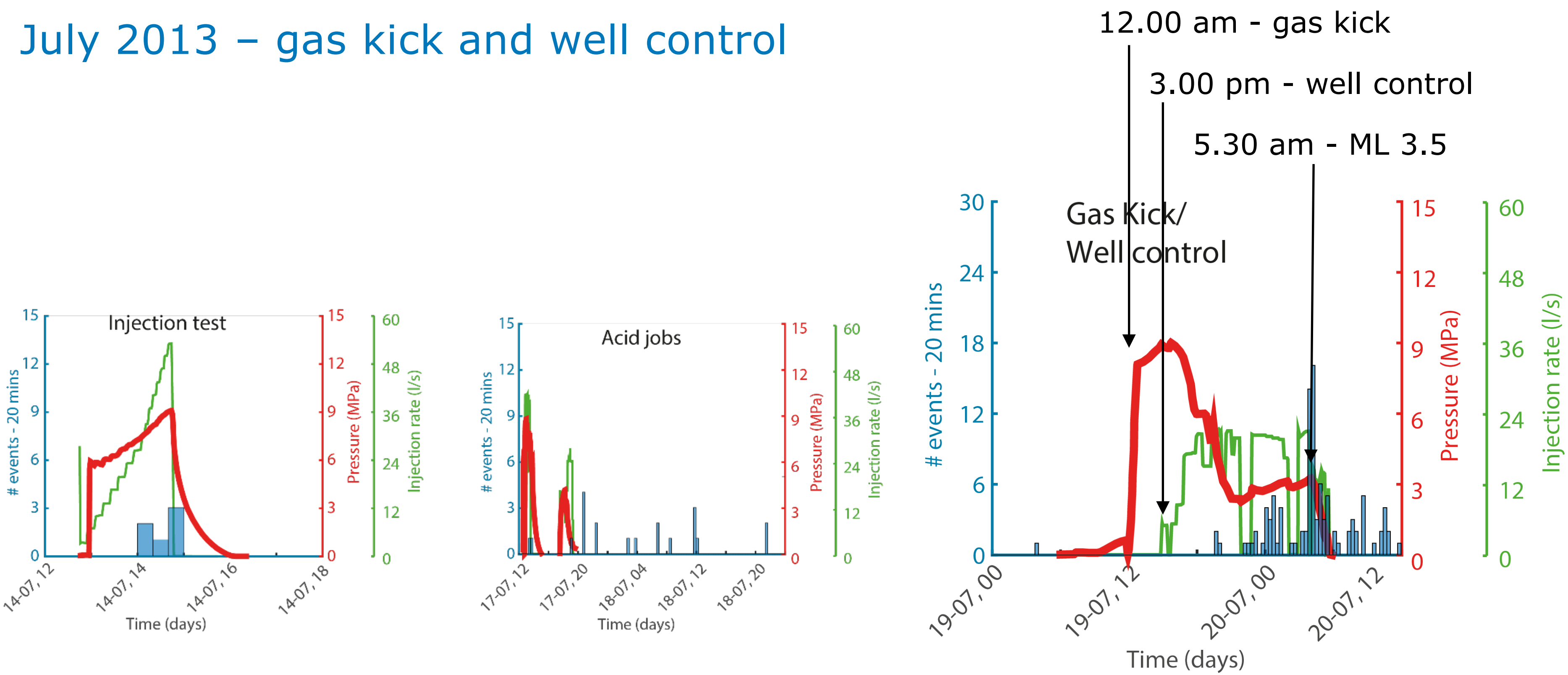
17 July

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 m³)

17 July

Acid stimulations (290 m³)

19/20 July

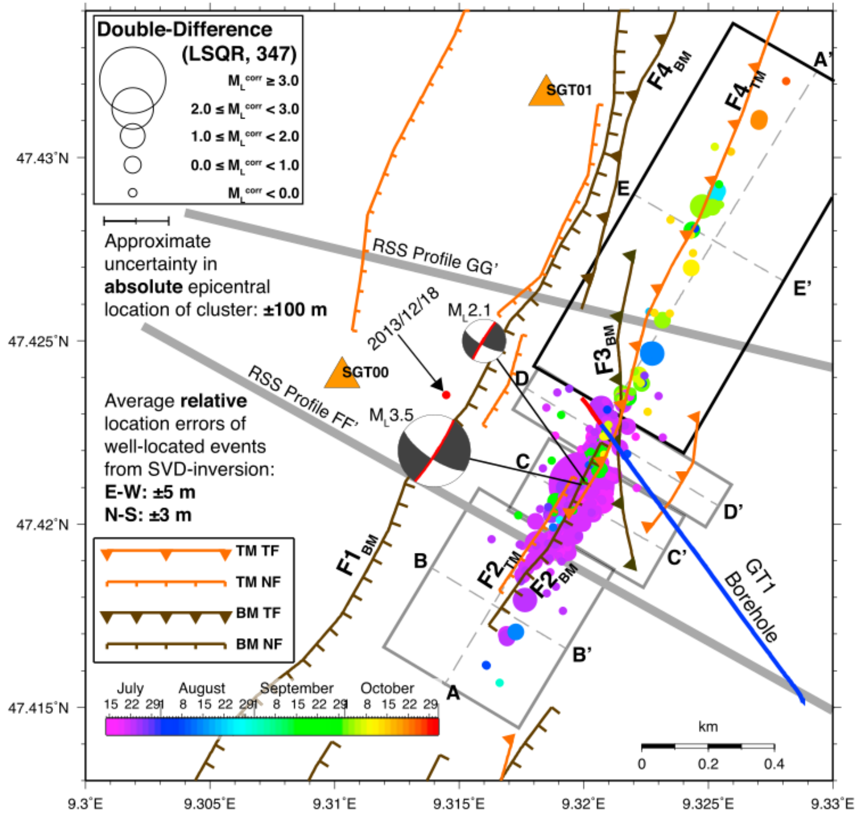
Gas kick and well control measures (700 m³)

