Influence of reservoir geology on seismic response during decameter scale hydraulic stimulations in crystalline rock at Grimsel

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Harvesting deep geothermal energy

- Major issues for Deep Geothermal Energy:
  1.) Create sufficient heat exchanger
  2.) Keeping risk of induced earthquakes at acceptable levels

Debris of collapsed wall after the Pohang 5.5 mag. eq. in 2017 (source: www.eenews.net)
Why do we need in-situ experiments?

- **Laboratory scale**:
  - 10 cm
  - ++ accessibility, controllability
  - -- lag realistic boundary conditions

- **Reservoir scale**:
  - 1 km
  - ++ accessibility, controllability
  - -- lag realistic boundary conditions

- **In-situ scale**:
  - Bedretto-scale, 100 m
  - Grimsel-scale, 10 m
  - ++ accessibility, controllability
  - -- more realistic boundary conditions
  - + geological, stress field complexity
  - - temperature and stress level different

- **Basel-Reservoir**

- **Reservoir scale**
The hydraulic stimulation experiments at Grimsel

Gischig and Preisig, 2015
The seismic monitoring network

- 26 uncalibrated acoustic emission sensor (green cones)
  - 8 installed in boreholes surrounding the injection intervals
- 5 calibrated accelerometer on a tunnel level (red cones)

initial injectivity, jacking pressure

stimulation

final injectivity, jacking pressure
Experiment HS4 in shear zone S3.1
Hydrofracturing experiments:
• seismicity preferentially propagates downwards
• fracture orientation at wellbore according to stress field
• later interaction with geological structures

Hydro-shearing experiments:
• seismicity generally constrained to shear zones
• more seismic events in higher transmissive S3 shear zones
• evenly distributed seismicity S1 stimulations
• more clustery character of S3 stimulations

Locations: 5139
Magnitude range: MA -6 to -2.5
Distance range: 2 – 50 m
Seismic event statistics

- **Highly variable seismic response** (i.e., the variability in b-values, and seismogenic indexes) over the experiments
  - b-value: ratio of large to small induced magnitudes
  - Seismogenic index (injected volume normalized a-value): productivity, seismoteconic state of a reservoir location

- **Dependency on geology!!!**
  - High seismic response (i.e., low b-value, high seismogenic index) for S3 stimulation experiments (HS4, HS5, HS8)
  - Also, high seismic response for experiment HF2
Seismic event statistics

- No correlation of induced maximum magnitude with injected volume
- Increasing trend of maximum induced magnitude with seismically activated area
- High variability in seismically activated area
Despite similar injection protocols and injected volumes:

- Increased seismic response for S3 injection experiments in brittle–ductile, highly fractured shear zones, with high initial injectivity
- But no, or limited injectivity gain for S3 stimulations
- Final injectivities in same order of magnitude
- More planar seismicity clouds for S1 stimulation compared to S3 seismic clouds of clustery character
- Deformation to large extend aseismic (i.e., > 98%)
Implications for managing induced seismic risk at reservoir scale

- Anticipate variability
- Selective stimulation (zonal insulation, be able to skip and seal insulated zones, pre-stimulation)
- Update induced seismic hazard forecasting models (based on pre-stimulation)
Overviewing publications
- Mechanical/hydrological
  HF: (Dutler et al., 2019)
  HS: (Krietsch et al., in prep.)
- Seismicity
  all: (Villiger et al., in prep.)
- Velocity variations
  (Doetsch et al., 2018), (Schopper et al., in prep.)
- Pre-/post hydrological stimulation
  (Brixel et al., under review)

Continuing work
- …stimulation mechanism?
- …deformation in combination with permeability change?
- …modeling?
- …

Example: Combining seismicity and strain observations
Thank you for your attention!
References


- Majority of HS seismicity clouds oriented in S3, EW direction
- Only seismic cloud of HS1 oriented in S1, NE-SW direction
- Orientation possibly dominated by geological features
Cluster 1: main stimulation in metabasic dyke region; Cluster 2: cluster from adjacent fractures; Cluster 3: newly induced fracture (orientation perpendicular to sigma 3 of perturbed stress state)

- HS4 stimulation confined in comparable small volume
- HF5 seismicity cloud oriented ESE, possibly dominated by stress field (perturbed stress state)
- HF8 seismicity cloud oriented EW, dominated by stress field (unperturbed stress state), or geological features?
HF2, cluster 1 orientation ESE, possibly stress field dominated

HF2, cluster 2 orientation EW, geology or stress field dominated?
- Seismicity propagating in various directions
- Repeated rupturing on seismically active patches
- Results in estimate of seismically activated area
Lessons learned, suggestions

- **Magnitude computation**
  - Place piezosensors close (not too close) to injection and collocate them with accelerometers

- **Location**
  - Anisotropic/heterogeneous velocity model useful

- Seismicity from monitoring boreholes
  - Matlab .fig file
Additional material