The Reykjanes DEEPEGS Demonstration Well – IDDP-2

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ABSTRACT

The DEEPEGS demonstration well at Reykjanes, SW Iceland, was drilled to a depth of 4,659 m and cased with a production casing to almost 3,000 m depth. The well was angled towards the main up-flow zone of the Reykjanes high temperature geothermal system. Based on alteration mineral assemblages, the bottom hole temperature is estimated to be approaching 600°C. The DEEPEGS project, supported by the EU Horizon 2020 research and innovation programme, has the principal aim to demonstrate the feasibility of Enhanced Geothermal Systems (EGS) for delivering renewable energy for European citizens. The DEEPEGS project was meant to demonstrate advanced technologies in three types of geothermal reservoirs, 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. The Reykjanes demonstrator is just about to be flow tested at TRL level 6 in expected environment. The flow testing and pilot study is expected to begin in June 2019 and is of value to find out if the deep fluid is fit for direct use, with or without chemical mitigation, for producing electricity, and/or for other geothermal usage in the Reykjanes geothermal resource park, or if the well is better fit for deep re-injection. This demonstration system operating in operational environment at precommercial scale will be 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.

A major problem encountered during drilling of the IDDP-2 well in 2016-2017 was the total loss of circulation below 3.2 km depth and continuing to the final depth. Drilling proceeded without recovering any drill cuttings and consequently several spot cores provided the only deep rock samples from the well. These cores are characteristic of a basaltic sheeted dyke complex, with hydrothermal alteration mineral assemblages that range from greenschist to amphibolite facies, enabling investigation of water-rock interaction in the active roots of an analogue to submarine hydrothermal systems, as the Reykjanes geothermal fluid is of oceanic origin. 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.

The drilling of this deep IDDP-2 well achieved several scientific- and engineering firsts. It is the deepest and hottest drill hole so far sited in an active mid-ocean spreading center. It penetrated an active supercritical hydrothermal environment at depths analogous to those postulated as the high temperature reaction zones feeding black smoker systems. The total loss of circulation throughout the drilling and subsequent 1.5 year of re-injection tests demonstrate that an EGS system will simply be created with further reinjection down to the 400-600°C hot environment. The DEEPEGS demonstrator well at Reykjanes, IDDP-2, had an immediate impact on the accepted and used geothermal reservoir model at Reykjanes – and thereby the size of the geothermal reservoir, which increased in exploitable volume by some 40-50 %.

A second major impact already resulting from the deep IDDP-2 drill hole, is the connectivity to the surrounding production wells, which allows us to conclude that we have already proven that the EGS concept will work for the Reykjanes demonstrator.

For the first time drilling into an active supercritical regime in an ocean floor setting has succeeded. Such an active system has never been drilled into before and the resulting scientific impact is beyond the state of the art. The scientific work currently undertaken will have exceptional visibility and socio-economic impact.

1. INTRODUCTION

The Iceland Deep Drilling Project (IDDP) was established in year 2000 (www.iddp.is). 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. From the beginning the IDDP consortium program has been to investigate three high temperature systems in Iceland (figure 1).

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.

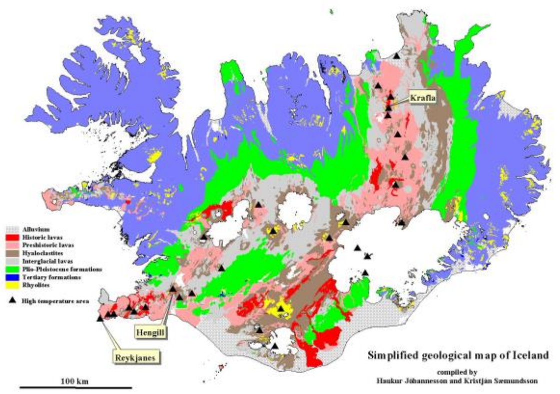

Figure 1: Simplified geological map of Iceland showing the location of the three high-temperature geothermal fields attended by IDDP, namely Krafla in NE-Iceland and Reykjanes and Hengill in SW-Iceland, hosting wells IDDP-1, IDDP-2 and IDDP-3 respectively. The detailed drill site of IDDP-3 remains to be dealt with.

