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Seismic Monitoring During Drilling and Stimulation of Well RN-15/IDDP-2 in Reykjanes, SW-Iceland

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ABSTRACT

The Reykjanes geothermal system is located at the southwest tip of the Reykjanes Peninsula in Iceland, precisely where the Mid-Atlantic Ridge comes onshore. It has been utilized for power production by HS Orka Ltd. since 2006 with a power production of 100 MW_e at present.

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 as a competitive energy alternative for commercial use. Within the framework of the DEEPEGS project, the deep geothermal well RN-15/IDDP-2 was drilled at Reykjanes from August 2016 to January 2017, to a total depth of 4659 m, where it reached supercritical conditions. A total loss of circulation was encountered during drilling from 2.5 km depth to the final depth.

To monitor the seismic activity during drilling and stimulation of the well, a temporary seismic network was installed in Reykjanes from October 2016 to September 2017, in addition to the permanent seismic network in the area. Interestingly, a zone from roughly 3 to 6 km depth below the producing geothermal field at Reykjanes which was aseismic prior to the deep drilling, became seismically active during drilling and stimulation of the well.

Results of the seismic monitoring are presented, giving insight into the geological structures and processes that may be responsible for permeability in the deep reservoir. The seismic catalogue covering the timespan from the start of drilling to the end of the main stimulation phase contains over 2300 earthquakes, which have been manually picked. Fault plane solutions are computed to help characterize the local stress field, and the spatial and temporal development of the seismicity is used to investigate fractures created and/or re-activated during the drilling and stimulation. Hence, we aim at gaining knowledge and understanding of the architecture of the deep part of the reservoir at Reykjanes.

1. INTRODUCTION

The Iceland Deep Drilling Project (IDDP) consortium was established in 2000. It was funded by three Icelandic power companies (HS Orka Ltd., Landsvirkjun and Orkuveita Reykjavíkur), together with the Energy Authority of Iceland (Orkustofnun) and later with additional funding from Statoil. The aim of IDDP and the idea of deep drilling is to explore the feasibility and technology of producing deep, high-enthalpy, supercritical geothermal resources as possible energy sources (Friðleifsson and Albertsson, 2000; Friðleifsson et al., 2014a, b; 2018). The first well, IDDP-1, was drilled in 2008-2009 within the Krafla geothermal field in NE-Iceland (Pálsson et al., 2014). Unfortunately, the drilling of well IDDP-1 had to be terminated due to intersection of >900°C magma at a depth of 2104 m. However, IDDP-1 became the world´s hottest producing geothermal well at the time, yelding more than 450°C of dry, superheated steam at the well head (Elders et al., 2014).

The second well, IDDP-2, was drilled from August 2016 to January 2017 within the Reykjanes geothermal field in SW-Iceland. Drilling started on the 11th of August 2016 and was completed on the 25th of January 2017, i.e. in 168 days, by deepening the pre-existing production well RN-15 (Weisenberger et al., 2017). Well RN-15 was selected as a target well, as it had already been vertically drilled to a depth of 2507 m in 2004 (Jónsson et al., 2010). Measurements confirmed the well reached supercritical conditions at the slant depth of 4659 m (referenced to the rig floor of the drill rig Þór, ~4500 m vertical depth), and so it became the hottest (>426°C) and deepest geothermal well drilled in Iceland (Friðleifsson et al., 2018; Weisenberger et al., 2019). The well was drilled vertical down to 2750 m and then deviated (220°) towards the main up-flow zone of the Reykjanes geothermal system. After completion of the well, it was submitted to cold water injection and stimulation until August 2018, when warmup was started to prepare the well for discharge testing in late 2019 (Sigurðsson, 2019).

Since 2013, ÍSOR, on behalf of HS Orka Ltd., has operated a permanent network of ten seismic stations on the Reykjanes Peninsula, with seven of the ten stations in a dense network around the Reykjanes geothermal field. The seismic monitoring at Reykjanes has provided highly valuable data for understanding the structure and dynamics of the Reykjanes geothermal system, e.g. as a significant input for the 2016 conceptual model of Reykjanes (Khodayar et al., 2016). The depth of earthquakes since 2013 confirms earlier observations that the brittle-ductile boundary below Reykjanes is generally at 5.5–6 km depth. However, from 2013 to 2016, an aseismic body was evident between 3 and 6 km depth, below the central core of the production field in Reykjanes. The nature of the aseismic body was unknown, and there was no past evidence for seismic activity within the body. As the Reykjanes area is micro-seismically very active, it was important to monitor seismic activity during drilling and stimulation of well IDDP-2, because the well was intended to enter deep into the aseismic body. Within the framework of the H2020 funded DEEPEGS project, a temporary seismic network of nine stations was installed by ÍSOR and KIT in Reykjanes from October 2016 to September 2017, in addition to the permanent network in the area (Gaucher et al., 2016).

1.1 Geological, Tectonic and Geothermal Setting

The Mid-Atlantic Ridge comes onshore at the southwestern tip of Iceland, on the Reykjanes Peninsula. The peninsula marks the southwestern most part of the active volcanic and rift zones of Iceland and forms the transition from the Reykjanes Ridge in the west to the South Iceland Seismic Zone in the east (Einarsson, 1991). Reykjanes is the southwest tip of the Reykjanes Peninsula, with the Reykjanes geothermal system in its center (Figure 1).

