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Drilling into the Roots of the Reykjanes Geothermal Field – the IDDP-2 drilling

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ABSTRACT

Drilling of RN-15/IDDP-2 in the Reykjanes geothermal field in southwest Iceland, was carried out in 2016 and 2017. With a total measured depth of 4650 m the well RN-15/IDDP-2 marks the deepest well drilled in Iceland to date. Drilling was completed in 168 days by deepening the pre-existing production well RN-15, which had previously been drilled in 2004 down to 2507 m. During drilling of RN-15/IDDP-2 a total loss of circulation occurred between 2507 and 3000 m and below 3200 m. In addition, 13 core runs were conducted during drilling of phase 4 and 5. In order to construct a geological model for the deep well, drilling performance and data is evaluation, which is validated with core observation. Further, feed zones are identified and related to the structural framework of the Reykjanes geothermal field. The high-temperature conditions indicate by core observations was confirmed by a temperature and pressure log reaching supercritical fluid conditions that was carried out on January 3rd, 2017, yielding a minimum temperature of 426°C and pressure of 340 bar.

1. INTRODUCTION

The drilling scheme is part of the Iceland Deep Drilling Project (IDDP), which aims to drill deep wells down to 4–5 km depth into geothermal systems in Iceland (Friðleifsson and Albertsson, 2000; Friðleifsson et al., 2014a, b). The IDDP consortium was established in 2000 (Friðleifsson and Albertsson, 2000) to investigate the feasibility and economics of deep, high-enthalpy geothermal resources, and especially supercritical hydrothermal fluids, as possible energy sources. The first well in the series, IDDP-1, was drilled in 2008–2009 within the Krafla geothermal field in NE Iceland (Hólmgeirsson et al., 2010; Pálsson et al., 2014). However, the drilling of the IDDP-1 well had to be terminated at a depth of 2104 m when it intersected >900°C magma (Hólmgeirsson et al., 2010; Pálsson et al., 2014).

It was decided to drill the second well in the series, IDDP-2, in the Reykjanes geothermal field, which is exploited by HS Orka for power producation. The chief motivation of HS Orka to undertake such a challenging drilling operation was to address several basic questions for commercially viable reasons (Friðleifsson et al., 2014b): (i) Where is, and what is the nature of the base of, the Reykjanes hydrothermal reservoir? Is it possibly heated by superheated steam from below? (ii) Can the deep heat sources be exploited by injecting fluid into the hot rocks beneath the most productive part of the well field? (iii) Will productive permeability be found at such great depths within the approximate center of the fault-related up-flow zone? (iv) Does a supercritical reservoir exist at 4–5 km depth under the Reykjanes reservoir or does it lie deeper still? (v) What is the nature of the ultimate heat source of this saline seawater recharged hydrothermal system; is it a sheeted dike complex or a major gabbroic intrusion? Individual dikes may cool to ambient temperatures in a few years, depending on thickness, while large gabbro intrusions may act as a heat source for thousands of years.

Well RN-15 was selected as target well for the IDDP-2 project, as it had already been drilled to a depth of 2507 m. Well RN-15 is located on the northeast side of the Reykjanes production field (Figure 1) and was drilled vertically in the year of 2004 down to its final depth of 2507 m (reference level rig-floor; 6.86 m above ground level, Table 1).

Table 1: Drilling and casing depths of well RN-15 and RN-15/IDDP-2. The drilling depths are measured from the rig floor (RF) of each drill rig. Þór: 9.0 m above ground level, Jötunn: 6.86 m above ground level, Saga: 2.0 m above ground level.

Drill rig	Phase	Depth (m)	Depth reference	Bit size	Casing type	Casing depth (m)	Casing depth reference
Saga	Pre-drilling	86.5	Saga RF	26"	22½"	84.4	Ground surface
Jötunn	1. phase	300	Jötunn RF	21"	18⅝"	292.8	Ground surface
Jötunn	2. phase	804	Jötunn RF	17½"	13⅜"	793.8	Ground surface
Jötunn	3. phase	2507	Jötunn RF	12¼"	No casing		
Þór	3. phase	3000	Þór RF	12¼"	9⅞"	445	Ground surface
					9⅝"	445-2932.4	Ground surface
Þór	4. phase	4626	Þór RF	8½"	7" liner	2871.2-4591.2	Ground surface
					7" sacrificial casing	1303.7	Ground surface
Þór	5. phase	4659	Þór RF	6"			

