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Detailed Resistivity Models of Sub-Areas of the Hengill Geothermal Field, Iceland

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ABSTRACT

In 2016 additional 65 TEM/MT data pairs were collected in the Hengill geothermal field in order to explore the geothermal field and its potential in a greater detail. Using the new and existing data, three new 3D models were obtained. The models cover the following areas; 1) The Meitlar area, a greenfield located SW of the main production area; 2) The Hverahlíð area where production has recently started and 3) the Skarðsmýrarfjall area, east of the center of current production. The models were all created using the WS3DINV code, where static-shift corrected MT data were inverted for. In all cases the data were rotated into the dominant strike direction (N30°E) and the off-diagonal elements of the impedance tensor were used. The effect of nearby oceans was taken into account and several initial models were used.

1. INTRODUCTION

The Hengill area is one of the largest high-temperature geothermal field in Iceland (Figure 1). It is a triple junction as it sits between three plate boundary zones; the divergent Western Volcanic Zone is to the north-east, the Reykjanes Peninsula oblique rift is to the south-west and the South Iceland Seismic Zone is to the east (Einarsson, 2008).

The Hengill geothermal field encompasses several geothermal systems that are being exploited at the Hellisheiði and Nesjavellir geothermal power plants (Figure 1). The Hellisheiði power plant was commissioned in 2001 and has a capacity of 303 MW of electricity and 133 MWth of hot water. The Nesjavellir power plant was commissioned in 1990 and has a capacity of 120 MW of electricity and 300 MWth of hot water.

A 3D resistivity model of the Hengill area, based on inversion of static shift corrected MT data, was published by Árnason et al. 2010. The model revealed the large-scale resistivity structure of the area. In 2016 a total of 65 additional TEM/MT soundings pairs were added to three sub-fields of the Hengill geothermal field (Figure 1) in order to get a better picture of the sub-surface resistivity structure of the area. The three sub-fields are: the Meitlar, Hverahlíð and Skarðsmýrarfjall area (see outlines in Figure 1). They are all located within the bounds of the previous model of Árnason et al. (2010).

A resistivity model was constructed for each of the three sub-fields by inverting for static shift corrected MT data. Here, we present the main results of the final models of each field

2. INVERSION PROCEDURE

The three models, described below, were obtained using the same inversion strategy. Before the 3D inversion, 1D (layered Earth) models were constructed at each sounding site through a joint inversion of co-located MT and TEM soundings. The MT data were static shift corrected by the joint inversion (see further discussion on static shift correction in Árnason (2008)). By interpolating the 1D models a semi-3D model is obtained. This model is often a good indicator of what to expect from the 3D inversion. However, if the structure in the survey area varies significantly in three dimensions, the assumptions of one-dimensionality made in the 1D joint inversion are not valid and the 3D inversion might give different results. Usually the 3D inversion sharpens the structure from the 1D model, just like when one puts on glasses to see better.

An inversion problem, such as the one reported on here, is a highly underdetermined problem and, therefore, the problem needs to be regularized. Here, different initial and prior models are imposed. The initial model defines the structure at the start of the first iteration of the inversion. In the calculations, the misfit between measured data and calculated response from the model, and the deviation of the model from the prior model, are minimized. Because of the latter regularization, the inversion seeks to maintain any resistivity structure present in the prior model and therefore different starting/prior models are tried.

The 3D inversion was performed using the inversion program WSINV3DMT written by W. Siripunvaraporn (Siripunvaraporn et al., 2005; Siripunvaraporn and Egbert, 2009). WSINV3DMT uses finite difference forward algorithm and utilizes a formulation of the inverse problem in the data-space rather than in the model-space. This reduces the dimensionality of the problem dramatically and makes 3D inversion of MT data attainable.