IDDP intended to drill the first well in 2005-2006 at Reykjanes in SW Iceland (figure 1). In 2005 HS Orka offered the IDDP consortium to deepen to 5 km depth, a 3 km deep production well, RN-17, which was just being drilled at that time. Before deepening and casing of the well, the HS company decided to flow test the well without a casing support (barefoot) and during that flow test the rock formation collapsed into the well. Despite severe attempts with a drill rig to recondition the well, the well finally needed to be abandoned and the IDDP consortium had to look for another opportunity to drill the first superdeep well.

In 2009 the well IDDP-1 was drilled by Landsvirkjun in Krafla in NE-Iceland (figure 1), into an aphyric 900°C hot rhyolitic magma at only 2.1 km depth. The well had to be completed at that depth and was finished with a sacrificial casing, partly cemented towards the surface, with ~100 m long perforate liner next to the bottom, closest to the magma heat source. The idea was that the IDDP consortium should "take over" and fund the deep well section together below 3.5 km depth to completion, but this well never progressed to that stage because of the magma intervention. However, IDDP consortium participated in the finishing of the well above the magma and in subsequent testing, while majority of the cost was born by Landsvirkjun. During the subsequent flow tests, which extended to 2012, the well yielded 452°C hot superheated steam at surface. At a max flow rate at 20 bar pressure it could have generated up to 36 MWe, while it was extensively flow tested the following years at much higher pressures (~140 bar), leading to a conclusion that the world's first magma enhanced geothermal system had been created (Friðleifsson et al., 2015, and references therein). The IDDP-1 well was the world´s hottest production well for a while, but in 2012 the well had to be terminally abandoned due to valve failures and was cemented up. Nevertheless, the lesson learned was significant - similar wells can be drilled again towards shallow magma bodies in high temperature systems and magma-EGS systems created. At Krafla, however, the current idea is to establish an extensive volcanological and geothermal research program called Krafla Magma Testbed (KMT) (www.kmt.is).

In 2017 the world's first supercritical well, IDDP-2, was drilled to 4.659 m slant depth at Reykjanes in SW-Iceland (figure 1). This corresponds to about 4.5 km vertical depth from the surface (figure 2). Its bottom hole temperature is believed to be close to 600ºC, while during drilling after only 6 days heating, 426°C was measured at 4.550 m depth at 340 bar pressure, which is truly a supercritical for both fresh water and saline. The critical point for fresh water is 374°C at 221 bar pressure, while it is elevated for saline water to 406°C and 298 bar pressure (Bischoff and Rosenbauer, 1988). From the scientific point of view, this location at Reykjanes is of great interest because the Reykjanes Peninsula is the landward extension of the Mid-Atlantic Ridge. Furthermore, the geothermal reservoir fluid in the Reykjanes system is modified seawater, with similar chemical composition as some sampled ocean floor geothermal systems. Therefore, it is possible at Reykjanes to test a subaerial analogue of the mid-ocean ridge "black smokers", some of which yield supercritical fluid at the ocean floor at great depths (e.g. Koshchinsky et al., 2008). Drilling deep enough into a saline geothermal system on land at a ridge crest like at Reykjanes, which is recharged by seawater, could yield fluids at similar P-T conditions and in analogue settings as in the ocean floor ridge systems, geologically speaking, from within a sheeted dyke complex. This makes the Reykjanes system unique and appealing for research.

In 2015 a part of the IDDP consortium members joined in a consortium of 10 partner organization from the geothermal industry, technical and oil- and gas sectors, coming from five European countries, and submitted a proposal to the European Union's Horizon 2020 research and innovation programme. The project was called DEEPEGS (www.deepegs.eu) received funding for 4 years under grant agreement No 690771, beginning 1st December 2015 (Fridleifsson et al., 2016, Bogason et al., 2019).