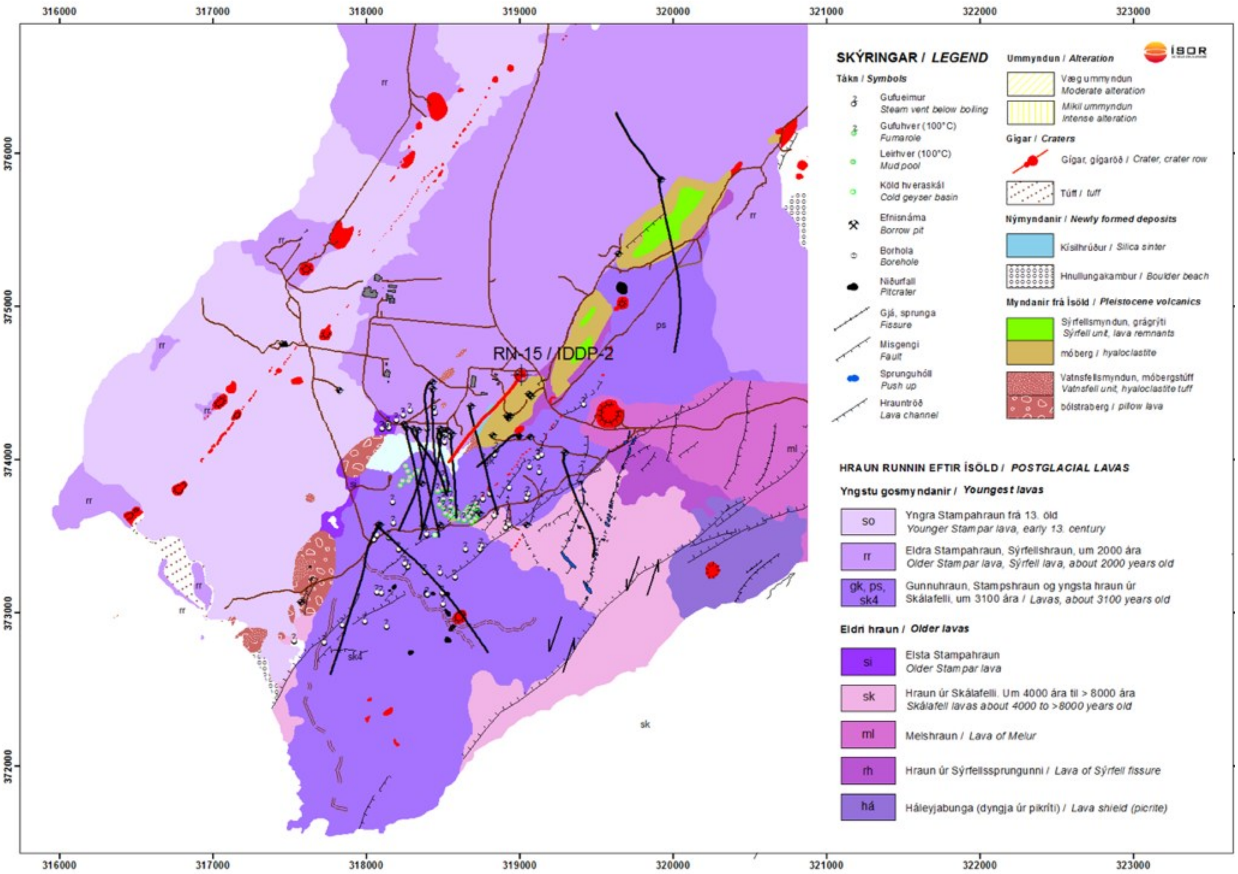

Figure 2: Geological map of the Reykjanes geothermal field showing the location of the well-head of RN-15/IDDP-2 and the red line shows the well path extrapolated to the surface. Black lines show well paths extrapolated to the surface (map based on Sæmundsson et al., 2016).

2. GEOLOGY

2.1 General geology

The Reykjanes area is largely covered by sub-aerial basalt lavas erupted in postglacial times (<12.5 ka) along with low-rise hyaloclastite ridges from the last glacial stage. A study of the stratigraphy shows a dominance of pillow basalt formations below about 1100 m b.s.l. (below sea level) that gradually change to a succession of tuffaceous volcanic formations of Surtseyan type above about 1000 m depth, with intervening shallow water fossiliferous tuffaceous sediments. Shallow marine tuffaceous rocks predominate up to about 100 m depth where sub-aerial lavas top the sequence. Intrusions are commonly found in the succession below about 800 m depth. These are mostly fine- to medium-grained basalt dikes and/or sills. An abundance assessment suggests they may reach up to 60% of the succession at deeper levels. Younger dikes can act as heat sources and dikes provide a significant control on the permeability structures at depths (Franzson et al., 2002; Franzon, 2004).

2.2 Lithologies

2.2.1 Cutting analysis

Due to the total loss of circulation within the entire drilling phase 3 and below a measure depth of 3200 m within drilling phase 4 cuttings were only retrieved within the depth interval between 3000 and 3200 m (Figure 2, 3).

The lithological descriptions for the well before side tracking (from 3000 to 3069 m) indicate the presence of dense medium-grained, grayish basaltic intrusions that are intercalated with fine- to medium-grained dense basaltic rocks which are, in contrast, black in color (Figure 2). A large quantity of secondary minerals, including epidote, quartz and pyrite/chalcopyrite, are found, which also appear as fracture fills. At 3021 m a garnet-filled fracture was observed. Formation after side tracking from 3040 to 3200 m consists exclusively of an alternating sequence of crystalline basaltic rocks which most likely represent a sheeted dike complex. Fresh, grayish to reddish medium- to coarse-grained plutonic rocks that are lighter color due to the abundance of plagioclase are the dominate the lithology, and are intercalated with finer-grained dark (more mafic) fresh dolerite (Figure 2).

