Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

The IDDP-2 DEEPEGS Demonstrator at Reykjanes – Overview

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Keywords: DEEPEGS demonstrator at Reykjanes, IDDP-2

ABSTRACT

The DEEPEGS demonstration well IDDP-2, in the Reykjanes high-temperature geothermal field in SW Iceland, achieved several scientific- and engineering firsts. It is the deepest and hottest drill hole so far sited in an active mid-ocean spreading center. The reservoir fluid in the Reykjanes system is modified seawater. IDDP-2 penetrated an active supercritical hydrothermal environment at depths analogous to those postulated as the high temperature reaction zones feeding black smoker systems. IDDP-2 was drilled to a total depth of 4,659 m and cased with a production casing to almost 3 km depth. The well was angled towards the main up-flow zone of the Reykjanes geothermal system, so its vertical depth is about 4.5 km. Based on alteration mineral assemblages, joint inversion of geophysical data, and the rate of heating measurements, the bottom hole temperature appears to be 550-600°C.

The DEEPEGS project received funding from the European Union's Horizon 2020 Research and Innovation Programme with the principal aim of demonstrating the feasibility of Enhanced Geothermal Systems (EGS) to deliver renewable energy in Europe. The DEEPEGS aims to test stimulation technologies for EGS in deep wells in different geological settings, a high enthalpy system at Reykjanes with temperatures up to 550°C, and in two deep hydrothermal reservoirs in southern France with temperatures up to 220°C. For local administrative reasons only one French demonstration site could be drilled, located in Vendenheim, NE-France.

A major problem encountered during drilling the IDDP-2 well in 2016-2017 was total loss of circulation below 2.5 km depth that continued to the final depth. After cementing the production casing at 2.941 m depth, total circulation losses continued despite 12 attempts to plug the loss zones with cement. At 3.2 km depth the operator abandoned the plugging attempts and drilled blind to the total depth. The deep feed zones indicate that the Reykjanes conventional reservoir needs be enlarged by at least 1 km downwards, from about 3 km down to ~4 km depth, which is a major achievement by the deep drilling. Some drill cutting samples were retrieved from the interval immediately above and below the production casing but drilling the remainder of the well proceeded without recovering any drill cuttings. The only rock samples recovered from the well came from 13 spot coring attempts. These cores are characteristic of a basaltic sheeted dyke complex, with hydrothermal alteration mineral assemblages ranging from greenschist to amphibolite facies, enabling investigation of water-rock interaction in the active roots of an analogue to submarine hydrothermal systems. Petrological and fluid inclusion studies imply that the current bottom hole temperature is likely to be close to 600°C.

Earthquake activity monitored with a local seismic network during drilling of the deep well detected abundant small earthquakes (M_L ≤ 2) within the depth range of 3-5 km. A zone at 3-5 km depth below the producing geothermal field, generally aseismic prior to drilling, became seismically active during the drilling.

The total loss of circulation throughout the drilling and subsequent 1.5 year of re-injection tests demonstrate that an EGS system would be created with further reinjection into the 400-600°C hot environment. During the stimulation and injection test the production casing was damaged between 2,307-2,380 m depth, presumably due to cyclic heating-up and cooling of the casing, and the lowest part of a 4.5 km long stimulation pipe suffered from some corrosion. Attempts to inject chemical tracers were not as successful as anticipated, but regular chemical monitoring of neighboring wells showed clear dilution of the geothermal brine from the freshwater used during drilling and subsequent injection and stimulation tests.
A flow testing experiment was planned to begin in April but was delayed until late summer 2019. Its purpose is to find out if the deep fluid can be used directly use to produce electricity, with or without chemical mitigation, and/or for other geothermal uses in the Reykjanes geothermal resource park. The other option is to use the well for deep re-injection to mine heat from the root zone of the Reykjanes geothermal reservoir and result in an EGS system, to improve the performance of the overlying geothermal reservoir.

This DEEPEGS demonstration well is in an operational environment at precommercial scale, operating at TRL 7 level as all the infrastructure needed is already installed at the Reykjanes power plant. The resulting business model may bring the DEEPEGS concept to TRL level 8-9, depending on the result from the flow test and pilot study.

1. INTRODUCTION

The IDDP is a long-term project (www.iddp.is) aimed at greatly increasing the production of usable geothermal energy by drilling deep enough to reach the supercritical conditions believed to exist beneath high-temperature geothermal fields in Iceland. When the IDDP consortium was formed in year 2000, three geothermal fields in Iceland were chosen as suitable to search for supercritical resources, Krafla in the north-east of Iceland, and Nesjavellir (within Hengill volcano) and Reykjanes in the south-west (Friðleifsson et al., 2003; Figure 1).

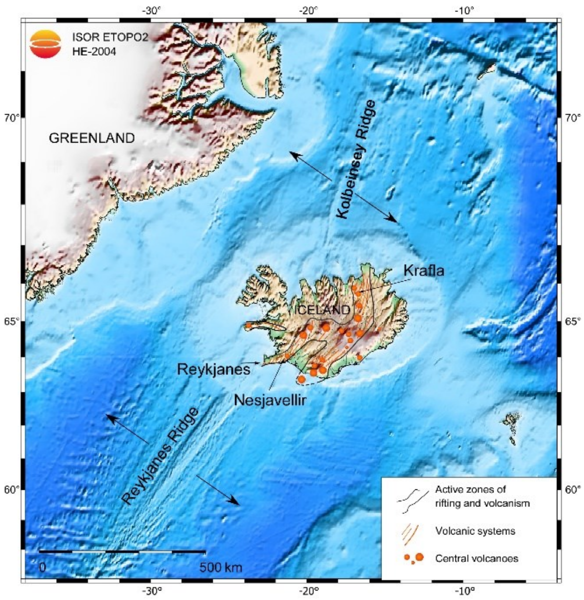

Figure 1: The Krafla, Nesjavellir and Reykjanes systems, chosen for IDDP deep drilling, all rest within the active volcanic rift zone of Iceland, which is a part of the Mid-Atlantic Ridge system.

