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The IDDP success story - Highlights

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ABSTRACT

This paper highlights the main achievements attained by the Iceland Deep Drilling Project (IDDP), which is aimed at investigating the supercritical geothermal resources in Iceland. In 2008-2009 the well IDDP-1 in the Krafla geothermal field in NE Iceland, was planned to be drilled as a production well from the surface down to about 4.5 km depth. After severe drilling difficulties and getting stuck twice, which required side tracking, drilling had to be terminated at only 2,104 m depth, when it became clear that we had drilled into ~900°C molten rhyolite (magma). Despite this unexpected situation the IDDP consortium decided to attempt to flow test the well. A sacrificial casing was inserted and cemented towards the bottom of the well and a perforated liner ~100 m long closest to the magma. A successful flow test was then conducted until 2012 during which the hostile fluid chemistry was successfully dealt with. The world's first Magma-EGS system had been created. During the flow test the IDDP-1 was the world's hottest production well producing 452°C superheated steam at 142 bars. Its power production potential for electrical generation reached up to 36 MW_e for untreated steam. However, to enable its utilization chemical cleaning of the steam was necessary and would have resulted in lower power output. The successful mitigation method used involved a simple wet scrubbing of the steam, cleaning out all silica, chlorine and sulfur. The operator at Krafla was just about to scale up the pilot test to use the steam for the installed steam turbines when failure of several surface valves called for rapid cooling of the well resulting in severe casing failures. After close inspection attempts to repaired it had to be abandoned and the well had to be plugged up by cement. Nevertheless – the successful experiment had opened a window for enhanced power production at Krafla by creating a Magma Enhanced Geothermal System (MEGS). When considering the size of the huge magma chamber situated at shallow depth in Krafla power production could probably be multiplied by an order of magnitude from the currently installed capacity of 60 MW_e. Before that happens, however, several engineering challenges need to be dealt with related to casing integrity, cementing issues and the quality of surface valves and other surface installations.

The second IDDP well, IDDP-2 was drilled in 2016-2017 into the Reykjanes saline geothermal system in SW Iceland. An existing 2.5 km deep production well, RN-15, was deepened and cased to almost 3 km depth, and then drilled to 4,650 m slant depth, corresponding to about 4.5 km vertical depth from surface. Supercritical conditions (426°C at 340 bars) were measured during drilling at ~4,550 m depth. 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. Coring was attempted 13 times below 3 km depth, altogether returning some 27 m of drill cores. As the well was drilled with total circulation losses most of the time these core samples comprise almost the only rock samples from the well below 2.5 km depth. Petrological studies, on mineral assemblages, chemistry and fluid inclusions from the drill cores, show absolutely a unique data set from a sheeted dike complex currently at temperatures up to 600°C near the bottom of the well. The active geological settings at Reykjanes is an analogue of the root zones of the world's oceanic black smokers and drilling into such rocks at such extreme temperatures is unprecedented. A major achievement of the IDDP-2 well was to demonstrate that it is possible to drill into a supercritical geothermal reservoir, while there are shallower feed points that produce subcritical fluids. Whether the mixture of the saline fluid from different depths will be capable of generating electric power remains to be seen. Nevertheless, the major success of the IDDP-2 well is the finding of primary and/or enhanced deep permeability in very hot rocks. The implication of this finding needs to be evaluated in the wider context of worldwide supercritical geothermal systems. Firstly, it appears that the exploitable volume of the geothermal reservoir needs to be expanded about 1 km downwards, from about 3 km towards ~4 km depth. Current reservoir models have fixed the bottom at about 3 km depth, which need to be modified. Secondly, multiple feed zones were detected during the entire drilling to the bottom of the well. Part of the circulation losses may relate to induced fracturing by thermal and/or hydraulic cracking from the several km long cold-water column during drilling. Nevertheless, it is clear from the drill core samples that open fractures, partly mineralized, also exist at great depths and apparently contain chemically hostile brine fluid, based on fluid inclusion data. It is quite clear also that huge volumes of water can be injected into the very hot rocks immediately beneath the conventional geothermal reservoir. Therefore, a deep superhot EGS system can be created. This would both enhance and extend the lifetime of the harvestable geothermal system and to demonstrate this will surely be a part of the IDDP success story. The data already gathered from the DEEPEGS Demonstration Well – IDDP-2 - is of paramount importance for future economics of high temperature geothermal systems comparable to Reykjanes. The IDDP-2 well has been heating up since September 2018 after almost 1.5 years of continuous cold-water injection, including the lost fluid circulation during drilling. This fluid loss amounts up to 1.5-2.0 million tons of fresh water. A flow test is expected to begin in September 2019 and data from the flow test should be available to report at the WGC-2020. The fluids produced will be both contaminated by fresh water at the beginning, and a mixture from several feed zones from different depths with increasing temperatures towards the bottom.