The high content of epidote and quartz and lesser amount of actinolite, garnet and sulfides (pyrite and chalcopyrite) indicates significant porosity and permeability. The intrusive rocks are quite dense and the secondary minerals are most likely related to pore-space, associated with fractures. Mono-mineralic fragments of secondary phases can reach up to several millimeters in size. However, the grains are anhedral. The lack of euhedral secondary minerals, characteristic of open space veins, indicates that most of the fractures are totally sealed with secondary minerals. The intrusive rocks are in general fresh. Nevertheless, minor amounts of altered igneous grains are present. This implies that the alteration is not pervasive. It is most likely related to the fracture and selvage zones adjacent to the fracture pore space. The occurrence of epidote, actinolite (amphibole) and garnet indicates high temperature conditions characteristic of upper greenschist facies alteration.

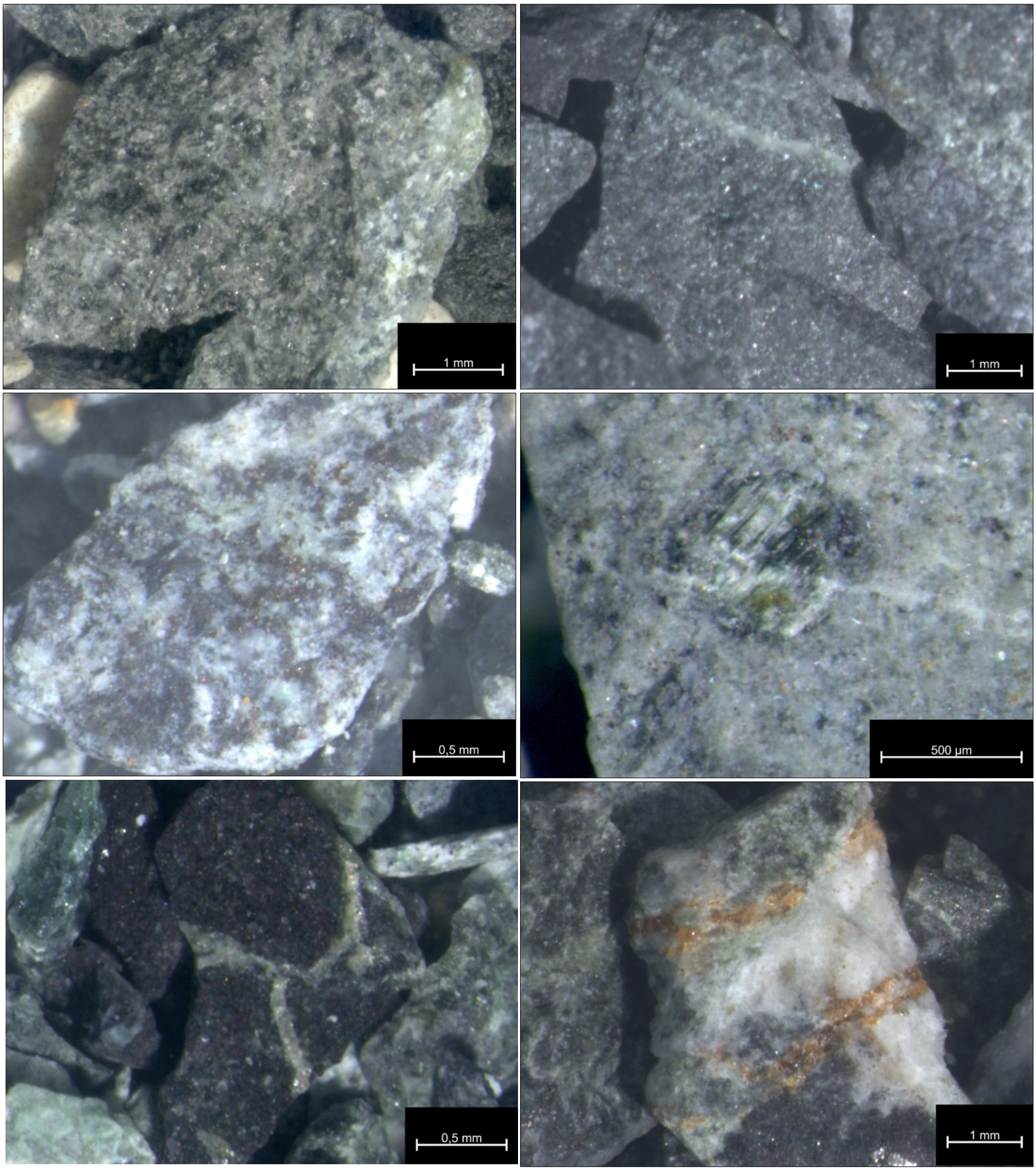

Figure 3: Microphotographs or cuttings samples. Upper left: Grayish, medium-grained basaltic intrusion containing some epidote and quartz at a depth of 2970 m. Upper right: 'Mafic 'fine- to medium-grained dolerite at 3017 m. The dolerite cutting grain in the center shows a fracture totally filled with epidote. Middle left: 'Felsic' medium- to coarse-grained dolerite at 3067 m. Middle right: Altered intrusive rock 3084 m, showing the pseudomorphic replacement of pyroxene by actinolite. Lower left: Dark, fine-grained basalt that shows a fracture network filled with secondary minerals (3136 m). Lower right: Quartz-garnet vein at 3021 m.

