A geothermal well in southwest Iceland has successfully penetrated a supercritical regime - an update on the Iceland Deep Drilling Project

Wilfred A. Elders[1] and G.Ó. Fridleifsson[2]
[1]Department of Earth Sciences, University of California, Riverside, CA 92521, USA. Email: wilfred.elders@ucr.edu. [2]HS Orka, Svartsengi 260, Iceland.

ABSTRACT

The Iceland Deep Drilling Project (IDDP) is exploring the technical and economic feasibility of producing supercritical geothermal resources. In 2016 the IDDP-2 well was drilled in the Reykjanes saline geothermal system in southwestern Iceland, on the landward extension of the Mid-Atlantic ridge, where we can study an analogue of the root zone of a black smoker. In 2009, Phase 1 of the IDDP was unsuccessful in reaching supercritical conditions in the Krafla volcanic caldera in northeastern Iceland when the IDDP-1 well unexpectedly encountered a rhyolitic magma of 900°C at a depth of only 2.1 km. The wellhead temperature was 453°C with sufficient enthalpy and flow to generate ~35 MWe.

In August 2016, Phase 2 of the IDDP-2 began by deepening an existing production well of 2.5 km depth to a total depth of 4659m. Below 3.3 km depth total losses of circulation occurred that could not be cured by lost circulation materials of by multiple attempts at cementing. Consequently, the drilling continued 'blind' to full depth, with no return of drill cuttings. We made 13 attempts to take drill cores below 3 km deep, half of which recovered some cores. These cores are basalts and dolerites with alteration that ranges from green-schist facies to hornblende hornfels (lower amphibolite) facies, which suggests temperatures of metamorphism >450°C. Following an initial report on IDDP-2 drilling, scheduled for mid-2017, IDDP's scientific team and collaborators will conduct detailed petrological, petrophysical and geochemical analyzes of cores and results will be reported in a special issue of a major scientific journal.

When drilling was completed, early in January 2017, we measured temperature, pressure and injectivity after only 6 days of heating. Supercritical conditions were measured at the bottom of the well of 427°C at 340 bar pressure. These logs showed the main permeable zones at depths of 3360m, 4200m, 4370m and 4550m. Estimates suggest that ~30% of 40 l/s injected into the well entered the three deeper feed zones. We will try to improve this permeability by continuing massive stimulation by injecting cold water with the objective of demonstrating the feasibility of enhanced geothermal systems (EGS) at high temperatures.

While it is too early to speculate on the energy potential of this well and its economics, the IDDP-2 is a milestone in the development of geothermal resources and the study of hydrothermal systems. It seems to be the first well that successfully penetrated supercritical conditions, with potentially very high power output, and in which the contact metamorphism in the action of lower amphibolite facies can be observed. The drilling of the IDDP-2 was funded by the field operator HS Orka, by the industrial consortium of IDDP, and by the oil company Statoil. The International Continental Drilling Program and the IDDP scientific program funded the core drilling.

Keywords: Supercritical geothermal resources, Reykjanes, Iceland, Iceland Deep Drilling Project, IDDP.

Un pozo geotérmico en el suroeste de Islandia penetra un régimen supercrítico - Una actualización sobre el Proyecto de Perforación Profunda de Islandia

RESUMEN

El Proyecto de Perforación Profunda de Islandia (Iceland Deep Drilling Project, IDDP) está explorando la factibilidad técnica y económica de producir recursos geotérmicos supercríticos. En 2016 se perforó el pozo IDDP-2 en el sistema geotérmico salino de Reykjanes, en el suroeste de Islandia, en la extensión terrestre de la dorsal del Atlántico Medio, donde se puede estudiar un análogo de las raíces de una ventila hidrotermal submarina. En 2009, la Fase 1 del IDDP no tuvo éxito en alcanzar condiciones supercríticas en la caldera volcánica de Krafla, en el noreste de Islandia, cuando el pozo IDDP-1 encontró inesperadamente un magma riolítico a 900°C a una profundidad de sólo 2.1 km. La temperatura medida en el cabezal del pozo fue de 453°C con suficiente entalpía y flujo para generar unos 35 MWe.