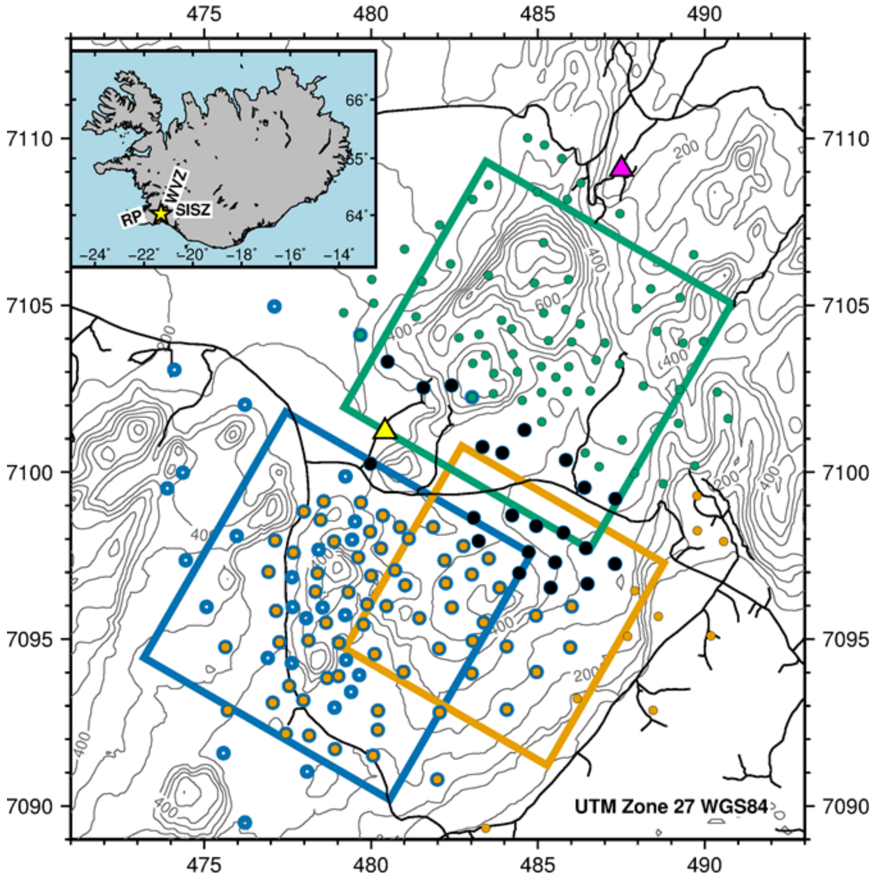

Figure 1: Location map of the three survey areas. Blue, green and orange boxes outline the Meitlar, Skarðsmýrarfjall and Hverahlíð survey areas, respectively. Circles are co-located TEM and MT soundings. Black, blue and circles with blue circumferences were used for the 3D model of the Meitlar area, the black and yellow circles were used for the 3D model of the Hverahlíð area and black and green circles were used for the 3D model of the Skarðsmýrarfjall area. Thick black lines are roads and gray lines show topography with contour lines every 50 meters. Yellow and purple triangles are the Hellisheiði and Nesjavellir power plants, respectively. The small inlet in the upper left corner shows the location of the map in relation to Iceland as a yellow star. RP=Reykjanes Peninsula, WVZ=Western Volcanic Zone and SISZ=South Iceland Seismic Zone.

In the WSINV3DMT code the surface is flat. This seems to be a limitation, but prior to the inversion, the MT data are corrected for static shift and this correction removes topographic effects in the data to a large extent. The inversion is performed for the complex off-diagonal elements of the MT impedance tensor, i.e. 4 parameters (2 real and 2 imaginary parts) for each period of each sounding. The model cells that contain ocean are fixed at 0.3 Ωm, the average resistivity value of seawater.

The processed MT data have the x-axis pointing toward true north. In the 3D inversion a local coordinate system is defined with the x-axis pointing toward the geological strike. In the three models, presented here, the main fault strike is N30°E. The x-axis of the local coordinate system, therefore, points toward N30°E and the y-axis in N120°E, 90° clockwise of the geological strike. The MT impedance tensors were rotated accordingly, after correcting the magnetic declination, 30° clockwise to align with the local coordinate system.

In this work, the prior- and starting models are the same within an inversion run (consisting of a few iterations) but they differ between runs. After a few iterations (usually 3–5) the resulting best model is used as the initial and prior model for the next run and the best model from that run is used as the initial and prior model for the next run, and so forth. With this inversion scheme the root-mean-square misfit decreases consistently, first by large amounts and then more slowly with increasing number of runs, flattening out at a root-mean-square misfit value below 2 (Figure 2).

Below we discuss the different attributes of each model.

