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Comparison of Down-Hole Data and Surface Resistivity Data from S-Hengill, a High Temperature Geothermal Field in SW-Iceland

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ABSTRACT

Resistivity logs from 72 boreholes in southern part of Hengill high temperature field, and resistivity interpreted from surface measurements, TEM and MT soundings, are compared. The resistivity is also compared to the first appearances of alteration minerals. The full comparison was made with an interpolated 3D model based on joint 1D inversion of TEM and MT electromagnetic soundings, where the resistivity was projected on the well paths and formed pseudo logs, which were compared to the resistivity logs which had been up scaled to the same resolution as the resistivity from TEM/MT. In addition pseudo logs were made based on a 3D resistivity model from a joint inversion of the TEM/MT data. These were compared to averaged logs from the resistivity logs in a similar resolution and to the already made pseudo logs from the 1D model. For preparing the data the available resistivity logs from each section of drilling were combined for each well and inserted into Petrel, a 3D visualization software, for geological and geophysical data. Previous studies of resistivity from high temperature geothermal systems in Iceland have shown a low resistivity cap on the outer margins of the reservoir underlain by higher resistivity and further down a deep conductor. The resistivity pattern has been explained with variations of resistivity of temperature alteration minerals and represents a “maximum thermometer” if a geothermal system has cooled. A further comparison with alteration zones in the wells also shows that the onset of the smectite zeolite zone correlates with the lowering of the resistivity, and that resistivity starts to increase again at the upper boundary of epidote-chlorite alteration and in some cases amphibole. The 3D resistivity model deduced from the TEM/MT electromagnetic soundings has much lower resolution than the interpolated model from the 1D inversion and the former showed less of the features seen in the averaged resistivity logs than the pseudo logs deduced from the 1D inversion. Resistivity well logs in 5 selected wells are shown in the paper. The resistivity model found by interpolating the 1D inversions of TEM/MT data and the more recent 3D model found by inversion of the same data and the averaged logs as well as the alteration minerals as well as an example of the neutron-neutron and gamma-logs will be given.

1. INTRODUCTION

The aim of this study was to combine multiple data sources from surface and sub-surface exploration of a high-temperature field, each defining the properties of the reservoir. In the study the focus is on three data sources, i.e. two types of resistivity surveys done in the Hengill reservoir and their relation to changes in hydrothermal alteration. An interpolated model from the 1D resistivity found in a previous joint inversion of TEM and MT (surface resistivity measurements) has been compared with resistivity logs in 72 boreholes (Haraldsdóttir et al., 2012). In addition a more recent 3D joint inversion resistivity model based on the same TEM and MT data is presented as an example of projected model on well paths for comparing with the well logs and the previously interpreted 1D resistivity. The wells used in this study include the first exploration well in S-Hengill which was drilled in 1984 to the last one which was drilled 2010.

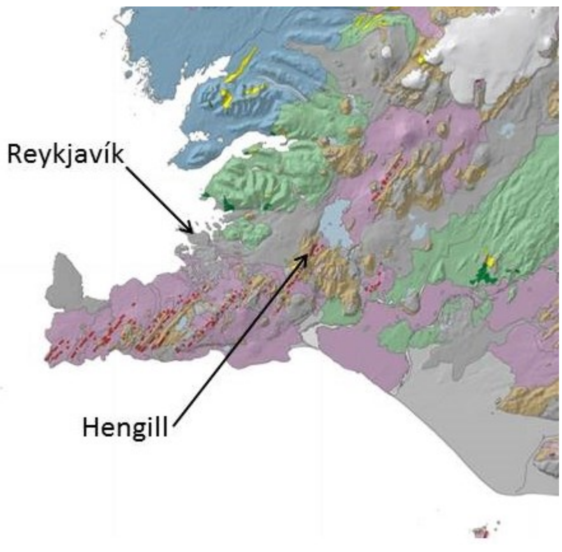

Figure 1. Geological map of SW-Iceland, the central volcano Hengill, and Reykjavík, the capital of Iceland.

The S-Hengill high temperature geothermal system, often referred to as Helliheidi, is a part of the Hengill volcanic system in SW-Iceland (Figure 1). It is located at a triple junction, where volcanic zones and the South Iceland seismic zone form excellent conditions for high temperature geothermal fields (HT), with sufficient heat, water and good permeability caused by seismic activity forming fissures, a perfect combination for possible utilization of geothermal energy.

The main purpose of Reykjavík Energy in investigating the Hengill area was to enable harnessing of the geothermal resource for electricity and hot water production for the city of Reykjavík and surrounding communities.

The Hengill geothermal reservoir is formed by the percolation of groundwater to the heat source at the base of the central volcano and subsequent up flow of geothermal fluid. The temperature of the reservoir ranges from 200 to 340°C.

