Characterization of the Rittershoffen Deep Geothermal Reservoir by seismicity monitoring

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Introduction

- When a geothermal reservoir does not have a natural injectivity/productivity high enough to operate the system economically, reservoir stimulation is necessary to create additional permeability.

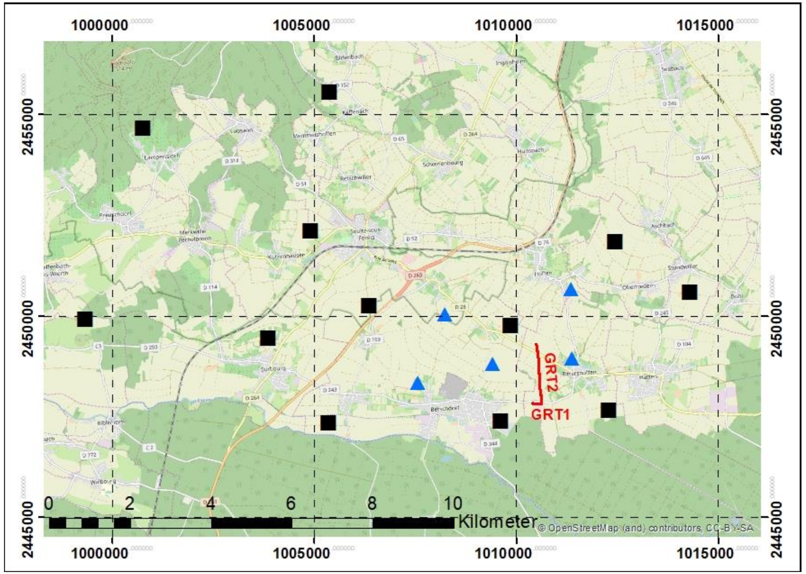
- Induced seismicity during stimulation operations is a common phenomenon.
- It is linked to the applied stimulation procedures and the geomechanical state of the reservoir.

- Analyzing the induced seismicity can therewith
  - help to analyse the effects different stimulation approaches have on the reservoir.
  - be used for reservoir characterization.

- This presentation focuses on the seismicity induced during thermal and hydraulic stimulation of the well GRT1 of the Rittershoffen deep geothermal site

Rittershoffen Geothermal Site

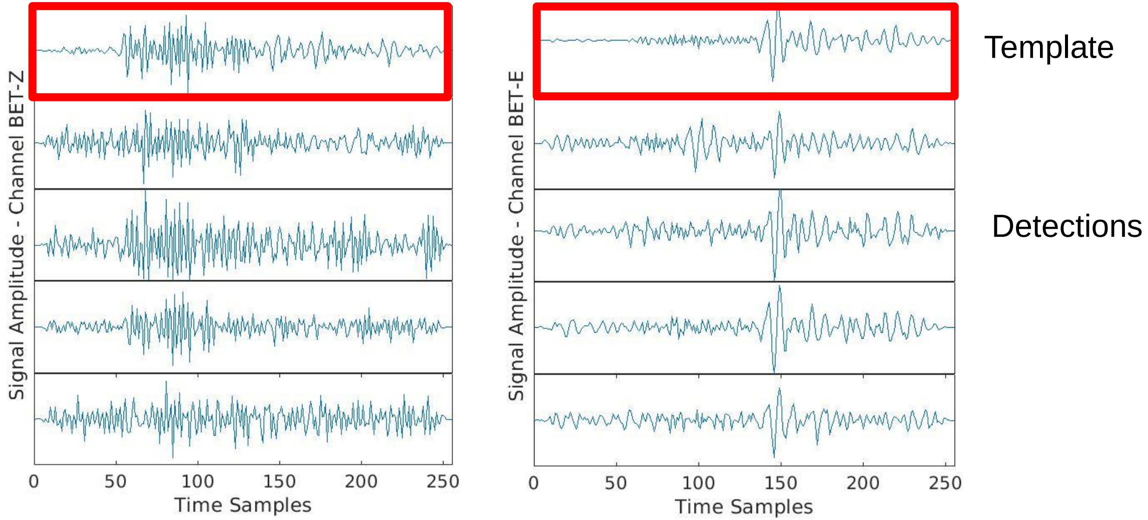
- Situated in the Upper Rhine Valley near the Soultz geothermal site
- Well doublet GRT1/GRT2, drilled to around 2.5 km depth in 2012 (GRT1) and 2014 (GRT2)
- Targeted reservoir: just below the transition from sedimentary cover to granitic basement, intersected by a major fault zone
- GRT1 underwent thermal, chemical and hydraulic stimulation in 2013



