The Most Productive Low-Temperature Geothermal Production Well in Iceland/the World?

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ABSTRACT

The low temperature geothermal field at Hjalteyri, Eyjafjordur, Iceland, has been utilized since 2003 when well HJ-19 was connected to Nordurorka's district heating facilities for Akureyri. An initial 9-month production test along with the first years of utilization, indicated a highly permeable and productive reservoir. In 2005 another well, HJ-20, was drilled to increase production from the powerful geothermal system. The drawdown evolution so far, with up to 115-135 l/s average production of 87°C hot water, over the last fifteen years has validated a high-permeability model for the Hjalteyri geothermal system. Hence, a new well, HJ-21, was drilled in 2018. Permeability tests performed on HJ-21 indicate permeability properties beyond previously known capacities, both in terms of production index and estimated transmissivity. The simulation of the pressure response of the well during initial flow- and buildup-testing at the end of drilling on basis of a pressure diffusion equation solution for a lateral reservoir of constant thickness, uniform permeability and infinite extent, yielded a good fit to observed pressure changes. The simulation results indicated a permeability thickness of more than 1000 Darcy-m near well HJ-21.

1. INTRODUCTION

Nordurorka is a municipal utility company serving the city of Akureyri (population 18,000) in central N-Iceland and surrounding areas with cold water for consumption, geothermal water for space heating and electricity as well as operating the local sewage disposal system. It has also taken over service in 3 other separate communities in the region; Ólafsfjördur, Hrísey and Grenivík (Flóvenz, Ó.G. et al., 2010). The Hjalteyri geothermal system, which is located on the western shore of the Eyjafjordur fjord in central N-Iceland (Figure 1), was discovered after a shallow well drilled there revealed an above average temperature gradient. Following this extensive and detailed geothermal prospecting was conducted in the area, which culminated by the drilling of a highly productive production well during the summer of 2002. It intersected productive aquifers at around 1200 m depth with a temperature of 90°C, associated with a basaltic dyke, which had been targeted. In 2005 a second production well, HJ-20, was successfully drilled. Testing of that well and further testing and lumped parameter modelling of pressure changes within the Hjalteyri area (Axelsson, G. et al., 2015) confirmed that the two existing wells are not able to match the total capacity of the geothermal reservoir and in 2017 it was decided to drill the third production well with a wide casing program, well HJ-21, for providing Nordurorka thermal power for continuously increasing demand, for both district heating and industrial purposes.

2. THE HJALTEYRI GEOTHERMAL FIELD

2.1 Geological Setting

The Hjalteyri geothermal field is located at the western coast of Eyjafjördur. Geothermal wells cut a pile of flood basalts consisting of tholeiitic basalts (Figure 1). They belong to the Eyjafjördur-basalts, formed during the tertiary period, 6-10 m.y ago. Basaltic lava layers dip 4-5° towards SSE and are interbedded with oxidized and permeable sedimentary layers and scoria. They are covered with fluvial sediments, which are up to 70 m thick (Flóvenz, Ó.G. et al., 2002; Jóhannesson, H. and Hjartarson, A., 2003).

Structural lineaments have been investigated using surface mapping, magnetic surveys, earthquake distribution, temperature measurements and borehole televiewer imaging. Magnetic surveys have revealed NNE-SSW striking dike complex that can be traced from the well field towards the coastline (Gautason, B. et al., 2005). The NNE-SSW orientation has also been recorded on dikes and fractures on surface near Hjalteyri (Flóvenz, Ó.G. and Sæmundsson, K., 1999). The temperature anomaly is adjacent to the NNE-SSW striking dike complex (Figure 2).

Borehole televiewer imaging has been performed in three of the Hjalteyri geothermal wells; HJ-13 (exploration well), HJ-20 and HJ-21 (production wells). Televiewer results show mainly NW-SE to NNW-SSE striking fractures, dipping towards SW. Fractures that are near feed zones show a various strike and dip direction, but the most common strike is NW-SE and dip direction towards SW. Drilling induced fractures were analyzed in HJ-21. They indicate the strike of the current stress field, with the maximum horizontal principal stress (S_{Hmax}) striking NW-SE (Árnadóttir et al., unpublished). NW-SE to NNW-SSE striking fractures have also been mapped on surface slightly north of Hjalteyri (Flóvenz, Ó.G. and Sæmundsson, K., 1999). Seismic studies from 1994-1996 have revealed an active fault, striking NNW-SSE along the coastline of Árskógsströnd (Flóvenz, Ó.G. and Smárason, Ó.B., 1997), but earthquake distribution has also shown a NNE-SSW trend (Flóvenz, Ó.G. et al., 2002).

