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1. Executive Summary

The report "*D6.3 Field scale RJD stimulation for magmatic site*" describes activity in WP6 in the SURE project that is related to activity on Radial Jet Drilling (RJD) in Iceland, including:

- Site characteristics including rock and fluid properties (task 6.1)
- Radial Jet Drilling operation (task 6.2)
- Testing the effect and sustainability of stimulation by Radial Jet Drilling (task 6.3)

In task 6.1, potential well candidates in Iceland were searched for and evaluated. A candidate, well HN-13, a low-temperature well located in Eyjafjörður at site Botn, N-Iceland, stood out as prime target mostly because of its particularly low output after drilling, despite being drilled in between two producing wells. The well was intended for hot-water production for the district heating in town Akureyri with roughly 20.000 inhabitants and nearby communities. The well was drilled and completed in September 2016 to 1905 m depth. However, contrary to all expectations, it was a non-producer, producing only 5-6 l/min during air-lifting. Obviously, the well is poorly connected to feed zones that feed the other two producing (deep) wells, BN-1 and HN-10, on the same platform.

To gather data on the wellbore and formations in the well to verify its availability for the SURE project, a downhole wireline logging campaign was conducted. It included: gamma, neutron, resistivity, SP and caliper down to 1840 m. Additionally, sonic and Televiewer logging was conducted, but could only be logged down to ~1400 m due to a blockage in the well. A geological model was compiled in Petrel. Blocks of rocks representative of the formations found in the well, collected in nearby quarry were sent to Bochum for testing. This work was conducted within WP5. Results indicated that jetting through hard basaltic rocks (with low matrix permeability) was not feasible and almost non-drillable with the jetting parameters used. Therefore, a potential target was defined through a sedimentary layer that was found between basaltic formations at a depth of approximately 954-968.5 m (from surface). Wireline logging interpretation determines the softest part of the layer at <u>956-963.5 m</u> depth (from surface) which was selected as the main target depth.

Based on the work in task 6.1, RJD field test was performed in the chosen well HN-13 in Botn, N-Iceland. This work is part of task 6.2. Consortium partner WSG (Well Services Group) performed the RJD along with a drill-rig company RSFS (Ræktunarsamband Flóa og Skeiða). Due to a failed first attempt in October 2018, a second field test was done in June-July 2019.

During run-in-hole with the equipment for RJD in the first attempt, an incident occurred where the bottom hole assembly (BHA) that included a deflector shoe, attached geophone instrument and some ~80 m of NQ drillrods were accidentally lost in the hole. The incident lead to two unsuccessful fishing trials. Time limits of the rig operator RSFS and jetting

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partner WSG resulted in termination of the trial without the possibility to perform any jetting trials.
At a later stage a consortium decision was taken to continue from where the first trial ended with a second field test. A larger drill rig capable of running conventional drillpipes was used instead of the smaller rig used in the first trial. To prepare the well, RSFS fished out a part of the lost assembly found at ~1400 m depth but the BHA and geophone were not retrieved. With the fish out of the way RJD operation was initiated by placing the deflector shoe at the selected depth. Directions were confirmed by gyroscope logging conducted by ÍSOR. The advised directions for the radial jet drilling were easterly and north-easterly directions. If jetting speeds were sufficient, jetting would also aim towards secondary directions. The primary directions chosen were NE (45°) and E (90°), and secondary directions were N (0°), SE (135°), SW (225°) and NW (315°). The primary target depth was chosen as 956-963.5 m (from surface). During jetting the indications on surface suggested that jetting through the targeted inter-layers was successful, but half way through the operation it became clear that the jetting equipment was not working properly, rising suspicions if the initial laterals were actual drilled laterals. The total number of attempts were 28 to 8 depths and 6 planned directions. The RJD operation began on June 24th 2019 and was concluded on July 5th 2019, achieving milestone M6.2 *RJD performed in magmatic site*. However, a video log that was performed after the operation showed no indications of jetted holes, confirming the suspicions of unsuccessfully drilled laterals.

The objective of task 6.3 the objective was to test the short-term and long-term effect of stimulation by RJD. Prior to the field test operation, the baseline of inflow into the well was measured. Same measurements were repeated after the operation (note that these measurements were done prior to the video logging). The results showed no measurable increase in productivity from the well. Efforts based on monitoring the long-term sustainability of the performance increase were therefore obsolete.

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2. Introduction

This report describes activity connected to radial jet drilling (RJD) in Iceland in WP6 – Macro Scale in the SURE project. Well HN-13, located in N-Iceland close to the town of Akureyri was selected as a candidate for RJD trials within the SURE project. It was drilled in between two prior drilled low-temperature geothermal wells, HG-10 (a.k.a. HN-10) and BO-01 (a.k.a. BN-01), that are both productive and used for district heating of Akureyri and nearby communities. Although the location was in between two producing wells, it was a poor producer only producing 5-6 liters per minute (0,1 l/s) while being air lifted. For comparison, the mean production from well HG-10 that sits 20 m NNE of HN-13, is about 25 l/s of 90°C hot water. HN-13 was therefore valued as an excellent candidate for demonstration of the stimulation technology, as any increased production after RJD will clearly be revealed. Jetting experiments in WP5 into basalt rock types sent from Iceland to Bochum were shown to be impractical as high pressure and velocities are required. Therefore, softer inter-basaltic layers were targeted. Main information on well HN-13, nearby wells, target depth as well as the RJD field testing are described in this report.

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3. Site characteristics

3.1. Jettability of Iceland rock samples

Three block samples of basaltic rocks and one block sample of an inter-basaltic sedimentary layer were collected in a quarry at Moldhaugnaháls in N-Iceland (Figure 1) and sent to the SURE partner, International Geothermal Centre (GZB) in June 2016. A second block sample of an inter-basaltic layer was sent to Bochum in November 2017. Initial jetting results showed that high pressure and nozzle velocities (above 500 bar and 300 m/s) were required in order to penetrate the basalt samples, i.e. to ablate rock surface, create hole or shoot through/fracture the specimens (Figure 2).

Figure 1. *Quarry at Moldhaugnaháls in N-Iceland where basalt and intrabasaltic layer samples were collected (location: N65 44.459 W18 13.166)(Picture: ÍSOR/Bjarni Gautason).*

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VBA6-IC2	VBA6-IC3	VBA6-IC4

Tholeiite basalt	Porphyritic basalt (plagioclase porphyritic basalt)	Olivine-basalt

Figure 2. *Basalt samples from Iceland tested in WP5 and their field classifications (Hahn, 2017).*

The first inter-basaltic rock sample was tested in a surface experiment with static and rotating nozzles. So called jettability, a measure of how easily the rock could be penetrated, was somewhat better than for basalt. But as the rock sample was very heterogeneous and consisted mostly of basaltic scoria, it was decided to acquire a second more homogeneous sample representing the inter-basaltic layer that was the prime target to drill. This sample was transported from N-Iceland for further testing at GZB in Bochum. The second rock sample of an inter-basaltic layer (Figure 3) was sent to Bochum in November 2017. This time the sample consisted mostly of sediments and contained less basaltic scoria than before. The difference between the two samples can be seen in Figure 4. The second inter-basaltic sample was tested in same manner as before in a surface experiment with static and rotating nozzles. This time the experiment showed promising results and the sample was easily penetrated (Figure 5).

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Figure 3. *Second sample of intrabasaltic layer collected in same quarry as before (Moldhaugnaháls). (Picture: ÍSOR/Sigurveig Árnadóttir).*

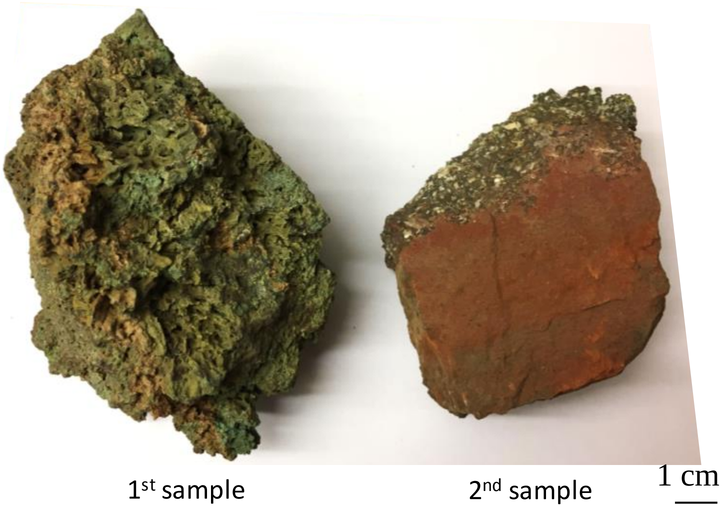

Figure 4. *Intrabasaltic layers from N-Iceland. Basaltic scoria part of 1st sample and more uniform, sedimentary part of the 2nd sample (Picture: ÍSOR/GSK).*

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Figure 5. *Sample of inter-basaltic sedimentary layer jetted at HBO/GZB in Bochum (picture: HBO/GZB).*

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Part of the inter-basaltic sample was also sent to Technical University Delft (TUD) for mechanical testing in WP4, see their summarized results below.

Summarized mechanical results by Richard Bakker (TUD) and Christian Kluge (GFZ):

- Porosity ranges between 20-25 % for the red sediment part, ~18% for basalt part.
- Acoustic wave speeds ranges: 3.3 – 3.8 km/s (v_p); 2.0 – 2.3 km/s (v_s). Basalts seem slightly faster, but no clear differences.
- Tensile strength: 8.0 MPa (stdev: 2.0) for red sediment, 7.3 MPa (stdev: 2.2) for basalt.
- Fracture toughness 0.711 MPa.m$^{0.5}$ (stdev: 0.153) for red sediment, 0.709 MPa.m$^{0.5}$ (stdev: 0.174) for basalt.
- Uniaxial Compressive Strength tests:
    - Ultimate strength: 58 - 68 MPa (red sediment), 34 - 52 MPa (basalt)
    - Young's modulus: 9.3 - 11.4 GPa (red sediment), 11 - 13 GPa (basalt)
    - Poisson's ratio: 0.15-0.20 (red sediment), 0.19 - 0.24 (basalt)
- Permeability: indicative values only, precise measurements pending. red sediment: ~10^{-19} m^2 (pulse decay method) basalt: 1.22 x 10^{-16} m^2 (ruska air permeameter). Results may be highly variable, connectivity measured on cm-scale.

Figure 6. *Sample locations used for mechanical testing. Picture by TUD/GFZ.*

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Complimentary to the jetting trial in GZB, WSG conducted jetting tests on the inter-basaltic sedimentary sample from N-Iceland. Initially this was tested at maximum operating pressure of 300 bar by HBO in Bochum, which showed that the rock was jettable although slow rate of penetration (ROP) was achieved. WSG test was conducted with actual field equipment that is used for downhole jetting and with pressure setting that can be used in the field tests, at 500 bar. Results from the test indicated that use of acid (Stimwell HTH) did not have an effect due to slow reaction to the rock. Both static and rotating nozzles showed promising results, and the rotating nozzle had better ROP than a static nozzle. Similar jetting test was conducted with Icelandic basalt, where high pressures of 700-800 bar were needed in order to penetrate the rock. The results from WSG are shown in Figure 7 and Figure 8.

#	Rock	Nozzle	Pump	Time	Outcome	
7	Sedi ment	Static	500 bar 22 l/min	10:00 min	Good penetration towards end of experiment	
8	Sedi ment	Rot.	500 bar 21 l/min	3:00 min	Complete penetration	
9	Sedi ment	Rot. + acid	500 bar 21 l/min	2:00 min	Complete penetration + core broken	
10	Sedi ment	Static + acid	500 bar 22 l/min	10:00 min	Complete penetration + core broken	

Figure 7. *WSG jetting test results on sedimentary layer at extreme high pressures (from SURE deliverable D5.2).*

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#	Rock	Nozzle	Pump	Time	Outcome	
11	Hard	Rot.	700 bar 27 l/min	15:00 min	No full bore hole, but 30 mm deep	
12	Hard	Rot.	800 bar 29 l/min	15:00 min	No full borehole, same shape as exp. 11, but slightly deeper 32 mm	
13	Hard	Rot.	800 bar 35 l/min	6:00 min	Full penetration, lateral 150 mm long	
14	Hard	Rot.	700 bar 33 l/min	10:00 min	Full borehole, but not jetted through, lateral 117 mm deep	

Figure 8. *WSG jetting test results on Basalt at extreme high pressures (from SURE deliverable D5.2).*

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3.2. Well selection for RJD operation in Iceland

Inquiries were made to Icelandic power companies and the SURE project got letters of intent from the power companies Norðurorka, Rarik and ON Power/Veitur. The participating power companies provided well candidates that could be used to drill RJD laterals within the project. The availability of wells depended highly on their productivity. A schematic of the geothermal locations within Iceland of the participating power companies is shown in Figure 9.

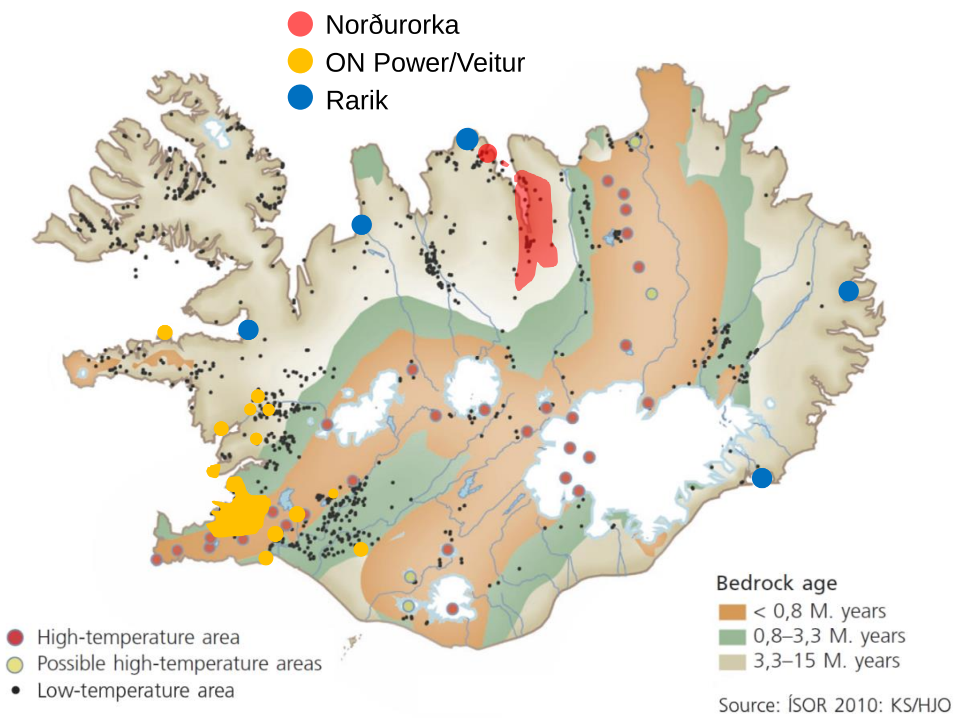

Figure 9. *Geothermal premises of the participating power companies Norðurorka, Rarik and ON Power/Veitur.*

Several wells were considered, of which two wells were most promising. Both wells are owned by Norðurorka and located in Eyjafjörður, North Iceland. The wells are ST-12 in Sigtún and HN-13 in Botn near hamlet Hrafnagil, see Figure 10. ST-12 was first considered but newly drilled well HN-13 was more promising as it is a deep well (TD = 1905 m) and almost with no productivity (5-6 L/m during air-lifting). The well have low to no productivity even though nearby wells have shown good productivity.

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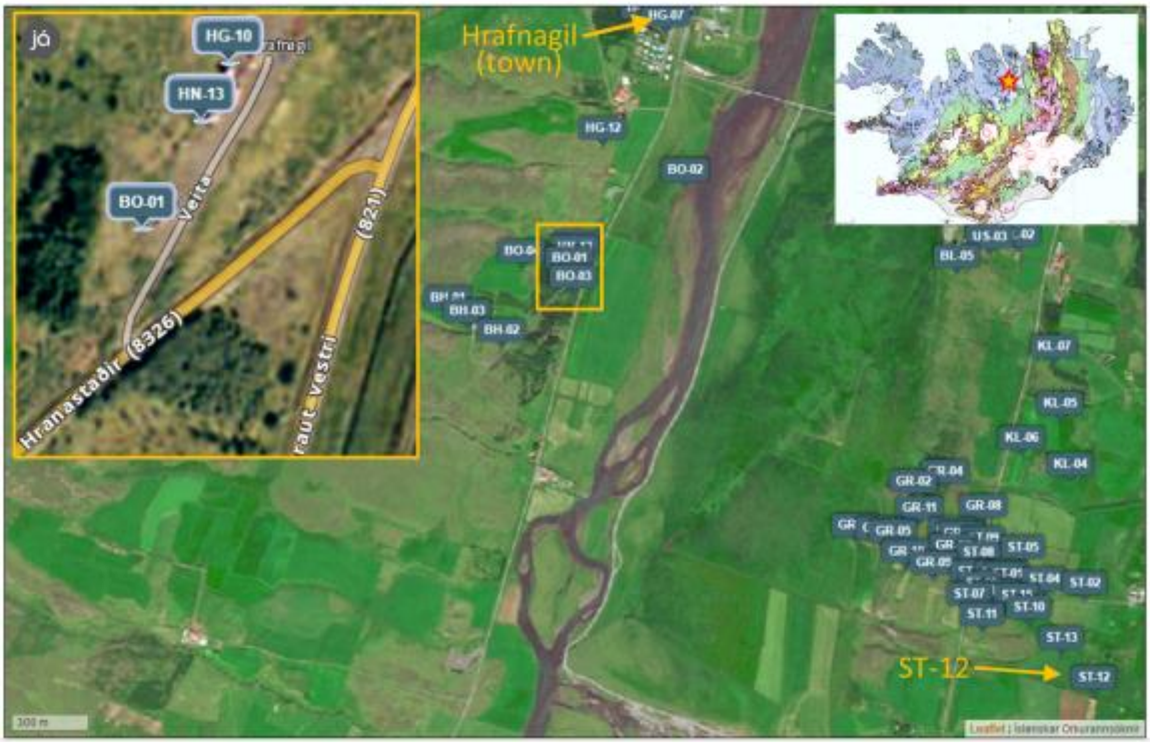

Figure 10. *Wells HN-13 in Botn near to Hrafnagil and ST-12 in Sigtún (about 2.5 km distance between the wells).*

Well ST-16 in Sigtún, Eyjafjörður, Iceland, was drilled in the summer of 2000 as a 1000 m deep exploration well. Its purpose was to attempt drilling into intrusions that potentially govern flow of hot water from deep sections of the formation to surface to the direction towards Grýtulaug (hot spring). The results were not up to expectations. The well was drilled with Drillmec G-102 drillrig Sleipnir to total depth (TD) of 1001 m. The well is cased down to 300 m with a 10¾″ outer diameter casing. The well is collapsed at 830-840 m depth. Further information is provided in report „OS-2001/034 Borun holu ST-16 við Sigtún í Eyjafjarðarsveit", in Icelandic (written in the year 2001 by Arnar Hjartarson and Bjarni Gautason). The well was not selected, because of the collapse and reason that it is not near to infrastructure.

Well HN-13 in Hrafnagil, Eyjafjörður, Iceland was drilled in May to September 2016 with drillrig Nasi to TD of 1905 m. The well was drilled between two producing wells and despite that it is ill connected to permeable structures. Since the wells output is next to none, any improvements would easily be noticed. Additionally, infrastructure is on site and if any improvements are shown in flow, the well could easily be connected to the existing pipeline. The well was therefore selected for RJD in SURE.

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3.3. Well HN-13

3.3.1. Introduction

HN-13 is located in Botn, N-Iceland south of Akureyri (***Figure 11***, Figure 13 and Figure 14) nearby the small hamlet Hrafnagil and was drilled in the fall of 2016. The power company Norðurorka, Akureyri’s district heating company, owns the well. Hopes of intersecting feed zones were dashed after reaching total depth of 1905 m, as the production from the well was close to nothing, 5-6 l/min (0,1 l/s) during air lifting. For comparison the output from a productive well HG-10, located only 20 m to the NNE of HN-13, is on average 25 l/s using submersible pump.