Time

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

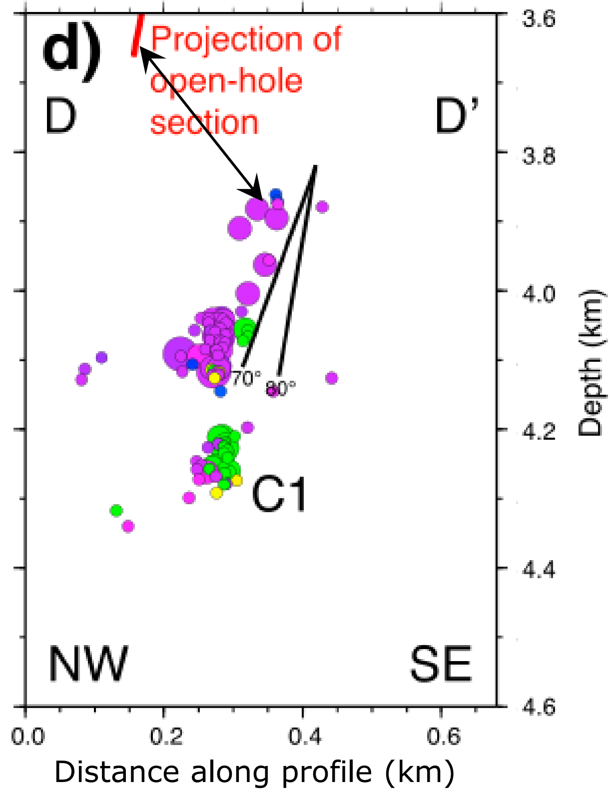
Spatial distribution of seismicity

Map view



Diehl et al., 2017

Seismicity **several hundreds of meters** distant to the borehole

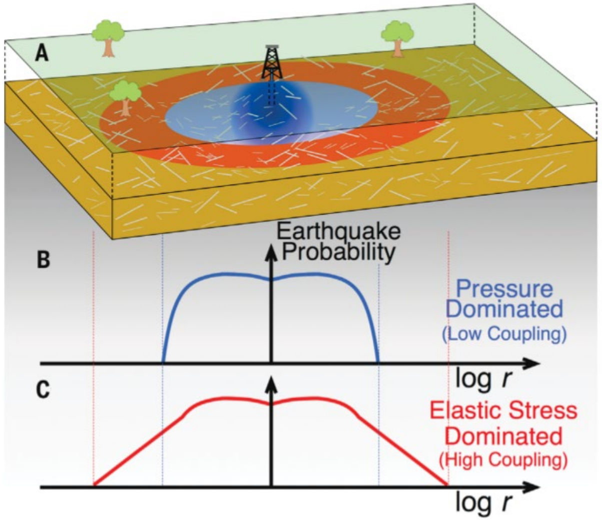


Diehl et al., 2017

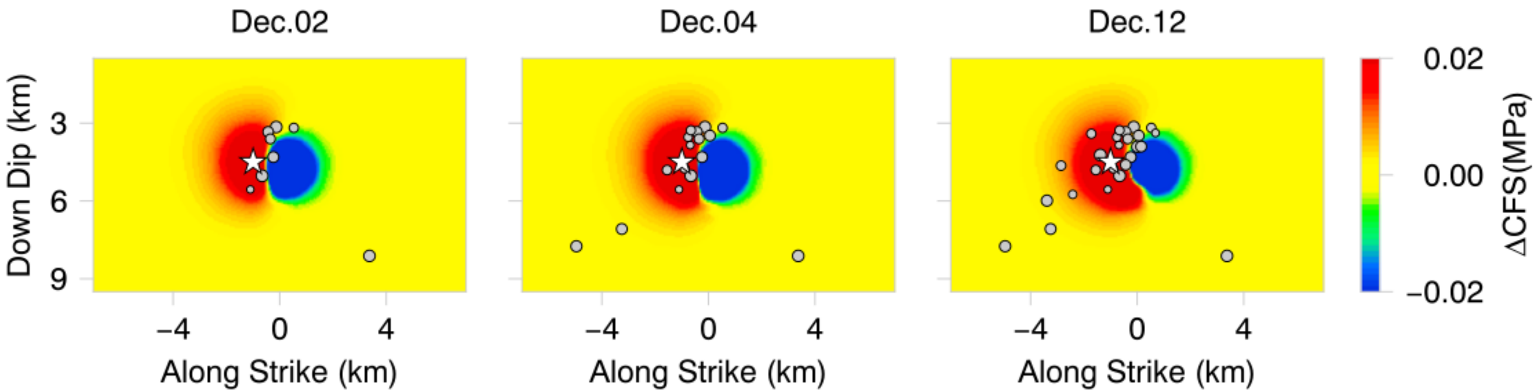
Induced seismicity by poroelastic stress changes

Injection-induced seismicity (Goebel and Brodsky, 2018)

Near-field: Pressure dominated
Far-field: Elastic stress dominated

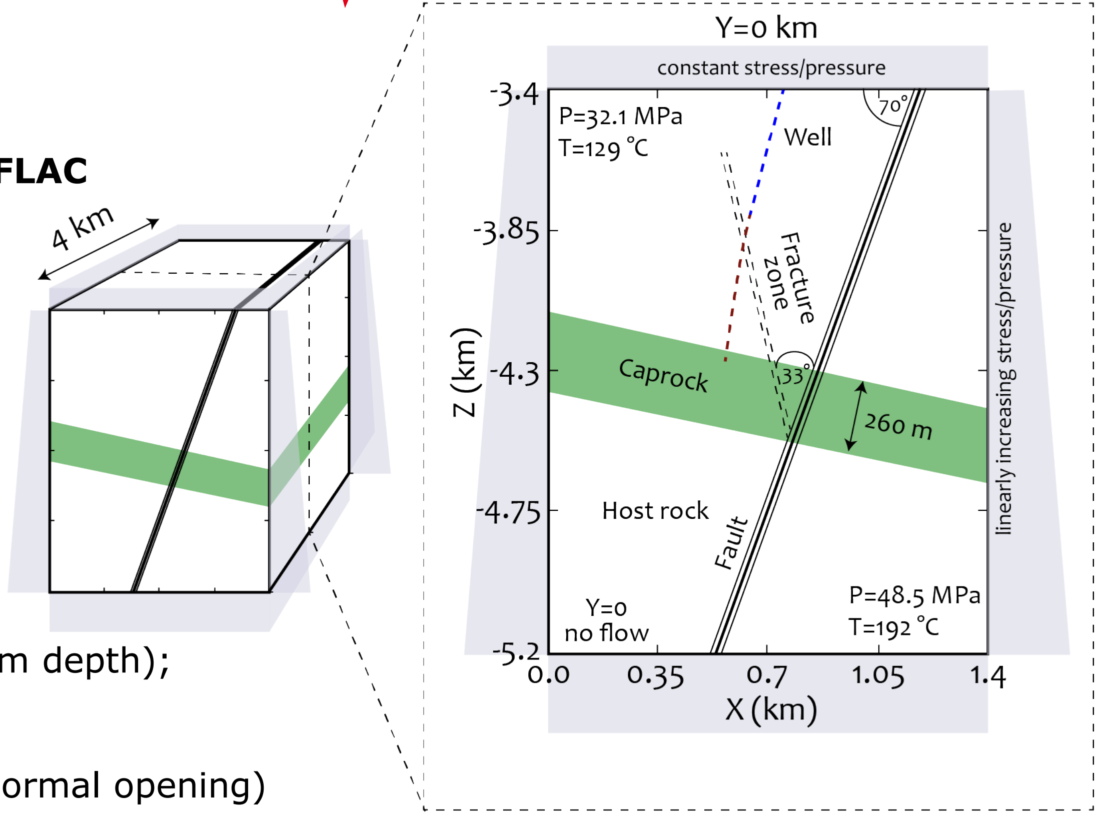


Hydraulic fracturing in Crooked Lake area, Central Alberta, Canada (Deng et al., 2016)



The numerical model

Hydro-mechanical simulator TOUGH-FLAC
(Rutqvist, 2011)



3 scenarios:

Mini fracture: 20 m x 250 m x 115 m

Medium fracture: 20 m x 500 m x 660 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 (Moeck, 2016)

S1 parallel to fracture zone (optimal for normal opening)

Hydro-mechanical coupling

Stress update in FLAC3D

$$\sigma_{ij}^{corr} = \sigma_{ij} - \alpha \Delta P \delta_{ij}$$

Porosity update in TOUGH2

$$\Delta\varphi = f(\alpha, \varphi, K)\Delta P + \Delta\varphi^{corr}$$ (Kim et al., 2012)

Model calibration

Data inversion with iTOUGH-PEST

- Well pressure in borehole GT-1 as data

- Inverted model parameters:
  - Fracture aperture
  - Host rock permeability
  - Fracture zone Young's modulus
  - Host rock Young's modulus

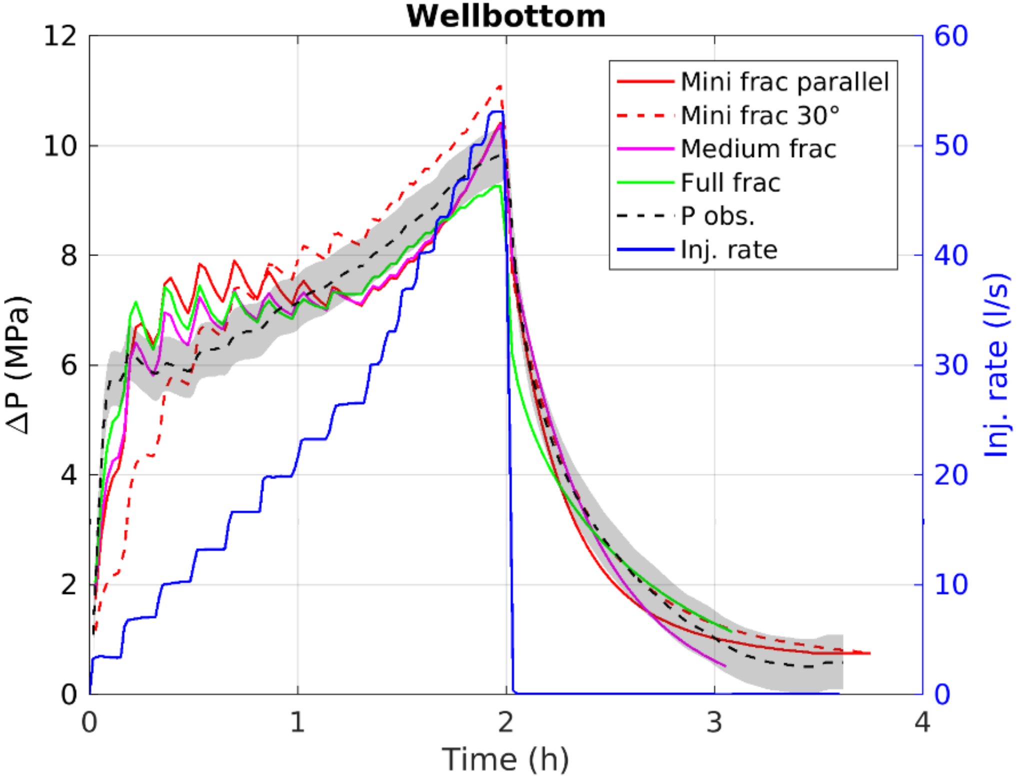
Stress-dependent fracture permeability

$$b = b_{res} + b_{max}\exp(\beta\ \sigma_N')$$

(e.g. Rinaldi and Rutqvist, 2019)

