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Geophysical Exploration of High Temperature Geothermal Areas using Resistivity Methods. Case Study: TheistareykirArea, NE Iceland

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ABSTRACT

Measuring the electrical resistivity,ρ, of the subsurface is the most powerful geophysical prospecting method in high temperature geothermal exploration and the main method used in delineating geothermal resources. Resistivity surveys using TEM and MT methods have been done in the Theistareykir geothermal area since 2004 and in this work; sixteen TEM and MT soundings on two profiles have been jointly inverted based on 1D models. Cross sections and iso-resistivity maps of the joint inversion models of the TEM and MT data from Theistareykir geothermal area reveal features similar to other high temperature areas in Iceland with a resistive zone reflecting unaltered rock formations, shallow conductive cap and a resistive core reflecting chlorite-epidote alteration. Two deep conductors (<10 Ωm) possibly related to the heat source have been interpreted north of Bóndhólsskarð and north east of Stórihver. Good correlation between the subsurface resistivity and hydrothermal alteration in borehole ThG-05 was confirmed.

1. INTRODUCTION

Theistareykir high temperature geothermal area is located in NE Iceland. The geothermal area has been the subject of surface exploration off and on for almost 40 years with the utilisation of geothermal energy for electricity production as a long term goal (Gautason et al., 2010).In this report, a total of sixteen TEM and MT soundings acquired from Theistareykir between 2009 – 2011 on two profiles have been processed. The results are presented as inversion resistivity cross-sections and iso-resistivity maps. A description is given on data acquisition in the area, processing, joint-inversion of the data, discussion and comparison of resistivity results with hydrothermal alteration/borehole temperatures. Finally, conclusions and discussions are presented.

2. CHARACTERISTICS OF THE THEISTAREYKIR HIGH-TEMPERATURE GEOTHERMAL AREA

The Theistareykir high-temperature geothermal area lies in the Theistareykir fissure swam within the volcanic zone in northeast Iceland (Figure 1).For centuries it hosted the main sulphur mine in Iceland, providing the Danish king with raw material for gun powder (Ármannsson et al., 1986). The active part of the geothermal area lies in the eastern half of the Theistareykir fissure swarm. The geothermal activity covers an area of 10.5 km2. The most intense activity is on the northwest and northern slopes of Mt. Bæjarfjall and in the pastures extending from there northwards to the western part of Mt. Ketilfjall.

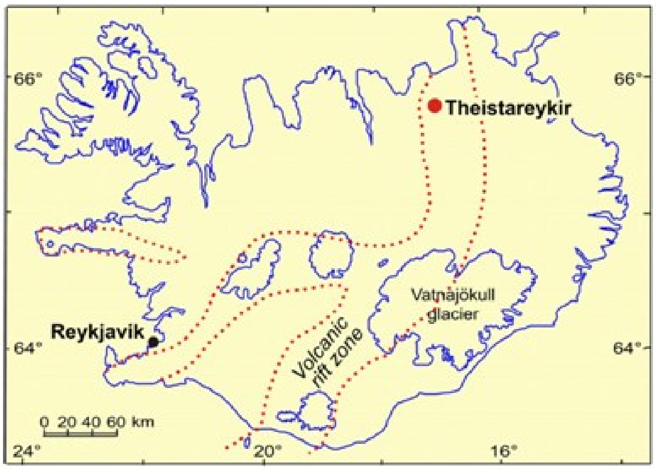

FIGURE 1: Map showing location of Theistareykir high- temperature geothermal field

Hydrothermal alteration is evident on the western side of the swarm, but surface thermal activity seems to have died out some 1,000 years ago (Grönvold and Karlsdóttir, 1975). If the old alteration in the western part of the swarm is considered to be a part of the thermal area, its coverage is nearly 20 km (Grönvold and Karlsdóttir, 1975).

Saemundson (2007) thoroughly studied the geology of Theistareykir area and the following description is based on his publication. The bedrock in the area is divided into hyaloclastite ridges formed by subglacial eruptions during ice age, interglacial lava flows, and recent lava flows (younger than 10,000 years); all basaltic. Acidic rocks are found on the western side of the fissure swarm, from subglacial eruptions up to the last period. Rifting is still active in the fissure swarm (Figure 2).