The first attempt to drill into a supercritical reservoir was made in 2008-2009 in the Krafla caldera, but the IDDP-1 well did not reach supercritical fluid pressures because drilling had to be suspended at only 2,104 m depth after having intersected a 900°C hot rhyolitic magma. The IDDP-1 well was completed with a liner set above the rhyolite intrusion and produced superheated steam at 452°C during a long-term flow test at 140 bar pressure. At higher flow rate (lower pressure) the well proved capable of generating about 35 MWe. After two years of flow testing repair of some of the surface installations was necessary. After series of valve failures cooling the well with cold water proved necessary which resulted in severe casing damages and finally abandonment of the well. A Special Issue of Geothermics, volume 49, January 2014, is devoted to IDDP containing 15 articles, mostly on well IDDP-1 in Krafla (https://www.sciencedirect.com/journal/geothermics/vol/49).

The second attempt to drill into a supercritical reservoir was made in 2016-2017 at Reykjanes, where the mid-Atlantic ridge emerges ashore. That attempt was successful in reaching supercritical conditions at depth, as 426°C at 340 bar pressure was measured during drilling of the IDDP-2 well at about 4,550 m depth (Friðleifsson et al., 2017, 2018). An overview on the IDDP-2 drilling and the main scientific result gathered this far is the topic of this paper, while closer details on the IDDP-2 and the DEEPPEGS project are described in a series of papers in the WGC-2020 proceedings (Albertsson et al., 2020; Bali et al., 2020; Bogason et al., 2020; Bordvik et al., 2020; Darnet et al., 2020; Driesner et al., 2020; Elders et al., 2020; Friðleifsson et al., 2020; Gibert et al., 2020; Guðnason et al., 2020; Haaf et al., 2020; Halldórsdóttir et al., 2020; Ingason et al., a, b, 2020; Jóhannesson et al., 2020; Karlsdóttir et al., 2020; Kruber et al., 2020; Magnúsdóttir and Jónsson, a, b, 2020; Mesfin et al., 2020; Naumann et al., 2020; Níelsson et al., 2020; Óskarsson, 2020; Peter-Borie et al., 2020; Sigurðsson et al., 2020; Sigurðsson, 2020; Stefánsson et al., 2020; Tran et al., 2020; Tulinius et al., 2020; Wang et al., 2020; Weisenberger et al., 2020; Zierenberg et al., 2020; Þorgilsson et al., 2020).

1.1. Short introduction on IDDP

IDDP has the main goal to find supercritical hydrothermal fluids by deep drilling and test the utilization of such fluids which develop in the roots of high-temperature systems in vicinity of cooling magmatic intrusions. Supercritical geothermal wells could produce up to ten times more power than the usual subcritical geothermal wells, which evidently is appealing for the geothermal industry. The IDDP program was established by a consortium of three the largest energy companies in Iceland, Landsvirkjun (National Power Company), Reykjavik Energy and HS Orka (formerly Hitaveita Suðurnesja), and Orkustofnun (National Energy Authority of Iceland). Later Alcoa (international aluminum company) and Statoil (the Norwegian oil and gas company) joined the consortium for several years during the drilling of IDDP-1. And few years later Statoil (now Equinor) joined the consortium again with a contract extending to 2020. Since 2005, the International Continental Scientific Drilling Program (ICDP) and the USA National Science Foundation (NSF) provided grants for scientific coring and academic water-rock studies of drill cores. The ICDP and NSF grants have now been used up while the IDDP consortium continues in its effort and intends to complete flow testing and pilot tests of well IDDP-2 and is already preparing ahead for the drilling of well IDDP-3, which may be drilled after 2020.

1.2. Short introduction on DEEPEGS

The DEEPEGS project received funding from the European Union's Horizon 2020 Research and Innovation Programme with the principal aim of demonstrating the feasibility of Enhanced Geothermal Systems (EGS) to deliver renewable energy in Europe. The DEEPEGS aims to test stimulation technologies for EGS in deep wells in different geological settings, a high enthalpy system at Reykjanes with temperatures up to 550°C, and in two deep hydrothermal reservoirs in southern France with temperatures up to 220°C. For local administrative reasons only one French demonstration site could be drilled, located in Vendenheim, Alsace, NE-France. The present paper only deals with the Reykjanes demonstration site. The DEEPEGS well at Reykjanes is in an operational environment at precommercial scale, operating at TRL 7 level as all the infrastructure needed is already installed at the Reykjanes power plant. The resulting business model may bring the DEEPEGS concept to TRL level 8-9, depending on the result from the flow test and pilot study.

2. THE IDDP-2 DRILLHOLE

IDDP-2 was drilled to a total depth of 4,659 m and cased with a production casing to almost 3 km depth. The well was angled towards the main up-flow zone of the Reykjanes geothermal system, so its vertical depth is about 4.5 km. A major problem encountered during drilling the IDDP-2 well in 2016-2017 was total loss of circulation below 2.5 km depth that continued to the final depth. After cementing the production casing at 2,941 m depth, total circulation losses continued despite 12 attempts to plug the loss zones with cement. At 3.2 km depth the operator abandoned the plugging attempts and drilled blind to the total depth. During drilling 426°C at 340 bar pressure had been logged at 4550 m depth, which truly represent supercritical condition (Friðleifsson et al., 2017a). Some drill cutting samples were retrieved from the interval immediately below the production casing but drilling the remainder of the well proceeded without recovering any drill cuttings. The only rock samples recovered from the well came from 13 spot coring attempts. These cores are characteristic of a basaltic sheeted dyke complex, with hydrothermal alteration mineral assemblages ranging from greenschist to amphibolite facies, enabling investigation of water-rock interaction in the active roots of an analogue to submarine hydrothermal systems. Petrological and fluid inclusion studies imply that the current bottom hole temperature is likely to be close to 600°C (Zierenberg et al., 2020; Bali et al., 2020). Joint inversion of geophysical data, and the rate of heating measurements had suggested the formation temperature the bottom hole temperature might be close to 500°C (Hogstad and Tanavsuu-Milkeviciene, 2017; Tulinius 2017). Petrological and fluid inclusion studies imply that the current bottom hole temperature is likely to be closer to 600°C (Zierenberg et al., 2020; Bali et al., 2020).