En agosto de 2016 comenzó la Fase 2 del IDDP, con la profundización de un pozo productor previo de 2.5 km de profundidad hasta una profundidad total de 4659 m. Se encontraron pérdidas totales de circulación abajo de 3.3 km de profundidad que no pudieron ser taponadas pese a múltiples intentos, por lo que la perforación continuó a fondo perdido sin retorno de los recortes de perforación. Si realizaron 13 intentos de cortar muestras de núcleo a profundidades mayores de 3 km de profundidad. En la mitad de los intentos se recuperaron algunos núcleos con muestras de basaltos y diabasas (doleritas) con alteración hidrotermal que va desde la facies inferior de esquistos verdes hasta la facies de hornfels de hornblenda (anfibolita inferior), lo que sugiere temperaturas de metamorfismo >450°C. Después de un informe inicial sobre la perforación del pozo IDDP-2, previsto para mediados de 2017, el equipo científico y colaboradores del IDDP llevará a cabo análisis petrológicos, petrofísicos y geoquímicos detallados en núcleos, cuyos resultados se publicarán en un número especial de alguna revista científica especializada.

A principios de enero de 2017, cuando se concluyó la perforación, se midió la temperatura, la presión y la inyectividad con sólo seis días de calentamiento. Se midieron condiciones supercríticas al fondo del pozo, con 427ºC de temperatura y 340 bar de presión. Los registros de temperatura revelan que las principales zonas permeables están alrededor de los 3360 m, 4200 m, 4370 m y 4550 m de profundidad. Se estima que el 30% de un volumen de 40 l/s inyectado en el pozo se absorbió en las tres zonas de alimentación más profundas. Se intentará mejorar esta permeabilidad mediante una estimulación masiva, inyectando agua fría, con el objetivo de demostrar la factibilidad de desarrollar sistemas geotérmicos mejorados (EGS) a elevadas temperaturas.

Si bien es demasiado pronto para especular sobre el potencial energético y económico de este pozo, el IDDP-2 puede representar un hito en el desarrollo de los recursos geotérmicos y el estudio de los sistemas hidrotermales. Parece ser el primer pozo que alcanzó con éxito condiciones supercríticas, con un potencial de producción muy alto, y en el cual se pueden observar condiciones de metamorfismo de contacto en facies de anfibolita inferior. La perforación del pozo IDDP-2 fue financiada por la compañía que opera el campo geotérmico, HS Orka, por el consorcio industrial IDDP y por la petrolera noruega estatal Statoil. La obtención de los núcleos fue financiada por el International Continental Drilling Program y por los el programa científico del IDDP.

Palabras clave: Recursos geotérmico supercríticos, Reykjanes, Islandia, Iceland Deep Drilling Project, IDDP.

Introduction

The Iceland Deep Drilling Project passed a significant milestone in the geothermal industry when its

IDDP-2 well at the Reykjanes Peninsula in Iceland reached the depth of 4659 meters on the 25th of January 2017, after 168 days of drilling. The IDDP-2 achieved its initial targets: (a) to drill deep enough to reach supercritical conditions (4 to 5 km), (b) to measure the fluid temperature and pressure, (c) to search for permeability, and (d) to recover drill cores. After only 6 days of heating, the temperature measured at the bottom of the well was ~427°C, with fluid pressure of 340 bars, and indications of permeability at depth (Figure 1; all figures at the end of the text), and drill cores were retrieved. It is clear that the bottom of the well reached fluids at supercritical conditions, so that the main objective of the drilling phase of the project had been achieved.

The critical point of fresh water occurs at 374°C and 221 bars. The reservoir fluids currently produced from the Reykjanes field have a salinity of seawater which has a critical point of the 406°C at 298 bars (Bischoff and Rosenbauer, 1988). The fluids at the bottom of the IDDP-2 well when the PT log shown in Figure 1 was measured, were a mixture of injected surface water and formation fluid. Although we do not yet know the salinity of this mixture, it is hard to argue that it was not at supercritical conditions during the logging operation.

The Iceland Deep Drilling Project (IDDP)

The IDDP is a long-term project by a consortium of Icelandic energy companies, aimed at greatly increasing the production of usable geothermal energy by drilling deep enough to reach the supercritical conditions believed to exist beneath existing high-temperature geothermal fields in Iceland (Friðleifsson and Elders, 2005; Friðleifsson, Elders, and Albertsson, 2014). Modeling indicates that a well producing from a supercritical geothermal reservoir could produce an order of magnitude more usable energy than that produced by a conventional high-temperature (~300°C) geothermal well. This is because of both the higher enthalpy of supercritical fluid and its more favorable flow properties, due to its very low viscosity.