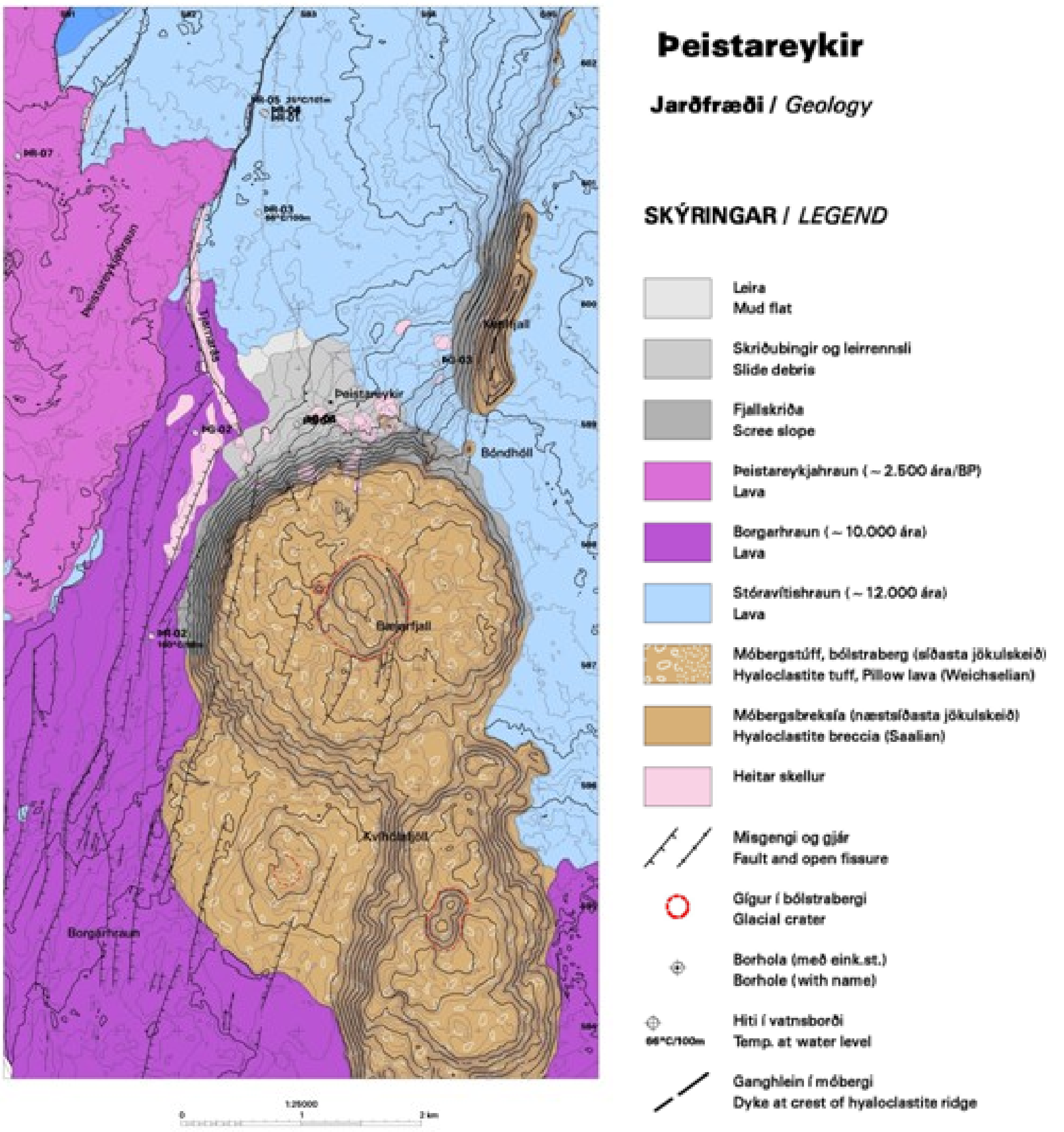

FIGURE 2: Geological map of Theistareykir geothermal area (Modified from Sæmundsson, 2007)

Volcanic activity has been relatively dormant in the area in recent times with approximately 14 eruptions in the last 10,000 years but none in the last 2,500 years. Large earthquakes up to a magnitude of 6.9 occur mainly north of the area in the Tjörnesfracture zone, which is a right-lateral transform fault in the fissure swarm during rifting. The Tjörnes fracture zone strikes northwest crosscutting the north striking fractures as it enters into the fissure swarm north of the thermal area. The volcanic activity ceases in the fissure swarm as it crosses the Tjörnes fracture zone although its northern part remains seismically active (Ármannsson et al., 1986).The most active parts of the area are related to active fractures, increasing permeability and acting as conduits to geothermal fluids to flow.

3. RESISTIVITY PROSPECTING OF THE THEISTAREYKIR GEOTHERMAL FIELD

Iceland GeoSurvey – ÍSOR carried out TEM and MT soundings in the Theistareykir geothermal field between 2009 and 2011.From that survey, two profiles (profiles 3 & 4) with nine and seven TEM and MT soundings respectively have been processed and interpreted in this paper. For location see Figure 3.

3.1 TEM data processing and inversion

The TemX program written by Árnason (2006a) at ÍSOR was used to read the raw files (*fru format) from the PROTEM receiver. The TemX programme performs normalisation of the voltages with respect to the transmitted current, turn off time, gain and effective area of the receiver and transmitter coils and then displays all the data graphically, allowing the user to omit outliers, calculates averages over datasets and calculates late time apparent resistivity (Árnason, 2006a).

For the inversion of TEM data, the TEMTD programme (Árnason, 2006b) was used to perform the 1D Occam inversion of the data. The programme assumes a square source loop and the receiver loop/coil at the centre of the source loop. The current wave-form is assumed to be half-duty bipolar semi-square wave with exponential current turn-on and current turn-off.

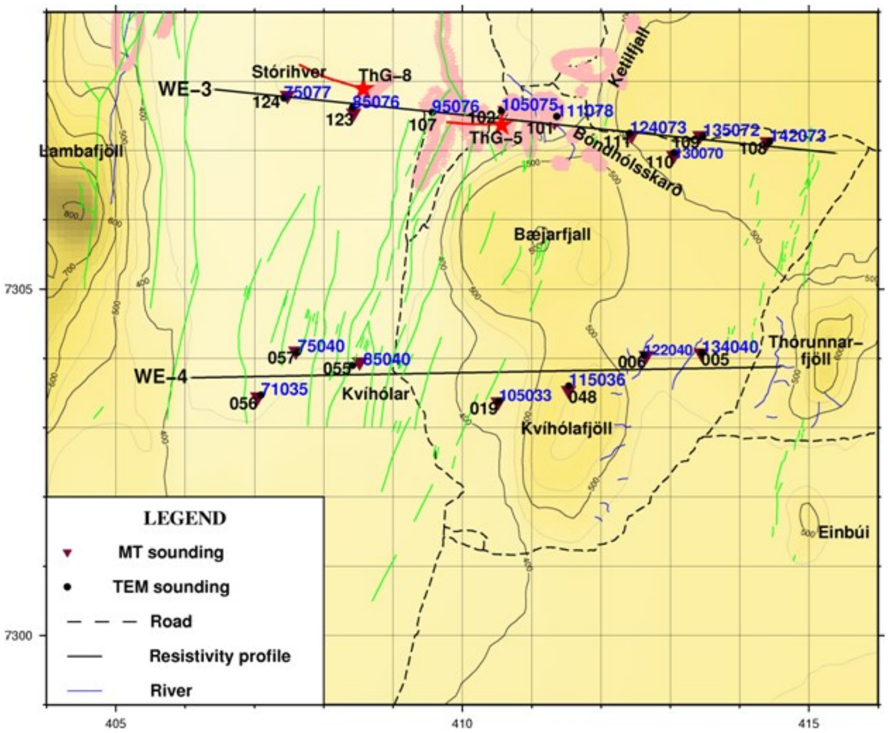

FIGURE 3: Location of the resistivity profiles and TEM and MT soundings. Red stars denote directional wells. (ThG-5 & ThG-8) and green lines geological fractures. Surface manifestations are light red shades.

The programme offers the possibility to keep models smooth, both with respect to resistivity variations between layers and layer thicknesses. The damping can be done both on the 'first derivatives', which counteracts sharp steps in the model (on log scale), and on 'second derivatives' which counteracts oscillations in the model values (on log scale). The actual function that is minimised is in this case not just the weighted root-mean-square mistfit, chsq, but the 'potential':

$$Pot = Chisq + \alpha \cdot DS1 + \beta \cdot DS2 + \gamma \cdot DD1 + \delta \cdot DD2$$

Where DS1 and DS2 are the first and second derivatives of log-conductivities in the layered model and DD1 and DD2 are the first and second order derivatives of the algorithms of the ratios of layer depths. The coefficients α,β,γ and $\delta$are the relative contributions of the different damping terms and are specified by the user.

