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The Reykjanes Geothermal System – An Extended Conceptual Model

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ABSTRACT

The geothermal system at Reykjanes, SW Iceland, is the landward extension of the North Atlantic Ridge. HS Orka commissioned a geothermal power plant in May 2006 with capacity of 100 MW_e utilizing a two-phase reservoir from ~1000 m b.s.l down to ~2500 m b.s.l. At 1500 m b.s.l. the reservoir is ~280-290°C. Seismic data had revealed the brittle-ductile boundary in the area to be at 5,5 – 6 km depth and an aseismic body between 3-6 km depth underneath the main geothermal field. The Horizon 2020 project „Deployment of deep enhanced geothermal systems for sustainable energy business" (DEEPEGS) aims at demonstrating the feasibility of deep enhanced geothermal systems (EGS) as a competitive energy alternative for commercial use. As a part of the Horizon 2020 DEEPEGS project well RN-15/IDDP-2 was deepened from 2509 m down to 4650 m total measured depth from August 2016 to January 2017 to explore and investigate the roots of the Reykjanes geothermal system. The aim of this paper is to collect new information gained from the DEEPEGS project and update the pre-existing conceptual model of the Reykjanes geothermal field.

1. INTRODUCTION

In 2006 a 100 MW_e geothermal power plant was commissioned at Reykjanes. The Reykjanes field has a long exploration history with the first exploration well drilled in 1956 and the first deep well (RN-8) was drilled in 1969 down to 1754 m. To date 37 wells have been drilled in the area. The power plant utilizes a two-phase reservoir from ~1-2,5 km depth. On the ground of existing data at the time a very extensive work was carried out by Khodayar et al. (2016) in making a very comprehensive conceptual model of the Reykjanes field. The work of Khodayar et al. (2016) is the foundation for this abstract. As a part of the Horizon 2020 DEEPEGS project (grant agreement No. 690771) well RN-15/IDDP-2 was deepened from 2509 m down to 4650 m total measured depth from August 2016 to January 2017 to explore and investigate the roots of the Reykjanes geothermal system. The data sets acquired with the drilling gives opportunities to extend the conceptual model down to 5 km depth (fig. 2).

2. GEOLOGICAL SETTING

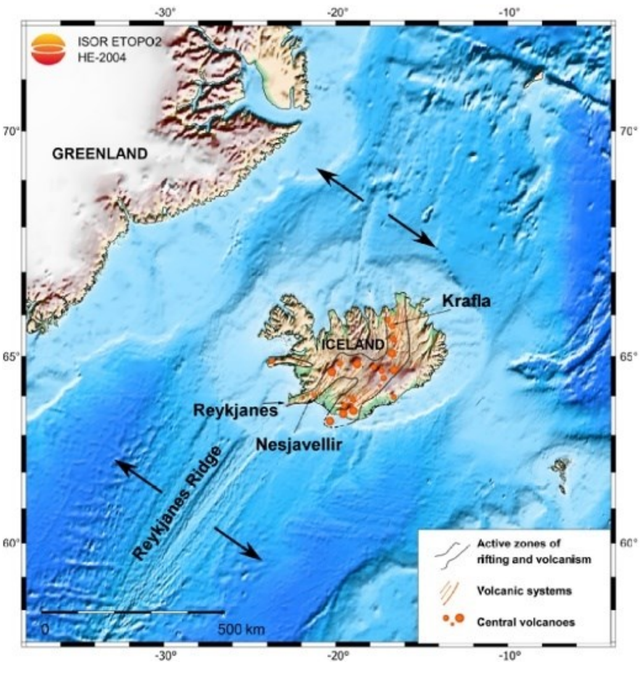

Figure 1: The location of the Reykjanes geothermal field shown and its position on Iceland on the Mid-Atlantic Ridge (Friðleifsson et al., 2018).