Results of NW-SE striking drilling induced fractures, as well as NW-SE to NNW-SSE striking fractures that are linked to feed zones, indicate that the most recent structural features, formed in the current stress field, strike NW-SE to NNW-SSE whereas NNE-SSW striking dikes and fractures are more likely to have been developed in a former stress field.
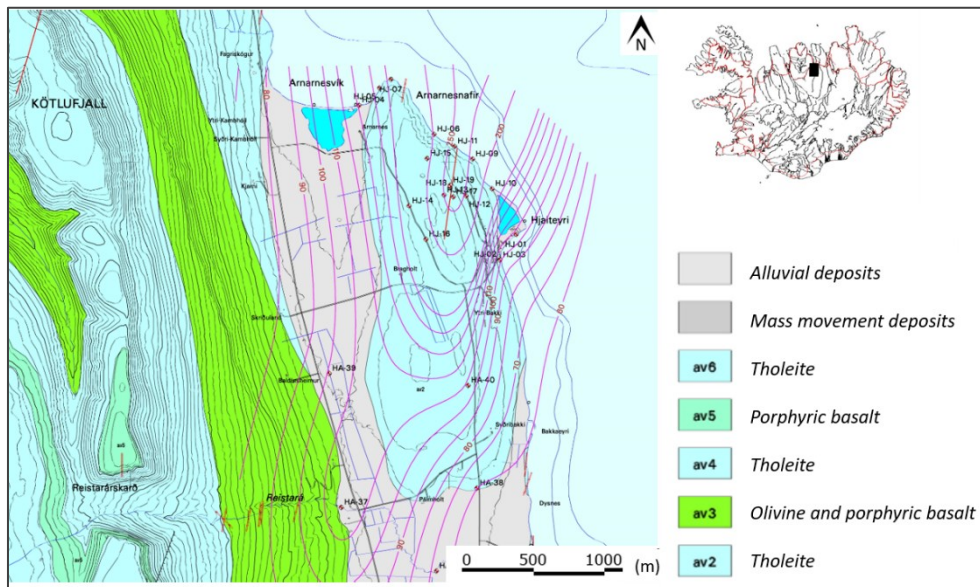
Figure 1. A geological map of Hjalteyri and surroundings (Jóhannesson and Hjartarson, 2003).
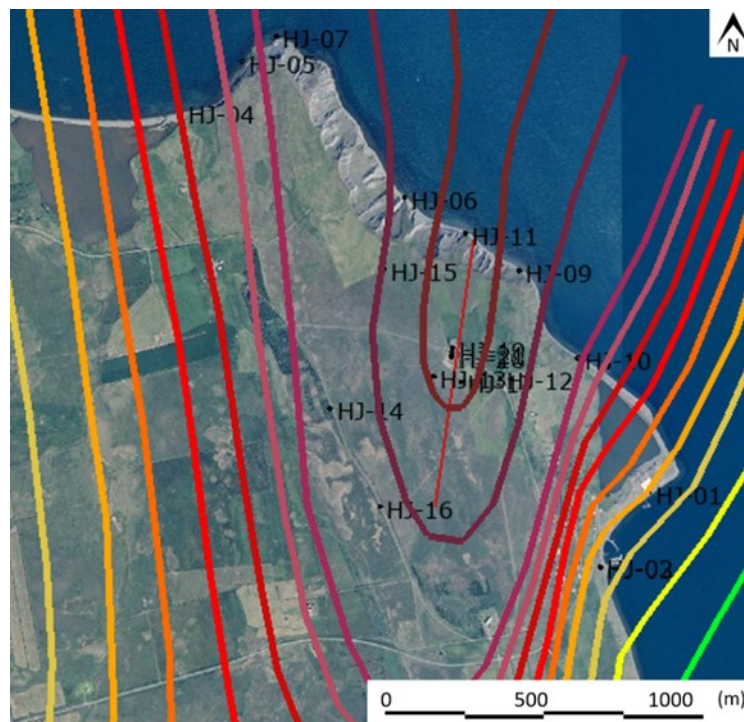

Figure 2. The Hjalteyri geothermal field. Red line, striking from HJ-16 towards the coast is showing the NNE-SSW striking dike complex, supported by magnetic surveys. Contour lines represent the temperature anomaly, with the highest temperature (250 °C) along the dike complex.

2.1 Drawdown in the Hjalteyri geothermal field

During the research for a geothermal reservoir at Hjalteyri, 18 thermal gradient wells were drilled, (Figure 3). Of them, wells HJ-9 to HJ-18 form a network for monitoring the pressure status with time. Additionally, the water level in the two production wells has been monitored all their utilization time. In Figure 4 it is shown how the drawdown has developed, first after eight years and then after fourteen years of utilization. There it can be seen that a drawdown cone extends out to about 500 m from the production wells that are located within 30 m from each other. The drawdown effect is clear towards wells HJ-14 and HJ-15 that are located south-south-west and north-east of the production wells, respectively. However, little drawdown is detected in wells HJ-9, HJ-10 and HJ-11 that are located on the coast, east of the production wells. No drawdown is detected in well HJ-16 which is located 700 m south west of

