PROCEEDINGS, 49th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 12-14, 2024
SGP-TR-227

Towards Utilization of Superhot Geothermal Resources – the IDDP Project and Beyond

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Keywords: IDDP, deep drilling, superhot geothermal, Hengill, well technology, injection, hybrid superhot EGS, EGS

ABSTRACT

The interest in superhot geothermal has grown substantially in recent years. There are few ongoing projects focused on opening these resources for utilization, such as the New Zealand Geothermal Next Generation Project, the Japan Beyond Brittle Project, and the Iceland Deep Drilling Project (IDDP). The IDDP was launched in the early 2000's. The three biggest power companies in Iceland; Landsvirkjun, HS Orka and OR – Reykjavík Energy, formed a consortium with domestic and international partners to work towards the goal of drilling supercritical production wells. Each of the abovementioned power companies committed itself to drill a superhot ~4.5 km deep well in its production field. The first well of the project, IDDP-1, was drilled in Krafla, N-Iceland. That well was drilled into magma at a depth of 2.1 km. It was possible to do flow tests in that well and it yielded superhot steam. The data gathered in those flow tests were very interesting. It was, however, difficult to handle the fluid due to corrosion and scaling. Moreover, the casing failed and the well had to be abandoned. The second well of the project, IDDP-2, was drilled in Reykjanes, SW-Iceland. That well reached a depth of 4.6 km and core samples were collected from that depth. The casing, however, failed during recovery and the production part of the well is not accessible. The next well of the project, IDDP-3, is now being planned by OR in the Hengill area in SW-Iceland. The main lesson learned from previous IDDP wells is that there are a number of technical and geoscientific challenges that must be solved before drilling a deep well. The biggest issue is well integrity, and it is evident that a new well design is needed for successfully drilling and operating such a well. OR is now involved in an EU funded project called COMPASS with the goal of developing flexible casing concepts to mitigate thermal stresses and innovative cladding technologies for corrosion resistance of casing pipes. The IDDP consortium has also revisited the goal of the project. Previously the goal was to reach supercritical condition. Now the goal is to reach "superhot" conditions, i.e. drill into a formation where the enthalpy of the fluid is greater than 3000 kJ/kg. The deep heat utilization efforts of OR are not limited to the IDDP concept, i.e. producing fluid from deeper formations. OR is also looking into reaching the energy from deeper formations through deep injection. This concept has been called hybrid superhot EGS and the goal is to reach for the resources below the conventional resources. Injection into superhot formations below the reach of production wells of conventional high enthalpy geothermal field will create and stimulate permeability there. The injected water will then carry the heat from the deeper superhot formation towards the production wells and support the already existing production. The main advantage of the superhot hybrid EGS concept is that it can be achieved using existing well technology. When successful, this method will prolong the lifetime of conventional high enthalpy geothermal projects by enlarging the reservoir downwards and decrease the need for make-up drilling. Moreover, superhot hybrid EGS is an important milestone in developing superhot EGS. This paper will present the deep utilization journey of OR and partners with a focus on future plans, technical challenges and the work already put into solving these challenges.

1. INTRODUCTION

The Iceland Deep Drilling Project (IDDP) was launched in early 2000's. The goal was to drill a deep well (~4–5 km) into supercritical conditions (T>373.95°C, P>220.64 bar) and produce fluid from there. Preliminary estimates suggested that it would be possible to generate 50 MWe from one such well. However, it was clear from the beginning that great technical challenges must be solved before being able to achieve economically sound power production from supercritical conditions.

The idea of the IDDP was sparked by well NJ-11, that was drilled in the Nesjavellir field, in the Hengill area, SW-Iceland in 1985. That well was unexpectedly drilled into a very hot (>380°C) formation at the depth of 2.1 km. It should be noted that the upper limit of the measuring range of the probe used to measure the temperature was 380°C and the formation temperature was probably higher. In the two measurements that are available from the bottom part of the well the temperature reading was flat 380°C in the bottom part. No direct pressure measurements were done in the well. However, the bottom pressure was estimated to be higher than 220 bar, i.e., the well was drilled into supercritical conditions (Guðmundsson et al. 1985, Steingrimsson et al. 1990). Due to internal flow in well NJ-11 it was impossible to control it. The well was equipped with only ~560 m long production casing and highly permeable feed zones were located just under the casing shoe. It was not possible to stop the internal flow from deeper feed zones up to the feed zone just belove the casing. Such was the power of the internal flow that it was not possible to stop it by pumping cold water under pressure into the well. Thus, the bottom part of it had to be filled with gravel and the present depth of the well is 1600 m. Even though the deepest 500 m were filled up, the well is still one of the most powerful wells in the Nesjavellir field.