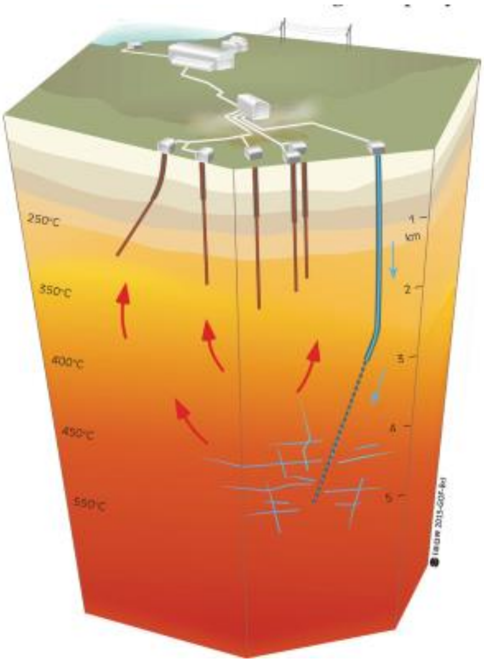

Figure 2: Schematic model of well IDDP-2 at Reykjanes. The IDDP-2 well basically began at 3.5 km depth, involving deepening of an existing production well, RN-15, which was first deepened to 3.5 km by HS Orka and Statoil (Equinor), and then finished by IDDP consortium participation to final depth, 4659 m from rig floor. DEEPEGS participates in the deepening effort and the well completion, including stimulation, flow test and pilot test.

The DEEPEGS project's total budget of 44 million Euro received an EU grant of about 20 million Euro making it one of the larger publicly funded H2020 projects. The ambition of the project is to explore the possibilities of producing energy from deep geothermal systems in Iceland and France, systems which are enhanced by stimulation following drilling to depths of 4-5 km. The project was meant to demonstrate advanced technologies in three types of geothermal reservoirs, 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. However, for administrative reasons within France the location of the two originally suggested demonstrators there had to be moved twice within France, involving considerable delay in the project execution (Bogason et al., 2019). When this paper is written, a request from the French energy company, Fonroche Geothermie, to move the France demonstrator site to Vendenheim in Alsace is hopefully just about to be accepted by EU. There, two deep wells have already been drilled, the first one reaching record temperature for central Europe of ~200°C in a granite basement close to 5 km depth. The present paper, however, will not discuss the French demonstrator much further, while figure 3 is used to schematically describe different scenarios for potential energy outputs from different high-temperature geothermal systems.

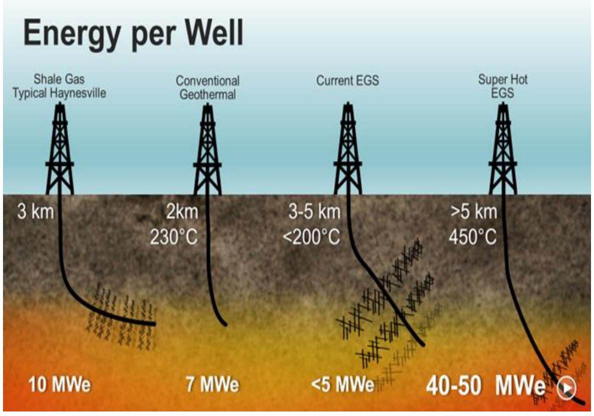

Figure 3: Schematic model showing comparative energy output of different high temperature well scenarios including current EGS systems. Super-Hot EGS systems are yet to be established, while the IDDP-1 magma drilling at much shallower depth surely resulted in one such system. (diagram borrowed from NNDP proposal),

IDDP-1 could be grouped with the Super-Hot EGS systems, while only drilled to 2.1 km into magma. Well IDDP-2 could also be grouped in that category too as a clear connection between the deep reservoir and the overlying shallower reservoir has already been demonstrated as will be described below.

2. THE IDDP-2 WELL AT REYKJANES

The drilling and key results of the of the IDDP-2 well at Reykjanes have been extensively described and publicized by Fridleifsson (2017), Fridleifsson and Elders, (2017 a, b), Fridleifsson et al., (2017, 2018) and Stefánsson (2017), Stefánsson et al. (2018), and others. In this chapter a short summary is presented based on the referred publications and additional new data and information.