the production wells. Compared to other geothermal fields utilized by Nordurorka, Hjalteyri is outstanding as seen from the unit response graph drawn on Figure 5.
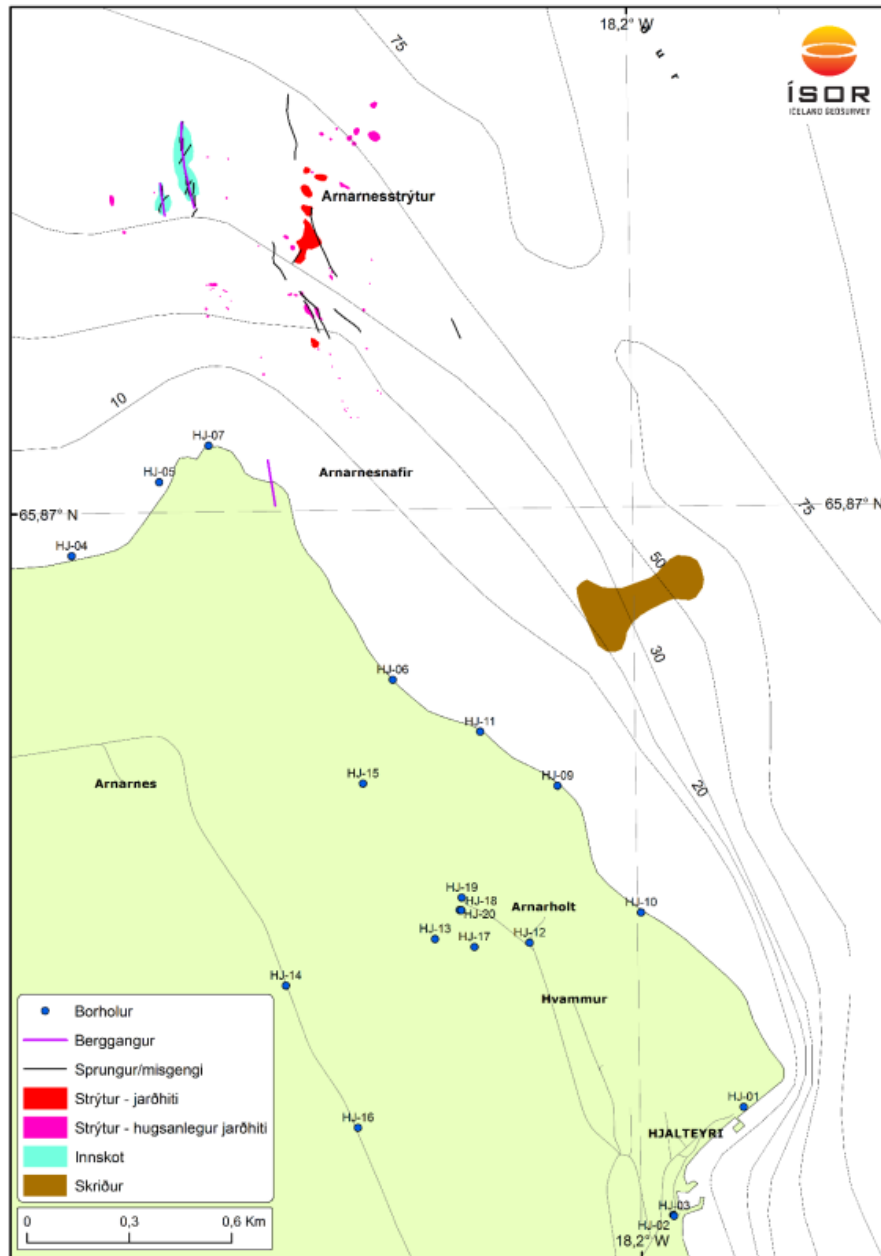
Figure 3. A map of Hjalteyri area that shows research well HJ-1 to HJ-18 and the production wells HJ-19 and HJ-20. Additionally, the location of the submerged artesian aquifer Arnarnnesstrytur is shown.

2.2 Arnarnesstrytur

In 2004 a submerged artesian aquifer, Arnarnesstrytur, was found about 2 km north of the geothermal field at Hjalteyri (e.g. Valtýsson, H.Þ. et al., 2009; Price, R. et al., 2017). They are considered to connect directly with the Hjalteyri reservoir but how exactly is not known, neither in terms of permeability nor other reservoir parameters. The flow through this aquifer has not been estimated but the highest temperature measured is about 78°C. After fourteen years of utilization of the Hjalteyri field the flow at Arnarnesstrytur is regarded to be relatively unchanged. However, a sharp eye must be kept on if that flow changes and if remarkable pressure drawdown is detected since pressure drop at Arnarnesstrytur is regarded to predict danger of cold sea inflow into the Hjalteyri reservoir.

When the drawdown observed in the Hjalteyri reservoir is graphed versus the logarithmic distance from the production wells it fits very well and when the line connecting the data points is extended to the distance of Arnarnesstrytur, current drawdown is about 28 m, see Figure 6.
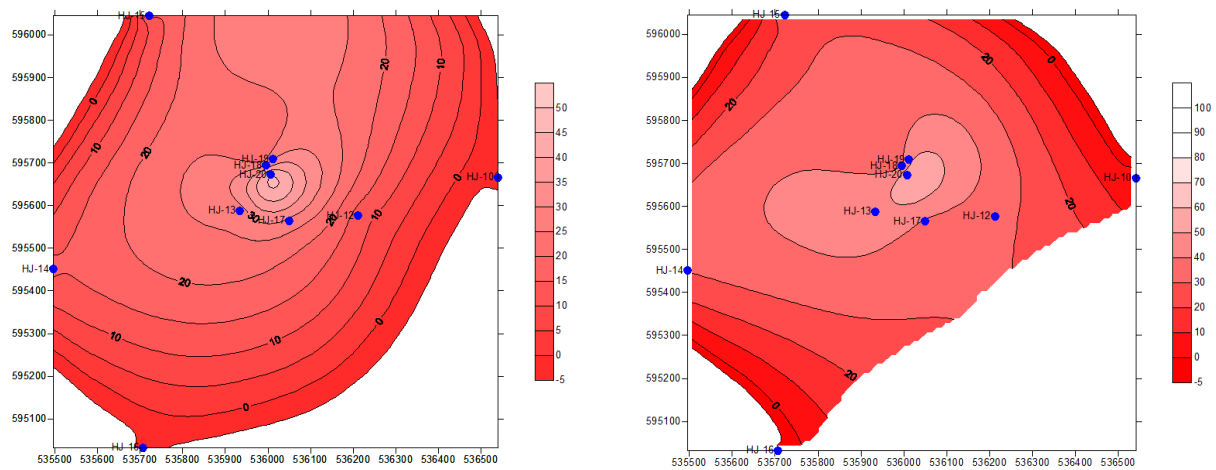
Figure 4. Isoline graph for the drawdown in the Hjalteyri geothermal reservoir [in m] in 2010, after eight years and after fourteen years of utilization.
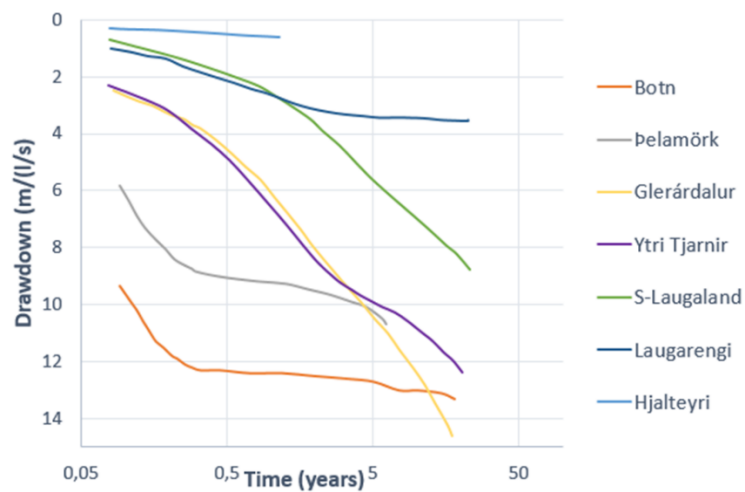