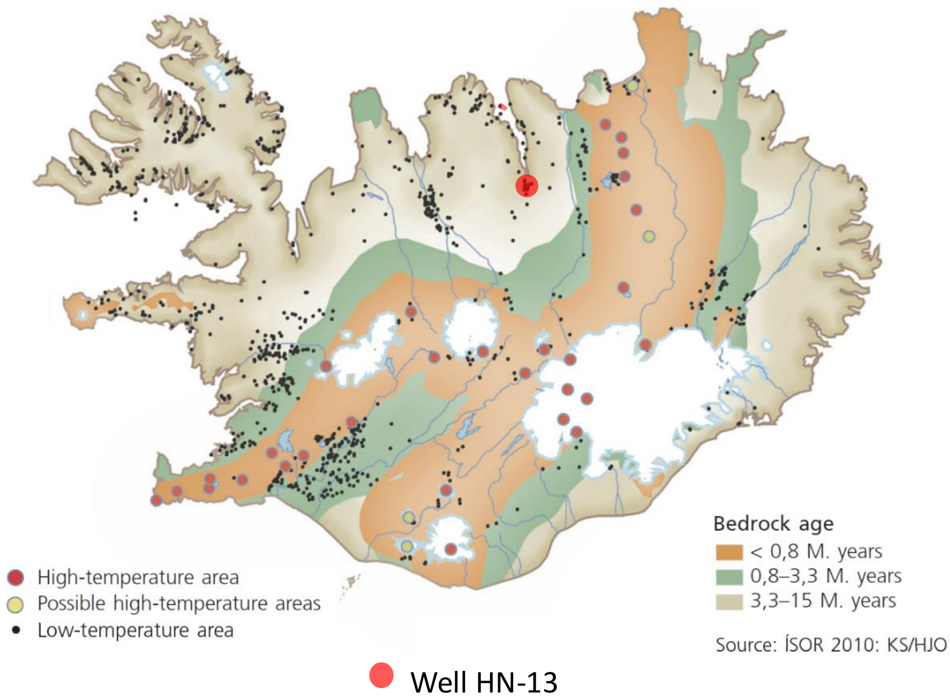

Figure 11. *Location of well HN-13 in N-Iceland. The well is owned by the local power company, Norðurorka.*

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Figure 12. *Drillrig Nasi on well HN-13 on September 23rd 2016 (Photo: Auðunn Níelsson)*

Figure 13. *HN-13 sits between wells BO-01 and HG-10 (picture by Auðunn Níelsson).*

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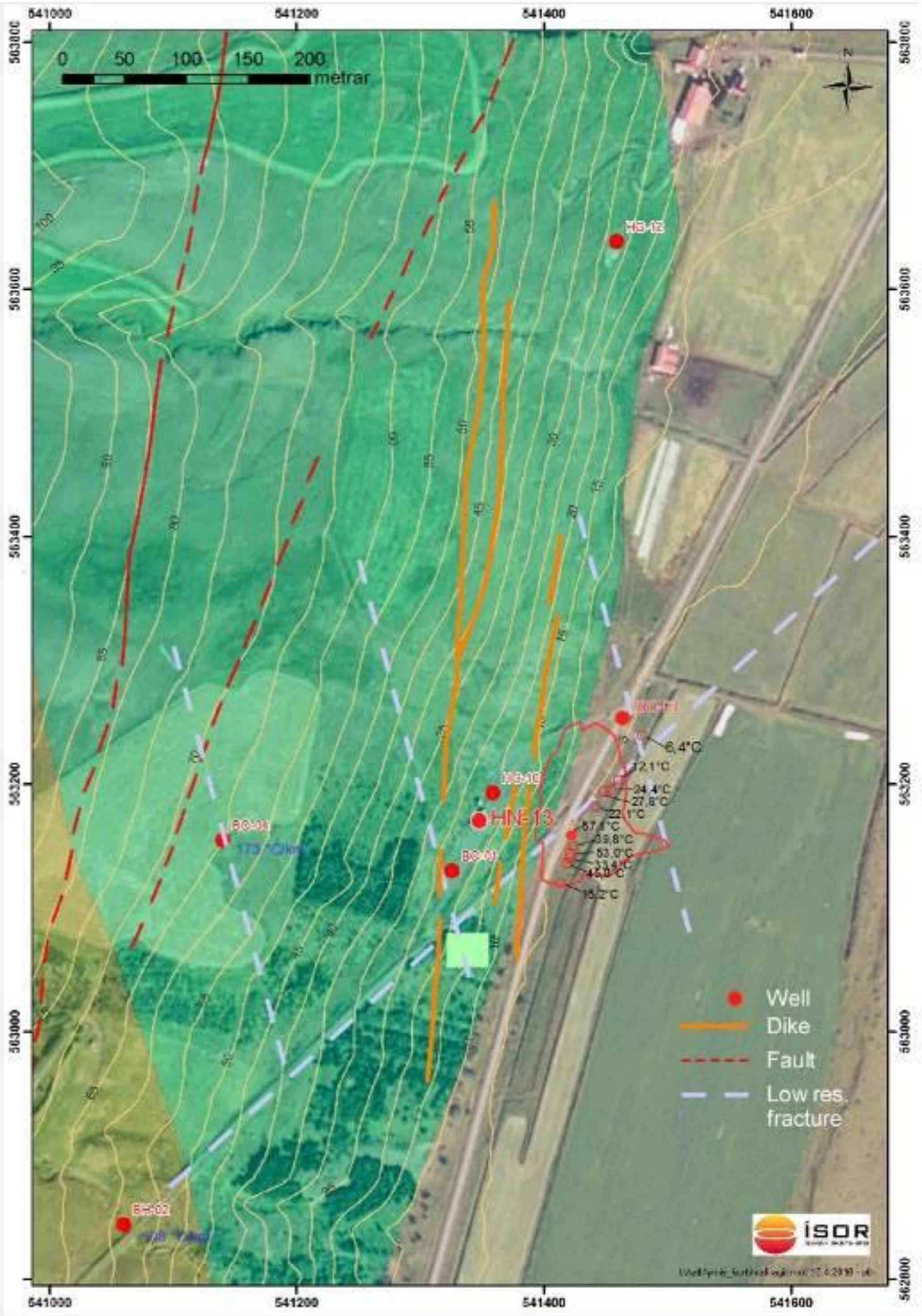

Figure 14. *Location of well HN-13 at Botn/Hrafnagil. Also shown are some of the dykes, low resistivity (i.e. permeable) fractures and faults located in the area. The location of warm springs is displayed, as well as the extent of an area where soil temperatures exceed 13°C at 50 cm depth (figure from Gautason, et al., 2017).*

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3.3.2. Drilling of the well

The well was drilled for power company Norðurorka in May-September 2016 with Ræktunarsamband Flóa og Skeiða (RSFS) drillrig Nasi to total depth (TD) of 1905 m. The well was cased with 14″ casing down to 11 m and with 10¾" casing down to 283 m (Figure 16, Table 1). The 10″ drillbit was lost in the well at 820 m depth which called for cementing and sidetracking with a 8½″ drillbit. After drilling down to 1400 m, the 8½″ drill bit returned to surface without the wheels which were then fetched with a magnet. Drilling was then proceeded with 6″ drillbit down to TD.

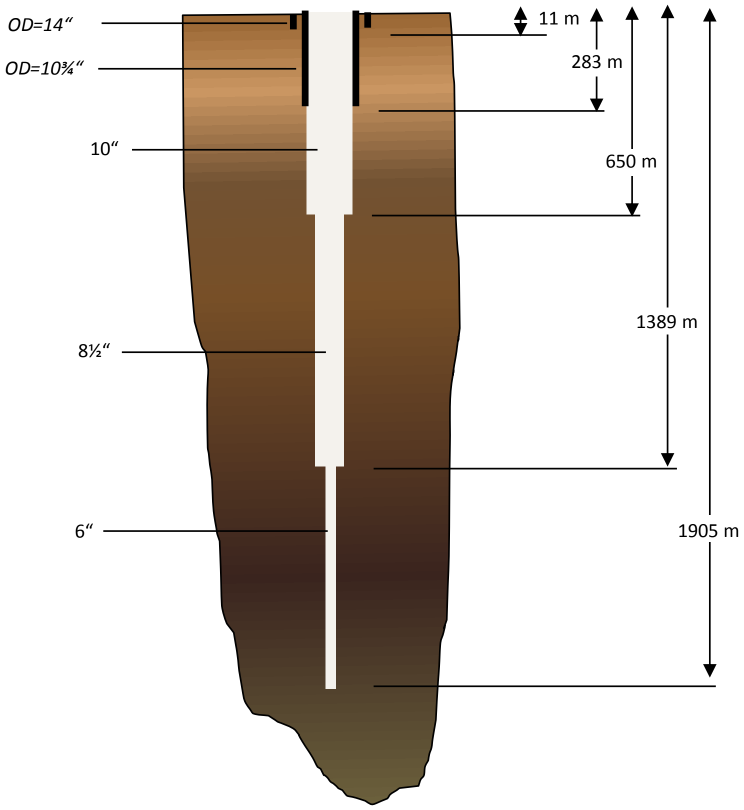

Figure 15. *Schematic of well sections. Potential target zone is at ~960 m depth within 8½″ diameter. The well seems to be blocked at ~1400 m depth as last logging job was unable to reach deeper.*

Table 1. *Drilling depths, casing depths, drill bit sizes and casing diameters in well HN-13. All depths are from the drillrig floor 1.6 m above ground surface.*

Drill rig	Drill bit size	Depth (m)	Casing depth (m)	Casing size
Nasi	14″	11	11	14″
Nasi	12¼″	283	283	10¾″
Nasi	10″	283-820		
Nasi	8 ½″	634-1389		
Nasi	6″	1389-1905		

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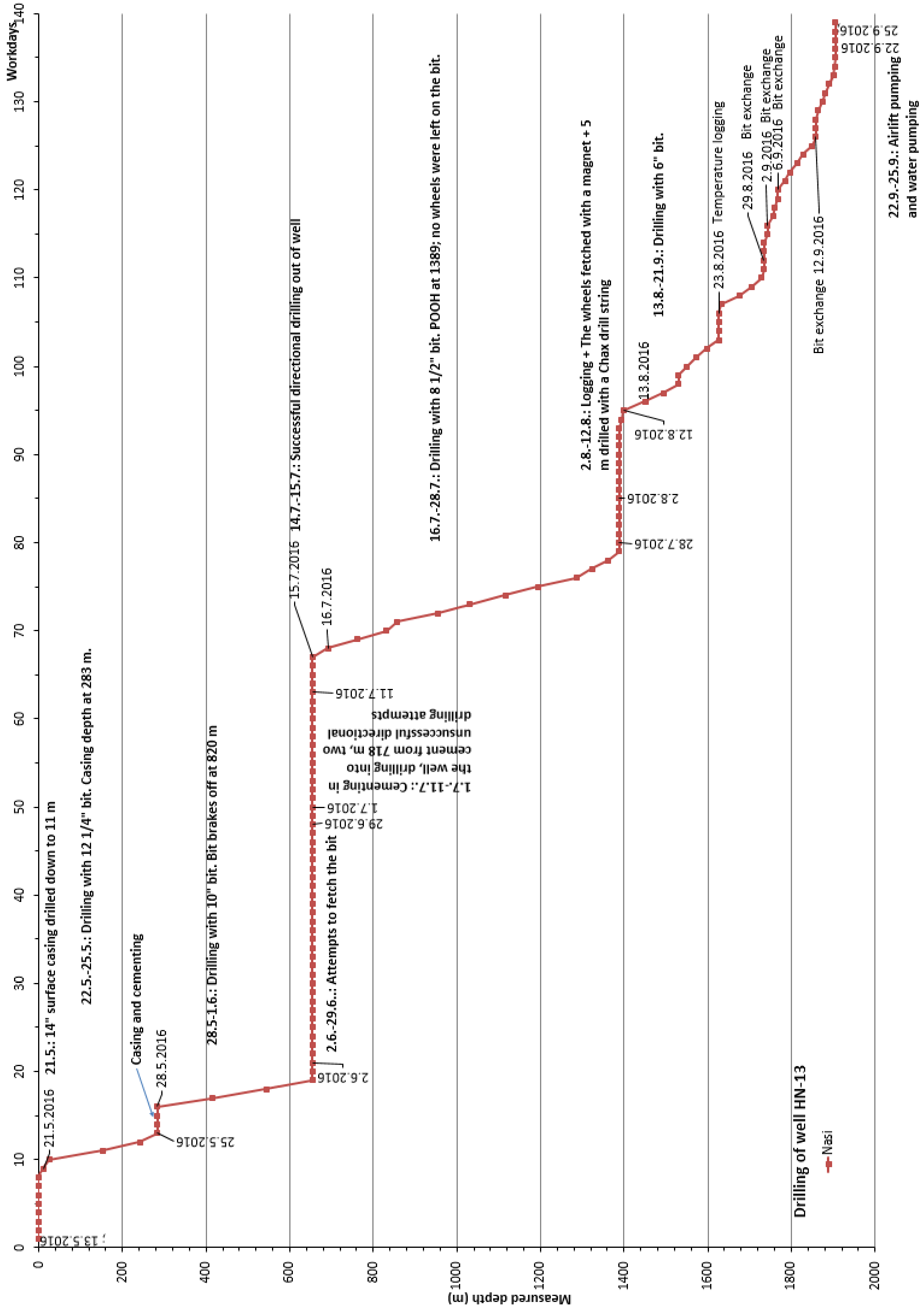

Figure 16. *Drilling process of HN-13.*

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3.3.3. Well output and status before RJD

The status of the well was analyzed before the RJD field testing. Due to drawdown, the well does not build wellhead pressure while production is ongoing in the nearby wells. When production is stopped a mild pressure builds on the producing wells (~1 bar). In its idle state, the well is kept closed with a plate bolted on the wellhead flange (Figure 17). The well sits in the middle of approximately 20 m wide and 80 m long drillpad, see Figure 18. While production is ongoing in the nearby wells, the water table sits at ~70 m depth.

Figure 17. *Well HN-13 closed and without wellhead pressure. House of well HG-10 is seen in background about 20 m away. Picture taken in March 2018 (Picture: ÍSOR/GSK).*

Figure 18. *Drillpad of HN-13. The well sits in the middle of the drillpad, that is 20 m wide and 80 m long.*

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The system is hydrostatic and builds up ~1 bar pressure if pumping from the nearby wells is stopped. The maximum observed temperature in the well is about 88°C at 1200 m depth. A flow test was carried out on September 3, 2018. When the technicians opened the well, it was full of water but the flow from the well was minimal. It was estimated to be less than 2 dl/min. Water was pumped out of the well until the water level was 20 m below the wellhead after 2.5 hours of pumping. Then the depth down to the water table was measured repeatedly for over 24 hours, most frequently during the first hour but then at greater time intervals as time progressed. The inner diameter of the casing is known so it was easy to calculate the inflow (Figure 19). Previous observations were confirmed, i.e. the well is far from being productive and the flow less than 0.2 l/min. This is the baseline for any potential improvements.

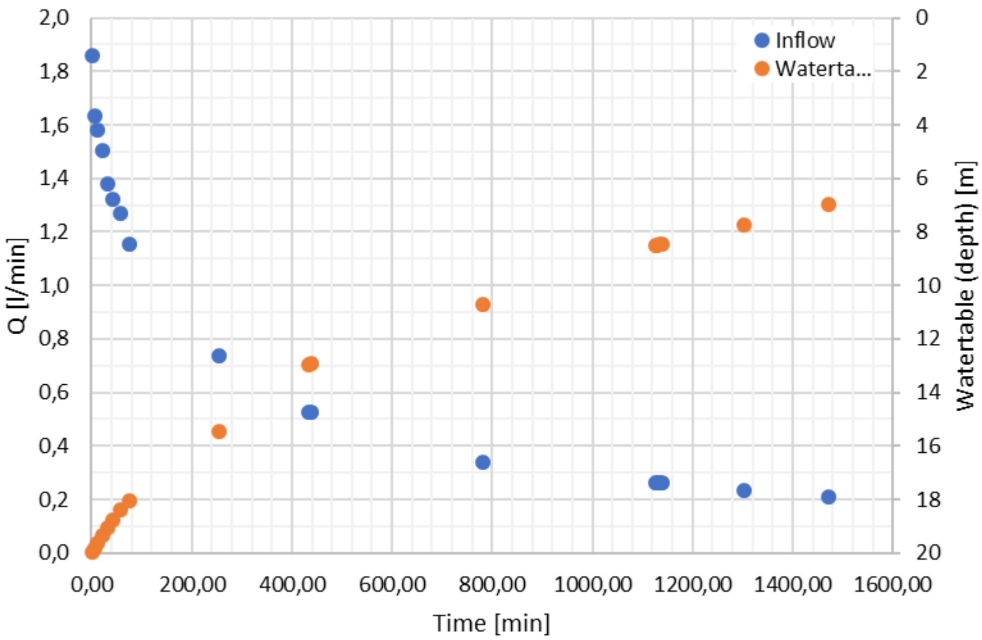

Figure 19. *Results from the flow test on September 3, 2018. Flow out of the well is estimated to be less than 2 dl/min.*

On September 10, 2018, temperature and pressure logs were made with a Kuster K10 tool. The results of the logging are shown in Figure 20. Note that the nearby well HN-10 (which is situated ~25 m north of HN-13) had not been produced with down-hole pumping for some time prior to the logging described here. At the time HN-10 was free flowing (artesian flow) some ~5-6 L/s of (81.5°C) hot water.

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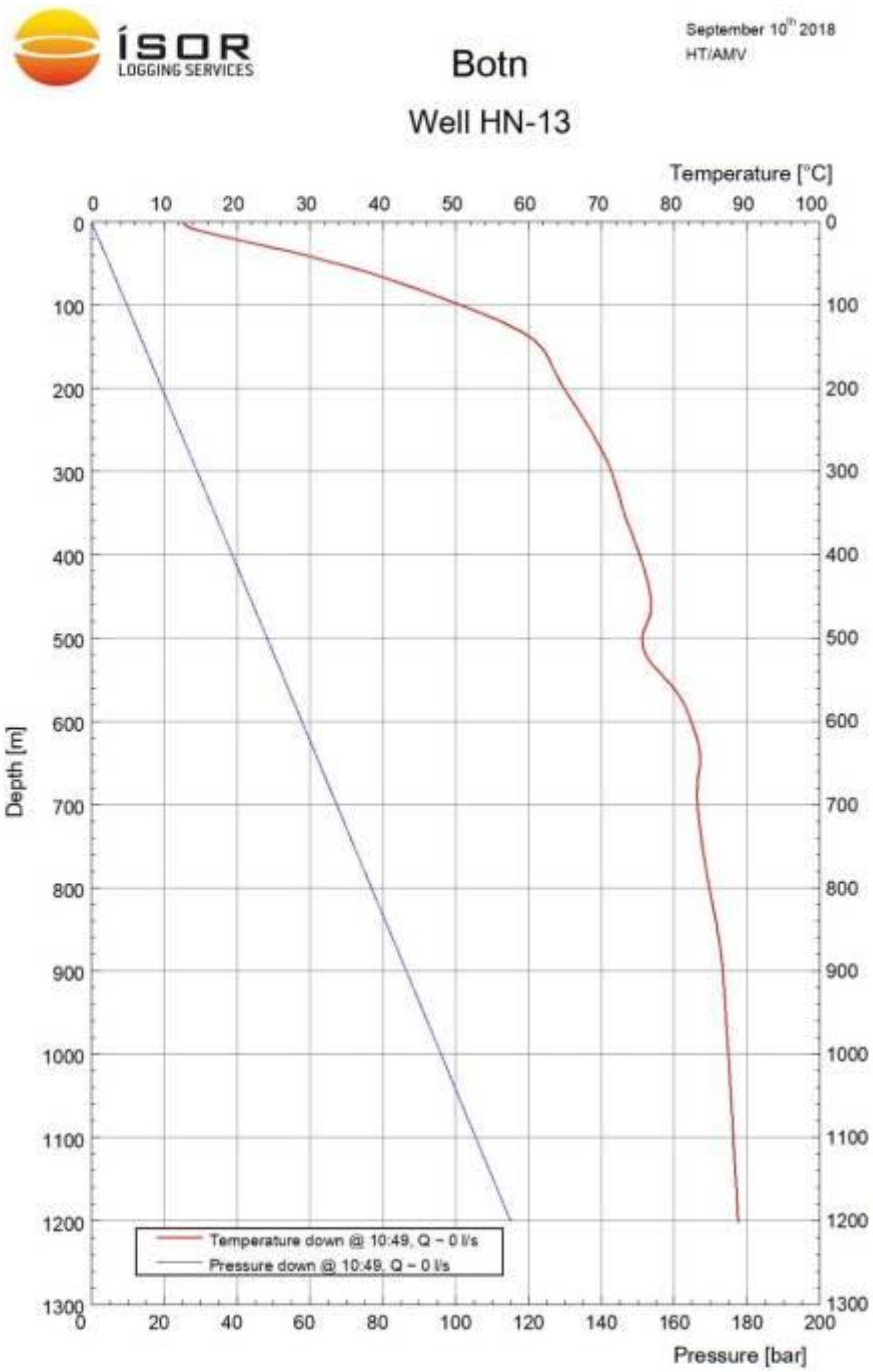

Figure 20. *Temperature and pressure in HN-13 on September 10.*

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3.3.4. Geology and wireline logging data

According to inspection of drill cutting samples retrieved from the borehole during drilling, the strata pile in the well mostly consists of alternating basaltic lava flows and thinner layers of scoria and red oxidized inter-basaltic sedimentary beds. The inter-basaltic sedimentary beds are ancient soils, formed during repose periods between eruptions of lava flows and are often contaminated with basaltic scoria from the top of the underlying lava. The lava pile is cut by basaltic intrusions, which are considered to be most often sub-vertical (dykes). The lavas and the inter-basaltic beds differ in thickness and properties. The size of the crystals that form the lavas varies from fine to coarse (cf. fine/medium/coarse grained). Most of the inter-basaltic sedimentary beds are very thin, although several thicker and more pronounced sedimentary layers are present in the well, with the thickest layer recorded in the drill cuttings at 956.5-968.5 m depth (from surface). The upper part of this layer consists of a red, oxidized inter basaltic bed, while the lower part is an altered tuff layer, abundant with precipitations. This layer is the recommended target layer for the radial jet drilling operations, discussed in section 3.3.7.

However, as the recorded depth value of a cutting sample is the depth of the drill bit at the time of sampling at surface, and it takes the cuttings some time to reach the surface, these values are slightly higher than the actual depth of the corresponding lithological layer. In addition, the samples are often mixed with cuttings from layers higher up in the well. Thus, the cutting sample analysis does not give the exact location of the layer. Therefore, wireline logs are used to acquire more exact location of the sedimentary layer (954-968.5 m from surface), and more importantly, of the softest part of this layer (956-963.5 m from surface), which is the recommended target zone. These depth differences are listed in Table 2. Wireline logging is discussed in the following text.

Table 2. *Depth values used for the sedimentary layers based on different references.*

	Sedimentary layer, depth values acquired from cutting analysis	Sedimenatary layer, depth values acquired from well logs	**Target zone**=softest part of the sedimentary layer (depth values acquired from well logs)
Measured from drill rig (1.6 m above ground level)	958-970 m	955.6-970 m	957.5-965 m
Measured from ground level (surface)	956.5-968.5 m	954-968.5 m	**956-963.5 m**

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Temperature logs conducted during and after drilling (Figure 26) show bottomhole temperature of 92°C. Wireline logging conducted in January 2017 revealed a blockage at ~1400 m depth. Potential targets are however shallower (see section on target below) so this will not cause problems in the RJD experiment. Open hole borehole logs in HN-13 consist of acoustic Televiewer, Sonic, neutron response (NN), resistivity, natural gamma radiation, caliper and temperature.

The borehole logs provide information on rock properties and were used in combination with the drill cutting analysis to differentiate between lavas and intrusions, and to confirm locations of sedimentary layers. The Sonic data, in combination with gamma radiation, enabled estimation of formation properties such as porosity and matrix density, while the Televiewer data provided locations, orientations and apparent apertures of fractures in the well.