Three power plants are operated in the Hengill area, the oldest one at Nesjavellir north of Hengill and two plants at Hellisheidi in the southern part of Hengill (Figure 2) which started operation in 2006 and 2011. The present production at Hellisheidi is 303 MW_e, and 103 MW_{th}. A total of 74 exploration, production and reinjection wells have been drilled south of Hengill (Figure 2) and their measured depth range is around 1000 to 3300 m.

This paper first describes the relevant earlier studies in the Hengill area followed by the methodology of data preparation. A comparison is introduced, where resistivity well logs in selected wells are compared with resistivity from 3D inversion of TEM/MT surface electronic soundings and the interpolated model from the 1D inversion of the same TEM/MT data is also compared as well as the appearance of alteration minerals in the boreholes. Additionally an example is shown of neutron-neutron logs and natural gamma logs with the other well logs and surface resistivity. Finally the results and conclusions are presented.

2. BACKGROUND – PREVIOUS STUDIES OF THE S-HENGILL AREA

2.1 Geology, hydrology and surface geophysics

A wide range of publications is available on the Hengill central volcano and it's large geothermal resource. The first geothermal investigations in the Hengill area were made during the years 1947-1949 (Einarsson et. al., 1951, Böðvarsson, 1951). Sæmundsson (1994) mapped the surface geology and tectonic features which are necessary as a background for other investigations in the area and results from geophysical surface exploration are presented in Hersir et al. (1990), Árnason and Magnússon (2001) and Árnason et al. (2000, and 2010). Franzson et al. (2000, 2005, 2010), Helgadóttir et al. (2010), Níelsson and Franzson (2010), Helgadóttir (2011), Níelsson (2011), Snæbjörnsdóttir (2011) mapped the subsurface geology and hydrothermal alteration of the reservoir. A comparison between TEM/MT, borehole resistivity and alteration was done in nine wells as a prelude to this study (Haraldsdóttir et al., 2010) and later with the whole borehole resistivity dataset (Haraldsdóttir et al., 2012) which is partly repeated here to prepare the persent investigation by connecting to this detailed study.

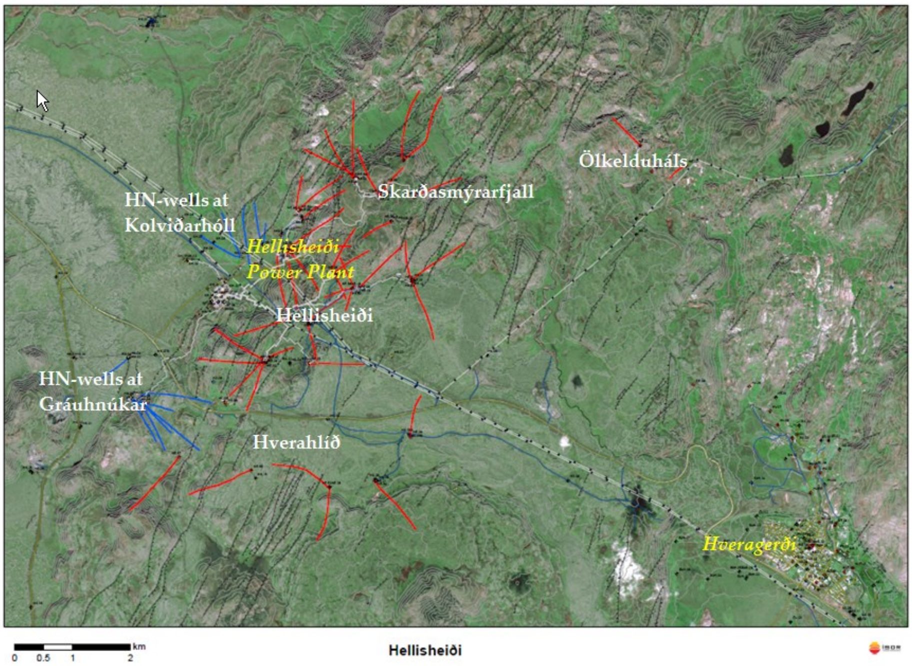

Figure 2. South-Hengill. Boreholes are projected on the surface, red: research and production wells, blue: reinjection wells. Note that the lines indicate directional wells, while vertical wells appear only as a dot.

Figure 2 shows a projection to the surface of the wells in the S-Hengill area, where red lines show directional production and exploration wells and blue lines show directional reinjection wells. A vertical well appears as a dot.

The resistivity pattern has been explained with variations of resistivity of temperature alteration minerals. Low resistivity is found coinciding with the clay mineral smectite, which is formed at around 30°C, and mixed clay layer, formed at around 200°C, while entering the chlorite, formed at approximately 230°C and epidote, formed at approximately 240-250°C. Alteration zones relate with increasing resistivity. The resistivity is linked to the alteration minerals and they show a "maximum thermometer" representing the alteration minerals which remained when a geothermal system cooled.

Previously a low resistivity layer was shown to be present in the well-logs in the Hengill area (Haraldsdóttir et al., 2010 and Haraldsdóttir et al., 2012) as well as in the resistivity from the 1D TEM/MT electromagnetic soundings. Here the studies are taken further by including the 3D inversion of TEM/MT in the comparison in few wells.

