Controlling Fluid-Induced Seismicity during a 6.1-km-Deep Geothermal Stimulation in Finland

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Introduction

• Seismic events possibly related to EGS have seriously affected/terminated some geothermal projects
• Implementation of safe stimulation strategies is critical for public acceptance of EGS projects

This study

• Near-realtime seismic monitoring allowed managing hydraulic energy input and avoid project-stopping M2.1 event during stimulation of a 6.1 km-deep geothermal well near Helsinki, Finland
St1 Deep Heat project
Located in Helsinki suburban area (Aalto University, Espoo)
Provide sustainable baseload for the campus-area district heating network
Project site

- Well OTN-3: **6.4 km MD**
- Open bottom-hole **1000 m** inclined at **45°**
- Target formations at **5.1-6.1 km** depth with bottom hole temperature **120°C**
- Simple geology
  - 10 m sedimentary overlay
  - Precambrian granites, gneisses, amphibolites
- Complex small-scale tectonic structures
  (folded, foliated, jointed, faulted...)  
  - Broad steeply dipping damage zones trending SE-NW (drilling problems) 
  - FZ 8km away (M2.6), Inactive TF 1.5km away
OTN-3 stimulation campaign in June-July 2018

- **Five** stimulation stages selected using borehole logs
- Continuous stimulation of selected stages: **49 days**
  - Water injected: **18,500 m³**
  - Well head pressures: **60-90 MPa**
  - Injection rates: **400-800 l/min**

**Comparison:**
- **Cooper Basin:** **20,000 m³**
- **Basel:** **11,500 m³**
Seismic activity during stimulation campaign

6,152 located in the vicinity of the project site with magnitude estimate within 5 minutes after occurrence → TLS system
+10 minutes with manual refinement

St1: $M_{max}$ 1.9 @ 18,500m$^3$ injected

No project-stopping red alert ($M_{LHEL}$ 2.1)

Cooper Basin: $M_{max}$ 3.7 @ 20,000 m$^3$
Basel: $M_{max}$ 3.4 @ 11,500 m$^3$

Postprocessing:
Pick/amplitude pattern matching:
+40,000 events ($M_{LHEL}$ >-1.21)
DD relocation: ~2000 events
(rel. precision 66-27m for 95%-68% of dataset)
Seismicity during stimulation

- Three major clusters activated simultaneously
- No spatiotemporal correlation injection ports-seismicity → leak bypassing stage packers near borehole
- Downward migration, propagation of seismicity along SE-NW subparallel to the direction of $S_H^{MAX}$
Controlling induced seismicity (Phase P1)

- Seismic activity occurs immediately after 75 MPa of WHP is exceeded  ➔ no Kaiser effect
- Seismic energy release proportional to the hydraulic energy (P*V)
- Quick reduction of seismic activity after injection subphases
Controlling induced seismicity (Phase P2)

- Change in injection strategy led to accelerated seismic moment release
- Series of large events forced premature finish of P2
- Stimulation stopped for a few days.
Controlling induced seismicity (Phase P2)

- Increase of $M_{\text{max}}$ with cumulative injected fluid volume. Trend following *Galits et al. (2017)*.
  - $M_{\text{max, arr}}$ depends on amount of stored elastic (~hydraulic) energy available for rupture propagation
  - Modified injection strategy: Reduce the amount of stored energy!
Controlling induced seismicity (Phase P3 P4 P5)

- P3: Reduction of WHP to < 90 MPa,
- P4-P5: Changing injection plan: up to 18 hrs injection / up to 12 hrs resting period, direct reaction on accelerating seismicity and occurrence of large events ➤ Stabilized injection efficiency

\[ I_{\text{eff}} = \frac{E_0}{E_H} \]
Successful control of $M_{\text{max}}$ likely due to:

- Adaptive injection strategy guided by real-time seismic monitoring - limiting hydraulic energy input rate.
- Possible favorable stress conditions, and geological basement structures of the reservoir
- ...Fortune favours the brave
Re-activation of distributed fracture network (1)

- DD relocated data provides no evidence for alignment of seismicity along a large fault
- Damage zones visible in available engineering (log) and geological data
- Significant drop-off in the number of events above M>1.5
  
  No faults large enough to sustain larger events? Faults can’t store enough elasing energy to support a runaway rupture?
- Seismic injection efficiency suggest reactivation of limited fracture network
Re-activation of distributed fracture network (2)

- Seismicity shows no evidence for alignment along a large fault
- Damage zones visible in available engineering and geological data
- Significant drop-off in the number of events above M>1.5
  