The Reykjanes geothermal field is positioned at the tip of the Reykjanes peninsula which is the landward extension of the Reykjanes Ridge and is the westernmost fissure swarm of the Reykjanes-Langjökull Rift Zone (fig. 1). The Reykjanes peninsula is on the trace of the South Icelandic Seismic Zone (SISZ) (Einarsson, 1991). The spreading direction on the Reykjanes Peninsula is 103° (DeMets et al., 2010) and rifting occurs along NE normal faults, open fractures and eruptive fissures (e.g. Sæmundsson and Einarsson, 2014). According to Einarsson (2008) transform faulting is accommodated along NS and ENE strike-slip faults and both directions are seen on surface and seen in seismic activity on the Reykjanes Peninsula (e.g. Guðnason et al, 2015, e.g. Árnadóttir et al., 2008; Hjaltadóttir, 2010).

The Reykjanes geothermal field is covered with Holocene lava flows on surface and to lesser extent hyaloclastites (e.g. Khodayar et al. 2018, Sæmundsson et al. 2019, Sæmundsson et al., 2018), see figure 2. The hyaloclastites appear as ridges with lava flows surrounding them. The age of the lava-flow is from 12,500 years to 800 years old. The basaltic lavas are primitive in composition ranging from tholeiites to picrite (Jakobsson et al., 1978). Based on earthquake data the brittle-ductile boundary beneath the Reykjanes Geothermal system is at 5,5-6 km depth (Guðnason et al, 2015).