When the IDDP consortium was formed, three geothermal fields in Iceland were chosen as suitable to search for supercritical resources, Krafla in the north-east of Iceland, and Hellisheidi and Reykjanes in the south-west (Figure 2, inset). The first attempt to drill into a super critical reservoir was made in 2009 in the Krafla caldera, but the IDDP-1 well did not reach supercritical fluid pressures because drilling had to be suspended at a too shallow depth (Elders, et al., 2009). This is because 900°C rhyolite magma flowed into the well at only 2100 m depth. However, the IDDP-1 was completed with a liner set above the rhyolite intrusion. When the well was tested, it produced superheated steam at 452°C at a flow rate and pressure sufficient to generate about 35 MWe. After two years of flow testing, unfortunately repair of the surface installations was necessary, and the well had to be quenched due to failure of the master valves. This caused collapse of the well casing and abandonment of the well.

The IDDP-2

The IDDP consortium then decided to make the Reykjanes geothermal system the focus of its next attempt at drilling to supercritical conditions (Friðleifsson, Elders, and Bignall, 2013). This geothermal field lies near the southern tip of the Reykjanes Peninsula, which is the landward extension of the Mid-Atlantic Ridge. Some 34 production, injection, and observation wells supply steam to a 100 MWe power plant, from a 300°C reservoir at 1 to 2.5 km depth. It is unique among Icelandic geothermal systems in that its reservoir fluid is modified seawater, and that seawater is used to cool its steam condensers. Figure 2 shows a conceptual model of the drilling target of the IDDP-2 well, based on the existing extensive well and geophysical data.

The IDDP-2 well took advantage of an existing production well, the RN-15, which was 2500 meters deep. This well was deepened and cased to 3000 m depth and then deepened to the total depth of 4659 m. The deepest existing geothermal wells at Reykjanes are about 2.5 deep. The IDDP-2 has the deepest casing and is also the deepest well in Iceland. Figure 3 is a map showing the track of the well as it was drilled, together with the tracks of existing wells.

The IDDP-2 was drilled vertically down to 2750 meters and below that drilled directionally to the southwest to intersect the main upflow zone of the Reykjanes system as indicated by geophysical surveys. The bottom of the well has a vertical depth of about 4500 meters, and is situated 738 meters southwest of the well head.

Various challenges arose as the drilling progressed; there were weather delays, problems with hole stability that required frequent reaming, and the drilling assembly becoming stuck several times. Each instance was successfully solved as it happened. However, the major unsolved problem was a complete loss of circulation below 3060 m depth that could not be cured with lost circulation materials, or by multiple attempts to seal the loss zone with cement. As cementing was not successful, below 3180 m, drilling continued without any return of drill cuttings to the surface. Consequently, the drill cores were the only deep rock samples recovered.

In the beginning, we had difficulties recovering drill cores and overall only a total of 27.3 meters of core were retrieved in 13 attempts. These cores indicate that the IDDP-2 drilled through a basaltic sheeted dike complex that shows progressive metamorphism from green-schist, to lower amphibolite facies, consistent with hydrothermal alteration at temperatures of up to 450°C, with low water/rock ratios. The deepest core, returned from the bottom of the well, is quite fresh dolerite, with minor intrusions of felsite. The main indications of hydrothermal alteration in this rock are quartz + biotite + hematite mineralization on fracture surfaces.

Another interesting aspect of the temperature log in Figure 1 is that, in addition to the major loss zone at 3400 m, there are lesser permeable loss zones at 4450 m and just below 4500 m depths. After that PT logging run, a 7” slotted hanging liner was inserted to the bottom. Subsequently a 7” sacrificial casing was lowered from surface down to 1,300 m, and cemented up to the surface. Casing shoes were then drilled out and the well deepened by 6” bits, ending with three successive coring runs to the 4659 m final depth.

After the deepest coring run, a 3½” drill string was lowered to the bottom of the hole. The aim is to enhance the permeability deep in the hole by pumping in cold water for several months through the 3½” drill string. There are already some positive indications of enhancement of injectivity. Tests made after the last coring runs showed that cold water injection increased the injectivity index from 1.7 (l/s)/bar to 3.1 (l/s)/bar. We expect that continued deep stimulation with cold water is likely to further improve the fracture permeability at depth.