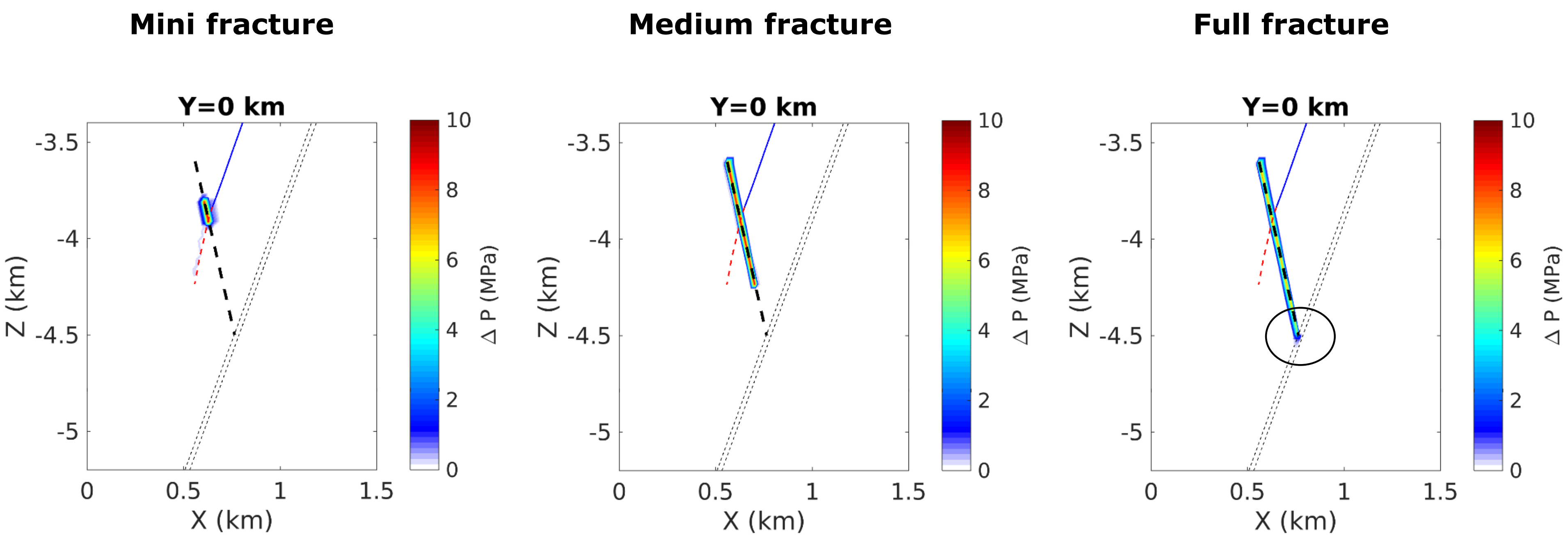
$$\kappa_{hm} = \frac{b^3}{12 s_f}$$

(Cubic law)



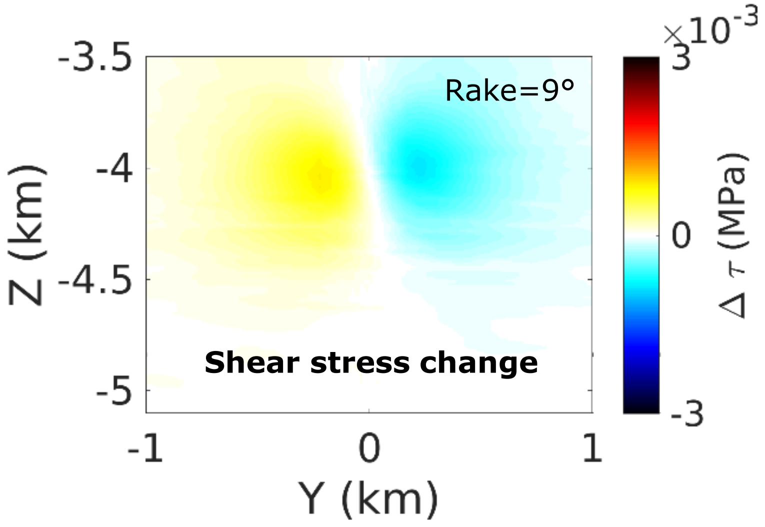
Pressure from Wolfgramm (GTN), 2014

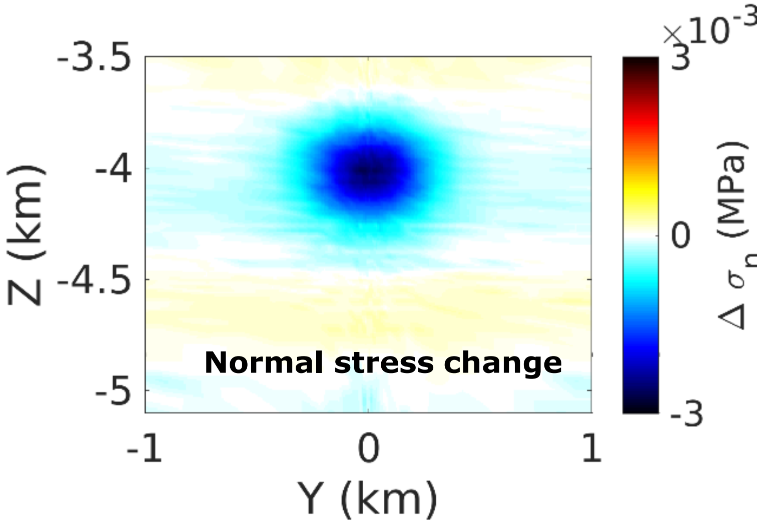
Model comparison



- Maximum pressure (ΔP=9 MPa) reached after 2 hours (shut-in time)
- Pore pressure front caused by the injection reaches the fault only for the full fracture model