In the minimum structure (Occam) inversion, the layers thickness are kept fixed, equally spaced on log scale, and the conductivity distribution is forced to be smooth by adjusting α and β in Equation 23.A typical Occam inversion model of a TEM sounding is shown in Figure 4.

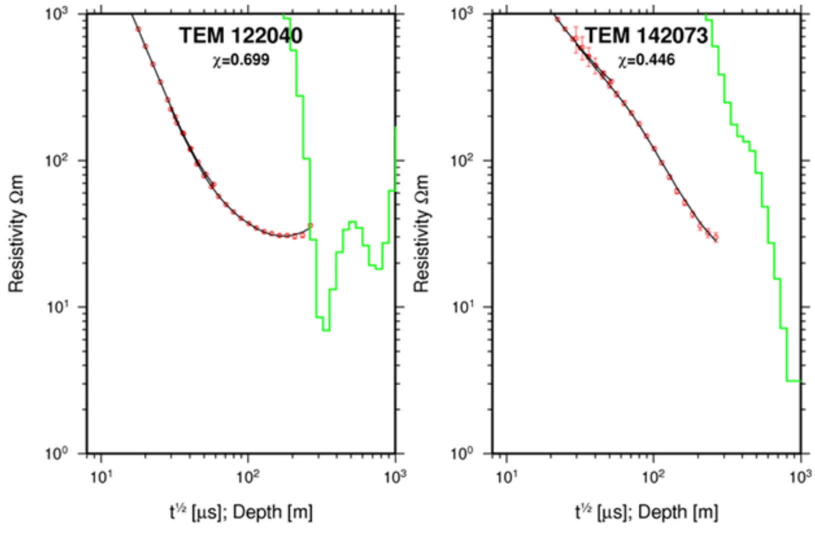

FIGURE 4: Typical TEM soundings from Theistareykir area and 1D inversion. Red circles: measured late-time apparent resistivities; black line: apparent resistivity calculated from the model shown in green. The number on the top of the figures (TEM 122040 & 142073) corresponds to the name of the stations; χ shows the fit between measured and calculated data

3.1.1 TEM resistivity Cross-sections

From the 1D inversion results of the TEM data, cross-sections were plotted using the programme TEMCROSS (Eysteinsson, 1998) developed at Iceland GeoSurvey. The programme calculates the best line between selected sites on the profile and plots resistivity isolines based on the 1D model generated for each sounding. The programme contours the logarithm of the resistivity and thus an exponential colour scale through contour number lines are resistivity values. A number of cross sections at varying depth have been plotted for the two profiles depending on the structures of interest and extent of depth penetration of the MT sounding.

Profile WE_3 lies to the south of Stórahver, across Theistareykir and Bóndhólsskard cutting through wells ThG-5 and ThG-8 (Figure 3). TEM data have been used to plot cross-section for the upper-most 600 m a.s.l (Figure 5).To the east and west of Bóndhólsskard, a high resistivity layer (>100 Ωm) is seen down to a depth of 120 m to the west and over 400 m to the east. This high resistivity reflects unaltered rock formation. Below the high-resistivity layer, a low resistivity cap is found that reaches the surface in Theistareykir with wide spread surface manifestations in the area. This low-resistivity layer correlates with the smectite-zeolite alteration layer.Below the low- resistivity cap rock emerges a high resistive core (>100 Ωm) correlating with the chlorite-epidote alteration zone.

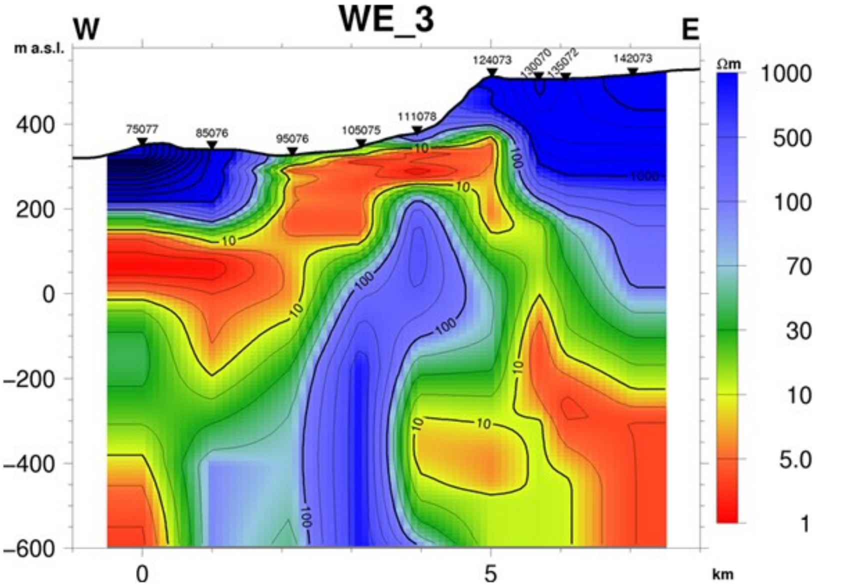

FIGURE 5: Resistivity Profile WE_3 based on TEM data down to 600 m b.s.l.

*Profile WE_4 l*ies to the north of Kvíhólar and Kvíhólafjöll all the way east to Thórunnarfjöll (Figure 3). It presents a typical resistivity section expected in a high temperature geothermal area with a high resistive layer of unaltered rock formation close to the surface down to a depth of 200-250 m below the surface (Figure 6). At 0-200 m a.s.l., the low resistivity layer emerges shallower to the east than to the west extending to a depth of 100 m b.s.l. to the east and 1300 m b.s.l. to the west. Below the conductive layer there is a resistive core (> 100 Ωm) which correlates with the chlorite-epidote high temperature hydrothermal alteration zone. The low resistivity cap reaching the surface is most probably the up flow zone during the formation of the geothermal system which could have cooled with time due to scaling of fractures and other fluid conduits.