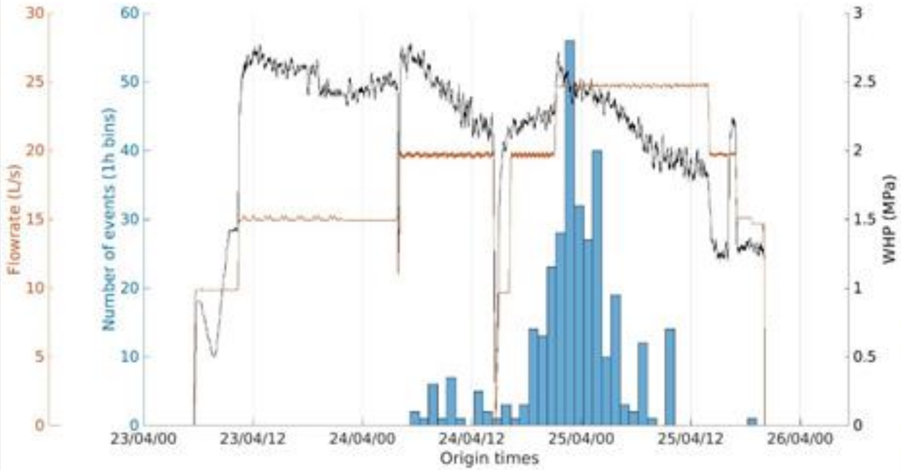
- Continuous waveforms recorded since 2012 by different seismic networks
- Permanent network: 12 stations (black squares), operational during all stimulations
- Temporal network: 5 additional stations (blue triangles) operational during chemical and hydraulic stimulation

Methodology

- Template matching:
  - Templates: known seismic events (e. g. STA/LTA detected or manually picked)
  - Computation of cross correlation between template waveforms and continuous waveform records
  - High correlation coefficient signals detection of events
- Template database: STA/LTA detected and manually revised seismic catalogue published in Maurer et al. (2020) covering thermal and hydraulic stimulation of GRT1