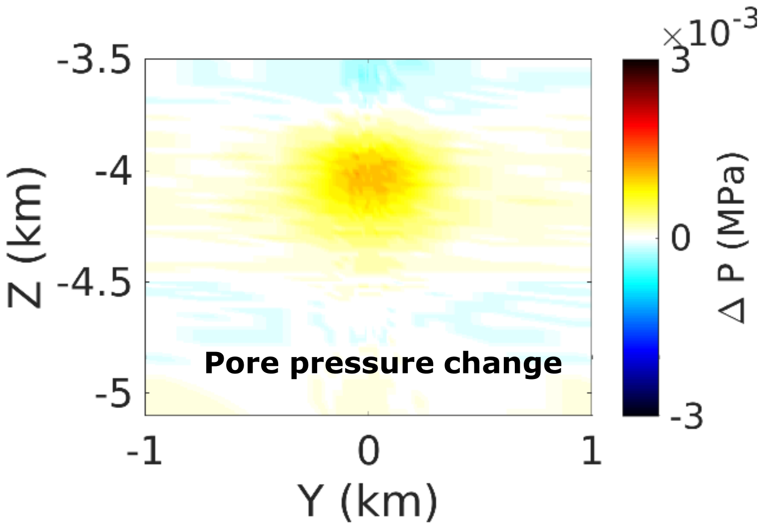
Stress change on fault: mini fracture





Stress change on fault after 2 hours

Negative stress is compressional

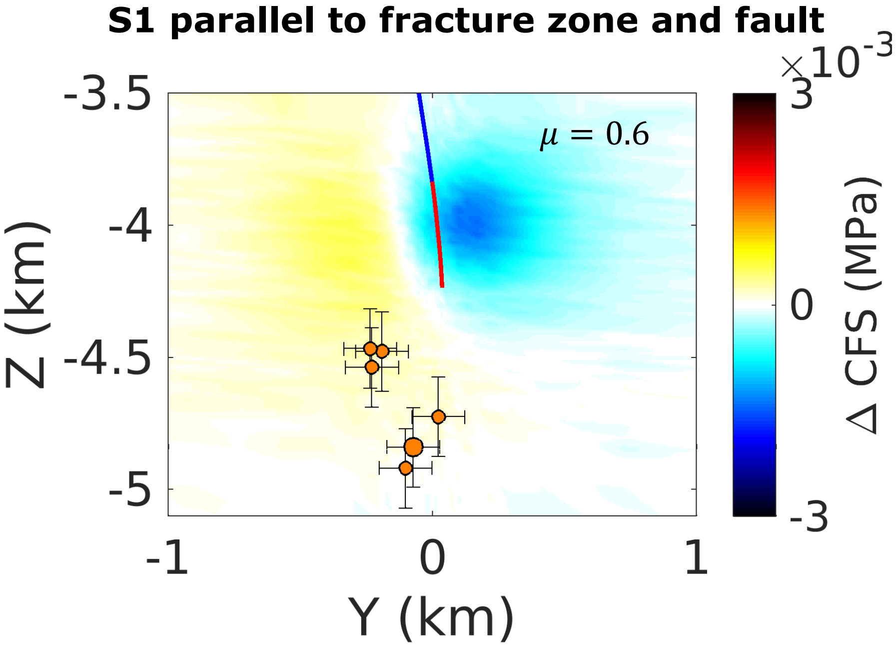


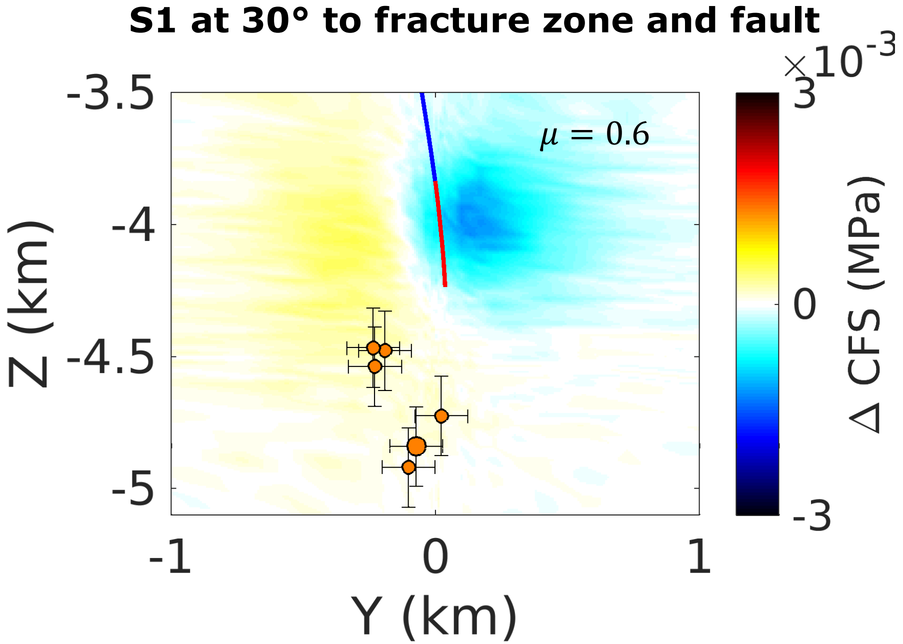
Coulomb stress change: mini fracture

Coulomb stress change

$$\Delta CFS = \Delta\tau + \mu\Delta\sigma'_N$$

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





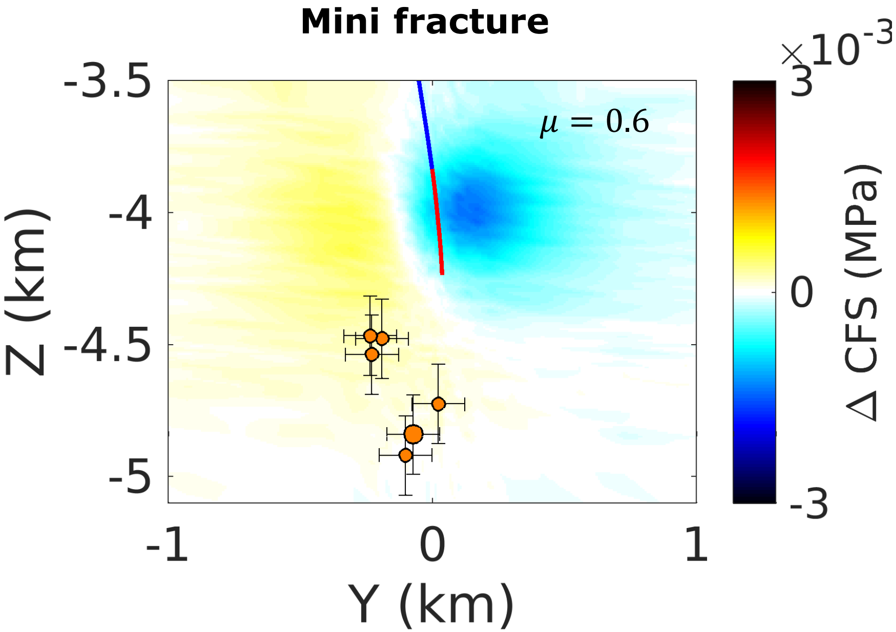
Catalog of relocated events with absolute uncertainty
Diehl et al., 2017