The Televiewer data indicates that fractures in the well strike primarily NNE-SSW, most often dipping in westerly directions (Figure 21). Six large open fractures that dip >55° from horizontal were identified; at 827 m, 835 m, 869 m, 1066 m, 1298 m, and 1307 m. These fractures strike N-S and NNE-SSW and dip mainly towards west (

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Table ***3***). As no feed-zones are in the well, none of these fractures are permeable. Drilling-induced tensile fractures (DIF), identified in the Televiewer data, indicate that the orientation of S_{Hmax} is NW-SE, or approximately N121°E.

A simplified model of the stratigraphy in the well is based on a composite comparison of the borehole logs and the results of the drill cutting analysis (the simplified geological model is presented along with other borehole data in Figure 22). Comparison of these same parameters also enabled identification of potential targets for radial jet drilling experiments (several potential targets in addition to the target at ~960 m are presented in the detailed drilling report).

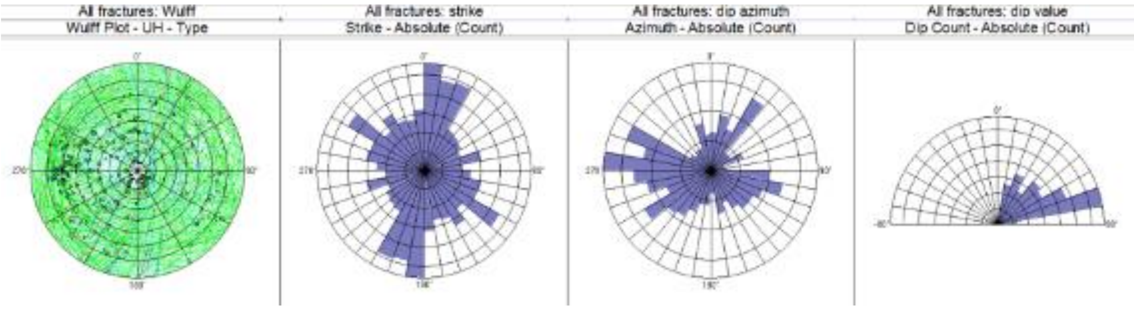

Figure 21. *All fractures identified in the Televiewer images.*

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Table 3. *Large open fractures that dip >55° from horizontal, identified in the Televiewer data (measured from ground level). Please note that the fracture apertures are apparent apertures, which are larger than the true apertures, and also probably overestimates due to scattering of the ultrasonic acoustic pulse at the edge of the fracture.*

Depth (m)	**Strike**	**Dip direction**	**Dip value (°)**	**Aperture (mm)**	**Confidence**
827.46	N1.22°E	WNW (271.22)	73.87	21.8	Medium
834.95	N24.82°E	WNW (294.82)	75.26	19.79	High
869.02	N18.23°E	WNW (288.23)	80.37	17.25	High
1065.68	N32.19°E	SE (122.19)	81.49	9.37	High
1297.96	N15.97°E	WNW (285.97)	80.52	30.96	High
1307	N179.27°E	W (269.27)	70.4	21.46	High

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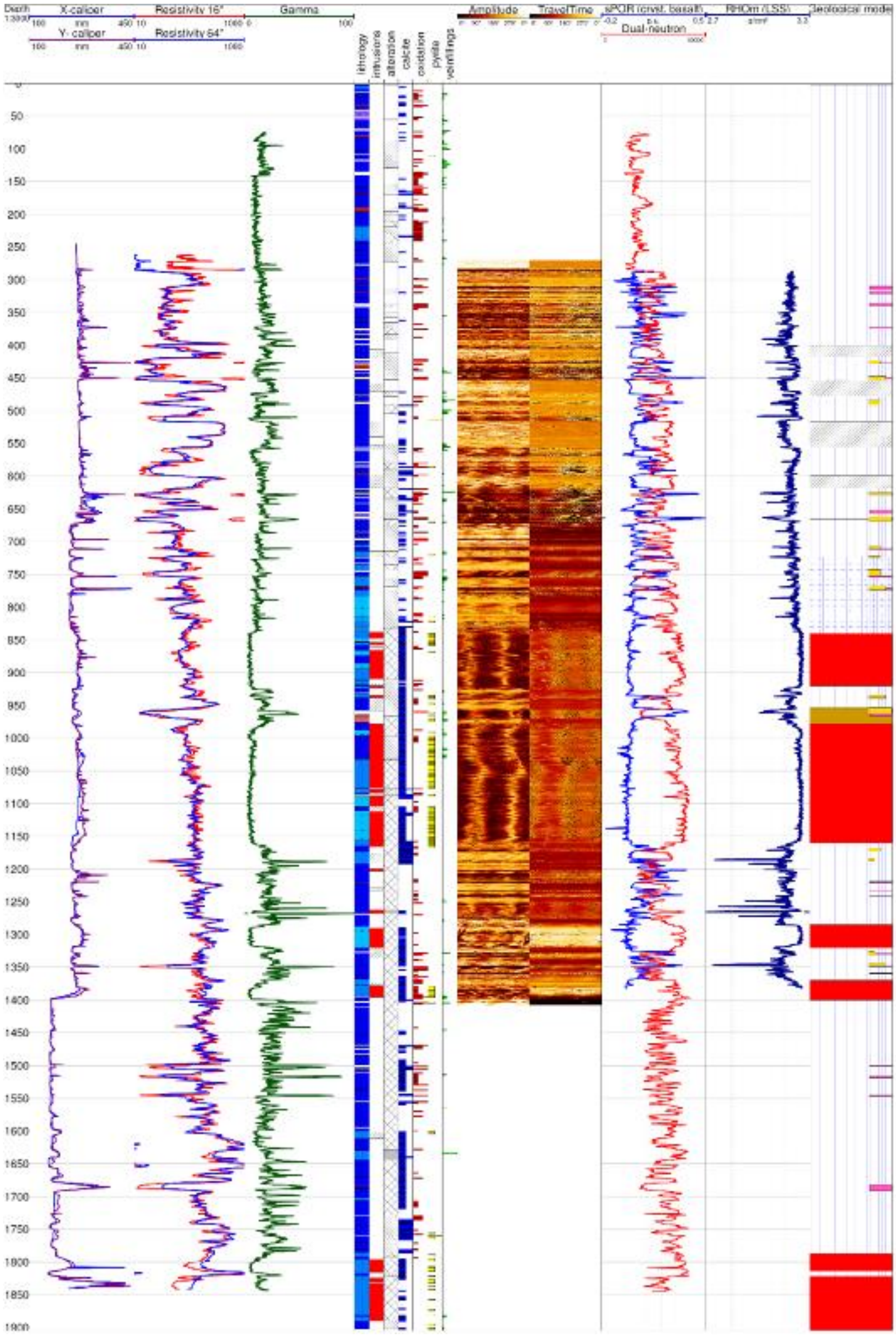

Figure 22. *Borehole logs, drill cutting analysis, matrix density, apparent porosity, and a simplified model of the stratigraphy. See legend in Figure 23.*

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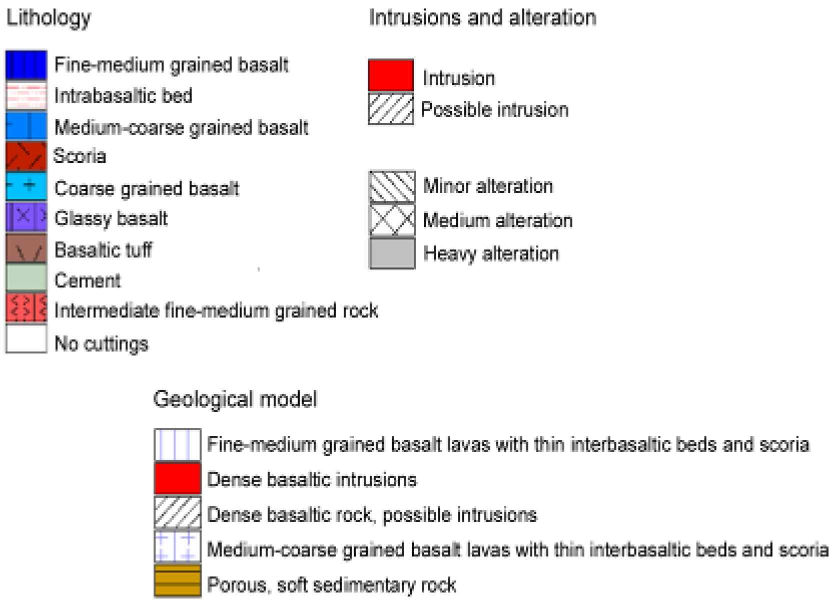

Figure 23. *Legend for Figure 22.*

Sonic log integration has shown potential target zone at approximately 960 m: *Between 780 and 1160 m, a distinct, very tight and homogenous formation can be seen throughout all logs, with P-wave velocities of about 5.8-6 km/s. Within this formation, a zone of soft sediments is seen between ~950-960 m. Due to the thickness (circa 10 m) and high apparent porosity (35-40%) this zone indicate a good target for jetting.* Memorandum on integration of sonic log by Felix Kästner is shown in appendix.

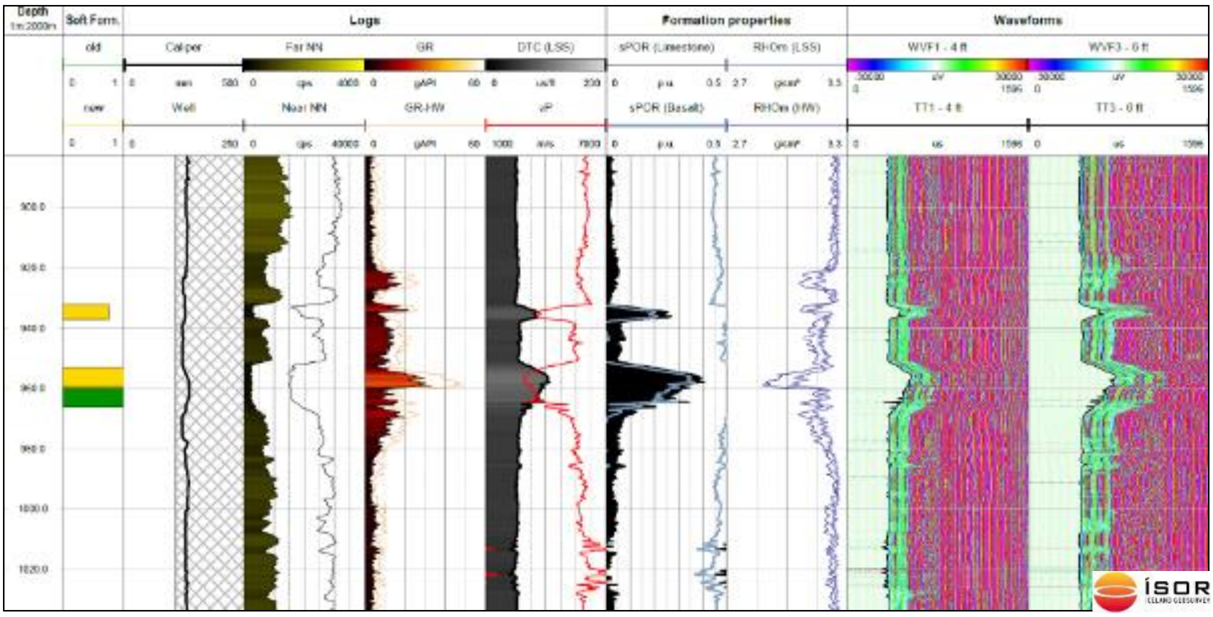

Figure 24. *Sonic log integration showing potential target zone at 952-960 m (from rig floor) shown in yellow (Felix Kästner 2017).*

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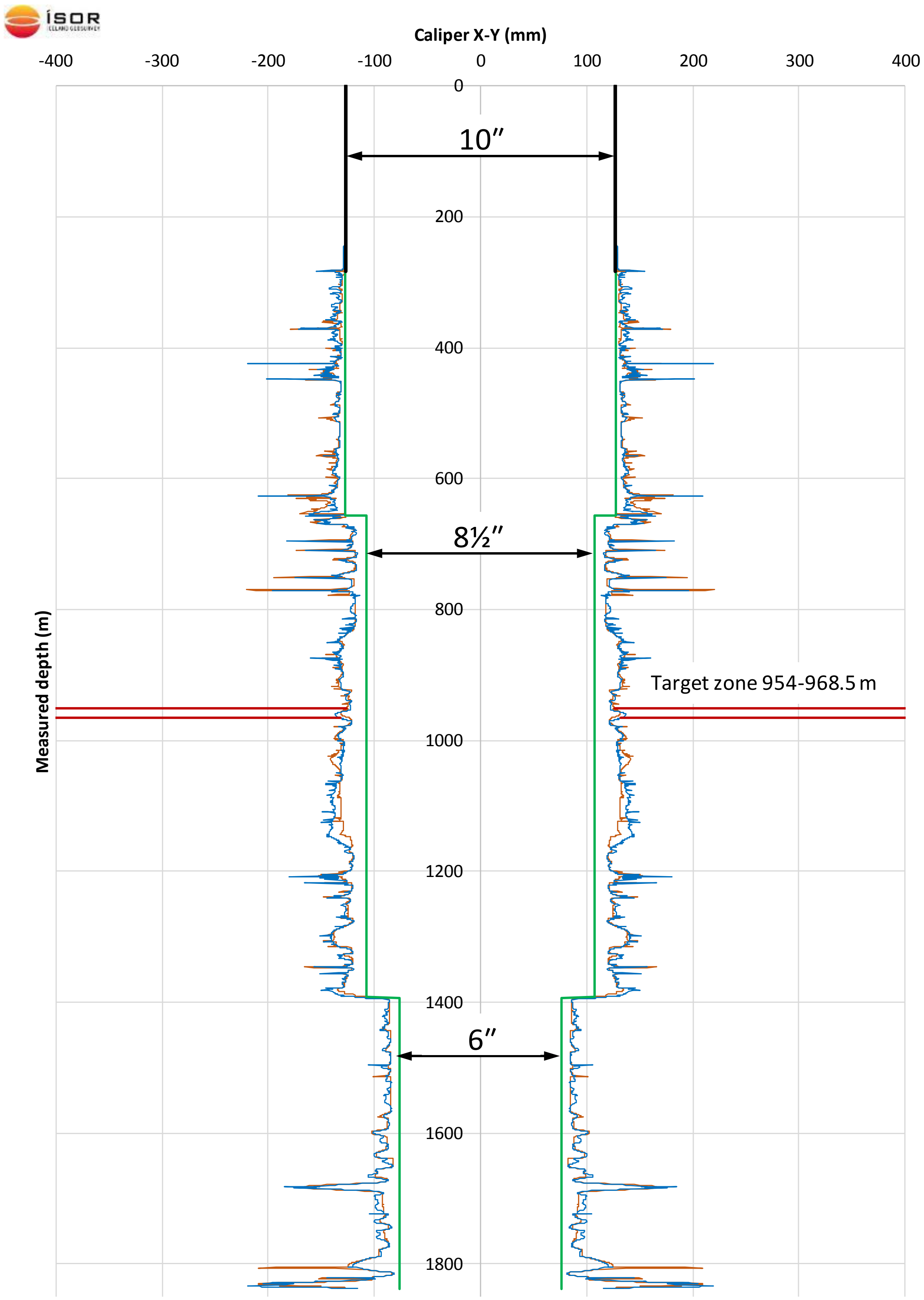

Figure 25. *Caliper log of well HN-13. The log is presented in greater detail in Appendix.*

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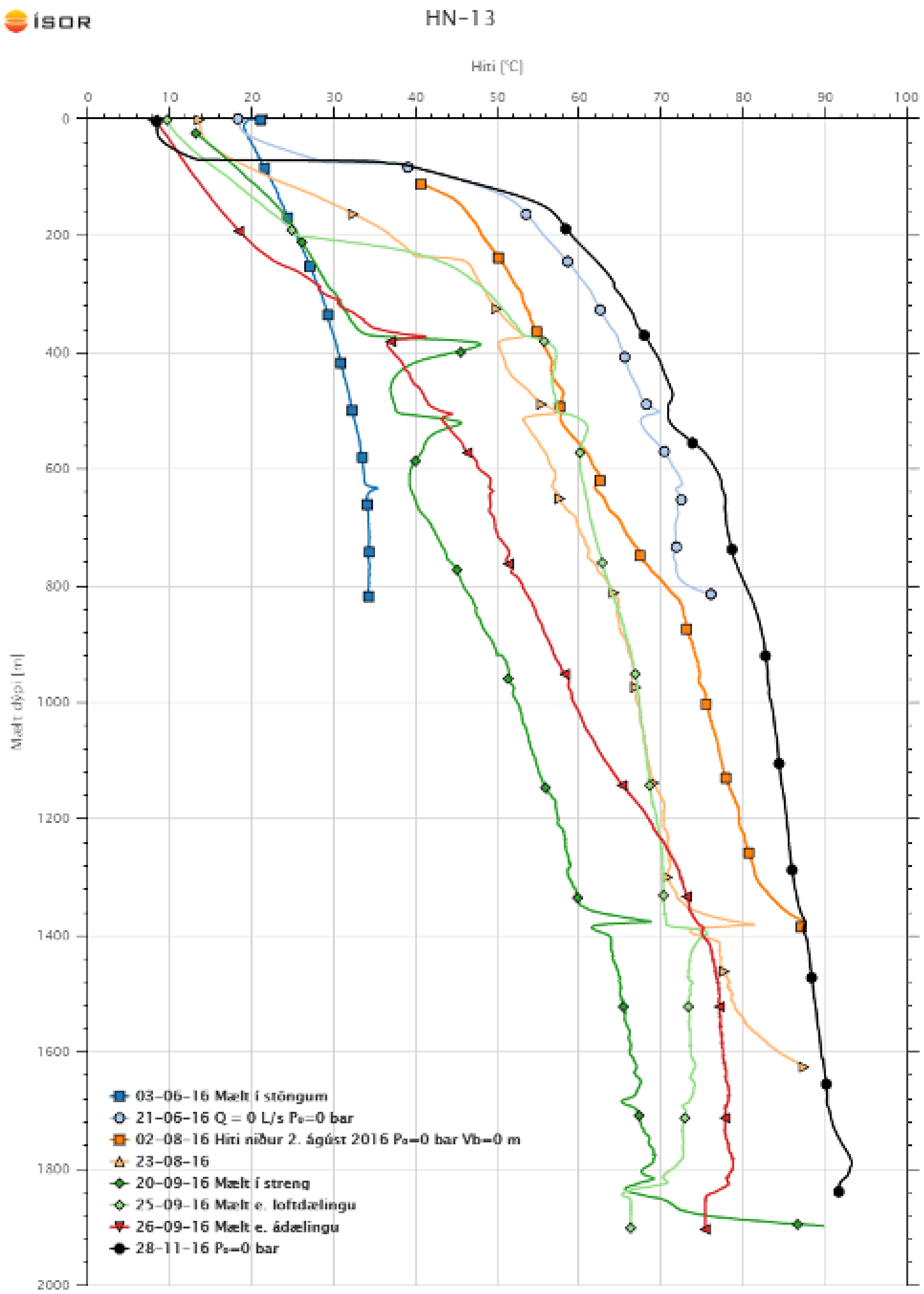

Figure 26. *Temperature logs of HN-13. Measurements on 25th September 2016 were made after airlifting and on 26th September 2016 was taken after injection tests.*

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3.3.5. Nearby wells (BO-01 and HG-10)

Well HG-10 (also known as HN-10) was drilled in spring-fall of 1980 to a depth of 1050 m. Spudding with air hammer to 41 m depth was followed by 8½″ rotary drilling to 1050 m depth. At 489 m depth 20 l/s of 80°C water was flowing out of the well. At 530 m the flow increased to 24 l/s. After summer holidays 16 l/s were flowing from the 636 m deep well. Drilling further the flow increased at 813 m, measured at 824 m as 36 l/s. The maximum temperature in the well was 88°C (Guðmundsson, 1980).

Well BO-01 (also known as BN-01) was drilled in 1981 to depth of 1830 m. According to information in ÍSOR's database the first 27.5 m were drilled by the rig "Höggbor 6" which employed a DTH (pneumatic) hammer. A 16" surface casing was run to 10.5 m depth. A limited televiewer run in well BO-01 detected a casing down to ~ 25 m depth (Ásmundsson et al. 2008) which is probably a 10" production casing.

The two wells have been in almost constant production since they were completed. A key characteristic of the wells is that there is considerable draw down during pumping. However, if pumping stops, the wells will start to flow after a short while. This is one of the motivations for continuing research in this area. It seems that the resource is formidable, but production wells are poorly connected it. Temperature in the well HN-10 has decreased by few degrees but temperature in BO-01 has remained stable, see temperature history form years 1980-2002 in Figure 27 and water table and production history in Figure 28.