  No faults large enough to sustain larger events? Faults can’t store enough elastic energy to support a runaway rupture?
- Seismic injection efficiency suggest reactivation of limited fracture network
Low stress perturbation (1)

- Lower background tectonic stresses
- No pronounced clustering
- Minor triggering? Minor stress transfer?
- Relatively rapid dissipation of injected hydraulic energy
- Stationary b-value in later injection phases – no change in deviatoric stress?
- Hazard seemingly controlled by GR a-value changes

Low stress perturbation (2)

- Lower background tectonic stresses than at other sites (Basel, Pohang)
- No pronounced clustering → minor triggering? → limited stress transfer?
- Relatively rapid dissipation of injected hydraulic energy
- Stationary b-value in later injection phases → no change in deviatoric stress? \textit{(Scholz, 1968)}
- Hazard seemingly controlled by GR a-value changes

\textit{b-value stationarity: ADF test (Dickey and Fuller, J. Am. Stat. Assoc, 1979)}
Summary and conclusions

- Project stopping $M_{LHEL}$ 2.1 earthquake was successfully avoided by adapting injection operations using near-realtime monitoring of induced earthquake rates, locations, magnitudes, and evolution of seismic and hydraulic energy.
- Fluid injection was likely performed into a complex fracture/fault network leading to low stress perturbation. No major faults are known/were found in the reservoir.
- Successful operation required close cooperation of seismologists, site operator, TLS team and local authorities during stimulation.
- The outcome of the St1 DH project may indicate a possible approach allowing to manage induced seismicity in similar geothermal projects.
Thank you very much for your attention!

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Stay tuned!

➤ Kwiatek et al. (2019), Science Advances, in press
Spare slides
Re-activation of distributed fracture network (3)

- Seismicity shows no evidence for alignment along a large fault
- Damage zones visible in available engineering and geological data
- Significant drop-off in the number of events above M>1.5
  
  No faults large enough to sustain larger events? Faults can’t store enough elastic energy to support a runaway rupture?

- Seismic injection efficiency suggest reactivation of the fracture network

\[ I_{\text{eff}} = \frac{E_0}{E_H} \]

Bowland Shale: $10^{-1}$
Horn River Basin $10^{-2}$
Basel $7 \times 10^{-3}$
This study $3 \times 10^{-3}$
Aspo laboratory $10^{-5}$
Horn River Basin $10^{-5}$
Barnett: $10^{-9} - 10^{-7}$
Laboratory: $10^{-10} - 10^{-7}$

Seismic injection efficiencies Goodfellow et al., GRL, 2015
Seismic monitoring networks

Stimulation
12 Shallow (0.3-1.3 km) borehole geophones
12 Deep (2.0-2.6 km) borehole sensors in OTN-2 TLS network
Surface 17 geophones
Stress magnitudes at the drill site were estimated from wellbore breakouts and minifrac shut-in pressures measured down to a depth of 1.8 km (13). Extrapolated to 6.1 km depth, these were estimated to be a $S_h^{\text{min}}=110$ MPa, a $S_v=180$ MPa, and a $S_h^{\text{max}}=240$ MPa. Pore pressures were assumed to be hydrostatic, equaling to approx. 60 MPa. Assuming a friction coefficient of 0.6, these results suggested that optimally oriented fractures and faults could be readily activated with moderate fluid pressure increases.
Data extension and refinement

Data reprocessing

- data refinement
- data reduction:
  - Full catalog including detections (~43,000 earthquakes above $M_{1.21}$), sometimes constrained to $M_{1.0}$ due to night-day cycle > energy budget, b-value
  - Relocated catalog using DD method (~1,950 earthquakes) with relative location precision ~60 m (95% confidence ellipse) > spatio-temporal evolution, clustering
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Traffic Light System

- Thresholds based on PGV (critical facilities located nearby)
- All $M_{LHEL} > 1.2$ reported within 20 minutes to local authorities.
- $M_{LHEL} > 2.1$ Stop of the stimulation (...and waiting for approval from Finnish Authorities)
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Seismic center operation

- Performance for $M>1.1$ without/with manual reprocessing: 5 / 15 minutes
Public response

- No complaints on ground motions during whole stimulation
- ... but nature likes to surprise us
Public response

- Over 60 complaints related to audible earthquake signals
- Remedy: Don’t inject in the night
Detection limits

- Target: TLS (location+magnitude), tracking fracture network (optional)
- Outcome: EQs with $M > -0.3$ possible to locate, detection limit $M \simeq -1.4$

 Courtesy of fastloc GmbH