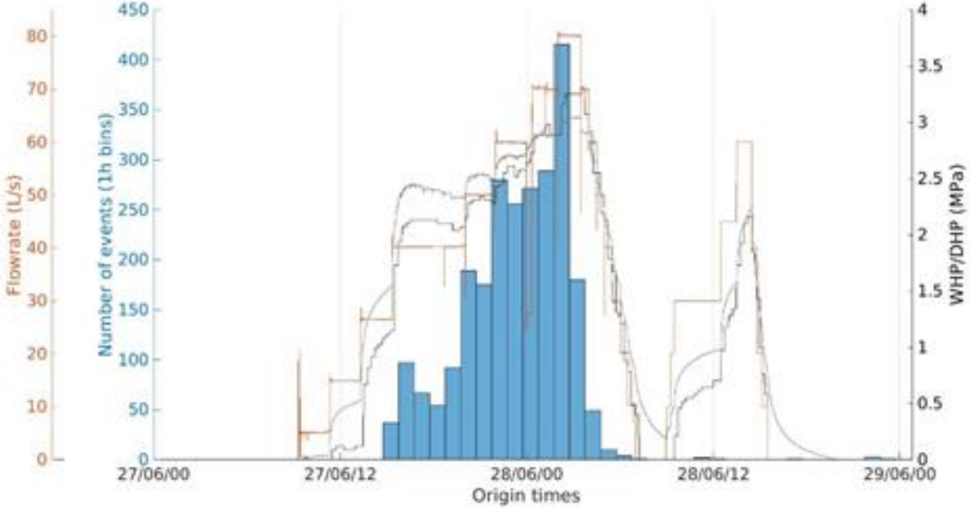


Seismicity Rate in relation with flowrate and pressure



- Thermal stimulation:
  - Duration: 62.5 hours
  - Total injected volume: 4,230 m^3
  - Maximum flow rate: 25 L/s
  - Seismicity started with a delay of 24 hours at an injection flowrate of 20 l/s and WHP of 1.7 MPa
  - Max. seismicity rate: 55 events/h

- Hydraulic stimulation:
  - Duration: 21 h, 42 min
  - Maximum injection flowrate: 80 L/s
  - After stimulation: injection test at flowrates up to 60 l/s
  - Total injected volume: 3,180 m^3 (stim.) + 820 m^3 (inj. test)
  - Seismicity rate increased gradually with increasing flowrate to ~450 events/h, only 3 events during inj. test
  - Four days after shut-in: short seismicity burst of 469 events, the majority within two hours



- Blue bars: seismicity rate in 1h bins; Orange curve: Flowrate; Black curve: WHP, Grey curve (only hyd. Stim.): DHP

Seismicity Rate and Magnitudes for thermal and hydraulic stimulation in direct comparison