2.1 Siting of the IDDP-2 drillhole

The most feasible target for the IDDP drillhole at Reykjanes was originally proposed in 2003 to be close to well RN-12, in the IDDP Feasibility Report (Friðleifsson et al., 2003). A decade later this was re-evaluated including data from many additional drillholes and described in the special IDDP issue of Geothermics (Friðleifsson et al., 2014), again a site close to well RN-12. At that site we assumed that a new well of similar design as IDDP-1 would be drilled. HS Orka, after considerable evaluation, decided to offer well RN-15 for deepening as a "well of opportunity" for IDDP-2. This was accepted with the condition that the well would be directionally drilled southwestwards towards the center of the up-flow field, passing a great depth between RN-11 and RN-12 which both are good production wells. The drilled well path is shown on Figure 2, which also shows the location of the main feed points and the location of other production wells like RN-11 and RN-12.

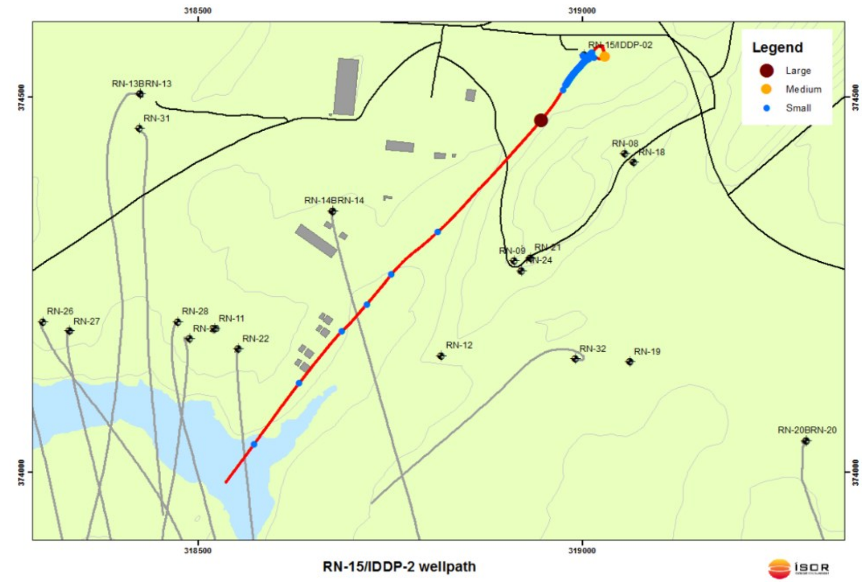

Figure 2: The IDDP-2 well involved deepening of production well RN-15, from 2.5 km depth to 4650 m depth. It was drilled southwestwards (red line) with a KOP (kick-off point) at 2,750 m to 4,650 m length from wellhead. The true vertical depth is close to 4,5 km. Circulation loss points (feed points) are marked with circles colored blue, yellow and brown, for small, medium and large feed points respectively. The location of production wells, like RN-11 and RN-12 is also shown on the map. (map in Weisenberger et al., 2017)

2.2 Drilling the IDDP-2 demonstration well

The preparation for the RN-15/IDDP-2 drilling started at full force in December 2015 by ordering the wellhead valves, casings, casing accessories and other drilling materials. Negotiations with Iceland Drilling as the drilling contractor began January 2016, and a day rate contract was signed shortly later. The drill rig Þór (Thor) 350Hp Bentec rig was to be used for the drilling of the well (Figure 3). After slowly cooling the RN-15 well down, the first drilling operation was to deepen it from 2,500 m depth, with 12 ¼" rotary assembly, to about 3,000 m. An anchor casing (9 7/8" and 9 5/8") should follow and be cemented to surface. Thermocouple cables, from surface to about 2,700 m, a strain gauge (0–26 m) and a fiber optic cable (0–900 m) were to be strapped to the outside of the anchor casing string. An inclination to about 20° max, was to be built up for southwestward drilling (210°) from a KOP at 2,750 m depth. 20° inclination should be reached at about 3,100 m depth (MD). From 3,100 m Azimuth and Inclination should be kept (Hold drilling). The plan was to have the MWD tool in the drill string during the Hold section until its temperature limit was approached. The plan was then to drill to target depth of 4,500 m to 5,000 m with a conventional hold assembly, preferably including high temperature downhole motor. During the drilling from ~ 3,100 m depth to the bottom, around 15-20 spot cores were planned to be drilled at regular intervals. A 7” perforated liner was then to be set from 2,970 m to TD. Thereafter a 7” production casing (sacrificial casing) to be RIH from top to about 1,300 m depth, and cemented in. The drilling operation was to be completed by RIH with 3 ½” drill string which should be left at bottom for post drilling soft hydraulic stimulation. Estimated overall timing for the drilling operation was 151 days.

Figure 3. Drilling rig Þór (Thor) at RN-15/IDDP-2 drill site at Reykjanes (photo TBW)

Most of the drilling operation proceeded according to plan. The operation took 168 days, the final depth was 4,659 m from rig floor, the KOP was at 2,750 m. The casings were set as planned and cemented in. The thermocouple cables with 9 sensors and a fiber optic cable were fasten to the outside of the production casing and cemented in. 13 core drilling trips were made with relatively poor recovery to begin with. Altogether some 27.3 m of cores were retrieved, 3 the most successful ones, 22,61 m, retrieved from the very bottom of the well with a 6” core bit on a 3 ½” drill string. The inclination of the well built-up increase was about 3° per 100 m between KOP down to ~3,638 m. From there down to ~4,282 m, the inclination stayed almost constant between 28-30°, while in the lowermost section the inclination increased sharply to a maximum of about 40° towards the bottom. The azimuth value shows a general trend towards 220° SW. The increased inclination as well as multiple drilling problems called for the end of drilling at 4,659 m depth below the rig floor.