2.1 The Meitlar Area

The model cells in the densest part of the model grid were 250 meters by 250 meters, spanning 8500 meters in each horizontal direction (34 cells). The densely gridded area is shown as a blue rectangle in Figure 1. A total of 110 sounding pairs were used for this model. Four initial models were tested; three homogeneous half-spaces with a resistivity value of 10 Ωm (H10 model), 50 Ωm (H50 model) and 100 Ωm (H100 model) and an initial model compiled from 1D joint inversion of TEM and MT data (J1D model). The main features of the models were similar above 2000 meters below sea level but considerable difference was between the models where the initial model had been a homogeneous half-space compared to the J1D model below that depth. The J1D model showed a deep lying low-resistivity layer whereas the H10, H50 and H100 models did not. This difference is very important as the survey area sits between areas where the deep low-resistivity layer has been observed (e.g. underneath Hengill central volcano (Árnason et. al. 2010) and underneath the highlands of Iceland) and areas where it has not been observed (e.g. Krýsuvík on the Reykjanes Peninsula (Hersir et al, 2018)). Here we focus on the structure at reservoir level (>2000 meters below sea level) and chose to present the H50 model.

2.2 The Hverahlíð Area

The model cells in the densest part of the model grid were 250 meters by 250 meters, spanning 7000 meters in each horizontal direction (28 cells). A total of 119 sounding pairs were used for this model. The densely gridded area is shown as an orange rectangle in Figure 1. Two initial models were tested, one with a homogeneous half-space starting model with the resistivity of 50 Ωm (H50 model) and the other with a starting model compiled from the joint 1D inversion (J1D model). They were compared and showed similar main features. The model we present here is the H50 model.

2.3 The Skarðsmýrarfjall Area

The model cells in the densest part of the model grid were 250 meters by 250 meters, spanning 8500 meters in each horizontal direction (34 cells). A total of 89 sounding pairs were used for this model. The densely gridded area is shown as a green rectangle in Figure 1. As with the Hverahlíð area two initial models were tested, one with a homogeneous half-space starting model with the resistivity of 50 Ωm (H50 model) and the other with a starting model compiled from the joint 1D inversion (J1D model). They were compared and showed similar main features. The model we present here is the H50 model.

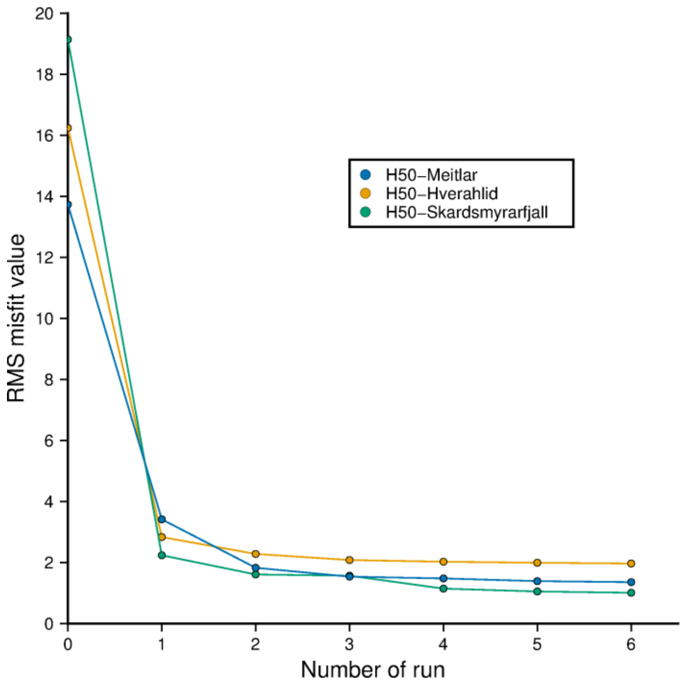

Figure 2: Root-mean-square misfit plotted against number of run for the three sub-fields presented.

3. RESULTS

Below the results of each model are discussed and presented in forms of horizontal cross-sections through the final 3D model. Also, a bottom-of-clay (BOC) figure is presented for each sub-field. Such a figure shows the depth of the transition between the low-resistivity cap and the resistive core beneath and that interface is interesting because it marks the transition to clay minerals that form at 230°C. It is important to note that the top of the low-resistivity clay cap is very well determined but the bottom of it is less well resolved. That is because the electromagnetic waves need to travel through a very conductive body causing the amplitude of the wave to reduce, and therefore also the depth resolution (skin depth). The BOC maps are useful to understand the extent and geometry of the geothermal reservoir but the exact depth of the boundary should **not** be taken as accurate.

