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Six Kilometers to Heat: Drilling, Characterizing & Stimulating the OTN-3 Well in Finland

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ABSTRACT

In 2018 the Finnish company St1 objective Deep Heat Ltd completed the 1st phase of a 6.1 km deep EGS development on Aalto University's Otaniemi campus. The I aim is to pilot test EGS district heating for the city of Espoo. This talk presents a summary of the project's drilling, characterization, and stimulation of its 6.4 km MD injection well, OTN-III, which in 2019 is being followed by an equally deep, nearby production well.

In 2015 St1 cored a 2.015 km OTN-I pilot hole to assess drilling and temperature conditions. Entirely in basement, it was extensively logged, establishing a gradient of ~18oC /km (at bottom, OTN-3 is ~120^{o}C.) In 2016 air hammer drilling of production and injection wells began. A 1.8 km, 24-level seismometer chain was installed in OTN-1 for Drill Bit Seismic while OTN-2 was drilled to 3.325 km. OTN-3 was air hammered to 4.2 km, then water hammered to 4.5 km. OTN-III was then mud drilled to TD, deviating ~45o from 4.9 km, normal to the WNW-ESW stress maximum.

Well logs show rock properties at OTN have power-law length scales and lognormal populations meaning a few large features dominate small local ones –be they electrical, elastic, or thermal one. Temperature profiles reveal numerous meter-scale, 0.1oC incursions, several decameter-long isothermals below 4000 m, and a remarkable 260 m long isothermal between 4770 and 5030 m.

After reaching a measured depth of 6.4 km, the last open-hole 1260 m was completed with a stimulation assembly. The stimulation assembly consisted of 5 Stages of ball operated sleeves, separated by packers roughly 200 m apart. The Stages in the assembly were sequentially pumped in a 5 Phase program of seismic-activity controlled clean water injection. Including hours-to-days long rest periods, the stimulation lasted 47 days. It appears that due to either limited packer seal or near-well fractures all Stages and Phases were in partial communication with each other. Further, based on engineering data it appears that the Stage 2 sleeve did not operate properly and Phase 2 pumping is more closely associate with Stage 3.

Thousands of microearthquakes were detected by a 3-tier Traffic Light System, none exceeding an M2.1 Red-light. Development at the project continued with a VSP for seismic velocity control, followed in 2019 by deepening of the OTN-II and stimulation to form an EGS doublet.

1. INTRODUCTION

In a shared effort, energy companies St1 (as operator) and Fortum (as client) are drilling to a depth of around 6.1 km in the bedrock under Espoo, Finland, deeper than ever before in this country (Fig 1). The goal of this pilot project is to build the first industrial-scale geothermal heat plant in Finland at Fortum's heat plant at Otaniemi, on the campus of Aalto University (St1 website). St1 has prior experience in sustainably, renewable energy, and geothermal heat is a natural next step for the company. However, heat flow in Finland is very low, necessitating costly deep drilling in basement rock.

Cost effective penetration of the granitic bedrock just 10 m below the heat plant site required a purpose-built drilling plan. First, a test well was core drilled to a depth of 2 km to begin assessing drilling conditions. Drilling of production and injection wells was begun using air hammer technology. These reaching depths of 3.3 and 4.5 km. Drilling of the injection well continued for a short section with water hammer, and finally with deviated rotary drilling methods. With a total measured depth of 6.4 km, the bottom hole temperatures of this OTN-3 well settled at ~120 C.

In addition to the drilling environment, another challenge of the project is achieving water flow between the two boreholes. In this phase hydraulic stimulation was used to investigate how water pumped in the injection well might flow between cracks in the fractures of the bedrock. The resulting induced microearthquake is now being used to guide the trajectory of the production well.

