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3D Resistivity Model (MT) of Reykjanes High Temperature Field in SW Iceland.

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ABSTRACT

The resistivity structure of Reykjanes is presented, derived from 3D models developed in 2014 and 2016. The models are the final results of a 3D inversion of MT data, corrected for static shift by joint inversion with TEM soundings at the same location as the MT sites. In the model presented here (REYSAND), a total of 136 sounding pairs are used for the inversion. The model covers Reykjanes area and Sandvík potential geothermal area. The Reykjanes models reveal a conventional resistivity structure for a high enthalpy geothermal system, i.e. a low resistivity cap underlain by a high resistivity core. The low resistivity cap reaches surface in the hot spring area, Gunnuhver, and dips down in all directions forming an elongated area of 2.5 km x 3 km in dominating fault direction down to 1 km depth bounded by the low resistivity. The resistivity of the low resistivity cap is less than 3 Ωm and is underlain by a high resistivity core with resistivity of 10–30 Ωm down to 3 km depth. At greater depth, high resistivity anomalies are prominent with a zone of lower resistivity, in dominating fault direction, under the main field. This zone coincides with an aseismic zone at depth and may indicate a fracture zone with higher temperature and/or permeability within the geothermal system. Comparison to data from the IDDP-2 drilling as well as seismic monitoring confirm that suggestion.

1. INTRODUCTION

The Reykjanes high enthalpy geothermal system is situated on the south-westernmost tip of Reykjanes Peninsula, the onshore continuation of the Mid Atlantic Ridge (Figure 1). A transition zone characterized by active seismicity and volcanism connects the Mid Atlantic Ridge to the SW volcanic zone through Hengill and the South Iceland seismic zone. Reykjanes Peninsula hosts a few known geothermal high temperature areas, Reykjanes, Eldvörp, Svartsengi and Krýsuvík, as well as areas that are considered potential geothermal areas. HS Orka harnesses energy at Reykjanes and Svartsengi geothermal fields. At present, the power generation in Reykjanes is 100 MWe while Svartsengi provides hot water for space heating (190 MWth) and generates electricity (74 MWe).

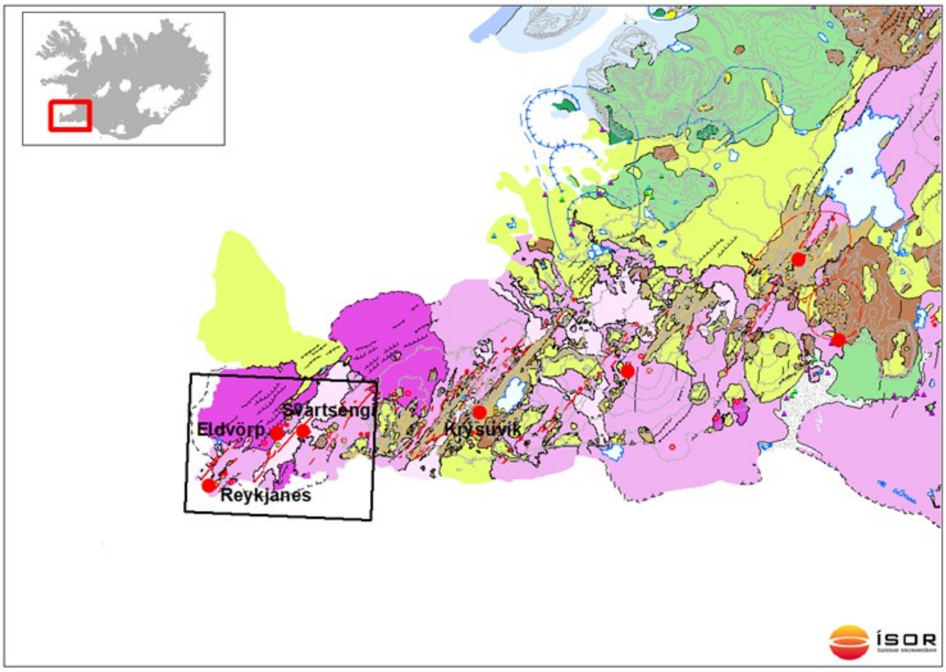

Figure 1: A geological map of the Reykjanes peninsula (Árni Hjartarson and Kristján Sæmundsson, 2014). The black box shows the survey area of the Reykjanes geothermal area, shown in Figure 2.

2. DATA ACQUISITION AND PROCESSING

Iceland GeoSurvey (ÍSOR) performed numerous controlled source electromagnetic (EM) surveys in and near the high temperature geothermal fields of the Reykjanes Peninsula in the late 20th and early 21st century for HS Orka (and their predecessor). The central-loop transient electromagnetic (TEM) method was most widely used to image the subsurface resistivity structure in the uppermost kilometer of the crust. In order to resolve deeper structures within the geothermal systems, magnetotelluric (MT) measurements have been performed in recent years. The MT method is a passive EM technique that utilizes the time varying geomagnetic field as a power source. This natural occurring source has a broad spectrum and hence the MT method can resolve structures from depths of tens of meters to tens of kilometers. The main emphasis of this article is on the results, delineating only a few practical points regarding the survey setup and the data processing. For better account of the methodology, refer to Hersir et.al., 2018 and references therein.

Like all resistivity methods measuring the electric field at the surface, MT suffers the telluric shift problem, or "static shift". The cause of this can be near-surface resistivity irregularities close to the MT site as well as topography effects (e.g. Sternberg et al., 1988; Árnason et al., 2008. The result of this is that the apparent resistivity values have an unknown multiplier (same value for all frequencies). As the TEM method only relies on the magnetic field, it is much less affected by local irregularities and do not suffer this problem. Joint 1D inversion of TEM and MT was used to determine and correct for the static shift in the MT apparent resistivity curves.

3. THE REYKJANES MT SURVEY

MT surveying in the Reykjanes Peninsula has extended almost a decade. The first MT survey was performed in Krýsuvík high temperature field in 2007 (Hersir et al., 2011. The first MT measurements in the Reykjanes geothermal field were performed as a part of a MT profile in 2008 from Krýsuvík, across Svartsengi to Reykjanes geothermal field (Rosenkjær and Karlsdóttir, 2009). An MT survey started in Reykjanes high temperature field in 2009 (Karlsdóttir and Eysteinsson, 2010) and was continued over the years to come until 2013 and resulted in 3D inversion models in 2012 (Karlsdóttir et al., 2012) and 2014 (Karlsdóttir and Vilhjálmsson, 2014), here referred to as REY model. A comprehensive MT survey over the Reykjanes, Svartsengi and Eldvörp high temperature fields and the potential field Sandvík, was performed during the summers of 2013 and 2014 and resulted in a 3D model (Karlsdóttir and Vilhjálmsson, 2015), here referred to as SES-model. More TEM and MT soundings were added in the summer 2015 for a 3D model of Sandvík (Karlsdóttir and Vilhjálmsson, 2016a) and finally a 3D model (here referred to as REYSAND model) was made of Reykjanes geothermal field extending to north east to include Sandvík potential geothermal field (Karlsdóttir and Vilhjálmsson, 2016b). The fine gridded areas of the three models REY, REYSAND and SES are shown in Figure 2.