2.2.2 Core observation

Because of the total loss of circulation in RN-15/IDDP-2 below 3200 m depth, spot cores are the only rock samples available from the deeper section of the well. Coring was difficult, and in total only 27.3 m were recovered (Weisenberger et al., 2017). The IDDP-2 cores include a series of dolerite dikes with chilled margins interpreted to originate from a sheeted dike complex (Friðleifsson et al., 2018; Zierenberg et al., 2017). Many of the rocks were found as "rollers" on top of cores from unknown depths above coring intervals. These include dolerites, basalts, and a few hyaloclastite and volcanic sandstone/siltstones with alteration similar to the RN-17B and RN-30 cores (Friðleifsson et al., 2018; Zierenberg et al., 2017). The lowermost cores of altered dolerites, contain thin felsic veins that are the first identification of evolved rocks within the volcanic rock series within the Reykjanes geothermal field. Cross cutting veins are relatively uncommon and open space filling veins are nearly absent, although the rocks appear to be pervasively altered (Friðleifsson et al., 2018; Zierenberg et al., 2017).

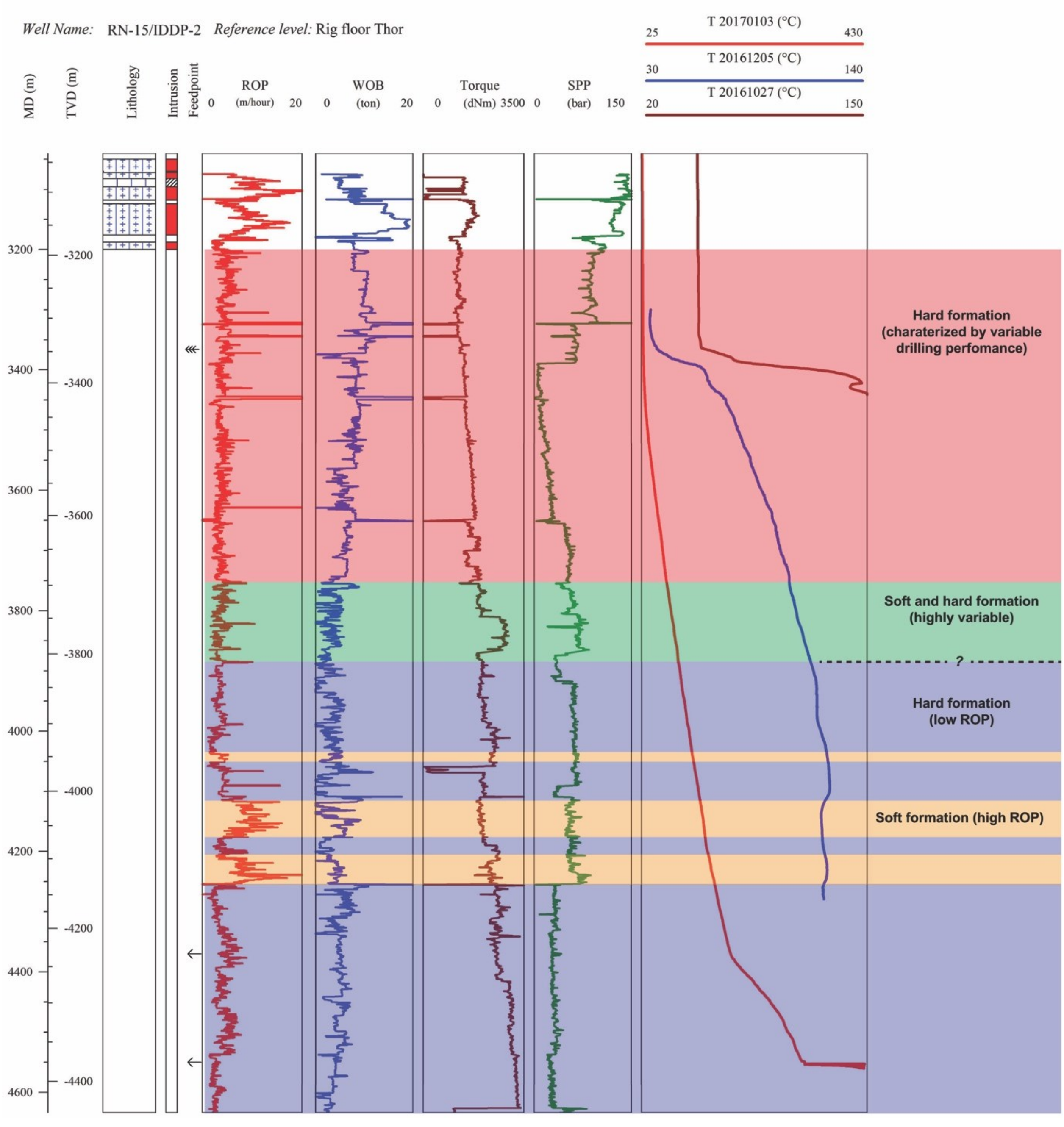

Figure 3: Comparison of lithology, selected drilling parameters and temperature logs (modified afterWeisenberger et al., 2017).