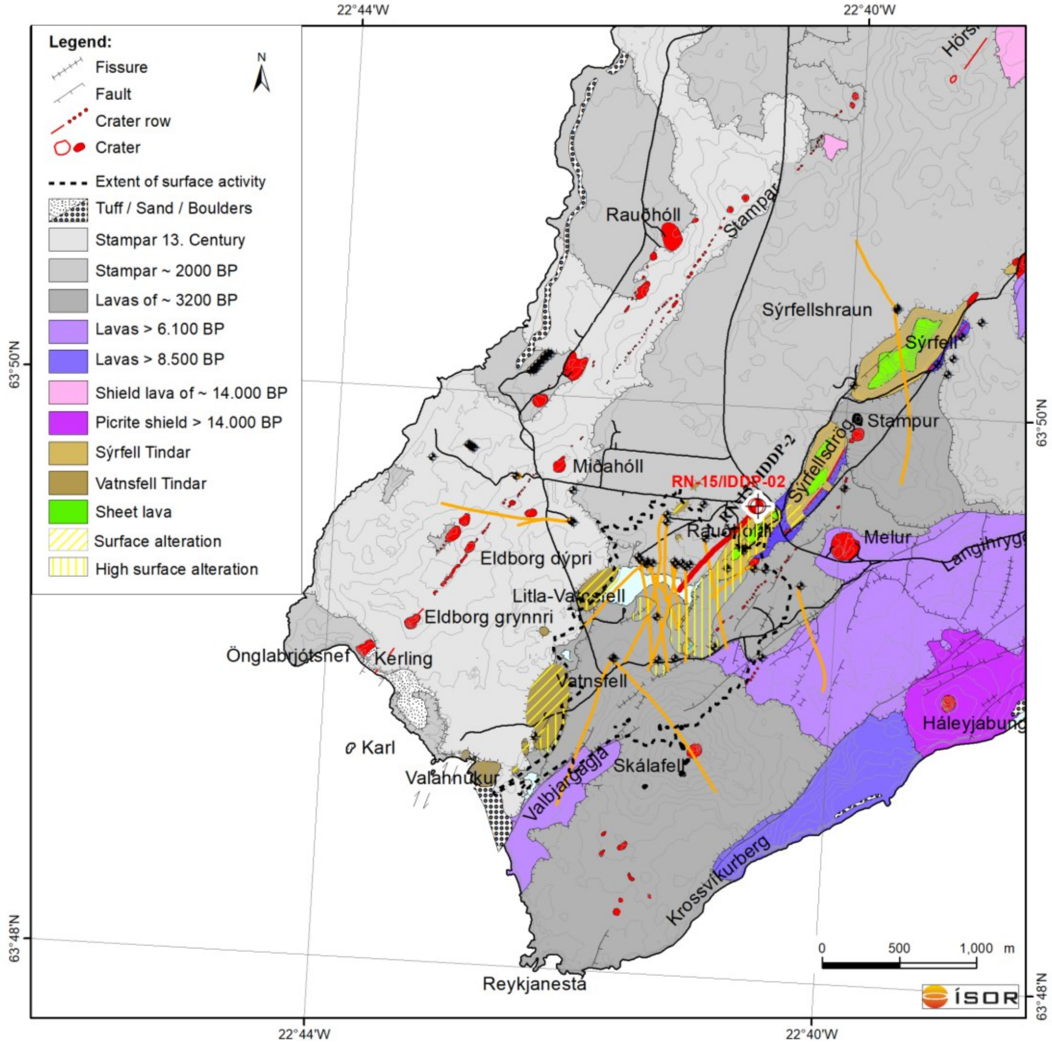

Figure 1: Geological map of the Reykjanes geothermal field. All drill holes are marked with black circled crosses, while orange colored lines show the direction of inclined wells. Well RN-15/IDDP-2 is emphasized with a red circled cross and line. Most of the geothermal wells are located within the hydrothermally active field (dashed black line), while re-injection, exploration and shallow water wells are mostly outside this area. The main landmarks referenced in the text are marked in the figure.

The geology of the Reykjanes Peninsula is characterized by Pleistocene basaltic lavas, hyaloclastite ridges and postglacial lava flows (Sæmundsson and Einarsson, 1980). At Reykjanes, only tholeiitic basalts have been erupted. Eruptions have occurred on a series of NE-SW trending eruptive fissures which can be grouped into four en echelon volcanic fissure swarms (Sæmundsson, 1978). The fissure swarms consist of normal faults and extensional tension fractures in addition to the eruptive fissures, and they are intersected at an oblique angle by a series of near vertical N-S right-lateral strike-slip faults (Keiding et al., 2009). Five high-temperature geothermal systems are present on the Reykjanes Peninsula, located primarily at the intersection of the fissure swarms and the strike-slip faults. The geothermal systems are, from west to east, Reykjanes (100 MW_e), Eldvörp, Svartsengi (75 MW_e), Krýsuvík and Brennisteinsfjöll.

Shear fractures are common in Reykjanes, within two ENE Riedel shear zones, indicating a minimum of a 7.5 km wide transform zone (Khodayar et al., 2016, 2018). The greatly deformed southern Riedel shear zone in Reykjanes is bounded to the north and to the south by the 1972 and 2013 earthquake swarms. This shear zone contains the Reykjanes geothermal field in a highly fractured block, where the predominant NE-SW fault direction can be dissected into N-S, ENE, NW/WNW and NNE fractures.

The Reykjanes geothermal system has been utilized for electrical power production by HS Orka Ltd. since 2006 with a power production of 100 MW_e at present. However, the exploitation of the field goes back to 1956 when the first exploration well was drilled, and the first deep well (RN-8) was drilled in 1969 down to 1754 m. HS Orka Ltd. acquired the development of the geothermal field in the 1990's and drilled its first well for electrical generation in 1998. Since 1956 to date, 37 wells have been drilled in Reykjanes for exploration, production, or geothermal re-injection. The power plant utilizes a two-phase reservoir from ~1-2.5 km depth, with a reservoir temperature of ~280-290°C at 1.5 km depth.

1.2 Historic Activity

The Reykjanes Peninsula is one of the most seismically active parts of Iceland, especially at the micro-earthquake level. The seismic zone, which extends from the western tip of the peninsula towards the Hengill triple junction in the east, is not a single fault, but rather a series of strike-slip and normal faults (Einarsson and Björnsson, 1979). Seismicity is continuous along the plate boundary, while seismicity on the western part of the peninsula, especially in and around the Reykjanes geothermal field and of the Reykjanes Ridge to the southwest, is characterized by episodic earthquake swarms, whereas fewer but larger earthquakes are typical of the eastern part (Tryggvason, 1973; Einarsson, 1991). Earthquake swarms on the western part typically last for a few days where no main event can be identified (Klein et al., 1977).

Reliable historical accounts of earthquake activity in Reykjanes exist since the construction of a lighthouse in 1878 and permanent settlement in the area thereafter (Thoroddsen, 1905; Björnsson and Einarsson, 1974). During the summers of 1967 and 1968, micro-earthquake activity was monitored for the first time on the Reykjanes Peninsula when seismographs were operated for a few days near the Reykjanes and Krýsuvík geothermal fields, with close to 20 earthquakes located per day in the surroundings of Reykjanes (Ward and Björnsson, 1971). An intense swarm of several thousand micro-earthquakes occurred in 1972, on a ENE-WSW striking 2 km wide and 12 km long zone, just northwest of the Reykjanes geothermal area (Klein et al., 1973; 1977). Hypocentral depths were mostly between 2 and 5 km depth and the largest earthquakes of magnitude ~4.