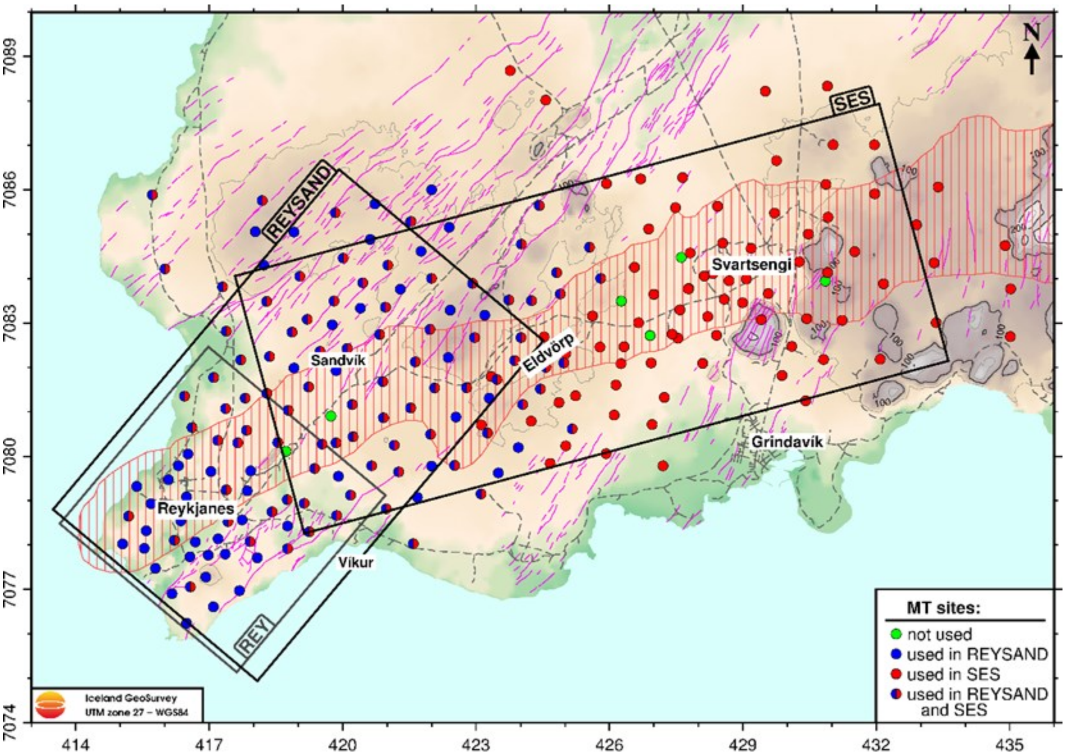

Figure 2: MT soundings in the outer part of the Reykjanes Peninsula. The black boxes mark the fine grid of three 3D resistivity models in this area. Two models cover Reykjanes geothermal area, REY and REYSAND, and SES covers the geothermal areas Eldvörp and Svartsengi. The potential geothermal system at Sandvík is covered by REYSAND and SES.

3.1 The Model Grid

The origin (center) of the REYSAND 3D model is at the UTM (zone 27) coordinates (in km) 421.35 and 7082.27 (at the center of the area of interest and data coverage), and with axis positive towards N40°E and towards N130°E. The mesh has 59 vertical grid planes in the x-direction (perpendicular to the x-axis) and 55 vertical grid planes in the y-direction and 31 horizontal grid planes.

The grid is dense in the area of interest (and area of data coverage) with grid plane spacing of 250 m, that is in the range of +/-5 km in the SW-NE direction and +/-3 km in the NW-SE direction in internal model coordinates. Outside the dense area the grid spacing increases exponentially to the edges at approximately ±135 km. All resistivity cross sections are given names with reference to their position in the grid and the distance from origin. The horizontal grid planes are likewise dense at shallow depth, 16, 26, 36, 50, 76, 100, 158, 200 m etc. but eventually with exponentially increasing spacing to the bottom at the depth of 161.464 km.

3.2 Initial, Prior Models and Inversion

3D inversion of MT data is a highly underdetermined problem, i.e. the number of unknown resistivity values is much higher than the number of data values. In the REYSAND model the number of data points is 11968 (136 soundings x 22 periods x 4 real and imaginary off-diagonal tensor elements, see below) but the model has 99000 unknown resistivity values (in the 66 x 50 x 30 blocks) or more than 8 times the number of data points

The inversion was implemented using a parallel version of the WSINV3DMT code using the Message Passing Interface (MPI) parallel computing environment (Siripunvaraporn, 2009). To investigate the influences of the initial model on the resulting models, inversions were done with four distinct initial models. In all cases the same model was used as an initial and a priori model. The four initial models were a model compiled from joint 1D inversion of individual TEM/MT sounding pairs and three homogeneous half-space models with resistivity 5 Ωm, 10 Ωm and 20 Ωm. All resulting models are scrutinized carefully with respect to their sensitivity to the input model. All model cells in the sea were assigned the average resistivity of seawater (0.3 Ωm) and they were kept fixed in throughout inversion.

The model compiled from the joint 1D inversion of the TEM/MT soundings acquired the best RMS misfit and will be presented here.

4. PRESENTATION OF THE 3D MODEL

The final models are presented here in two different ways, i.e., as a resistivity map for different elevations (depths) and as resistivity cross sections through the model. As mentioned earlier the 3D inversion is run with different input models in order to study the robustness of the model and to recognize artefacts that may be created by the 3D inversion in areas outside the area of data coverage. The 3D program assumes flat surface of the ground. The MT data were corrected for static shift prior to the inversion and this correction removes topographic effects in the data, to a large extent. The resistivity models resulting from the inversion were elevation corrected, i.e. the depths below each model cell were converted to meters above/below sea level.

4.1 The Low Resistivity Cap

The Reykjanes high temperature geothermal system is a brine system and hence all resistivity structures have lower resistivity than expected in fresh water systems inland. In a fresh water geothermal system, the low resistivity cap holds resistivity lower than 10 Ωm whereas the resistivity of the low resistivity cap in Reykjanes holds resistivity lower than 3 Ωm. Consequently, all volumes influenced by the geothermal fluid hold lower resistivity than experienced in fresh water systems.

The Reykjanes model reveals conventional resistivity structures of a high temperature system i.e. a low resistivity cap doming up over a resistive core. As mentioned earlier a deep seated low resistivity is not encountered in the high temperature systems in Reykjanes Peninsula and that goes for the Reykjanes system. However, within the high resistivity core, a zone of lower resistivity, elongated in dominating fault direction under the main geothermal field is present. This zone extends down to a few km´s depth.

Another feature in the Reykjanes model has to be regarded when scrutinizing the model. At shallow depth, horizontal low resistivity anomalies are present indicating the water table and or off flow from the geothermal system, given the fact that the brine fluid has extremely low resistivity and therefore shows up in the model. This is clearly seen on the resistivity cross section on Figures 7 –10 below.