Well IDDP-3 is planned to be drilled to 4-5 km depth at Hellisheidi within the Hengill volcano sometime after 2020.

1. INTRODUCTION

The paper highlights the main achievements attained by the Iceland Deep Drilling Project (IDDP). IDDP began in 2000 by establishing an IDDP consortium of three Icelandic energy companies (HS, LV, OR) and the National Energy Authority (OS) of Iceland and the selection of three geothermal systems for deep drilling (figure 1). An invitation for an international collaboration was published the same year (Friðleifsson and Albertsson, 2000). An international advisory board (SAGA: Science Application Group of Advisors) was established in 2001 attached to the IDDP, and still active. Numerous international workshops have been conducted by IDDP all of which are described in the so-called SAGA Reports available at the IDDP website (www.iddp.is). Alcoa, the international aluminum company, and Statoil, the Norwegian oil and gas company, joined the IDDP consortium as funding partners during the drilling and testing of IDDP-1, and Statoil (now Equinor) joined the consortium again during drilling and testing of IDDP-2. In addition, ICDP (International Continental Scientific Drilling Program, since 2001) and US NSF (National Science Foundation, since 2005) granted funds for core drilling and science studies of the cores, used in IDDP-1 at Krafla and in IDDP-2 and other wells at Reykjanes since 2006. The IDDP-2 received additional funding from the EU H2020 supported DEEPEGS project during 2015-2019 (Friðleifsson et al., 2019).

The main purpose of the IDDP project is to study the feasibility and economics of extracting energy and chemicals from hydrothermal systems at supercritical conditions. To study the supercritical hydrous fluid, advanced drilling technology and novel fluid handling and evaluation systems need to be applied. The basic idea by the IDDP is to drill deep enough into the roots of a conventional high temperature hydrothermal system to produce water at ***supercritical conditions*** and bring it to the surface as 400-600°C ***superheated steam***, at subcritical pressures (<220 bar). In the case of low permeability systems, by injecting cold fluid into the hot rocks, fractures can be induced to complete the thermal mining cycle.

Potential benefits include:

1. Increased power output per well, perhaps by an order of magnitude, and production of higher-value, high-pressure, high-temperature steam.
2. Development of an environmentally benign, high-enthalpy energy source below currently producing geothermal fields.
3. Extended lifetime of the exploited geothermal reservoirs and power generation facilities.
4. Re-evaluation of the geothermal resource base.
5. Industrial, educational, and economic spin-off.
6. Knowledge of permeabilities within drill fields below 2 km depth.
7. Knowledge of heat transfer from magma to water.
8. Heat sweeping by injection of water into hot, deep wells.
9. Possible extraction of valuable chemical products
10. Advancing research on ocean floor hydrothermal systems.

The IDDP consortium began by preparing for drilling a 4-5 km deep drill hole into a high-temperature hydrothermal system to study the potential of producing energy from 400-600°C hot supercritical hydrous fluids. A feasibility report was completed in 2003 (Friðleifsson et al., 2003; Thórhallsson et al., 2003; Albertsson et al., 2003), and the first drilling was planned to take place in 2006 in the Reykjanes geothermal field in SW Iceland by deepening a 3 km deep well of opportunity, well RN-17. That well however, was lost during a flow test when 3 km deep, and despite serious attempts it proved impossible to recondition the well for IDDP deepening. Sunken costs for this R&D well are about 5 m€.