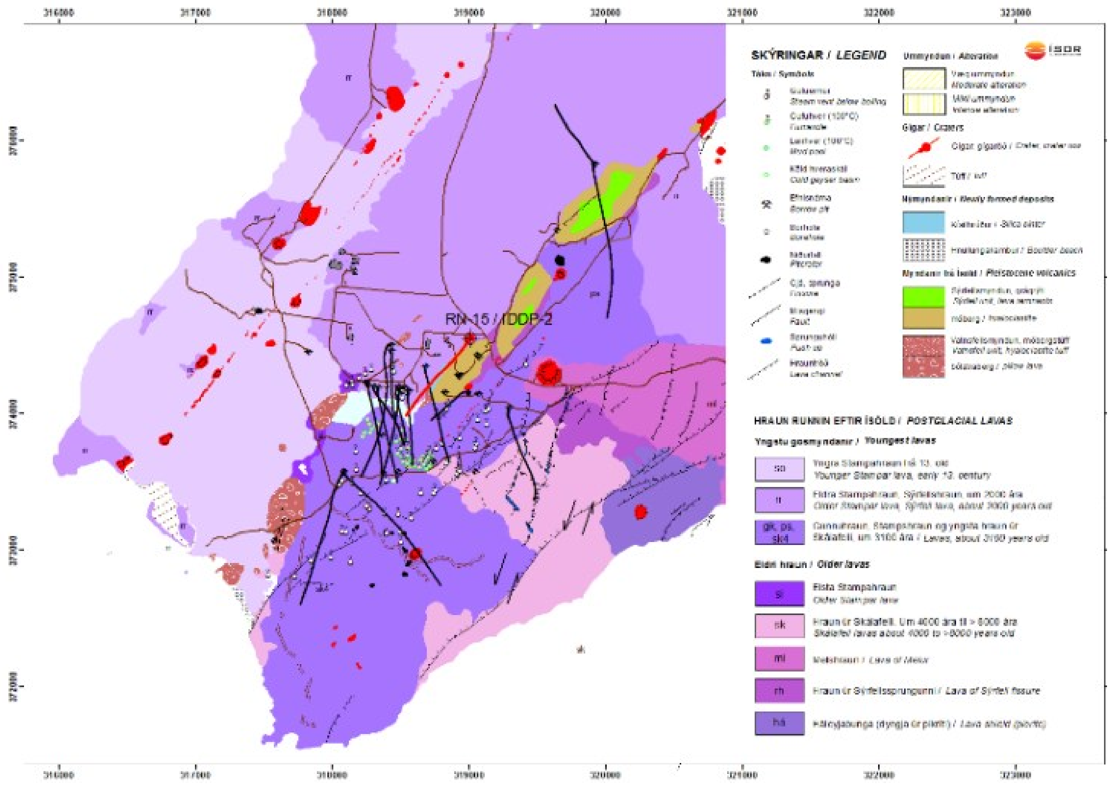

Figure 2: Geological map of the Reykjanes geothermal field showing well paths of the the field and in red the well path of RN-15/IDDP-2 is shown (derived from Sæmundsson et al., 2016).

3. THE REYKJANES GEOTHERMAL FIELD - 2016 CONCEPTUAL MODEL

In the multi-disciplinary study of Khodayar et al. (2016) available datasets were included both from surface and sub-surface data. This chapter is based on Khodayar et al. (2016) and Þorbjörnsson et al. (2014).

The geothermal field at Reykjanes estimated to be 1-1,5 km^2 (Khodayar et al., 2018) which seems to outline the area most favorable for production (Khodayar et al., 2016). It seems though to have a greater lateral extent with depth based on mapping of alteration from well data and geophysical surveys (e.g. Karlsdóttir, 2016). According to Khodayar et al., (2016) the reservoir has a circular shape bounded with Riedel shears and faults to the NW and SE of the field. Before the production started in the Reykjanes field the reservoir was liquid dominated. Production has led to a pressure drop leading to pressure decrease in the field and formation of a steam cap above 1000-1100 m depth in the field. The average reservoir temperature in the field is 270-290°C. Before drilling of RN-15/IDDP-2 well the reservoir was thought to extend down to around 3000 m depth and therefore the volume of the reservoir at the Reykjanes field was estimated to be ~3 km^3.

The fluid in the Reykjanes field originates from seawater and due to boiling and fluid/rock interactions concentrations of K, Ca, SiO_2, CO_2 and H_2S increase while concentrations of SO_4 and Mg decrease due to dissolution of basalts, precipitation of alteration minerals and possible addition of magmatic gases (Tómasson and Kristmannsdóttir, 1972; Arnórsson, 1978; Ólafsson and Riley, 1978; Arnórsson, 1995; Óskarsson et al., 2015).

The stratigraphic succession in the Reykjanes Geothermal Field is built of by sub-marine volcanic strata (e.g. Franzson et al., 2002; Franzson 2004; Friðleifsson and Richter, 2010; Friðleifsson et al., 2014). From surface to 200 m depth lava-fields and laminated pillow breccia is dominant. From below 200 m depth where phreato-magmatic tuffs, breccia, sedimentary tuffs and marine fossili-ferrous sediments are dominant followed by pillow basalts dominantly below 1200 m.

Below 1500 m intrusive volcanic rocks make appearance and become more dominant and coarse-grained with depth. At 3000 m depth the lithology is dominated by intrusive rocks. The 2016 conceptual model postulated that this could be a thick sequence of intrusions either a sheeted dyke complex or sills. By mapping the intrusion density in the field (Weisenberger et al 2016) an up-doming is seen beneath the center of the Reykjanes geothermal field (fig 3). Other sub-surface datasets such as alteration and resistivity models show the same up-doming effect beneath center of the field (figure 4). This accumulation of intrusive rocks is thought to be the heat source of the Reykjanes field.