The first permanent seismic stations were installed on the Reykjanes Peninsula by the Icelandic Meteorological Office in 1991 (blue triangles in Figure 3), as a part of the regional seismic network in Iceland (the SIL network). The Reykjanes station (RNE) was installed in May 2008, and it increased the sensitivity of the SIL network in and around the Reykjanes geothermal field. Three short-lived earthquake swarms (1-2 days) occurred southeast of Reykjanes in 2006, and one in 2008, following the start of production in Reykjanes.

Since 2013, ÍSOR, on behalf of HS Orka Ltd., operated a permanent network of ten seismic stations on the Reykjanes Peninsula, i.e. from Reykjanes to Svartsengi, with seven of the ten stations in a dense network around the Reykjanes geothermal field (green triangles in Figure 3). In addition, on-line data from four stations of the SIL network were available. Moreover, within the framework of the EU-funded IMAGE project, a temporary network was operated from April 2014 to August 2015 with a total of 54 additional seismic stations (Blanck et al., 2018), i.e. 30 on-land and 24 Ocean Bottom Seismometers (OBS).

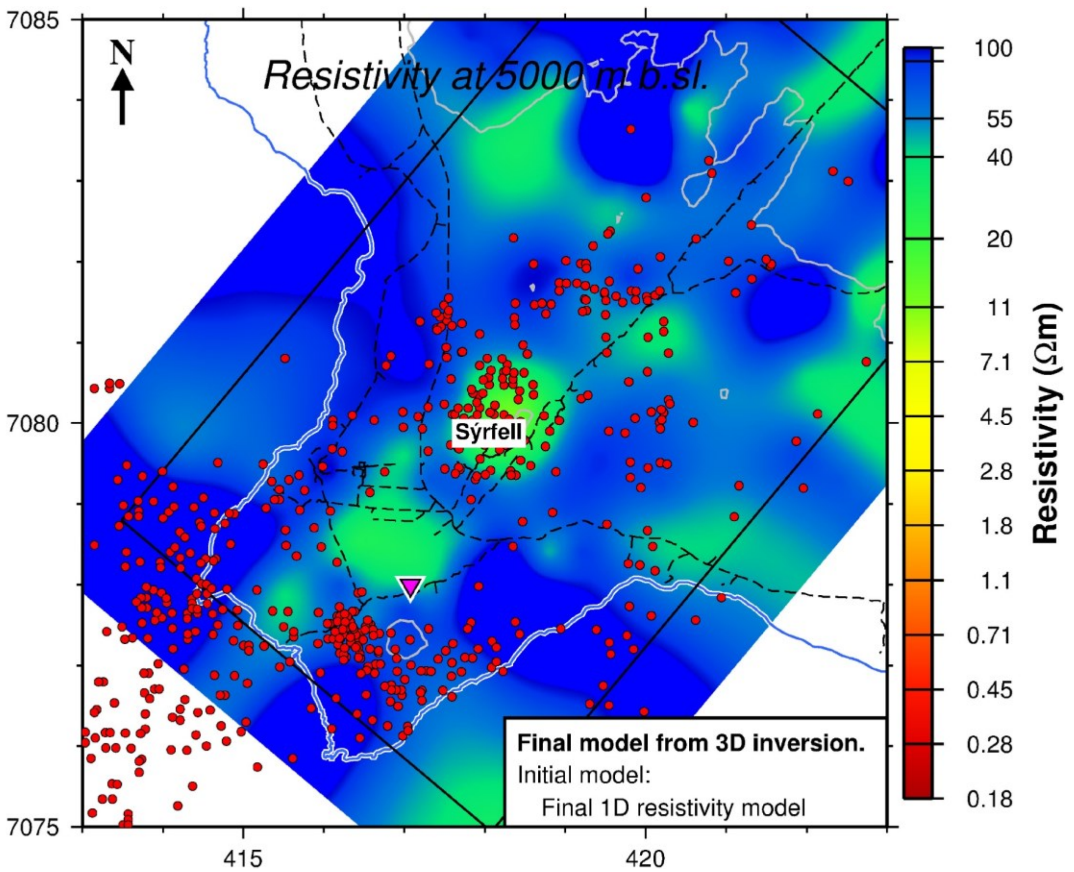

Figure 2: Earthquake locations in Reykjanes (in red) from January 2013 to July 2016 in a 1 km thick layer from 4.5 to 5.5 km depth, compared to the resistivity structure at 5 km b.s.l. The aseismic body below the central core of the production field in Reykjanes coincides with the low resistivity zone within the high resistivity core at depth (from Karlsdóttir et al., 2018).

The seismic monitoring since 2013, as previously mentioned, has provided a large and highly valuable dataset for understanding the structure and dynamics of the Reykjanes geothermal system, as the area is micro-seismically very active with scattered earthquakes and occasional earthquake swarms. From January 2013 to August 2018, around 6200 earthquakes occurred in and around the Reykjanes geothermal field, with one major swarm of ~900 earthquakes southeast of Reykjanes in October 2013 (Guðnason and Ágústsson, 2014; Guðnason, 2018).

Stimulation with injection of freshwater and later re-injection into well RN-34 has induced massive seismicity, with both scattered activity and several medium-large swarms, approximately where the re-injected fluid escapes the well. Re-injection of up to 200 kg/s into well RN-20b since 2013 has not induced any significant seismicity within the production field, while small-scale re-injection into well RN-33 has induced micro-seismicity at a low rate, approximately where the re-injected fluid escapes the well.

The majority of located earthquakes below the production field in Reykjanes are small, i.e., of $M_L \leq 2.0$ in magnitude, while larger earthquakes tend to occur outside the production field, mainly offshore to the southwest of Reykjanes. The depth of earthquakes from January 2013 to November 2018 confirms earlier observations that the brittle-ductile boundary below Reykjanes is generally at 5.5–6 km depth (Guðnason, 2018). Earthquake activity in the uppermost 2 km in Reykjanes, i.e. at reservoir depths, is concentrated below the production field, most likely associated with the geothermal activity and production, while earthquake activity outside the production field is generally located below 3 km depth.