The drilling began by deepening an existing 2.5 km, well RN-15 to 3 km, and case it with 9 7/8"– 9 5/8" casing and cementing to surface. To reach the main up-flow zone of the Reykjanes system it was necessary to build the well inclination from 2,750 m with an azimuth of 210°deg (figure 4). Total loss of circulation was experienced most of the time to the end of drilling. An exception to this was just after casing and repeated plug cementing below 3 km to about 3.2 km, after which the well was drilled totally blind to final depth. A 7" perforated liner was run into hole and then a 7" production (sacrificial) casing to 1,300 m and cemented to surface. This was followed by running in with 6" rotary assembly to drill out casing shoes for the sacrificial casing and the liner. A 6" pilot hole was then drilled for 8 m before pulling out for 3 successive 6” spot coring runs to final depth. The well was left with 3 ½” drill pipe to 4,590 m for long term stimulation and tracer injection.

The existing 2.5 km deep production well, RN-15 was drilled by HS Orka in 2010. First it was cooled down slowly and then deepened and cased to almost 3 km depth in 2016. Equinor funded that effort with HS Orka, including further deepening to 3.5 km depth. From there on to final depth of 4,659 m depth, completed January 2017, the IDDP consortium funded the drilling itself. DEEPEGS participated in the funding through all this effort apart from the drilling itself, but including materials, loggings and miscellaneous research including extensive stimulation efforts. Drill coring with spot coring equipment was attempted 13 times from 3 km depth to the bottom, resulting in some 27 m of valuable drill cores. All the spot core drilling was funded by ICDP and NSF. The funding overview here is just made to stress the fact that many geothermal stakeholders and research agencies are supporting this R&D program for enhanced geothermal energy by deep drilling.

As the well was directionally drilled, from 2.7 km depth to bottom, the vertical depth from surface to bottom is close to 4.5 km. The well track is shown in figure 4. Supercritical conditions were measured during drilling at ~4,550 m depth of 426°C at 343 bars. Prior to this temperature log Ketil Hogstad from Equinor had used Bayesian inversion of available geophysical data from Reykjanes to model the bottom hole temperature distribution, which reached over 500°C (Hokstad and Tänavsuu-Milkeviciene (2017). This prediction of very high temperatures was later supported by petrological and fluid inclusion studies of the drill cores.

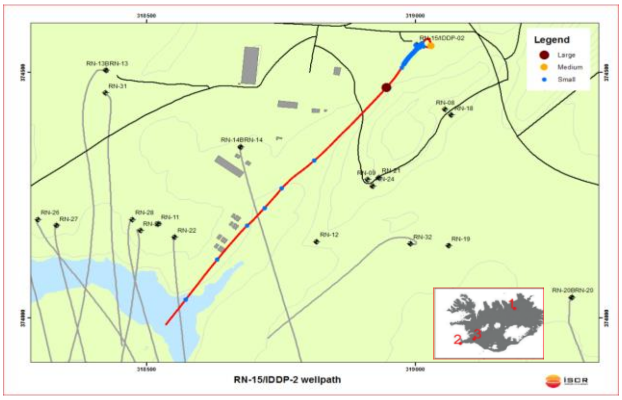

Figure 4: A map showing the track of the inclined well IDDP-2, towards SW from the RN-15 wellhead in the NE. Main feed points are shown by brown, yellow and blue dots on the track line. Partly open fracture (not shown as blue dot) was seen in the one of the lowermost drill cores at the bottom.

After the temperature logging January 6th, 2017 during drilling, the well was deepened by additional 100 m, a liner inserted, and a 6” pilot hole and 3 successive drill cores retrieved from the very bottom of the well. Altogether some 27 m of drill cores, from 13 coring attempts below 3 km depth, were retrieved from the well (Table 1). As the well was drilled with total circulation loss most of the time these core samples comprise almost the only rock samples from the entire well deeper than 2.5 km depth. An exception to this is from the interval below the cemented production casing at 3.0-3.2 km depth from where some drill cutting samples exist (Weisenberger et al. 2017).