2.2.3 Drilling parameters

Drilling parameters show only minor variations and are indicative for drilling into relative hard formations. However, small variations did occur, which may reflect changes in lithology or penetration into soft formations, and could be related to fracture zones (Figure 3). Within the shallower part (3000–3185 m), which was cemented multiple times due to the high fluid loss, the drilling crew reported a large variation in the fluid circulation as well as in the stand-pipe pressure, which may indicate the penetration of narrow fracture zones. However, no indications are observed on the temperature logs which were carried out during drilling, of any major feed points within this depth interval. While drilling from 3305 to 3312 m a drop in the stand-pipe pressure (95–80 bar) was observed, which may indicate the penetration of a permeable zone. While drilling from 3373 to 3375 m, the weight on bit decreased while the rate of penetration increased. This is at a similar depth where a larger fracture zone was detected. Drilling parameters indicate that in general the formation from 3400 to about 3750 m consists of a relative uniform, hard formation, which is most likely represented by the core retrieved during core run 3. The peak in rate of penetration at a depth of 3710 m indicates a thin soft layer, or possibly a fault zone. A thicker soft zone occurs between 3751 and 3754 m, as indicated by the drastic change in drilling parameters (e.g. rate of penetration). From 3755 to 3816 m the drilling parameters show significant fluctuations which may indicate the penetration of a heterogeneous units, where hard and soft layers intercalate. Below 3816 m, drilling parameters show only minor variations except for a significant increase in the rate of penetration between 3884 and 3887 m. This may reflect a formation boundary. Another sharp peak in the rate of penetration is observed at a depth of 3990 m. The spike in torque just below 4000 m indicates the penetration of an open structure. In addition, at 4000 the MWD showed a drop in the inclination of about 2.5°. Between 4118 and 4160 m the rate of penetration is quite high (8–15 m/h), which indicates a rather soft formation in comparison to the unit above and below. Within this interval, the well inclination built up, which may indicate the penetration of a fault/fracture zone. Subsequently, the rate of penetration declined, but at about 4210 m, the rate of penetration increased again with an outstanding spike at about 4240 m indicating again a weak/softer formation. Below about 4250 m the rate of penetration dropped back to lower numbers and does not indicate any major variations in lithology. It should be mentioned that the temperature log carried out on December 6th shows a similar undulating pattern as the rate of penetration pattern between 4100 and 4250 m and may reflect the different cooling behavior of the formations (Weisenberger et al., 2017).

Although we do not see any indication for major lithological variations, the drilling parameters show significant pattern changes. This changes may be related to the brittle/ductile transition (Figure 3).

2.3 Alteration

A regular progression in hydrothermal alteration with increasing depth was noticed from the alteration mineral assemblage in well RN-15. Such depth and temperature controlled mineral alteration zoning is well known in Icelandic hydrothermal systems (e.g. Kristmannsdóttir and Tómasson, 1978; Weisenberger and Selbekk, 2009). Low-temperature minerals, like fine-grained clay (smectite) and zeolites occur at shallower levels (Gautason et al., 2004). High-temperature minerals, like epidote and coarse-grained chlorite appear at deeper levels in the well. Epidote was first observed at a depth of 716 m (Gautason et al., 2004; Jónsson et al., 2010). The 13⅜" production casing of well RN-15 was set at 793.8 m (reference to ground level) and based on the mineral assemblage, the production casing of RN-15 extends well into the geothermal reservoir, where abundance of epidote (>230–250°C) was noticed in cutting samples. Furthermore, garnet and actinolite (>280°C) were first observed at 1378 m and 1560 m respectively.

Based on cutting analysis in the depth range from 3000 to 3200 m in RN-15/IDDP-2, high-temperature minerals, like epidote, garnet and actinolite, could be identified, but epidote was the dominant secondary mineral (Figure 2). Visual core inspection, accompanied by initial thin section observations of the retrieved cores reveals that epidote is common in a sample of core 3 (3648.0–3648.52 m), locally accompanied by minor amounts of chlorite. Epidote and chlorite are absent in core run 5 and below (Friðleifsson et al., 2018; Zierenberg et al., 2017). In contrast, calcic-plagioclase and hornblende were identified by microscopic observation. Biotite was observed as minor mineral phase in core 8 (4254.6–4254.88 m) as well as in core 11 (4634.20–4641.78 m).

The mineral assemble plagioclase-hornblende is a characteristic mineral assemblage found in meta-basaltic rocks of amphibolite facies rocks. The presence of hydrothermal biotite is consistent with this high temperature alteration of intermediate to felsic rocks, but biotite alteration is unusual in low K tholeiitic basalts. Pyroxenes are a common part of the alteration assemblage in the deepest part of hole. However, a detailed pressure-temperature estimation requires a more thorough mineralogical and petrological study, as well as considerations of the effects of mass transport and metasomatic alteration.