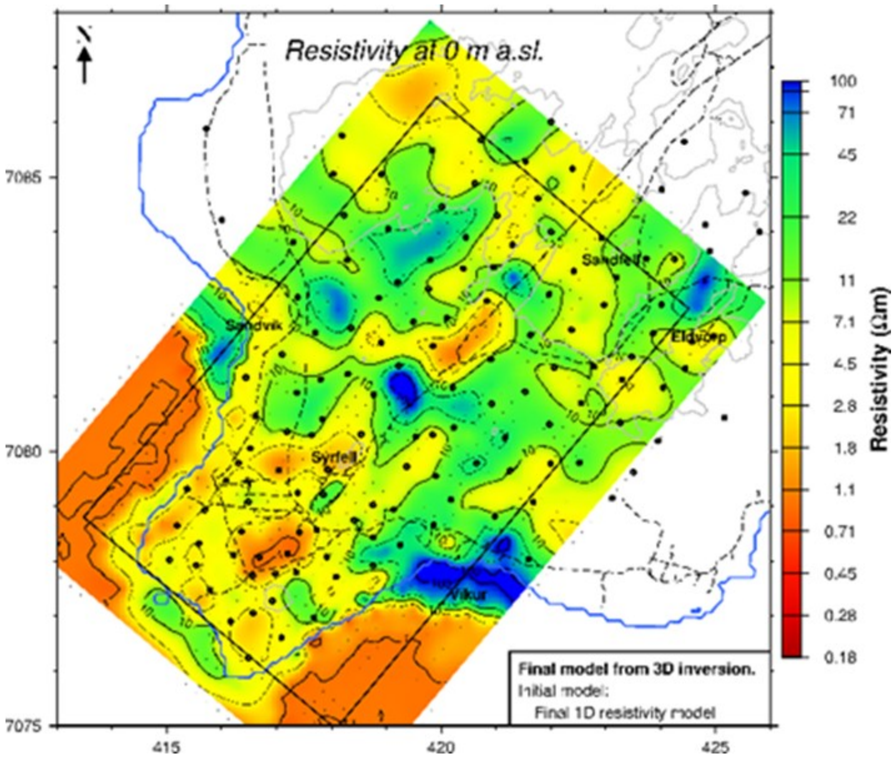

Figure 3: A resistivity map at sea level in the REYSAND model.

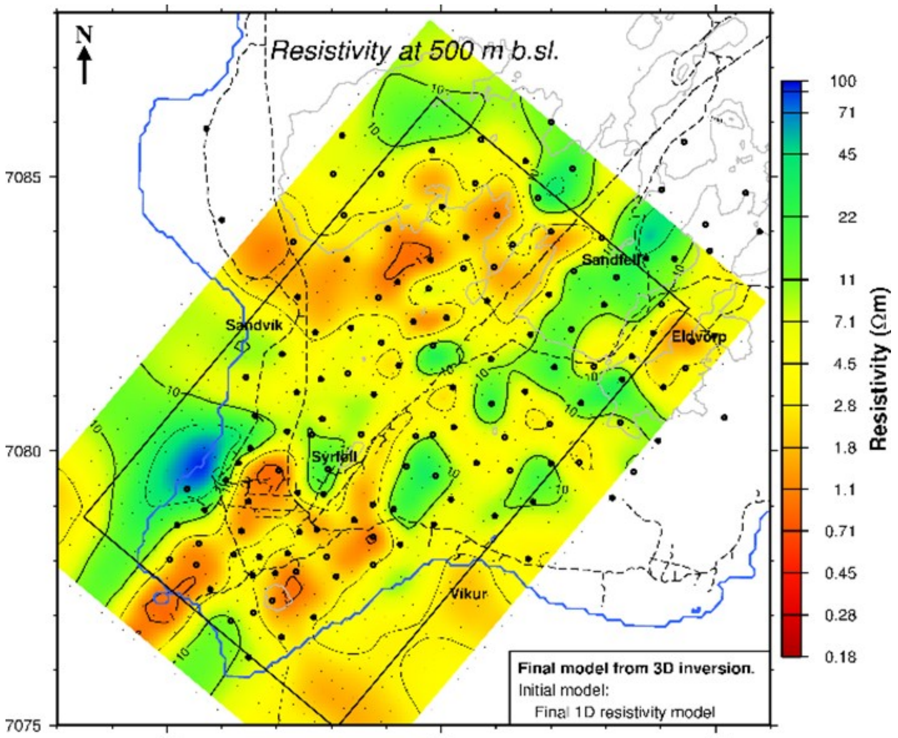

Figure 4: A resistivity map at 500 m b.s.l. in the REYSAND model.

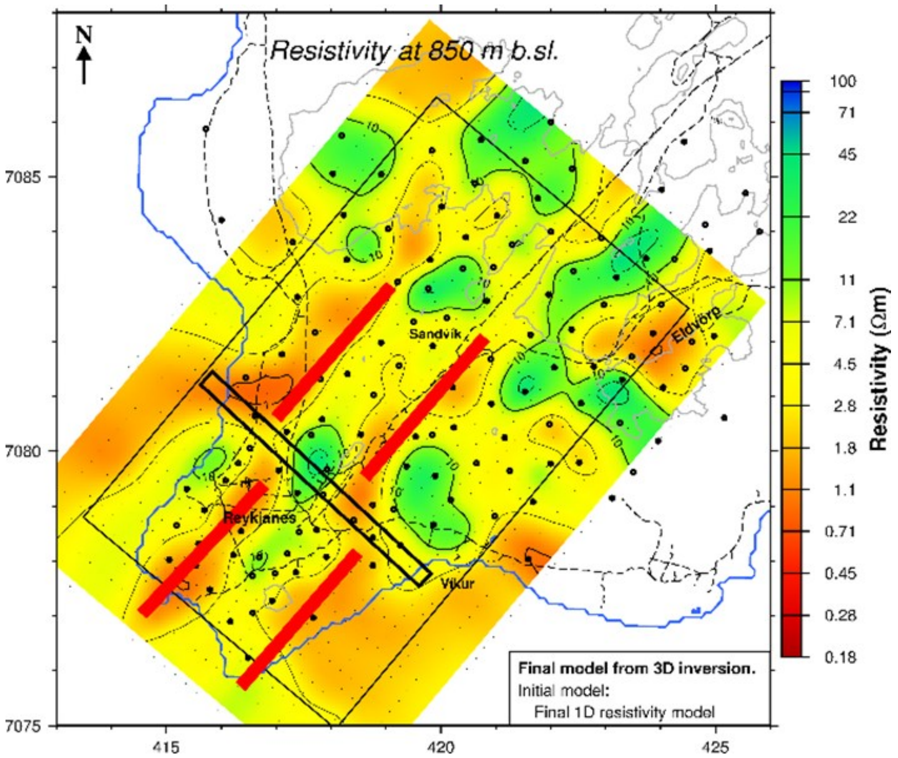

Figure 5: A resistivity map at 850 m b.s.l. in the REYSAND model.

The resistivity map at sea level (Figure 3) shows the low resistivity cap (red anomaly) at the surface by Gunnuhver, the area of the main surface manifestations. The orange coloured anomalies away from Gunnuhver, but still within Reykjanes reflect the off flow zones mentioned. The map also shows clearly the low resistivity of the sea-control file. At 500 m b.s.l. (Figure 4) the low resistivity cap diverges, and the top of the resistive core emerges between red anomalies that denote the low resistivity cap. The same feature is seen in the north eastern part of the model i.e. the low resistivity cap circling a high resistivity core. This is the potential geothermal system Sandvík where resistivity surveys have revealed a structure similar to that of a geothermal field. That may represent an up flow of geothermal fluid in this area at present or be a geothermal system that has cooled down. Sandvík will not be topic of this paper. At 850 m b.s.l. (Figure 5) very interesting features are to be seen. Two elongated low resistivity anomalies lie parallel NE-SW in Reykjanes and denote the low resistivity cap as it descends towards northwest and southeast with an elongated area of higher resistivity, the high resistivity core, between (blue elliptical shape). At Sýrfell there seems to be a shift in the low resistivity anomalies to the northwest and they continue in the same direction and embrace the potential geothermal system Sandvík.

