Engineered Geothermal at Otaniemi and Basel: “end”-members in drilling and induced seismicity?

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and
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In December 2006, a 5.5 km deep, rotary drilled, million-liter, brine-injection under the city of Basel, Switzerland, induced an M3.4. The result was a several million Euro road-bump for EU EGS. The aim of the injection was to create a single, ~km square, fracture system in which water could be circulated and heated for both electrical power generation and municipal district heating. Now 10 years, on Basel has become the international by-word for EGS induced-earthquake show-stoppers.

Set against this background, st1 Deep Heat, a joint venture with the Scandinavian petroleum distribution company ST1, is attempting a slightly deeper, but much smaller volume and rate stimulation, district heating EGS development. The development is located on the Otaniemi campus of Aalto University, immediately west of Helsinki, Finland.

In this case the initial stimulation well was first air hammered 4500 m, setting a Scandinavian drilling record for both total depth and a one-day run of 252 m. Water hammer drilling was then tested to continue deeper, but after a 3-bit run yielded only 60 m of hole, a switch was made to rotary drilling. Deviation to ~30° was also begun. At 5020 m a highly fracture zone required extensive cementing, taking up 3 weeks of drilling effort. A similar zone was encountered at 5250 m, taking up another week. But, despite these time losses, it is now evident that there are permeable fracture systems at depth.

At the moment, straight hole drilling continues at ~35° with the aim of reaching a measured depth of 6500 m. Our R&D venture was selected for the seismic monitoring of both Basel and Otaniemi. At Basel, we installed six, 0.35 to 2.4 km deep, stations of downhole 2 Hz seismometers and 4-g accelerometers. At Otaniemi we are completing a 11-station net of 0.35 to 1.2 km deep, 4.5 Hz seismometers. We are also a 2240 to 2680 m deep, 12-level seismic VSP array at the drill site.

A swarm of induced microearthquakes occurred during casing-cementing at both Basel and Otaniemi. But this appears likely to be the only induced-seismicity parallel between the two projects. Not only are the stimulation and traffic-light monitoring plans end-members, the tectonic settings are entirely different: a continental rift versus isostatic rebounding crust. The rocks in Finland are cold, only ~20°C/km. The Otaniemi wells have remained circular to less than a percent, suggesting low horizontal shear stress. The stimulation is scheduled for Dec/Jan 2018, a few days before the SMU meeting. Will the stimulation produce enough pressure to open fractures and induce a felt earthquake? We are planning to report on these efforts at the meeting.
The Innova rig, 307 mm air hammer and cuttings

Air hammer cuttings: “fingernail flakes”

Air hammer drilling rate

Seismic Monitoring Net (drill site at OTN-III) and a cementing induced microearthquake (0.5 s window)
Engineered Geothermal at Otaniemi and Basel:

“End”-members in drilling and induced seismicity?

Matt Siegler (SMU)
speaking for:
PE Malin et al.
(GFZ – Seismomechanics
Advanced Seismic Instrumentation and Research)
Swiss Federal Office of Energy project
Contracted to Geothermal Explorers
Single large fracture flow system in ~ 200 C
Primary direct use for municipal heating
Secondary power for pumps
Production from ~ 5 km

Otaniemi/Espoo - Finland
(2018 – “€30M”)
Joint st1 (O&G) and Fortum (municipal Heat)
Operators: st1 Deep Heat Oy
Close spaced double well system ~ 100 C
Primary direct use for municipal heating
Secondary power for pumps
Production from ~ 6 km

Basel - Switzerland
(2006 – “€20M”)

Fenno-Scandian Shield Faults
Induced Seismicity: The difference in geological settings
Induced Seismicity: The difference in geological settings

**Basel → Rift Subsidence**

- Basel
- Rift Subsidence
- Basel

**Extension**

- Mmax ~ 6.5

**Otaniemi → Glacial Rebound**

- Otaniemi
- Glacial Rebound

**Flexture**

- Mmax ~ 2.7
2006 - A Critical EU EGS Project in Downtown Basel, Switzerland!