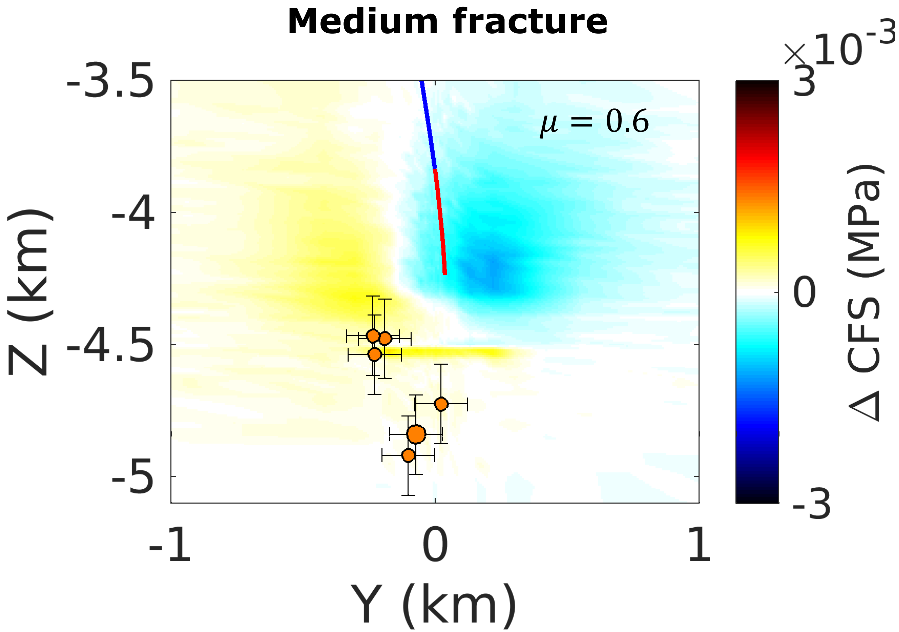
Mini fracture vs. medium-sized fracture

Coulomb stress change

$$\Delta CFS = \Delta\tau + \mu\Delta\sigma'_N$$

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





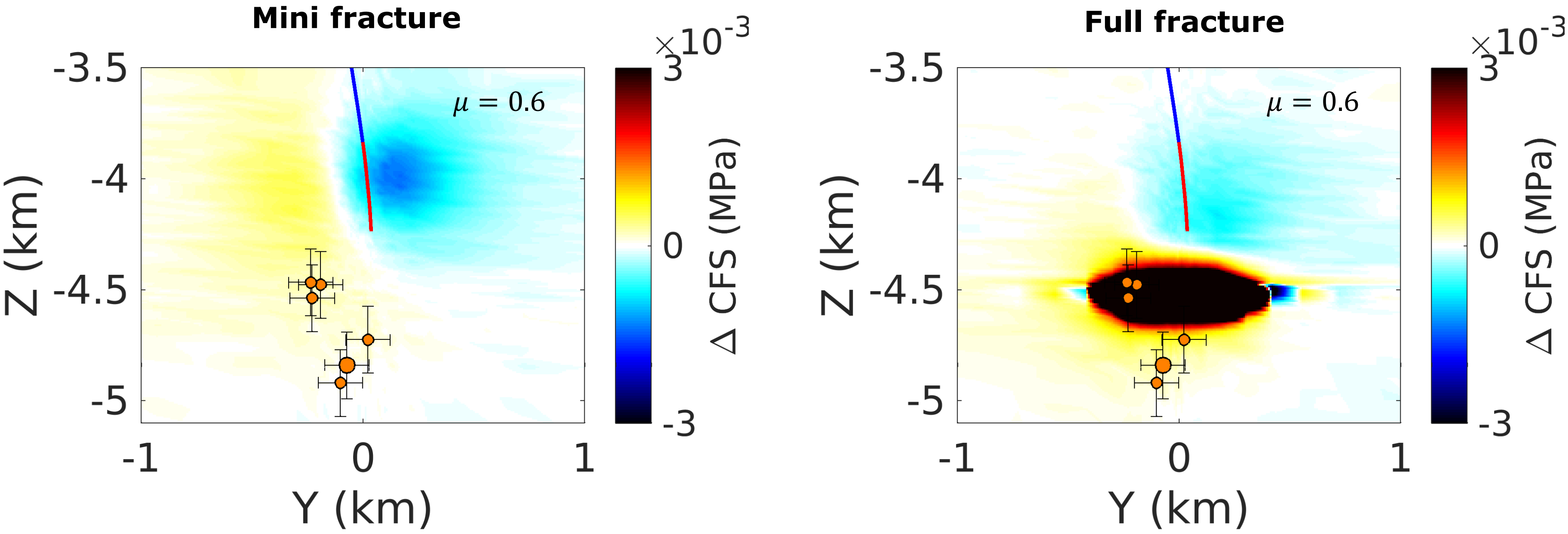
Catalog of relocated events with absolute uncertainty
Diehl et al., 2017

Mini fracture vs. full fracture

Coulomb stress change

$$\Delta CFS = \Delta\tau + \mu\Delta\sigma'_N$$

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



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

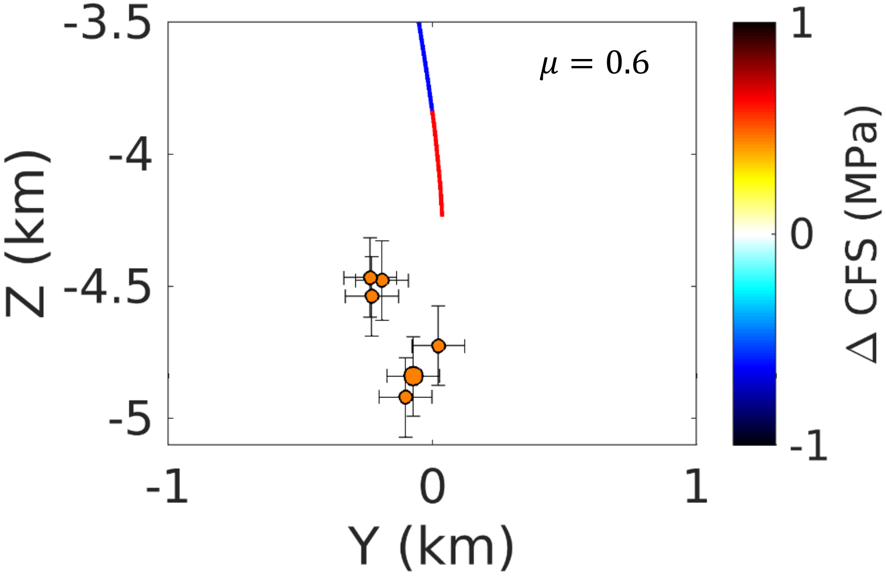
Mini fracture vs. full fracture

Coulomb stress change

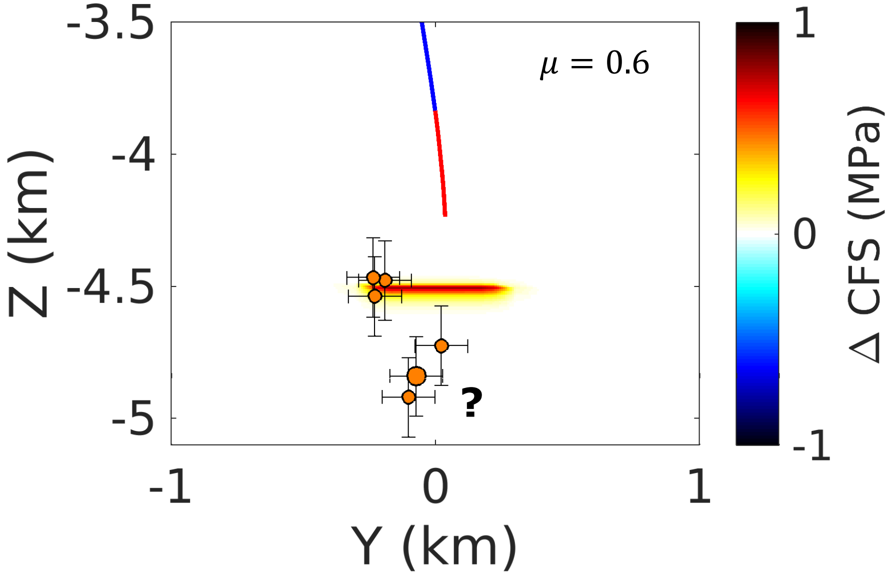
$$\Delta CFS = \Delta\tau + \mu\Delta\sigma'_N$$