3.1 The Meitlar Area

The survey area is centered near two hylaloclastite mountains, Stóri-Meitill and Litli-Meitill and has therefore been referred to as the Meitlar area (the plural of "Meitill"). Figure 3 shows horizontal cross-sections through the final 3D model at four different depths. The low-resistivity cap is very evident at sea level (Figure 3A) and at 300 meters below sea level the high-resistive core has started to appear, forming two elongated features following the orientation of the hyaloclastite ridges (Figure 3B). At 500 meters below sea level the resistive cores are well apparent (Figure 3C) and at 1000 meters below sea level they seem to almost merge (Figure 3D).

Figure 6A shows the depth to the deeper boundary of the low-resistivity cap for the Meitlar area. Two prominent up-doming features are present, both elongated in the main fault direction (N30°E). The eastern elongated feature is not as pronounced as the western one. Interestingly, the western orientation of the western feature changes abruptly from N30°E to N-S right at Stóri-Meitill (see location of Stóri-Meitill in Figure 3). The N-S orientation is the same as the orientation of the bookshelf faults of the South Iceland Seismic zone and the strike-slip faults on the Reykjanes Peninsula (Einarsson, 2008).

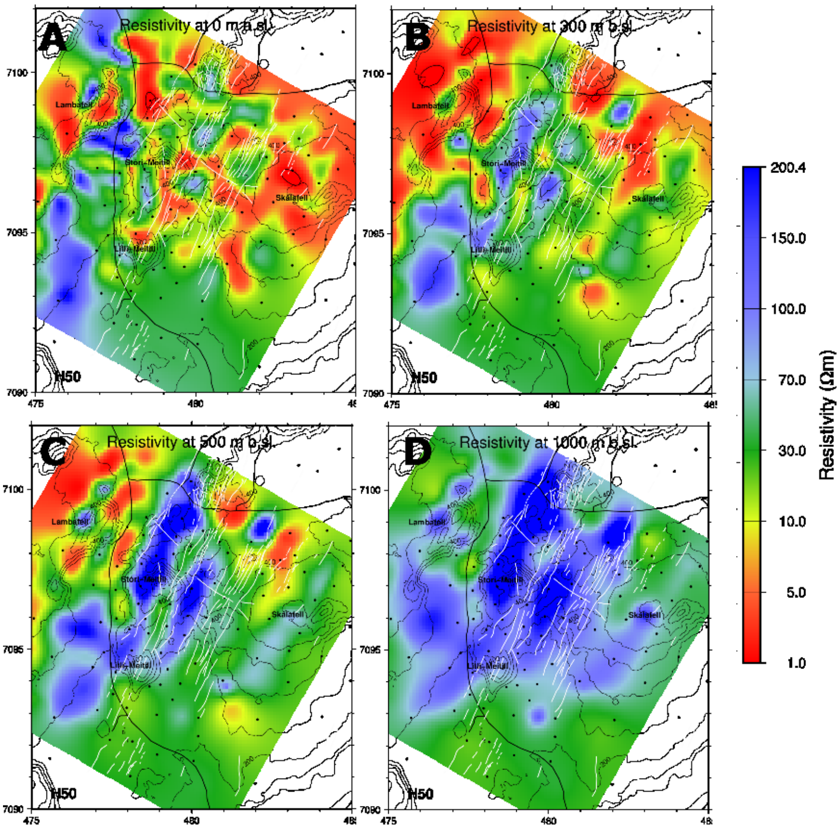

Figure 3: Horizontal cross-sections through the final model of the Meitlar area at sea level (A), 300 (B), 500 (C) and 1000 (D) meters below sea level. Black lines are roads, white lines are mapped faults and topographic contour lines are in gray. Black circles are sounding locations.