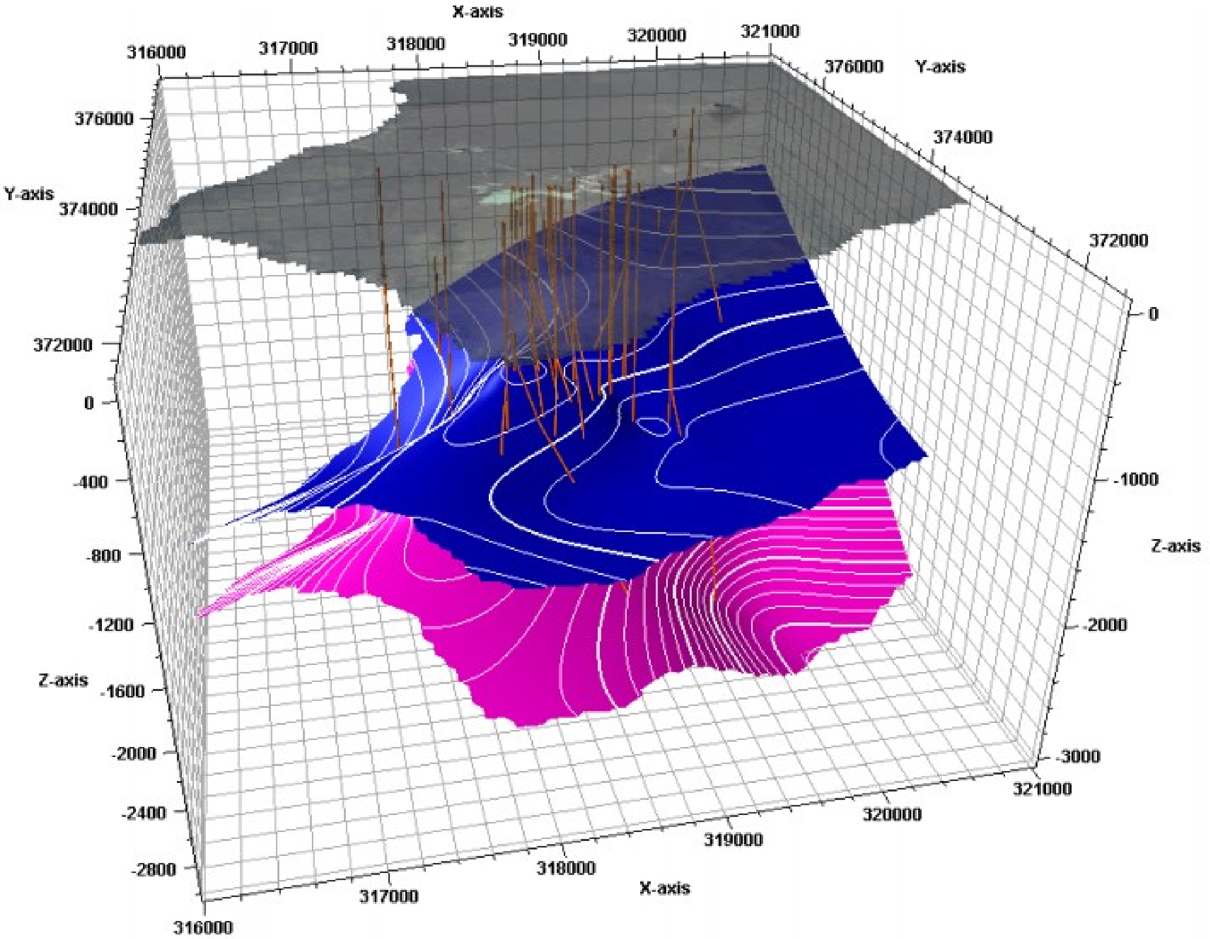

Figure 3: Lithological model made in Petrel of the Reykjanes geothermal field. The model is based on drill cutting analysis and shows up-domiming of the top of the medium grained (blue layer) and the coarse grained (purple layer) intrusives. Well paths are shown in orange. Figure from Khodayar et al., 2016.

