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Electrical Resistance Study between Well Casings at Reykjanes Geothermal Field

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ABSTRACT

Geothermal power production is highly dependent on fractures in the subsurface controlling the heat and mass transport towards production wells. This paper focuses on studying the fracture connectivity between geothermal wells at Reykjanes geothermal field in Iceland using a casing-to-casing resistance method. The method consists of connecting a pair of a current and a potential electrode to a steel casing and another pair to another casing for measuring the resistance between well pairs. The resistance measured between casings is considerably lower if the current is traveling from one casing to another through fractures filled with highly saline geothermal brine instead of going through less conductive rock. Hence, the resistance measured can give valuable information about the fracture network. At Reykjanes, six well pairs were studied including well IDDP-2 that has been deepened down to a depth of 4.7 km. Well IDDP-2 is not connected to any other wells via surface pipelines so the low resistance measured between the production casing of well IDDP-2 and surrounding wells indicates that the current is flowing through a channel of saline geothermal fluid. Taking advantage of using the steel casings as electrodes allows the current to travel along the casing deeper into the reservoir than if surface electrodes are used. Additionally, the difference in resistance values measured between different well pairs helps gaining knowledge about the fracture connectivity in the reservoir.

1. INTRODUCTION

Characterizing fractures in geothermal reservoirs is crucial for understanding the fluid-flow patterns in the reservoirs and for identifying promising drilling targets for new wells in order to run the power plants in an optimal way. Gaining information about the fracture configurations deep in the subsurface is a difficult task and currently none of the geophysical exploration methods commonly used is capable of providing an accurate high-resolution model of the fractures in the reservoirs at the required scale and cost. However, electrical resistivity methods have proven useful for studying geothermal fields due to the high contrast in resistivity between rock and geothermal brine. The resistivity of the subsurface depends on the rock type, fluid saturation, porosity, temperature and pore fluid salinity (Arnason et al., 2000; Storz et al., 2000, William et al., 1976).

In direct current (DC) resistivity studies, current and potential electrodes are generally arranged in a linear array such as the Schlumberger array or the dipole-dipole array (Beyer, 1977). However, other set-ups have been used including the cross-well method where one pair of a current and a potential electrode is placed inside a well and another pair inside another well. Then, the electrodes are moved vertically along the wells to get information about the resistivity distribution between them at different depths as demonstrated by Daniels and Dyck (1984). The Mise-A-La-Masse method is another possibility for mapping resistivity as used for investigating geothermal fields in Indonesia (Supriyanto et al., 2005) and Hawaii, USA (Kauahikaua et al., 1980) as well as to study oil fields in China (Li et al., 2008; Tan et al., 2004; Ling et al., 2003). The method involves connecting a charged current electrode to a conductive structure that goes deep into the surface, such as the steel casing of a geothermal well. Then, another current electrode is placed far from the survey area, possibly connected to another casing. In order to produce useful three-dimensional resistivity images, electric potential is measured on the surface using one fixed electrode and one electrode moving around the well.

The casing-to-casing resistance method studied in this paper consists of connecting a pair of a current and a potential electrode to a steel casing and another pair to another casing for measuring resistance between well pairs. This method provides limited information for constructing a three-dimensional resistivity map because only one value of resistance is measured between each well pair. However, the casing-to-casing resistance method can provide valuable information about the fracture connectivity between wells and using the conductive steel casing as electrodes allows the current to travel along the casing deeper into the reservoir than if surface electrodes are used. That way, the resistance measured between casings can help map the connectivity of fractures deeper in the subsurface than previously mentioned direct current (DC) resistivity methods and give information about which wells are connected and producing from the same aquifer.

Improving the depth resolution of geophysical exploration methods is becoming more important with increasing drilling depths. The Iceland Deep Drilling Project (IDDP) deepened a well, termed IDDP-2, to a depth of 4.7 km at the Reykjanes geothermal field in Iceland to reach supercritical fluids (Fridleifsson et al., 2017). Geothermal fluid at temperatures above the critical point of water (374°C and 22.054 MPa) has increased power-producing potential compared to subcritical fluids, thus causing increasing interest for drilling deeper wells to reach supercritical conditions. Planning is already underway for drilling another deep well, IDDP-3, at Hellisheidi in Iceland. As the depth of the wells increases, it becomes more difficult to investigate the fluid and heat transfer at the bottom of the wells. Hence, new developments for studying the deep subsurface and better understanding the interaction between the heat source and the reservoir is crucial. The casing-to-casing resistance method is a relatively low cost method that can be performed using existing casings to help deepen the current penetration during resistance measurements between wells and it can be performed without disrupting injection or production operations.