A major problem encountered during drilling the IDDP-2 well was the total loss of circulation below 3.2 km to final depth. The temperature logs showed the largest feed zone to be at about 3.4 km depth, while several smaller feeds were detected towards the bottom of the well (figure 4). The drilling operation took 168 days and during most of that time some 40-60 l/s of cold water were pumped through the drill string, including cooling water injected on the annulus to keep the casings cool, as the water table was at about 1 km depth. During the following stimulation effort cold water was injected continuously through a stimulation string for ½ a year (see below) and on the annulus as well, and for more than a year after the stimulation pipe had been removed. The total amount of injected cold water is in the order of 1.5-2.0 million tons of fresh water. Evidently this fresh water had to mix in with the saline geothermal reservoir fluid if the IDDP-2 feed zones were connected to the conventional reservoir, see further discussion in chapter 2.3 below.

2.1 Core drilling and petrological studies

Table 1 shows an overview on core recovery in 10 core runs with the IDDP 8 ½” coring tool and 3 successive core runs with 6” Baker Hughes tool at the bottom of IDDP-2, 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.

Table 1. Overview of 13 core runs in IDDP-2.

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 %		

The cores recovered were extremely valuable as they indicate that the IDDP-2 drilled through a basaltic sheeted dike complex that shows progressive metamorphism from greenschist facies to lower amphibolite facies, consistent with hydrothermal alteration at temperatures up to 450-600°C. A detailed description of the petrology of these cores is reported by Zierenberg et al., (2017). The deepest core, from the bottom of the well apparently contained reasonably fresh dolerite, with minor intrusions of felsite. Although the bimodal igneous association of basalt and felsite is observed in other geothermal systems in Iceland, this is the first time it has been observed at Reykjanes.

The main indications of hydrothermal alteration in this rock are quartz + biotite mineralization on some open space fracture surfaces. A red hematic stain on open space fracture surfaces and on the core surface in some cases, provides a clear evidence that supercritical fluid was in the open fractures and pores in the rock formation that was cored. Cooling and mixing of this fluid with the cold drilling water resulted in oxidation of the primary fluid, resulting in hematite staining on open fractures and in places on the outside of the core itself. Oozing of pore fluid post drilling further caused a yellowish precipitate of Fe-K chloride (Zirerenberg et al., 2017). Fluid inclusions in the stained quartz from the open mineral vein were studied in detail by Enikö Bali and described briefly at GGW-2018 (GEORG Geothermal Workshop), confirming homogenization temperatures close to 600°C. The petrological and fluid inclusion details of the unique core samples from IDDP-2 will be described in detail by Zierenberg et al. (2020) and Bali et al. (2020).

2.2 Seismicity during drilling and stimulation

The active rift crossing Iceland from Reykjanes through the country is seismically activity while variable over time, with scattered activity and occasional short-term earthquake swarms. Since 2013, a dense local seismic network of seven seismic stations has been operated at around the Reykjanes geothermal field, with an average spacing of ~0.5 km. In addition, on-line data from four seismic stations in the regional seismic network of Iceland (the SIL network) are available. Seismic activity was closely monitored during the IDDP-2 drilling from the 12th of August 2016 to the 25th of January 2017. During that period 650 earthquakes occurred in the field and more than 200 of them were located within less than 1 km of the IDDP-2 wellhead. The seismic catalogue, however, covering the timespan from the start of drilling to the end of the main stimulation phase that followed the drilling contains over 2300 earthquakes. The detailed results of the seismic monitoring during the DEEPEGS project will be reported, interpreted and discussed by Guðnason et al. (2020), and undoubtedly in follow-up papers.

Comparison of hypocentral depths with daily reports during the drilling progress, starting at 3 km depth, indicated that induced earthquakes appeared to follow the drill bit with time. Earthquake activity mainly occurred within the depth range where drilling activity took place, between 3-5 km. The regional brittle-ductile boundary at Reykjanes is generally believed to occur at about 6 km depth, while observations from the local seismic network had revealed an aseismic body between 3 and 6 km depth beneath the center of the production field. The uppermost part of this apparent aseismic body, from 3-5 km depth, became seismically active during the deep drilling. A possible explanation for the absence of natural earthquakes in this body is that its temperature is very close to the brittle-ductile boundary for normal strain rates (Guðnason et al., 2016). 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. This earthquake monitoring results for Reykjanes are of paramount importance for the development of EGS geothermal systems in general and thereby the DEEPEGS project (Friðleifsson et al. 2018).