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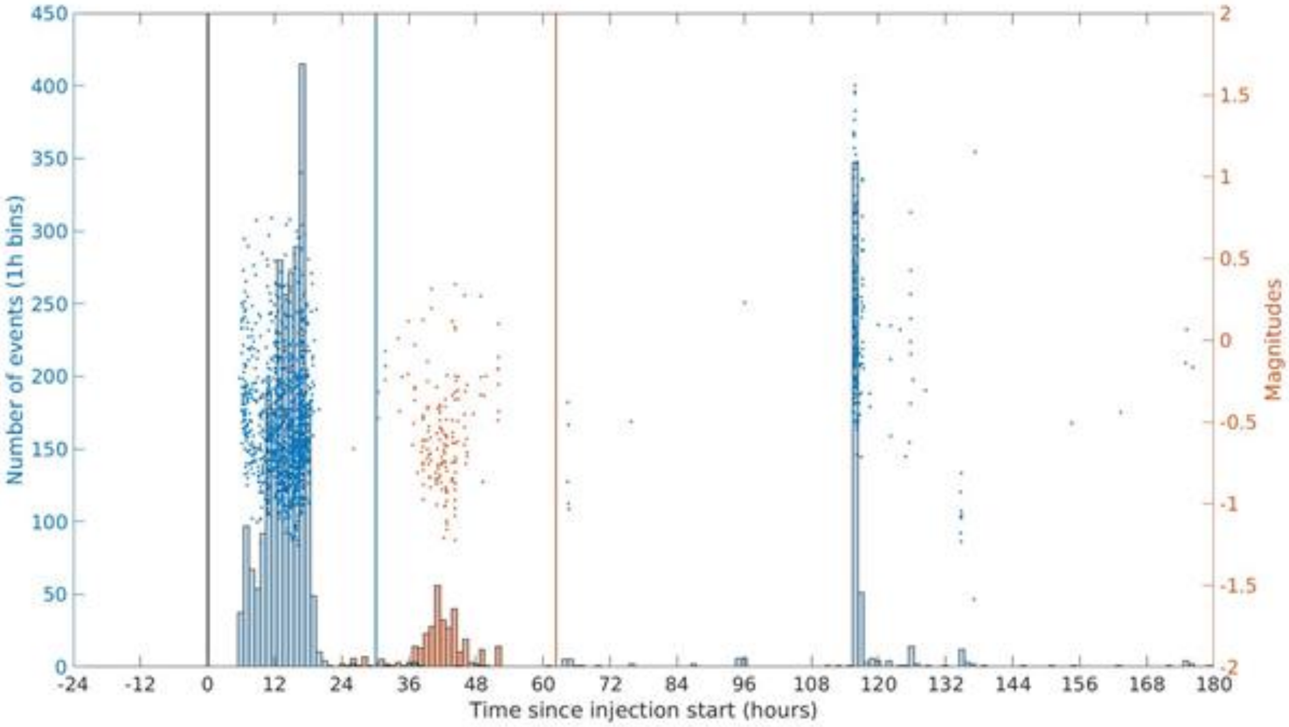
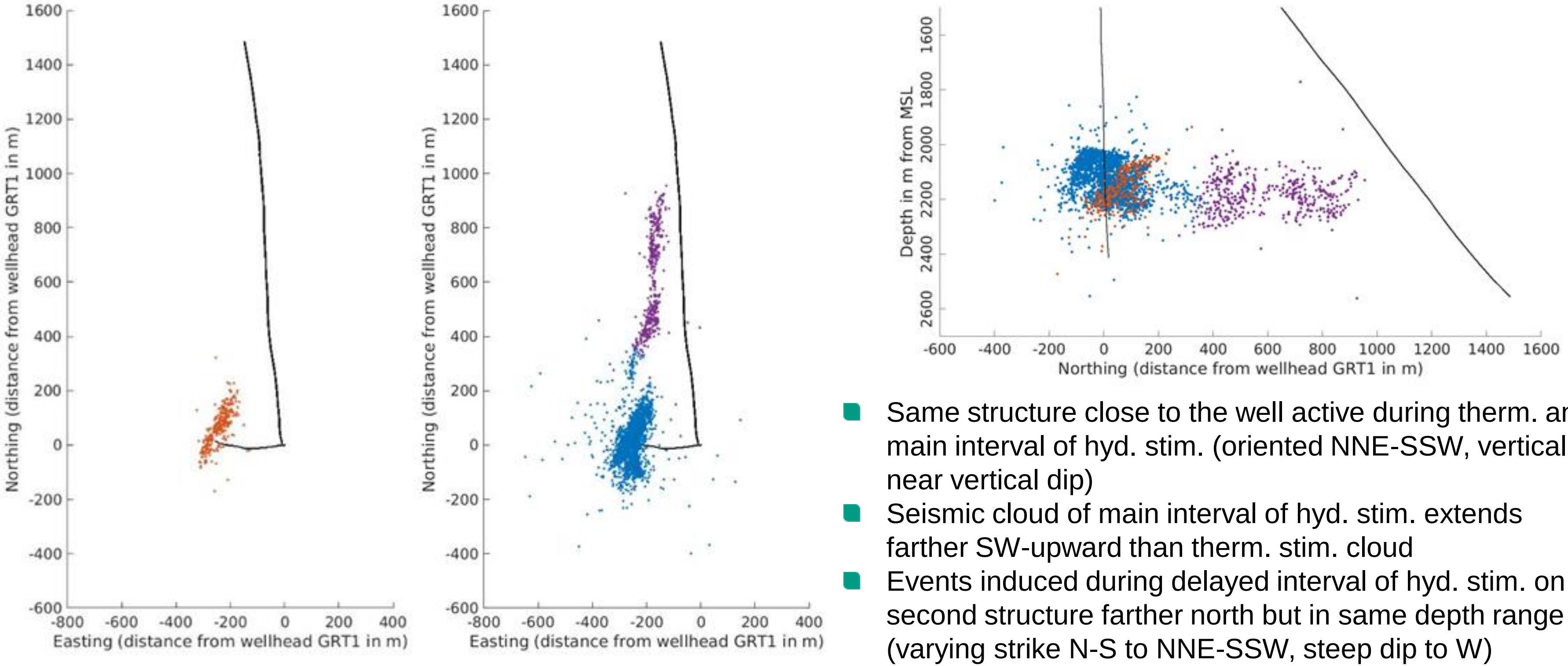


- Seismicity during hydraulic stimulation started with much shorter delay than thermal stimulation
- Much higher seismicity rates during hydraulic than thermal simulation
- Highest magnitudes:
  - 0.6 therm. stim.
  - 1.0 main interval hyd. stim.
  - 1.7 delayed interval hyd. stim.