An overview on the IDDP-2 drilling procedure is presented here while more detailed descriptions can be found elsewhere (Stefánsson et al., 2017, a, b, and 2020; Weisenberger et al., 2017).

2.2.1 Rotary drilling

On August 11th, 2016 the deepening of well RN-15 began. Known loss zones where located between 1,400 m to 2,400 m depth in the production section of well RN-15. Therefore, a total loss of circulation was to be expected and experienced from the beginning of the deepening operation. At KOP depth (2,750 m) an opening called for a cementing job to solve well cleaning problem, after which the well was drilled to 3,000 m depth. Wiper trip followed and then 9 7/8” – 9 5/8” casing string ran in. Cables from Petrospec, with 8 thermocouples (rated up to 600°C), were attached to the outside of the casing string as it was run into the hole. They were expected to enable continuous logging of temperatures at 341 m, 641 m, 941 m, 1,541 m, 1,841 m, 2,141 m, 2,341 m and 2,641 m depths. The thermocouple at 2,141 m was damaged during the insert of the casing. In order not to risk further damages the casing was only run in to 2,941 m. In addition, a pressure/temperature sensor was installed at 1,241 m depth, and a fiber optic cable for temperature, and seismic logging was installed to 841 m depth. Data from the thermocouples were used to evaluate the progress of the cementing operation. To cement the 2,941 m long casing string a reverse cementing method was used.

Drilling in formation below 3,000 m in the production part began on 38th workday, and drilling was concluded at 4,659 m on the 168th workday, 26th of January 2017. Various challenges arose as the drilling progressed; there were weather delays, problems with hole stability that required frequent reaming, and the drilling assembly became stuck several times. These instances were successfully solved as they happened. However, a major unsolved problem was a near complete loss of circulation just below the production casing, that could not be cured with lost circulation materials, or by successive attempts to seal the loss zone with cement which was repeated 12 times or until depth of 3,185 m. After a month’s work in trying to cement off the loss zone, including 2 failed coring attempts, plug cementing was stopped and rotary drilling with a downhole motor continued without any return of drill cuttings to the surface. Consequently, the drill cores were the only rock samples recovered from the deeper part of the IDDP-2 hole. An open fracture zone was intersected near 3,350 m depth, which most likely helped in the well cleaning process and cooling of the well while drilling. The ROP was kept below 5 m/h below 3,500 m to prevent stuck pipe and cleaning problems. Several more openings or feed points were intersected deeper down, mostly detected by down hole T-log near the end of drilling. The deep feed zones indicate that the Reykjanes conventional reservoir needs to be enlarged by at least 1 km downwards, from about a 3 km bottom, used in reservoir models down to ~4 km depth at least, which is one of the pleasant observation in the IDDP-2 drilling.

Rotary drilling with 8 ½” bit was stopped at 4,626 m, a 7” hanging (~2,842 m) liner inserted to ~4,562 m measured depth. After that a 7” specially selected grade Tenaris High Collapse and Sour Service TN 80HS liner was installed from ground level to measured depth of ~1,304 m and cemented in. The cement plug and packer were then drill out with a 6” bit on a 3 ½” drill string, followed by cleaning out the liner shoe and eventual debris at the bottom of the well, which then was deepened by the same rotary bit to 4634 m depth. After that a 6” coring tool from Baker Hughes was inserted 3 times in a row with highly successful core recovery to final depth at 4,659 m.

2.2.2 Geophysical logging

During the planning stage of deepening well RN-15 it was anticipated that losses would be small below 3,000 m depth. Known temperature at 2,500 m depth in the well was 285°C and the formation temperature was expected to increase with depth and likely approach the boiling point temperature (BPC) for seawater, which made the extrapolated temperature over 410°C at 5,000 m depth. Therefore, a rather fast warm-up below 3,000 m was to be expected which would disable the use of regular wireline logging tools. For obtaining logs from the deeper part of the well a search for LWT (logging while tripping) and LWD (logging while drilling) tools was conducted. However, as loss zones were encountered below 3,000 m during the deepening an attempt was made to obtain logs with the conventional logging tools rated for temperatures up to about 150°C.