4.2 The High Resistivity Core

The underlying high resistivity core domes up to 400 – 500 m b.s.l. under the main well field and levels at 1500 m b.s.l. away from the geothermal field as displayed on four resistivity cross sections through the geothermal system. Clay analysis are only available from a few wells in Reykjanes (Johnson, 1993; Khodayar et al., 2016). The zoning of the available wells is projected on to the resistivity cross section close to the wells in question. Figure 6 shows the central part of the well field at Reykjanes, the location of the resistivity cross sections and the wells referred to on the cross sections. Resistivity cross sections that well define the shape of the upper part of the geothermal system are chosen for display and available alteration data from nearby wells are projected onto the sections.

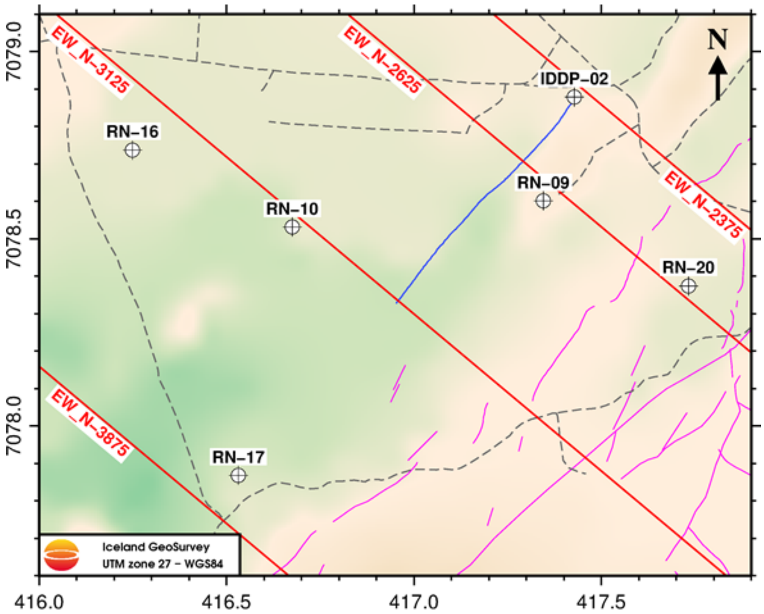

Figure 6: A map of the central part of the well field in Reykjanes. Locations of the wells referred to in the text are shown on the figure. Note the drilling path of IDDP-2 directional well. Other wells are vertical.

The resistivity cross sections reveal the up doming high resistivity core under the low resistivity cap. The high resistivity core holds resistivity values of 10 – 50 Ωm down to 3000 – 4000 m b.s.l. depth in the cross sections. At that depth the resistivity exceeds 50 Ωm and even 100 Ωm at greater depths. Low resistivity at depth indicating the heat up flow into high temperature systems in Iceland are present in all surveyed high temperature areas, except in Reykjanes, Eldvörp and Svartsengi in Reykjanes Peninsula. There is no deep seated low resistivity layer at depth under the system at Reykjanes displayed on the cross sections, however there is a zone of lower resistivity 30 – 50 Ωm lying SW – NE under the geothermal system. This zone appears as a green column on the cross sections, right under the up-doming area hence the geothermal system.

Section EW_N-3875 on Figure 7 crosses the southwestern part of the geothermal system. At 500 m further to the south west the low resistivity cap levels down to 1500 m b.s.l. and closes off the geothermal system. The section shows the up doming of the low resistivity cap where well RN-17 is projected on to the section. Data from the well show that the alteration corresponds well with the resistivity. There is an indication of the low resistivity zone within the high resistivity core at depth.

Section EW_N-3125 on Figure 8 crosses through the well field and the main surface manifestations at Gunnuhver Hot Spring. The low resistivity cap reaches surface at Gunnuhver. Alteration data from wells RN-10 and RN-16 are projected on to the cross section. Well RN-16 goes through the prominent low resistivity anomaly that closes off the main up doming on the north western side of the geothermal system. Well RN-10 is closer to the main up doming of the low resistivity cap. This corresponds well with the alteration and temperature data from the wells. The low resistivity zone at depth is well defined as a green column. At 4500 m b.s.l. a star marks the bottom of the deep IDDP-2 well (discussed later).

Section EW_N-2625 on Figure 9 crosses through the north eastern part of the main well field. The. Up doming of the low resistivity cap is clear, and it reaches surface in the well field and corresponds well with the alteration data from wells RN-9 and RN-20. The low resistivity at depth is clear in this section.

Section EW_N-2375 on Figure 10 crosses through the geothermal field and the deep IDDP-2 well. The drilling of the well stated in 2016 and was completed in January 2017. Drilling the IDDP-2 began by using an existing 2.5 km deep production well, RN-15. The hole was deepened to 3,000 m depth, cased, and then directed towards the main up-flow zone of the system, to a total slant depth of 4,659 m (~ 4,500 m vertical depth). The bottom is well within the low resistivity column under the well field right where resistivity cross section EW_N-3125 goes through (Figure 8).

A cross section through the geothermal system at the same location as EW_N-3125 shows temperature in the geothermal system derived from borehole data is shown on Figure 11. It clearly reflects the sharp temperature drop towards north west, also shown in the resistivity model where well RN-16 goes through the prominent low resistivity anomaly that closes the geothermal system in that direction.

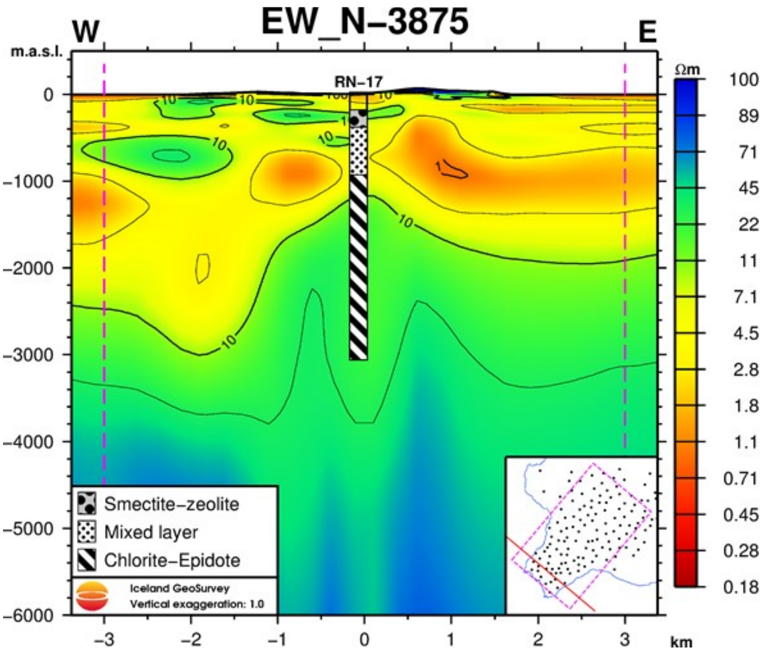

Figure 7: Resistivity cross section EW_N-3875. Alteration data from well RN-17.