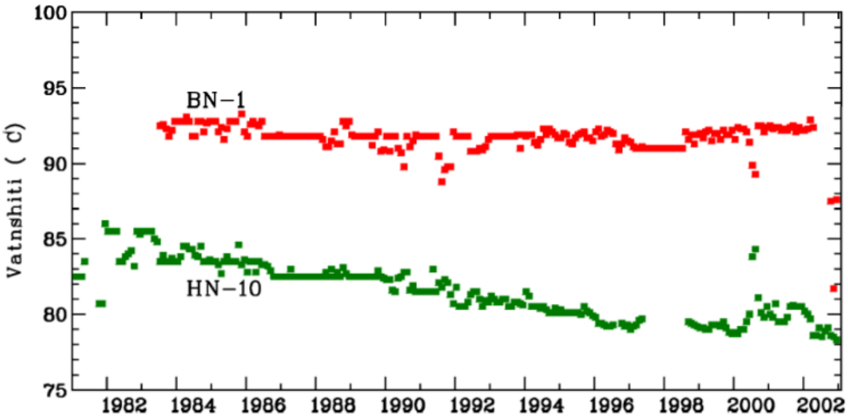

Figure 27. *Water temperature in production wells BO-01 (BN-1) and HG-10 (HN-10). As can be seen from the figure the temperature of the fluid produced from HN-10 has decreased by a few degrees while the temperature from BN-1 has been fairly stable. Deviations from the general trend result from changes in pumping. (Hauksdóttir, et al., 2003).*

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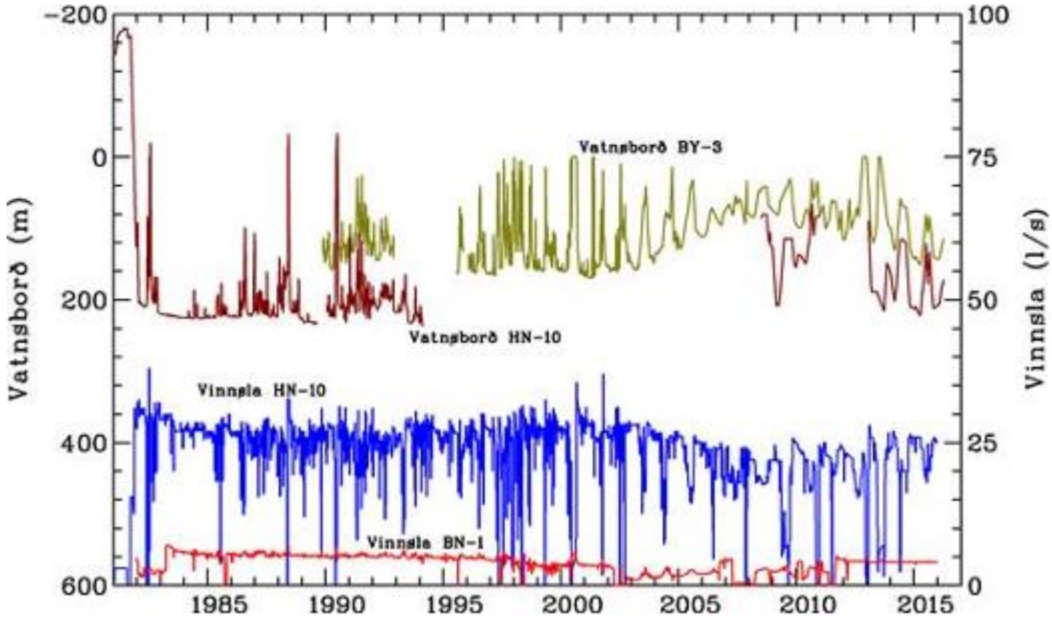

Figure 28. *Water table (vatnsborð) in well BY-3 (located 100 m SSE of BO-01) and production (vinnsla) in wells HG-10 (HN-10) and BO-01 (BN-01). When pumping is halted temporarily, the wells will return to artesian flow rather quickly (i.e. water level in BY-3 goes to 0 m) but the temperature of the fluid is lower than during pumping (Egilsson, et al., 2017).*

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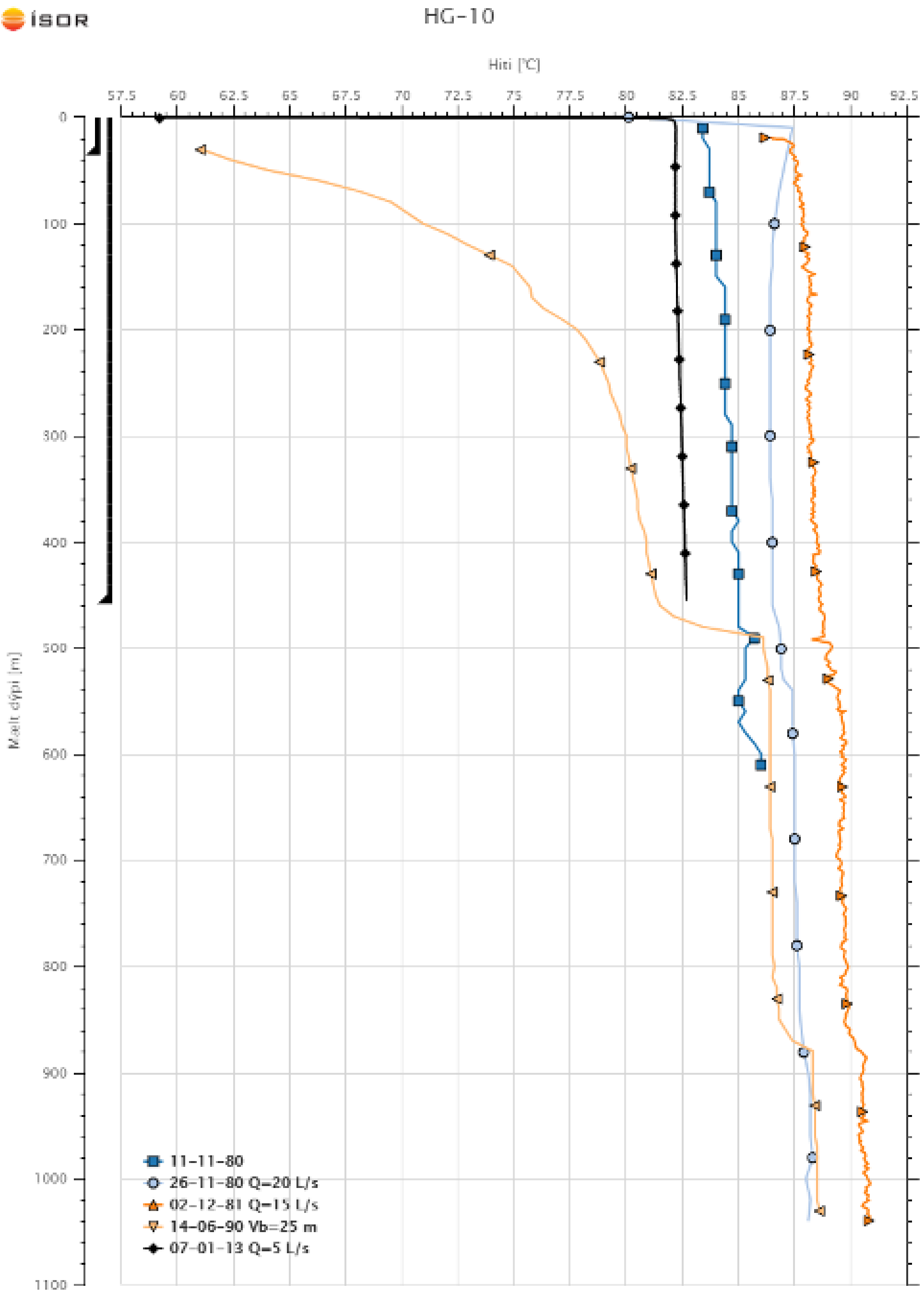

Figure 29. *Downhole temperature measurements in well production well HN-10 (located 20 m NNE of HN-13). The flow during logging is seen as "Q" in legend and "Vb" means water table.*

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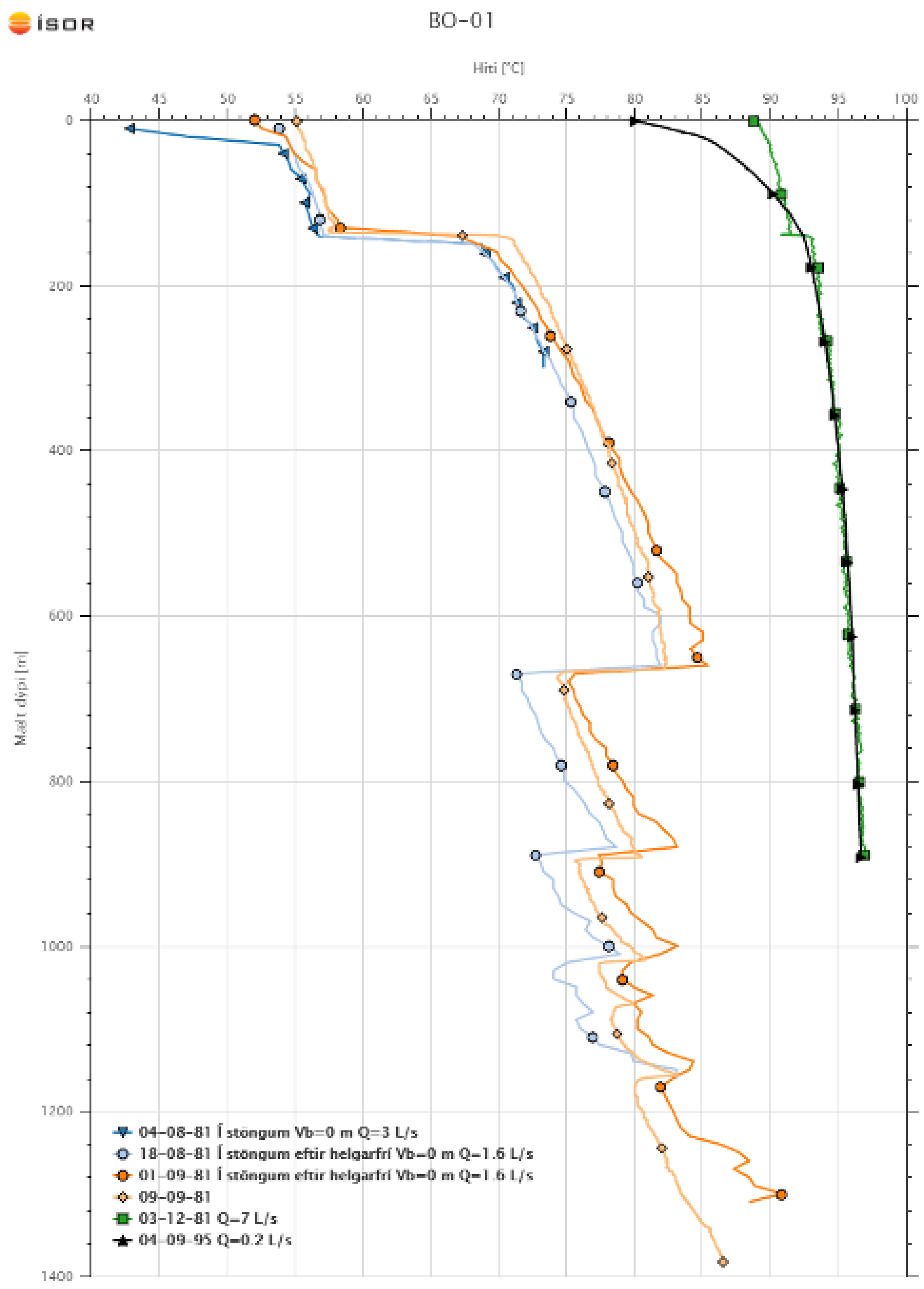

Figure 30. *Downhole temperature measurements in well production well BO-01 (located 50 m SSW of HN-13). The flow during logging is seen as "Q" in legend and "Vb" means water table. First 4 logs are done during drilling inside the drillstring.*

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3.3.6. Geological model of Botn

A simple geological model of the Botn area is described below. The model, built using the Petrel software from Schlumberger, covers a very small area. It contains the three deep boreholes BO-01 (B54401), HN-13 (54514) and HG-10 (54511). These boreholes are located on a 70 m long line. Figure 31 shows the wells and surrounding area.

Figure 31. *Map of boreholes HN-13, BO-01 and HG-10 in Botn.*

The data used in this model comes from these three boreholes as well as surface exploration carried out the 1980's (Figure 32). Surface exploration data was compiled from reports (in Icelandic) by Björgvinsdóttir (1982), Guðmundsson and Sæmundsson (1971) and Flóvenz et al. (1989). Borehole data from HN-10 is based on a report by Guðmundsson (1980) and unpublished results of Televiewer data.

Maps from the literature were georeferenced and selected features added to the model. Those are lineaments indicating structures (dykes and faults) inferred from magnetic surveys, and locations of now disappeared geothermal manifestations. Figure 32 shows the data compiled from these maps.

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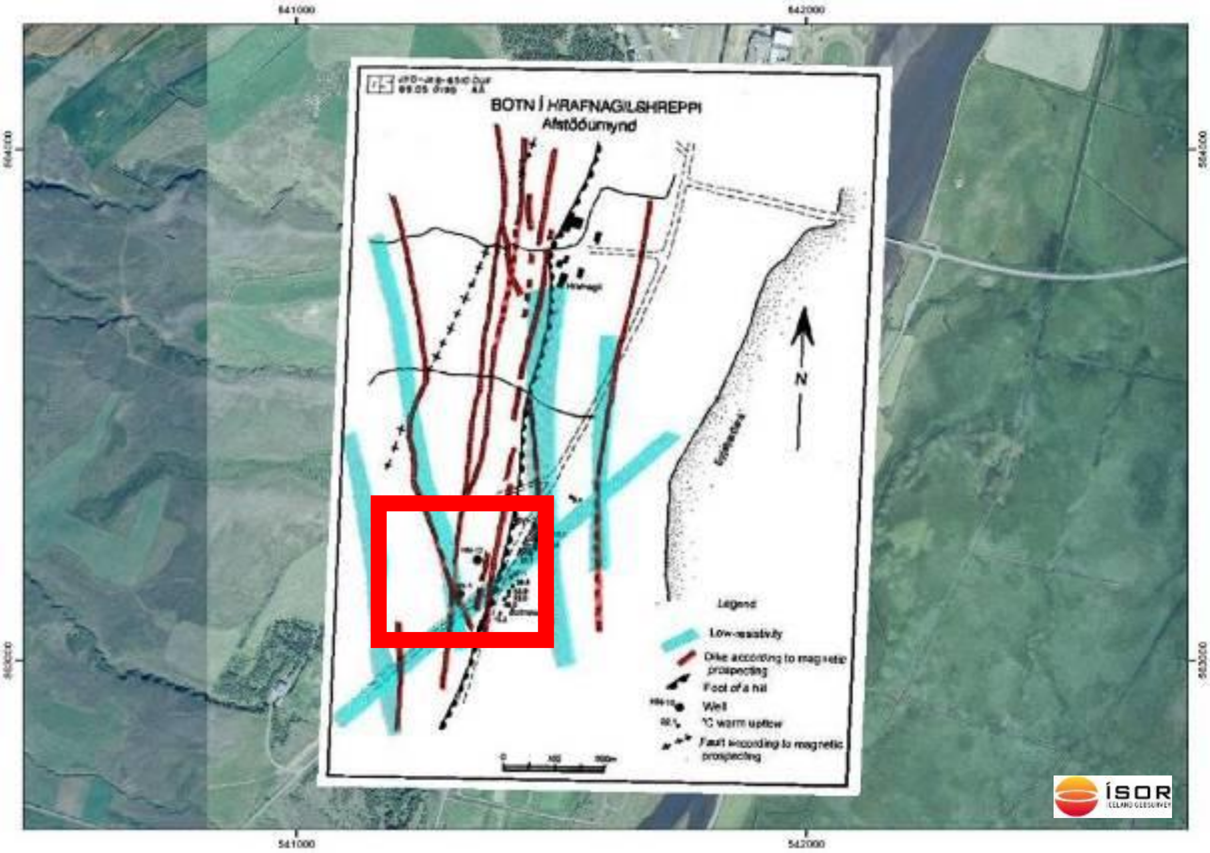

Figure 32. *Lineaments as interpreted from Magnetic and Resistivity surveys (Guðmundsson and Sæmundsson, 1971; Björgvinsdóttir, 1982; Flóvenz et al., 1989). Red lines indicate dykes, and blue lines (low-resistivity) indicate four permeable dykes and one permeable fault. The figure is modified from Flóvenz et al. (1989).*

These lineaments are included in the model as seen in Figure 33. Green structures indicate dykes interpreted from magnetic surveys, which are permeable according to the resistivity survey, and the blue line is a permeable fault.

The sub-surface model was based on data from the boreholes HG-10, BO-01 and HN-13. The alignment of the cross-sections is shown in Figure 34.

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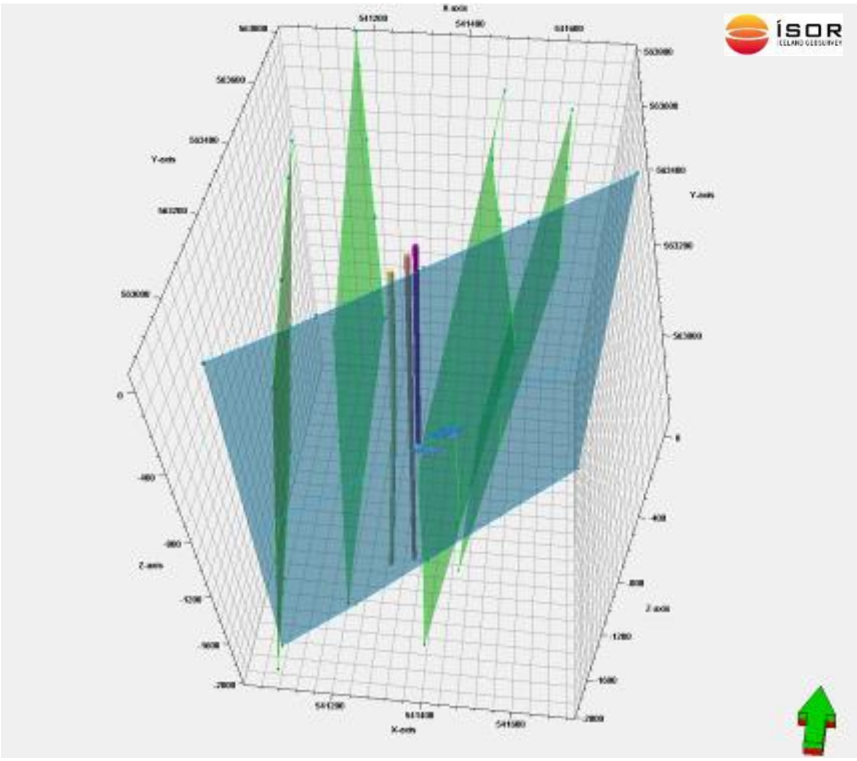

Figure 33. *Lineaments from the magnetic and resistivity surveys, mapped at surface, extended trough the subsurfaces.*

Figure 34. *Red line through wells BO-01, HN-13 and HG-10 indicates the cross-section presented in Figure 35.*

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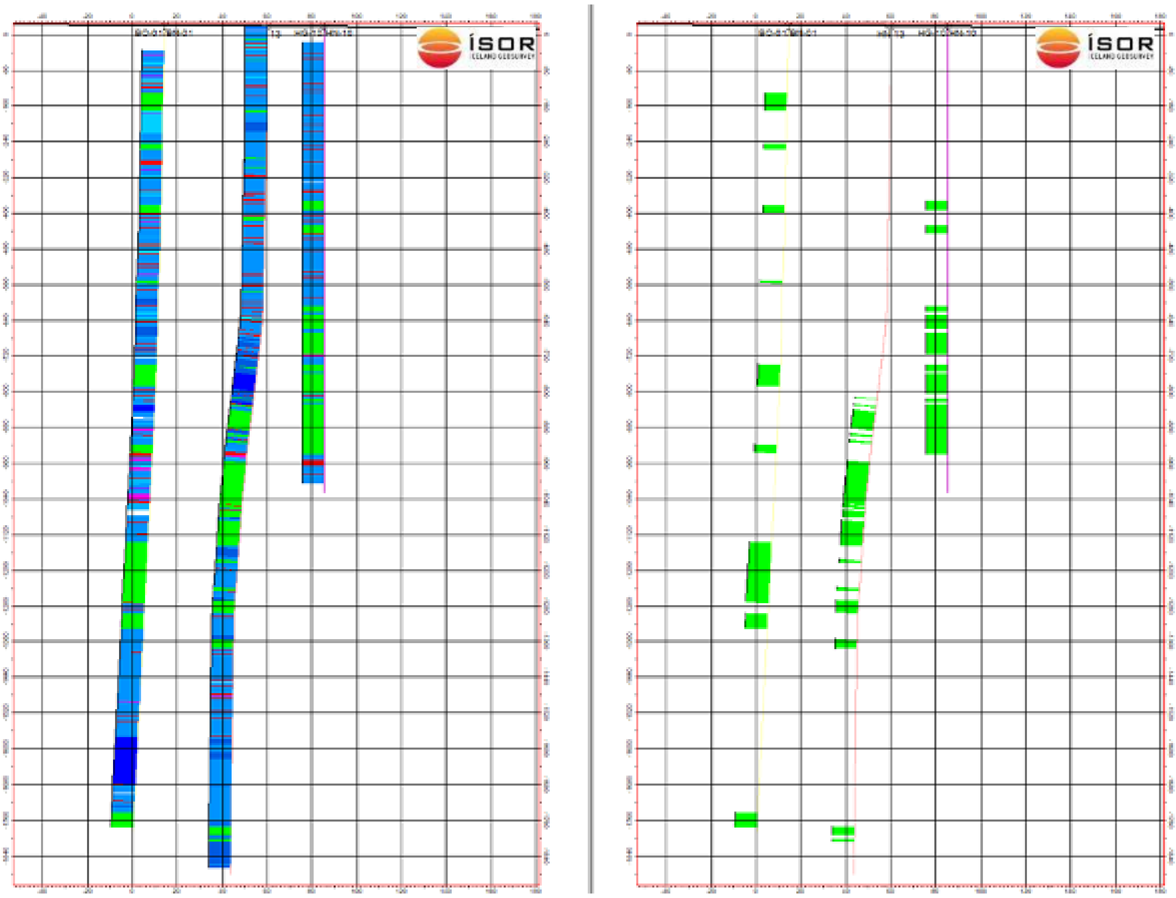

Figure 35. *Cross-sections showing well lithologies (left: all lithologic layers; right: only intrutions).*

The stratigraphic columns from wells HN-13, BO-1 and HG-10 are lined up in a cross-section shown in Figure 35. As the stratigraphy of the wells basically consists of basalt lavas and thin intrabasaltic bed, only two main sets of lithologies are mapped in this simplified model, i.e. intrabasaltic layers (1) are used as marker horizons where possible as contacts between the basaltic lavas (2).

The resulting model is shown in Figure 36. The model is visualized in a cross section through the boreholes, as no constraining data is available at depth to the east or the west. Green represents intrusions, orange are interbasaltic layers and between in blue are basalt lavas. The target zone is marked as a red layer. Correlations between the stratigraphy in these three wells are based on neutron response and gamma radiation logs (which are available from the three deep wells in the Botn area) in comparison with drill cutting analysis. The correlations indicate that no large faults are present between the wells. Feed-points from wells and lineaments from the literature are also shown in the figure. Green colored line represents a dyke based on resistivity mapping, but red line shows a dyke, which is supported by magnetic prospecting. Inclination of dykes in Western Eyjafjörður is in literature described as being 0-

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10° from vertical towards West, generally striking NNA-SSW (Björgvinsdóttir, 1982). The lines going through the cross-section in Figure 29 are the same as shown in Figure 33.