Alteration

Kristmannsdóttir et al. (1989) detected a system in the temperature alteration of minerals which has been useful and developed further by Franzson (1994) as is shown schematically in Figure 3 as the relation between zones of hydrothermal alteration, rock alteration and temperature.

Glass, which often predominates in hyaloclastites, is sensitive to alteration and starts to break down at relatively low temperatures dominantly into clays. These are smectite at low temperatures which transform into mixed layer clay and gradually to chlorite at higher temperatures (Figure 3).

Detecting the type of clay minerals in drill cuttings therefore indicates temperatures prevalent at the time of alteration. The clay alteration is progressive and assumed to be largely irreversible especially when high alteration state is reached. This information is important when viewed in relation to resistivity.

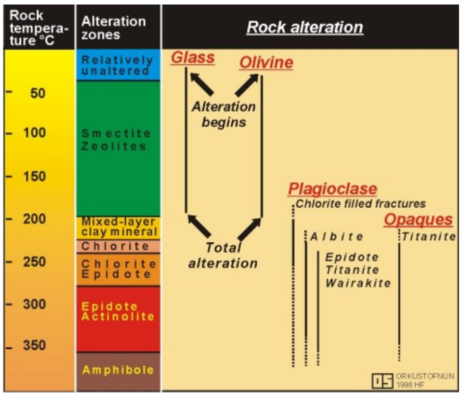

Figure 3. Zones of alteration and the corresponding rock alteration (Franzson, 1994).

Resistivity and alteration

Previous studies with electromagnetic soundings in high temperature areas (>200°C) in Iceland have shown high resistivity at the top of a low resistivity cap underlain by a high resistivity core (Árnason et al. 1987). It was found that the resistivity lowers in the smectite-zeolite zone and that the resistivity increases again in chlorite-epidote zone, as shown in Figure 4.

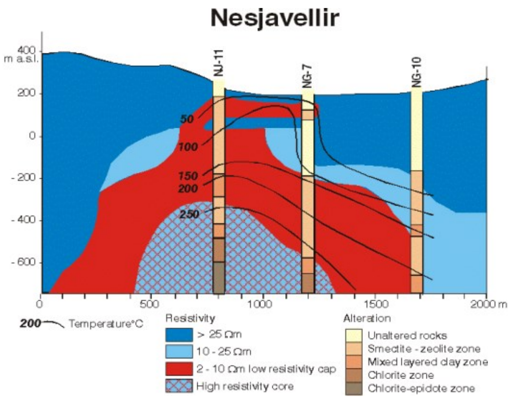

Figure 4. The relation between resistivity, temperature and alteration (Árnason et al., 1987).

The changes in resistivity were explained by different conduction of alteration minerals. These results were confirmed and reviewed in a recent paper about results from TEM and MT joint inversion in the Hengill area (Árnason et al., 2010). A deep conductor was also detected further down, at 3-10 km depth, which is below the scope of this study. The differences in resistivity were explained in the paper (Árnason et al., 2010, citing Deer et al., 1962) to be caused by loosely bound cations in the smectite and zeolite minerals which make them conductive, but in chlorite the cations are bound in the crystal lattice, hence increasing the resistivity.

Resistivity

The central loop transient electromagnetic method (TEM) was tested in Iceland 1987 and found to be superior to DC methods (Árnason et al., 2010).

Until the turn of the century the emphasis in resistivity surveys was to explore the uppermost 0.5-1 km of the geothermal resource which gave a good outline of the shape of the underlying reservoir. In recent years, however, significant advances have been made in deeper penetration by combining TEM and MT soundings, enabling a vision down to several kilometres depth. Several surveys of MT soundings have been done in the Hengill area since 1976 but only data from the last three surveys are included in the final work due to reformatting problems of the older data. The final data collection included 146 stations.

The range of periods recorded in the MT soundings was 0.0034 s to 100-1000 s.

The 146 TEM and MT stations can be seen as black dots on Figure 5 and at the top of the vertical lines in Figure 6. The line below each station is where the points from the 1D interpretation for the relevant station are located. A 3D grid or model was interpolated in a similar way as in the first part of the project but with thinner layers at the upper part. The description from Haraldsdóttir et al. (2010) is as follows: "TEM and MT measurements used in this study have been made at 146 sites. The resulting 1D resistivity profiles were included in Petrel and interpolated to make a 3D resistivity model with increasing thicknesses of the layers with depth. The interpolation was made with a Kriging algorithm using a Gaussian semi-variogram and their horizontal range was 2500 m and the vertical range 2000 m."

In Figure 5 examples of the results of interpretations of TEM and MT are shown a) at sea level and b) at 500 m b.s.l. The black dots show the locations of the TEM and MT stations. The figure is a result of a joint inversion of TEM and MT electromagnetic soundings which was done in the Hengill area for 146 stations (Árnason et al., 2010).