Figure 5. The light blue line shows the drawdown behavior of well HJ-19 in Hjalteyri compared to other geothermal fields in Eyjafjördur (modified from Flóvenz, Ó.G. et al., 2010).
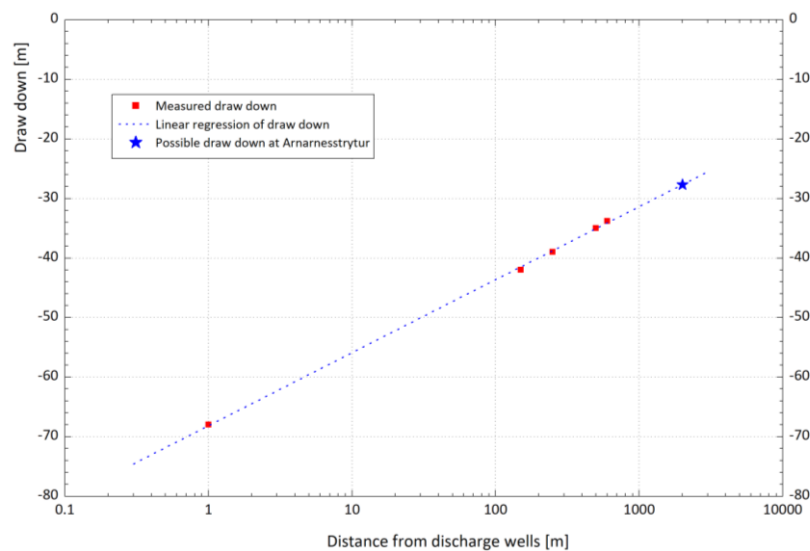

Figure 6. The observed curve with drawdown versus distance from production wells has a very good semi-logarithmic fit. Extended to the distance of Arnarnesstrytur indicates about 28 m of drawdown which corresponds to about 2 bar pressure decline.

2.3 Drilling of well HJ-21

Prior to the arrival of the drill rig Sleipnir some preparatory work on the drill pad had been undertaken. Sleipnir was the rig that drilled the previous production wells at Hjalteyri, HJ-19 in 2002 and HJ-20 in 2005. But the rig had since then been „beefed up" to accommodate a classic BOP-stack for drilling in high-temperature systems. Therefore, the rig needed better grounding and required a larger surface area, so the substratum was improved, and the well-pad was enlarged. Furthermore, a 22½" surface casing was emplaced to approximately 6 m depth relative to the well pad, prior to the arrival of the rig.

Well HJ-21 was planned as a vertical well drilled to approximately 1500 m (MD) with a 12¼" production section. There was also an option for continuing drilling with an 8½" down to 2000 m if it was deemed necessary.

Drilling operations for well HJ-21 commenced on May 6th, 2018. A 21" bit was used to drill to 54.4 m depth (relative to the Sleipnir rig-floor at 5.4 m above the well pad). The casing was cemented on May 11th, 2018. Drilling for the production casing commenced on May 13th and was completed ten days later. The well was logged prior to running in, and cementing, a 13 ⅜" casing to 395 m depth. Drilling of the production section started on the 27th of May. A broken pipe incident at 890 m followed by a successful recovery of the drill string caused minor delays. For the remainder of the drilling aeriated drilling was employed. After some short-term testing on June 15th drilling activities were halted at 1298 m depth.

The stratigraphy was as expected, like what had been encountered in wells HJ-19 and HJ-20 (Gautason, B. et al., 2005). Individual lava-flows and sedimentary horizons can be identified and traced between the wells in accordance with the regional strike and dip. This suggests that the wells are not separated by large faults, although some minor fault movement cannot be excluded. However, predicting the exact location of aquifers was more difficult and basaltic dikes were not always encountered were expected.

Well HJ-21 is the first low temperature well in Iceland that is drilled with a 12¼" production section. The ROP's in the production section were typically low (~1-4 m/hr). Due to the high permeability of the fractured formations it became increasingly difficult to get return of circulation after each added single. Since it was clear after some short-term testing (section 3) that the well seemed to have superb permeability, drilling activities were stopped at 1298 m depth.