The feasibility of the casing-to-casing resistance method for estimating fracture connectivity in geothermal reservoirs is studied in this paper. Measurements were performed at Reykjanes geothermal reservoir in Iceland where the geothermal brine has high salinity and is therefore highly conductive. Steel casings were used as electrodes and the resistances between the 4.7 km deep well, IDDP-2, and surrounding wells were measured. A total of six well pairs were studied and two of the wells were not connected to any surface pipelines. Therefore, the current is ensured to be travelling through the ground from one well to another instead of possibly traveling along the surface pipelines. The measured resistance values were used to gain information about the fracture connectivity between the wells.

2. REYKJANES GEOTHERMAL FIELD

The Reykjanes geothermal system is located at the tip of the Reykjanes peninsula in southwest of Iceland where the Mid-Atlantic Ridge comes ashore (Fig. 1). The ridge is slowly spreading at around 1.8 cm/year providing volcanic activity as a heat source for the geothermal system while frequent small earthquakes help maintain good permeability. The lithology down to around 2.5 km depth consists of basaltic lavas and thick interbeds of hyaloclastites and sediments. Below, simple ophiolitic sheeted dike complex provides heat and retains vertical permeability (Fridleifsson et al., 2003). The surface manifestation at Reykjanes covers about 1 km^2 and early surface direct current (DC) resistivity surveys as well as later transient electromagnetic (TEM) and magnetotelluric (MT) surveys estimate the geothermal system below 800 m depth to have an area extension close to 10 km^2 (Karlsdottir, 1997; 2005).

The first well drilled at Reykjanes in 1956 reached 185°C at 162 m depth. In 1962, the well was plugged and after a few more exploration wells the first proper production well was drilled in 1969 (Sigurdsson, 2010). In 2006, the power plant was commissioned to produce 100 MWe on two 50 MWe steam turbines. A total of 36 wells have been drilled since 1956 including exploration, production and injection wells. The pressure draw-down due to production has formed a steam cap at 800-1200 m depth (Fridleifsson et al., 2009). Some of the wells at Reykjanes target this steam cap for producing dry steam instead of liquid to decrease the mass of fluid produced from the system and thereby lessen the rate of pressure draw-down. Current plans involve adding several deep and shallow steam wells along with deep re-injection wells to increase the production to up to 180 MWe (Sigurdsson, 2010).

The Reykjanes geothermal system is unique because the area is penetrated by seawater causing the geothermal brine to have seawater salinity (Arnorsson, 1978). Subsequently, the resistivity of the brine at Reykjanes is considerably lower than that of the rainwater typically found in Icelandic hydrothermal systems. Reinsch at al. (2016) measured the resistivity of the brine at Reykjanes to be around 0.24 Ωm at 25°C and it decreases to a minimum of 0.05 Ωm at 245°C. For comparison, the typical resistivity values of rocks in Iceland are 100-3,000 Ωm for basalts, 5-15 Ωm for rock filled with brine, 1-100 Ωm for high-temperature areas with fresh water and 1-4 Ωm for high-temperature areas with brine (Hersir and Bjornsson, 1991). The resistivity of rock decreases with increasing saturation, porosity, temperature and salinity of the fluid and also depends on the water-rock interaction and alteration due to geothermal activity. TEM measurements at Reykjanes by Karlsdottir et al. reveal a low resistivity cap of 1- 3 Ωm down to 1 km depth, underlain by a high resistivity core of 10-30 Ωm down to 3 km depth (2005). This resistivity measured at Reykjanes is lower than typical fresh water systems due to the high salinity of the brine. At greater depth, high resistivity anomalies of 70-100 Ωm are observed. Additionally, a zone of lower resistivity at 20-40 Ωm is prominent under the main geothermal field in the NE-SW direction, i.e. the dominant direction of faults and fissures (Karlsdottir, 2005). This low resistivity likely indicates a high temperature fracture zone feeding heat into the system.