It was this incident of drilling unexpectedly into very hot formations that sparked the idea of doing it again and being prepared for the high temperature and high pressure. The three biggest power companies in Iceland, Reykjavík Energy, Hitaveita Suðunesja (now HS-Orka), and Landsvirkjun formed a consortium of domestic and international partners in order to pursue the goal of drilling into formations under supercritical conditions and produce fluid from there. The first well of the project, IDDP-1, was drilled in the Krafla field, N-Iceland in 2008. The planned depth of the well was ~4.5 km but it was unexpectedly drilled into magma at the depth of 2.1 km

(Hólmgeirsson et al. 2010). The production casing in the well was 2000 m long, so the open part of the well was approximately 100 m. Nevertheless, it was possible to do a flow test in the well and it became evident that these 100 m of open well, just above the magma, were permeable. The temperature on well-head during the flow test was 452°C at well head pressure of 142 bar. It was estimated that the power output of the well was equivalent to 30-40 MWe. However, there were major challenges in handling the fluid. It had the potential of being highly corrosive and silica in the steam condensed either as dust or scaling in pipes (Hauksson et al. 2014). The major problem was however the integrity of the production casing. Thermal expansion/contraction due to extreme temperature differences when the well heated up after drilling took place, and when it had to be shut in due to maintenance work the production casing failed. Therefore, the well had to be abandoned, but during the drilling and testing phase of the well very interesting data was collected (see e.g. Friðleifsson et al., 2021).

The next well of the IDDP was drilled in Reykjanes in 2017. It was drilled into the planned depth of ~4.6 km and core samples were collected from the deepest part of the well. The highest temperature and pressure measured in the bottom of the well during recovery were 426°C and 340 bar respectively, which is indeed supercritical (see e.g. Friðleifsson et al. 2021). However, the production casing failed shortly after, making it impossible to reach the lower parts of the well. The cause of the failure is believed to be a combination of a poorly cemented casing and the effects of thermal expansion.

Now the third well of the project, IDDP-3, is being planned in the Hengill area, SW Iceland. The emphasis has been on incorporating the lessons learned in the previous IDDP wells and other wells that have been drilled into very hot formations into the planning. The lessons learned have both been of a technical nature and a geological one. It is clear, that a conventional high-enthalpy well design is not sufficient when drilling such a well. Conventional casing materials are also not sufficient in the corrosive environment that can be found when drilling into very hot formations (Ingason and Arnason, 2023). Moreover, the geological conditions in the roots of high temperature volcanic geothermal systems, like in Iceland, are not necessary well known.

In recent years the partners of the IDDP consortium have been involved in a few research projects where the challenges of understanding and utilizing a deep hot geothermal reservoir have been addressed. Those projects are i.e., HotCaSe that was about developing a casing system for super high temperature geothermal wells and GeConnect that was about increasing the reliability of casings using flexible couplings for mitigating thermally induced stresses. Three research projects were on understanding the target, HEATSTORE, a project that was mainly focused on storing heat underground but did also tackle injection into super high temperature formations, GEOPRO that was about understanding the fluids in super high temperature formations, and DEEPEN, that was about de-risking the exploration of super high temperature formations. All the abovementioned programs have finished. The newest project titled COMPASS is about coming up with a new casing concept using foam cements and flexible couplings for stress mitigation and cladding for corrosion resistance. That project was launched in November 2022 and will conclude by the end of the year 2025.

OR is responsible for drilling the next well of the project, IDDP-3. The results from the abovementioned research projects have been incorporated into the planning of that well. The lessons learned from previous IDDP wells and other superhot wells have been compiled, technical challenges have been identified and solutions have been proposed. Moreover, new knowledge on the deepest parts of the geothermal systems has been gathered and methods to identify interesting targets for deep drilling have been investigated. Based on this work the aim of the IDDP has been repostulated and new methods of pursuing deep heat utilization have been identified.