Given that the stimulation took place beneath a urban area, the City of Espoo required that an earthquake management Traffic Light System (TLS; green, amber, red light equivalents) be developed and approved before stimulation (Ader et al., 2019). The stimulation of OTN-3 was performed in an area with very little natural seismicity and no data on induced seismicity: there was no guarantee that experience from other geothermal well stimulations would apply. The simplest thing to do was to place the limit for induced events on a small fraction of the Peak Ground Velocities allowed by Finnish Building Code and British Standards on surface vibrations and their relationship to human perception and buildings. Temporary 12-level geophones arrays were installed in the 2 km and 3.3 km wells, and a 12-station satellite network of 350 m borehole seismometer was built at distances of 1 to 7 km from the injection well. At ground level and in critical facilities such as medical clinics and supercomputer labs, 17 PGV recorders were secured to walls, floors, and outcrops. Signals from all 41 sensors was telemetered to a central station.

In June and July 2018, a total of 18,160 m3 of water was pumped into the rock formation at depths of 5.7 to 6.1 km (Kwiatek et al., 2019). The injection was divided between 5 intervals along the well and there were stoppages of a few days at various points. This injection produced more than 44,000 recorded microearthquakes, 6,000 of which were automatically located and characterized, and used to control the stimulation rate so that the TLS red light condition of M_L 2.1 and PGV 7.5 mm/s would not be exceeded.

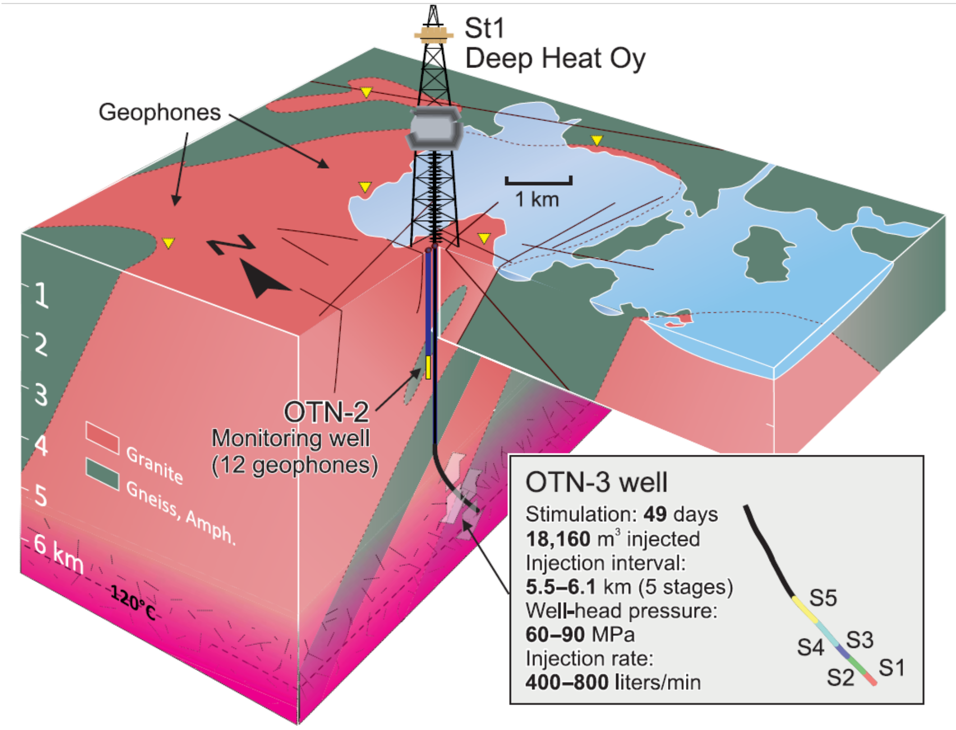

Figure 1: Block diagram of the Otaniemi EGS site on the western edge of Helsinki, Finland, on the campus of Aalto University. Shown are the 3.3 and 6.1 km deep production and injection wells at the time of the 2018 stimulation. The inset shows the open hole completion used for simulating the 5 stages in June to July. Also indicated are the 12-level geophone array in OTN-2 and several of the satellite stations. (Figure from Kwiatek et al., 2019.)