- Bars: seismicity rate in 1h bins
- Dots: magnitudes of events
- Blue: hyd. stim.
- Orange: therm. stim.
- Black line: injection start
- Blue line: shut-in hyd. stim.
- Orange line: shut-in therm. stim.

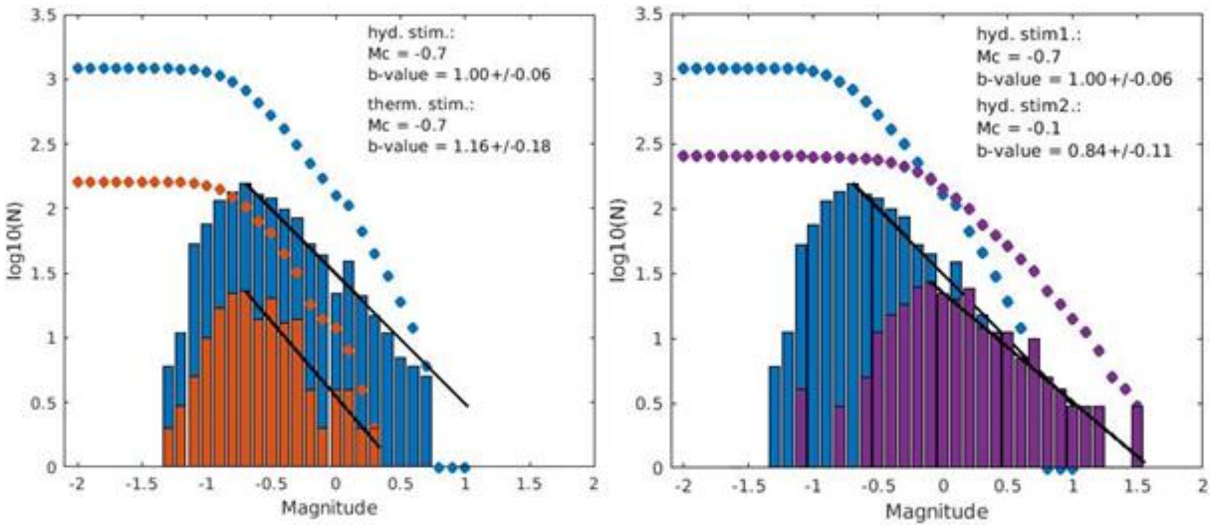
Spatial distribution of seismicity – Relative locations



- Orange: thermal stimulation, blue: main interval hydraulic stimulation, violet: delayed interval hydraulic stimulation

- Same structure close to the well active during therm. and main interval of hyd. stim. (oriented NNE-SSW, vertical to near vertical dip)
- Seismic cloud of main interval of hyd. stim. extends farther SW-upward than therm. stim. cloud
- Events induced during delayed interval of hyd. stim. on a second structure farther north but in same depth range (varying strike N-S to NNE-SSW, steep dip to W)
- Some events of the main interval of hyd. stim. are also located on this second structure

Magnitude distribution and b-value



- Left site: Magnitude distribution for thermal stimulation (orange) and main interval of hydraulic stimulation (blue)
- Right site: Magnitude distribution for the main interval (blue) and the delayed interval (violet) of the hydraulic stimulation
- Bars: magnitudes in bins of 0.1
- Dots: cumulative magnitudes
- Black line: GR-relationship