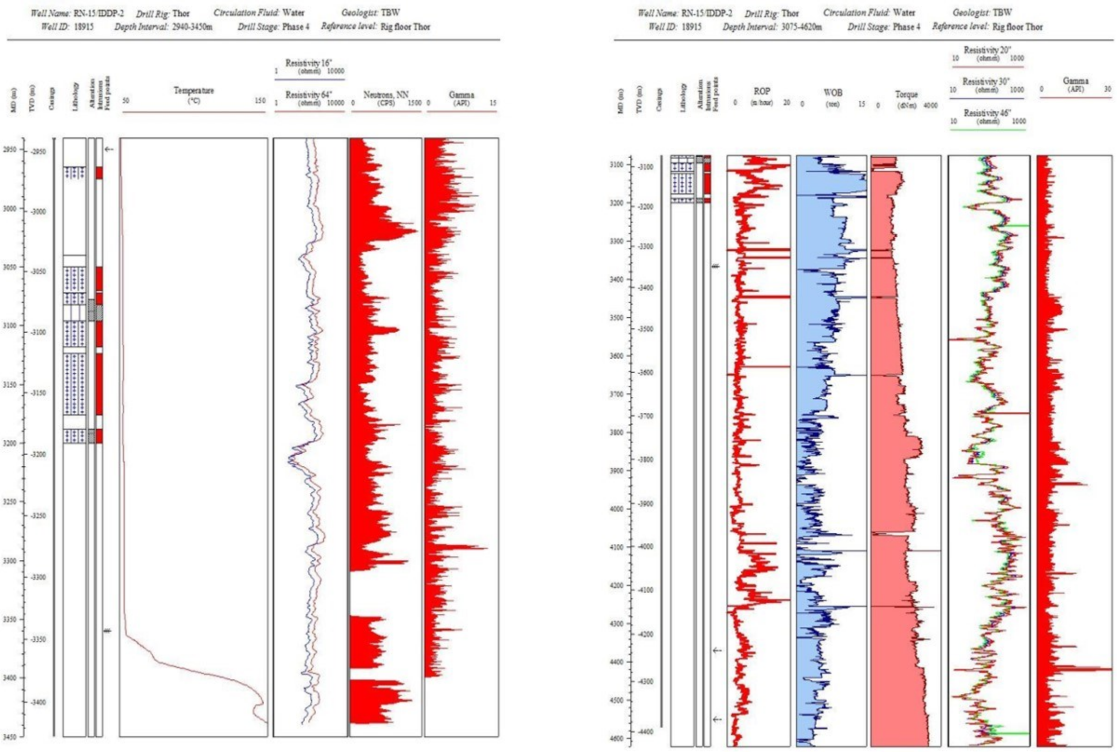

Figure 4: An overview of available lithology (to 3,200 m) (based on cutting analyses) and wireline logging (to 3,440 m) on the left, and selected drilling parameters and the logging-while tripping (LWT) Weatherford-tool data from 3,075 m to 4,620 m depth on the right. (diagrams in Weisenberger et al., 2017)

A regular logging suite was run in the well before cementing the production casing. The wireline suit consists of normal resistivity, neutron and natural gamma to 2,775 m, and XY-caliper to 2,870 m. The tools stopped at sills or washouts in the well and would not go deeper. Also, an acoustic televiewer imaging was obtained for selected intervals between 860-2,305 m. After casing, when the well was 3,648 m deep an attempt was made to log the well again with the available wireline tools. Normal resistivity, neutron and natural gamma, and sonic log was obtained from casing depth to 3,440 m. Televiewer log was attempted as well but had poor quality due to bad centralization. As earlier the tools stopped at some sills or washouts in the well that limited the depth coverage of the logs.

Close to the end of drilling when the depth was 4,626 m, before final deepening with coring tools, a special logging run with LWT tools from Weatherford was carried out. Never before had such tools been used in Iceland. The logging suite consists of natural gamma, temperature, pressure, and multi frequency resistivity from casing to 4,615 m (Figure 4). Micro-resistivity imaging to 4,490 m and acoustic velocity to 3,045 m. The acoustic tool and the imaging tool were damaged, possibly due to relatively stiff logging string and high rotation speed, hence the logs below the indicated depths are not reliable. With the circulation water, the temperature on the tools could be kept below 65°C during the entire log-run while the tools were logging rocks well over 400-500°C hot.

Additional to the above logs several temperature and pressure profiles were measured, CBL, gyros, MWD, injectivity and three spinner logs (3,158 m, 3,646 m, 4,420 m). In general, the logs give valuable information on the physical properties of the rock formations, especially as no drill cuttings were obtained.

Finally, a new multi sensor core logger (MSCL-scanner) borrowed from ICDP, was used to log the three drill cores from the very bottom of the IDDP-2 wells. Some of the logging suites are described in several WGC-2020 papers (Weisenberger et al., 2020; Mesfin et al., 2020)

2.2.3 Core drilling

Considerable difficulties were experience at the beginning in recovering acceptable amount of drill cores and a total of only 27.3 meters of core was retrieved in 13 attempts (Table 2). An IDDP designed 8 ½" coring tool (Skinner et al., 2010), was used, a tool that had yielded good core recoveries in RN-17B, an inclined 8 ½" hole from 2,800 m depth, and also from 3 successive core runs in well RN-30 at Reykjanes from similar depth, while below a 9 5/8" liner. Table 1 gives an overview of the IDDP-2 core recovery in 10 core runs with the 8 ½" coring tool, and also for 3 very successful core runs with a 6" Baker Hughes tool from the very bottom of the IDDP-2 well, beneath the 7" liner. Prior to coring with the 6" tools, an 8 m deep 6" pilot hole had been drilled with tri-cone bit from 4,626-4,634 m, to clean out the bottom fill after casing and to condition the well. Detailed descriptions on these core runs and lithological logging results were made by the on-site science team during drilling (Friðleifsson et al., 2017a; Weisenberger et al. 2017) and briefly described shortly afterwards (Zierenberg et al., 2017; Friðleifsson et al.,2017a, Friðleifsson et al. 2017b).

Table 1. Overview of the 13 core runs attempted in well RN-15/IDDP-2 at Reykjanes.

Core run	Start	Coring interval	Cored length [m]	Drilling time [h]	ROP [m/h]	Core recoverd [m]
1	18.9.2016	3068,7-3074,1	5,4	7,12	0,8	0
2	4.10.2016	3177,6-3179,0	1,4	2	0,7	0
3	30.10.2016	3648,0-3648,9	0,9	5	0,2	0,52
4	2.11.2016	3648,9-3650,7	1,8	10,25	0,2	0
5	11.11.2016	3865,5-3869,8	4,3	8,5	0,6	3,85
6	12.11.2016	3869,8-3870,2	0,4	2,5	0,2	0,15
7	22.11.2016	4089,5-4090,6	1,1	2,25	0,5	0,13
8	28.11.2016	4254,6-4255,3	0,7	5,5	0,1	0,28
9	6.12.2016	4308,7-4309,9	1,2	3	0,4	0
10	7.12.2016	4309,9-4311,2	1,3	8,25	0,2	0,22
11	16.1.2017	4634,2-4642,8	8,6	1,25	6,9	7,58
12	17.1.2017	4642,8-4652,0	9,2	1	9,2	9
13	19.1.2017	4652,0-4659,0	7	0,75	9,3	5,58
Total			43,3			27,31
				Core recovery about 63 %		