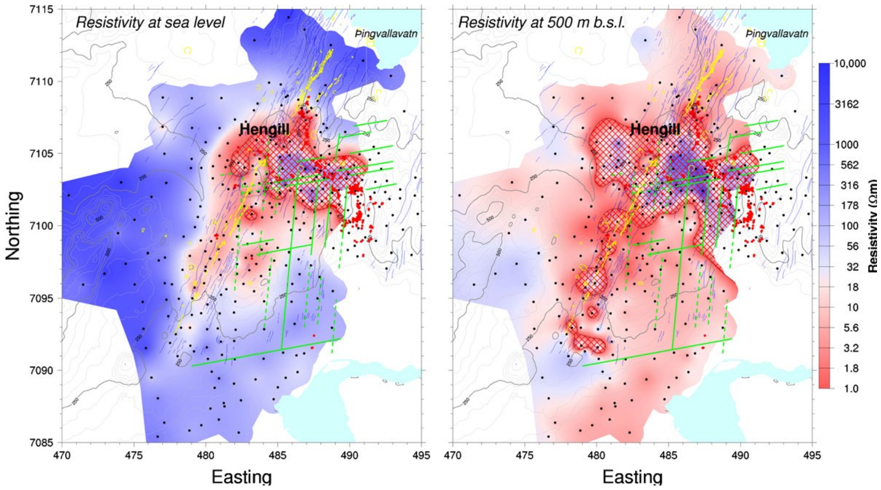

Figure 5. Resistivity maps from the Hengill area based on 1D inversion of TEM data: (a) at sea level and (b) at 500 m b.s.l. Geothermal activity at the surface is shown as red dots, faults and fractures mapped on the surface are shown in blue, faults inferred from seismicity are shown in green and volcanic craters and fissures in yellow. The contour lines show elevation ranging from 100-700 m a.s.l. (From Árnason et al., 2010.)

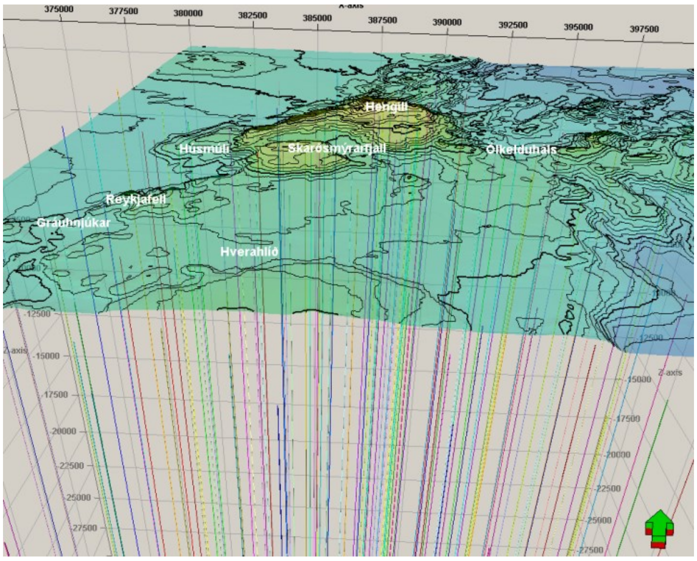

Figure 6: Henda: Locations of the TEM and MT electronic sounding stations, below which vertical lines indicate locations for 1D interpretations. The north arrow is at bottom right.

In addition to the resistivity from 1D inversion several experiments with 3D inversion have been made based on the same TEM/MT electromagnetic soundings as the 1D model. Examples of "pseudo logs" from a 3D model from ÍSOR are presented in the paper whereas the main analysis has been based on the 1D inversion.

The borehole design

The boreholes in the study are either directional (see Figure 2) or vertical. An example of the design of a directional well is shown in Figure 7.

The production wells are normally drilled in four stages i.e. for surface, safety and production casings and lastly for the production part. The “kick off” depth in directional wells is normally just below the safety casing at approximately 300 m depth. Each section is finished with a cemented casing and the production part with a slotted liner

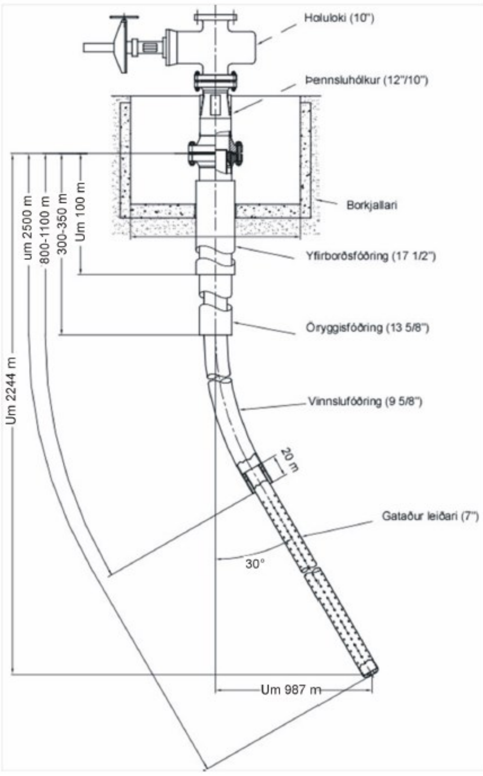

Figure 7. A typical design of a wide, directional well.