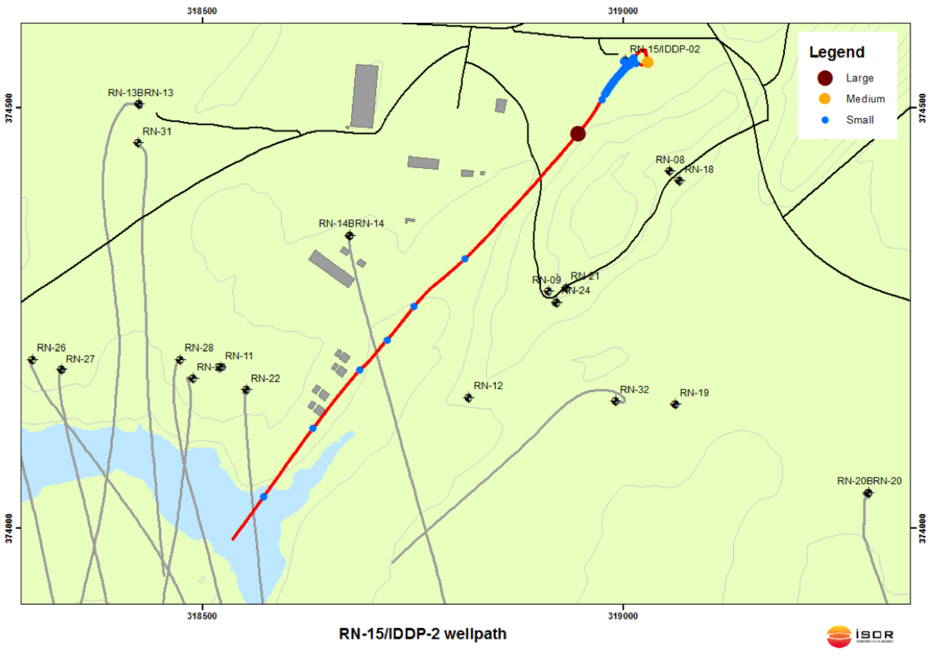

Figure 4: Map view showing the well path of RN-15/IDDP-2 (red) and the location of feed zones and their relative sizes (blue).

2.4 Feed zones

Permeable zones in RN-15/IDDP-2 are summarized in Table 2 and marked along the well path in Figure 4. The zones with high fluid permeability haven been identified by circulation losses during drilling and the evaluation of geophysical logging data, which was carried out during the drilling activity. Minor permeable zones have also been detected by detailed studies of drilling parameters. After the production phase had been cemented and drilling phase 3 was completed, temperature logs revealed a small feed zone between the casing shoe and the final depth of drilling phase 3 at 3000 m. While drilling the top part of drilling phase 4, from 3000 to 3185 m, the drilling crew observed a constant increase in circulation loss. Furthermore, circulation losses fluctuated as drilling progressed.