As can be seen from table 1 above the core recovery in the first 10 runs is very poor except for run 5. For core run 5 we had shortened the IDDP core barrel by half in case that would give better result – which it apparently did - but not so well in the subsequent runs. Probably the main problem related to the too close diameter of the 8 ½" hole and the 8 ¼" core bit and reamers and the hole inclination. The coring tool had worked properly in well RN-30 referred to above, where it had plenty of clearance inside the 9 5/8" casing. A comparable and similar situation with the 6" Baker Hugh core barrel was experienced in core runs 11-13, running the coring tool through the 7" casing and 8 ½" hole, plus an 8 m long 6" pilot hole to the coring face for core run 11. The successive core runs, 12 and 13, were exceptionally smooth as well, only took about 1 hour each in the 550-600°C hot rocks. The cooling efficiency of the Baker Hugh tool was not a problem as the coring operation in the very hot semi-ductile rocks progress very smoothly. The lesson learned is relatively straight forward, the cooling efficiency of coring tools does not appear to be an issue for smooth coring in hot rocks, and clearly a small diameter coring tools should be used for spot coring to obtain high quality cores for scientific studies where the core diameter is not an issue for qualitative rock studies. This would require reaming of the core hole up to the well diameter before continuing rotary drilling, requiring more rig time.

2.2.4 Core research

The IDDP-2 drill cores are the first samples ever recovered from the supercritical roots of an active basalt-hosted geothermal system. The three cores from the very bottom of the hole are from a sheeted dyke complex which is generally pervasively altered. Despite heavy alteration, veining is relatively rare and open mineral veins sparse in the three cores. However, these bottom cores do not represent the entire interval drilled in the supercritical regime below ca. 4 km depth. 426°C at 340 bar pressure were measured during drilling at just below 4,550 m depth, and several small feed points above that detected in temperature logs up to ca. 4,200 m depth. While small, those feed points probably represent open fractures. The mineralized veins in the core samples are discontinuous and lack sharp contacts and therefore interpreted as hydrothermal replacement veins formed in transition zone between brittle and ductile deformation (Zierenberg et al. 2017). Important features include transition from epidote—actinolite alteration to hornblende hornfels in core 3 at 3,648 m depth, and development of biotite in rocks below within and below core 8 (>4,255 m). Felsic segregation veins are relatively common in cores below 4,300 m depth, while felsic rocks are not found on the surface or in drillholes of the Reykjanes peninsula south of the Hengill central volcanic system, so a pleasant first finding of felsic segregates within the Reykjanes geothermal system (Friðleifsson et al., 2018).

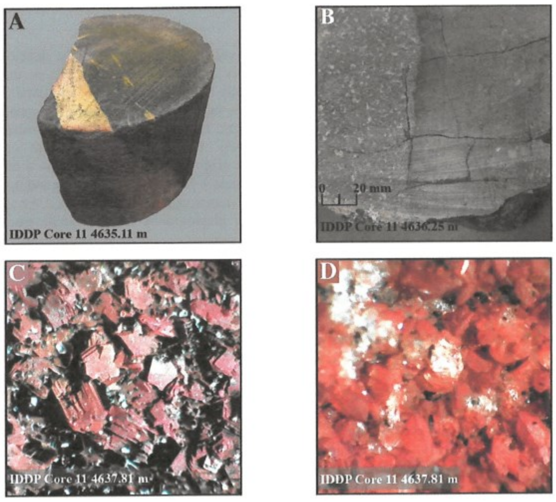

Figure 5: A) Felsite cutting basaltic dike; B) Chilled dike margin; C) Hydrothermal biotite in an open vein surface, stained by iron-oxide formed by mixing of drilling fluid and supercritical vein fluid; D) Euhedral quartz on the same vein surface, also stained by iron-oxide.

The initial detailed petrological and fluid inclusion studies on the cores are described in detail by Zierenberg et al. (2020) and Bali et al. (2020) and petrophysical properties (Gibert et al. (2020). Figure 5 shows a few examples from the cores being studied. The main results concerning the possible rock temperature, close to the bottom of the IDDP-2 well, all suggest formation temperature close to 600°C. So, with the addition of more than 400°C hot fluid temperature measured during drilling at 4,550 m, the formation temperature is likely to range downwards from ~400°C to ~600°C below ~3600 m depth. Unfortunately, because of casing damage at 2.3-2.4 km depth, the static formation temperature below that depth can not be logged by wireline logging as it is too risky to insert wireline tools through the damage zone. All the more important are the sparse core samples available for detailed petrological and petrophysical studies to better constrain the supercritical regime in the well.

2.2.5 Earthquake monitoring

Earthquake activity monitored with a local seismic network during drilling of the deep well detected abundant small earthquakes ($M_L \leq 2$) within the depth range of 3-5 km. A zone at 3-5 km depth below the producing geothermal field, generally aseismic prior to drilling, became seismically active during the drilling. A possible explanation is that the rock formation could be semi-brittle close to the brittle ductile boundary, supported by the on-going petrological studies deducing current formation temperatures. Most likely the primary cause for the induced seismicity related to the introduction of cold water into the zone of total circulation loss below 3.0 km depth, increasing the strain rate sufficiently to induce seismicity. These induced earthquakes were predominantly small, with magnitudes ranging from 0.5 to 1.9 M_L, with 95% of located earthquakes ranging from 0.5 to 1.5 M_L. A paper on the Reykjanes seismicity, prior, during and past the IDDP-2 drilling, is presented by Guðnason et al. (2020) to be discussed in detail or presented on a poster at the WGC-2020 conference.

2.2.6 Tracer tests and chemical monitoring

Attempts to inject chemical tracers were not as successful as anticipated, but regular chemical monitoring of neighboring wells showed clear dilution of the geothermal brine from the freshwater used during drilling and subsequent injection and stimulation tests. The DEEPEGS plan was to inject various types of tracers into the deep IDDP-2 well during stimulation efforts after drilling. These tracers needed to tolerate temperatures from 300-600°C. Only a few radioactive tracers and inert gas tracers were evaluated to survive such high temperatures.