DATA PREPARATION

Resistivity well logging

Geophysical well logging is done at the end of each drilling stage. In this project mainly the resistivity logs were studied. During the logging two simultaneous resistivity measurements are made, at 16" and 64" above an electrode which is at the lowest end of the logging cable. The construction is the so called normal set up (see e.g. Serra (1984), Stefánsson and Steingrímsson (1990) for details). The well logs penetrate the wall rock of the borehole, where the 64" resistivity penetrates a little further into the formation than the 16" resistivity. The results are stored in two files as measured depth (MD) and a signal.

Correcting and combining resistivity well logs

The main part of this project was to correct and prepare the resistivity well logs for further processing. They are available from 72 of the 74 holes already drilled in the S-Hengill area (Figure 8). Logs from two wells were missing due to problems during well logging. In all of the measurements during drilling the platform of the drill rig is used as a common reference, but after drilling the surface is the common reference. For having a common reference point for all well logs during and after drilling, the ones from the drilling period need to be corrected from the platform down to the surface. Afterwards they are corrected with respect to the casing depth from the previous section. The resistivity well logs from each section are corrected for effects of the drilling fluid, the width of the well and temperature, after which all of the measured sections are combined into one file for each well. These files are inserted into the Petrel 3-D software (Schlumberger, 2008) where the data are connected to the well paths through their measured depth (MD). The results are presented in Figure 8, where the 16" resistivity is shown along the well paths. The logarithmic resistivity scale in Ωm is shown in the upper left corner. The red colour indicates low resistivity which increases in yellow, green and the blue indicates the highest values.

The well logs can also be presented from the Petrel software as log plots along with other data as will be shown in the results chapter below.

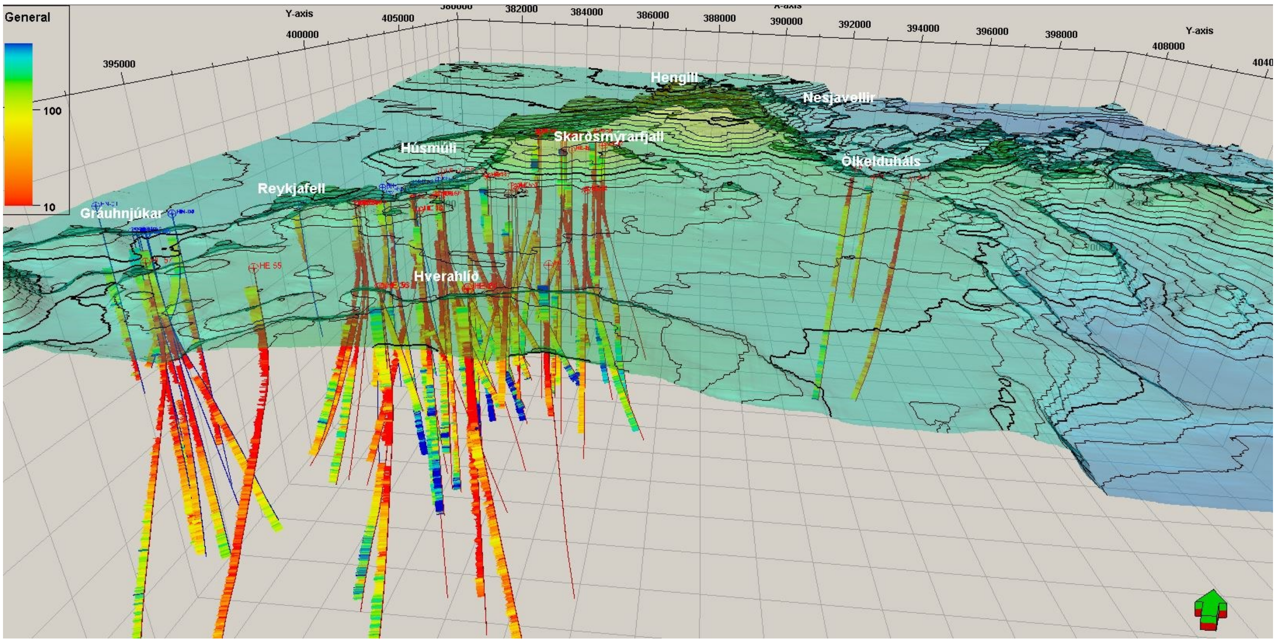

Figure 8. Boreholes south of Hengill with measured 16" resistivity. The resistivity scale (Ωm) is logarithmic and shown in the upper left corner.