2. DRILLING, CHARACTERIZING, AND STIMULATING OTN-3

2.1 Drilling and Well Completion

Considerable experience was gained from the test drilling of the 2 km OTN-1 and initially 3.3 km OTN-2 wells. OTN-1 was cored with standard 76 diamond drilling tools. OTN-2, and subsequently OTN-3, were both begun with air hammer drilling methods, OTN-2 to 3.3 km and OTN-3 to 4.2 km. OTN-3 was then deepen to 4.5 km using a water hammer – which appeared to be slightly slower. However, overall, even including the water hammer portion, the knowledge gained from OTN-2 made possible a 70% increase in drilling rate from 34 m/day to 54 m/day in OTN-3.

The 6400 m MD OTN-3 well was cased down to 5140 m, leaving the last 1240 m open. A double-packer separate, 5 Stage ball and sleeve operated, stimulation assembly was placed in this open hole section (Fig 1). A 5 Phase program of drinking quality water injection was planned for treating the permeability of each Stage. The Stages were roughly 200 m apart, with the packers being set at the well locations most likely to guarantee they would seal and separate these Phases. Due to borehole instabilities and near-by fractures, this effort was not entirely successful.

2.2 Characterizing

Current work shows that Engineered Geothermal Systems depend on both the existence of permeable fractures and the potential to open multiple paths through them. This was one of our main focuses in efforts to characterize the reservoir rocks in OTN-3. As it turned out, we found that the most direct evidence for the existence of such fractures comes from temperature logging (E.G. Leary et al, 2017). This was first encountered in the logging of test hole OTN-1 (Fig 2). Based on the results from OTN-1, a special effort was made to obtain similar high sensitivity temperature logs from the much greater depths of OTN-3. This turned out to be a difficult technical challenged below about 5 km. Nonetheless, good results were obtained to these depths, including evidence of both a potential isothermal interval and significant influx zones (Fig 3).

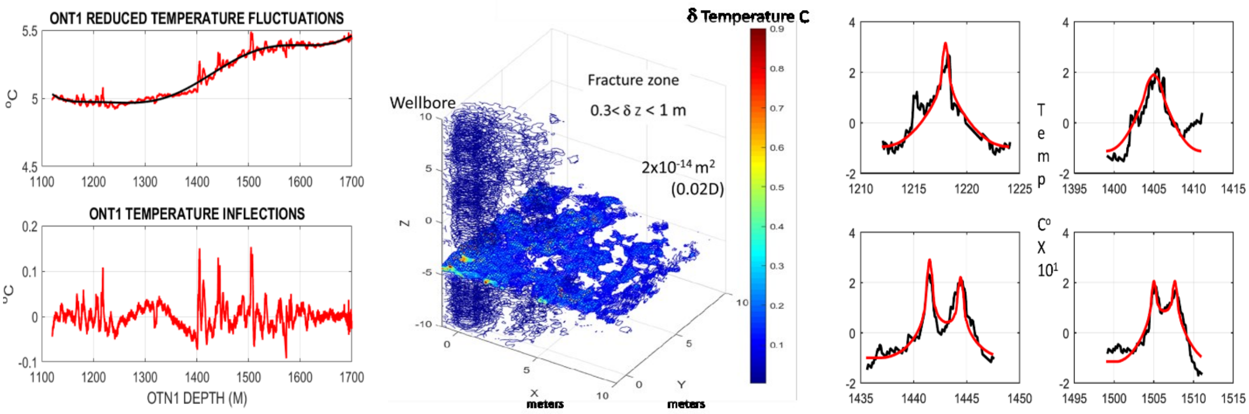

Figure 2: Temperature log from OTN-1 reveal the influx of thermal waters from permeable fractures. The left diagram shows several zones of warm fluids mixing with the water in this open borehole. The center diagram shows a block diagram of the heterogeneous permeablity finite element model use to model the temperature fluctuations. The Figure on the right shows the fits made with this model. (Figure curtesy of P.C. Leary.)