The Reykjanes geothermal system is a freely convecting hydrothermal system and liquid dominated below 1,200 m, i.e. below the steam cap at 800-1,200 m depth. The fluid temperature in the system is around 270-320°C and has been measured up to 345°C at 2,250 m depth in well RN-30 as well as at 2,800 m depth in well RN-17B (Fridleifsson et al., 2013). The temperature becomes higher with increasing depth and the deepest well at Reykjanes, well IDDP-2, measured 426°C at a depth of 4,560 m (Fridleifsson et al., 2017). The corresponding in-situ formation temperature once cooling during drilling has been taken into account is estimated to be even higher at that depth, in the range of 536-549°C (Tulinius, 2017). The IDDP-2 well makes the Reykjanes system a unique option and an interesting research opportunity for testing the casing-to-casing method due to the well reaching deep into the roots of the reservoir.

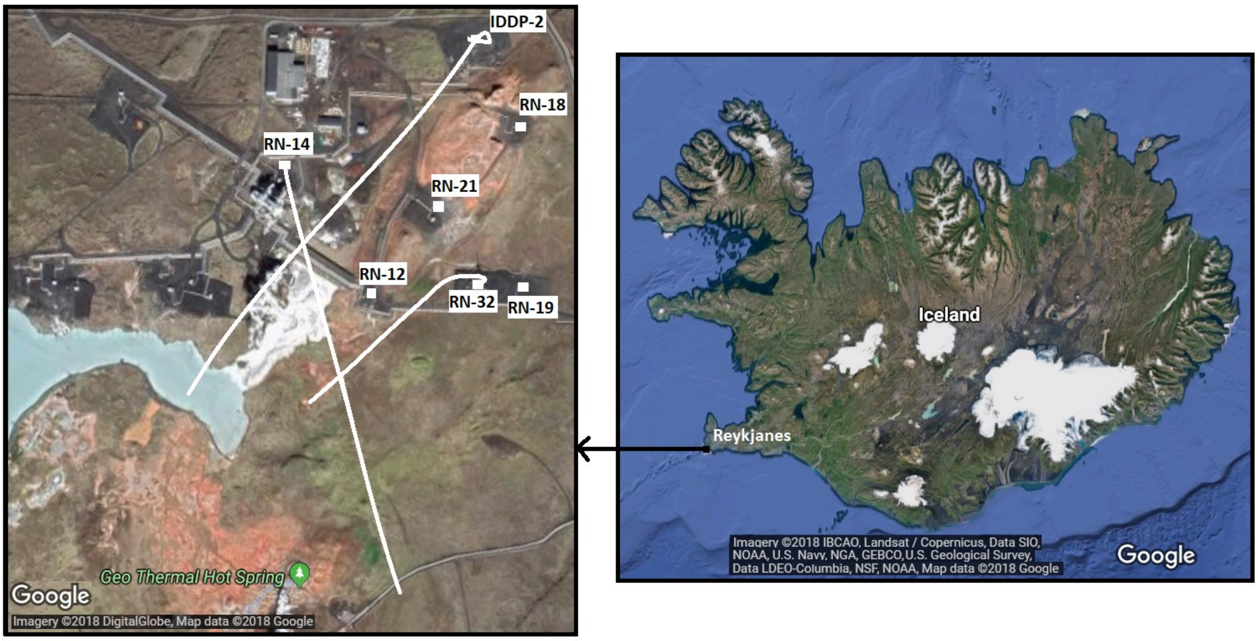

Figure 1: Reykjanes geothermal field with locations and tracks of wells considered in this study. Well track locations were adapted from Weisenberger et al. (2017).

3. CASING-TO-CASING RESISTANCE METHOD AT REYKJANES

The casing-to-casing resistance method involves using well steel casings as electrodes in a resistance study to estimate fracture connectivity between the wells. A direct current is sent from one casing to another while the voltage difference between the casings is measured. Then, the known input current and the measured voltage difference are used with Ohm's law to calculate the subsurface resistance between the casings as follows,

$$R = \frac{V}{I} \tag{1}$$

where R is the resistance [Ω], V is the measured voltage difference [V] and I is the input current [A]. The calculated resistance between the wells depends on whether the current is traveling through the rock or through brine and will therefore give information about the fracture connectivity between the wells.