2.3 Stimulation, tracers and chemistry

At end of drilling short stimulation with thermal cycling and pressurization was carried out. That increased the indicated injectivity index for the well to about 3.1 L/s per bar (Sigurðsson, 2019). The drilling operation was completed on January 25th, 2017 by installing a 3 ½” pipe to about 4589 m depth for deep stimulation, and the idea was also to inject gas tracer through the stimulation string. In 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 considered likely that the well could be “dry” below 3000-3500 m depth. 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 form. The plan was described by Peter-Borie et al., (2017).

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, briefly discuss elsewhere. 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. The injection to the well from the injection system had by then 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 open for the injection again. 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. Bearing in mind that considerable amount of fluid blocker material had been put into the well, which does not break down until temperature is 180°C or higher, the injectivity was deemed reasonably good. The details will be described by Sigurðsson (2020).

During the blind drilling and subsequent stimulation efforts, over 1.5 m^3 of cold water was injected to the IDDP-2 drill hole as said above. The plan was to inject gas tracers (FS_6 and Ar) and a liquid tracer deep into the system through the stimulation string in order to demonstrate connectivity to the overlying exploited geothermal reservoir. For several reasons the injection of the tracer proved unattainable once on drill site. However, connection to the surrounding production wells was pleasantly detected because of the fresh water injection. 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 it will be described by Þorgilsson et al. (2020).

2.4 Flow test preparation

Design of the IDDP-2 flow testing equipment had already been done by an IDDP working group prior to the drilling of the well. That design, however, needed to be re-addressed as the drilling proceed, and once finished a “Way Forward Workshop” helped setting the likely P-T condition to be dealt with on surface (SAGA report 11, available at www.iddp.is). The working group then completed the final design last autumn and most of the needed bidding and purchasing orders have already been made. The equipment construction on surface is expected to be completed in May 2019. The details of the design and proceeding will be described by Jóhannesson et al. (2020)

The original flow testing plan from 2017, was delayed by more than one year due to a casing damage at 2.3-2.4 km depth detected by downhole logging after the 3½” stimulation pipe had been removed from the well in July 2017. A small leak had been detected there and potential mitigation actions needed to be inspected carefully and decided upon. Finally, a decision was reached to leave it be and flow test the well under current condition. Heating up of the well began in September 2018 and the flow test was expected to begin in April 2019 but is already delayed to June. The outflow from the well will be a mixture of fluids from several feed zones at different depths, while majority of the flow is expected from the 3.4 km feed zone. Minor inflow to the well is expected from the leaky casing zone below 2.3 km, depending on flow rate. At low flow rate fluids may possibly flow out though the damaged casing, and possibly block it up by precipitates? Speculations on differential flows from different feed points continues in the flow test working group. According to calculations (Sturla Sæther, pers. com.) the lowermost and hottest feed zones could contribute to the total outflow from ~ 2% to 20%, again pending on flow rate, larger at low flow rates.

2.5 Scientific and engineering firsts in IDDP-2

Just to list up several scientific and engineering firsts related to the IDDP-2, we include this chapter. Amongst such „firsts“, was our decision to try to cement in several thermocouples outside the production casing. The manufacturer was Petrospec which also supervised its insert. The thermocouples worked well for a while but then started to fail. Only 3 of 9 are still working.

Also amongst first attempts was our decision to use reverse cementing method for the entire 3 km length of the production casing, which was done in one go cementing operation. The operation appeared successful, while we have still some concerns about the cement mixture and its integrity in the lower part of the well below the casing damage zone.

Prototype high-temperature downhole motor from Baker Hughes, tolerating up to 300°C, was also used during part of the directional drilling with good success, later described at an IADC/SPE technical conference in Texas by Stefánsson et al. (2018), including prototype high-T drill bits.

As total circulation loss, but very high temperature at the bottom of the well prevented conventional downhole geophysical logging in the IDDP-2 hole, a logging while drilling LWD (LWT) tool from Weatherford was hired and used for the first time in an Icelandic hole. Thereby we got proper geophysical logs almost to the bottom of the well (yet to be published), excluding the final core section at the bottom. Those cores however, were still geophysically logged on the surface with a MSCL scanner from ICDP to be described by Mesfin et al. (2020).