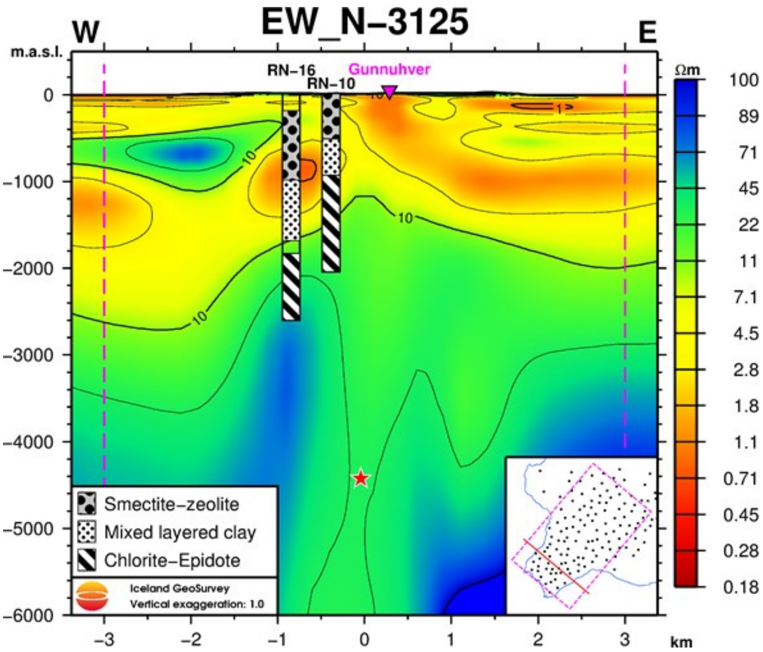

Figure 8: Resistivity cross section EW_N-3125. Alteration data from well RN-16 and. The red star marks the bottom of the IDDP-2 well under the well field.

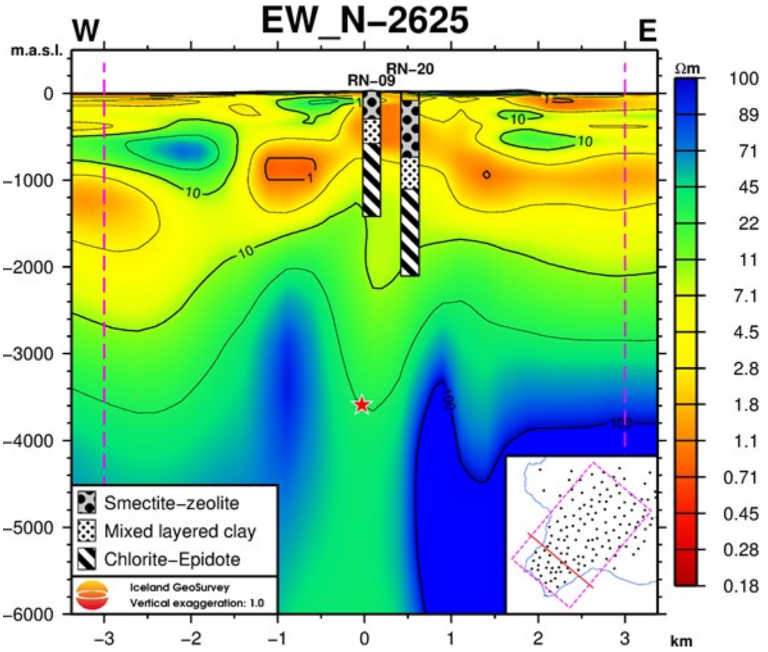

Figure 9: Resistivity cross section EW_N-2625. Alteration data from well RN-9 and RN-20. The red star marks the spot where the IDDP-2 well path goes through the cross section.

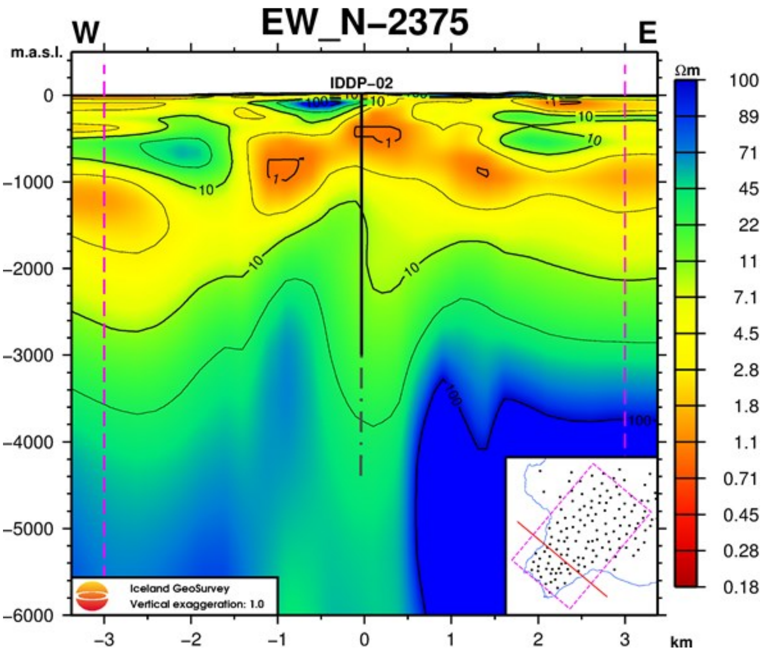

Figure 10: Resistivity cross section EW_N-2375 that goes through the IDDP-2 well. No data on alteration are available. The well is directionally drilled from depth 3000 m b.s.l. towards southwest under the well field (Figure 9).

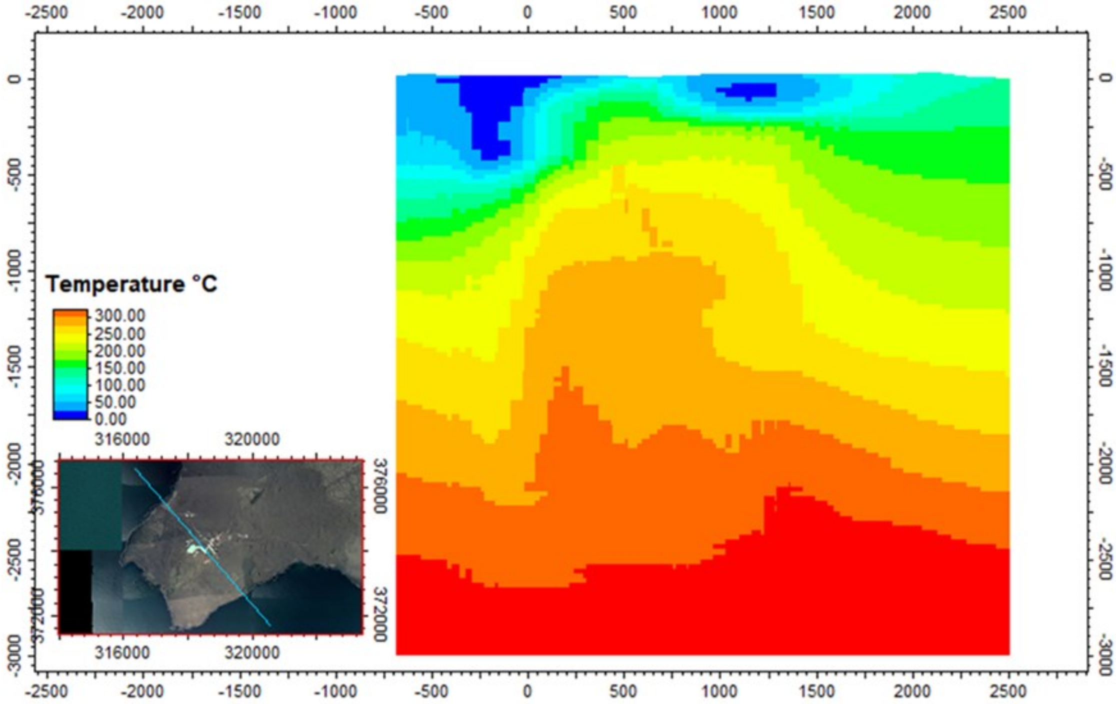

Figure 11: A cross section from PETREL visualizing software at the approximate same location as resistivity cross section EW_N-3125 on Figure 8, showing measured temperature in the system.