3. SHORT-TERM DISCHARGE TEST OF WELL HJ-21

After the well had reached 1298 m depth it obviously had strong oncoming feed zones and after each drilled single of 9 m it took more and more time to have the well returning fluid which was considered important to avoid cuttings flowing into already open feed zones. Prior to and after the flow test, temperature and pressure profiles were measured, see Figure 7. Prior to the test some feed zones are recognized with inflow at 487 m, 537 m, 600 m and 812 m depth. Besides, other feed zones are seen at 1070 m, 1180 m, 1214 m and 1285 m. After the flow test, the temperature of the well was governed by flow from feed zones below 1050 m, but the feed zone at 1285 m is probably the most permeable one. According to the pressure profiles shown in Figure 7, the discharge during the flow test seems to have made no changes of static conditions within the well. No water was injected to the well when the drill string was pulled out of hole and on the morning of June 15th, 2018 the well was ready for a short discharge test with a help of air-lift. Three different air-lift positions with an air-string were planned at 250 m, 325 m and 400 m but already with air-lift at 323 m the flow was about to exceed the Weir-box capacities, so the 400 m position was dropped in the test, see Figure 8. During the flow test a P/T logger tool was placed at 1200 m depth to measure changes in pressure and temperature as the flow was changed and an overview of the flow test with pressure, temperature and flow estimate is shown in Figure 9.

With the first air-lift position, at 250 m, the pressure data are noisy. Prior to the flow the pressure was 109.47 bar and at the end of the step the pressure oscillates around 108.38 bar with a flow estimate of 56.5 l/s. The pressure data quality obtained in this case is too poor for further analysis. After adding drill pipes for the air-lift from 323 m the P/T tool was replaced at 1200 m. As seen in Figure 9 the initial pressure prior to the air-lift from 325 m, 109.55 bar, is 0.08 bar higher than it was in former step. This corresponds to about 80 cm difference in location which is within location certainty at 1200 m depth with current depth counter system. After about two hours with estimated flow of at least 125 l/s the pressure at 1200 m depth was 109.27 bar when the air-lift was shut off and after 105 minutes of pressure build-up the pressure had reached 109.54 bar.
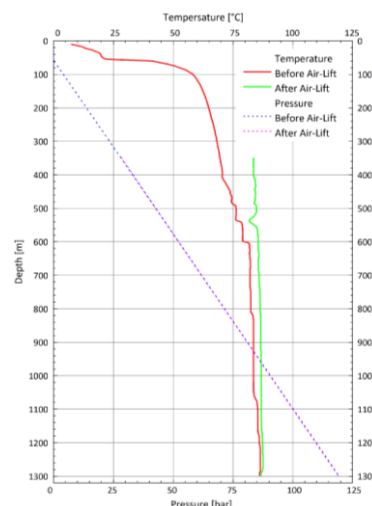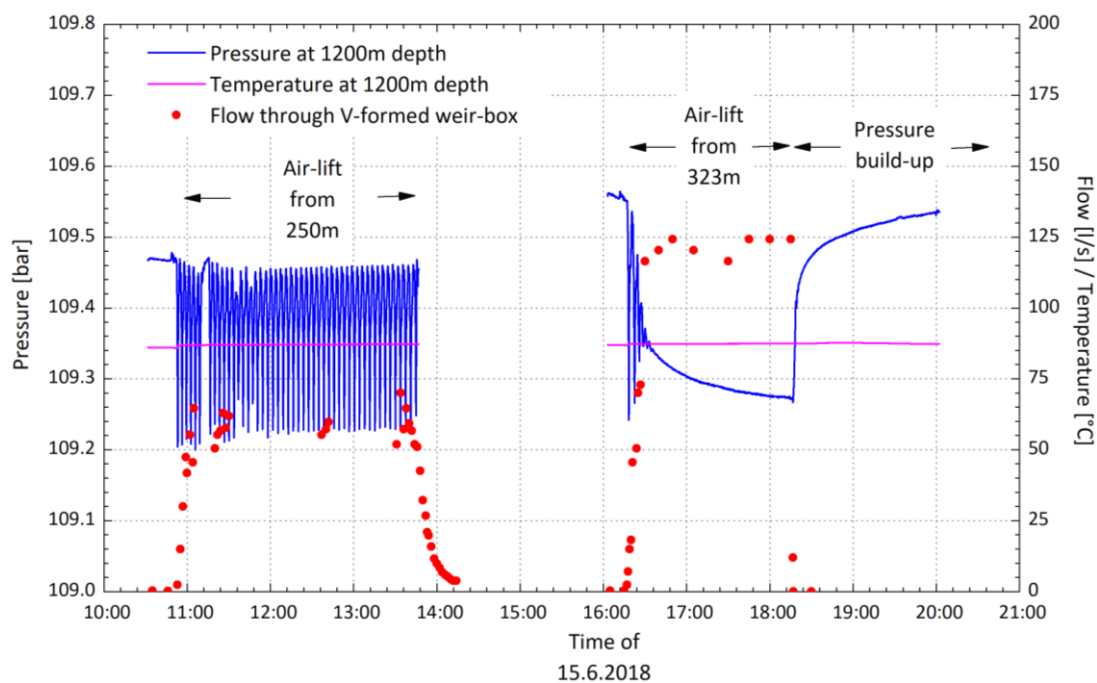

Figure 7. Temperature and pressure logs prior to and after the flow test. Feed zones are seen in the temperature logs.

Figure 8. V-formed weir box for flow measure. The flow from the well with an air-lift from 323 m about exceeds the flow capacity of the weir-box and was estimated at least 125 l/s.

Figure 9. Progress of the flow test on 15th of June 2018. The gap corresponds to the time of adding drill pipes for air-lifting.