The IDDP-1 well was drilled in Krafla, NE Iceland in 2008 and 2009. That well was scheduled to be drilled to ~4.5 km depth but drilling had to be terminated at 2.1 km depth due to intersection with a shallow rhyolitic magma body, at >900°C. In 2010-2012, the IDDP-1 well was flow tested and pilot tested for power production. At a max flow rate at 20 bar pressure it could have generated up to 36 MW_e, while it was extensively flow tested at much higher pressures (~140 bar), leading to the conclusion that the world's first magma enhanced geothermal system had been created (Friðleifsson et al., 2015, and references therein). For a while the IDDP-1 well was the world's hottest production well, but due to failure of several surface valves in 2012 the well had to be cooled down, cemented up and permanently abandoned. However, the drilling and testing of IDDP-1 resulted in an important part of the IDDP success story, summarized in this paper, while the detailed results are summarized in a special issue on IDDP in Geothermics 2014 (e.g. Elders et al., 2014; Friðleifsson, et al., 2014; Thórhallsson et al., 2014). Sunken costs for this R&D well are about 15 m€.

The drilling of IDDP-2 at Reykjanes began in August 2016 and was completed in January 2017. An existing 2.5 km deep depth, RN-15, was deepened and cased to almost 3 km depth, and then drilled to 4,650 m slant depth, corresponding to about 4.5 km vertical depth from surface. During drilling supercritical condition was measured at 4,550 m depth, 426°C at 340 bar pressure. The drilling was followed by a 5 months of deep stimulation test through an inserted 3 ½" drill string, until July 2017, and subsequently by cold water stimulation on wellhead until September 2018. The well was then allowed to heat up for about one year before being flow tested, scheduled to begin late August or early September 2019. Currently the IDDP-2 well is the world´s deepest and hottest well within an exploited high-temperature hydrothermal field, with bottom hole temperatures approaching 600°C (Zierenberg et al., 2020; Bali et al., 2020). While providing extremely valuable data on the deep reservoir the drilling operation suffered a bit from nearly total circulation loss of drilling fluids from the beginning to the end. Not only did the information gathered by IDDP-2 almost double the apparent exploitable volume of the Reykjanes reservoir, but also provided clear evidence that harvesting of the Reykjanes reservoir can be considerably enhanced by reinjecting fluid deep into the system. The data already gathered from the DEEPEGS Demonstration Well – IDDP-2 (Friðleifsson et al., 2019, and references therein) is of paramount importance for future economics of high temperature geothermal systems comparable to Reykjanes, irrespective of the outcome of a flow test and pilot tests for production. Sunken and estimated costs will be close to ~30 m€.

The IDDP-3 drillhole is planned to be drilled to 4-5 km depth within the Hengill geothermal system operated by Reykjavik Energy within the next 5 years or so. Estimated cost of drilling can be considered similar as for IDDP-2, about 30 m€, and to this we may to add some 20 m€ for pilot tests and power plants related to all the IDDP test sites (Friðleifsson et al., 2019) before the IDDP project is concluded. In summary, total accumulated cost for the IDDP project may approach 100 m€ before conclusion.

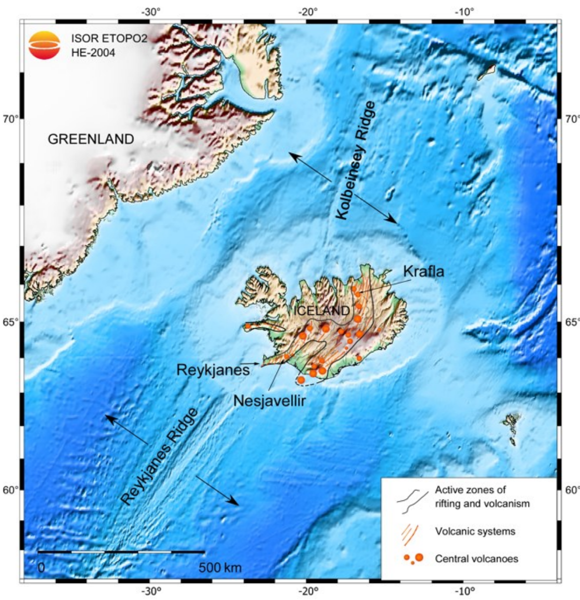

Figure 1: The Krafla, Nesjavellir (within Hengill volcano) and Reykjanes systems, selected for IDDP deep drilling, all rest within the active volcanic rift zone of Iceland, the landward extension of the Mid-Atlantic Ridge rift system.