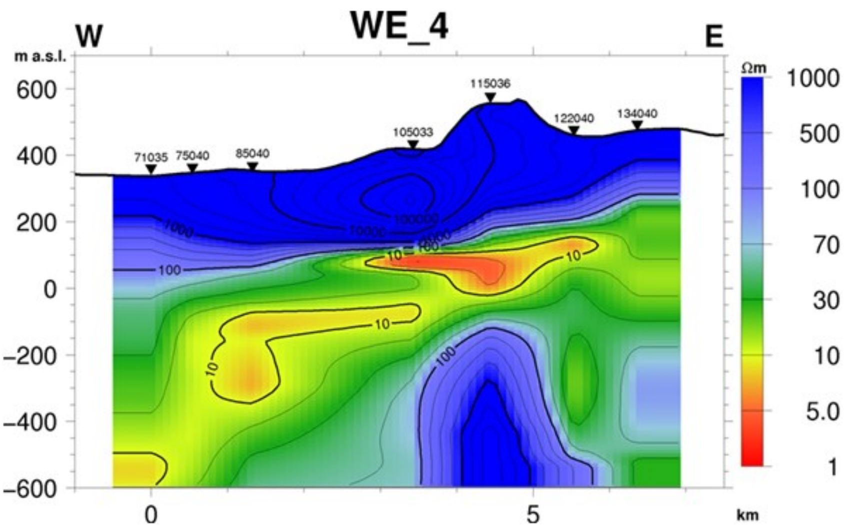

FIGURE 6: Resistivity profile WE_4 based on TEM data down to 600 m b.s.l.

3.1.2 TEM iso-resistivity maps

The TEMRESD programme (Eysteinsson) was used to generate iso-resistivity maps from the 1D Occam models. The resistivity is contoured and coloured in logarithm scale. Theistareykir area is on average 280-550 m a.s.l. For this work, iso-resistivity maps are presented from 300 m a.s.l. down to 10,000 b.s.l. with the upper iso-resistivity maps reflecting the TEM resistivity structures while deeper structures are reflected in MT data.

Resistivity map at 300 m a.s.l. from TEM data is shown in Figure 7.In the central part of the plot, a low-resistivity anomaly trending east west direction reaching the surface is observed. This is due to the smectite-zeolite alteration layer that reaches the surface and is evident by the numerous surface alterations in the area (Figure 3). The low-resistivity body is surrounded by the high-resistivity un-altered rock formation. The low resistivity cap reaching the surface most probably is the up flow region during the formation of the geothermal system which could have cooled due to scaling of fluid conduits or fractures which are the passage for hydrothermal fluids to the surface.

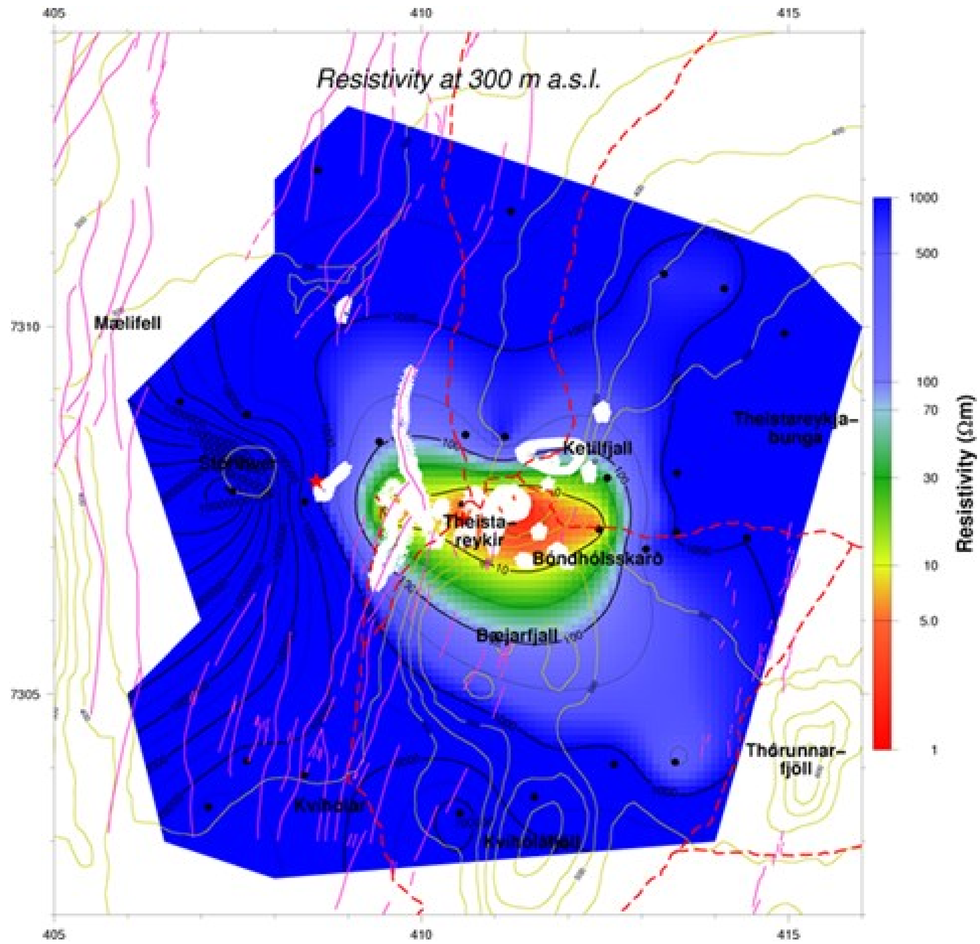

FIGURE 7: Resistivity in the Theistareykir area based on TEM data at 300 m a.s.l. Black dots are MT soundings, red lines are geological fractures, white shades are surface manifestations, magenta stars are wells and red dashed lines are roads

3.2 MT data processing and inversion

The time series files from the MT equipments were processed using the programme SSMT2000 provided by Phoenix Geophysics in Canada. The final cross- and auto powers, as well as relevant MT Parameters calculated from them such as impedances, apparent resistivity and phase, coherencies, strike directions were stored in *edi format and used as an input to the TEMTD programme for joint inversion(Figure 8). TEMTD was also used for joint inversion of TEM and MT data where the so-called static shift multiplier was determined. The programme uses gunplot graphics programme for graphical display during the inversion process. The apparent resistivity and phases derived from the determinant of the MT tensor were inverted jointly with the nearby TEM data. The measured TEM apparent resistivity (red/dark diamonds) curve that overlaps the MT apparent resistivity curve (blue) was used to correct the static shift; the shift multiplier of 0.517shown on the upper right corner (Figure 9).