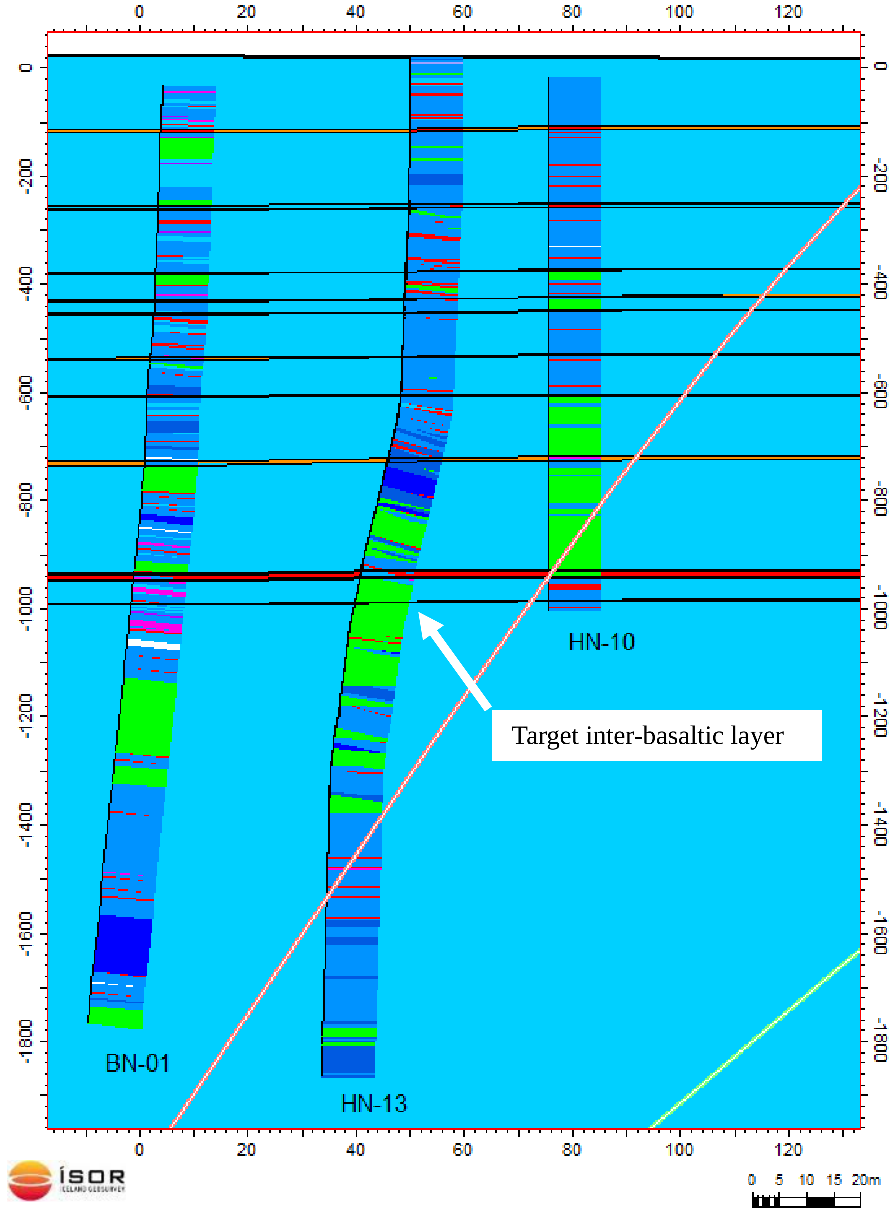

Figure 36. *Cross section of the geological model. Green layers represent intrusions, orange are intra-balsaltic layers and between in blue are basaltic formations.*

In Figure 37., feed-points from wells and faults identified in televiewer data are also marked on the borehole paths, and the arrows shown on the path for HN-13, show the inclination of faults. In addition to the well data, lineaments from the literature are included. Inclination of dykes in Western Eyjafjörður is in literature described as being 0-10° from vertical towards West, generally striking NNA-SSW (Björgvinsdóttir, 1982). The lines going through the cross-section in Figure 37 are the same as shown in Figure 33.

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Above, a model of the Botn geothermal system is described. The model is based on data from three wells and the model is based on correlations between these wells which are aligned approximately SSW to NNE (see Figure 34). No constraining data exists to the West or East of the cross-section and extension of strata in these directions is therefore only assumed. Projection of basaltic dikes with assumed inclination of 10° from vertical indicates which intrusions can be correlated between the wells.

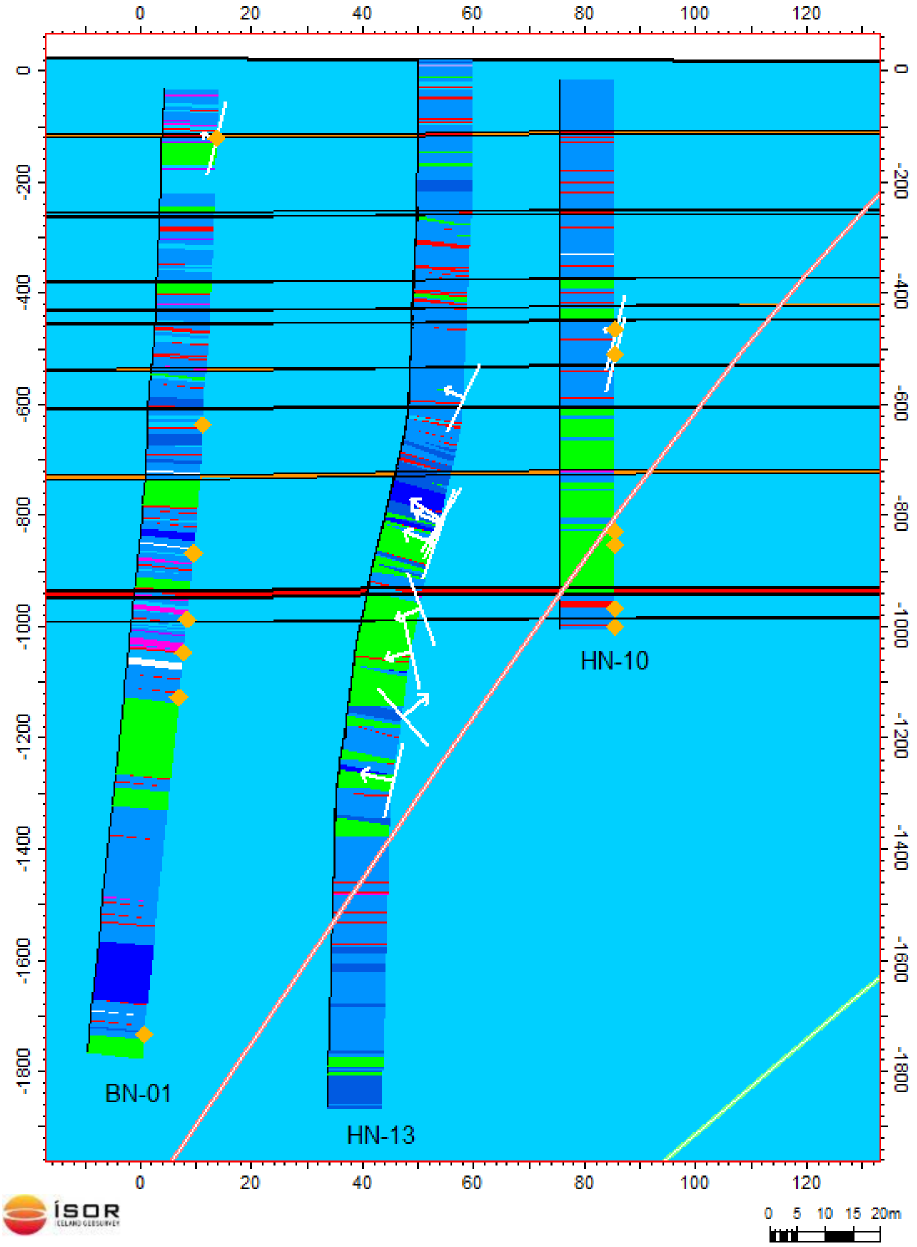

Figure 37. *Complete model with assumed 10° inclination (from vertical) of dykes towards West with NNA-SSW strike, as is described in literature.*

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3.3.7. Target for RJD based on wireline logging and model

As jetting through hard basalt was not shown to be feasible during initial testing within WP5 (D5.1), the primary target is through an inter-basaltic sedimentary layer located at ca. 960 m depth. This layer, shown in red in Figure 36, was identified in the drill cuttings at ca. 956,5-968,5 m (from surface), and wireline logs (gamma, NN, resistivity and Televiewer) indicate that the softest part of the layer is at ca. **956-963.5 m** (measured from ground level). No problems occurred during drilling at this depth interval.

The sedimentary layer appears in wells HN-13 and BN-1, but it is not seen in HN-10 as it intersects a dyke where the layer should appear. As the geological model does not have any constraining features beyond the three wells, it does not indicate the extent of the inter-basaltic layer. The layer is approximately 14 m thick and features relatively high apparent porosities (35-40% according to estimates from Sonic log) and drilling in any direction is possible. Without a definite target, multidirectional laterals are proposed at depths within **956-963.5 m** (from surface), i.e. within the softest part of the sedimentary layer (Figure 38).

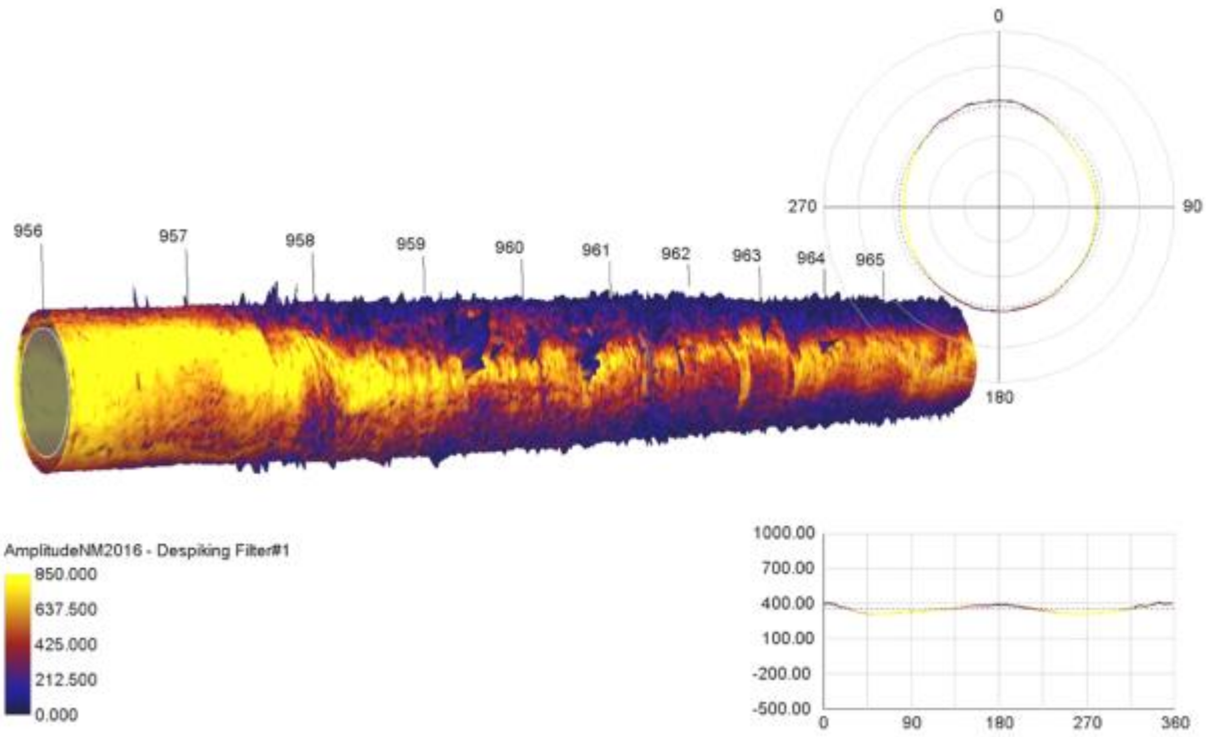

Figure 38. *Televiewer data indicates softest formations at 956-963.5 m depth from surface.*

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Table 3. *List of potential jetting targets (adjusted from Bjarni Gautason et al., in publication).*

Measured from drill floor (1.6 m)		Indicated by				
Depth from (m)	Depth to (m)	Dual-neutron	Resistivity	Caliper	Drill cuttings	Televiewer
310	315	x		(x)	?	x
317	321	x		(x)	scoria	x
335.5	340	x		(x)	sediment	x
372	374.5	x		x	sediment	x
425.8	426.8	x		x	sediment	x
449	451	x	x	x	sediment	x
627.3	628.5	x	x	x	sediment	x
651.9	656.8	x	x	x	sediment	x
710.5	712	x	x	x		x
752	754	x		x		x
771.4	774.4	x		x		x
959	966	x	x		sediment	x
1219	1221	x		x	sediment	x
1233	1234	x		x		x
1241	1242.9	x		x		x
1328	1330	x		(x)	?	x
1359	1360	x		x		x

Preferred directions for the radial jet drilling in HN-13 in the SURE project were suggested (Haraldsdóttir, 2019). The main emphasis was on the resistivity models presented by Vilhjálmsson and Karlsdóttir (2015), the warm springs in easterly direction from the wells, and that fractures would be hit if easterly directions are chosen. The locations of the warm springs as well as some of the fractures shown in the map in Figure 14 are in easterly directions from HN-13. The resistivity found from surface soundings is also lower in easterly directions. Regardless of the depth interval selected, **the advised directions for the radial jet drilling are easterly and north-easterly**. These seem to be the best candidates for hitting a porous, geothermal zone. The easterly directions are mainly based on:

- The location of low resistivity zones in easterly directions of HN-13 (Vilhjálmsson and Karlsdóttir, 2015) as well as further study of the resistivity models in Petrel.
  - south of east for 959-966 m depth
  - north of east for the upper part of the well
- The location of the hot springs which died after starting utilizing wells BN-01 and HN-10 in the Botn area in Eyjafjörður for Hitaveita Akureyrar, later Norðurorka.
- Possible fractures as shown in Figure 14.

The low resistivity is in easterly directions as are the warm springs which were close to HN-13 before the utilization of HN-10 and BO-01 was initiated. Some of the fractures according to previous resistivity studies and results of magnetic surveys are as well in easterly directions.

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4. Radial Jet Drilling Operation

4.1. Overview

The RJD operation in the well HN-13 was originally planned within the SURE project for summer 2017. Difficulties of jetting into basalt in laboratory at GZB (WP5) resulted in postponed operation by a year to allow room for further testing. The summer time is ideal for well workovers in N-Iceland while the least load is on the district heating system and weather conditions are favorable. The ideal timeframe is therefore from May to October.

Two field tests were conducted in well HN-13. The first field test was done with a compact truck mounted drillrig “Karl Gustav” in October 2018 (Figure 10) with selected light coring drillrods (NQ type) to ensure reaching required depth with the limited hookload of the rig. During run-in-hole, an incident occurred where the bottom hole assembly (BHA), was accidentally dropped in the hole. The incident lead to two unsuccessful fishing trials and due to time limits the field test had to be suspended. A consortium decision was taken to continuate with a second field test. The second trial test was carried out in June-July 2019, with a larger drillrig “Nasi” able to run conventional drillpipes. This was the same rig that drilled the well. Both rigs are owned and operated by RSFS (Ræktunarsamband Flóa og Skeiða). Before installing a new deflector shoe it was made sure that the well was accessible at the target zone. Both operations are described in detail below.

4.2. Field test 1 – October 2018

4.2.1. Description

In an EB meeting within the SURE consortium (18. August 2018) it was decided that the field test operation would kick off on the 15th of October 2018. The power company Norðurorka ordered a drill rig for the job that was available for the two weeks planned for the job. The field test trial was performed as planned in well HN-13 in Botn in N-Iceland in 15-24 October 2018. A small drill rig was hired from drilling operator RFSF (Figure 39) with necessary hookload and equipment to operate the RJD equipment. Well Services Group (WSG) arrived to Iceland with the coil equipment for RJD carried on two trailer trucks (Figure 40). On 16 October, while the drilling contractor was running in the drill string with a deflector shoe attached, an incident occurred on surface where the drill string along with the BHA (Figure 41) dropped into the well. Wireline logging conducted by ÍSOR showed that the top of the “fish” (the deflector shoe and ~80m of drill string) was located at 724 m depth. Attempts of fishing it out of the well were unsuccessful. This incident ultimately led to a delay that resulted in termination of the field test. The fish was left in hole after two unsuccessful fishing attempts.

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Figure 39. *Drill rig "Karl Gustav" operated by RFSF. Picture taken on 19 October during RIH.*

Figure 40. *WSG trailer trucks and drill rig "Karl Gustav" in distance.*

Table 4. *Operation plan highlights for field test in October 2018.*

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Well name	HN-13.
Location	Botn, Eyjafjörður, N-Iceland.
Coordinates	65.56398, -18.10453 (65°33'50.3"N 18°06'16.3"W).
Well diameter	10 inch down to 650 m, 8½ inch 650 – 1389 m (refer to caliper log in appendix).
Target depth	**956-963.5 m** from surface.
Target directions	Laterals jetted at 45-90° intervals.
Measure of success – 1	Laterals can be jetted and coil pulled out with ease.
Measure of success – 2	Air lifting through slotted drill pipe. Air compressor used to compress water column down to ~200 m depth out of slotted interval of the drill pipe, flow measurements on surface. Improvements should be clearly visible by increased flow out of the well.
Measure of success – 3	Post-operation flow testing shows increased flow when compared to pre-operation flow tests.
If improvements?	Continue to jet laterals to the direction where previous lateral gave improved flow out of the well at various depths.
Operation sequence	1. Pre-operation flow testing – done (see section 4.3) 2. Raekto set up drill rig 3. WSG/Raekto make up BHA and install deflector shoe at predefined depth within defined target depth. 4. ÍSOR run gyro for initial orientation of the deflector shoe. 5. WSG run in jet/coil, jetting of lateral. 6. Coil pulled out of hole 7. Air compressor and flow measurements on surface. 8. Deflector shoe repositioned, direction and/or depth. 9. Iteration of steps 4-7. 10. Post-operation flow testing. Televiewer/video imaging of the wellbore.

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Table 5. *Risks and mitigation for RJD (October 2018).*

ID	Risk	Consequence	Probability	Impact	Mitigation remarks
R1	Installation of deployment shoe unsuccessful	RJD cannot be performed	Low	High	Change in position of deployment shoe
R2	Deployment shoe lost in hole	Restriction in well	Low	Medium	Fishing by conventional means
R3	Target zone cannot be penetrated	Too hard material/too little pressure delivered to nozzle	Medium	High	Change in position/azimuth of deployment shoe
R4	Contamination of cuttings in nearby wells	Clogging of feed-zones	Low	High	Reduce flow from nearby wells during operation
R5	Coil/hose stuck in lateral hole	Coil/hose partially lost in hole, well clogged with equipment, operation cannot continue	Low	Low	Hose sheared and left in lateral hole

Figure 41. *Bottom-hole assembly (BHA) from left consisting of geophone, decentralizing spring, deflector shoe, decentralizing spring, universal bottom hole orientation sub and crossover to NQ threads (figure by WSG).*

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Figure 42. *Drillpipes used for deploying deflector shoe. This type (NQ) of drill pipes is normally used for coring and is lighter than usual drill pipes and are flush, i.e. the outer diameter is the same for the pipe body and the connection.*

Figure 43. *Raekto's custom made overshoot built around a sub with NQ threads used for second fishing trial (figure by Raekto).*

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4.2.2. Operation log for field test (October 2018)

Date/time	**Description**
Thursday 11 October	Well Services Group (WSG) personnel arrives to Iceland.
Friday 12 October	WSG trucks arrive and are released through customs at Þorlakshofn in S-Iceland.
Monday 15 October	Raekto's drill rig "Karl Gustav" on site at Botn, installation. WSG trucks on site. WSG meet with Raekto. Bottom-hole Assembly (BHA) with deflector shoe is made up (Figure 1). NQ type drill pipes (Figure 4) run in hole (RIH).
Tuesday 16 October	RIH continues. BHA and ~80 m of drill string fall into the well. ÍSOR logs the well and find the top of the string at 724 m depth. Planning for fishing. Fish (BHA and string) estimated to be around 700 kg.
Wednesday 17 October	Fishing methods discussed, e.g. fishing with wireline vs. drill string. Search for appropriate fishing tool for the string. Discussion of video logging the well before fishing operation starts. Well needs to be cooled before video logging. WSG make clear that they cannot stay longer than originally planned due to other obligations and need to leave Iceland latest on Friday 26. October. Planning for fishing operation with drillstring continues and other options deemed unpractical. Video logging + fishing foreseen to take until Monday morning.
Thursday 18 October	Preparation continues for RJD if fishing becomes successful. Water truck with feed from nearby stream set up. ÍSOR prepare video logging equipment. Raekto transfer fishing equipment and another drillstring for fishing from S-Iceland to Botn. Video logging discussed. Common decision taken to skip video logging before fishing to save time.
Friday 19 October	RIH with fishing tools starts at noon. About 100 m left to shoe at the end of the shift.
Saturday 20 October	RIH to depth of fish (724 m). Crew do not observe anything at surface and are not confident that fish has been reached.
Sunday 21 October	Drill string is run deeper to 738 m. Decided to use the trip to cool the well for video logging. Well cooled with water and then POOH. Fishing unsuccessful as fish is not retrieved to surface. ÍSOR video log the well. Video is poor due to dirt in water, top of drillstring is found to be centralized in the well and located at 743.2 m depth.
Monday 22 October	Raekto devise a new fishing tool (Figure 5), an overshoot built around a sub with same threads as fish. Decided to attempt a second fishing trip in the well. Fishing estimated to be finished

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	by noon tomorrow. RIH start.
Tuesday 23 October	Fishing takes longer than expected. WSG time window has become too narrow for RJD attempt if fishing proves successful. WSG decide to wait until morning for fishing results to be able to take the BHA back to the Netherlands.
Wednesday 24 October	WSG drive south to the harbor at Thorlakshofn. Fishing unsuccessful as fishing tool comes up empty. No other option than to leave the fish in the well. Raekto start packing up.