However, from 2013 to 2016, an aseismic body was evident between 3 and 6 km depth, below the central core of the production field in Reykjanes. The nature of this aseismic body under the production field was unknown, and there was no past evidence for seismic activity within this presently aseismic body. The aseismic body coincides with a low resistivity zone within the high resistivity core below the production field, as seen in Figure 2. Three hypotheses were put forward to explain this aseismic body (Guðnason et al., 2015): (a) The lack of earthquakes is a coincidence as seismic activity in Reykjanes is episodic and the 2013-2016 recorded earthquakes could correspond to a quieter period. (b) The geothermal production has led to drastic pore pressure reduction and is reflected by considerable subsidence (as seen in GPS, gravity and InSAR data), raising the critical stress and increasing the rock strength. (c) The temperature within this aseismic body is high enough (600°C ± 100°C) to prevent stress accumulation to result in faulting, i.e. the brittle-ductile boundary is at close to 3 km depth below the production field.

Fault plane solutions have been calculated for a number of selected earthquakes located in and around the Reykjanes geothermal field (Guðnason, 2018). Predominantly, the fault plane solutions are variable within the production field, where strike-slip, normal and even reverse displacements exist, while fault plane solutions outside the production field show mainly strike-slip displacements.

2. DATA ACQUISITION AND PROCESSING

In addition to the permanent seismic network in Reykjanes, nine temporary seismic stations were installed late September 2016 within the framework of the DEEPEGS project (Gaucher et al., 2016). Five stations were provided by ÍSOR and four by KIT. The sampling rate of all temporary stations and permanent ÍSOR stations was 250 samples per second, while the sampling rate was 100 samples per second at the SIL stations. The permanent seismic network has real-time data transmission and automatic location of events, while the temporary stations were off-line, with data retrieved manually. The temporary station locations were selected in places with existing basic infrastructure from the IMAGE project, that additionally optimized the azimuthal and inclination coverage of the whole seismic network, without being further than 7.5 km from the IDDP-2 wellhead. The whole network is shown in Figure 3.

Recorded earthquakes from October 2016 to September 2017 were automatically detected using a classic STA/LTA detection approach and located with the SeisComp3 seismological software for data acquisition and processing, run at ÍSOR (www.seiscomp3.org). All P- and S- phases have been manually revised. The NonLinLoc (NLL) localization algorithm was used in the location process (Lomax et al., 2000). NLL is a probabilistic earthquake location technique with non-linear, global search methods, which considers the elevations of seismic stations. The velocity model used is the SIL model, an average model derived from the western part of the South Iceland Seismic Tomography (SIST) refraction profile (Bjarnason et al., 1993). Double-difference earthquake relocations were computed using the double-difference algorithm of the hypoDD software (Waldhauser, 2001). Earthquakes chosen for double-difference relocations have been classified as well-constrained, using the "rules of thumb" provided by Husen and Hardebeck (2010), i.e. if they meet the criteria of (1) at least 8 travel time arrivals (in this case a min. no. of 16 travel time arrivals), of which at least one is an S-wave arrival and one from a station within a focal depth's distance from the epicenter, and (2) one S-wave arrival within 1.4 focal depth's distance from the epicentre. Fault plane solutions (FPS) are based on polarities and generated using the FPFIT program of Reasenberg and Oppenheimer (1985), which calculates best-fit double-couple FPS from the polarity data.

3. SEISMIC ACTIVITY

Over 2300 earthquakes occurred in and around the Reykjanes geothermal field from August 2016 until end of September 2017, i.e. during the timespan from the start of the IDDP-2 drilling to the end of the main stimulation phase. All earthquakes have been manually picked and well-constrained earthquakes have been relatively relocated (Figures 3 and 4). Earthquake activity during this period is characterized by (see Figure 1 for main landmarks):

i) shallow earthquakes at reservoir depths (uppermost 2 km) below the **well-field**, most likely associated with the geothermal activity and production,
ii) deep earthquakes (3-6 km depth) at **Önglabrjótsnef**, striking NNE-SSW,
iii) deep earthquakes (3.4-5 km depth) below **Skálafell** that belong to a large swarm in July 2017, striking NE-SW,
iv) induced seismicity to the north and south of **Sýrfell**, due to re-injection in wells RN-34 and RN-33, respectively,
v) induced seismicity during drilling, completion and stimulation of well **IDDP-2** (Guðnason et al., 2016, 2017).