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

Mini fracture

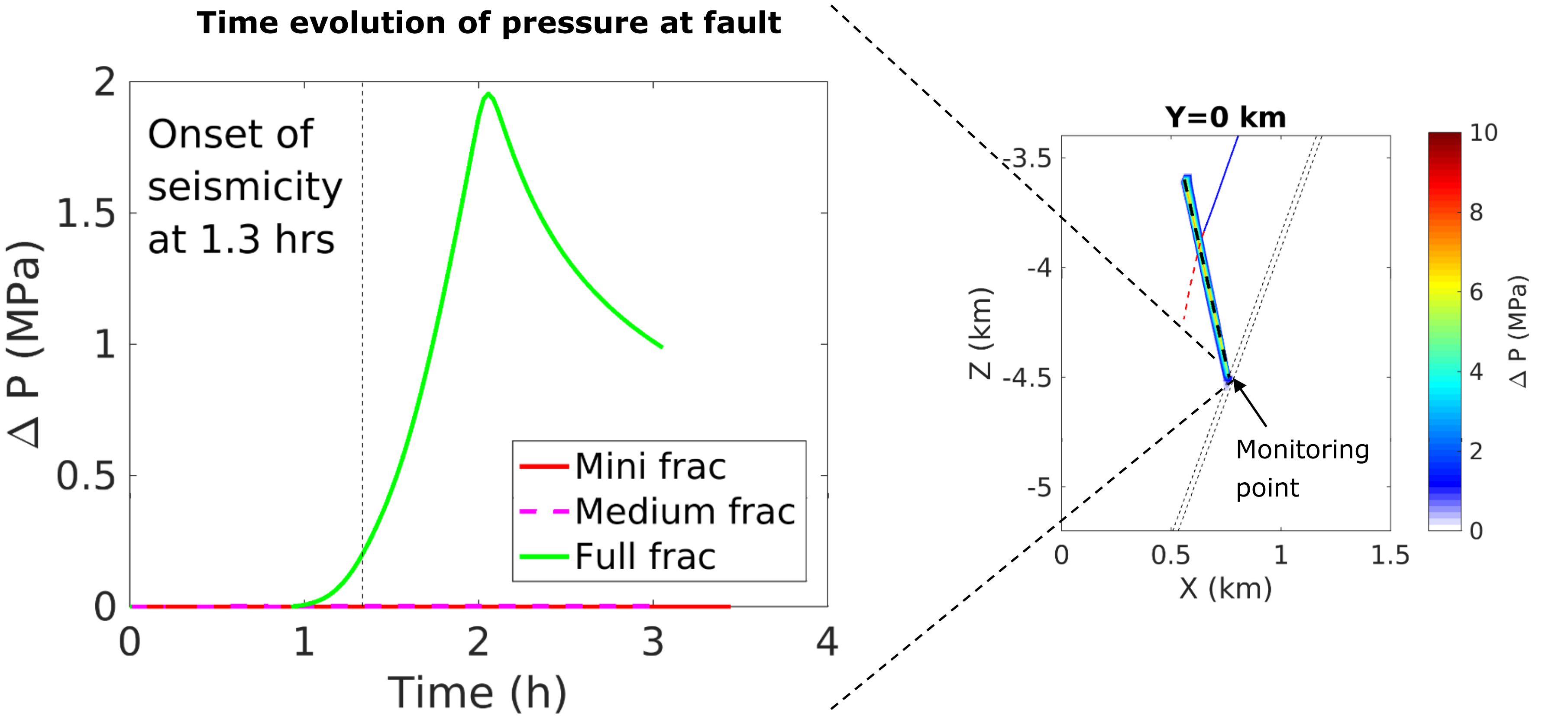


Full fracture



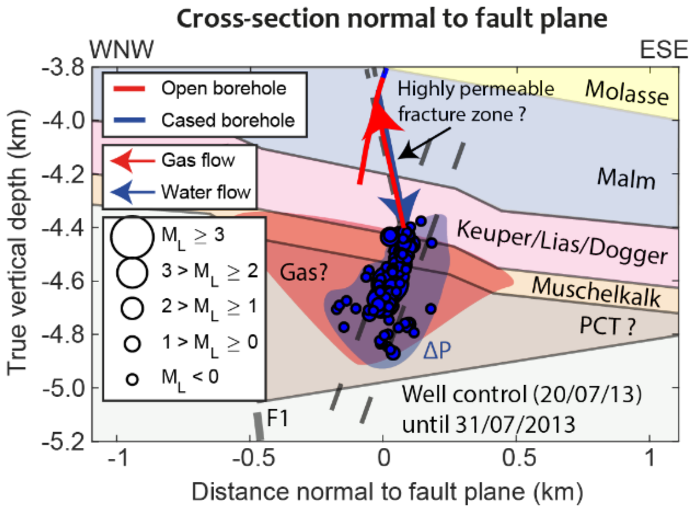
Catalog of relocated events with absolute uncertainty
Diehl et al., 2017

Full fracture – hydraulic connection



Gas kick and well control simulation

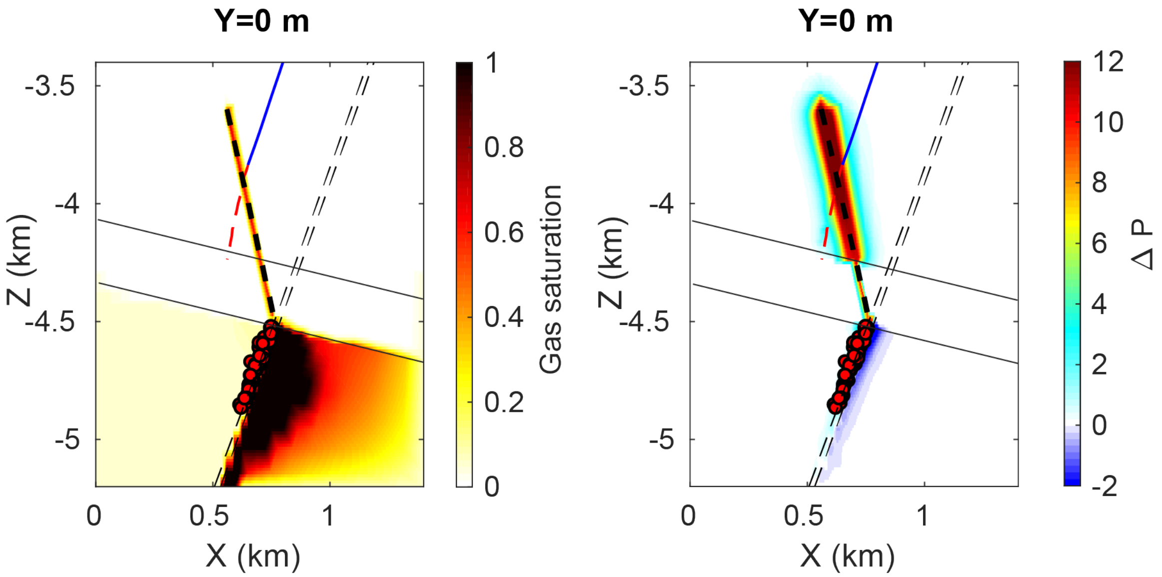
Observations



Catalog of relocated events - Diehl et al., 2017

Geological model after Heuberger et al., 2016

TOUGH2 coupled with a geomechanical-stochastic model (Rinaldi and Nespoli, 2017)

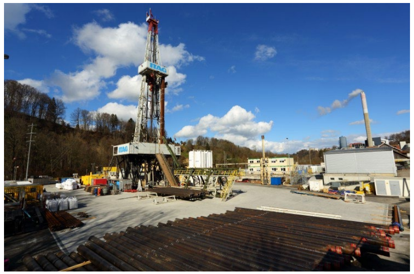


Gas kick can be modeled using the full fracture model and assuming an overpressurized gas reservoir at depth

Conclusions

- In St. Gallen, **poroelastic effects could have induced the seismicity** on a remote fault
- Relocated events of injection test are all **located in zones of positive Coulomb stress** change
- However, Coulomb stress change through a hydraulic connection could be **about 3 orders of magnitude higher**
- Seismicity could be induced **within ~1 hour** if a highly permeable fracture zone is present
- The timing and strength of the **gas kick could be simulated using the same fracture** zone as a conduit
- The fractured nature of the reservoir and the potential location of the gas **support the presence of a hydraulic connection**

Thank you for your attention



2013, Stadt St.Gallen / St.Galler Stadtwerke

This work was supported by a Swiss National Science Foundation (SNSF) Ambizione Energy grant (PZENP2_160555).

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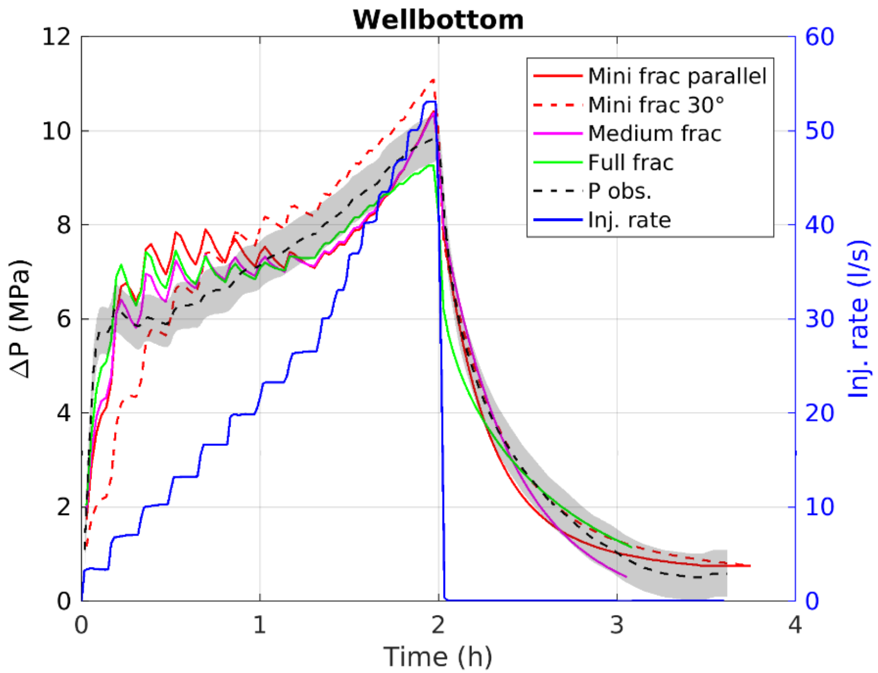
Back-up slides