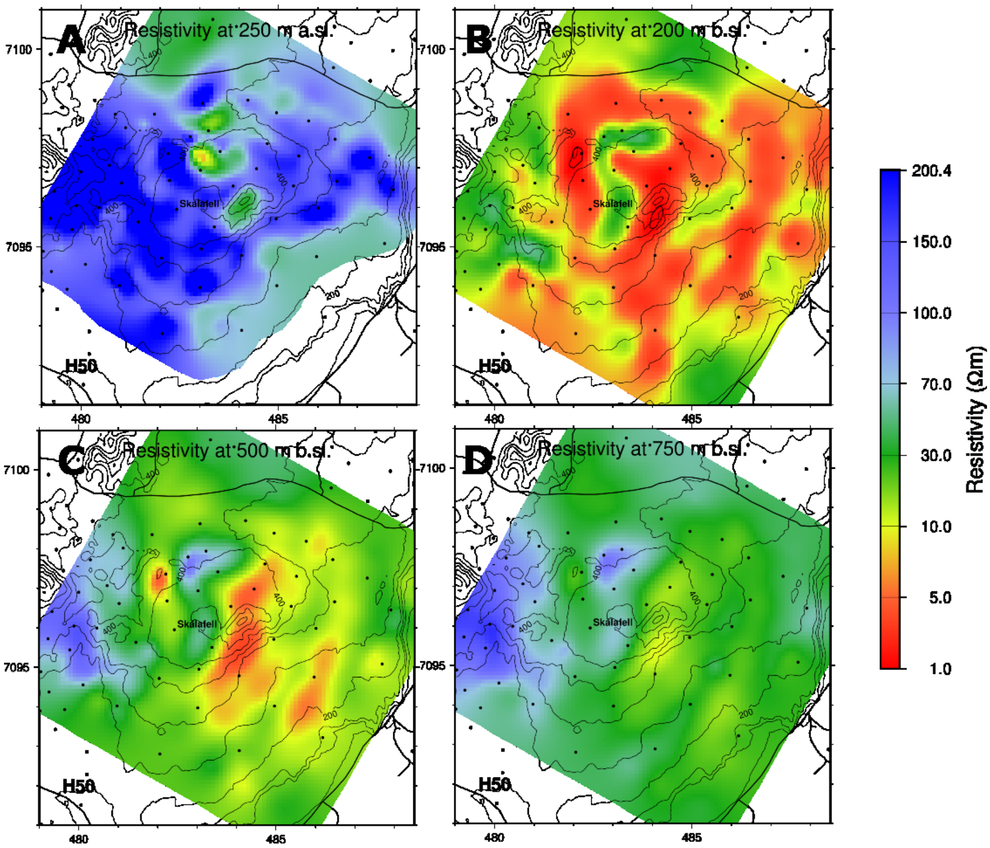

Figure 4: Horizontal cross-sections through the final model of the Hverahlíð area at 250 m above sea level (A), 200 (B), 500 (C) and 750 (D) meters below sea level. Black lines are roads and topographic contour lines are in gray. Black circles are sounding locations.

3.2 The Hverahlíð Area

The Hverahlíð survey area sits just east of the fissure swarm stretching south of the Hengill central volcano (Figure 1) and is mostly comprised of the hyaloclastite mountain Skálafell (Figure 3), sitting on top of an older shield volcano. Figure 4 shows horizontal cross-sections through the final 3D model at four different depths. The Hverahlíð area is not as complex as the Meitlar area, as the resistivity structure changes mostly with depth, i.e. the structure is mainly horizontally layered.

At 250 meters above sea level resistive lavas are present (Figure 4A) and at 200 meters below sea level the low-resistivity cap is apparent, surrounding the resistive core, which forms a reversed ‘seven’ (Figure 4B). At 500 meters below sea level the low-resistivity cap is still present, more so on the east side of the reversed seven than to the west (Figure 4C). At 750 meters below sea level the resistive core is still present, but the model is rather characterless which can be explained by the one dimensionality of the area.

Figure 6B shows the depth to the deeper boundary of the low-resistivity cap for the Hverahlíð area. The up-doming feature of the low-resistivity cap forms a reverse ‘seven’, the same shape as is seen in Figure 4B. This feature is very clear in the surrounding horizontally layered Earth.