3.3 MT resistivity cross-sections

Cross-section WE_3 from joint inversion of TEM and MT data is shown in Figure 10.The cross section is plotted down to 5,000 m b.s.l. and clearly reveals the low resistivity cap at shallow depth and the underlying the high-resistivity core (> 100 Ωm).The resistive core stretches from 1,000 m b.s.l. down to 4,000 m b.s.l. and correlates with the chlorite-epidote alteration zone. Below the resistive core there is a relatively conductive layer (Figure 11) which might indicate the heat source for the geothermal field.

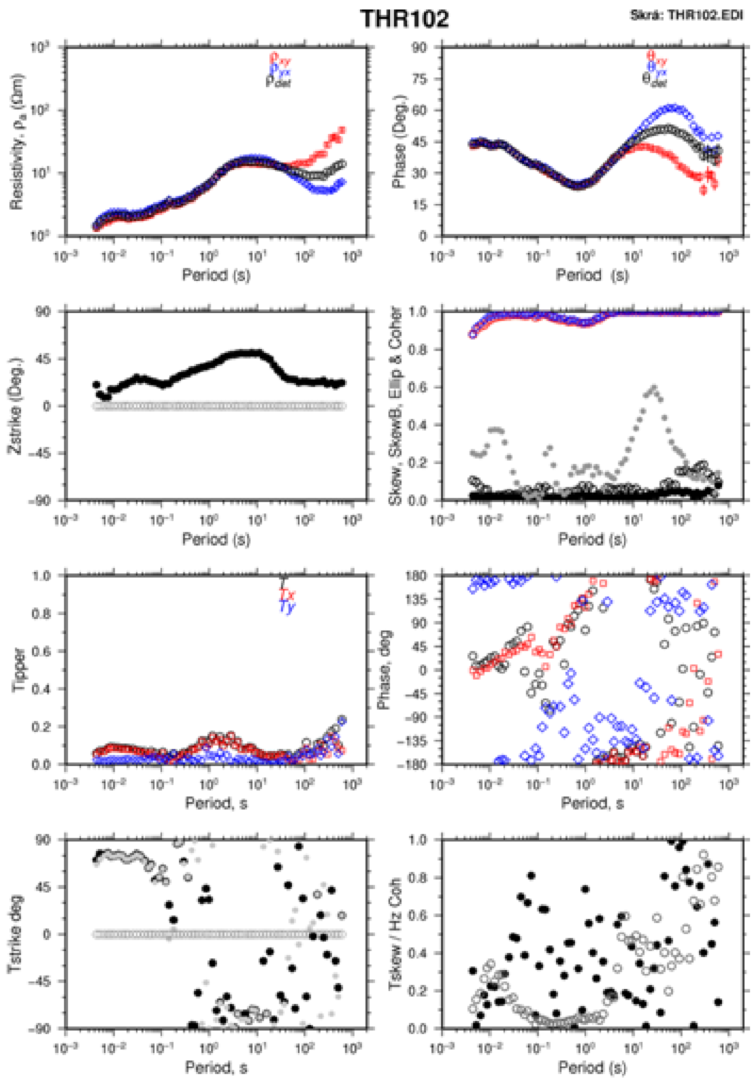

FIGURE 8: Results of MT data processing

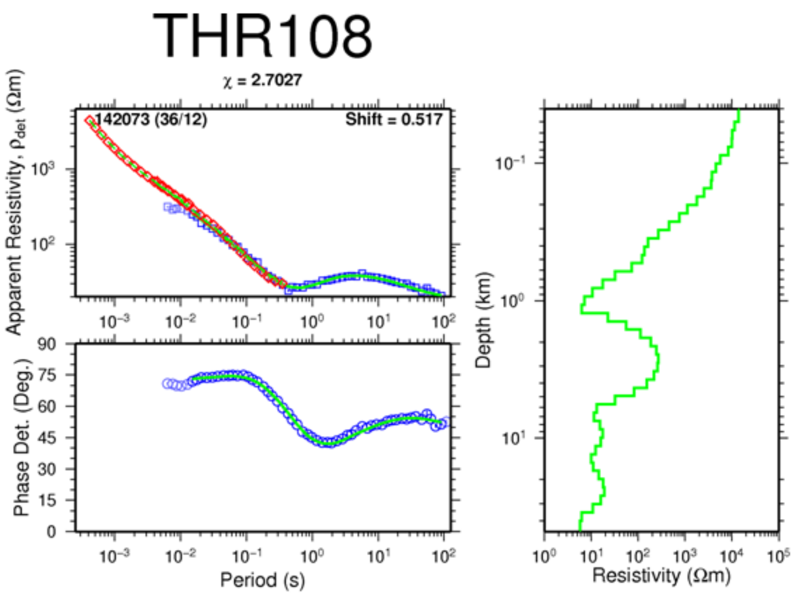

FIGURE 9: Typical result of a joint 1D inversion of TEM and MT soundings; red (dark) diamonds are measured TEM apparent resistivities and blue squares are the MT apparent resistivities. Solid lines show the response of the resistivity model to the right (green). The shift multiplier is shown in the upper right hand corner of the apparent resistivity panel and the Chi square,χ, is the misfit

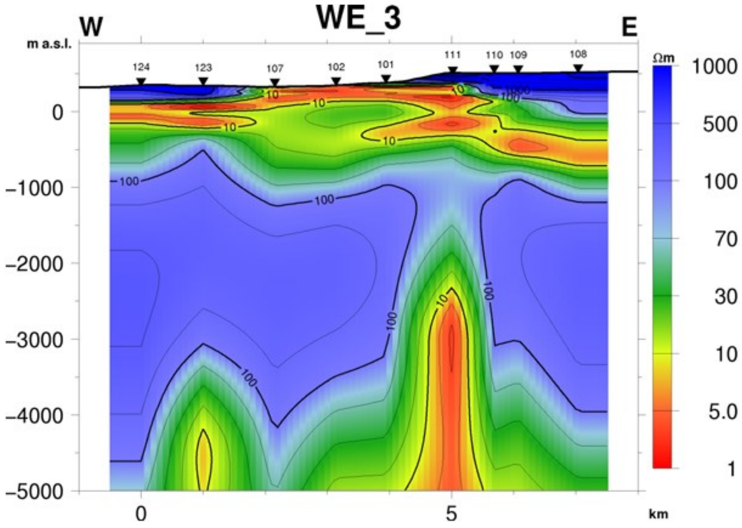

FIGURE 10: Resistivity profile WE_3 based on 1D joint inversion of TEM and MT data down to 5,000 m b.s.l.