2. LESSONS LEARNED FROM PREVIOUS SUPERHOT WELLS

2.1 Understanding the target – supercritical or superhot

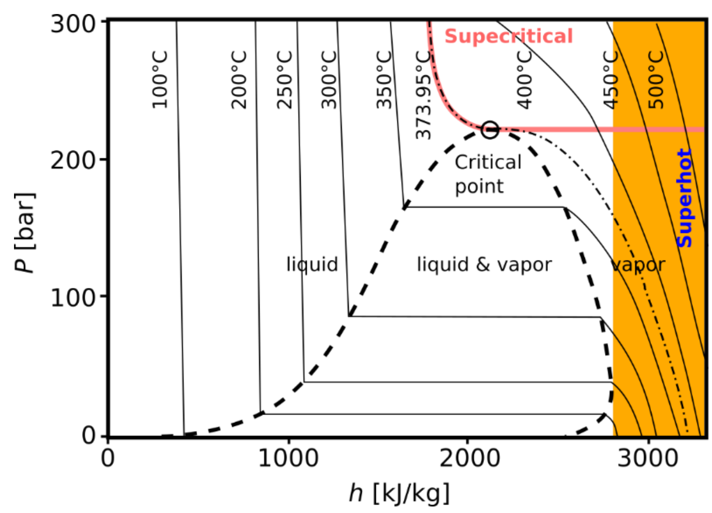

Figure 1: P-h phase diagram of water. The border of the *supercritical* regime is drawn into the chart with a pink line. The orange color area is the area where the fluid will always stay in vapor phase upon isenthalpic depressurization. This regime will be called *superhot*.

In Figure 1 a P-h phase diagram of water is shown. Isotherms are drawn into the diagram along with the two-phase envelope. It is quite helpful to look at the phase diagram this way if one wants to understand the challenges of deep drilling. When very high temperature geothermal is discussed the term *supercritical* is often used. Supercritical is when the temperature and pressure are above the critical values of those parameters (T>373°C and P>220 bar). As can be seen in the diagram in Figure 1 there are some problems with using supercritical conditions as a goal in deep drilling. The enthalpy of the supercritical state – i.e. the fluids' energy content – is not necessarily so high. Moreover, the enthalpy can decrease along the isothermal line when pressure rises. This means e.g. that supercritical fluid at 400°C has lower enthalpy when it is at a pressure of 300 bar than at 240 bar. What also can be seen when inspecting a P-h diagram is that the enthalpy in the supercritical state can be lower than of a fluid within the two-phase envelope. This means that condensation will occur if such fluid is depressurized, which is inevitable in a well bore and/or surface installations of a geothermal power plant.

Condensation of supercritical fluid is something that should be avoided at all costs. According to the experience from IDDP and other wells that have been drilled into superhot/supercritical conditions the corrosive environment is due to condensation. The steam contains a small amount of Cl gas. If condensation occurs all the Cl gas will immediately go into the droplets creating extremely acidic HCl containing droplets. In specific conditions this process can accumulate HCl rich water in the well even though the amount of Cl in the steam is relatively low. It is this process that is believed to be responsible for the corrosive environment discovered in many extremely hot wells.

Another issue with the fluid worth mentioning is dissolved silica in the steam. Solvability of silica rises with increasing pressure and when the fluid depressurizes in the well bore, silica scaling can pose a problem in the surrounding formation or in surface installations (Fridriksson et al. 2015).

2.2 Technical challenges

The technical challenges of drilling into superhot environment and producing the fluid from there are mainly of two causes: High temperatures and the chemistry of the fluid. The production casing in a superhot well will be around 2-2.5 km of length and it will be cemented at temperatures below 100°C. During recovery and later production one can expect the temperature within the well bore to increase to 450–500°C. Those extreme changes in temperature cause high stresses in casings due to thermal expansion. These stresses can deform the casing material and cause a casing failure, especially if the well must be shut in and the casings are cooled again. Casings from standard casing materials are known to fail under these extreme conditions as happened in both previous IDDP wells. Moreover, casing failures have several times been observed in conventional high-enthalpy wells. A novel solution to stress mitigation has been developed, so-called flexible couplings. The concept of flexible couplings is to allow each casing joint to expand into the coupling and thus release the axial stress caused by thermal expansion (see e.g. Kaldal and Thorbjörnsson, 2022).

As mentioned above, HCl rich droplets that are highly corrosive can form in the well bore and surface equipment. This process can create a highly corrosive environment that damages the casings made from conventional casing materials. Corrosion could be avoided by keeping the fluid within the well bore in a superheated state – i.e. in the vapor phase. However, during recovery when the well is heating up it is almost impossible to prevent some condensation of superhot fluid and thus corrosive environment.

Both of those abovementioned challenges, especially the corrosion issue, could potentially be solved using other casing materials, such as titanium alloys or advanced steel alloys (Karlsdottir et al., 2015). However, such materials are expensive and if one is going to make production of fluid from superhot formations economically viable it might be essential to look for cost effective solutions to those challenges. The quest for such a solution is currently one of the highest priorities of the Iceland Deep Drilling Project (IDDP). OR which is now leading the IDDP, is currently participating in the COMPASS research project, which is working towards such a solution. For mitigating casing failures novel foam cement solutions suitable for high temperature formations will be developed. This system would work with the abovementioned flexible couplings to mitigate high-temperature induced stresses and ensure well integrity. For corrosion resistance, cost-effective laser-cladding will be used to improve corrosion protection inside the casing pipes. The standard casing material will be coated with more corrosion resistance materials. If successful, the COMPASS well concept will pave the way towards profitable energy production from superhot resources.