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4.3. Field test 2 – June 2018

4.3.1. Description

After a consortium decision to continue operation in HN-13, the second trial test was carried out in June-July 2019. For increased control of the operation and based on the experience from the first trial, a larger drillrig was used that has higher hookload capacity and is therefore able to run conventional drillpipes (Figure 44). Drillpipes were selected according to WSG's requirements. Prior to the operation, in September 2018, a video log was conducted by ÍSOR to see the condition of the obstruction in the well. Visibility of the top of fish was poor due to sediments and grease at 752.3 m depth. Prior to this, in October 2018, the top of fish was located at 743.2 m (originally located at 724 m), so it was clear that it had sunk down in the well. Its depth was not known at this point. Therefore, there was no clear picture of the condition the pipe. It was decided that RSFS would condition the well before installing the deflector shoe. If not grabbed at the depth at first indications of it being reached, the fish will be pushed down to ~1400 m where the well becomes narrower increasing chance of catching a hold of the fish. If fishing will prove unsuccessful, the obstruction would be out of the way and RJD operation could go on. The dropped assembly was found at ~1400 m depth at the known narrowing in the well and retrieved partially. The coring rods were retrieved but the BHA was stuck and therefore left in hole. With the obstruction out of the way of the main target depth, the RJD operation was initiated by placing a new deflector shoe (Figure 45) at the selected depth. An injector head was held up by crane and the coil feed through from the coil unit (Figure 47). Prior to the 2nd operation the anticipated risks and mitigation for RJD were updated (Table 8).

Figure 44. *Drill rig "Nasi" operated by RSFS (picture taken in June 2019 during RJD operation).*

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Figure 45. *BHA consisting of de-centralizers and a deflector shoe (pictures by WSG onsite in June 2019).*

Figure 46. *WSG's coil unit and control unit (picture taken in June 2019 during RJD).*

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Figure 47. *WSGs coil and control unit running in hole through injector held up by a crane (picture taken in June 2019 during RJD).*

Figure 48. *Drill rig Nasi, WSG coil unit and ÍSOR logging truck (picture taken in June 2019 during RJD).*

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Table 6. *Operation plan highlights for field test in June 2019.*

Well name	HN-13.
Location	Botn, Eyjafjörður, N-Iceland.
Coordinates	65.56398, -18.10453 (65°33'50.3"N 18°06'16.3"W).
Well diameter	10 inch down to 650 m, 8½ inch 650 – 1389 m (refer to caliper log in appendix).
Target depth	**956-963.5 m** from surface.
Target directions	Laterals jetted at 45-90° intervals.
Measure of success – 1	Laterals can be jetted and coil pulled out with ease.
Measure of success – 2	Flow measurement shows improved flow out of the well. The well will be self-flowing as pumping from nearby wells will be stopped and approximately 1-2 bar overpressure builds in that well. Improvements should therefore be clearly visible by increased flow out of the well.
Measure of success – 3	Post-operation flow testing shows increased flow when compared to pre-operation flow tests.
If improvements?	Continue to jet laterals to the direction where previous lateral gave improved flow out of the well at various depths.
Operation sequence	11. Pre-operation flow testing – done (see Figure 19) 12. RFS set up drill rig (to be available on 24.06.2019) 13. WSG/RFS make up BHA and install deflector shoe at predefined depth within defined target depth. 14. RFS pump water through drill string to cool the well. 15. ÍSOR run gyro for initial orientation of the deflector shoe. 16. WSG run in jet/coil, jetting of lateral. 17. Coil pulled out of hole 18. Flow measurements on surface. 19. Deflector shoe repositioned, direction and/or depth. 20. Iteration of steps 4-9. 21. Post-operation flow testing. Televiewer imaging of the wellbore.

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Before running in with the coil, directions were confirmed by gyroscope logging conducted by ÍSOR. The primary directions chosen were NE (45°) and E (90°), and secondary directions were N (0°), SE (135°), SW (225°) and NW (315°). The primary target depth was chosen as 956-963.5 m (from surface). The total number of attempts were 28 at 8 different depths and 6 planned directions. The RJD operation began on June 24th, 2019 and concluded on July 5th 2019. While jetting into the inter-basaltic layer, indications on surface suggested that successful laterals were jetted (runs 1-11 in Table 7). However, difficulties followed while jetting into the harder basaltic formations, where indications on surface suggested that the wellbore was not penetrated. Unfortunately, there was no independent equipment to confirm if laterals were jetted or not. The only indication on surface was with weight balance of the coil system and monitoring of temperature changes of the returning water.

Table 7. *Overview of attempted lateral runs according to depth and weight control of WSG's coil equipment.*

Depth:	Direction:	Length:	Run nr:
958	90°	100m	1
958	45°	99m	2
958	135°	99m	3
958	225°	99m	4
958	315°	99m	5
957	315°	99m	6
957	0°	99m	7
957	45°	98m	8
957	90°	97m	9
957	135°	97m	10
957	225°	97m	11
997	45°	0m	12
997	90°	0m	13
958.5	0°?	0m	14
798	180°?	0m	15
798			16
698			17
957			18
957			19
1023			20
1023			21
1023			22
1023			23
738			24
738			25
738			26
738			27
738			28

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In run nr. 12 the problems were first noticed when the coil could be run in hole without pumping, clearly indicating that a lateral was not being drilled. Initially this was interpreted as the hose being run into the wellbore due to too much space between the wellbore wall and the deflector shoe, i.e. not being able to initiate a hole in the borehole wall. Runs 13-26, all aimed at fixing the problem by modifying the deflector shoe and centralizers as well as selecting depths where the wellbore was smooth and circular. A caliper log was performed to ensure that the wellbore shape was optimal where the RJD was to be tested. To check the status of the well to confirm if laterals were successful or not, a video log was done between runs 23 and 24. However, dirt in the well inhibited clear view.

A final test was done by WSG (runs 27-28), where a nozzle on the hose, not able to pass the deflector shoe was used. Despite this, WSG were able to RIH after tagging the shoe. WSG concluded that this meant that the coil connector was able to run past the hose within the drillpipe (the coil system is made of the coil, coil connector to hose, 100 m of high pressure hose and a jetting nozzle). Such internal diameters (2.4″ ID) have not caused problems with jetting for WSG in the past, but the combination of the hard formation and the bigger inner diameter is believed to have caused this problem. The time-consuming troubleshooting with the assumption of an offset between the deflector shoe and the formation later turned out to be not the actual cause of the jetting problems. Therefore, time for further attempts was out and the operation was discontinued. At that point, the chances that laterals were jetted in the softer formations at the main target depth were still believed to be possible but would need to be shown by testing and/or a camera run afterwards (discussed below). A production test of HN-13 was done by monitoring free inflow into the well, further discussed below. A camera run, made three weeks after the RJD was finished to allow the well to clear itself, showed that no laterals were drilled in the operation. The technical difficulties show that further work is needed to advance RJD in geothermal wells in magmatic environment where hard rock formations are found.

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Table 8. *Risks and mitigation for RJD – update for the 2nd field test. Risk R2 materialized in the field test trial in October. Added risks R6 and R7 are derived from R2.*

ID	Risk	Consequence	Probability	Impact	Mitigation remarks
R1	Installation of deployment shoe unsuccessful	RJD cannot be performed	Low	High	Change in position of deployment shoe
R2	Deployment shoe lost in hole	Restriction in well	Low	Medium	Fishing by conventional means
R3	Target zone cannot be penetrated	Too hard material/too little pressure delivered to nozzle	Medium	High	Change in position/azimuth of deployment shoe
R4	Contamination of cuttings in nearby wells	Clogging of feed-zones	Low	High	Reduce flow from nearby wells during operation
R5	Coil/hose stuck in lateral hole	Coil/hose partially lost in hole, well clogged with equipment, operation cannot continue	Low	Low	Hose sheared and left in lateral hole
R6	Fishing unsuccessful	Fish blocks the well at ~750 m	Medium	Low	Fish pushed down to narrowing at 1400 m
R7	Fish cannot be pushed down	Target depth at ~950 m cannot be reached	Low	Medium	Layers at ~600-750 m targeted

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5. Testing the effect and sustainability of a stimulation treatment by RJD

The effect of stimulation by RJD was tested by measuring inflow into the well by free recharge. In September 2018, prior to the field test operation the baseline of inflow into the well was measured as 0,2 L/min after 25 hours of free recharge (Figure 19). Same measurements were repeated after the second RJD operation in July 2019 (Figure 49). Unfortunately, the results showed no measurable increase in productivity from the well. Comparison between the two is shown in Figure 50. Efforts based on monitoring the long-term sustainability of the performance increase were therefore obsolete.

Video log was conducted on 12 August 2019 to confirm if any laterals were jetted in the operation. Depth intervals of interest where jetting trials were carried out, listed in ***Table 7***, were thoroughly investigated. No indications of jetted holes were found, only scratches on the wellbore wall made by the deflector shoe that pushed up against the wall. Snapshots from the video log are shown in Figure 51 and Figure 52.

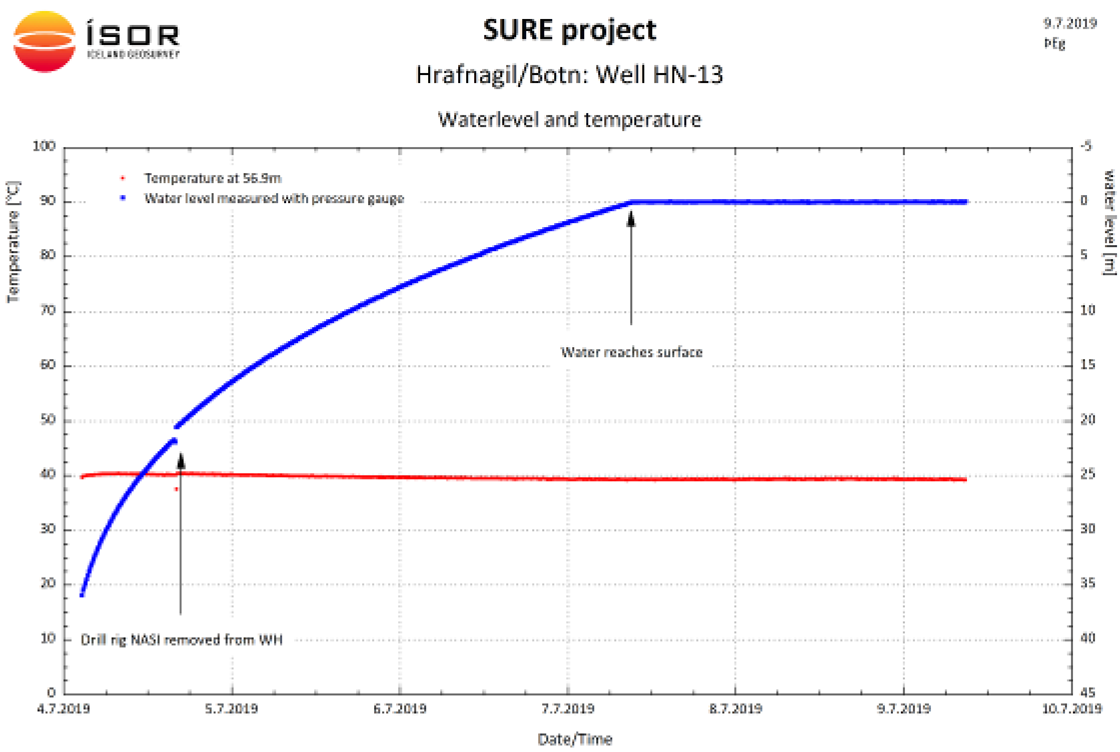

Figure 49. *Water level and temperature measurements in HN-13 after RJD operation.*

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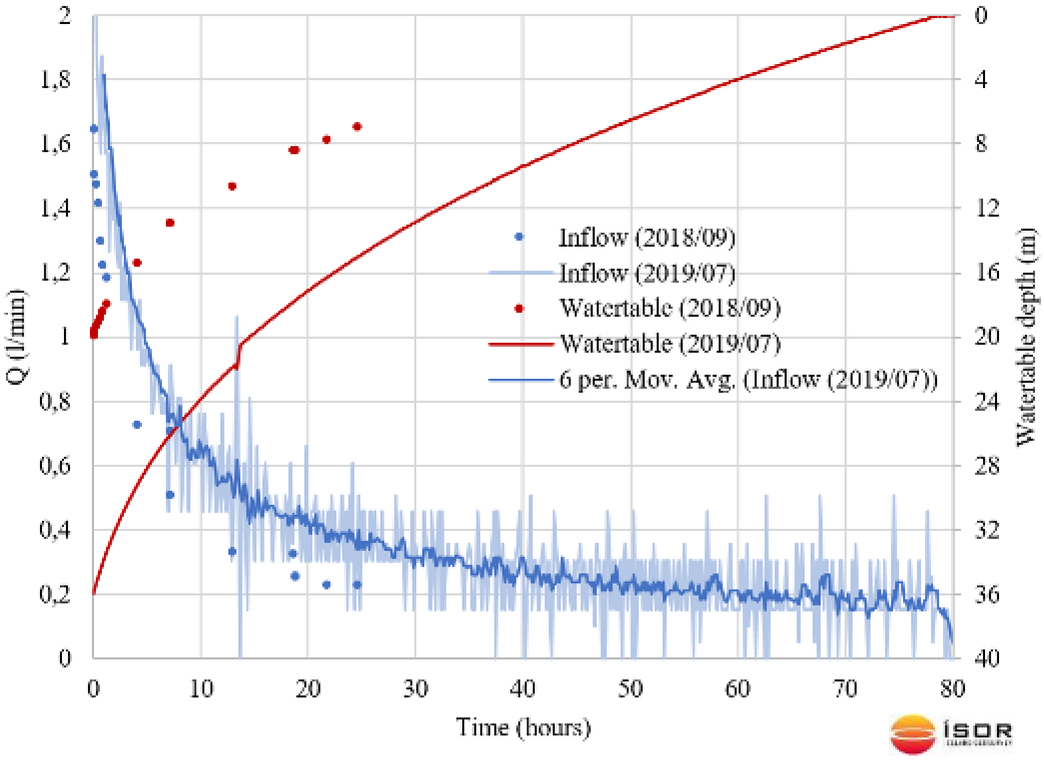

Figure 50. *Production tests of HN-13 by free recharge. After pumping out water until the water level was at 20 m depth after 2.5 hours of pumping (September 2018) the well was far from being productive with inflow less than 0.2 l/m (Vilhjálmsson & Tryggvason, 2018). Continuous production monitoring (July 2019) with a pressure gauge at 56,9 m depth done after jetting field test showing no improvements in inflow (Egilsson, 2019).*

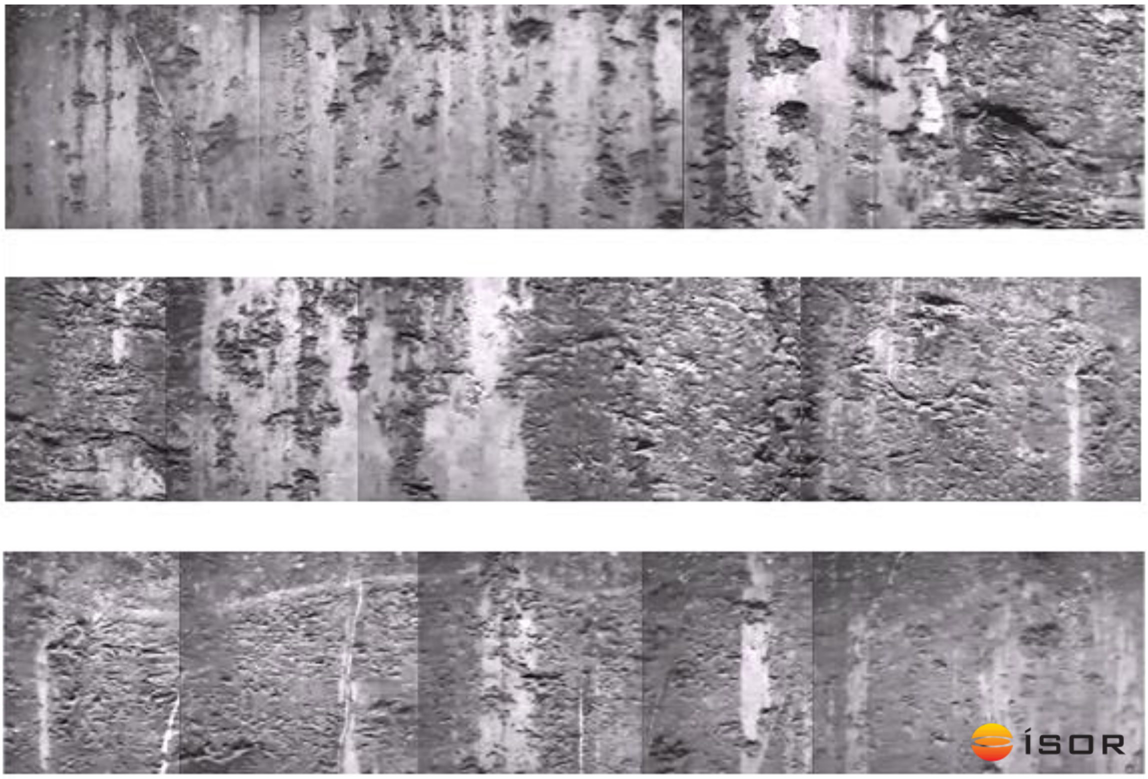

Figure 51. *Snapshots from video log in HN-13 at 958 m depth circumference showing scratches from the deflector shoe but no holes are visible (video log from 12 August 2019). Main zones of interest listed in* **Table 7** *were thoroughly investigated and no holes from RJD found.*

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DOI: 10.2312/gfz.4.8.2019.013

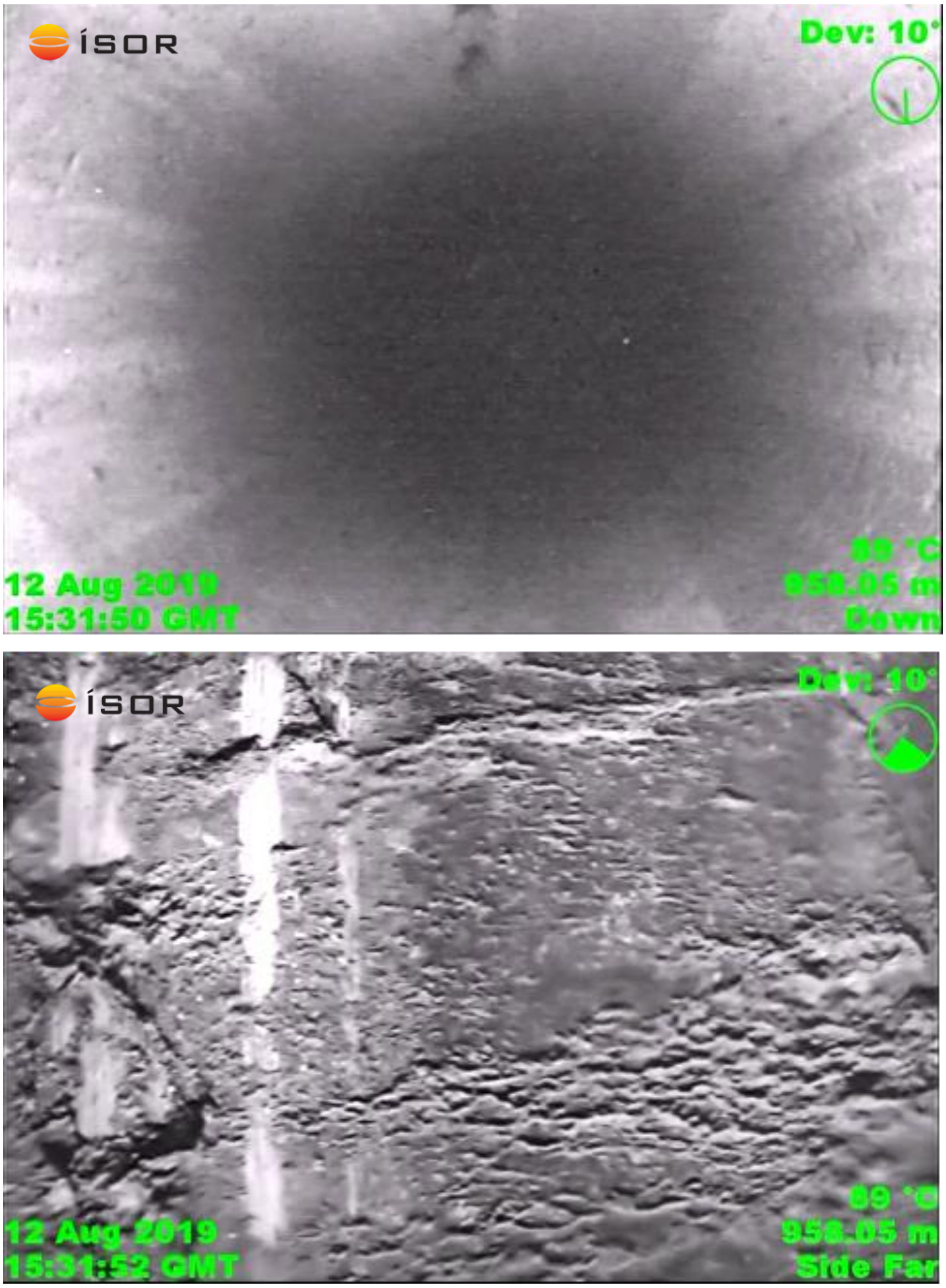

Figure 52. *Snapshots from video log in HN-13 at 958 m depth with no jetted holes visible (video log from 12 August 2019). Main zones of interest listed in* **Table 7** *were thoroughly investigated and no holes from RJD found.*

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6. Conclusions

The site characteristics of well HN-13, drilling data, wireline data, geological model, RJD targeting, risk evaluation and radial jet drilling operation in the well are described in this deliverable. Since jetting into the most common rock type, basalt, was not shown to be feasible, a target depth was selected where an interbasaltic layer sits in the well at 956-963.5 m depth (measured from ground level). Multidirectional laterals at 45-90° intervals and at various depths within the target depth were proposed along with targets dircetly aimed at jetting into basalt. Radial Jet Drilling (RJD) field tests were described. The well, HN-13, was selected as it was a non-producer sitting in between two productive wells that are used for district heating in the neighbouring communities. Due to the known baseline of low inflow into the well, it was an excellent candidate to test the stimulation technique. However, the RJD field test that was conducted in June-July 2019 did not show improvements of inflow into the well. Video logging showed that jetting laterals during the operation had been unsuccessful, showing no indications of jetted holes in the well. The cause for this is suspected to be a combination of the jetting equipment and the hard formations found in the well. Further work is needed to advance RJD in geothermal wells in magmatic environment where hard rock formations are found. Mapping the drilled laterals would give confidence in the method and feedback for further targeting during jetting operations. If the technology can in the future be implemented successfully in magmatic environment, a huge potential still exists for stimulation of low temperature geothermal wells in Iceland.