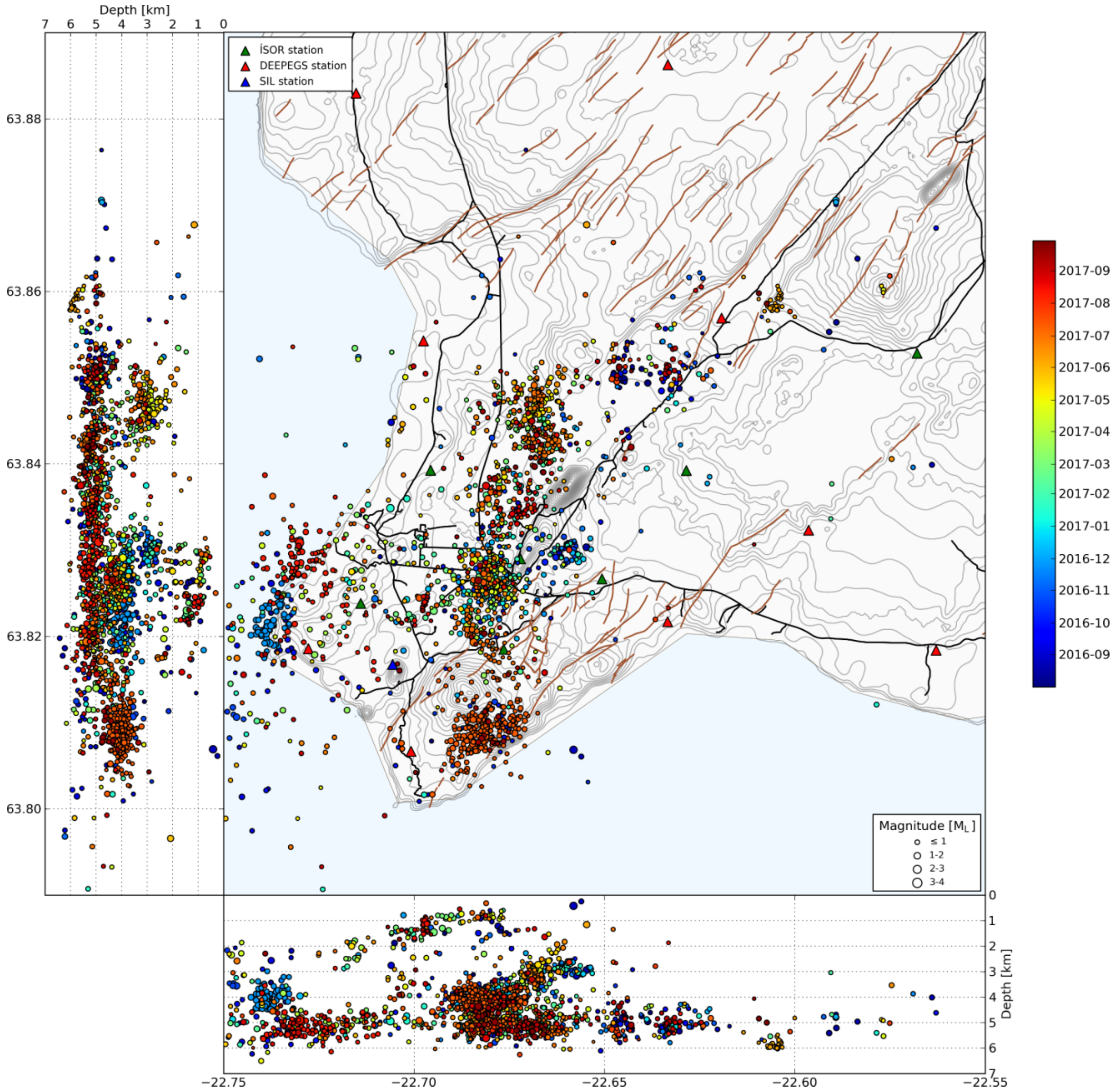

Figure 3: Double-difference earthquake relocations of well-constrained earthquakes in map view in Reykjanes from August 2016 to end of September 2017, colored by time and sized according to magnitude.

3.1 Permeability Below 3 km in Well IDDP-2

Before the drilling of well IDDP-2, the deepest production wells in Reykjanes reached down to about 2.5 km depth. Temperature and pressure logs carried out in well IDDP-2 on the 3rd of January 2017 yielded a temperature of 426°C and pressure of 340 bars at the slant depth of 4659 m depth (Weisenberger et al., 2017). At that time, the temperature of the well had not equilibrated from the cooling of the circulation fluid and is therefore a minimum value. This temperature-pressure condition is consistent with a supercritical fluid condition within the high-saline reservoir of the Reykjanes geothermal system. 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. A Horner plot estimate using temperature series from a weeklong heat-up interval in May 2017 gives an estimate of the formation temperature at the bottom of the well to be at least 535°C (Tulinius and Níelsson, 2020).

Well IDDP-2 was cased down to ~3 km depth due to a total loss of circulation from 2.5 km depth. Several permeable zones are identified in well IDDP-2 based on circulation losses during drilling and the evaluation of geophysical logging data, e.g. temperature logs (Weisenberger et al., 2019). A minor permeable zone is located just below the casing shoe at around 2940 m depth. Increasing circulation losses below that zone and finally a total loss of circulation from around 3200 m depth indicate the high permeability at this depth. The most prominent permeable zone is found at the depth interval between 3350 and 3380 m and most likely reflects a major fracture zone into which most of the injected fluid disappears. Several smaller feed zones or permeable zones are identified, whereas the deepest are located at a depth of 4375 m and 4550 m, respectively. This clearly indicates permeability below the conventional production field in Reykjanes, and it seems that major fracture zones in well IDDP-2 are related to compartments as defined by Khodayar et al. (2016). The well path and location of main feed zones as detected during drilling are shown in Figure 4.