3. REVISITING THE DEEP DRILLING GOALS

3.1 Choosing the target

The original goal of the IDDP was to drill down to supercritical conditions. However, as discussed above, the term supercritical is not always helpful when it comes to the energy content of the fluid, as supercritical fluid can have lower enthalpy than saturated steam at subcritical pressure levels. That means that the fluid can condense upon isenthalpic depressurization and the condensation causes corrosion. Condensation in the well bore should therefore be avoided at all costs and in order to do so *superhot* targets should be chosen. The goal of the IDDP should be to produce from superhot formations instead of supercritical. The criteria should be the energy content of the fluid not its state in the reservoir. So now the goal of the 3rd IDDP well is phrased as: *The goal of the IDDP-3 well is to identify and drill into a feasible superhot (h>2800 kJ/kg) target and solve the technical challenges of producing fluid from those targets in an economically sound way* (IDDP consortium, 2022).

Aiming for superhot instead of supercritical makes it possible to drill into shallower hot formations as one is not required to drill down to the depths of supercritical pressure (>220 bar). An important advantage of not going deeper where the pressure is higher is that solvability of silica is higher with higher pressure. Thus, if production from superhot conditions at lower pressures (from shallower sources) is possible, silica scaling will not pose a significant challenge. There are a few examples in Iceland of formations at high temperatures (>350°C) at depths around 2 km. The most prominent of these formations is the magma body that was drilled into in well IDDP-1. When reviewing down-hole data from the Hengill area, i.e., the intended site for the next IDDP well, it has been discovered that there are indications of superhot conditions in a few places there. One of those places is the site of well NJ-11 in Nesjavellir that was mentioned earlier, where a temperature of more than 380°C was measured (see Figure 2(a)). Recently, evidence of superhot conditions was found again in Nesjavellir, in well NJ-32 that was drilled in the vicinity of well NJ-11. High temperature (354°C) and corrosive environment were observed in the bottom part of that well (Fridriksson et al., 2022). Indications of superhot conditions have also been discovered in well HE-65 in the center of the Hellisheiði field. When the slotted liner was removed from the well during a redrilling operation in 2021 the lowest part of the liner was missing. A photo of the end of the recovered liner is shown in Figure 2(c). The depth of the corroded end was 2050 m, and such corrosion is a clear indication of the existence of superheated steam at that depth (see e.g. Gunnarsson et al., 2022 and Fridriksson et al 2022). In the Hverahlíð field, in the southernmost part of the geothermal fields in the Hengill area, measurements in well HE-21 have indicated a proximity of a hot formation. Higher temperatures (up to 337°C) were measured in the bottom of the well when it was logged after it has been flowing (see Figure 2(b)).

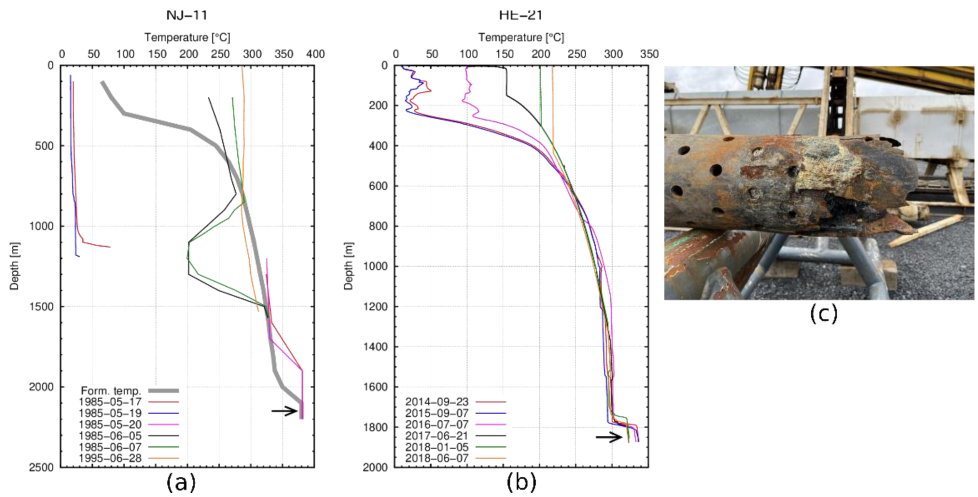

Figure 2: Evidence of superhot formations in the Hengill Area. (a) Temperature logs in well Nj-11 in Nesjavellir where the temperature reached >380°C. (b) Temperature log in well NJ-21 in Hverahlíð in the southern edge of the Hengill area. Step in temperature is visible after the well had been flowing for longer periods of time. (c) A corroded end of recovered liner from HE-65 in the center of the Hellisheiði field.