5.5 km deep municipal heating wells

Rotary/mud drilling: 1-5 m/hr
October 18, 2006

Basel emergency officials participate in earthquake preparedness exercise ....

.... on anniversary of 1356 M6.5.

December 9, 2006

Man-made tremor shakes Basel!

Drilling for geothermal power triggers small earthquake, causes minor damage...

.... City prosecutor launches investigation to find if the company should pay repairs.....
What happened?

.....25,000 Earthquakes!

Number of event per hour:

Detected —

Located —

Magnitude

9 hrs after shut in

Legal Limit = 3.4

Number of event per hour:

Detected —

Located —

Magnitude
2018 - Another Critical EGS Project

Aalto University, Finland!

6.4 km (target) deep municipal heating wells

Air hammer drilling: 5-10 m/hr
(to 4500 m – rotary/mud to 5700 m)
The Otaniemi District Heat Plant – circa 1949
Helsinki District Heat Plant Network - all fossil fuel fired

More than 20 metropolitan Helsinki ...and more than 300 in the country
Air hammer cuttings: “fingernail flakes...

...and walnut shells.”

Air Hammer Drilling

20 percussions/sec & 60 revolutions/min...

...200 – 300 bars of pressure.
AIR HAMMER DRILLING OTN-II – TO DEPTH 3325 M & STOPPED

Average for 35 days = 3 m/hr

AIR HAMMER DRILLING OTN-III – TO DEPTH 4500 M, THEN TO ROTARY/MUD

Average for 35 days = 7 m/hr

Record = 10 m/hr for 30 hrs
Drill Bit Seismic imaging using MH air hammer drilling into PH array

For 80 m sensor spacings the number of sample points per wavelength along array are:

- 14 deg & 30 Hz → 10 excellent
- 14 deg & 60 Hz → 5 very good
- 70 deg & 30 Hz → 2.4 usable?
- 70 deg & 60 Hz → not usable

Resolution → 50 m (1/4 wave criterion)
→ 25 m
→ 50 m

<table>
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<th>ST</th>
<th>Depth</th>
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<tr>
<td>24</td>
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<tr>
<td>1</td>
<td>80</td>
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<tr>
<td>0</td>
<td></td>
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</table>

V real = 6 km/s

Apparent wavelengths at 60 Hz
- 14 deg → 400 m
- 70 deg → 105 m

Apparent wavelength at 30 Hz
- 14 deg → 800 m
- 70 deg → 210 m

5 km MH & 2 km PH

Buried MEQ St

PH array with 80 m spacing

ST Depth

14 → 24 km/s V apparent

70 → 6.3 km/s V apparent
Drill Bit Seismic imaging using MH air hammer drilling into MEQ net work
Deconvolved Air Hammer Source - Drill Bit at 1350 m

Drill Sensors

Borehole

Loss zone

Depth: P S
Faulted Reflector at ~2140 m

Drill Bit Depth (file no.)

Borehole sensor at 1840 m

Mutated 1st break

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Source</td>
<td>1840 m</td>
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<tr>
<td>TWT to reflector</td>
<td>0.1 s</td>
</tr>
<tr>
<td>OWT to reflector</td>
<td>0.05 s</td>
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<tr>
<td>P reflection into Sv?</td>
<td>6.00 km/s</td>
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<tr>
<td>P depth from source point</td>
<td>300 m</td>
</tr>
<tr>
<td>Reflector at</td>
<td>2140 m</td>
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<tr>
<td>S reflection into Sv?</td>
<td>3.46 p / sqrt 3</td>
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<tr>
<td>S depth from source point</td>
<td>173</td>
</tr>
<tr>
<td>Reflector at</td>
<td>2013 m</td>
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</table>
Induced Seismicity: The difference in Traffic Light Systems

Basel → 6 borehole seismic stations

Otaniemi → 12 surface; 12 borehole; 12 level VSP
st1 Otaniemi Heat Mine 3-C borehole seismic net

This diagram shows the design principles for the network and calibration shots.