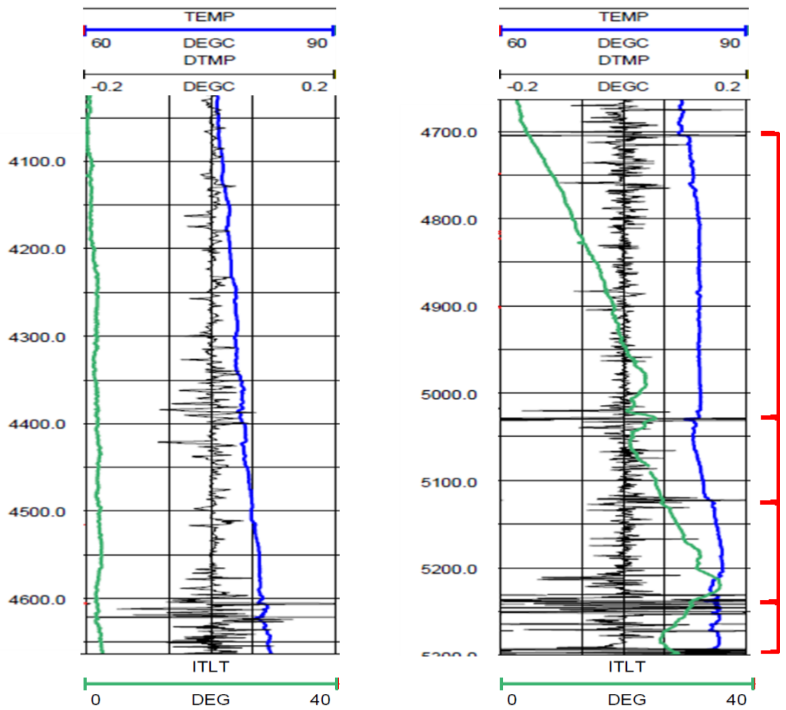

Figure 3: The temperature log from OTN-3c also reveal the influx of fluids from permeable fractures. Blue line shows the raw temperature with depth. The black line is the local differential of the blue curve. The green line show borehole inclination, which transitions from the vertical to deviated section 4600 to 4700 m. The left diagram shows a more or less uniform gradient with a number of small influx zones. The right diagram reveals a complex set of isothermal and inverted temperature gradients, along with significant influx zones. (Figure curtesy of I. Kukkonen and St1.)

2.3 Stimulating

EGS typically requires opening of fluid flow channels – especially zones of weakness that yield to modest hydraulic pressures and can be made to stay open. At OTN the 18,160 cubic meter stimulation was injection rate–controlled, with flow rates varying between 400 and 800 liters/min for wellhead pressures of 60 to 90 MPa. As mentioned, the bottom 1260 m of OTN-3c was uncased, but completed with a 5 Stage, ball and sleeve operated, stimulation assembly. Stages were separated by an average of 200 m. Pumping was performed in 5 injection Phases lasting 2 to 14 days. These were to be completed through the completion Stages shown in the inset in Figure 1. It appears that phase P2 stimulation was likely performed through the stage S3 port due to technical difficulties with port S2. Each phase contained multiple alternating injection and resting periods (Fig 4).

One key to confirming permeability creation is the microearthquake activity stimulation produces. The activity commonly appears as a cloud of earthquakes surrounding the stimulation well. The result at OTN was no different in this respect, as is seen in Figure 5. During the stimulation, a total of 8412 microearthquakes were automatically catalogue within 5 min of their occurrence, the location of 6150 of which were used to measure the Stimulated Resource Volume, as seem in Figure 5.

This earthquake key also has its drawbacks in terms of a social license to operate. Several unfortunate members of this key have resulted in questioning the future liabilities of EGS over environmental advantages. While the experiment necessary to prove that the pumping strategy shown in Figure 4 limited the size of induced events below the TLS M2.1 red light event would have been to deliberately exceed it, it does seem it worked.