While this ‘soft’ stimulation is going on, a surface test bed, with two parallel flow lines, will be designed and constructed ready for long term flow testing. Only after these fluid handling and flow tests are concluded can we determine the nature of the formation fluids, their enthalpy and flow characteristics, and hence estimate their engineering and economic potential. The total loss of circulation below 3 km depth was unexpected, but the existence of large permeability, a kilometer deeper than the current production zones at Reykjanes, may have implications for the future development of the geothermal resource that are independent of supercritical production.

Significance of the IDDP-2

The geological environment of the Reykjanes geothermal field is of great interest to the scientific community, situated as it is on the landward extension of the Mid-Atlantic Ridge that forms part of the world-encircling system of divergent plate boundaries, or oceanic spreading centres (Elders and Friðleifsson, 2010). These are regions of frequent volcanic eruption, high heat flow, and submarine hot springs. The IDDP-2 is a unique opportunity to examine the roots of a black smoker.

In future, our demonstration that it is possible to drill into a supercritical zone could have a large impact on the economics of high-temperature geothermal resources worldwide. By extending the available economic reservoir downwards we can extend the lifetimes of existing producing fields. As higher enthalpy fluids have greater power conversion efficiencies, fewer turbines are required for a given power output. Similarly, as fewer wells are need for a given output, we can increase the productivity of a geothermal field without increasing its environmental footprint.

Iceland is fortunate in having several likely sites for such developments. Planning for drilling the IDDP-3 well at Hellisheidi is already underway, and, subject to the availability of funding, drilling could begin in 2020. However supercritical conditions are not restricted to Iceland, but should occur deep in any young volcanic-hosted geothermal system. Deep wells drilled in geothermal fields such as Kakkonda in Japan, Larderello in Italy, Los Humeros in Mexico, and The Geysers and Salton Sea in USA, have encountered temperatures above 374°C. Development of supercritical geothermal resources could be possible there and in many other volcanic areas worldwide.

More information on the IDDP can be found at www.iddp.is and at www.deepegs.eu.

Acknowledgements

The IDDP-2 was funded by HS Orka, Landsvirkjun, Orkuveita Reykjavíkur, and the National Energy Authority in Iceland, together with Statoil, the Norwegian oil and gas company. The IDDP has also received funding from the EU Horizon 2020 (project DEEPEGS), and science funding from ICDP and the US National Science Foundation. The drilling contractor was Iceland Drilling Company.

References

Bischoff, J.L., and R.J. Rosenbauer, 1988. Liquid-vapor relations in the critical region of the system NaCl-H_2O from 380°C to 414°C: A refined determination of the critical point of seawater. *Geochimica et Cosmochimica Acta,* 52*, pp.* 2121-2126.

Dobson, P., H. Asanuma, E. Huenges, F. Polletto, T. Reinsch, and B. Sanjuan, 2017. Supercritical Geothermal Systems - A Review of Past Studies and Ongoing Research Activities. *Proceedings, 41st Workshop on Geothermal Reservoir Engineering,* Stanford University, Stanford, California, February 13-15, 2017. SGP-TR-212.

Elders, W.A., and G.Ó. Friðleifsson, 2010. Implications of the Iceland Deep Drilling Project for improving understanding of hydrothermal processes at slow spreading mid-ocean ridges. *In:* Diversity of Hydrothermal Systems on Slow Spreading Ocean Ridges. *American Geophysical Union, Geophysical Monograph Series, 188,* pp. 91-112.

Elders, W.A., G.Ó. Friðleifsson, R.A. Zierenberg, E.C. Pope, A.K. Mortensen, Á. Guðmundsson, J.B. Lowenstern, N.E. Marks, L. Owens, D.K. Bird, M. Reed, N.J. Olsen, and P. Schiffman, 2011. Origin of a rhyolite that intruded a geothermal well while drilling in a basaltic volcano, at Krafla, Iceland. *Geology,* 39, No. 3, pp. 231-234.

Friðleifsson, G.Ó., and W.A. Elders, 2005, The Iceland Deep Drilling Project: A search for deep unconventional geothermal resources. *Geothermics,* 34, pp. 269–285.

Friðleifsson, G.Ó., W.A. Elders, and G. Bignall, 2013. A plan for a 5 km-deep borehole at Reykjanes, Iceland, into the root zone of a black smoker on land. *Scientific Drilling*, 16, pp. 73-79.