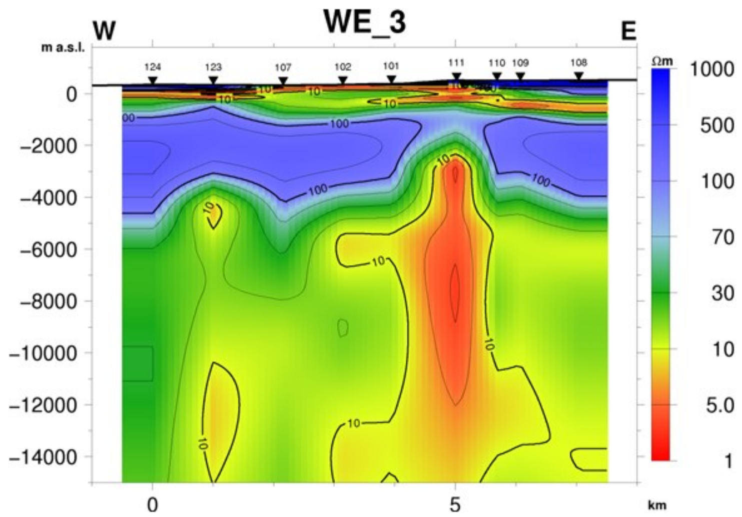

FIGURE 11: Resistivity profile WE_3 based on 1D joint inversion of TEM and MT data down to 5,000 m b.s.l.

Cross-section WE_4 from joint inversion of TEM and MT data is shown in Figure 12.Three layers are revealed by cross-section WE_4 and these include a high resistivity layer near the surface due to un-altered formations; underlying it is a low-resistivity layer correlating to the smectite-zeolite alteration zone and the high-resistivity core emerging shallower to the east than the west.

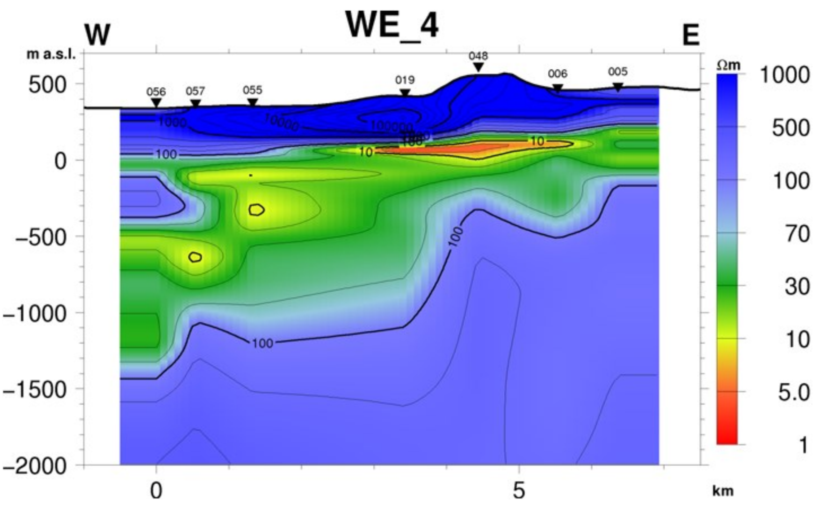

FIGURE 12: Resistivity profile WE_4 based on 1D joint inversion of TEM and MT data down to 2,000 m b.s.l.

6.6 MT iso-resistivity maps

Resistivity map at sea level. There are two distinct low-resistivity bodies observed at sea level that are at 350 m depth from the surface (Figure 13).These two anomalies are part of the low-resistivity smectite-zeolite zone reaching the surface in Figure 13.

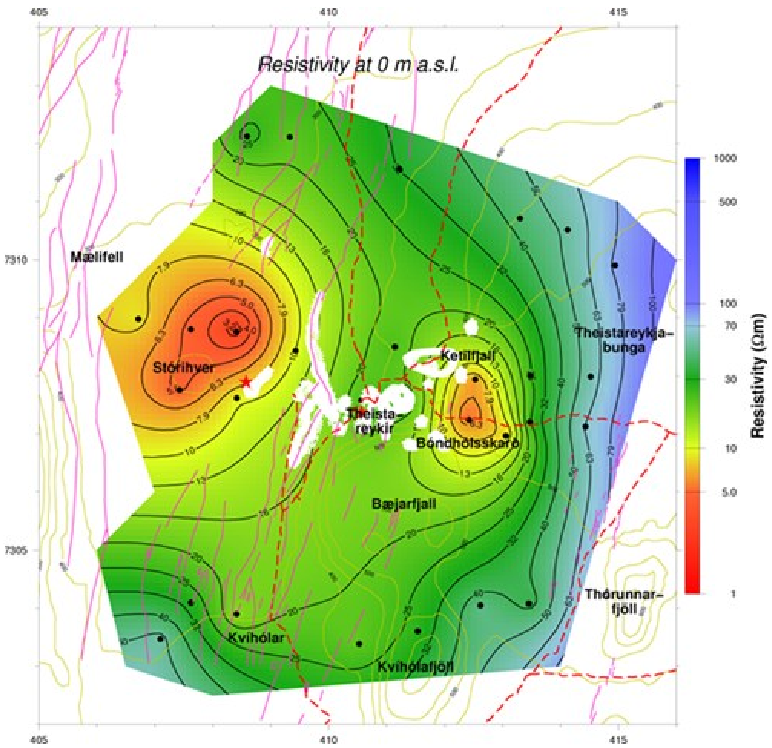

FIGURE 13: Resistivity in the Theistareykir area based on 1D inversion of TEM & MT data at sea level. Black dots are MT soundings, magenta lines are geological fractures, white shades are surface manifestations, red stars are wells and red dashed lines are roads.

Resistivity map at 500 m b.s.l. is shown in Figure 14. Two high resistivity anomalies align themselves in NW-SE orientation at about 850 m depth below surface; representing the resistive core. The low resistivity at the edges of the map shows the low resistivity cap as it tilts down away from the centre of the geothermal system at Bóndhólsskarð.