2. THE SUCCESS STORY OF IDDP-1

Final depth: Drilled into 900°C hot magma at 2,104 m

Well was cased with a solid cemented liner to 1,935 m, and with a perforated liner from there to 2,072 m. Obsidian bottom fill of 19 m measured above bottom (Pálsson et al., 2014).

2.1 Observations on the IDDP-1 and their possible interpretation

1) Total circulation loss experienced before and after hitting magma and resulting that no cutting samples were retrieved of the rocks closest to the magma chamber. The contact zone of the magma is permeable and suitable for extracting heat.

2) IDDP-1 drilled into magma 3 times, got stuck twice and was sidetracked twice. The third time circulation with cold water was maintained for more than 24 hours with total circulation loss, without attempting to free the drillstring. After about 2 hours, water returns to the surface started, dark red to begin with and then with abundant black obsidian sand. Returns to surface were then pulsating for 3-4 hours, after which total loss continued. Once attempted after 24 hours, the drill string proved to be free (Pálsson et al., 2014).

3) Hard rock in the metamorphic aureole above the magma, with ambient temperatures close to 500°C, was thermally fractured by the drilling fluid (Pálsson et al., 2014, Mortensen et al., 2014, Schiffman et al., 2014)

4) Circulation loss presumably moved up and outwards into the overlying hydrothermal reservoir with temperatures measured in neighboring wells up to 340°C.

5) Cold water injection lasted during most of the drilling period and for 7 months afterwards.

6) Heating up to ambient temperature took an extremely long time due to no flow around the base of the IDDP-1 during the heat up period.

7) Once IDDP-1 was opened for flow, the surrounding and overlying ~300°C hot fluid system moved downwards into the low-pressure regime around the perforated liner just above the magma. That fluid heated up to 450°C on its way down before flowing up through the wellbore.

8) Severe corrosion on the casings only took place while two-phase condition prevailed in the well but once the flow became superheated, corrosion at least ceased considerably if not completely. Enthalpy gradually rose to ~3200 kJ/kg.

Acid gas (90 ppm HCl, 70 ppm HF) was carried with the steam, as well as gaseous sulfur (80-100 ppm) droplets and silica dust and dissolved silica, all of which could be washed out by wet scrubbing (Hauksson et al., 2014).

9) Remaining steam was inert and ready for power production without further mitigation, but evidently with somewhat reduced power output due to the wet scrubbing and drop in pressure (Markússon, 2015).

10) Maximum flow rate without scrubbing reached up to 50 kg/s, corresponding power output estimated close to ~36 MWe (Ingason et al., 2014).

2.2 Possible utilization based on IDDP-1

Basically, there are two alternatives for utilizing the Magma-EGS system:

(i) direct use of superheated steam with chemical mitigation on surface.

(ii) reinjection into magma contact wells and utilizing conventional two-phase fluid through shallower wells above.

While option (i) needs chemical mitigation, basically wet scrubbing on surface and associated power reduction, alternative (ii) will constantly be threatened by casing corrosion due to acidification in the two-phase fluid system. Accordingly, alternative (i) seems more feasible for enhanced power production, in Krafla, or in any comparable magma driven hydrothermal settings. A large magma chamber at 3-7 km depth in Krafla, split into western and eastern parts, was delineated on basis of S-wave shadow by Einarsson (1978, 1991). Figure 2 shows the areal extent of the eastern part of the magma chamber, covering more than 6 km^2. Theoretically one could assume that 900-1200°C hot magma should be expected to be intersected by drilling deeper than 3 km within this area. Therefore, the most favored location for an IDDP-1 well was originally sited alongside then magma chamber on the southern or northern border (Friðleifsson et al., 2003) while other reasons resulted in the final location for the IDDP-1 well (Friðleifsson et al. 2014) shown in figure 2. While molten magma could have been expected below 3 km depth we did not expect magma bodies of substantial size much shallower, while the opposite proved to be the case in IDDP-1, at only 2.1 km depth. In 2008 magma had also been intersected at about 2,600 m depth in the directionally drilled KJ-39 well (Mortensen et al., 2010). Other but less certain incidents of suspected shallow level magma encounters exist, like from well KJ-09 (Gudmundsson et al., 1983) and from the blow-out well KG-04 (Kristmannsdóttir, pers com.). These incidents in addition to the very recent Krafla fires, volcanic episode during 1975-1984, need to be taken as strong indication that magma pockets of some shapes should be expected to be widespread above the main magma chamber below 2 km depth. During the Krafla fires magma only surfaced in volcanic eruption within the central rift zone of the caldera, while inclined dikes and sheets may have spread laterally. In any case, the main result from the IDDP-1 incident with the rhyolitic magma pocket at 2.1 km depth implies that such magma pockets can be drilled into without too high risk of failure and utilized for power production by creating a Magma-EGS system. The pilot test for power production that followed the IDDP-1 flow test showed that the hostile chemistry could be made harmless by wet scrubbing (Markússon, 2015, Hauksson et al., 2014) and in principle that a Magma-EGS system had incidentally been created by flowing the IDDP-1 well (Friðleifsson et al., 2015).