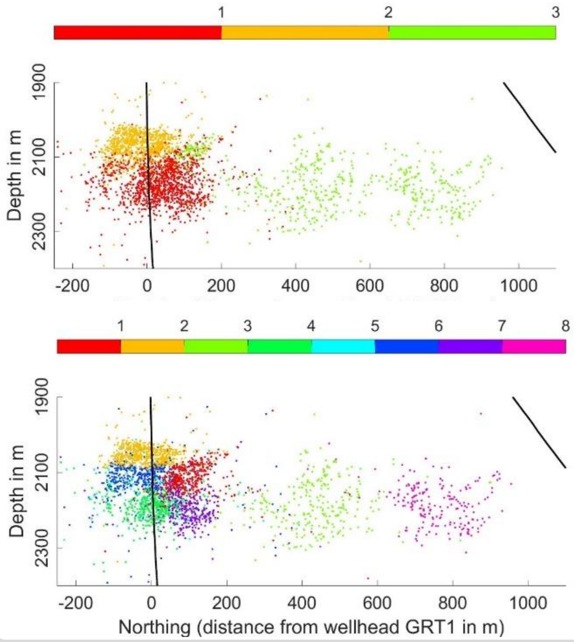
- Relative magnitudes computed for new detections relative to template magnitudes

- Magnitude of completeness:
- -0.7 for therm. and main interval of hyd. stim.
- -0.1 for delayed interval of hyd. stim.
- Higher magnitude of completeness because of daytime vs. nighttime

- b-value computation after Utsi (1965) adopted from Aki (1965)
- b-value highest for therm. stim. (1.16) and lowest for delayed interval of hyd. stim. (0.84), could indicate different fault re-activation mechanism for the two faults

Clustering analysis

- Method:
  - K-means clustering: partitioning of n observations into *k* clusters by minimizing the sum of distances between each cluster member and cluster mean (= cluster center)
  - In our case: observations are for each event a vector with correlation coefficients between this event and all other events
  - With this approach, events with similar correlation patterns to all other events are grouped together in a cluster



- Clustering analysis was performed for 3 <= k >= 10, results are shown here for k = 3 and k = 8
- With increasing number of clusters up to k = 8 it can be observed that clusters of events based on waveform similarity are largely also spatially grouped together (with the exception of cluster 5)
- The same clusters active during therm. stim. are still active during main interval of hyd. stim. -> Waveform similarity is not bound on stimulation operation
- The events from the main interval of the hyd. stim. that are co-located with the events from the delayed interval belong partly to cluster 3 (mostly active during the delayed interval), partly to cluster 7 (active during the whole main interval of hyd. stim.), indicating two different sets of waveforms in that area

Summary

- During thermal and hydraulic stimulation of the well GRT1, Rittershoffen, two faults became seismically active
- The first fault is intersecting the well, it is seismically active during the thermal stimulation and during the injection period of the hydraulic stimulation
- The second fault is located north of the first one and became seismically active at the very end of the injection period of the hydraulic stimulation and then again during a seismic period four days after shut-in
- The first fault as an NNE-SSW orientation and vertical to near vertical dip, the second fault has a varying strike N-S to NNE-SSW and a steep dip to the west
- The seismicity induced at the first fault has a higher b-value than the seismicity induced at the second fault
- The clustering analysis showed that clusters of similar waveforms correspond also to spatial clusters and that the same fault patches that were active during the thermal stimulation were active again during the injection period of the hydraulic stimulation
- The events of the injection related seismicity during hydraulic stimulation, which are located on the second fault, belong to two different clusters: one active during the whole injection, one mainly active during the delayed seismicity interval
- To conclude, the two faults show different characteristics in terms of induced seismicity, likely caused by two different fault reactivation mechanism: the first was activated as direct response to the fluid injection, the second likely triggered by the stress changes in the reservoir caused by the activation of the first fault

Acknowledgements

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