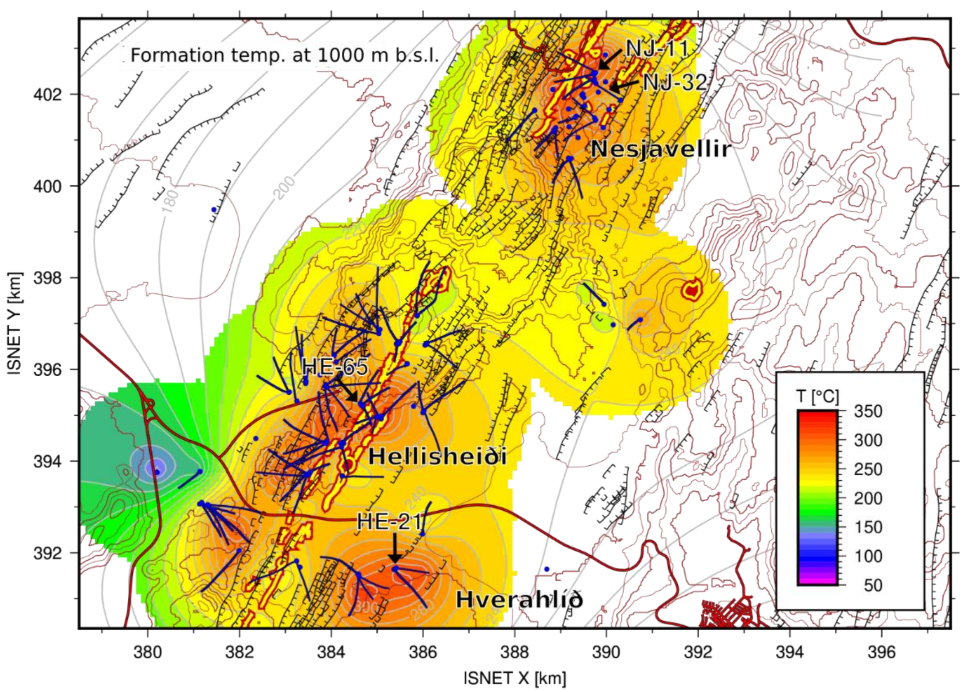

Figure 3: Estimated formation temperature in the Hengill area. Four wells where evidence of superhot shallow (~2 km depth) formations have been observed are shown on the map.

The locations of the abovementioned wells in the Hengill area where evidence of superhot formations have been found are shown in Figure 3, along with the estimated formation temperature at 1000 m b.s.l. As can be seen, the formation temperature is characterized by relatively sharp structures with narrow hot areas separated by cooler ones. This has been interpreted as evidence of shallow heat sources and/or sharp changes in permeability. There are also other clues of superhot formations in the area not mentioned here.

To summarize, it likely that superhot formations can be found at relatively shallower depths in numerous places in volcanic geothermal systems in Iceland. Thus, the most promising target for an IDDP well, i.e. a superhot production well, is a relatively shallow (2-2.5 km) superhot formation. Locating such a target is an interesting challenge, which was the subject of the DEEPEN project. The goal of that project was to better understand the roots of magmatic geothermal systems through observations and modeling, as well as to develop techniques and work flows to find such deep and superhot resources.

3.2 Different production scenarios

The focus of the IDDP is to produce fluid from superhot formations. However, as mentioned above, producing fluid from such formations is not the only way of extracting heat from there. In Figure 4 different production scenarios for extracting heat from deeper superhot layers are shown. In Figure 4(a) the IDDP concept, the deep producer, is depicted. The well is isolated from the upper conventional reservoir by a long casing and the fluid is produced from formations below. In Figure 4(b) deep injection is depicted. As in the case of the deep producer the conventional system is isolated from the well by a long casing. Thus, the water is injected into the hot formation below the production wells. The goal is to provide pressure support for the conventional production above and flush the heat from below upwards towards the production wells. Therefore, the injection will not only provide mass recharge to the conventional system, but also energy recharge. In Figure 4(c) a superhot injector-productor well duplet, representing a superhot EGS, is depicted. As in the previous examples both of those deep wells are isolated from the conventional system by long production casings. Thus, the thermal stimulation of permeability will occur below the casing shoe. This case, i.e., the superhot EGS, requires the most advantage technology for implementation – both for choosing the target and drilling and operating the wells. However, this method could be applied in more geological settings than volcanic geothermal systems in a rift zone of Iceland.