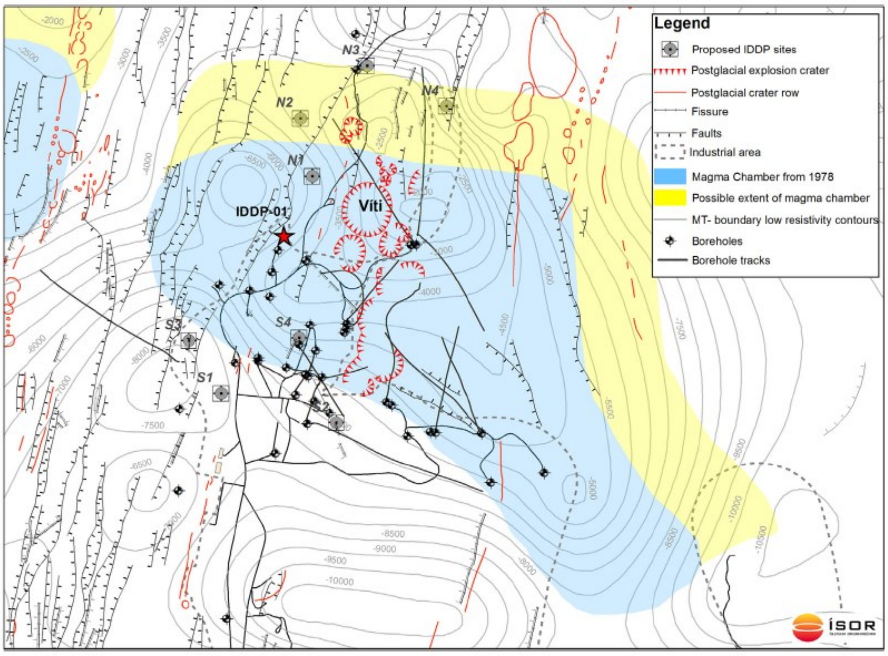

Figure 2: The figure above is borrowed from fig. 6 in Friðleifsson et al., 2014, and shows the assumed eastern part of a large magma chamber within the Krafla caldera, delineated on basis of S-wave shadows (Einarsson, 1978, 1991, and pers. com.). The assumed magma chamber at about 3 km depth and deeper is shown by blue colored area, with a possible northern extent expanded by a yellow area. The delineated magma chamber shown above is roughly 3 km in length and 2 km in width, approaching 6 km^2. The current drill field at Krafla is shown by the location of boreholes within a defined industrial area (hatched).

Based on the IDDP-1 data, provided the design, drilling and completion technology of wells to 2.1-3.0 km depth above the magma chamber in Krafla is successful within the current production field, or in similar settings elsewhere, substantial power production should be possible. The production casings should be deep enough to screen off the conventional two-phase fluid system roughly below 340°C, roughly down to 1,800 m close to the IDDP-1 well, but possibly somewhat deep elsewhere. A perforated liner at suitable depth below ~2.000 m should then be inserted downwards as close to the magma interphase as feasible. After reasonable injection and hydraulic stimulation above the magma within the contact aureole, the well should be given time to heat up and the fluid flow then turned around from the conventional reservoir above, to be heated up on its way downwards to be returned as superheated steam at surface. Evidently all casings, well head valves and surface flowline equipment need to be designed to withstand hostile and hot conditions, for a long-term operation for power production. Considerable experience has been added since IDDP-1, the flowline design of IDDP-2 for instance using experience and lesson learned from IDDP-1. The casing integrity and cementing procedure still need serious attention by the IDDP team and the international collaborators on superhot and supercritical wells. This should be attainable within few years provided testing and successful experimentation. Successful deployment of flexible couplings is one example (Thorbjörnsson et al., 2017) We believe that there is a bright future ahead for enhanced power production from superhot geothermal systems.