Friðleifsson, G.Ó., W.A. Elders, and A. Albertsson, 2014. The concept of the Iceland Deep Drilling Project. *Geothermics*, 49, pp. 2-8.

FIGURES IN THE FOLLOWING PAGES

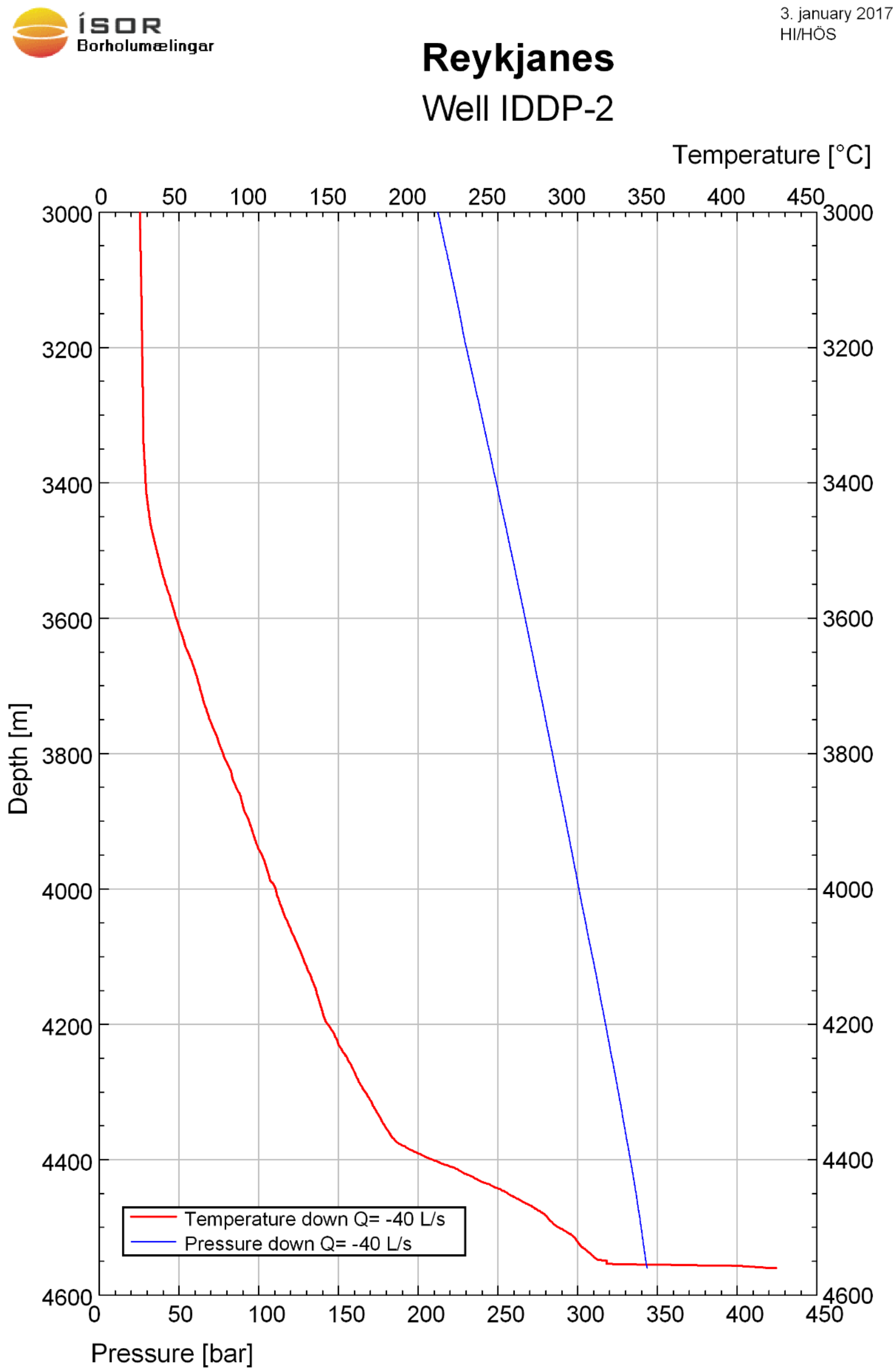

Figure 1. Temperature and pressure log to 4560 m depth in IDDP-2 after only 6 days of heating. As can be seen from the temperature profile, because of cold water injection, the well is far from thermal equilibrium. When thermal recovery is complete, it is likely that temperatures will exceed the estimated 427° C measured at the bottom of the hole. The PT logging was done with a K-10 logging tool, which was calibrated to only 380° C. (Source ISOR logging group.)