The superhot injector (Figure 4(b)) is something that can be achieved using "off the shelf" geothermal well technology which makes it a logical option for studying superhot formations further. Moreover, this option is probably a necessary interlude in the quest for both a superhot producer and superhot EGS.

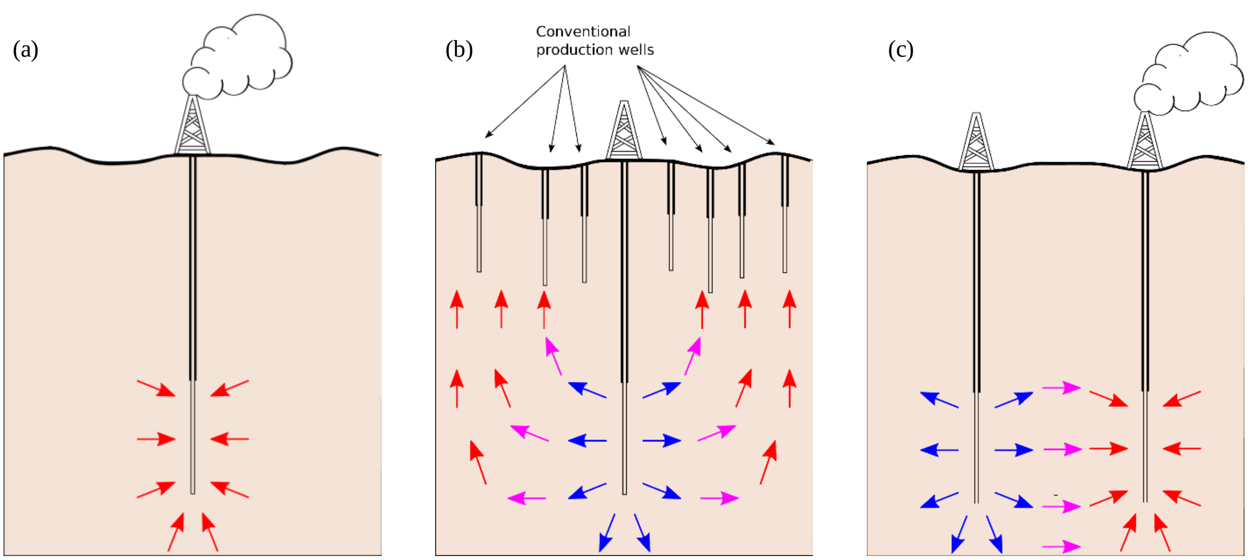

Figure 4: Different production scenario from superhot formation. (a) Direct production from superhot formation. The upper layers of the geothermal system are isolated from the well by a long production casing. (b) Deep injection. Superhot hybrid EGS. (c) Supehot Engineered Geothermal System (EGS).

4. HYBRID SUPERHOT EGS

Recently OR and subsidiaries have started to take a broader approach to deep heat utilization. The goal is now to produce energy from the superhot formations below the conventional production field without limiting oneself to one particular method. The work towards the superhot producer will continue in the context of the IDDP project. OR will also investigate other feasible methods of producing energy from the deeper formations. Drilling a deep injector (see Figure 4(b)) is possible using the currently available technology. According to present knowledge on high enthalpy geothermal reservoirs in the volcanic active area in Iceland this method might be a viable solution in getting the heat from the depths in an economically sound way. Moreover, a deep injector is believed to be a necessary milestone in the quest for a superhot production well and superhot EGS (Figure 4(c)).

As postulated, the deep injector is essentially one end of a well pair in a superhot EGS. Given its operating principles are similar to those of superhot EGS, it has been given the working title *hybrid superhot EGS*. This method will test the hypothesis that injection of cold water into superhot formation can create and maintain permeability though thermally induced creation and opening of fractures. Heat extraction in the roots of high-enthalpy geothermal systems through such processes has been described by Lister (1974) and recently by Halldórsdóttir et al. (2023).

Preliminary studies on the concept of hybrid superhot EGS have shown that it can benefit the production from the conventional production wells if water is injected into the superhot formations below (Yapporova et al. 2022). Moreover, studies done within the GEOPRO project indicated that deep injection would be economically beneficial for the existing production above. Operational data from Hellisheiði also suggest that hybrid superhot EGS could benefit the existing production.

