Hydro-Mechanical Modeling of the Induced Seismicity during the Deep Geothermal Project in St. Gallen, Switzerland

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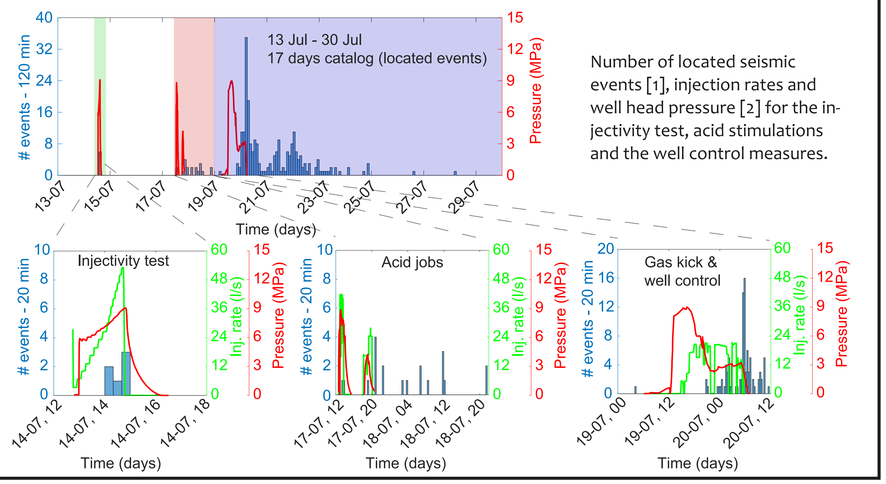
1 The St. Gallen Geothermal Project

The deep geothermal project in St. Gallen in 2013 - operated by the city of St. Gallen - targeted a carbonate aquifer at a depth of 4 km to be used for electricity production and district heating. A few days after the first injection test, overpressurized methane gas entered the well bottom, and the subsequent well control measures lead to substantial seismicity [1]. After a production test in October 2013, it was found that the reservoir was not as permeable as expected and the project was halted permanently. The St. Gallen project is a prime example to study the fluid-rock interaction at depth and the physical processes causing the seismicity. Here, we perform hydro-mechanical simulations to better determine the reasons for the induced seismicity in St. Gallen.



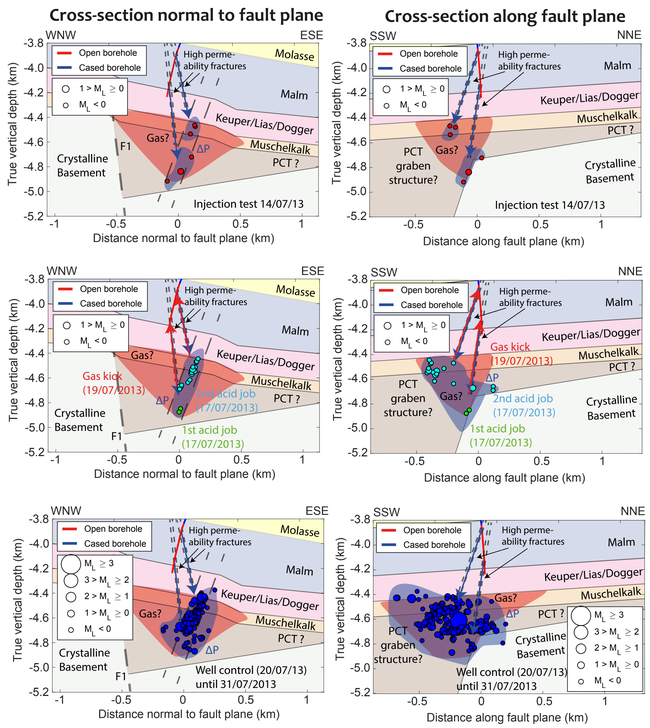
Number of located seismic events [1], injection rates and well head pressure [2] for the injectivity test, acid stimulations and the well control measures.