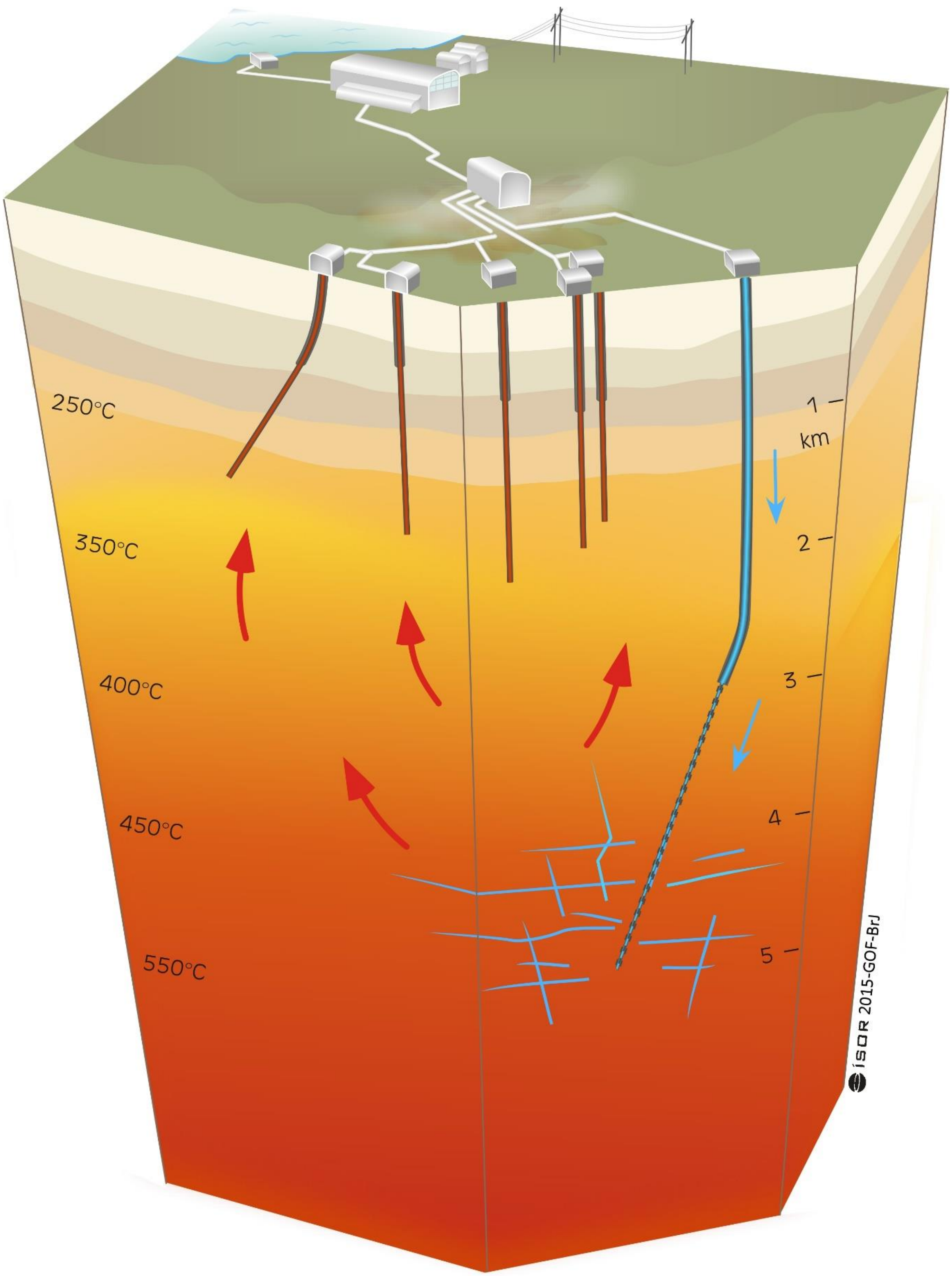

Figure 2. Conceptual model of the roots of the Reykjanes Geothermal field indicating existing wells (brown) and the track of the IDDP-2 well (blue) to intersect the supercritical zone beneath the producing reservoir.