Since late 2014, the operations of the Hellisheiði field have been experimenting with in-field injection. Due to a lack of injection capacity, three "unsuccessful" production wells were converted to injection wells (Gunnarsson and Mortensen, 2016). The locations of those wells (KhG-1, HE-13 and HE-40) are shown on the map in Figure 5(a). The most interesting of those injection wells "converts" is HE-40, which is directionally drilled under a production well, HE-06, close to the center of the field (see Figure 5(a)). Several temperature measurements from that well and estimated formation temperature are shown in Figure 5(b). Permeable feed zones are located relatively shallow in the well or at the depth of 500–750 m below sea level. The deepest part of the well is very hot (> 300°C) but the feed zones there have low permeability. It should be noted that this elevated temperature in the bottom part was only visible during flow tests.

During operation, the upper feed zones yield most of the produced fluid. Below them the well is normally full of water. However, the lower feed zones yield a small amount of hot fluid into the lower part of the well, slowly heating the water column until it reaches boiling point curve. When the water column reached boiling point curve, it boiled, causing the well's output to increase while the water was boiling off. The lower feed zones were not powerful enough to maintain the boiling in the water column below the upper feed zones so after the boiling incident it was filled with colder water which started to heat up again. This resulted in a pulsing well which was almost impossible to operate.

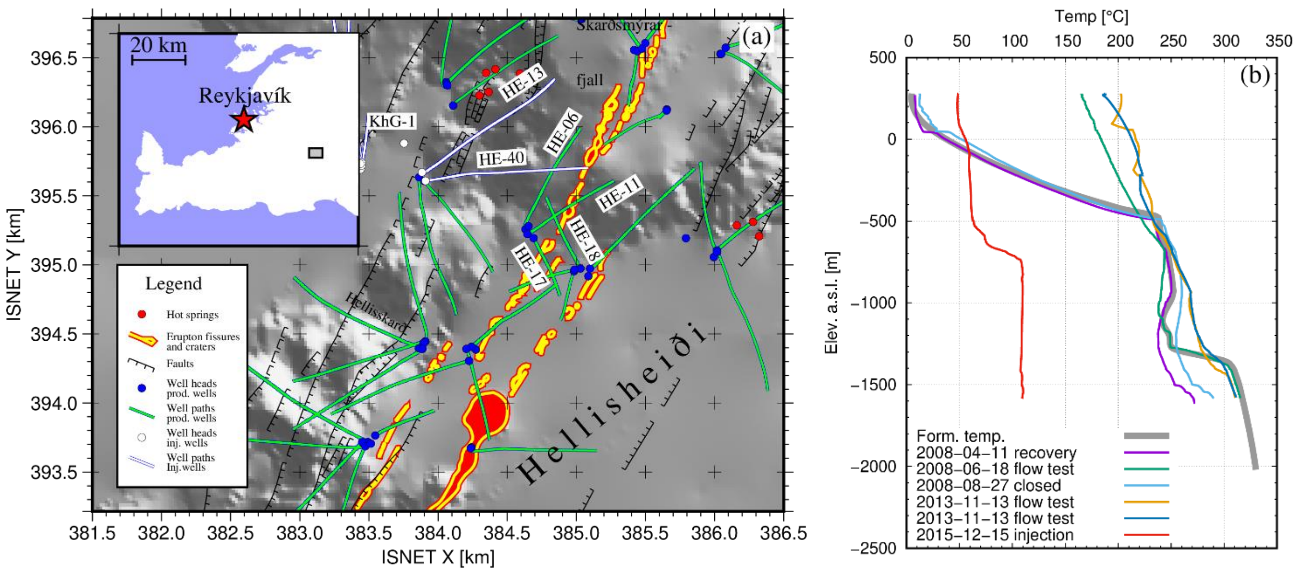

Figure 5: (a) A map showing the location of in-field reinjection wells in the center of the Hellisheiði field, SW-iceland, which is located ~25 km East of Reykjavík (see inset). The reinjection wells are close to powerful production wells, e.g. injection well HE-40 is drilled under production well HE-06. (b) Few temperature logs from well HE-40. Note that the high temperature in the bottom was only visible during flow tests.

The operation of the in-field injection wells started slowly. The aim was to provide pressure support to the center of the field where the production density is high, without causing thermal breakthrough (Gunnarsson and Mortensen, 2016). The neighboring production wells, which are some of the most powerful production wells of the Hellsheiði Field (HE-06, HE-11, HE-17, and HE-18), were monitored closely.

When looking at the temperature logs done during injection (the measurement from December 15, 2015) the cooling due to injection reaches the bottom of the well. The upper feed zones from 550 m down to 750 m below sea level yield a considerable amount of fluid into the well as can be seen from increasing temperature. The water then flows down to the feed zones in the bottom of the well, the same feed zones that turned out to be poor during flow tests.