The design criteria are:

1. 3-C borehole seismometers to record both P & S for epicenter and depth control.

2. Progressive station radial distances to 1.5 times 5 km target depth for epicentral (horizontal) location control.

3. Progressive 0.2 to 0.5 km station location tolerance.

4. Triangular inner, mid, and outer ring station configuration covers azimuthal gaps.

5. Stations st01, st10 & st11 can be eliminated without significantly effecting events in NW epicenter locations.
<table>
<thead>
<tr>
<th>Owner</th>
<th>Network Name</th>
<th>Purpose</th>
<th>Locations</th>
<th>Details</th>
<th>Status</th>
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</thead>
<tbody>
<tr>
<td>st1 Deep Heat</td>
<td>Surface</td>
<td>To monitor surface vibrations for the TLS</td>
<td>Twelve</td>
<td>Geophone locations and number to be confirmed. Network to be installed by Kalliotekniikka. Data to be made available to ISUH as described below.</td>
<td>Installed</td>
</tr>
<tr>
<td>Satellite</td>
<td>To locate and estimate magnitude of seismic events for the TLS</td>
<td>Twelve boreholes</td>
<td></td>
<td>One geophone per borehole installed at depth between 300 and 1,200 m depth.</td>
<td>Existing</td>
</tr>
<tr>
<td>Vertical</td>
<td>Engineering data collection to support detailed design of doublet</td>
<td>One borehole</td>
<td></td>
<td>12 Level MEQ VSP array installed vertically to 3 km depth.</td>
<td>Installed</td>
</tr>
<tr>
<td>ISUH</td>
<td>HEL</td>
<td>Temporary monitoring by ISUH</td>
<td>Five</td>
<td>Weak motion seismometers.</td>
<td>Existing</td>
</tr>
</tbody>
</table>

Notes:
1. In the event of an exceedance by the Surface network, the Satellite network will be used by st1 DH to evaluate magnitude and location of seismic events.
Stimulation plans....

...Seismic mitigation

<table>
<thead>
<tr>
<th>Activity</th>
<th>Expected</th>
<th>Maximum</th>
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<tbody>
<tr>
<td>Stimulation Duration</td>
<td>20 days</td>
<td>40 days</td>
</tr>
<tr>
<td>Daily Pumping Period</td>
<td>12 hours / day</td>
<td>24 hours / day</td>
</tr>
<tr>
<td>Post Pumping Rest Period</td>
<td>12 hours</td>
<td>12 hours</td>
</tr>
<tr>
<td>Water Volume</td>
<td>8,650 m³</td>
<td>100,000 m³</td>
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<tr>
<td>Injection Rate</td>
<td>10 L/s</td>
<td>30 L/s</td>
</tr>
<tr>
<td>Over pressure</td>
<td>400 bar</td>
<td>1,000 bar</td>
</tr>
</tbody>
</table>

**CONDITIONS & ACTIONS**

**GREEN**

- PGV & Magnitude based:
  - PGV < 1 mm/s & M < 1.0
  - < 1.2
  - See TLS Plan
- Actions: Continue

**AMBER**

- PGV ≥ 7.5 mm/s & M ≥ 2.1
  - ≥ 1.2 & < 2.7
  - See TLS Plan
- Actions: Notify & Continue

**RED**

- PGV ≥ 7.5 mm/s & M ≥ 2.1
  - ≥ 2.7
  - See TLS Plan
  - STOP & Notify
  - Resume only with permission
Where is the project at:

- Today, Peter Malin isn’t here because he is serving on a public panel on Finnish national TV to discuss the upcoming frack (likely in March or April) and the potential for induced seismicity.

- Hole 1 was “air hammered” to 3325m, Hole 2 to 4500m.

- Tricone Drilling has proceeded on Hole 2 to 5600m

- March- Hydrofrack will be made in hole 2 at ~6000m depth, then hole 1 will be drilled to intersect fracture network