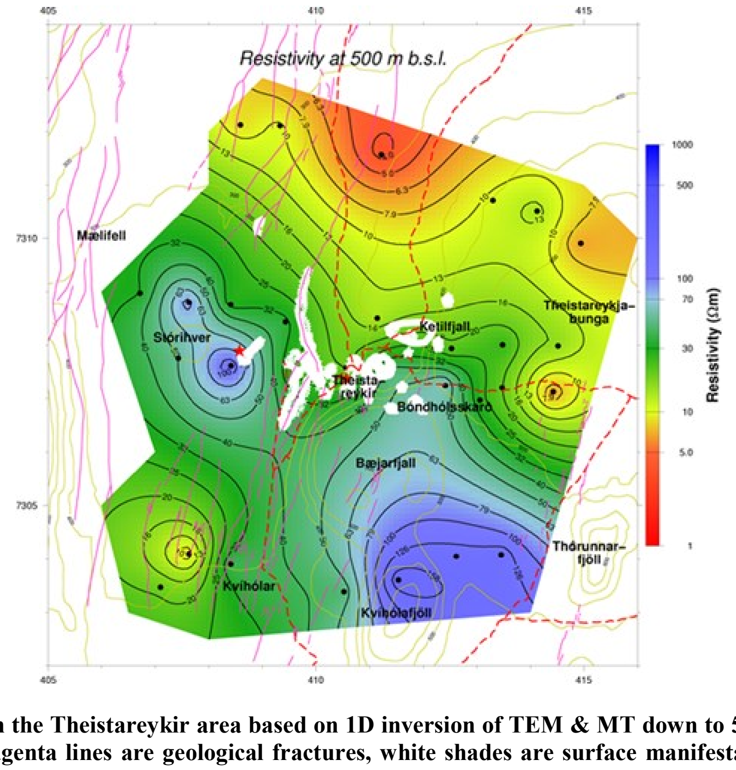

FIGURE 14: Resistivity in the Theistareykir area based on 1D inversion of TEM & MT down to 500 m b.s.l. Black dots are MT soundings, magenta lines are geological fractures, white shades are surface manifestations, red stars are wells and red dashed lines are roads

Resistivity map at 1000 m b.s.l. At a depth of 1400 m, the high resistivity core correlating to the chlorite-epidote alteration zone is clearly mapped trending in the east west direction (Figure 15).

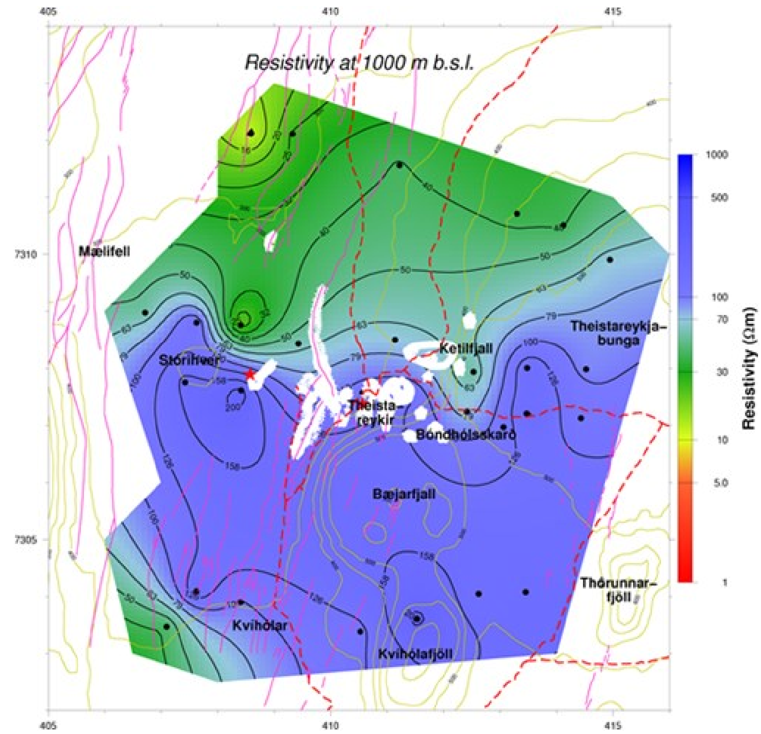

FIGURE 15: Resistivity in the Theistareykir area based on 1D inversion of TEM & MT down 1000 m b.s.l. Black dots are MT soundings, magenta lines are geological fractures, white shades are surface manifestations, red stars are wells and red dashed lines are roads

Resistivity map at 3000 m b.s.l. (Figure 16).Two low-resistivity anomalies appear in the central part of the area, close to Bóndhólsskarð to the east and Stórihver in the west. This could be an indication of a deeper conductor related to the heat source. The low-resistivity layer is clearly mapped at 5000 m b.s.l. and extends to the north of the area (Figure 17).

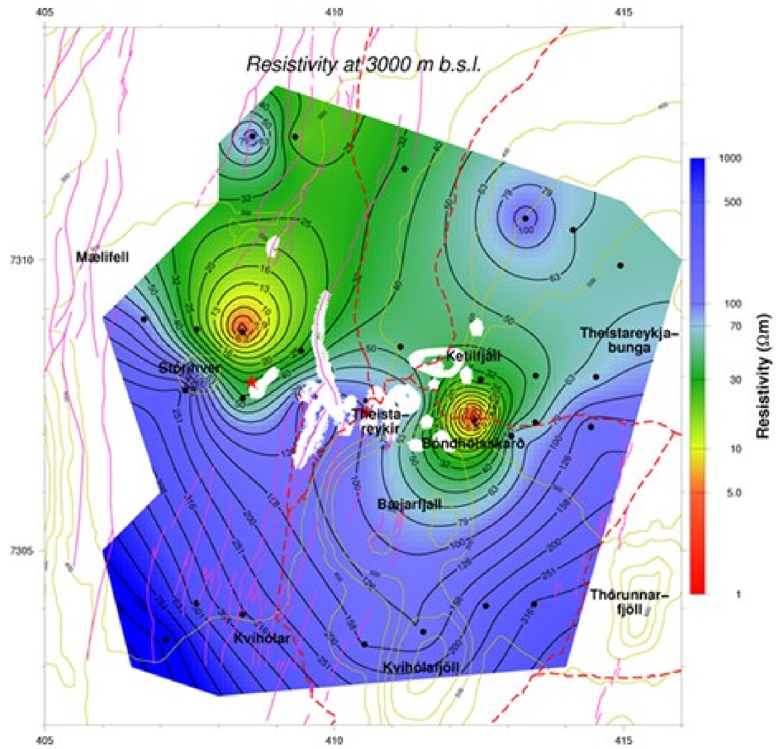

FIGURE 16: Resistivity in the Theistareykir area based on 1D inversion of TEM & MT down to 3000 m b.s.l. Black dots are MT soundings, magenta lines are geological fractures, white shades are surface manifestations, red stars are wells and red dashed lines are roads