Alteration minerals

Information on hydrothermal alteration is derived from binocular and petrographic microscopes along with XRD-analysis. Furthermore, detailed studies of alteration minerals in boreholes at S-Hengill have been conducted recently as parts of MSc projects at the University of Iceland and ÍSOR (Níelsson, 2011; Helgadóttir, 2011; Snæbjörnsdóttir, 2011, Gunnarsdóttir, 2012).

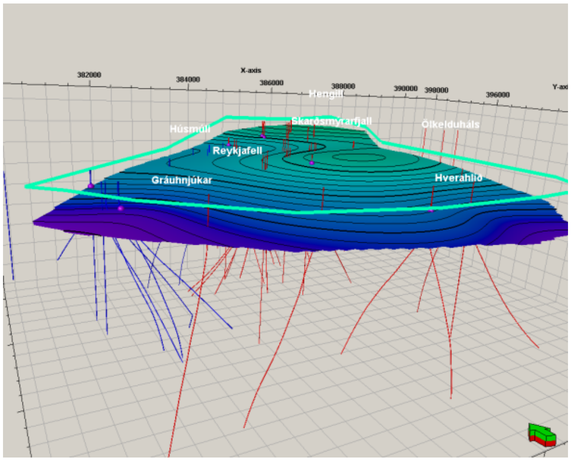

Figure 9: A depth contoured map of S-Hengill showing the upper boundary of smectite based on borehole data. North arrow at bottom right.

The depth to the first appearance of an alteration mineral in a well is one of the data gathered partly in order to relate to the present formation temperature and from that deduce the temperature changes occurring in the reservoir through time. One of the conclusions from those studies indicates that some parts of the reservoir are cooling while others have recently heated up (Franzson et al., 2010).

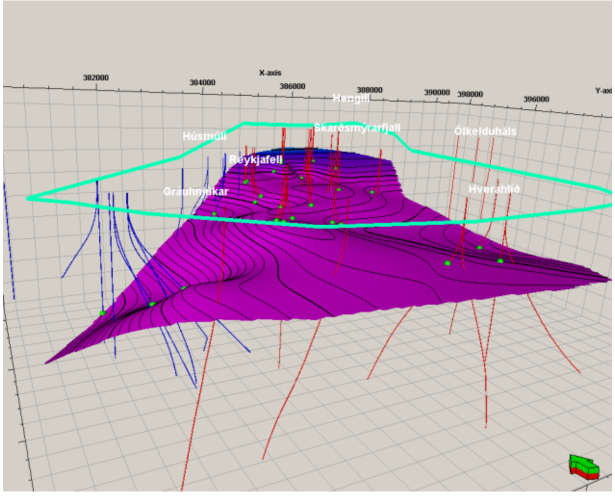

Figure 10. A depth contoured map of S-Hengill showing the upper boundary of chlorite based on borehole data. North arrow at bottom right.

The measured depth to the uppermost appearance of the relevant mineral in a well was inserted into Petrel after which an interpolated layer was made through all these known locations. Examples are shown in Figures 9 and 10 of smectite and chlorite respectively. It may be noticed that the curvature can be large where the range of depths for the relevant mineral is high within a short distance (Figure 10). The well paths cut through the surface which appears as the first appearance of the mineral in the relevant well.

Petrel: Well logs, “pseudo logs”and alteration

The steps of the process in Petrel were the following:

1a) 16" and 64" resistitivity well logs were corrected, combined from the well sections to form continuous logs for each well and inserted as MD and value and linked to the well paths.

1b) A similar process to 1a) was performed for neutron-neutron and gamma well logs.

2a) 1D resistivitiy from TEM and MT for each station was inserted into Petrel (i.e. values at different depths under the station).

2b) A 3D model was made from the 1D resistivity from TEM/MT.

2c) The 3D grid was projected on the well paths as “pseudo logs” with resolution according to the grid at the respective location.

3) The 16" and 64" well logs were averaged to the same resolution as the TEM-MT “pseudo logs”.

4a) Each alteration mineral was inserted into Petrel as MD and linked with the relevant well path.

4b) Surfaces were made for each alteration mineral.

5a) A 3D resistivity model from inversion of TEM/MT was inserted into Petrel.

5b) The 3D model was projected on the well paths as “pseudo logs” with resolution according to the grid at the respective location.

5c) The 16" and 64" well logs were averaged to the same resolution as the 3D TEM-MT “pseudo logs”.

The measured 16" and 64" resistivity well logs and the “pseudo logs” from both of the TEM/MT models were combined in a log plot for comparison. In addition to that the depth of the uppermost appearance of some of the alteration minerals was marked on the log plot, or the intersection of the well path with the relevant layer of alteration mineral as well as some layers where the relevant mineral became more dominant.

A log plot was made with NN, gamma, 16” and 64” resistivity and the pseudo log from the 3D inversion and up scaled 16” and 64” resistivity. A similar presentation as the above was for the alteration minerals.