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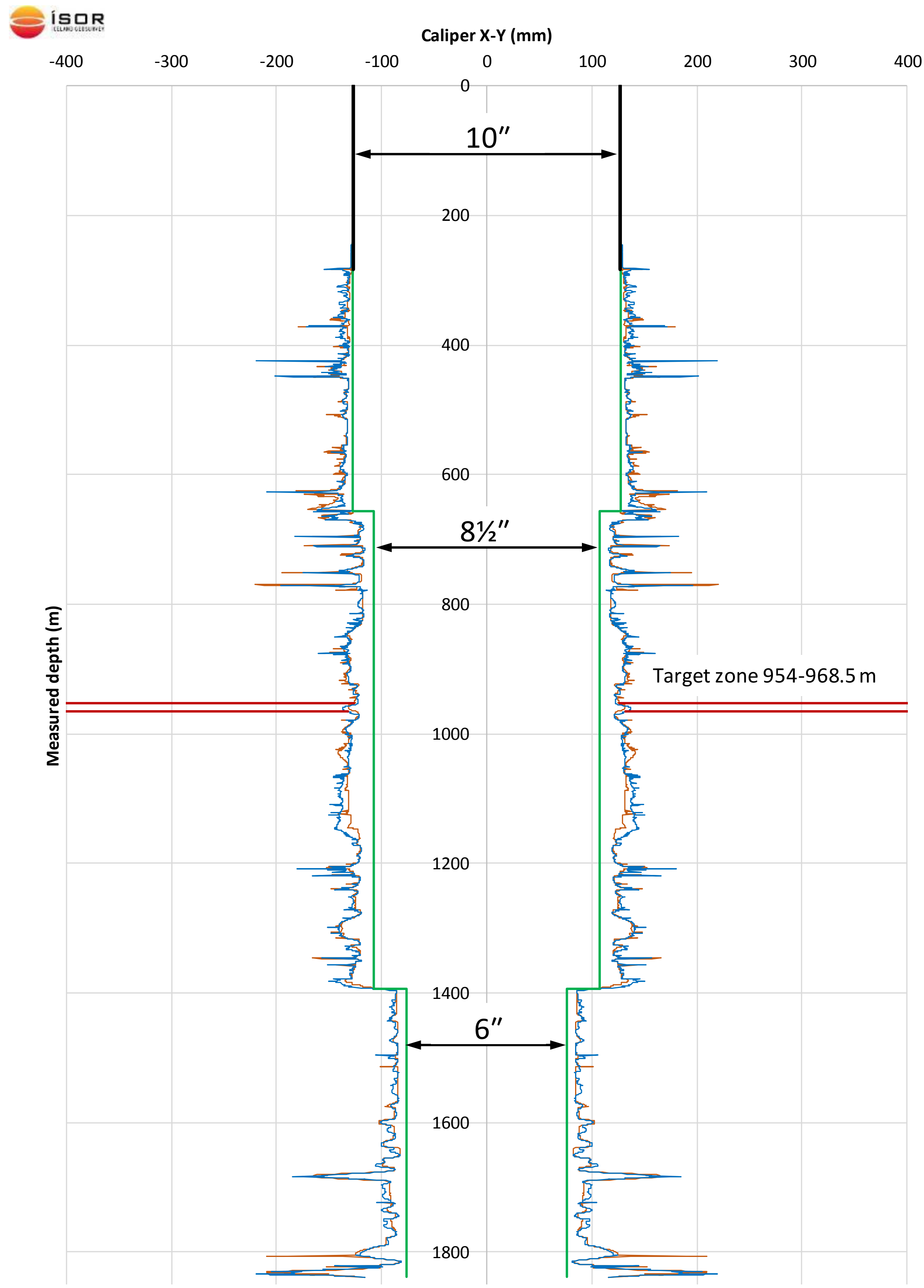
Appendix – Caliper log



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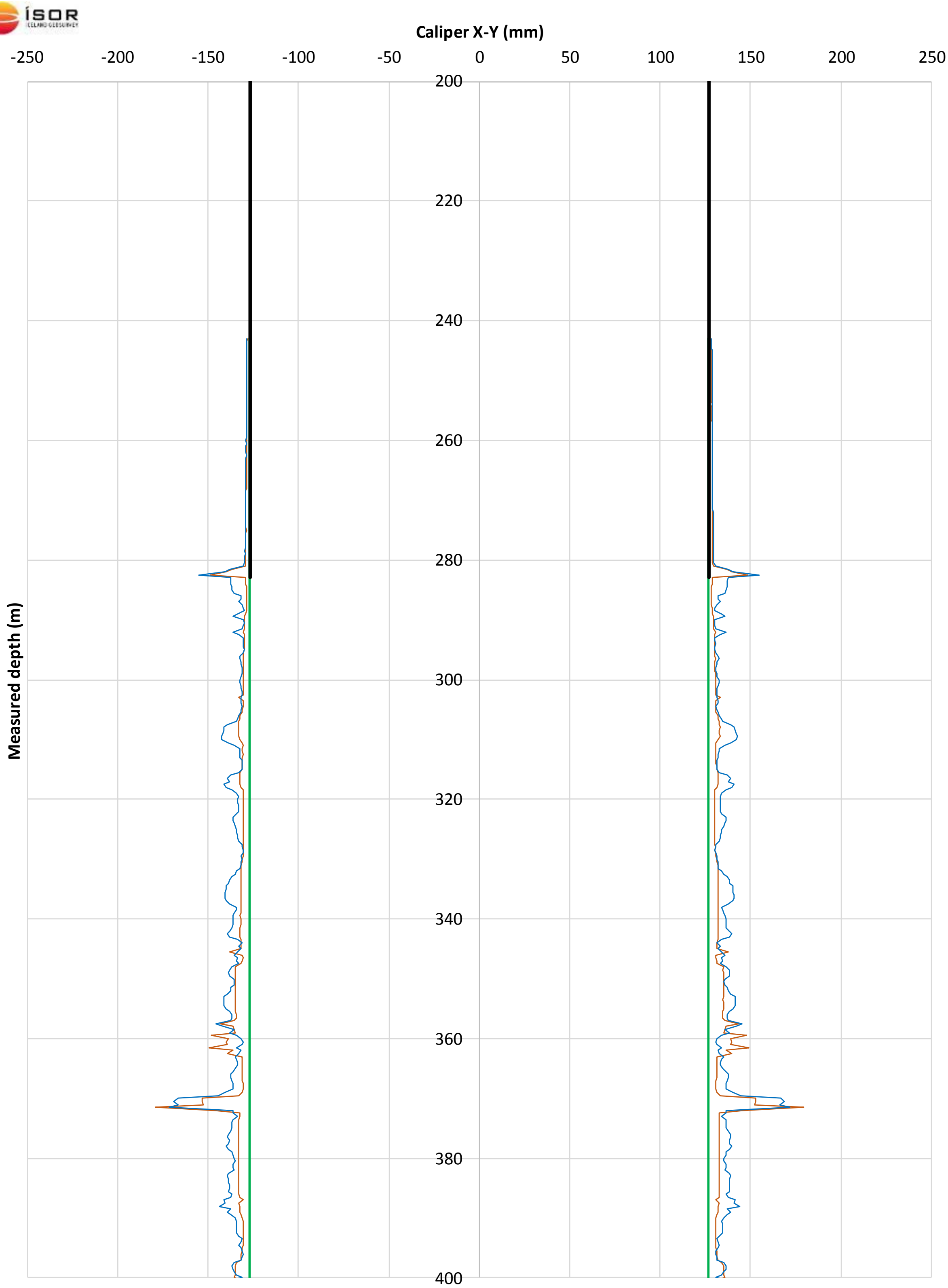

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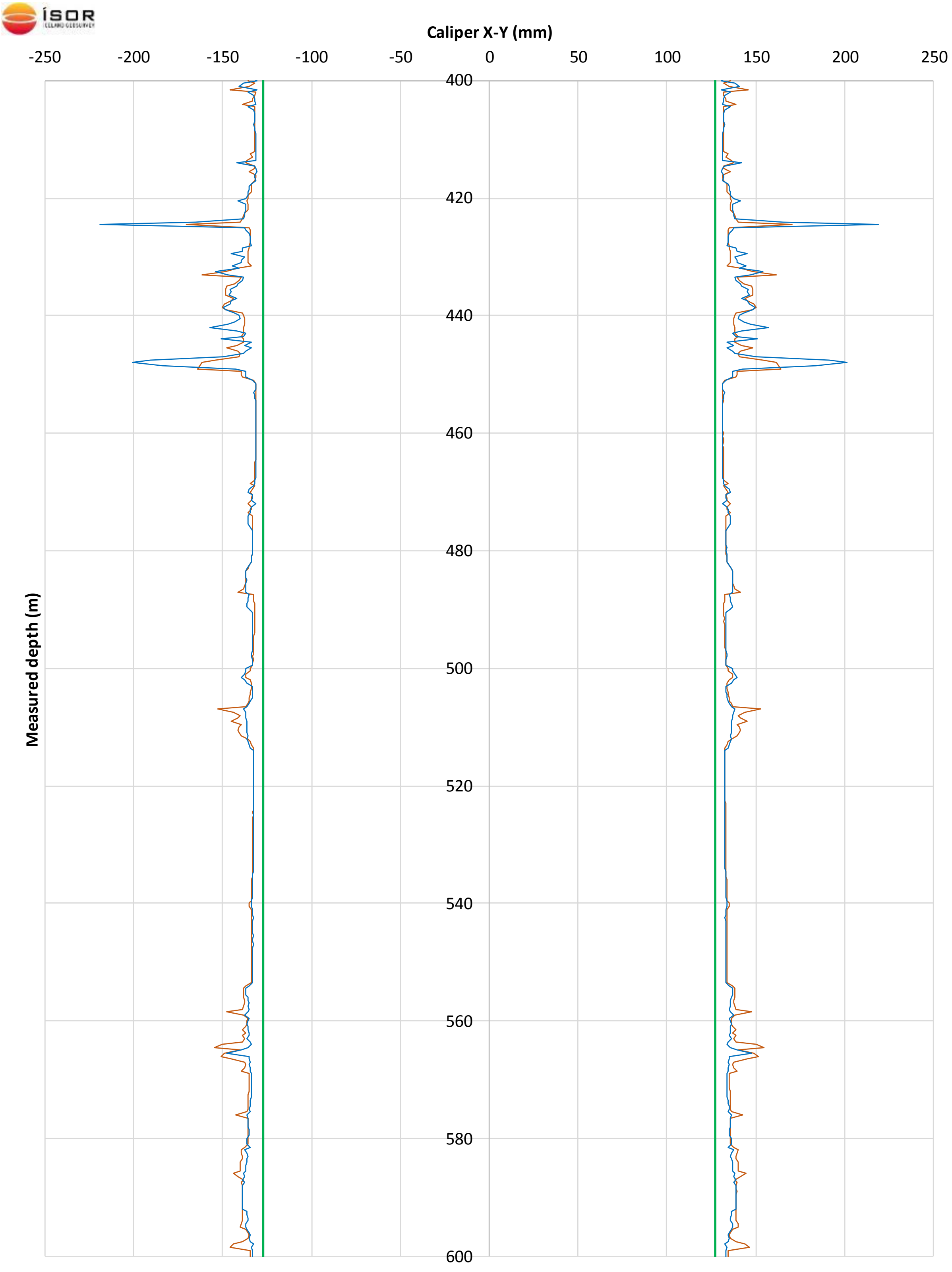

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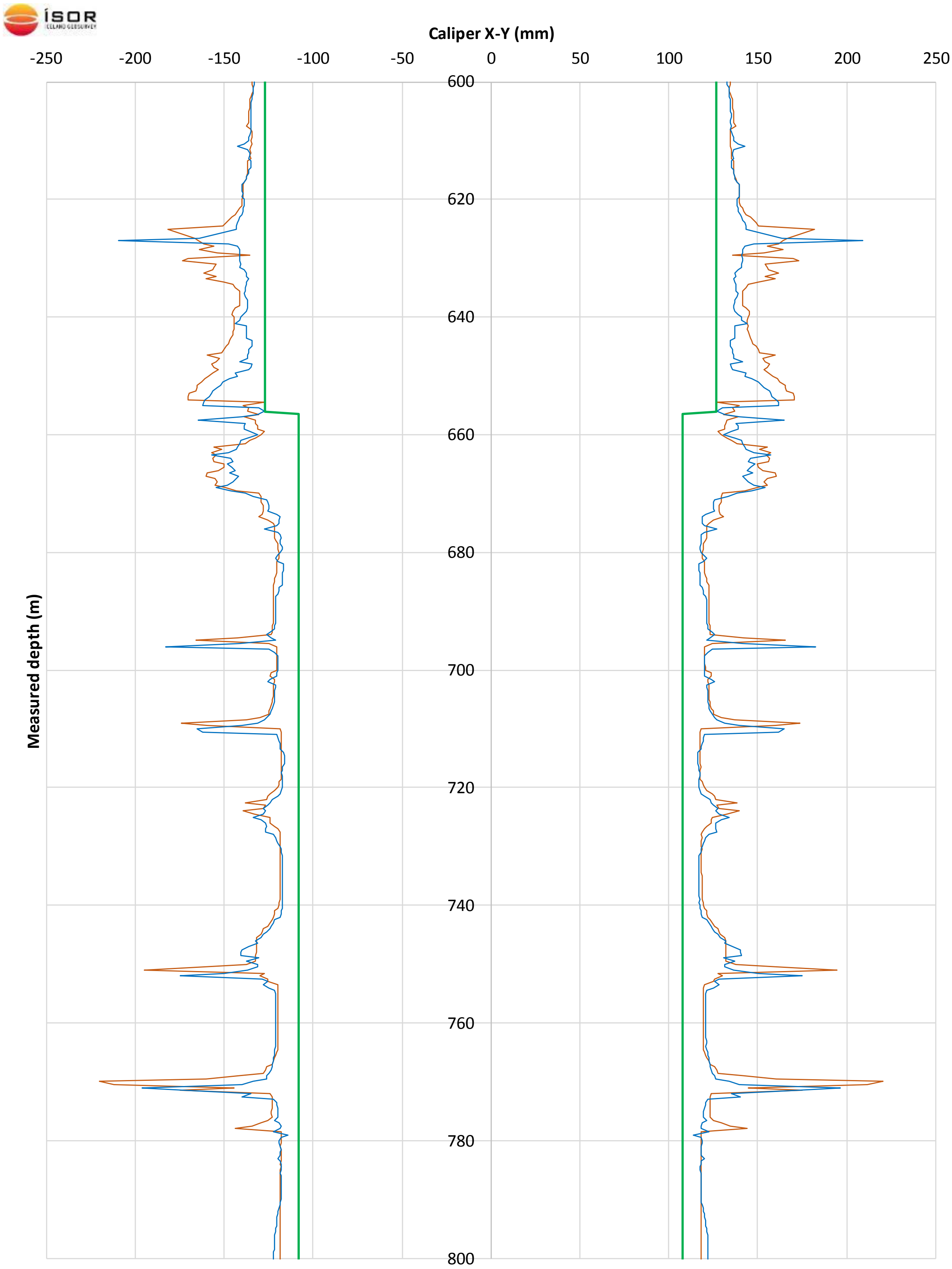

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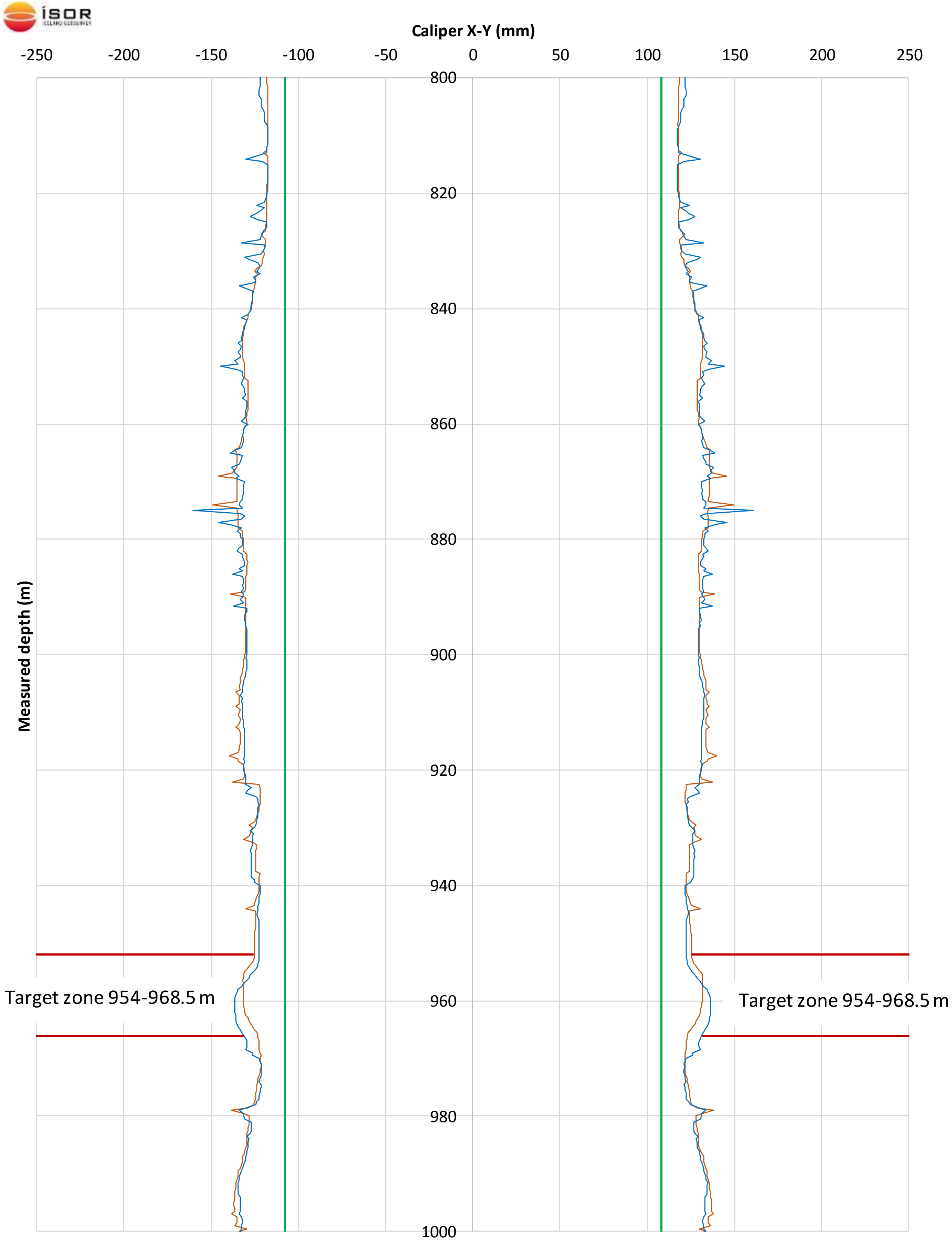

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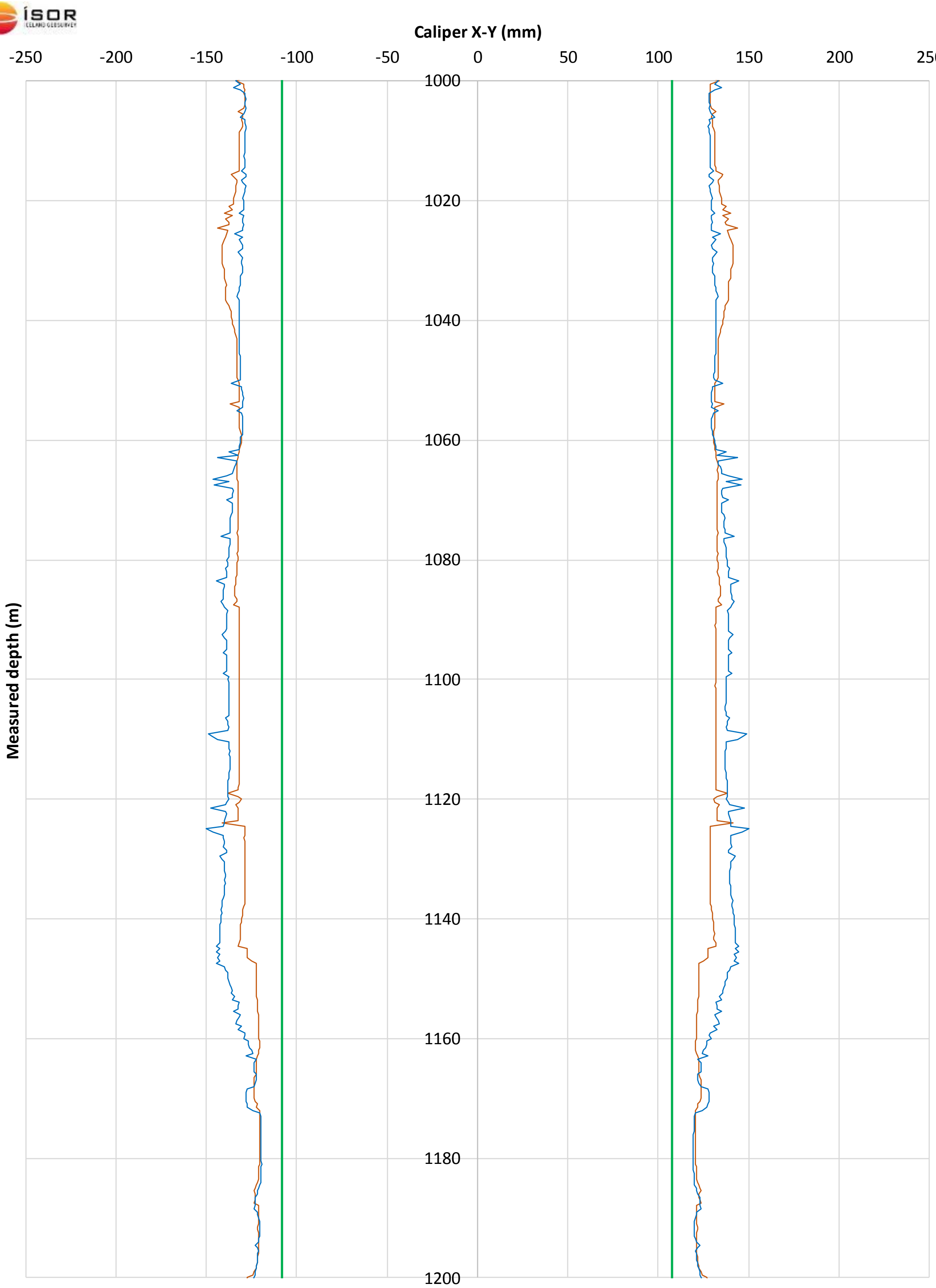