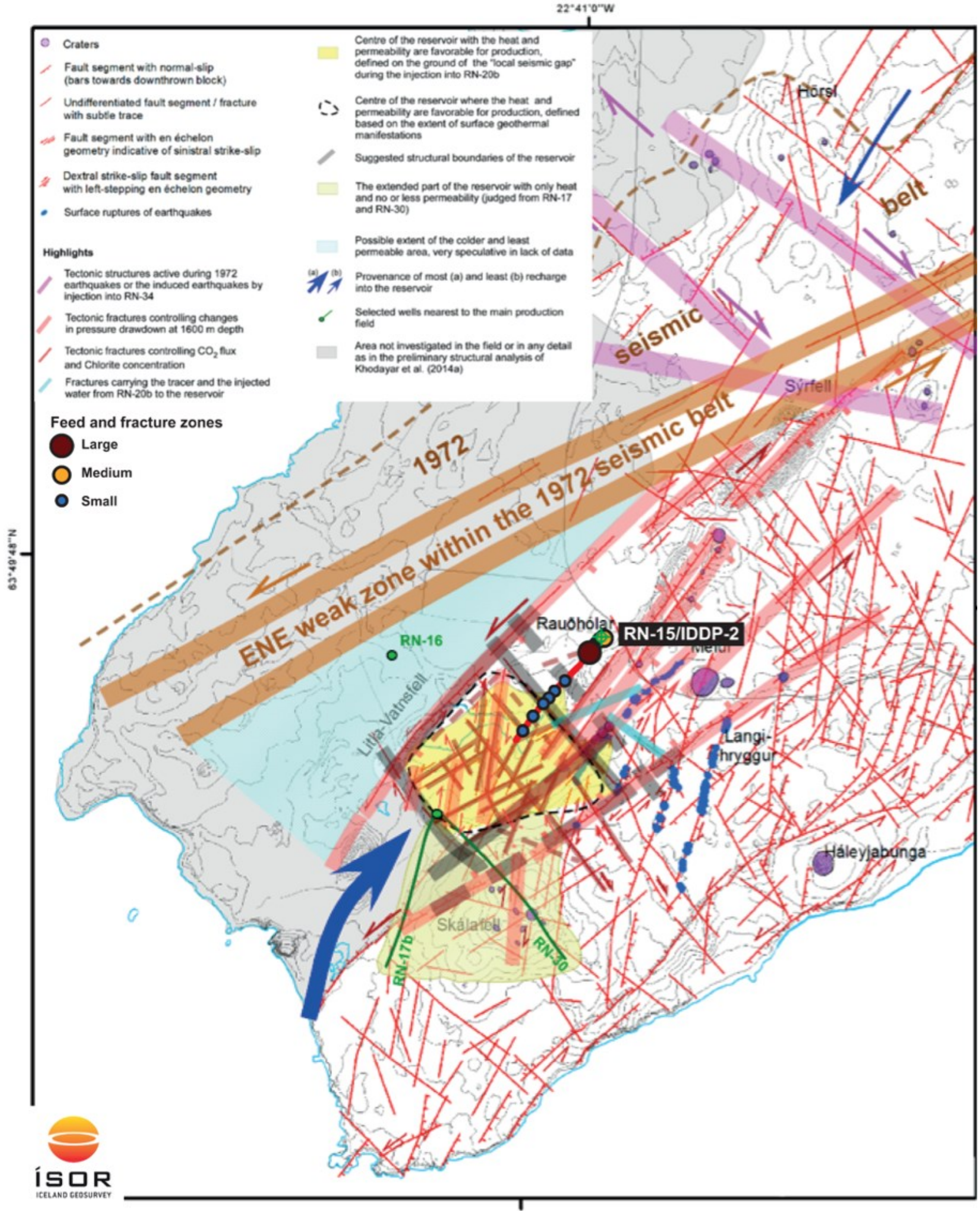

Figure 5: Well path RN-15/IDDP-2 and the location of feed and fracture zones along the path in relation to the tectonic model of the Reykjanes geothermal field (Khodayar et al., 2016a).

The most prominent loss zone is located at about 3350 to 3380 m. All temperature logs, which were executed after this depth had been achieved, indicate that most of the pumped fluid disappears at a depth of about 3365 m and only a small portion of the pumped fluid travels further down the well. This indicates that a major fracture or fault is located at this depth. However, a temperature log carried out on January 3rd, 2017, indicates that small loss zones are present in the well at even deeper levels. For example, at about 4375 and 4550 m, minor loss zones may be present. Although fluctuations in some drilling parameters (e.g. stand-pipe pressure, torque) seem to indicate some softer zones that possibly indicate higher permeability (e.g. 4000 m), temperature logs do not reveal any indications of feed or fracture zones at those depths.

It should be emphasized that during the blind drilling from 3200 to the final depth at 4659 m a minimum volume of 53 m^3 rocks was extracted. The total loss of circulation implies that the large volume of cuttings was transferred from the wellbore into the rock formation. This probably occurred along fracture zones. Considering the large estimated volume of cuttings, it may be assumed that major permeability exists in the vicinity of the wellbore.

Figure 5 shows the well path of RN-15/IDDP-2 and the location of fracture and feed zones along the well path in relation to the tectonic model of Reykjanes based on Khodayar et al. (2016a). It seems that the major fracture zones in RN-15/IDDP-2 are related to compartments as defined by Khodayar et al. (2016a, b).

Table 2: Fracture and feed zones in well RN-15/IDDP-2 after Weisenberger et al. (2017).

Depth (m)	Fluid loss (L/s)	Relative size*	Comments
90		Small	Gautason et al. (2004)
280		Small	Gautason et al. (2004)
900	1	Small	Jónsson et al. (2010)
1000	1	Small/medium	Jónsson et al. (2010)
1300	12	Small	Jónsson et al. (2010)
1720	9	Small	Jónsson et al. (2010)
2395	23	Medium	Jónsson et al. (2010)
2970-2980	12	Small	temperature log 12.09.2016, spinner log 03.10.2016
2941-3185	5 to >45	Small	permeable interval, based on circulation losses during drilling
3160-3170	20 to >45	Small	Spinner 28.10.2016, 23.01.2017
3210	>45	Small	temperature log 27.10.2016
3350-3380	>45	Large	temperature log 28.10.2016, 03.01.2017
3820	>45	Small	temperature log 03.01.2017
3990	>45	Small	based on drilling parameters and drillers report
4100	>45	Small	temperature log 03.01.2017
4200	>45	Small	temperature log 03.01.2017
4375	>45	Small	temperature log 03.01.2017
4550	>45	Small	temperature log 03.01.2017

** Well RN-15 was a moderate producing well and the estimated size of the feed zones was probably underestimated in drilling reports.*

3. SUMMARY

Drilling of well RN-15/IDDP-2 was commissioned by HS Orka in 2016. Drilling was performed by the drill rig Þór (Iceland Drilling, Jarðboranir) and drilling was completed in 168 days (August 11th, 2016 to January 25th, 2017). The well represents the second well of the Iceland Deep Drilling Project (IDDP). It is the deepest (4659 m measured depth, referenced to the rig floor Þór) and hottest (>426°C) geothermal well drilled in Iceland. For this purpose, well RN-15 was deepened, but it had previously been drilled in 2004 down to 2507 m (reference rig floor Jötunn).