In this paper, the focus is on mapping the resistance between wells for predicting if the current is flowing from one casing to another through brine-filled fractures or through less conductive rock. Resistance measurements were performed at Reykjanes geothermal field in Iceland between well IDDP-2 and surrounding wells shown in Fig. 1. Well IDDP-2 is not connected to surface pipelines, only to an injection well further away from the surrounding production wells. Hence, the current from well IDDP-2 is flowing through the ground from one casing to another instead of possibly flowing through conductive surface pipelines. Additionally, well RN-32 is not connected to any surface pipelines. A total of seven wells were studied, thereof three directionally drilled and four vertically drilled. The tracks of vertically drilled wells are shown in Fig. 1. Five of the wells are in production and the remaining two wells are not currently producing. The depths of the wells, the depth and diameter of the production casings and the status of each well during measurements are summarized in Table 1.

Table 2: Well depths, production casing depths and diameters, and status of each well.

Well	Depth of well [m]	Production casing diameter [mm]	Production casing depth [m]	Status
IDDP-2	4,659.0	244.5	2,900.0	Not in production
RN-12	2,506.4	339.7	841.7	Production
RN-14b	2,426.0	339.7	795.5	Production
RN-18	1,814.7	339.7	749.5	Production
RN-19	2,248.0	339.7	688.6	Production
RN-21	1,713.3	339.7	609.0	Production
RN-32	1,202.0	339.7	1067.7	Not in production

The resistance measured between two wells at Reykjanes is expected to be low due to the conductive brine in the reservoir, therefore making the accuracy of the measurements crucial. In a two-wire resistance method, two probes are used (i.e. a wire is connected to each casing) and the current magnitude is measured in the circuit as well as the voltage drop over the power source.

Another approach is the four-wire resistance method which uses separate pairs of a current-carrying wire and a voltage-sensing wire (i.e. two separate wire connections to each casing) for separately measuring the current injected into the ground via the power source and the corresponding voltage drop in the ground. A two-wire resistance method is more convenient than a four-wire method because of fewer connections and less wire needed. However, measurement errors can occur in a two-wire method because the total resistance measured includes not only the resistance between the wells but also the resistance of the wires used for the measurements. The test current causes a voltage drop across the wires that can be significant compared to the low voltage drop across the brine possibly connecting the two wells. In order to avoid measuring the resistance of the wires and to only measure the resistance of the ground, a four-wire resistance method was used in this study as demonstrated in Figure 2.

The measurement set-up consists of five 12 V batteries connected in series, an ammeter measuring the current going through the circuit, a button to ease the process of connecting and disconnecting the circuit and a waveform generator to generate a square-wave current going from one casing to another (Fig. 2). Separately, a voltmeter is connected to each casing to measure the voltage drop across the ground. The wires are connected to the production casings via parts of the well-head and a good electrical connection from the wire to the production casing is ensured. A direct current is preferred over an alternating current because it allows for a great depth of investigation and avoids ground inductance and capacitance complexities as well as effects of resistivity being dependent on frequency. However, an actual direct current is not used because charge build-up can occur between the electrode (i.e. the casing) and the surrounding soil if the direction of the current is always the same, although this is not likely to be a problem if the steel casings are connected via conductive brine. Additionally, alternating the direction of the current can filter out natural currents and potentials in the Earth that are usually unidirectional or slowly time-varying, and polarized ionization fields do not have sufficient time to develop. In our study, a low frequency of 5 Hz was used so that the measured resistance is essentially the same as a direct current resistance.

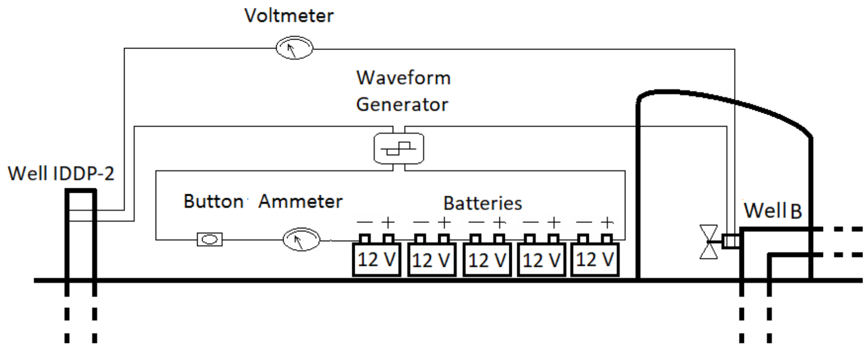

Figure 2: Measurement set-up.