2 What may have happened in St. Gallen

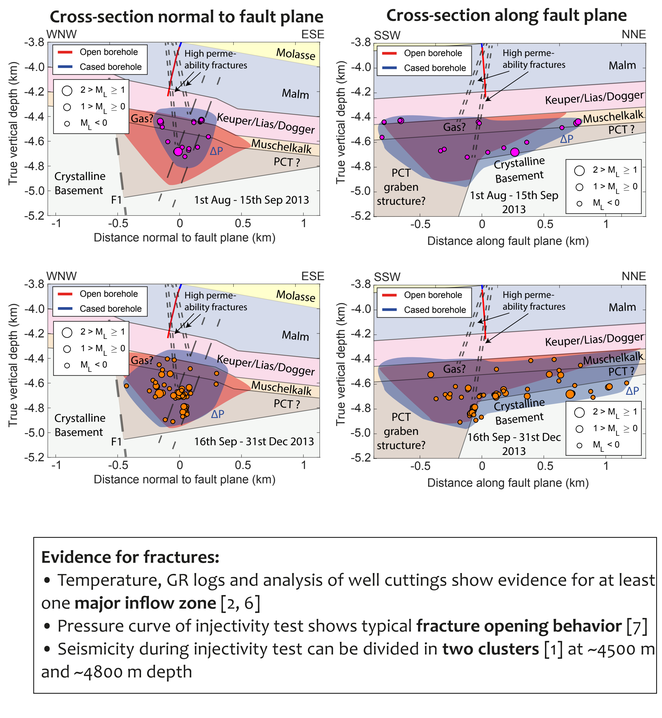
14 Jul: P increase during injectivity test opens up fractures and fluid flows to fault
14 - 17 Jul: Seismicity from injectivity test/acid jobs breaks seal to gas reservoir
17 - 19 Jul: Gas enters fractures and subsequently the borehole (gas kick)
19 -20 Jul: Injection during well control and gas destabilizes fault leading to M_L 3.5 event

1st Aug - 15th Sep: Quiet period - only a few seismic events. Seismicity starts to propagate to the north-east.
16th Sep - 31 Dec: Borehole operations, mud losses [6] - seismicity increases again. Seismicity propagates further to the north-east. Seismicity ceases in the end of Oct 2013.

Main sequence July 2013

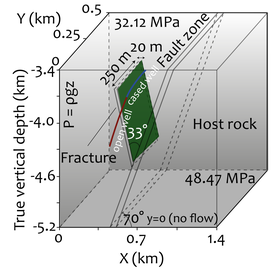


August - December 2013



Evidence for fractures:
- Temperature, GR logs and analysis of well cuttings show evidence for at least one **major inflow zone** [2, 6]
- Pressure curve of injectivity test shows typical **fracture opening behavior** [7]
- Seismicity during injectivity test can be divided in **two clusters** [1] at ~4500 m and ~4800 m depth

3 Numerical Model

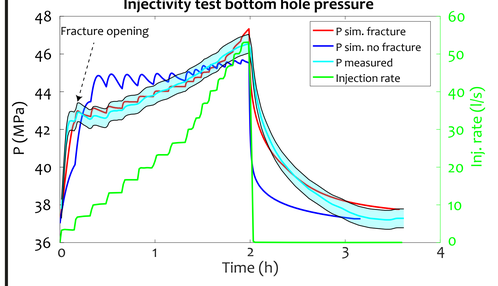


Strike-slip regime [4]
$\sigma_2 = \rho_{rock} gz$
$\sigma_1 = 1.03\ \sigma_2$
$\sigma_3 = 0.57\ \sigma_2$

Pressure-dep. κ [5]
$\phi = (\phi_i - \phi_r)\exp(\alpha \Delta P) - \phi_r$
$\kappa = \kappa_i \exp(c_1(\phi/\phi_i - 1))$

ϕ_i: Initial Porosity (%);
κ_i: Initial Permeability (m^2);
ϕ_r: Residual porosity;
c_1, α (Pa^{-1}): Fitting parameters

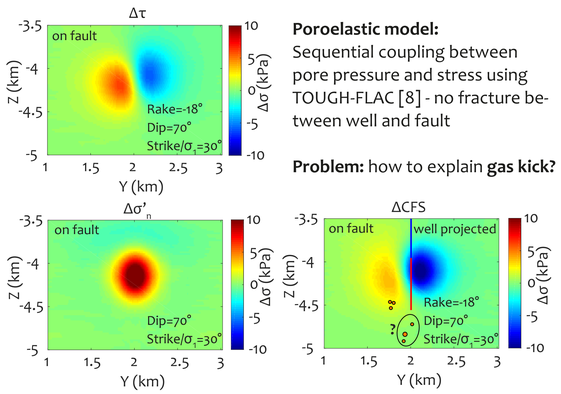
Injectivity test bottom hole pressure



Calibrated parameters with iTOUGH-PEST [3]