Model calibration

Data inversion with iTOUGH-PEST

- Well pressure in borehole GT-1 as data
- Fracture zone and host rock properties as model parameters



Pressure from Wolfgramm (GTN), 2014

Calibrated model parameters

	Mini frac	Mini frac 30°	Medium frac	Full frac
b_{res} (μm)	5	1	7	9
b_{max} (μm)	4144	5000	4264	4599
β (MPa^{-1})	0.24	0.14	0.25	0.26
E_{frac} (GPa)	15.0	11.1	14.4	15.0
E_{host} (GPa)	20.0	20.0	27.1	20.0
κ_{host} (m^2)	2.1e-16	2.0e-16	1.7e-17	7.4e-18
α_{frac}	0.1	0.1	0.01	0.01
α_{host}	0.75	0.75	0.75	0.75

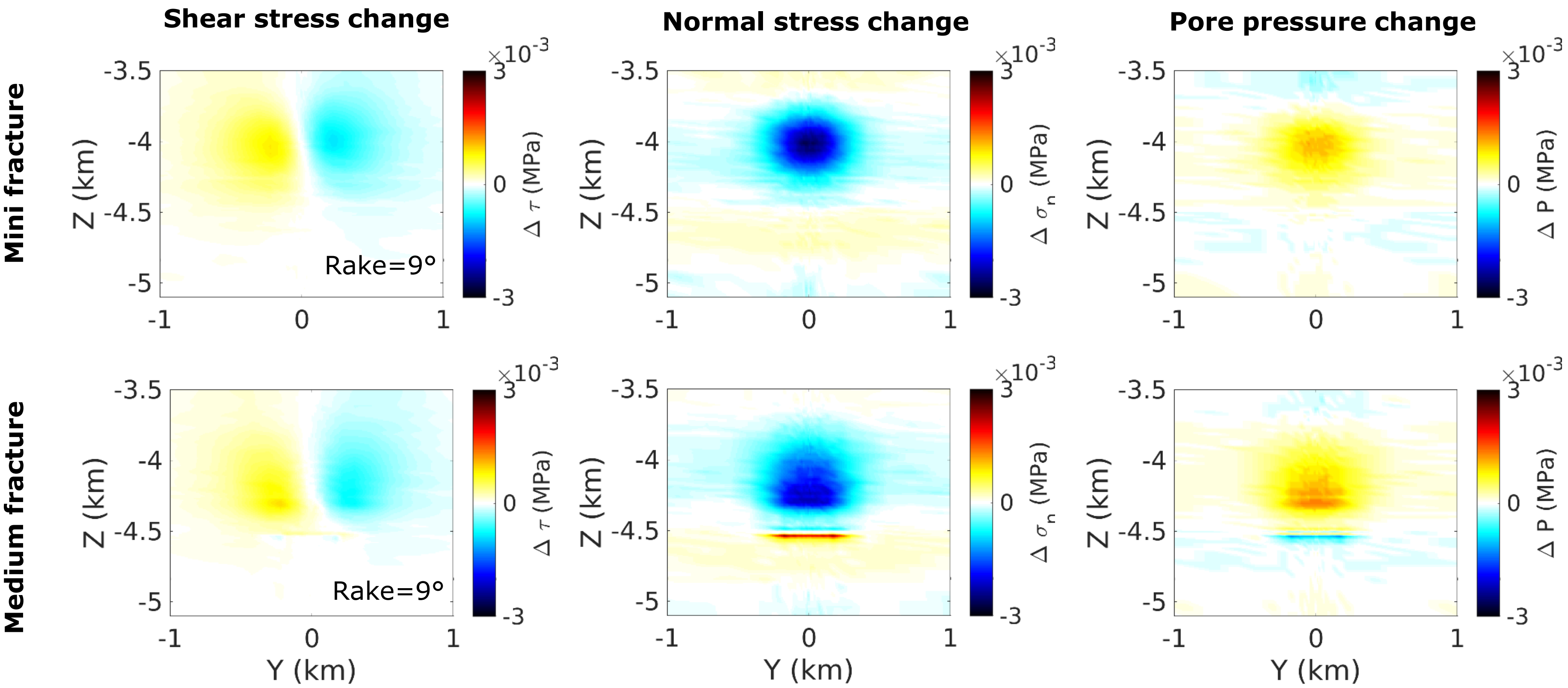
Fixed model parameters

	Host rock	Frac zone	Fault	Fault core	Cap rock
E (GPa)	cal	cal	10.0	10.0	20.0
ν	0.25	0.25	0.25	0.25	0.25
ρ (kgm^{-3})	2650	2650	2650	2650	2650
κ (m^2)	cal	cal	1e-14	1e-22	1e-22
φ	0.05	3e-5	0.10	0.01	0.01