4.3 Resistivity at Depth

In all high temperature fields in Iceland where TEM/MT electromagnetic surveys have been conducted, a deep seated low resistivity layer/body at depth indicating the heat source of the geothermal system, has been encountered, except in the high temperature fields surveyed in the Reykjanes Peninsula. The geothermal systems in the Reykjanes Peninsula seem to have somewhat different resistivity structure. In Krýsuvík there is an indication of a deep low-resistivity body (Hersir et al., 2013). In Reykjanes, a zone of lower resistivity goes through the high resistivity core at depth and has a SW – NE direction as the dominant regional fracture systems (Karlsdóttir and Vilhjálmsson, 2014, 2016). This low resistivity layer lies at 8 to even 14 km´s depth in the near vicinity of the geothermal fields and domes up under the geothermal systems and may indicate the heat flow into the systems. An MT profile across the volcanic zone near the Askja volcano in NE Iceland shows the low resistivity layer at 8 – 10 km´s depth being away from any known geothermal activity (Vilhjálmsson et al., 2008).

In Reykjanes a low resistivity layer at depth is not present but all 3D models of the Reykjanes high temperature field show the elongated low resistivity zone that lies SW-NE under the geothermal system (Karlsdóttir et al., 2012, Karlsdóttir and Vilhjálmsson, 2014 and Karlsdóttir and Vilhjálmsson, 2016). It has been suggested and debated that the low resistivity zone within the high resistivity core indicates higher permeability and higher temperature.

Why is there a lower resistivity zone within the high resistivity core at depth in Reykjanes? Clearly, there is a question of the resolution of the MT soundings at this depth to consider. This feature is present in all three 3D models of the Reykjanes system. In two of the models the input model used was the 1D joint inversion model showing low resistivity column under Reykjanes system and could be a possible bias to the outcome of the 3D models (Karlsdóttir and Vilhjálmsson, 2014 and 2016). In the first 3D model however (Karlsdóttir et al., 2012) the input model used was a homogeneous model (30 Ωm) and the 3D model showed clearly the low resistivity zone under the geothermal system. This shows that the low resistivity zone appears in all 3D models regardless of the input model.

The IDDP-2 well was drilled into the low resistivity column down to 4500 m depth. Data from the well logging strengthen the suggestion of high permeability and high temperature. Drilling of the IDDP-2 began by using an existing 2.5 km deep production well, RN-15. The well was deepened to 3,000 m depth, cased, and then directed towards the main up-flow zone of the system, to a total slant depth of 4,659 m (~ 4,500 m vertical depth). During drilling and after only about 6 days of heating, temperature-pressure conditions of 426°C at 34 MPa were measured close to the bottom of the well. However, the bottom hole temperature, based on alteration mineral assemblages, joint inversion of wireline logging data, and rate of heating extrapolation, is estimated to be about 535°C. Total circulation losses were encountered during drilling at 2.5-3.0 km depth before inserting and cementing the production casing, and that continued below 3 km depth to the final depth (Saemundsson et al., 2018; Weisenberger et al., 2017,).

From 3000 meters depth IDDP-2 was drilled directionally towards the alleged up flow zone under the main well field. It´s bottom at vertical depth of 4500 m b.s.l. is right where resistivity cross section EW_N-3125 goes through the well field (Figure 8). The red star that marks the bottom of the IDDP-2 well is within the low resistivity column. The fact that total circulation losses were encountered from 3200 m b.s.l. depth to bottom shows high permeability in that depth range. This would support the theory that the low resistivity zone indicated high permeability and high temperatures and hence the heat flow into the geothermal system.

4.4 Resistivity Compared with Seismicity at Depth

An interesting feature has been encountered in the Reykjanes area. Through monitoring of seismic activity in 2013 to 2015 an aseismic zone was revealed at depth in Reykjanes (Guðnason et al., 2015). Figure 12 displays two maps showing seismic activity at depth intervals 3-4 km and 4-5 km during the 3-year period. The aseismic zone prevails at least down to 6 km´s depth (not shown here). Comparing this aseismic zone to the resistivity at depth in Reykjanes, a resistivity map at 5 km´s depth is shown on Figure 13 together with seismic activity at 4.5-5.5 km depth from January 2013 until the end of July 2016. It is clear that the aseismic zone coincides well with the low resistivity zone under the Reykjanes geothermal system on the resistivity map at 5 km´s depth (Figure 13).

A dominant low resistivity anomaly is observed under the mountain Sýrfell, (Figure 13) in a very critical location within the model. It is questioned due to lack of data under the mountain. In order to make constraints on the anomaly runs were made with control model. A block with fixed resistivity was inserted into the initial model below 1500 m b.s.l. reaching down to 2500 m b.s.l. The horizontal extension was 1 x 1 km with center 750 meters to the southwest of the origin point of the grid. This was done to see if the resulting model would change, compared to the results of the 1D initial model, except for the given volume. It turned out that the 3D models with and without the block, are almost identical above the inserted volume. At 1500–2500 m b.s.l. the low resistivity anomaly under Sýrfell is not as prominent but there still is a low resistivity anomaly close up to the block of fixed resistivity (12 Ωm). That means that the data demand a low resistivity in this area, but it may be argued how prominent the anomaly is.

There is a plausible explanation of the low resistivity zone down to at least 5 km´s depth i.e. the cause being higher heat and/or higher permeability. This is in fact confirmed by the data from the deep IDDP-2 well down to 4.5 km´s vertical depth. At greater depth the low resistivity zone coincides with an aseismic zone under Reykjanes at least down to 6 km´s depth. Low resistivity at 5 – 6 km´s depth may indicate high heat. The fact that there were no earthquakes within the aseismic zone prior to the drilling of the IDDP-2 well may indicate that below 5 km´s depth the zone may hold ductile rocks and even magma pockets.