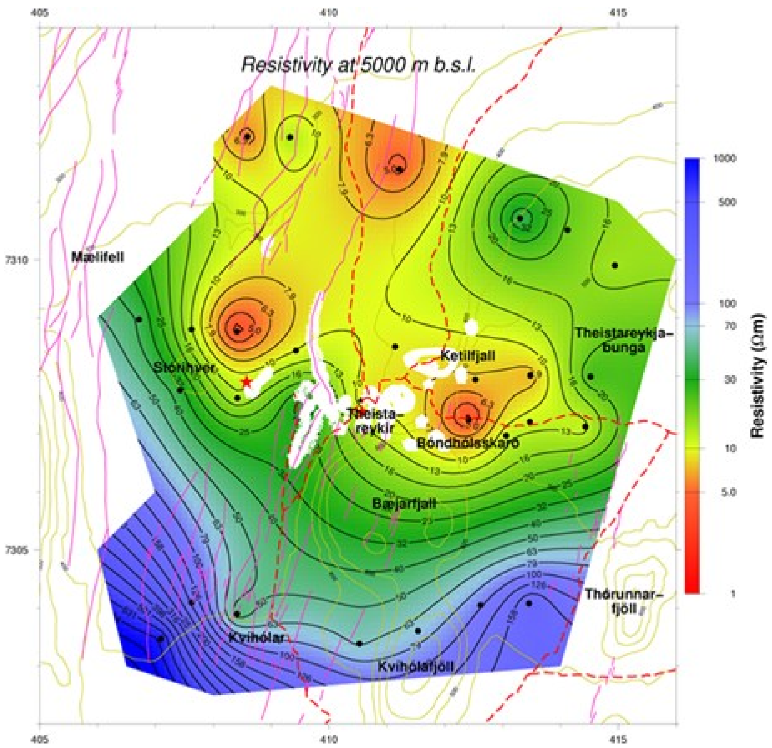

FIGURE 17: Resistivity in the Theistareykir area based on 1D inversion of TEM & MT down to 5000 m b.s.l. Black dots are MT soundings, magenta lines are geological fractures, white shades are surface manifestations, red stars are wells and red dashed lines are roads

7. COMPARISON OF RESISTIVITY RESULTS WITH HYDROTHERMAL ALTERATION AND TEMPERATURE FROM BOREHOLES IN THE THEISTAREYKIR AREA

This section shows a comparison of the observed resistivity structure with the available borehole alteration and temperature logs. Resistivity cross-section WE_3 is within 50-100 meters of boreholes ThG-05 and ThG-08 (Figure 18).These are directional wells that have been drilled to an average of 2 km. However, for boreholeThG-08, only temperature information is available for comparison.

Figure 18 shows a very good correlation between the resistivity and temperature for well ThG-05 as well as temperature for well ThG-08.The low-resistivity layer correlates well with the borehole smectite-zeolite zone reaching the surface and borehole temperature for both boreholes at 200°C.

The chlorite-epidote alteration zone in the borehole correlates well too with the high-resistivity of the cross-section and formation temperature of 250°C and 300°C for wells ThG-05 and ThG-08 respectively.

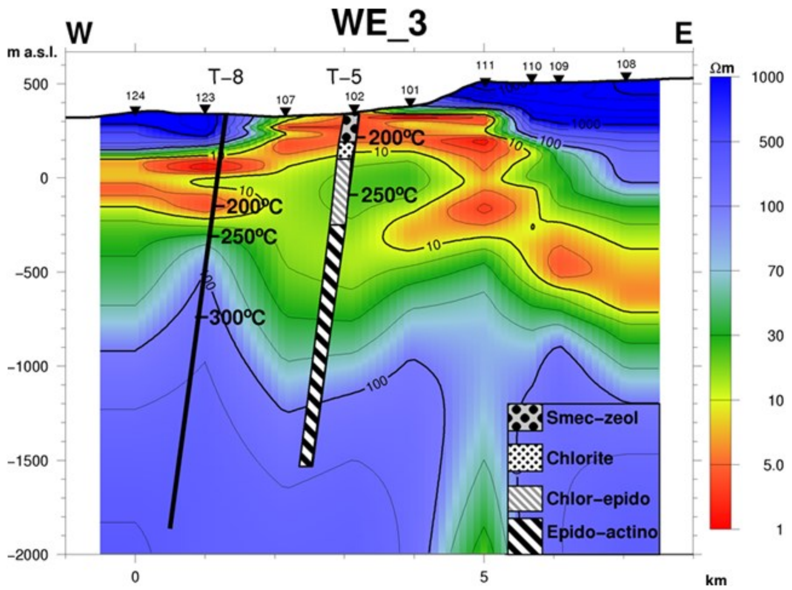

FIGURE 18: Resistivity cross-section WE_3, temperature logs in boreholes and alteration zoning

8. CONCLUSIONS AND DISCUSSION

Interpretation of joint inversion TEM and MT results of the two profiles (WE_3 & WE_4) based on cross-sections and iso-resistivity maps generated with additional two profiles (WE_1 & WE_2) reveal the following resistivity layers;

• A low-resistivity layer near the surface (> 1000 Ωm) to a depth of 200-300 m correlating to the un-altered rocks.

• Underneath the high resistivity layer is a conductive cap (< 10 Ωm) which reaches the surface in areas such as Theistareykir where there are evident number of surface manifestations and alterations. This conductive layer correlates to the smectite and zeolite zone and mineral conduction dominates in this zone.

• Below the conductive layer is a highly resistive core (> 100 Ωm) that is evident in both cross sections and emerges at 500 m b.s.l. in iso-resistivity maps. The existence of the resistive core indicates reservoir temperatures exceeding 250 °C correlating to the chlorite-epidote zone.

• A low-resistivity anomaly (< 10 Ωm) possibly a deep conductor is evident on cross section WE_3at depth of 4.5 -5 km and emerges on Iso-resistivity maps at 5000 m b.s.l. This low resistivity anomaly lie to the north east of Stórihver and north of Bóndhólsskarð.

There is a good correlation between the subsurface resistivity and borehole alteration/temperature logs. The smectite-zeolite zone is found where the subsurface resistivity is low or reaching the surface while the resistive core correlates with the deep alteration zone consisting of chlorite-epidote.

From the analysis of the resistivity layers of Theistareykir geothermal area and their comparison to borehole hydrothermal alteration/temperature logs, it is confirmed that resistivity methods (TEM & MT) are a powerful geophysical prospecting method in high temperature geothermal areas in delineating geothermal resources.

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