3.3 The Skarðsmýrarfjall Area

The Skarðsmýrarfjall area is encompasses Mt. Hengill and Mt. Skarðsmýrarfjall (Figure 5). The topography is very rugged in the survey area and the resistivity structure in this area is the most complex of the three sub-areas discussed in this paper. Figure 5 shows horizontal cross-sections through the final 3D model at four different depths. At 250 meters above sea level the low-resistivity cap is present (Figure 5A) and 200 meters below, at 50 meters above sea level the resistive core has started to show (Figure 5B). The area marked with a dashed line in Figure 5B is inside the resistive core, underneath the low-resistivity cap. The complexity of the area is seen in the structures within the bounds of the dashed lines; three small up-doming areas are observed and outlined in Figure 5B, trending in the same direction as the main faults in the region, N30°E.

At 200 meters below sea level (Figure 5C) the area located underneath the low-resistivity cap has become broader and the three elongated up-doming areas are still present. At this depth, a low-resistivity column is evident, which is also seen at 1000 meters below sea level (Figure 5D). The low-resistivity column is seen to extend down to 2-3 kilometers depth. Three soundings are located above the anomaly and it is therefore rather well constrained and unlikely an artefact of the inversion.

Figure 6C shows the depth to the deeper boundary of the low-resistivity cap for the Skarðsmýrarfjall area. It is evident that there is a lot of structure in the survey area and out of the three sub-areas in this paper, this one is by far most complex. The BOC map is useful, as it draws out some of the main features of the model, but other anomalies, such as the low-resistivity column, disturb the map.

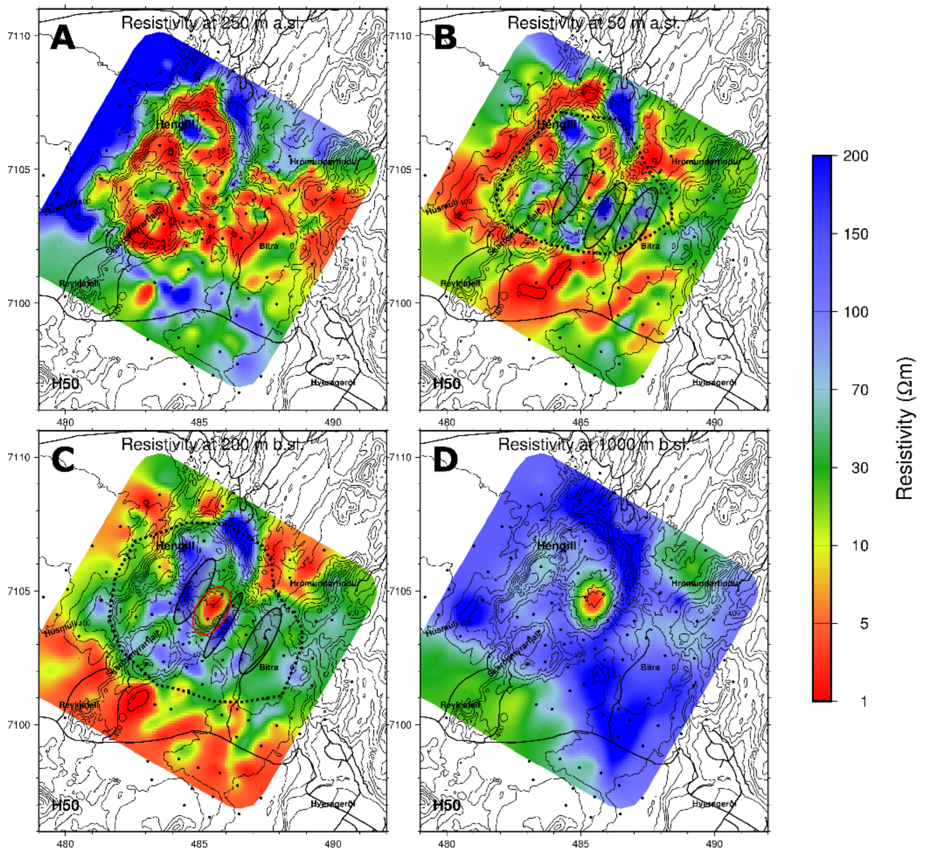

Figure 5: Horizontal cross-sections through the final model of the Skarðsmýrarfjall area at 250 m above sea level (A), 50 m above sea level (B), 200 meters below sea level (C) and at 1000 meters below sea level (D). Black lines are roads and topographic contour lines are in gray. Black circles are sounding locations