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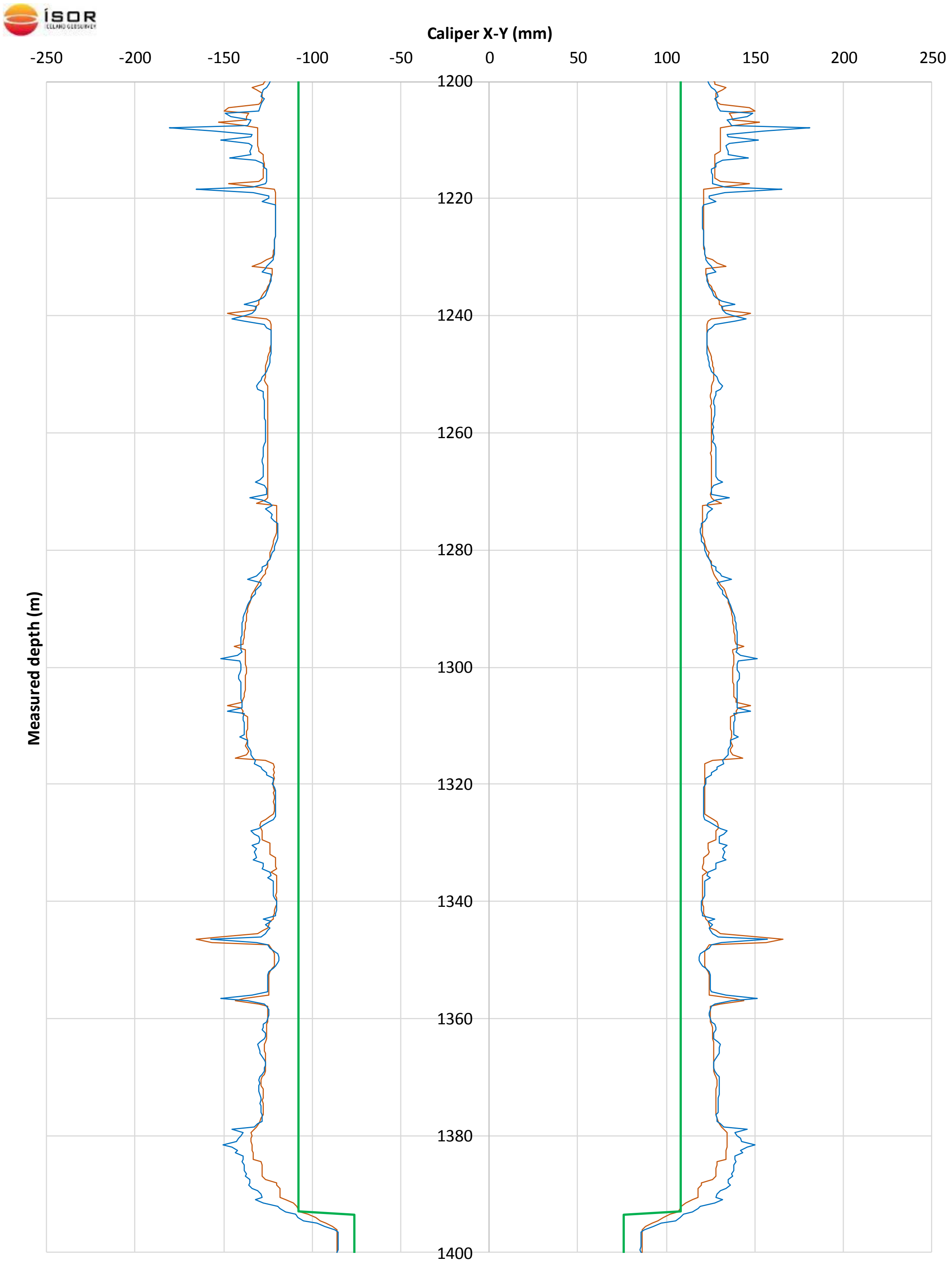

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Appendix – HN-13 Integration of Sonic Log (memo)

F. Kästner

Sonic log data were recorded in well HN-13, on December 13, 2016, using the Robertson Geologging Full-Waveform Sonic Sonde (RG-LSS). Data were recorded from 1900 m depth up to 265 m, while logging up. Together with the full-waveform data, natural gamma ray (GR) and spontaneous potential (not shown) were logged with this sonde. The line speed was about 7-8 m/s with some minor fluctuations. Transit times (DT) for the compressional (P) waves were determined and corrected for borehole effects by the acquisition software, during recording. The borehole-compensated transit times (DTC) were used to calculate the interval P-wave velocities of the surrounding rock formations (vP). Additionally, in a preliminary attempt, transit times and natural gamma radiation were used to estimate formation properties such as porosity (sPOR) and matrix density (RHOm), respectively. The porosity or apparent porosity was determined by applying the Wyllie's time-average equation (Wyllie et al., 1956). Therefore, a limestone matrix velocity of 6.4 km/s (47.6 µs/ft), a basalt matrix velocity of 5.3 km/s (57.5 µs/ft), and a fluid velocity of 1.6 km/s (189 µs/ft, corresponds to water with 125000 ppm of NaCl) were chosen. The results show similar apparent porosities with an average of 9 percent and generally lower values with the basalt matrix velocity as with the limestone matrix velocity. Furthermore, the matrix density was determined using the relation by Jónsson and Stefánsson (1982), who made density and porosity estimations from the IRDP hole, in Iceland. The matrix density was calculated for two gamma logs, which were logged with the Robertson Geologging (LSS) and the Hot Well (HW) tool, respectively.

It must be noted that the calculated formation properties are a first approximation based on empirical relations, inherently including uncertainties due to its strong simplification. Especially where the sonic data is noisy, porosities can be estimated too high or too low (even below zero). This is mainly caused by falsely picked first-arrival times, which lead to incorrect transit times and, consequently, to wrong porosities. Another reason is the constant matrix velocity used, which changes for different formation. However, latter one may be neglected since most of the present rocks are basaltic.

The attached composite log combines previous well logs (GR, caliper, neutron-neutron (NN)) with the sonic data (DTC, waveforms) and its derived parameters (vP, sPOR, RHOm). Additionally, zones of soft formations determined from previous logs were reevaluated and integrated into this composite log (see „Soft. Form.“ column, green: from previous log analyses, yellow: from integrated sonic). The highlighted zones are also indicators for potential jetting targets (cf., „Drilling of Well HN-13 – A candidate for jetting within the SURE project“, Gautason et al., 2017[1]). A summary of the used parameters is given in **Table 4**

From 280-500 m, transit times show (i.e., velocities) strong fluctuations indicating alternating rock formations. Between 780 and 1160 m, a distinct, very tight and homogenous formation can be seen throughout all logs, with P-wave velocities of about 5.8-6 km/s. Within this

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formation, a zone of soft sediments is seen between 950-960 m. Due to the thickness (circa 10 m) and high apparent porosity (35-40%) this zone indicate a good target for jetting. Other potential target zones, which have not been detected previously, are at 660-668, 933-937, and 1182-1186 m.

Table 4. Parameters used in the integrated sonic composite log.

Name	Description	Unit	Remarks
Caliper	borehole caliper	millimeter, mm	averaged from XY-caliper values
Near, Far NN	Near (14.6") and far (26.5") dual-detector neutron	counts per second, cps	
GR	Natural gamma ray	American Petroleum Industry, API	
DTC	Compensated compressional transit times	microseconds per feet, µs/ft	
vP	compressional (P) wave velocity	meter per second, m/s	calculated from transit times: $vP=10^6(DTC/0.3048)^{-1}$
sPOR	apparent porosity	porosity units, p.u.	calculated with Wyllie's time-average equation
RHOm	matrix density	grams per cubic centimeter, g/cm^3	calculated using empirical relation
WVF	full-waveform sonic	microvolts, µV (amplitude)	variable density log for two transmitter-receiver combinations (4 ft and 6 ft)
TT	travel times	microseconds, µs	automatically picked during acquisition

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[1] Preliminary report prepared for SURE (ÍSOR-17030).

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ÍSOR ICELAND GEOSURVEY

HN-13

Tuesday
6. June 2017

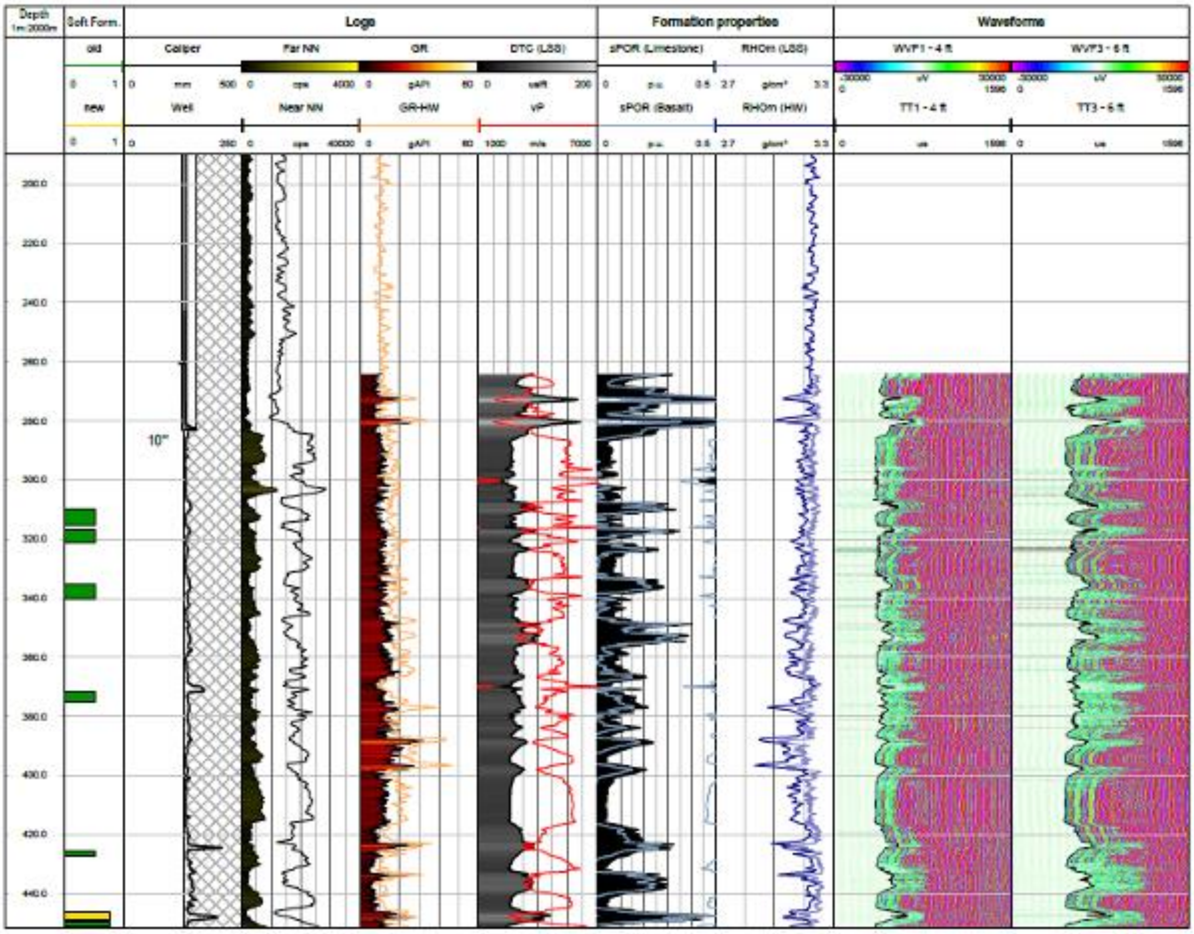
Site : Hrafnagil **54514** **Rig :** Nasi

Customer company : Nordurorka
Drilling company :

Depth interval : 190-1550
Drill bit diameter :

Section :
Drilling fluid :

Staff member :



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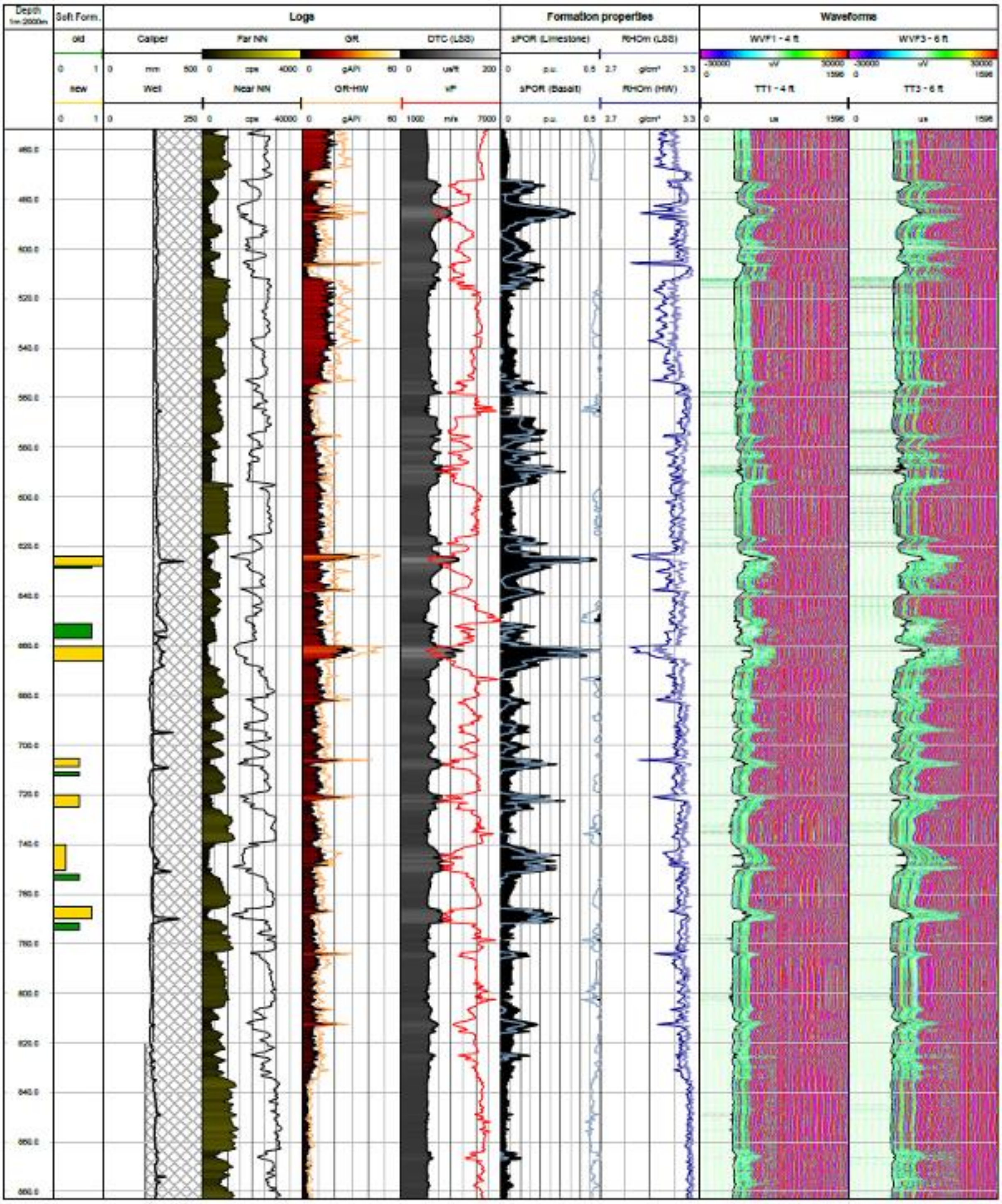

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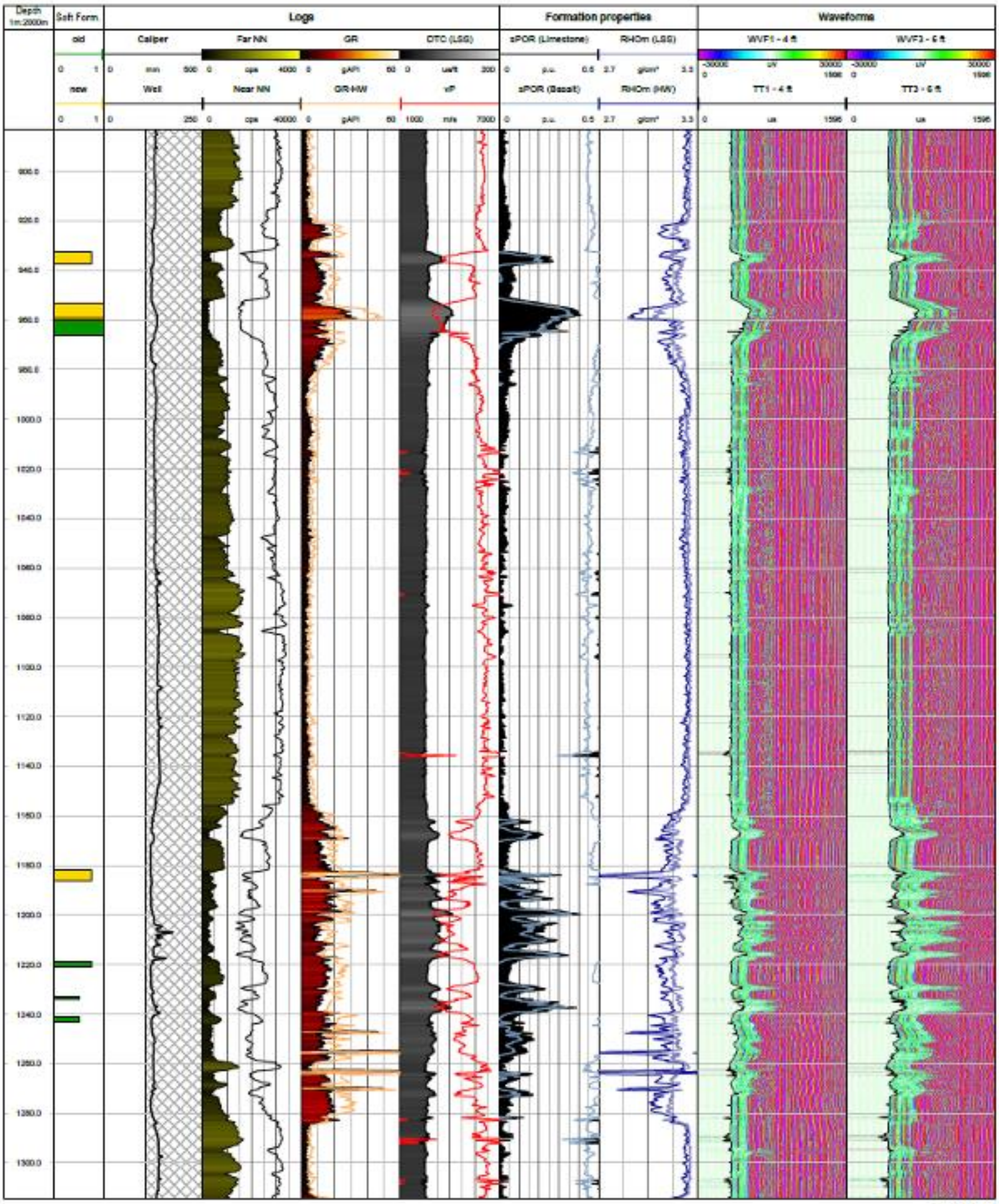

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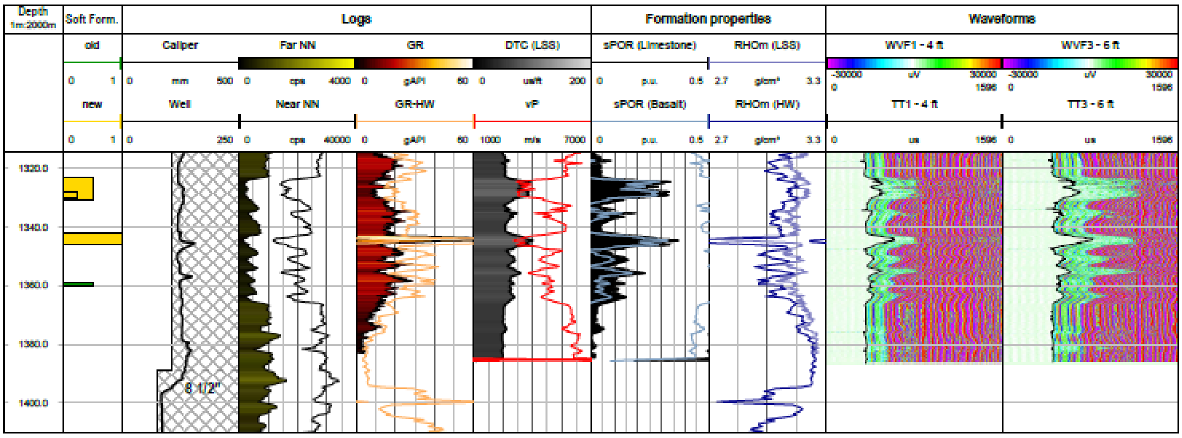

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