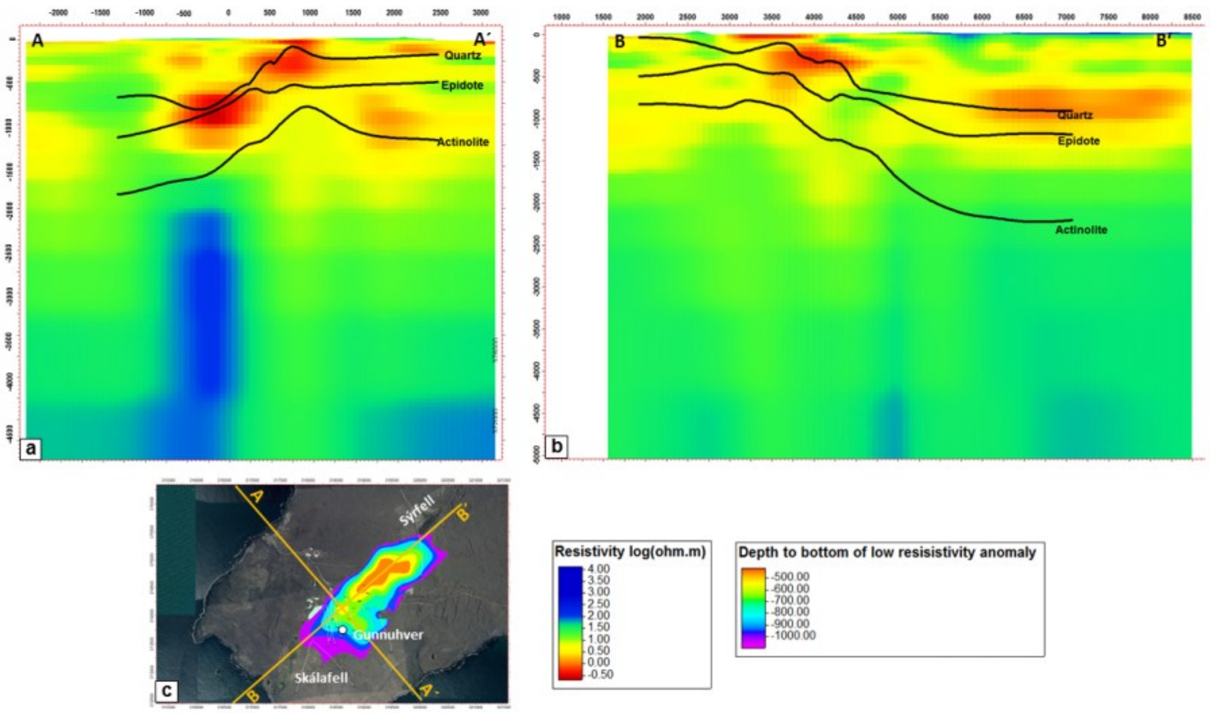

Figure 4: Two cross-sections, Figure 4a and Figure 4b, through resistivity and alteration models made in the Petrel software platform from the Reykjanes geothermal field. First appearance of temperature dependent alteration minerals, quarts (180°C), epidote (230-250°C) and actinolite (280°C) are shown in black lines and also shown is the resistivity model from Karlsdóttir and Vihjálmsson (2016). The alteration and resistivity show the same trends. Figure 4c show the bottom of the low resistivity anomaly at 5 Ωm and the cross-section. Figure from Khodayar et al. (2016).

As stated, the brittle-ductile boundary is generally at 5,5-6 km depth at Reykjanes Peninsula. However, beneath the centre of the Reykjanes geothermal field an aseismic body appears below 3 km depth (Guðnason et al., 2015). One explanation is that the seismic gap corresponds to a very hot body with temperatures of 600°C ± 100°C, which is typical of the brittle-ductile boundary at 5.5-6 km depth but elevated to only 3 km depth under the geothermal field and therefore indicating an anomaly in concentration of intrusives beneath the core of the Reykjanes geothermal field.

Most of the re-charge of the field is thought to be from the southwest and northeast of the field and is supported by tectonic analysis of the field (Khodayar et al. 2014) and by the numerical model of the field (Berthet and Arnaldsson, 2015). The Reykjanes geothermal field seems to be tectonically compartmentalized as shown by (Khodayar et al., 2014) and supported by tracer test (Hickson and Nielsson, 2015).