4. CONCLUSIONS.

The resistivity structure of three sub-areas within the Hengill geothermal field has been investigated by inverting static shift corrected MT soundings in three dimensions. The three areas are structurally very different, despite their proximation to one another. The resistivity structure in the Meitlar area, located in the fissure swarm southwest of the central volcano, is controlled by the hyaloclastite ridges in the fissure swarm, exhibiting a two-dimensional structure. The resistivity structure in the Hverahlíð survey area, located east of the fissure swarm stretching south of the Hengill central volcano, is the simplest. The geothermal footprint is clearly seen as the up-doming feature of the low-resistivity cap emerges through the otherwise 1D structure of the survey area. The Skarðsmýrarfjall area is located at the central volcano and is by far the most complex area of the three, exhibiting a highly three-dimensional structure. The bottom of the low-resistivity clay cap was mapped and in two out of the three cases was very useful in understanding and visualizing the main features of the 3D resistivity model better; in the Skarðsmýrarfjall area, where the structure was very complex, the map was less helpful in understanding and visualizing the 3D resistivitay model better.

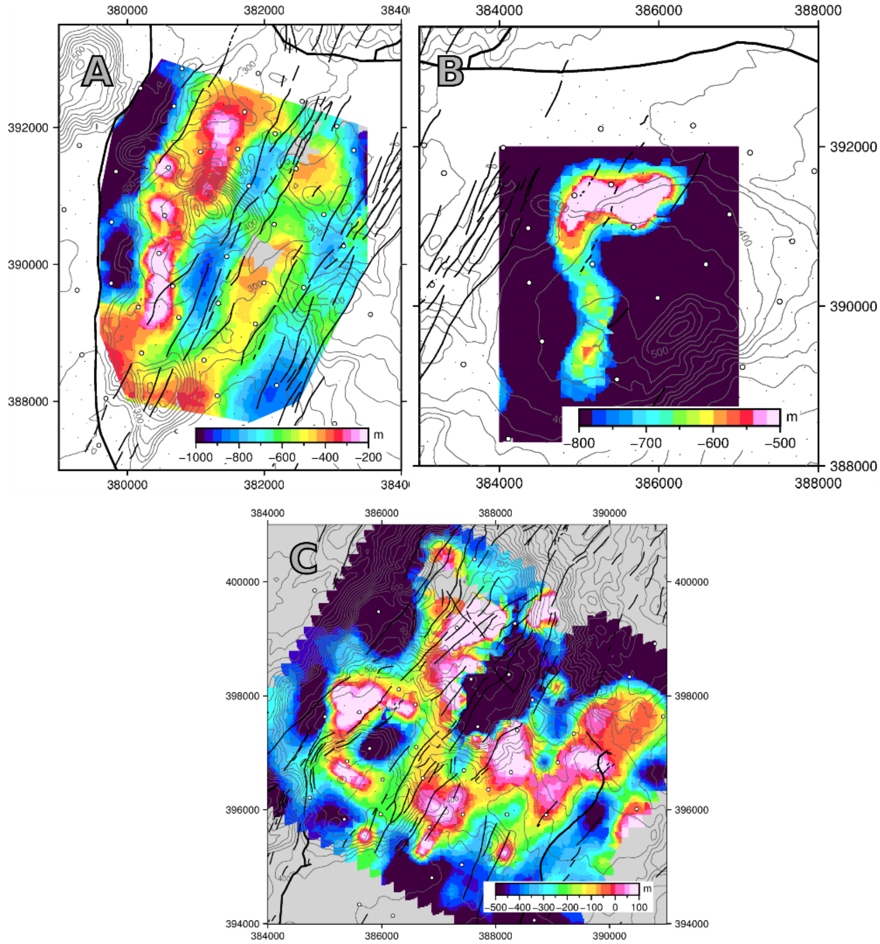

Figure 6: Bottom of clay maps for the Meitlar area (A), Hverahlíð area (B) and Skarðsmýrarfjall area (C). The color scale shows the depth down to the bottom of the low-resistivity clay cap. Note that the color scale is different for each region. Black solid thick lines are roads, black solid thinner lines are faults, gray lines are topographic contour lines and white circles are sounding locations.

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