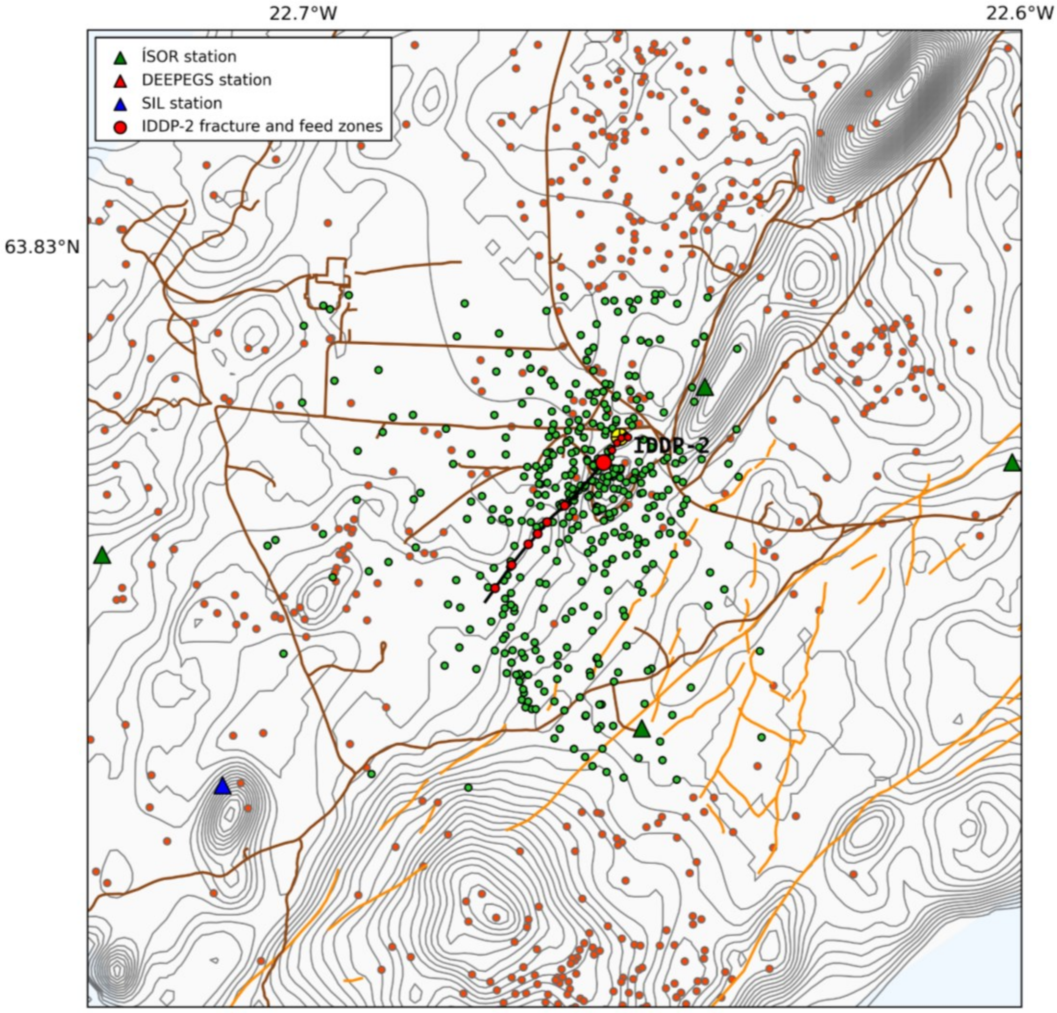

Figure 4: Double-difference earthquake relocations of well-constrained earthquakes in map view within the Reykjanes well-field from August 2016 until end of September 2017. In green: IDDP-2 induced seismicity below 3 km depth. In pink: Background seismicity during this period. The well path of well IDDP-2 is shown with a black line, and location of main feed zones as detected during drilling and their relative sizes with red circles. Surface fractures and roads are shown with orange and brown lines, respectively.

3.2 Seismic Activity During Drilling, Completion and Stimulation of Well IDDP-2

Interestingly, since the IDDP-2 drilling started on the 11th of August 2016, seismicity has been induced within the **eastern part** of the previously postulated aseismic body (Guðnason, 2018). As previously mentioned, 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 induced seismicity occurs just below the total loss of circulation, i.e. essentially from 3.5 down to 5.6 km depth. The induced earthquake activity was more or less scattered and ongoing below 3.0 km depth during the drilling, completion and stimulation of the well, with no large induced swarms.

The average injection rate of freshwater during the almost 6 months period of drilling is estimated by Þorgilsson et al. (2020) to be almost 30 L/s. Induced seismicity during the drilling phase was scattered and ongoing with no specific induced swarms and predominantly small earthquakes, i.e. magnitudes ranging from 0.5 to 2 M_L (Figure 7). One injection test was carried out after completion of phase 4 on the 3rd of January 2017, when the injection rate was increased from 15 to 45 L/s and decreased again to 15 L/s during a two-hour period (Weisenberger et al., 2017; Sigurðsson, 2019). The injection test yielded an injectivity of 1.7 (L/s)/bar but no specific earthquake activity followed (Figure 7).

As a part of the well completion, two injection tests were performed after drilling to the final depth of 4659 m was completed (Weisenberger et al., 2017; Sigurðsson, 2019). The first on the 20th of January, when the injection rate was first increased from 15 to 45 L/s and decreased from 45 back to 15 L/s during a 1½ hour period. The second was on the 23rd of January, when the injection rate was first decreased from 45 to 15 L/s and increased from 15 to 45 L/s during a 1½ hour period. The injectivity index was estimated in the range of 2.8 to 3.5 (L/s)/bar and is somewhat higher in the second test, indicating that the first stage of stimulation had affected the permeability. No specific earthquake activity followed the two injection tests (Figure 7).

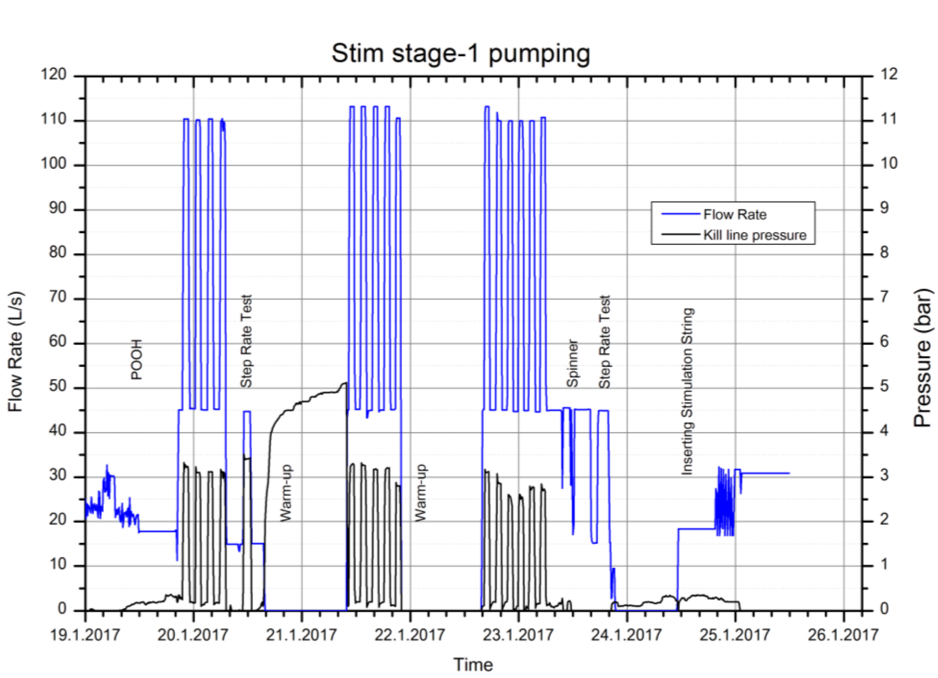

Figure 5: Pumping rate during the final days of the drilling operation. The oscillating injection rate during the stimulation and the warm-up periods in between. The first stage of stimulation ended by inserting the 3-1/2" stimulation string (from Sigurðsson, 2019).

Stimulation efforts in well IDDP-2 were carried out from February until July 2017 (Sigurðsson, 2019). On average, 10-15 L/s were injected from February until the middle of May, during which time induced seismicity was scattered and ongoing with no specific induced swarms (Figure 7). A stronger stimulation effort started on the 16th of May, when pumping with rig pumps started. From the 16th of May and until the 20th of June, around 60 L/s were injected for a week, followed by a week of 5 L/s injected. This cycle was repeated three times, followed by an intense stimulation in the end from the 20th of June until the 28th of June.