Figure 3 shows the simplified conceptual model for the Reykjanes geothermal field as put forward by Friðleifsson et al., (2016).

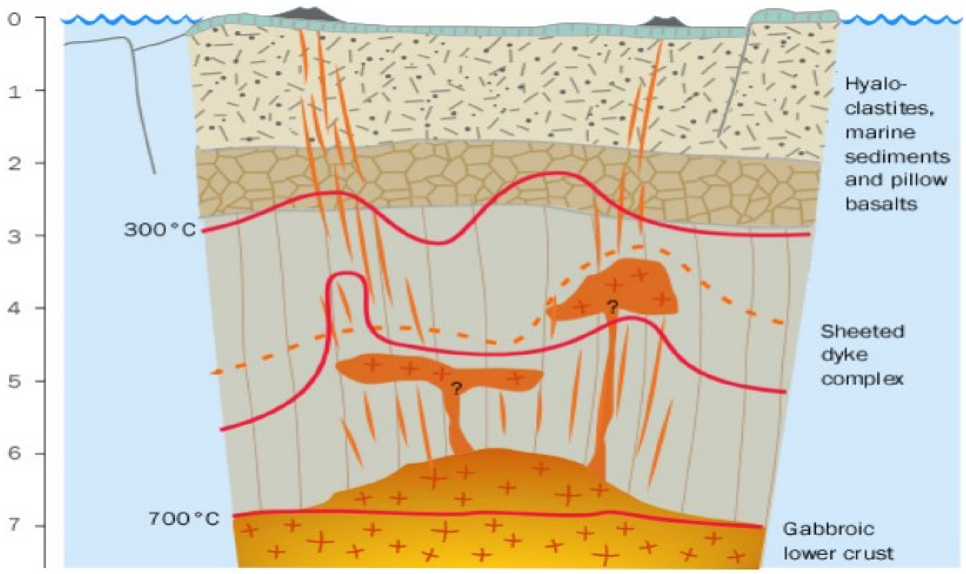

Figure 3: Simplified geothermal model of the Reykjanes field including the lithology, the temperature isolines and corresponding depths (from Friðleifsson, 2016).

3. RESULTS FROM DRILLING OF RN-15/IDDP-2

The well RN-15/IDDP-2 was finished in January 2017. The well has production casing down to 3000 m depth and a production part was drilled down to 4650 m depth (with reference to ground level). As seen on figure 2 the well is deviated towards the centre of the geothermal field in Reykjanes. Significant permeability was encountered just below the production casing at 3000–3200 m, a fracture zone with permeability is located at ~3365 m depth and permeability were encountered at 4370 and 4550 m showing that fracture permeability exists in the deeper part of the reservoir. At the end of the drilling a temperature was measured to be 426°C and pressure of 340 bar within the deep reservoir at Reykjanes (fig. 4). Based on estimated of rate of heat-up, inversion of geophysical data and alteration mineral assemblage the bottom hole temperature is estimated to be ~535°C. Indicating super critical conditions in the deeper part of the reservoir at Reykjanes.