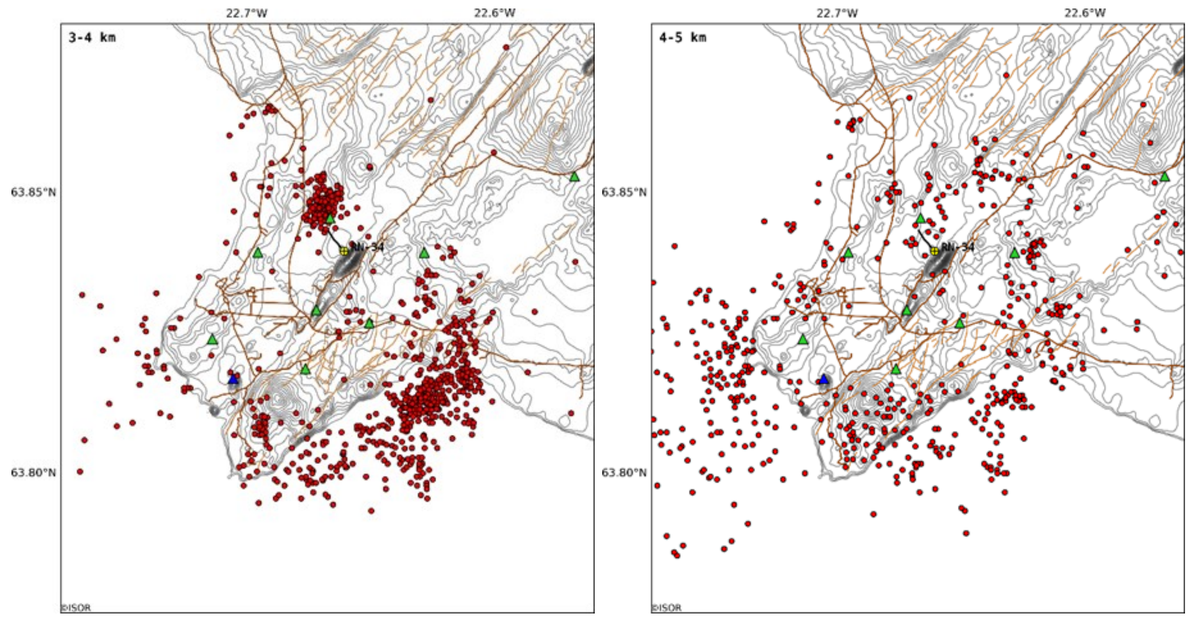

Figure 12: Maps that show seismic activity in Reykjanes at 3 – 5 km´s depth range during 2013 – 2015 (Guðnason et al., 2015). An aseismic zone is present under the main geothermal system at this depth.

New information on the seismic activity in Reykjanes in 2016 and 2017 is available. The drilling, completion and stimulation of the IDDP-2 well in 2016-2017 induced seismic activity within the eastern part of the previously postulated aseismic body, i.e. from 3-6 km depth, Figure 14, beneath the central core of the production field in Reykjanes (Guðnason et al., 2017).

Increasing circulation losses below 3.0 km depth and a total loss of circulation from around 3.2 km depth indicate the high permeability at this depth, while several more permeable zones are identified down to around 4.6 km depth. The majority of the induced earthquake activity occurs just below the zone of total loss of circulation, i.e. from 3.5 km and down to 5.6 km depth. A likely explanation for the induced seismicity is that the total circulation loss 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., 2017).

Calculated fault plane solutions (FPS) for a number of the induced earthquakes are mainly intermediate events having both normal and strike-slip displacements, i.e. mostly dip-slip (normal) with some strike-slip component. The majority of the FPS show NW-trending right-lateral displacements or NE-trending left-lateral displacements. These FPS only represent particular events, but they are indicative of the average mechanism of the induced seismicity at this depth. The right-lateral displacement on NW-trending planes of the majority of calculated FPS from 2016 and 2017 is consistent with the NW-SE striking trend that characterizes the induced seismicity. This suggests that the more probable plane of motion in this area is NW (Guðnason et al., 2017).

It is interesting that this direction is approximately the same as in the shift in the resistivity model in this area. This may indicate a NW-SE fraction zone.

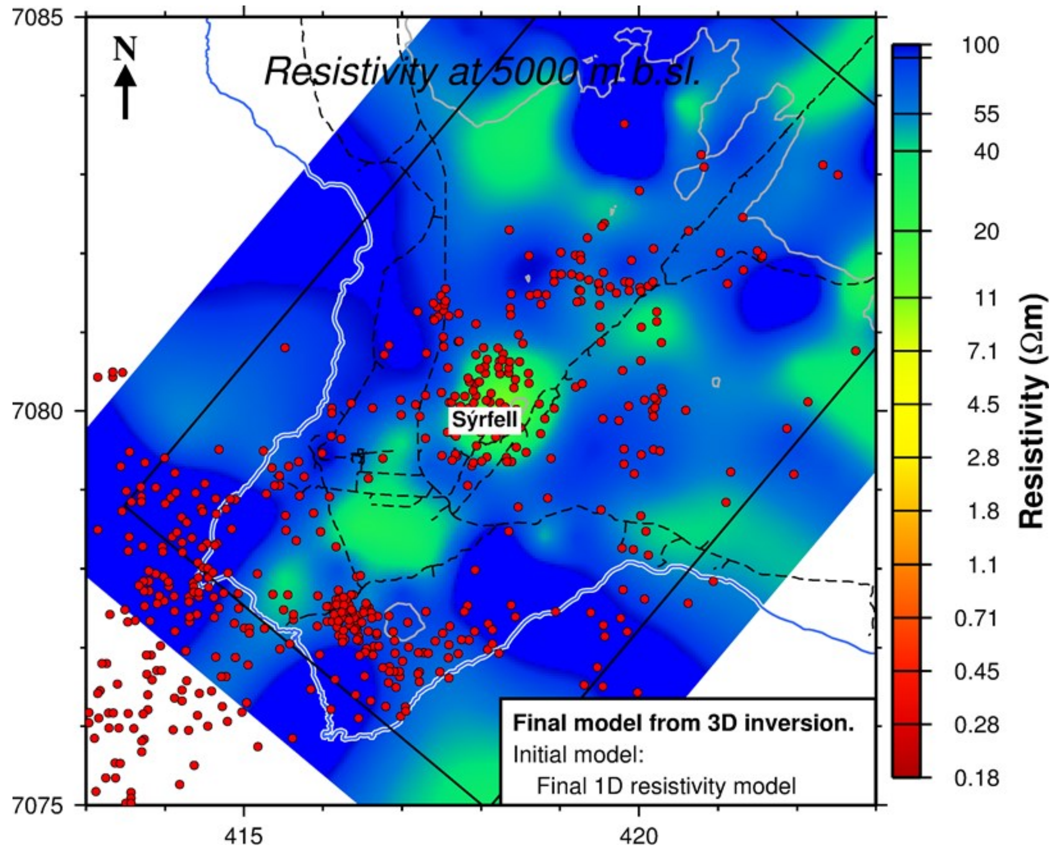

Figure 13: The aseismic zone compared to the resistivity. The red dots represent all earthquakes at 4.5–5.5 km depth from January 2013 to July 2016.