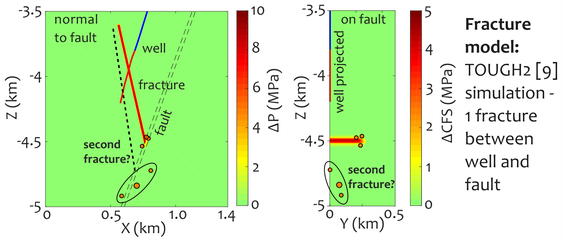
	κ_i (m^2)	φ_i (%)	φ_r (%)	c_1	α (Pa^{-1})
Fracture	$5 \cdot 10^{-16}$	10^{-2}	0	55.6	$2.0 \cdot 10^{-8}$
Host rock	$7 \cdot 10^{-19}$	5	1	45.0	$8.9 \cdot 10^{-9}$
Fault	10^{-15}	10	-	-	-

4 Seismicity Induced by Poroelastic Stress Changes?



Poroelastic model:
Sequential coupling between pore pressure and stress using TOUGH-FLAC [8] - no fracture between well and fault

Problem: how to explain **gas kick?**

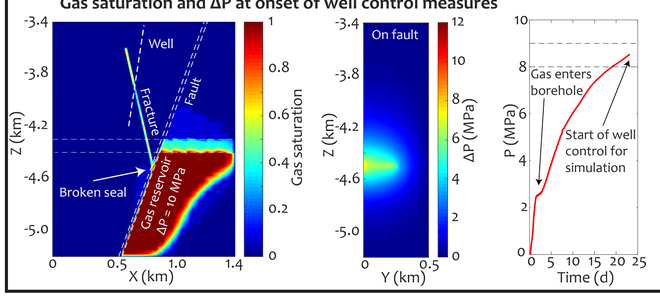


Fracture model:
TOUGH2 [9] simulation - 1 fracture between well and fault

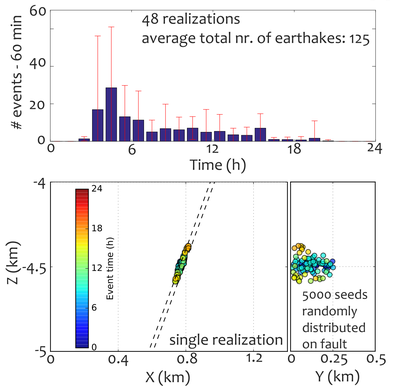
5 Did the Gas Amplify the Seismicity?

1. **Calibration of gas kick** with overpressure at well head (8-9 MPa measured in SG)
2. Fault is **pre-pressurized by the gas by 6-7 MPa** prior to well control injection
3. 24 hours after injection start - **116 recorded events vs. 125 simulated events**

Gas saturation and ΔP at onset of well control measures



Well control simulation with TOUGH-seed [5]



6 Conclusions

1. Seismicity either induced by **poroelastic stress changes or hydraulic conduit** (highly permeable fracture)
2. Induced seismicity **more probable** for fracture model since stress changes on fault are several orders of magnitude higher
3. **Gas kick is related to seismicity** only when a fracture is present
4. Gas may destabilize fault and hence **more seismicity may be induced** - to be tested more accurately
5. Observations in St. Gallen agree well with results of numerical simulations

Next steps: More accurate calibration of seismicity in St. Gallen, sensitivity study on gas overpressure, quantify relative influence of gas on seismicity

References:
[1] Diehl et al. (2017). *JGR*.
[2] Wolfgramm, M. (2013). Geothermieprojekt St. Gallen Test und Stimulation. Feldtestbericht 1.8.2013, sgsw, not publ.
[3] Finsterle, S. (2007). iTOUGH2 User's Guide.
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[7] Rutqvist, J. (2015). *Geofluids*.
[8] Rutqvist, J. (2011). *Comp. & Geosc.*
[9] Pruess et al. (2011). TOUGH2 User's Guide.

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