During drilling a decision was reached to inject a SF_6 gas tracer into the drilling fluid and monitor it in neighboring wells for several weeks. However, after several weeks monitoring no sign of the tracer was detected. The injected quantity may have been too small and diluted out. Then a modified tracer plan was implemented – to get enough SF_6 tracer, an inert Krypton (Kr) gas tracer, and an organic 1-naphthalene sulfonate fluid tracer. The idea was to inject these tracers through the 3½" drill string. The tracers, however, had not arrived to the country when the deep stimulation effort finished, and both a severely corroded 3½" pipe and detected casing damage at 2.3-2.4 km, prevented a new insert of the pipe into the well. Accordingly, all further tracer tests had to be abandoned. Lack of funding prevented an attempt to insert a pipe through the damage zone for such injection and save wireline logging.

Despite the lack of tracer tests, useful results came from regular chemical monitoring in neighboring wells. A clear dilution of the Reykjanes brine fluid was detected in several wells, like RN-12 and RN-11. During the blind drilling and subsequent stimulation efforts, over 1.5 million m^3 of cold fresh water had been injected into the IDDP-2 drill hole. The chemical dilution can be seen in Figure 6. The implications for understanding the reservoir system from this dilution are discussed in more detail by Þorgilsson et al. (2020).

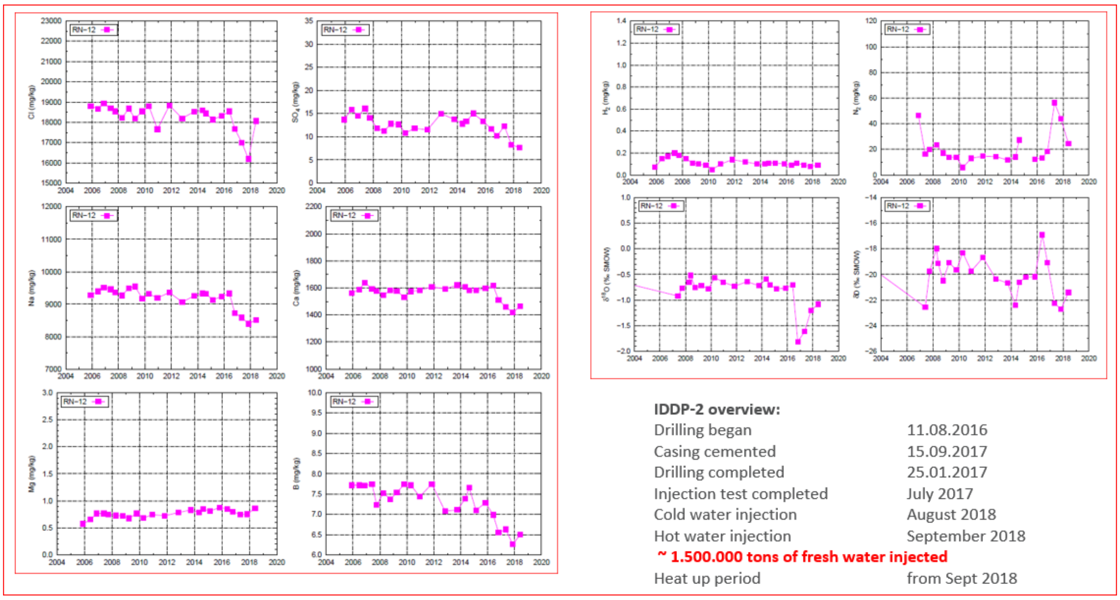

Figure 6: Regular chemical monitoring of well RN-12 since 2006 to date. A clear evidence of brine dilution in RN-12 caused by the fresh water used during drilling and stimulation of well IDDP-2 is seen on the diagrams. An overview for the IDDP-2 drilling and inject effort is also shown. The distance between the IDDP-2 well path and production well RN-12 can be viewed in figure 2. The main feed zone in well RN-12 is at ~2200 m depth.

The significance of this finding, demonstrated in figure 6, is of paramount importance for future utilization of the IDDP-2 well. Will it become a suitable production well, producing mostly from a depth of 3.4 km, or will the well better serve as a re-injection well? As can be seen in figure 6 above, the former production part of the RN-15/IDDP-2 well was open for fresh water injection from early August 2016 until the production casing had been cemented (15.09.2016), or roughly 40 days. If cold water usage amounted 60 l/s some 5,000 tons of cold water were injected daily to reach about 200,000 tons during this period when the well was directly connected to the production reservoir at Reykjanes. Whether that is sufficient to cause dilution of the RN-12 well fluid, remains speculative, while some 800,000 tons of fresh water were injected during the following 4 months. All that water disappeared into the reservoir into a fracture zone at about 3,4 km depth. A connection between this fracture and the RN-12 well seems somewhat more likely than a connection between horizontal feeds at about 2.4 km in both production wells, RN-12 and RN-15. The remaining injection of some 700,000 tons mostly disappeared into the main feed zone at 3.4 km. Well RN-12 will be chemically monitored onwards and possibly add valuable data on the connection between the deep IDDP-2 well and the conventional wells.

2.3 Stimulation of the IDDP-2 demonstration well

At end of drilling short stimulation with thermal cycling and pressurization was carried out. That increased the indicated injectivity index for the well from about 1.7 l/s/bar measured earlier to about 3.1 L/s per bar (Sigurðsson, 2020). On January 25th, 2017, the drilling operation was completed by installing a 3 ½" pipe to ~4,589 m depth for deep stimulation. The idea was also to inject gas tracer through the stimulation string as discussed above. When planning the deep drilling it was expected that permeability would decrease with depth in a similar manner as predicted reduction of porosity from MT-resistivity profiles in the area. Therefore, it was expected likely that the well could be "dry" below 3000-3500 m depth - which turned out to be vey wrong. It was also predicted that temperature would increase with depth so for a soft stimulation it was planned to put in a stimulation pipe and circulate cold water through it for several months, in order to create enough temperature difference for contraction fractures to develop, a plan described by Peter-Borie et al. (2018).