This drastic change in the permeability of the bottom feed zones of the well when injecting into it is something that has been observed in other injection wells in the Hengill area. Studies done in reinjection wells have shown that their permeability, or more specifically their injectivity index, is highly dependent on the temperature of the injected water, the colder the water the higher the permeability. The permeability of the reservoir is fracture dominated and this temperature dependent permeability is believed to be due to opening of fractures when the injected water cools the surrounding rocks (Gunnarsson, 2013; Gunnarsson, 2011). One can expect that as the temperature difference between the formation and the injected water is higher, the bigger is the increase in permeability of the formation.

This process of increasing permeability due to opening of fractures as the formation cools and contracts is a key element in Lister's (1974) description of how water penetrates hot rock. A cold front migrates into hot ductile rocks. As the rock cools below the brittle-ductile transition, fractures are formed, and they open as the rock cools further. The water circulation can flow along the newly formed fractures carrying the heat away, cooling the formation further and enhancing the permeability as the rock contracts and the fractures open. Halldórsdóttir et al. (2023) have further elaborated on this process using numerical simulations.

It has been speculated that injection into IDDP-1, that was as mentioned above, drilled into magma, has stimulated permeability in the hot formation close to the magma by speeding up processes as described by Lister (1974) creating a Magma-EGS system (Friðleifsson et al. 2021). It was, however, not possible to verify if the permeability in the open part of IDDP-1 was originally there or created by the injection. It can also be argued that the injection in well HE-40 has partly proven the concept of hybrid superhot EGS. The low permeability of the bottom feed zones of the well has increased significantly due to injection of cold (~50°C) water. Moreover, no thermal break-through has been observed in neighboring production wells, even though HE-40 is drilled below the production well HE-06 (see Figure 5(a)). This injection in well HE-40 has been nicknamed "proto superhot injection" and preliminary studies on the effect of the in-field injection have shown that it has benefitted the production in its vicinity and the risk of it is acceptable (Gunnarsson, 2023). Those results along with the results of the modelling studies of Yapporova et al. (2023) mentioned above indicate that the hybrid superhot EGS concept is a viable option for utilizing heat from superhot resources below conventional high-enthalpy geothermal fields.

5. SUMMARY AND CONCLUSION

The IDDP project has been ongoing since the early 2000's. The original goal of the project was to drill down to 4-5 km and produce supercritical fluid. Two wells have been drilled in the project, IDDP-1 in Krafla, and IDDP-2 in Reykjanes. IDDP-1 was drilled into magma at the depth of ~2.1 km. Although drilled into magma, it was possible to perform flow tests in the well. The temperature was 452°C at well head pressure of 142 bar. The estimated power output was 30-40 MWe. However, the production casing was damaged and the well had to be abandoned. IDDP-2 reached the planned depth of ~4.6 km. Supercritical conditions were measured in the well and core samples were recovered from its bottom part. Unfortunately, the casing failed while the well was heating up and its production part was not accessible. Moreover, it has not been possible to do flow tests in that well.

The next well of the project, IDDP-3, is now being planned in the Hengill area, SW-Iceland. Evidence of superhot formations at ~2 km depth has been observed in a few wells in the area. Thus, it should be possible to find a suitable target. Compiling lessons learned from previous IDDP wells and other wells that have been drilled into superhot formations is an important part of the preparation of the next well.

The goal of the IDDP was redefined according to the lessons learned during the project. Drilling into and producing from supercritical formations is no longer the goal. The target is now superheated (h > 3000kJ/kg). The enthalpy, i.e. the energy content, of the fluid in the formation is now what matters, not the state of the fluid in the formation. Thus, superhot formations at shallower depths (~2 km) are now preferrable targets because the pressure there is likely to be below supercritical pressure. Moreover, the silica content of the produced fluid would be lower if high enthalpy fluid could be produced from shallower (i.e. lower pressure) formations, thus scaling should be a lesser concern.

Conventional well technology is insufficient for producing fluid from superhot formations. New well technology that can handle the corrosive environment and extreme temperature differences needs to be developed. Moreover, such technology must be economically sound, i.e., the benefits of using it must outweigh the costs. The aim of the COMPASS project is to come up with such a solution using flexible casing systems for stress mitigation and cladding for corrosion mitigation.

Production from superhot formations is not the only option of harnessing the energy from there. OR has been working on so called hybrid superhot EGS. That is practically injecting into superhot formations below conventional well depths. The injection will provide pressure support to the existing production above and recharge the reservoir with hot fluid heated by the deeper formations. Preliminary studies show that this method is a viable option for deep heat utilization and the biggest advantage of hybrid superhot EGS is that it can be achieved using "off the shelf" well technology. Moreover, we believe that hybrid superhot EGS is a necessary milestone in the quest for a superhot producer and a superhot well duplet, i.e. superhot EGS.

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