For comparison of the two air-lift steps the pressure values were adjusted to the former one and graphed with estimates discharge flow against measured pressure at 1200 m for productivity estimated, see Figure 10. As seen, the data points line up relatively well and a least square fit to them has a slope of 440 l/s/bar which is the estimated productivity index of the well, but it has to be pointed out that only small changes in pressure have great effect on the productivity index during the flow test since changes in measured pressure due to large changes in flow are very small.

The pressure data gathered during the latter step of the flow test are of fair quality, but some oscillation effect appears the first eighteen minutes after the air-lift at 323 m commenced. However, the pressure data quality after the air-lift was shut off is good (Figure 11) and is used for further analysis to obtain well and reservoir parameters.
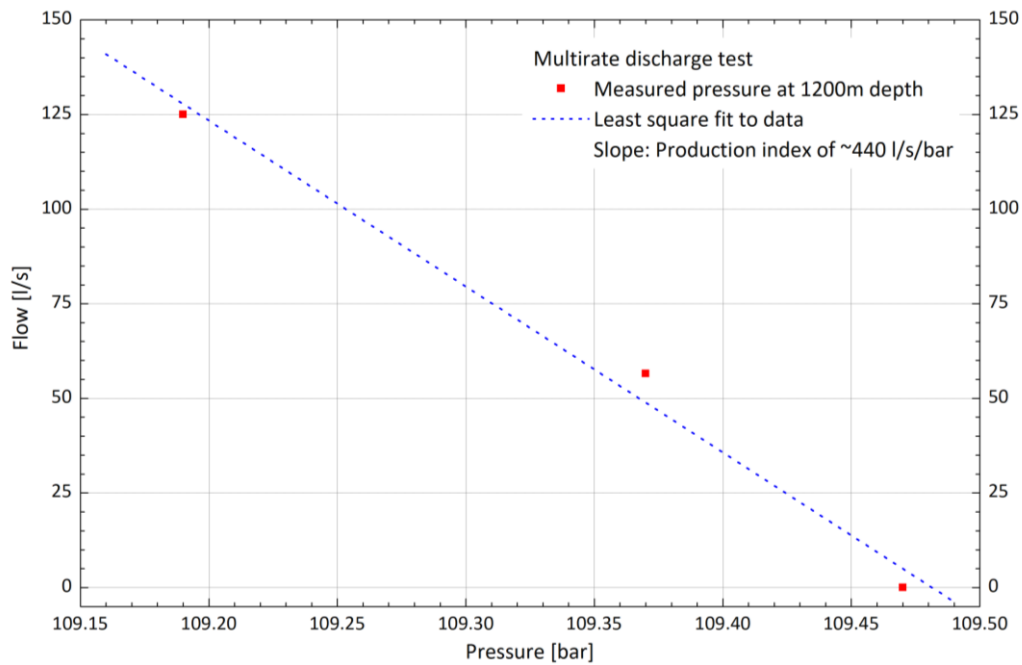
Figure 10. Estimated flow from the well plotted against measured equilibrium pressure at 1200 m. The slope of the regression line, 440 l/s/bar represents the well's high productivity index.

4. PRESSURE DATA MODELLING AND ITS RESULTS

The model simulation is based on Theis' solution of the pressure diffusion equation that describes pressure propagation that governs flow in an infinite horizontal water filled porous reservoir (Grant, M.A. and Bixley, P.F., 2011). With the model calculation, its properties and characteristics are determined to obtain the best fit possible between observed pressure and corresponding model response. The simulation process is performed with ÍSOR's WellTester® software (Júlíusson, E. at al, 2007).

To optimize the model results for both well and reservoir response to utilization any known parameter is important, i.e. reservoir type, boundary type and wellbore type (Table 1). Also, known well and reservoir properties are important to be able to extract physical properties such as skin effect, reservoir permeability and reservoir thickness. Those are the well radius, reservoir temperature, estimated reservoir thickness, estimated porosity and rock type since fluid viscosity and fluid compressibility depend on temperature and pressure and the rock compressibility depends on the rock type. Corresponding properties are listed in Table 2.

The model simulation introduced here for well HJ-21 are run on the pressure build-up that started when the air-lift from 323 m was shut off at 18:16:30 on June 15th, 2018 with about four-hour pressure recording at 1200 m depth (Figure 11). The simulation results are shown with two figures and one table that lists the derived well and reservoir properties that gave the best fit to the pressure data, based on the characteristics listed in Table 1 and Table 2. The former figure (Figure 12) shows pressure changes occurring when the air-lift was shut off and the logarithmic time derivative $\left(\frac{\partial P}{\partial \ln t} = t \cdot \frac{\partial P}{\partial t} \right)$ with both pressure and time on a logarithmic scale. Goodness of the fit to the logarithmic time derivative indicates how well the applied geothermal model corresponds to the actual reservoir response (Horne, R.N., 1995). The latter figure (Figure 13) shows how well the simulated response fits the actual pressure data recorded at 1200 m. The reservoir properties obtained by the simulation are listed in Table 3.

The main results of the model simulation are the high transmissivity close to the well ($3.8 \cdot 10^{-6}$ m³/s/Pa) and a skin effect (-4.0) that indicates good connection between the well and reservoir. Besides, the production index for this step is extreme (475 l/s/bar), a bit higher than the combined production index for the whole production test (Figure 10). Because of high transmissivity, the well shows high permeability thickness.

Table 1. Overview of well and reservoir parameters used to simulate the pressure data.