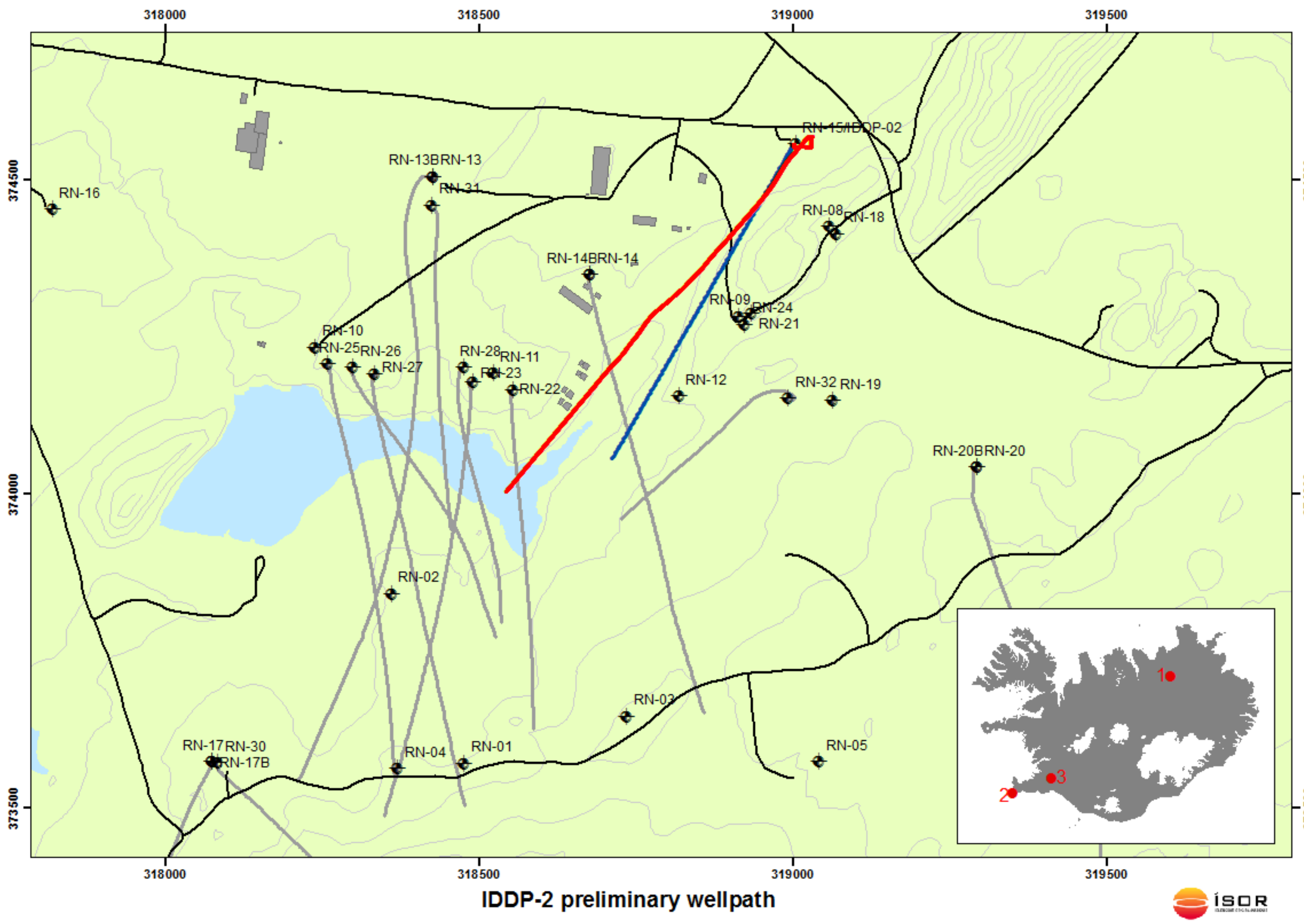

Figure 3. The locations and tracks of wells in the Reykjanes geothermal field. The red line shows the track of well RN-15/IDDP-2. The inset (bottom right) shows the location of the Reykjanes, Helisheidi and Krafla geothermal fields.