More than 2.1 km of blind drilling involved losing of about ~ 60 m^3 of cuttings into the rock formation. Such a blind drilling to a record depth of 4,659 m into a formation at supercritical temperature is evidently a noteworthy achievement. The drilling operation could have been extended at bit deeper while repeated blockages and increased torque left us deciding to stop the drilling operation.

Last but not the least, the IDDP-2 is the deepest and hottest drill hole so far sited in an active mid-ocean spreading center. It penetrated an active supercritical hydrothermal environment at depths analogous to those postulated as the high temperature reaction zones feeding black smoker systems.

3. CONCLUSIONS AND DISCUSSION

The DEEPEGS demonstrator well at Reykjanes, well IDDP-2, had an immediate impact on the accepted and used geothermal reservoir model at Reykjanes – and thereby the size of the geothermal reservoir, which increased in exploitable volume by some 40-50 % (almost doubled). Since 2006 high temperature fluid, from 220-320°C, has been harvested from some 18 production wells at Reykjanes to produce about 100 MW_e in two turbines. Most of the feed zones are located between 0.8 km to 2.3 km, i.e. below the production casing towards the bottom of the conventional production wells (2.2-2.8 km deep). The currently used reservoir model has set the bottom of the reservoir system at 3.0 km depth, assuming dense impermeable rocks below that depth. In the new IDDP-2 well the production casing was cemented in at 2,941 m depth, while the drilling suffered massive total circulation loss from that depth to the bottom of the well at 4,650 m. Twelve times cement plugging was attempted in attempts to heal the loss zones but proved unsuccessful so at 3.2 km depth no further plug cementing was attempted. Accordingly, the rest of the well was drilled with total circulation loss (blind drilling). During temperature downhole logging during and after drilling the main feed zone proved to be at about ~3.4 km depth in the temperature logs, screening off the apparent feed zones mentioned above, and then revealing several smaller feed-points down to bottom of the well. The massive loss zone at 3.4 km depth is about 1 km below the deepest significant feed points in other wells within the Reykjanes drill field, indicating that the exploitable reservoir needs to be sized up to at least that depth and the “floor” of the reservoir for modelling calculations to be set about 1 km deeper that in the current estimates. Irrespective of all other impact the deep IDDP-2 well may have, this is probably the most economic information resulting from the DEEPEGS demonstrator at Reykjanes. While it is too early to speculate on a significant impact from the remaining flow test of the IDDP-2, the primary goal of the IDDP project is to gain significant power output from such deep wells. The DEEPEGS primary goal of creating a workable enhanced geothermal system (EGS) however, has already been accomplished at Reykjanes.

A second major impact already resulting from the deep IDDP-2 drill hole, is the connectivity to the surrounding production wells. 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. This means that by drilling deep under the currently harvested geothermal reservoir, into much hotter rocks (500-600°C hot), and by re-injecting whatever fluid we like such as condensate water at some temperature, both temperature and pressure support will result in the overlying geothermal reservoir. In other words, we have already proven that the EGS concept will work for the Reykjanes demonstrator.

The third significant impact concerns the deepest part of the DEEPEGS demonstrator at Reykjanes, namely the extremely high temperatures in the lowermost 1 km, currently assumed to be close to 600°C at the bottom of the well. During drilling 426°C at 343 bar pressure was measured at 4.550 m depth after only 6 days heating. Most recent petrological studies of the IDDP-2 drill cores, including mineral geothermometry and fluid inclusion studies, all indicate that the bottom hole temperatures should be close to 600°C. All imply that we drilled into an active supercritical regime in an ocean floor settings of a sheeted dyke complex in a saline fluid system. Such an active system has never been drilled into before and the resulting scientific impact is beyond the state of the art. The scientific work currently undertaken will have exceptional visibility and socio-economic impact. Part of this impact data has already been published in peer reviewed journals, in Scientific Drilling (2017) and Journal of Volcanology and Geothermal Research (2018) (Fridleifsson et al., 2017, 2018), and there are more to be expected during this year and next (e.g. Zierenberg et al., 2020, Bali et al., 2020)

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IDDP-2 DEEPEGS demonstrator well at Reykjanes.