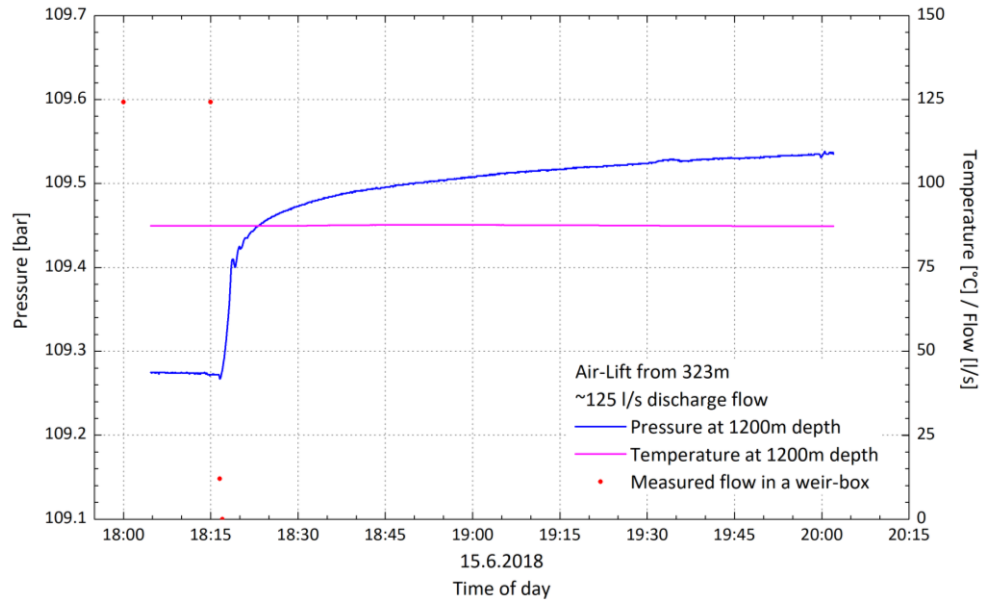| Type of reservoir and well	
Reservoir	Homogeneous
Boundary	Infinite
Skin	Constant
Wellbore storage	Constant

Figure 11. Temperature, pressure and flow measurements in the latter step of the flow test with air-lift from 323 m. The air-lift was shut off at 18:16:30. The pressure build-up was logged until 20:02.

Table 2. Overview of reservoir and fluid properties used in model simulation of pressure data.

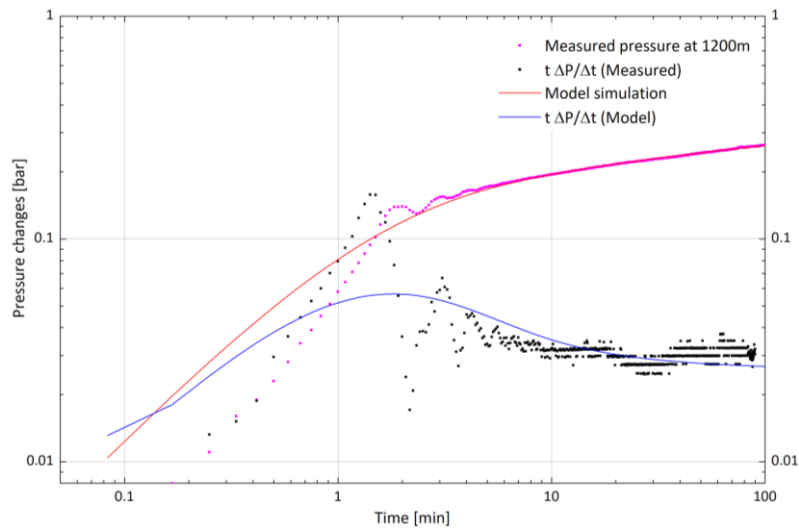| Property (symbol)	Value	Unit
Reservoir temperature (T_{est})	87	°C
Estimated reservoir pressure at 1200 m (P_{est})	~110	bar
Well radius (r_w)	0.16	m
Rock porosity (φ)	0.10	-
Water dynamic viscosity (μ)	$3.26 \cdot 10^{-4}$	Pa·s
Water compressibility (c_w)	$4.5 \cdot 10^{-10}$	Pa^{-1}
Rock compressibility (c_r)	$2.4 \cdot 10^{-11}$	Pa^{-1}
Water and rock combined compressibility (c_t)	$6.7 \cdot 10^{-11}$	Pa^{-1}

Figure 12. Measured pressure changes and logarithmic time derivative with corresponding simulation response on a logarithmic scale for both time and pressure.
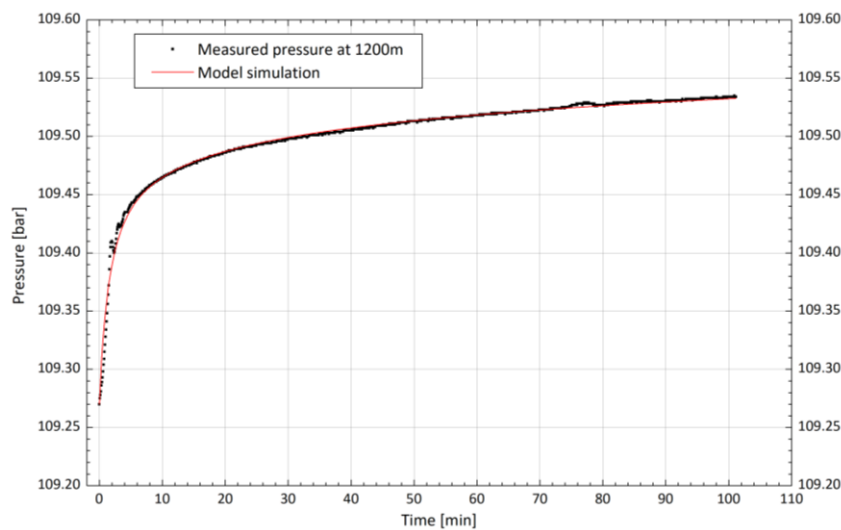

Figure 13. Measured pressure with corresponding simulation response on a linear scale for both time and pressure.