During the strong stimulation from the 16th of May until the 20th of June, no specific induced swarms occurred, but instead the activity was scattered and ongoing (Figure 7). However, induced earthquake activity was highest in the days following the intense stimulation (20th-28th of June), i.e. from the 30th of June until the 4th of July, with on average a daily rate of 13 earthquakes, including the largest induced swarm of 20 earthquakes per day on the 4th of July, which concluded with a magnitude 2.5 M_L earthquake. It strongly suggests that the intense stimulation induced the highest earthquake activity in well IDDP-2.

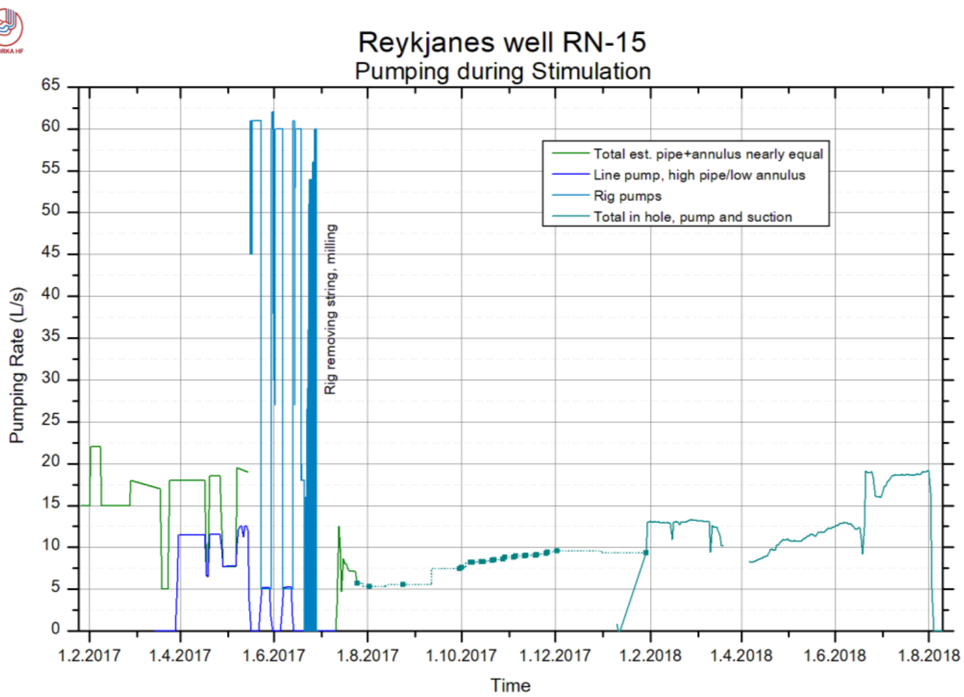

Figure 6: Injection rates into well IDDP-2 during long term cooling from the end of drilling operation on January 25th, 2017 and to the start of warmup on August 3rd, 2018 (from Sigurðsson, 2019).

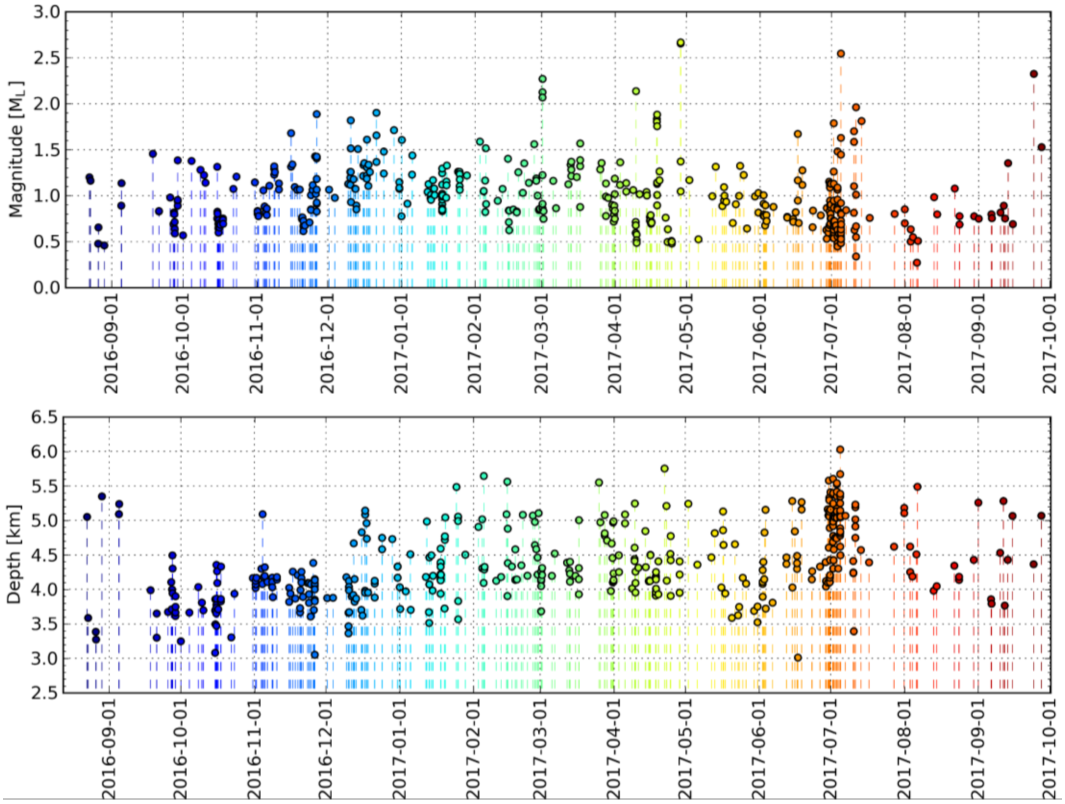

Figure 7: Magnitude (upper) and depth (lower) distribution with time of the relocated induced seismicity below 3 km depth during drilling, completion and stimulation of well IDDP-2 (green colored earthquakes in Figure 4).

In total, 458 earthquakes were located deeper than 3.0 km during the period from the start of drilling to the end of stimulation. Of the 458 earthquakes, 416 are well-constrained and have been relatively relocated (Figures 4 and 7). The majority of these earthquakes occurred between 3.5 and 5.6 km depth (95% of located earthquakes). The earthquakes are predominantly small, with magnitudes ranging from 0.2 to 2.7 M_L (Figure 7), but the majority ranging from 0.4 to 1.9 M_L (97% of located earthquakes). In total, nine earthquakes exceed magnitude 2 M_L, with three exceeding 2.5 M_L. A *b*-value calculation for IDDP-2 induced earthquakes larger than magnitude 1.0 M_L is around 1.2 (Guðnason et al., 2017). This *b*-value estimate is higher than average, and as experienced, this *b*-value of 1.2 signifies the dominance of micro-seismicity and the lack of larger earthquakes.