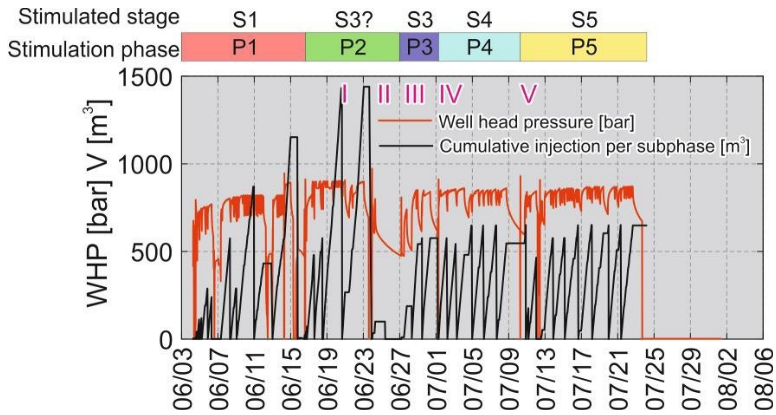

Figure 4: The time-pressure-flow history of the OTN-3 stimulation. Wellhead pressure is shown in bars and injected volume in cubic meters. Note the multiple rest periods that were necessary to release earthquake producing strains.

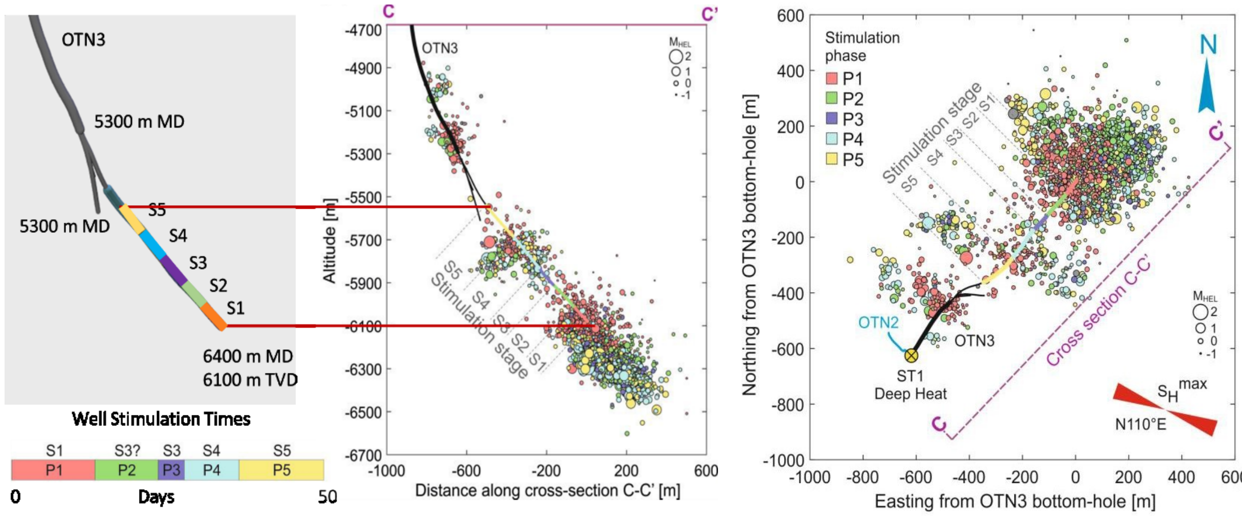

Figure 5: The microearthquake cloud produced by the OTN-3 stimulation. The events are shown in colored circles, each color indexed to its injection stage. Circle sizes indicate the relative magnitude of the microearthquake, the minimum being M_L -1.25 and the maximum M_L 1.9.

3. CONCLUSIONS

We have reported here the current basic results of one of the world deepest Engineered Geothermal System developments. The St1 O&G undertook this development with the aim of reducing municipal heat via expensive fossil fuels. A deviated injection well was completed to a true vertical depth of 6.1 km below the campus Aalto University near Helsinki Finland. The innovations tested included initial hammer drilling to 3.3 and 4.5 km for the production and injection wells. It also included use of a multi-stage bottom hole stimulation completion. Well logs indicate that even at more than 5 km there were natural fractures that grossly effect the local temperature profile by the influx of subsurface waters. Situated entirely in basement rocks from the surface down, it was possible to inject 18,160 cubic meters of pure water at depths ranging between 5.7 and 6.1 km depth – all without exceeding a Traffic Light System limit M2.1 earthquake. The cloud of resulting induced earthquakes is currently being evaluated for locating the extension of the 3.3 km deep production well into this presumed zone of permeable fractures. This work, and the testing of the pilot plant to boost heating waters scheduled to be completed in the first half of 2020

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