3. THE SUCCESS STORY OF IDDP-2

Final depth: Drilled into 600°C hot rocks at 4,650 m slant depth, corresponding to ~4.5 km vertical depth from surface.

Well was cased with a solid cemented 9 7/8" and 9 5/8" liner to 2,941 m depth, and with a perforated 7" liner hanging from 2,842 m depth down to 4,562 m measured depth, while the well depth was 4,626 m. After that a 7" high collapse and sour service TN 80HS liner was installed from surface down to 1,304 m and cemented in. A 6" rotary bit on 3 ½" drill string was used to drill out the casing shoes and deepen the well to 4,634 m depth, followed by three successive spot coring runs down to 4,659 m measured depth from rotary table (~9 m above surface).

A schematic model picture of the IDDP-2 well is shown in Figure 3. The well is almost twice the depth most of the surrounding production wells.

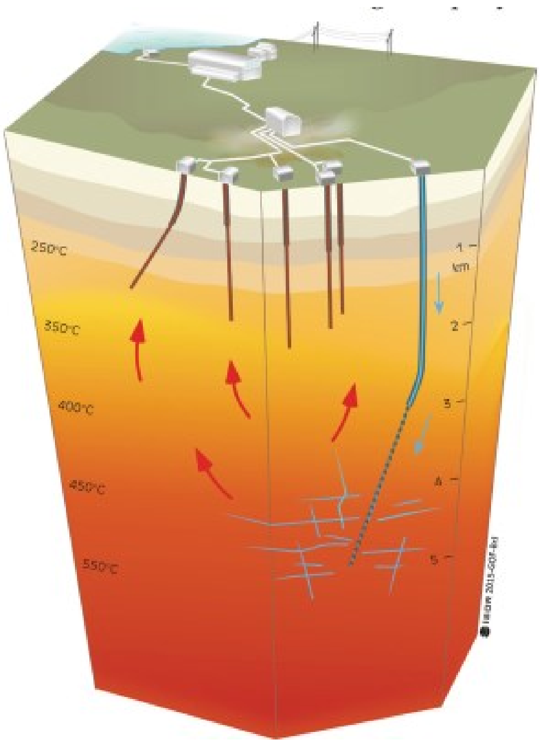

Figure 3. Schematic model of well IDDP-2 at Reykjanes. An existing 2.5 km deep production well, RN-15, was cooled down and deepened by HS Orka and Statoil (Equinor) to 3.5 km depth, then finished by IDDP consortium to the 4,650 m final depth. DEEPEGS participated in the deepening effort and the well completion, including stimulation, flow test and pilot test.