RESULTS AND CONCLUSIONS

Graphical presentation of the results

Figures 11-14 show examples of the results where the scale for the resistivity is logarithmic as in Figure 8, the range is 0.1-1000 Ωm and colours range from red for the low values to yellow, green and blue for the higher values. The scale has the same scale and colour scheme as for the 1D TEM/MT resistivity. The 3D resistivity model from TEM/MT was inserted into Petrel as a power of 10, therefore similar colours were selected as for 16” and 64” resistivity with linear scale and -1 (10^{-1}) as red and 3 (10^{3}) as blue and the scale is -1 to 3 and linear.

The first column from left is 16" resistivity, the second 64" resistivity, the fifth is the “pseudo log” from the 3D TEM and MT, and the third and fourth columns are 16" and 64" resistivity which have been averaged to similar resolution as the “pseudo log”. Columns 6-8 are similar to columns 3-5 except that they are for the 1D inversion of TEM/MT. The lines are where the well path cuts through the layer of the relevant alteration mineral. To give examples of temperature dependency of the alteration minerals, smectite is considered to form at ~30°C (Figure 9), epidote at 240°C, chlorite at 230°C and amphibole at ~280°C. A repetition of a mineral signifies that it has a stronger or more stable appearance.

The low resistivity layer can be seen in all of the wells both in the measured resistivity logs and the “pseudo logs” from both of the TEM/MT models, but as stated below, sometimes there is a difference in the depth of the layer, generally where the minimum values occur.

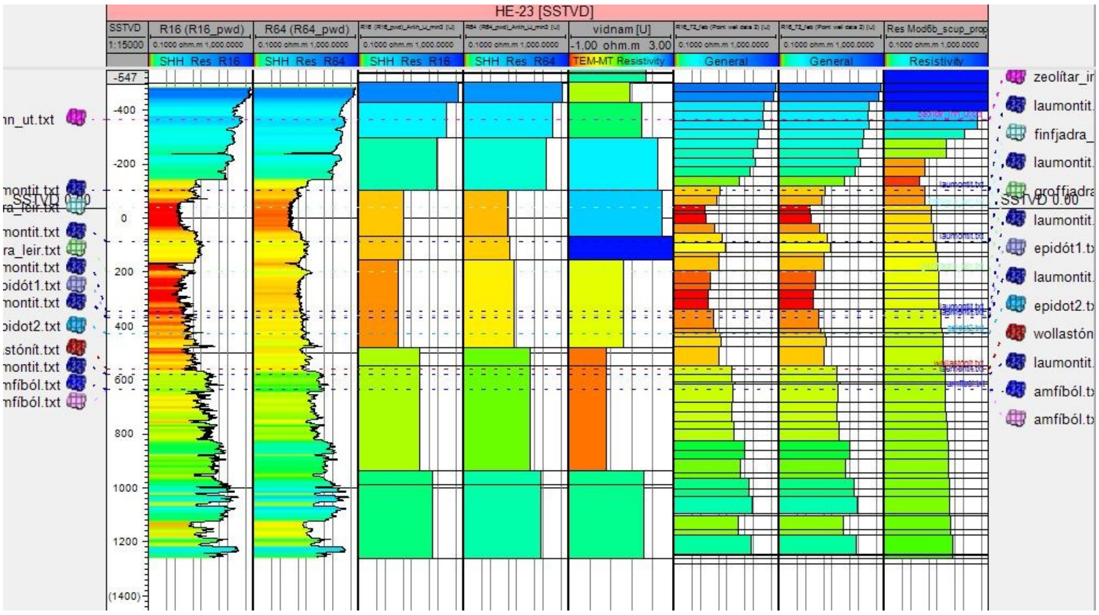

Figure 11. HE-23. Resistivity against vertical depth (m b.s.l.). 16" and 64" resistivity in col. 1-2, up scaled 16" and 64" and pseudo logs from 3D TEM/MT in col. 3-5, up scaled 16” and 64” and 1D TEM/MT in col. 6-8 (Scale in Figure 8.) Appearance of alteration minerals as horizontal lines.