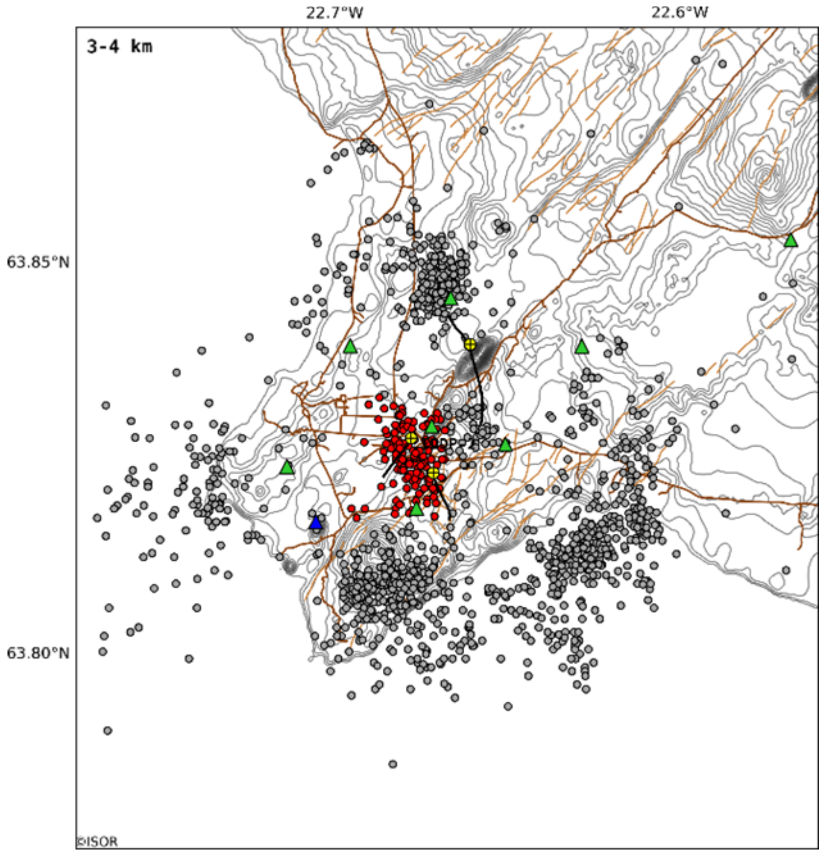

Figure 14: Seismic activity at 3-4 km depth in Reykjanes from January 2013 to November 2017. Red dots indicate induced seismicity during drilling and stimulation of IDDP-2.

Reykjanes Peninsula hosts a few known geothermal high temperature areas, Reykjanes, Eldvörp, Svartsengi and Krýsuvík, as well as areas that are considered potential geothermal areas. Resistivity 3D MT models have been performed of the area covering Svartsengi in the east to Reykjanes in the west. Figure 15 shows resistivity maps at 850 m b.s.l. depth in the REYSAND and SES 3D models. They show the high resistivity surrounded by the low resistivity cap in Reykjanes, Eldvörp and Svartsengi. The models also reveal areas that have the character of a geothermal up flow. One is in the area between Svartsengi and Eldvörp and that does not come as a surprise as the geothermal systems in Svartsengi and Eldvörp are connected (pressure-comunication). Two other areas have this character i.e. Sandvík and an area between Sandvík and Eldvörp. No geothermal manifestations are present on surface. If the two are indeed geothermal up flow areas will only be determined by drilling.

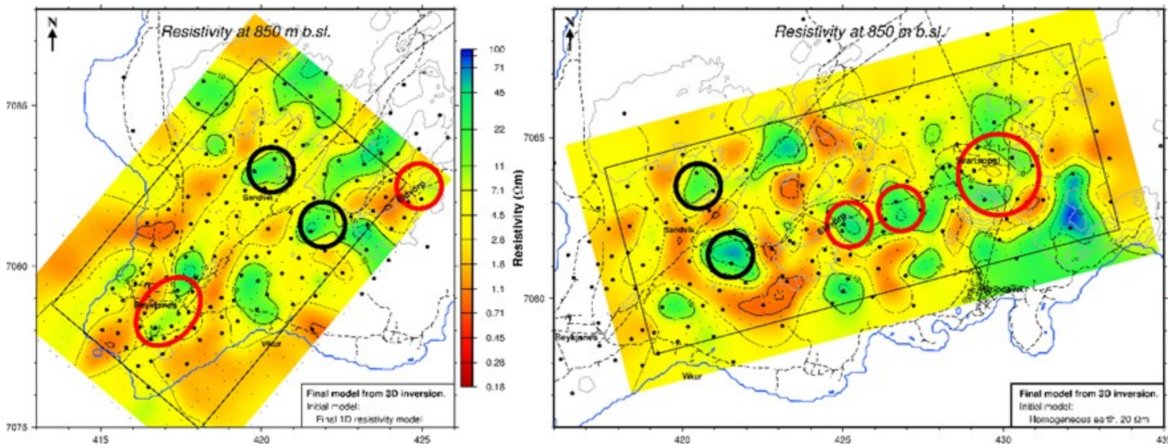

Figure 15: Maps showing resistivity at 850 m b.s.l. depth in 3D models REYSAND and SES. Red circles denote known geothermal systems and the black circles denote potential geothermal areas.

5. DISCUSSION AND CONCLUSIONS

The TEM/MT surveys in Reykjanes Peninsula reveal the conventional resistivity structure of high temperature geothermal systems in the uppermost 2 km below surface, i.e. a low resistivity cap underlain by a high resistivity core i.e. the resistivity structure reflects the temperature dependent alteration of the rocks. Comparison of resistivity and the dominant alteration in the geothermal system shows that the lower margin of the conductive cap denotes temperature in the range of 230 – 250°C. In all high temperature fields in Iceland where TEM/MT electromagnetic survey has been conducted, a deep seated low resistivity layer/body at depth indicating the heat source has been encountered, except in high temperature fields surveyed in Reykjanes Peninsula. The geothermal systems in the Reykjanes Peninsula seem to have somewhat different resistivity structure. There is no sign of a deep seated low resistivity of the extent to be detected by the electromagnetic survey. There is, however a low resistivity zone at depth within the high resistivity core that may indicate up flow of heat into the system.

A 3D inversion was performed for static shift corrected off diagonal impedance tensor elements of 136 MT soundings. To take a conservative approach, four different input models were used, for the inversion and the results compared in order to evaluate the constraints on the resulting model.

The main features of this 3D model are as follows: A low resistivity cap that reflects the zeolite/smectite zone is observed and covers the whole area. It reaches surface in Reykjanes. The low resistivity cap in the 3D model is comprised of connected low resistivity anomalies rather than a continuous layer. Thin horizontal layers with low resistivity immediately below surface, present in the most part of the survey area, are interpreted as off-flows of geothermal fluid from the geothermal systems infiltrating with the saline ground water. A high resistivity core reflecting the chlorite/epidote zone underlies the low resistivity cap. The boundary between the two reflects the 230–250°C temperature boundary provided there is an equilibrium between thermal alteration and temperature at present.

A shift in the resistivity structure that may indicate a shift in the tectonics at the north eastern margin of the geothermal system is seen in the low resistivity cap at 800–1000 m b.s.l. See Figure 5. The low resistivity cap at this depth, that embraces the Reykjanes geothermal system is shifted to the northwest and continues to the northeast where it embraces the Sandvík potential geothermal system. This NW-SE direction also shows up as the western margin of induced seismic activity during the drilling of the IDDP-2 well. This may indicate a fracture zone/transform fault in this area.

Low resistivity zones within the high resistivity core at depth may reflect a zone with higher permeability and or higher temperature. This is indeed confirmed by the drilling of the IDDP-2 well. The bottom of the well is at vertical depth of 4500 m b.s.l. under the well field (Figure 8) and lies well within the low resistivity column at depth. The bottom hole temperature, based on alteration mineral assemblages, joint inversion of wireline logging data, and rate of heating extrapolation, is estimated to be about 535°C. This confirms high temperature within the low resistivity column. Total circulation loss from depth 3000 m b.s.l. to bottom confirms high permeability.

The low resistivity zone within the high resistivity core under Reykjanes coincides with an aseismic zone revealed at 3 – 6 km´s depth during the monitoring of seismic activity in the years 2013–2015. Low resistivity at 5 – 6 km´s depth may indicate high heat. The fact that there are no earthquakes within the aseismic zone may indicate that below 5 km´s depth the zone may hold ductile rocks and even magma pockets.

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