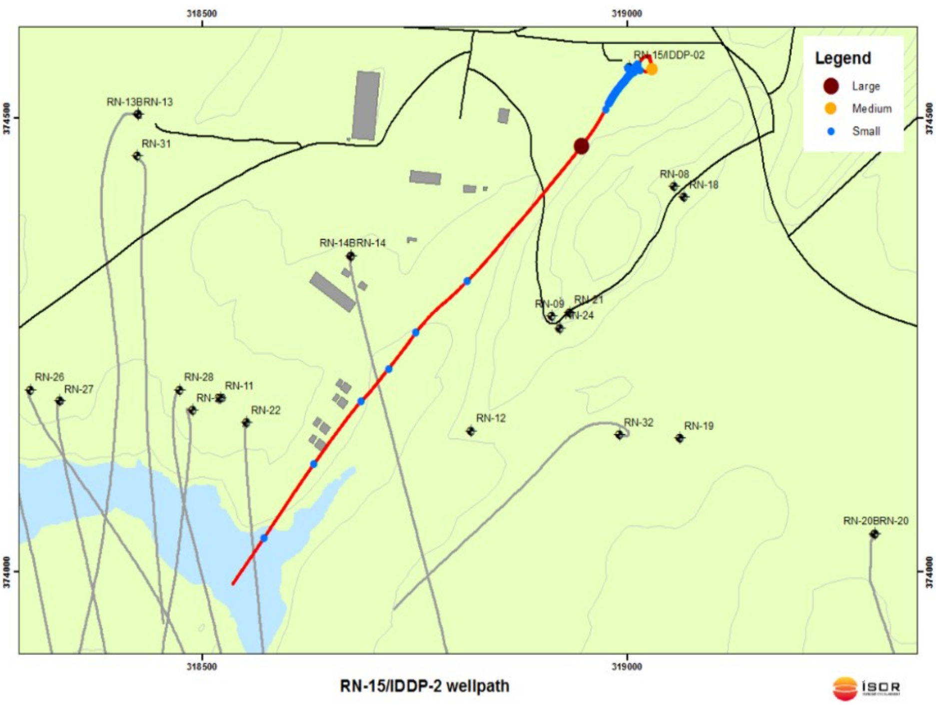

Figure 4: The IDDP-2 well involved deepening of production well RN-15, from 2.5 km depth to 4650 m depth. It was drilled southwestwards (red line), with a KOP (kick-off point) at 2,750 m, to 4,650 m length from wellhead. The true vertical depth is close to 4,5 km. Circulation loss points (feed points) are marked with circles colored blue, yellow and brown, for small, medium and large feed points respectively. On the map, majority of the feed points are closest to the wellhead. The largest feed point at 3.4 km is assumed to intersect a fracture zone.

3.1 Observation points on IDDP-2 and possible interpretation

1) Total circulation loss was experienced from the very beginning of the well deepening from 2.5 km. The best feed zone in the RN-15 well had been at 2,360 m depth.

2) The well was first deepened to about 3 km depth and a 9 5/8” production casing inserted. A cable with 8 thermocouples and 1 pressure-temperature sensor were fastened to the outside of the casing to be cemented in. During insert of the casing a signal loss from one of the sensors lead to the decision to stop casing insert at 2,941 m in the hope that other sensors would survive. A fiber optic cable from surface to about 800 m was also fastened to the production casing.

3) The casing was cemented in by a reverse cementing method which appeared to be quite successful. A retarder had been pre-mixed into the first portion of the cement slurry to prevent too fast hardening. This had been based on a temperature model calculation prior to the drilling. Due to total circulation loss during drilling, the well was much colder than expected in the modelled bottom section. Drilling after casing had to be continued without waiting too long for the cement to fully harden based on cement bond log data. In retrospect there are still some questions on the cement quality below 2.3 km depth, and especially between 2.3-2.4 km. All but one thermocouple sensors, however, worked properly during the cementing operation – and showed increasing temperature during the hardening time, except the sensor at 2.340 m which remained constant about 50°C during the hardening time.

4) Total loss of circulation soon continued during drilling of the 8 ½” production hole below the 9 5/8” casing. To begin with some 12 plug cementing attempts were made for a month, in order to heal the loss zones, but without success. Thus, the rest of the well was drilled blind while scattered drill cutting samples were recovered from the well between 3.0-3.2 km. Below that depth the only rock samples attained were from sparse drill cores recover from 13 spot coring attempts. The total length of cores obtained added up to 27.3 m.

5) The main loss zone seems to be at about 3.4 km depth according to temperature logs, but smaller feed points were detected on temperature logs towards to bottom of the well. The feed point location are shown in figure 4.

6) A 7” perforated hanging liner was inserted to 4,562 m depth. After that a 7” sacrificial casing was cemented in from surface to ~1,300 m depth. Some heating-up of the 9 5/8” casing below took place during that operation.

7) Deep stimulation injection with cold water lasted for 6 months after drilling through a 3 ½” drill string almost to the bottom. Attempts to temporarily block the shallower feed zones with a blocking material were successful, while some heating-up of the 9 5/8” casing may have occurred during the blocking time. The plastic material, called AltaVert, should dissolve at about 380°C. The deep stimulation effort did not seem to enhance the injectivity index (remaining 2.7-2.9 (l/s)/bar), while the blocking material may still have been blocking the upper feed zones during measurement.

8) Once retrieved, the 3 ½” stimulation pipe was severely corroded in the bottom section, due to oxidation and mixing of cold water with the supercritical brine. During a downhole logging run that followed a casing damage was observed in three intervals between 2,307 m to 2,380 m depth, leading to some inflow of fluid from the conventional reservoir downwards. Therefore, cold-water injection in the annulus was continued for more than 1 year while potential repair actions for mitigation were evaluated. At the beginning of this time a drill rig was still sitting on the well. An unsuccessful short attempt was made to drill out the casing damage with reaming tools. Finally, after serious evaluation, a decision was made to test the well at current condition. The well has been allowed to heat up since September 2018.