The deep stimulation was completed in July 2017, and after that cold-water stimulation was continued for more than a year, with relatively low flow rate on the annulus. The reason for the extension related to a casing damage between 2.3-2.4 km. The stimulation effort was concluded with hot condensate water injection for about 2 months. A short step rate injection test was carried out during that stage in September 2018, just over a month into the warmup period. By then the injection had been increased to about 50 L/s at temperature about 130°C. The test was done by shutting off the injection for some time and then continuing the injection. The results for the injectivity test yielded an estimated injectivity index of 2.7 to 2.9 L/s per bar which is not much lower than at end of the first stimulation stage and this injectivity was deemed reasonably good. A considerable amount of fluid blocker material could still be in the well at this time, put into the well during stimulation with the pipe. This blocker does not break down until at temperature about 180°C or higher. The details of the stimulation will be described by Sigurðsson (2020).

However, connection to the surrounding production wells was pleasantly detected because of the fresh water injection as discussed above. Regular chemical monitoring since 2006 of neighboring wells, like RN-11 and RN-12, showed clear chemical influence from the fresh water drilling fluid. Their salinity decreased temporarily during drilling and subsequent stimulation effort, and influx of atmospheric gas like nitrogen, carried with the cold drilling fluid, appeared as well as significant changes were seen in oxygen and hydrogen isotopes reflecting the freshwater dilution of the geothermal brine. The details of that will be described by Þorgilsson et al. (2020).

2.4 Flow testing the IDDP-2 well

A flow testing experiment was planned to begin in April but was delayed until late summer 2019. Its purpose is to find out if the deep fluid can be used directly use to produce electricity, with or without chemical mitigation, and/or for other geothermal uses in the Reykjanes geothermal resource park. The other option is to use the well for deep re-injection to mine heat from the root zone of the Reykjanes geothermal reservoir and result in an EGS system, to improve the performance of the overlying geothermal reservoir. As the flow test has not begun when this paper is written, a discussion on the fluid chemistry from the IDDP-2 well is premature. However, the saline fluid chemistry in IDDP-2 will be described by Óskarsson (2020) if sufficient data emerges from the flow test in 2019. Speculation on the potential fluid chemistry has been ongoing for years (e.g. Friðriksson et al., 2015). As we now know that the IDDP-2 well has several feed zones at different depths it will probably depend on the flow rate what kind of fluid mixture we will recover at the surface.

2.4.1 Flow test design

Considerable effort has been spent on designing the wellhead valve, spool-piece and flow line or the IDDP-2 well. A report on a detailed preliminary design was presented by Einarsson et al. (2015) at WGC-2015, prior to the IDDP-2 drilling. This design was later re-visited and modified during drilling of the IDDP-2 well. After drilling of the well a final approach was made after likely well condition had be addressed at an IDDP-2 “way forward workshop” in March 2018. A workshop report is available under SAGA reports at www.iddp.is. The flow line design was finalized later that year and early in 2019, all items evaluated for procurement and finally purchased and delivered to well site in May 2019. A presentation by will be made by Jóhannesson et al. (2020) at the WGC-2020 meeting.

2.4.2 Heating up of the well and flow test.

Heating up of the well began in August 2018 when cold water injection was stopped, and hot condensate water from the Reykjanes power plant was injected, first about 70°C hot, and few weeks later at about 130°C. Late September the well was closed and allowed to heat naturally. The well was temperature and pressure logged in August 2018 down to the casing damage zone at 2,307 m depth. Late May 2019 a new T-log was attempted to the same depth but an obstruction at 689 m, probably some scaling, prevented deeper logging attempt. The well heated up very slowly, probably disturbed or intervened by downflow from the casing damage zone at 2.3-2.4 km, and probably also from a downflow from the main feed zone at 3.4 km depth. Logging through and beneath the damage zone at 2.3 km is too risky and therefore we can only speculate on the well condition prior to initiating the flow. Some details from the flow test will be described at the WGC-2020 convention. We expect the flow test will have begun in September 2019 and that considerable data be available for discussion at the WGC-2020 convention.

3.0 Conclusion

The IDDP-2 well at Reykjanes was successively drilled into an active supercritical hydrothermal environment at depths analogous to those postulated as the high temperature reaction zones feeding black smoker systems on mic-ocean ridges. IDDP-2 was drilled to a total depth of 4,659 m and cased with a production casing to almost 3 km depth. The well was angled towards the main up-flow zone of the Reykjanes geothermal system, so its vertical depth is about 4.5 km. Based on alteration mineral assemblages, fluid inclusions data, joint inversion of geophysical data, and the rate of heating measurements, the bottom hole temperature appears to be approaching 600°C.

A major problem encountered during drilling the IDDP-2 well in 2016-2017 was total loss of circulation below 2.5 km depth that continued to the final depth. The total loss of circulation throughout the drilling and subsequent 1.5 year of re-injection tests demonstrate that an EGS system would be created with further reinjection into the 400-600°C hot environment. The deep feed zones indicate that the producible reservoir at Reykjanes needs to be enlarged by at least 1 km downwards, from about a 3 km bottom, used in reservoir models, down to ~4 km depth. While the result from the IDDP-2 flow test has yet to be determined, this DEEPEGS demonstration well is in an environment at precommercial scale, operating at TRL 7 level, as all the infrastructure needed is already installed at the Reykjanes power plant. The resulting business model may bring the DEEPEGS concept to TRL level 8-9, depending on the result from the flow test and pilot study. It is already clear that deep injection between 3-5 km in the long run can only enhance the performance of the overlying reservoir. Whether power production from the deep reservoir will also be of economical success remains unknown until extensive flow test and pilot test have been completed.

ACKNOWLEDGEMENTS

The IDDP-2 drilling was funded by HS Orka, Statoil (Equinor), Landsvirkjun, Orkuveita Reykjavíkur, and the National Energy Authority in Iceland. The IDDP-2 well has also received funding from the European Union's HORIZON 2020 research and innovation programme under grant agreement No 690771. Funding for obtaining spot cores at Reykjanes and elsewhere was provided by ICDP and the US NSF (grant no. 05076725). All these are greatly acknowledged.

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