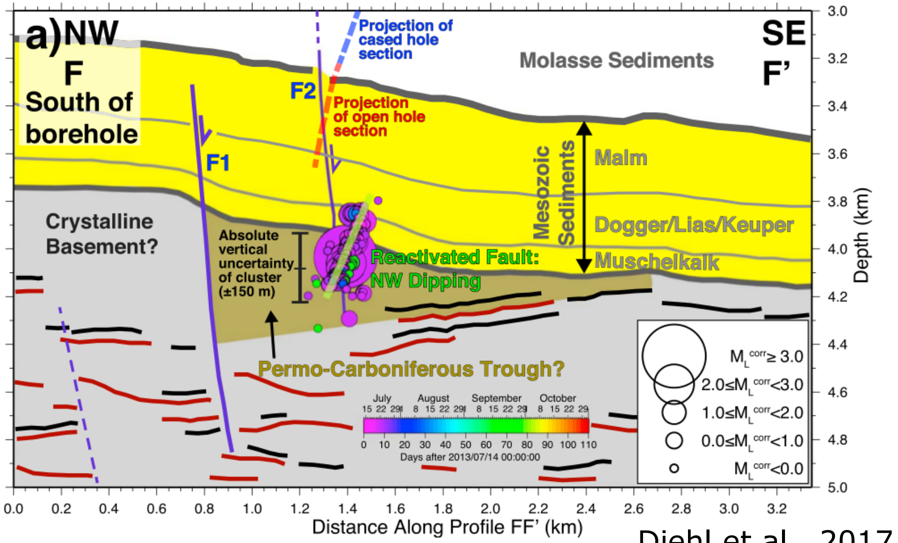
Mini fracture vs. medium-sized fracture

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

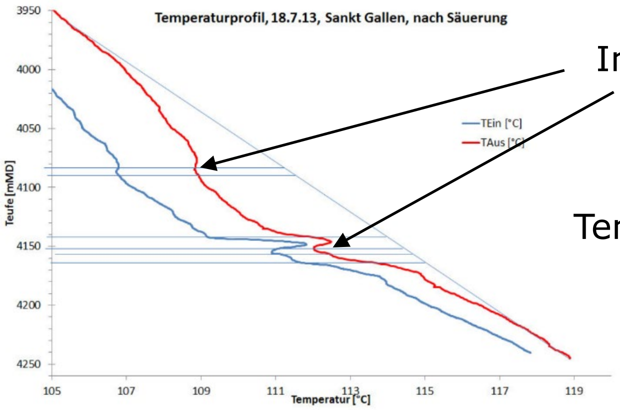
Negative stress is compressional



The conceptual model



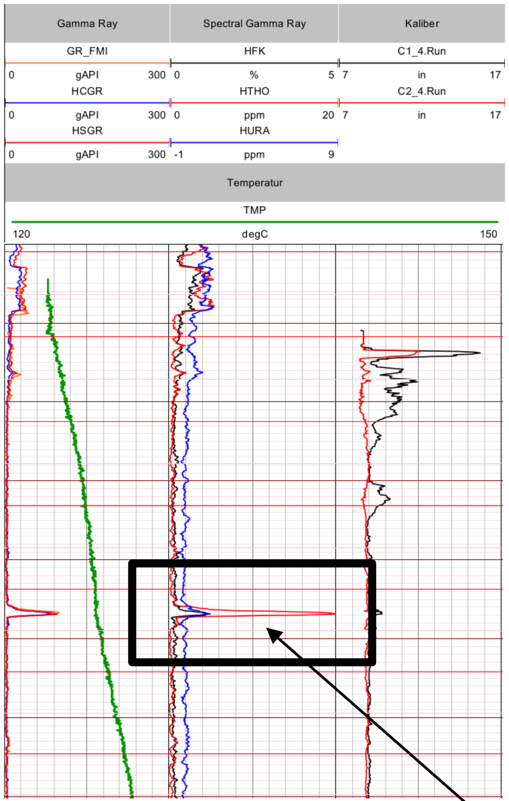
Diehl et al., 2017



Inflow zones

Temperature log

Wolfgramm (GTN), 2014



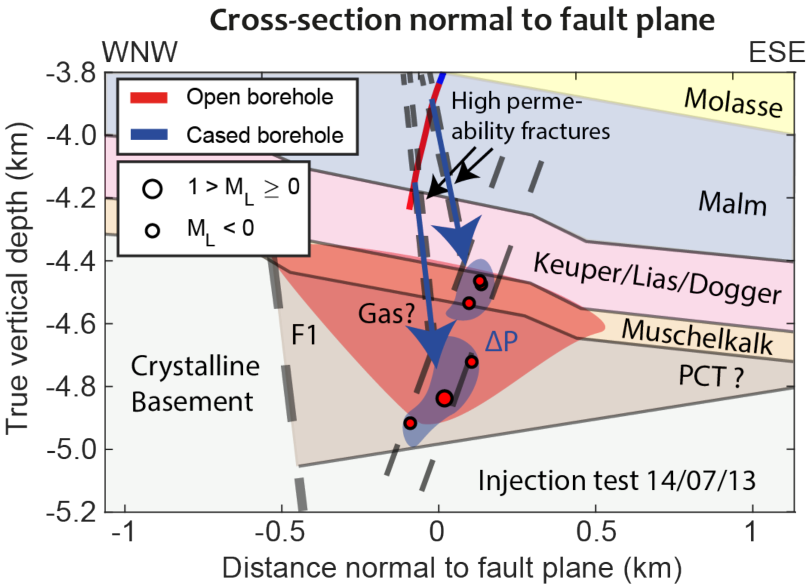
Naef and Schlanke (geosfer ag), 2014

Gamma ray log

Th anomaly (only observed at greater depth)

The conceptual model

Injection test (14 July) induces minor seismicity and opens up fractures



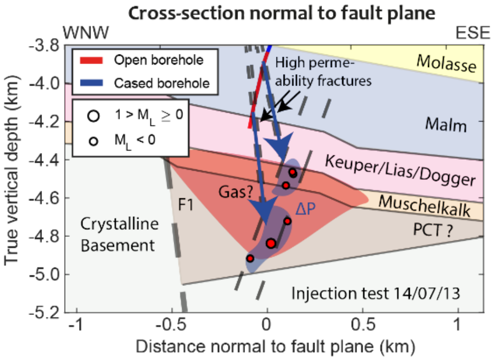
14 July

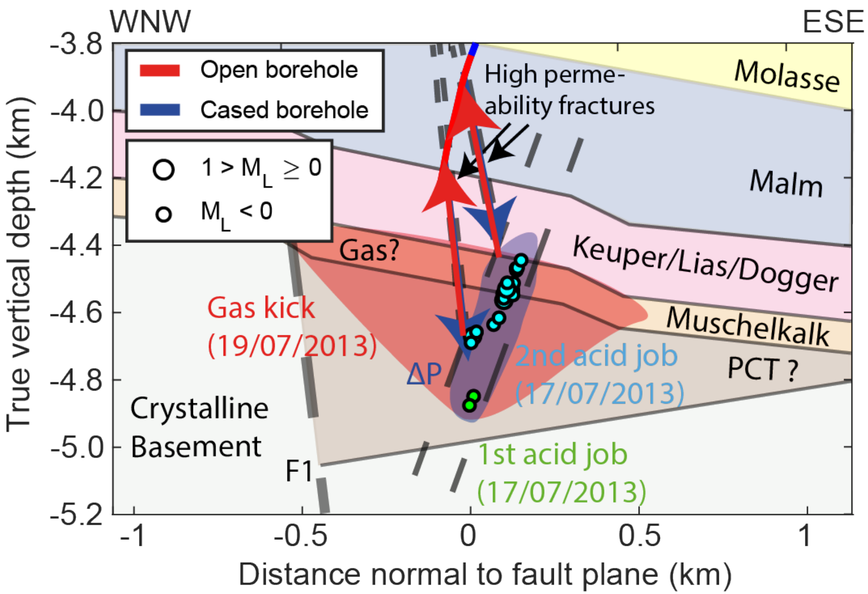
Injection test (175 m^3)

Time

The conceptual model

Acid stimulations (17 July) induce further seismicity and increase fracture permeability so that gas can migrate upwards





14 July

Injection test (175 m³)

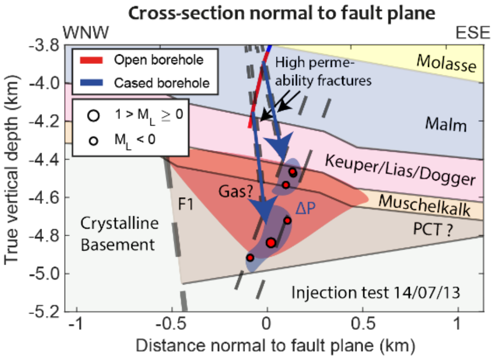
17-19 July

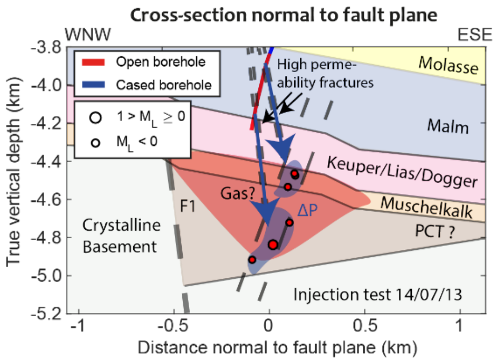
Acid stimulations and gas kick

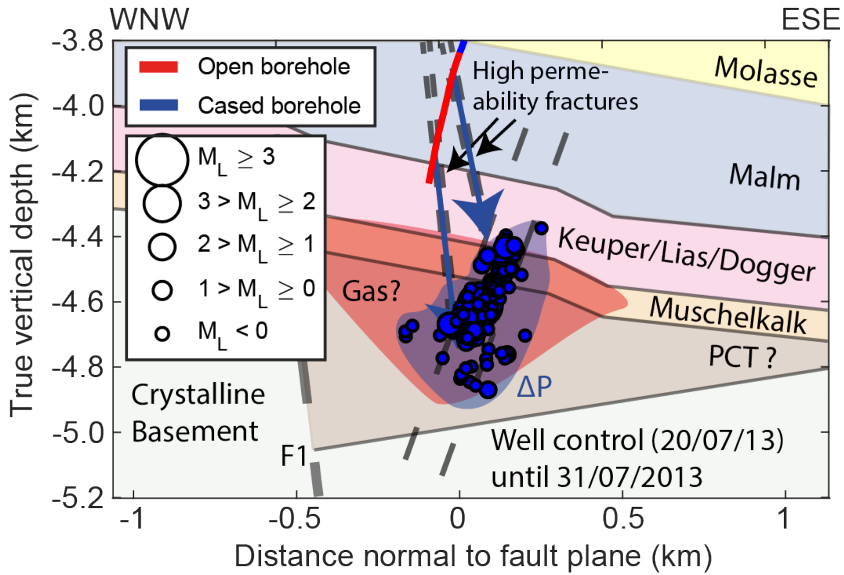
Time

The conceptual model

Well control measures (700 m^3 injected) induces main sequence







14 July

Injection test

17-19 July

Acid stimulations and gas kick

20 July

Well control measures

Time