According to the double-difference earthquake relocations, the induced seismicity seems to group into two different fault zones; a northern one from roughly 3.5 to 4.7 km depth, and a southern, deeper one which seems to delineate a fault going from the bottom of the well to SE, striking NW-SE (Figure 4). These different fault zones are even more pronounced when looking at the double-difference earthquake relocations of only earthquake swarms consisting of 10 or more earthquakes per day during this period (Guðnason, 2018). Comparing the depth distribution of the earthquakes with the drilling progress indicates that the induced earthquakes follow the drill bit fairly well with time (Friðleifsson et al., 2018).

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 well IDDP-2 has increased the strain rate sufficiently to make this volume seismically active (Guðnason et al., 2016). Consequently, the temperature of the previously aseismic body is almost at the brittle-ductile boundary for normal strain rates (Guðnason et al., 2016, 2017). This opens up possibilities to put better constraints on the temperature of the brittle-ductile boundary of basaltic crust in general.

According to the double-difference earthquake relocations, the **western part** of the previously postulated aseismic body is still more or less aseismic below 3 km depth (Guðnason, 2018). The fact that it is still aseismic might mean that the strain rate within that part is still sufficiently low to keep this volume aseismic.

3.3 Fault Plane Solutions

Since seismic monitoring started in 2013, the overall observation is that different areas exhibit different fault dynamics in and around the Reykjanes geothermal field (Guðnason, 2018). A number of fault plane solutions (FPS) have been calculated of earthquakes induced below 3 km depth during drilling, completion and stimulation of well IDDP-2 (Guðnason et al., 2016, 2017). The FPS in Figure 8 are a sample of the most common type of IDDP-2 calculated FPS, which all show comparable faulting mechanism within a similar depth range, i.e. below 4 km depth. These selected FPS are intermediate events having both normal and strike-slip displacements, i.e. mostly dip-slip (normal) with some strike-slip component. The FPS show right-lateral displacements on NW-trending and northerly dipping planes or left-lateral displacements on NE-trending planes. Although the FPS only represent particular events, they also represent some kind of average mechanism of the deep induced seismicity in well IDDP-2.

The right-lateral displacement on NW-trending and northerly dipping planes of these FPS from 2016 and 2017 is consistent with e.g. the NW-SE striking trend of the southern, deeper fault zone previously mentioned. This might suggest that the more probable plane of motion in the deep part of the reservoir is NW. It is interesting that this NW-SE direction is approximately the same as seen in the shift in the resistivity model in this area (Karlsdóttir et al., 2018). This further indicates a NW-SE fault zone at depth in this area.

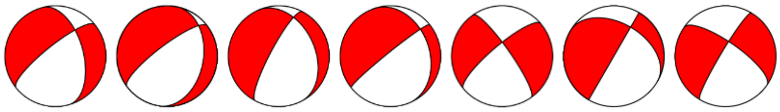

Figure 8: Selected fault plane solutions of the induced seismicity in well IDDP-2, below 4 km depth. These are lower hemisphere plots and compressional quadrants are red.

4. CONCLUSIONS

The drilling, completion and stimulation of well IDDP-2 in Reykjanes has induced seismicity within the eastern part of a previously postulated aseismic body below the central core of the production field in Reykjanes, while the western part is still more or less aseismic below 3 km depth. 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 has increased the strain rate sufficiently to make this volume seismically active.

The earthquakes are predominantly small, with the majority of $M_L \leq 2.0$. Increasing circulation losses below 3.0 km depth in well IDDP-2, and a total loss of circulation from around 3.2 km depth indicate high permeability below the proved production field in Reykjanes. All induced seismicity occurs just below the total loss of circulation, i.e. more or less from 3.5 down to 5.6 km depth and seems to follow the depth of the drill bit fairly well with time. The induced seismicity was more or less scattered and ongoing during this period with no specific induced swarms, except for the highest induced earthquake activity in the days following the intense stimulation at the end of June (30^{th} of June - 4^{th} of July). The largest induced swarm of 20 earthquakes per day occurred on the 4^{th} of July, which concluded with a magnitude 2.5 M_L earthquake.

Double-difference earthquake relocations of the induced seismicity map out two different fault zones with different fault dynamics below 3 km depth. A northern one from roughly 3.5 to 4.7 km depth, just below the largest feed zone between 3350 and 3380 m depth, and then a southern one which seems to delineate a fault going from the bottom of the well to SE, striking NW-SE and mapping possible fluid pathways from the deeper parts of the system to the present production field above 2.5 km depth. A recent study by Þorgilsson et al. (2020) proves that fluid pathways exist between the deeper part of the reservoir and the production field in Reykjanes by showing that the lowering of chlorite detected in the production fluid is likely induced by the pulse of freshwater injected during drilling of well IDDP-2.

Selected fault plane solutions of IDDP-2 induced earthquakes show comparable faulting mechanism within a similar depth range (below 4 km depth), i.e. they are intermediate events having mostly dip-slip (normal) displacements with some strike-slip component. The FPS show right-lateral displacements on NW-trending and northerly dipping planes or left-lateral displacements on NE-trending planes. The NW-SE trend is seen in resistivity data (Karlsdóttir et al., 2018), in the tectonic model of the Reykjanes geothermal field (Khodayar et al., 2016) as well as in the double-difference earthquake relocations of the induced seismicity, which might suggest that the more probable plane of motion is NW in the deep part of the Reykjanes reservoir.

The mapped fault zones provide input for numerical flow simulation such as carried out in the ERiS project (Berre et al., 2020). The proposed flow pathways will be used in the ongoing SiGS project to restrain thermo-mechanical models of the proposed conditions that enhance permeability by opening of fractures (Halldórsdóttir et al., 2020). Drilling into superheated formations in Reykjanes has revealed extensive fluid losses at depth for reasons that are not fully understood. A possible mechanism is that the introduction of cold drilling fluids leads to thermo-elastic contraction of the rock that opens fractures to significantly enhance the fluid injectivity. This is supported by the induced seismicity below 3.5 km depth during the drilling, completion and stimulation of well IDDP-2.

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