9) Due to the casing damage zone below 2.3 km depth, planned downhole logging deeper in the well has been abandoned for safety reasons. Fortunately, we got some logging data prior to discovering the casing damage, but the only knowledge remaining on the temperature and fluid condition in the deeper part of the well needs to be deduced by petrological studies on the sparse drill cores we got in the 13 spot coring attempts.

10) Extensive studies on the drill cores are on-going (Friðleifsson et al., 2018; Zierenberg et al., 2020; and Bali et al., 2020). So far, the main result indicates that up to 600°C hot brine fluid and a superhot steam are percolating in the rocks close to bottom of the well. During flow test this fluid should mix with the two phases fluid system expected above 3.4 km depth. The proportional contribution from the different feed zones are likely to depend on the fluid flow rate during the flow test.

3.2 Possible utilization at Reykjanes based on IDDP-2

A flow test of IDDP-2 should begin in early September 2019, with initiation of the flow assisted by airlift. A pilot test for energy production is expected to follow. As the main feed point is at 3.4 km depth and above one possibility is that the steam can be used directly for the existing 100 MW_e installed power plat at Reykjanes. While the future utilization of the IDDP-2 well remains to be determined, the data already obtained by drilling the IDDP-2 well is a major contribution to the future development of high-temperature geothermal resources in Iceland and elsewhere.

Basically, there seem to be two alternatives for utilizing the supercritical saline system at Reykjanes:

(i) direct use of superheated steam by slightly deeper production casings, likely with the addition of chemical mitigation on surface.

(ii) reinjection into the 500-600°C hot rocks to support the conventional two-phase fluid system above, with both pressure and temperature input to be utilized in the all the production wells above such deep wells.

Irrespective of the fate of IDDP-2 well, getting an access to rocks at an active black smoker setting at 600°C like at Reykjanes is unprecedented and will undoubtedly lead to more intensive studies and future drilling for sampling and utilization tests. At present however, the IDDP-2 well suffers from a casing damage at the depth of the current production zone for the geothermal field. This makes a selection between alternative (i) and (ii) above meaningless for the IDDP-2. Nevertheless, it is already quite clear that reinjection, as in (ii) above, is an option that can be utilized at Reykjanes to enhance the performance of the utilized geothermal system and prolong its lifetime. Direct or mitigated use of a hypersaline brine at supercritical condition along (i) above, will undoubtedly be difficult – while the possibility exists that a separated “clean” steam phase might flow from the deep system while a porphyry copper deposit type solid phase might be left behind in the rocks. The fluid inclusion studies in progress are suggestive that such phase separation may be occurring naturally in the system. Future research and deep drilling Reykjanes will continue to be quite exciting.

4. CONCLUSION

The results from research on the IDDP-1 and IDDP-2 wells thus far, for the future utilization of superhot geothermal systems at supercritical conditions, have already paid off in increased knowledge and understanding. It is quite clear that deep EGS systems can be created in superhot rocks up to magmatic temperatures. Permeable rocks are found to great depths and permeability is likely to be further enhanced by hydraulic and thermal cracking during drilling. The geothermal resource base for similar volcanic systems needs to be expanded downwards by at least 1 km. Magma EGS (MEGS) systems can be created. Supercritical saline systems are drillable and usable, if not for direct use, then definitely as deep EGS system in superhot rocks.

Within the next 5 years or so the IDDP-3 well is planned to be drilled to 4-5 km depth within the Hengill geothermal system, operated by Reykjavik Energy. Estimated cost of drilling and testing can be considered similar as for IDDP-2, or about 30 m€, and to this we may add some 20 m€ for pilot tests and power plants related to all the IDDP test sites (Friðleifsson et al., 2019). In summary, total accumulated cost for the IDDP project may approach 100 m€ before its conclusion. However, developing geothermal wells that have power outputs ten times that of currently producing high-temperature wells remains an alluring prospect, made more credible by the results to date from the IDDP.

ACKNOWLEDGEMENTS

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