During most of the drilling, a total loss of circulation was persistent and no cuttings were retrieved at the surface apart from the beginning of phase 4. Therefore, the information about the lithology is very limited and needs to be constrained from the limited cuttings (3000–3200 m) and from the retrieved core material. Mineralogical and petrographic observations yield that the rocks of the deeper parts in the well are equilibrated at amphibolite facies conditions. The high-temperature conditions of amphibolite facies conditions are confirmed by the temperature and pressure logs that indicates the presence of a supercritical fluid (Figure 6).

Lithological and textural observations, in particular the occurrence of chilled margins and the grain-size of the rocks indicate that the lithology is consistent with the existence of a sheeted-dike complex (e.g. Friðleifsson and Elders, 2005; Khodayar et al., 2016b; Weisenberger et al., 2016b). Figure 6a shows a simple geological sketch of the Reykjanes geothermal field, which is equivalent to an ophiolite model (Friðleifsson and Elders, 2005). The heat is most likely transferred by primitive magma that is emplaced in the lower oceanic crust by dike injections within the sheeted-dike complex, and by dike and sills injections within the shallower volcano-sedimentary sequence.

Textural observations of core 3 and interpretation of the cutting analysis suggests that the lithology at the top most part in drilling phase 4 (3000 to 3650 m) experienced high brittle deformation, which can be deducted by the high fracture density. Detected circulation losses at this depth are evidence for the brittle behavior, which results in a significant permeability.

Based on circulation losses and temperature logs, several permeability zones are identified. A minor permeable zone is located just below the casing shoe. Increased circulation losses below that zone, finally resulting in a total loss of circulation at about 3200 m, indicate the high permeability at this depth. The most prominent permeable zone is found at 3350 to 3380 m and most likely reflects a major fracture zone into which most of the injected pumped fluid disappear. Smaller feed zones or permeable zones are identified at 4375 m and 4550 m.

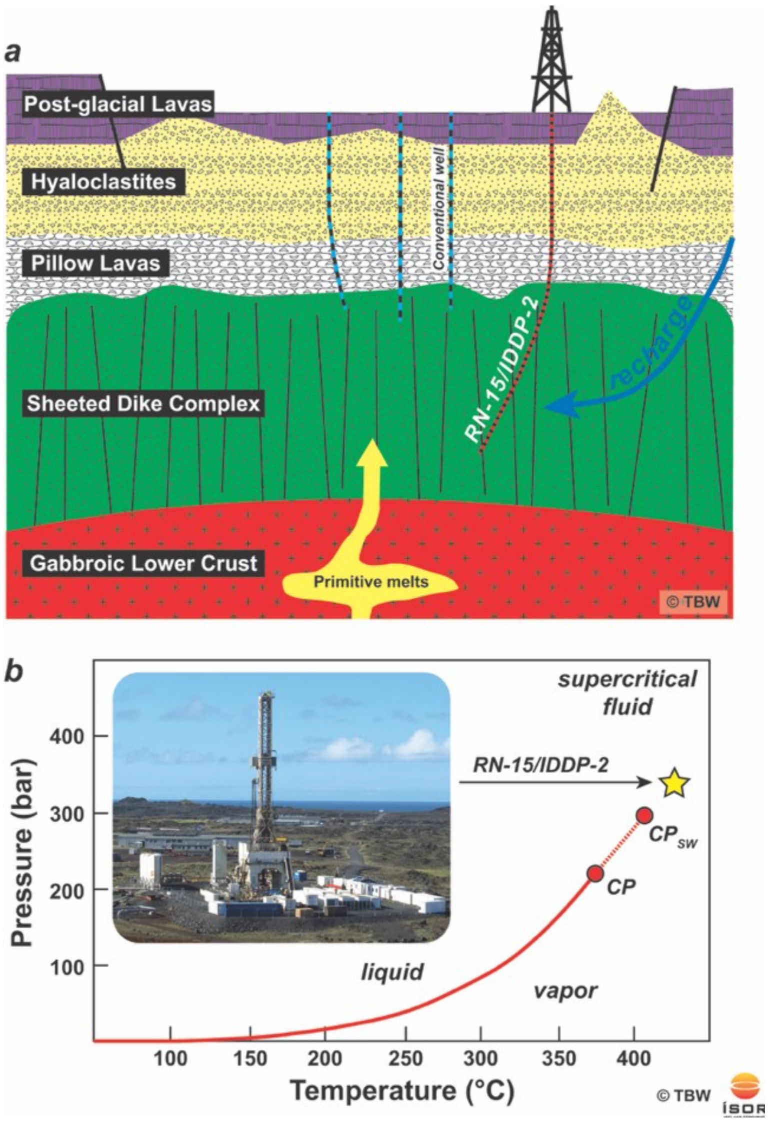

Figure 6: Summary sketch of the RN-15/IDDP-2. a) A simple model that shows the geology of the Reykjanes geothermal system. Sketch is not scaled. b) Temperature-pressure diagram showing the nature of supercritical conditions of the fluids within RN-15/IDDP-2 (CP: critical point; CPSW: critical point of seawater; yellow star: logging results of the temperature-pressure log carried out on January 3rd, 2017).

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