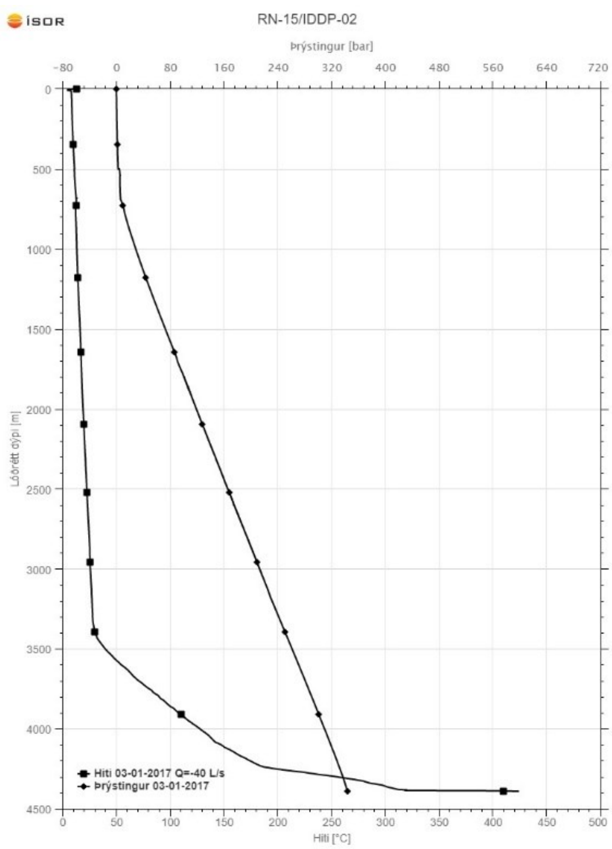

Figure 4: Measured temperature and pressure from the end of drilling, showing pressure of 340 bar and temperature of 426°C (Weisenberger et al., 2017).

Due to the total loss of circulation below 3200 m depth and therefore spot cores are the only rock samples from the production part of the well. In total 27.3 m of cores were recovered (Weisenberger et al., 2017, Friðleifsson et al, 2018). The RN-15/IDDP-2 drill cores include a series of dolerite dikes with chilled margins and are interpreted to come from a sheeted dike complex (Zierenberg et al., 2017). From the deeper part of the well felsic intrusive rocks were encountered which are the first evolved rocks found on the Reykjanes peninsula (Friðleifsson et al., 2018).The cores show the deeper cores have low porosity and fractures are very uncommon they are heavily altered and have amphibole- and pyroxene-bearing mineral assemblages that suggests high fluid rock/ratios through the medium of low viscosity supercritical water (Friðleifsson et al., 2018).

During drilling and stimulation of RN-15/IDDP-2 the upper part of the previously aseismic body at 3-5 km depth became seismically active. The seismic catalogue contains over 2300 earthquakes, which have been manually picked and relatively relocated. The consistency of the pickings improved by cross-correlation, and focal mechanisms are computed to help characterize the local stress field. The spatial and temporal development of the seismicity is used to investigate fractures created and re-activated during the drilling and stimulation. Interestingly, a zone from roughly 3.5 to 6 km depth below the geothermal producing field at Reykjanes, which was aseismic before the deep drilling, became seismically active during drilling and stimulation of the well. Increasing circulation losses below 3.0 km depth in the IDDP-2 well and a total loss of circulation from around 3.2 km depth indicate the high permeability at this depth. All the induced seismicity occurs just below the total loss of circulation and seems to group into two different fault zones with different dynamics of fault. A likely explanation for the induced seismicity is that the total loss of circulation of cold water (below 3.2 km depth) into the previously aseismic body during drilling, completion and stimulation of the IDDP-2 well has increased the strain rate sufficiently to make this volume seismically active. Therefore, the temperature of the previously aseismic body is almost at the brittle-ductile boundary for standard strain rates.

SUMMARY AND CONCLUSIONS

This paper summarizes the results of the 2016 conceptual model of the Reykjanes geothermal field by Khodayar et al. (2016) and the main findings from the drilling of RN-15/IDDP-2(Friðleifsson et al., 2018; Zierenberg et al, 2017; Weisenberger et al., 2017).

The main results derived from the drilling of well RN-15/IDDP-2 seem to confirm the conceptual model put forward by Khodayar et al. (2016). That the deeper part of the Reykjanes reservoir is made of intrusive rocks, either a sheeted dike complex or sills, that act as the heat source. These results give confidence in the multi-disciplinary approach used in Khodayar et al. (2016) and show its importance in the understanding of the Reykjanes geothermal system.

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