Table 3. Reservoir properties obtained with simulation that best fits the pressure response.

Properties	Value	Standard diviation (SD)	Uncertainty (%)	Unit
Transmissivity (T)	$3.8 \cdot 10^{-6}$	2.3E-08	0.6	m³/(Pa s)
Storativity (S)	$2.6 \cdot 10^{-8}$	8.3E-10	3.1	m/Pa
Skin effect (s)	-4.0	0.03	0	-
Wellbore storage (C)	$5.4 \cdot 10^{-4}$	$8.5 \cdot 10^{-6}$	1.6	m³/Pa
Productivity index	475	-		(l/s)/bar
Permeability thickness	$1260 \cdot 10^{-12}$	$8 \cdot 10^{-12}$	0.6	m²·m

As seen in Figure 12 the simple model is not able to precisely simulate the first three minutes of the step but thereafter a good fit is reached for both the pressure changes and the pressure logarithmic time derivative, so the applied reservoir model and boundary conditions are considered appropriate. The problem of simulating the first three minutes of the test concerns the wellbore storage which then is inaccurately estimated. Figure 13 shows the simulation results of the observed data on a linear scale.

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According to the feed zone analysis the effective reservoir thickness is estimated to be 6-800 m long which indicates reservoir permeability $1.6 \cdot 10^{-12}$ m^2 – $2.1 \cdot 10^{-12}$ m^2 which is more than 1000 times what is generally characteristic for geothermal fields in Iceland (Axelsson, G., 2004).

With the obtained model parameters, the pressure changes at the well with time can be calculated in Pa with the equation

$$\Delta P = Q \cdot \frac{2.303}{4\pi T}\left[\log(t) + log\left(\frac{4T}{S \cdot r^2}\right) - 0.251\right]$$

where the time, t is in seconds, the discharge, Q, is in m^3/s, the transmissivity, T, is in m^3/s/Pa, S is storativity in m/Pa and r is the well radius in m (Grant, M.A. and Bixley, P.F., 2011).

An updated lumped model for pressure drawdown because of utilization of wells HJ-19 and HJ-20 was published in 2013 with estimated permeability thickness of 200 Darcy-m. According to the model's reservoir properties the transmissivity is $T = 6,1 \cdot 10^{-7}m^3s^{-1}Pa^{-1}$ and the storativity $S = 6,70 \cdot 10^{-7}mPa^{-1}$ with 10% matrix porosity (Axelsson, G. and Egilson, Þ., 2013). In Figure 14, a comparison is made between these parameters and the short-term test results for well HJ-21 for 200 l/s production rate, and the figure also shows the current lumpfit models for the Hjalteyri geothermal field with two-tank open and three-tank closed reservoirs (Axelsson et al., 2005). According to the test results in well HJ-21, pressure drawdown after 20 years of steady 200 l/s discharge will be about 12 m while the model parameters interpreted from long-term utilization of wells HJ-19 and HJ-20 indicate 62 m drawdown with the same production rate. For the same discharge and time, twenty years with 200 l/s, the predicted drawdown with the current three-tank closed model is about 57 m while the current two-tank open model predicts 37 m drawdown.
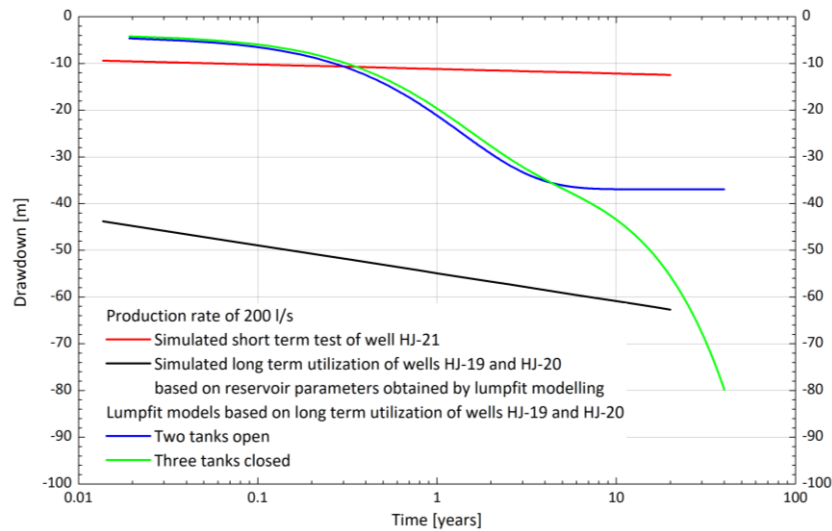

Figure 14. Drawdown comparison between wells HJ-20 and HJ-21.

4. CONCLUSIONS

According to production test results, the permeability close to well HJ-21 is unique. However, it must be kept in mind that the test performed, is only short term and future long-term testing and/or utilization of well HJ-21 will prove its connection to the Hjalteyri geothermal field and not least its connection to the nearby wells, HJ-19 and HJ-20. The most exciting question to be answered is if well HJ-21 was drilled into open fractures that wells HJ-19 and HJ-20 do not intercept. In advance, however, it cannot be expected that the long-term drawdown in the Hjalteyri geothermal field will be much different from what is predicted with the models developed in 2013 (Axelsson, G. and Egilson, Þ., 2013).

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