4. MEASUREMENT RESULTS

The objective of the experiments performed in this study is to investigate whether steel well casings can be used as electrodes in a resistance study of a geothermal field to gain information about the fracture connectivity in the subsurface. The results from the experiments are summarized in Table 2. These results include the measured voltage difference between production casings, measured electric current traveling between the casings, calculated resistance and the distance between wellheads. The main results observed by these experiments is the low resistance between well casings indicating that the electric current is traveling from the production casing of well IDDP-2, through the conductive brine to the production casing of the other wells. Hence, the results indicate that the steel casings can successfully be used to transfer the electric current deeper into the ground than when surface electrodes are used.

Table 2: Electric measurements between well IDDP-2 and surrounding wells.

Well A	Well B	Voltage difference [mV]	Current [A]	Resistance [mΩ]	Distance between wellheads [m]
IDDP-2	RN-12	120	7.337	17.04	442.0
IDDP-2	RN-14	132	7.374	17.36	387.0
IDDP-2	RN-18	107	7.394	14.88	157.1
IDDP-2	RN-19	174	7.340	22.34	413.2
IDDP-2	RN-21	120	7.287	15.92	279.2
IDDP-2	RN-32	104	7.298	16.85	404.9

The results are congruent with a tracer test performed at Reykjanes by Matthiasdottir et al. (2015) where a two-phase tracer was injected into well RN-20, located southeast of well RN-19. Tracer was recovered in all wells considered in this study including well RN-15, which is the well that was deepened from 2,500 m to 4,659 m to make well IDDP-2. The results of the tracer test indicated a strong connection between the injection site and the production site. Similarly, the results of the electric measurements in this study indicate that the wells considered are all connected via the main production zone, therefore resulting in good electrical connectivity between them.

An important aspect to consider in these experiments is how deep down the production casing the electric current is traveling. A standard geothermal well at Reykjanes has three casings; a surface casing, an anchor casing and a production casing. Additionally, a slotted liner is placed at the bottom of the production casing to the bottom of the well. For a well with a production casing down to a depth of 2,400 m, the surrounding anchor casing has a depth of approximately 800 m while the surface casing with the largest diameter has a depth of approximately 400 m. During drilling, the steel casings are lowered into the well and the space surrounding the casings, i.e. between different types of casings as well as between the casings and the drilled rock, is filled with cement. Hence, the production casing is surrounded by cement that anchors the casing and protects against possible corrosion by thermal brines. The resistance between the production casing and the anchor casing of a well at Reykjanes was measured in order to test if the electric current could be traveling from the production casing, through the cement and from there to the anchor casing. The resistance measured between the production casing and the anchor casing was of a significantly higher order of magnitude than the resistance measured between two production casings of different wells. Hence, these measurements indicate that most of the current is not traveling through the cement to the anchor casing and it is likely to reach the bottom of the production casing as long as the cement is fully covering the casing. From there, the electric current can travel into the surrounding formation via feed zones of highly conductive brine or travel further down the well via the steel liner.

Although wells IDDP-2 and RN-32 are not connected to any other wells through surface pipelines, some of the wells studied are connected. In those cases, there is a possibility that the current could travel from one casing, through the surface pipelines and the separator station, to surface pipelines and a casing of another well and from there to the ground towards the casing of well IDDP-2. Therefore, future work includes measuring the resistance along the surface pipelines to ensure that the resistance measured between the wells is the resistance of only the saline-filled fractures between the wells and not the surface pipelines.

5. CONCLUSIONS

Electrical measurements were performed at Reykjanes geothermal field in Iceland to investigate the possibility of using geothermal steel casing as electrodes in a resistance study to gain information about the fracture connectivity in the reservoir. Seven wells were studied, including well IDDP-2 that has been deepened down to a depth of 4,650 m during the Iceland Deep Drilling Project (IDDP). The low resistance measured between production casings of the different wells considered indicate that the steel casings can be used as electrodes to transfer electric current deeper into the ground than when surface electrodes are used. Additionally, the measurements suggest that the wells are all connected to the main production zone at Reykjanes and the electric current is likely traveling through brine-filled fractures from one production casing to another. These results are congruent with tracer tests that have been performed at Reykjanes geothermal field.

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