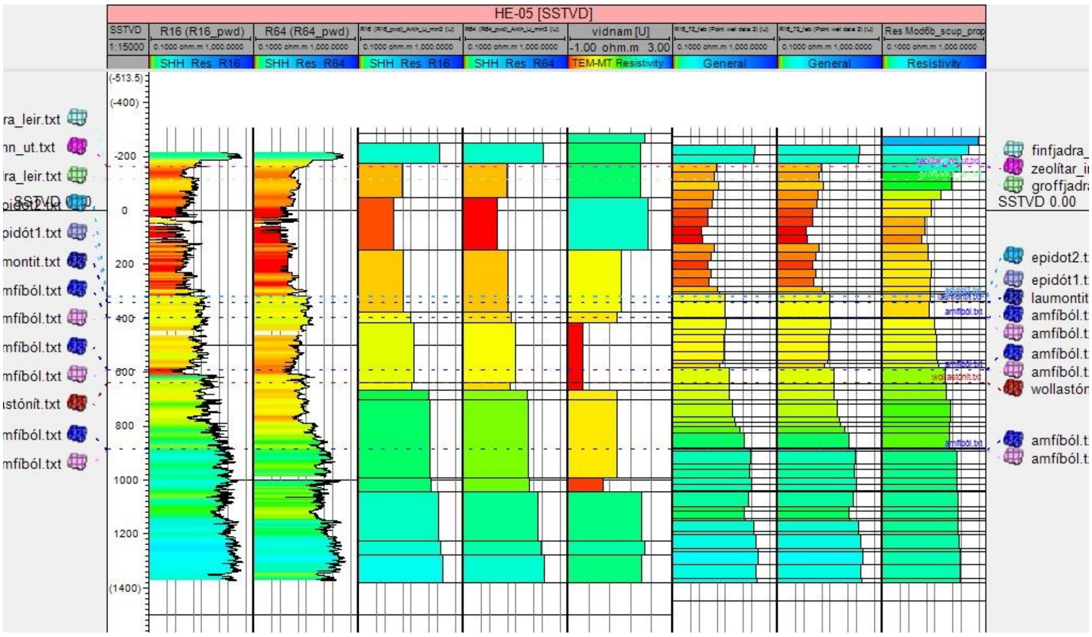

Figure 12. HE-05. Resistivity against vertical depth (m b.s.l.). 16" and 64" resistivity in col. 1-2, up scaled 16" and 64" and pseudo logs from 3D TEM/MT in col. 3-5, up scaled 16” and 64” and 1D TEM/MT in col. 6-8 (Scale in Figure 8.) Appearance of alteration minerals as horizontal lines.

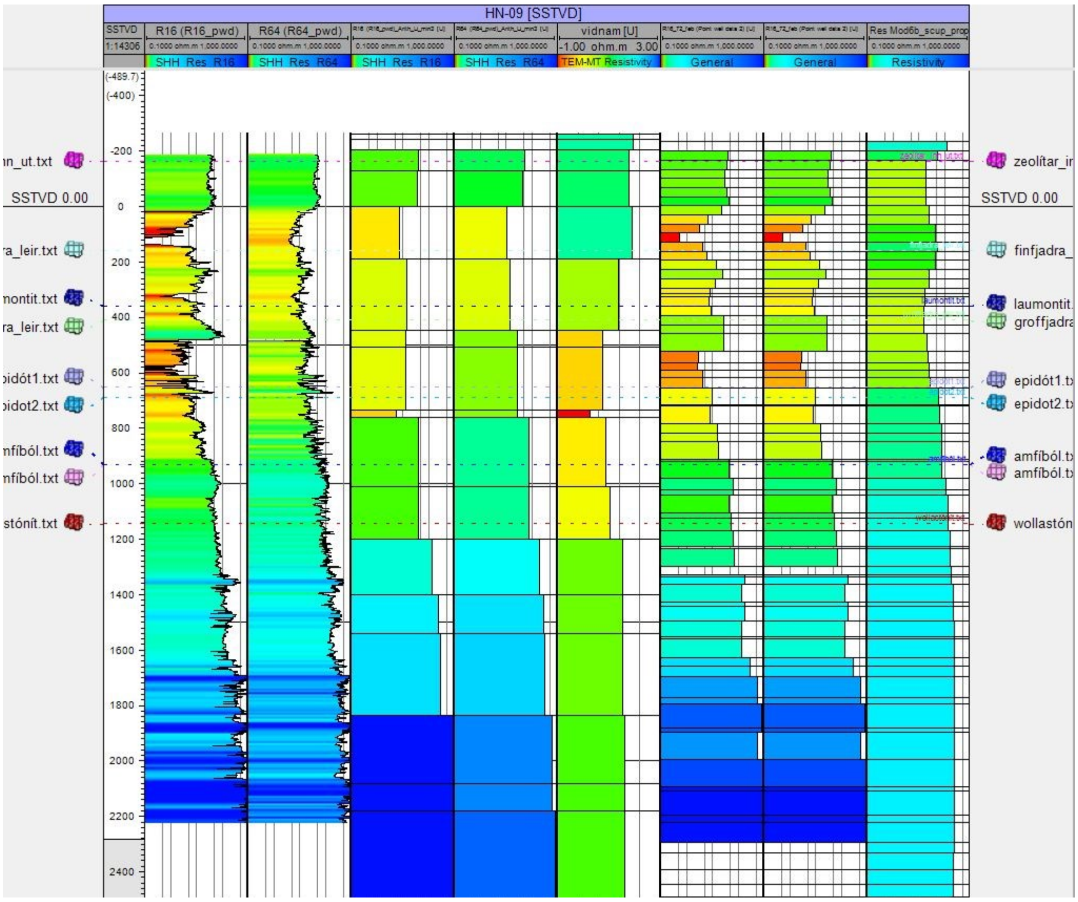

Figure 13. HN-09. Resistivity against vertical depth (m b.s.l.). 16" and 64" resistivity in col. 1-2, up scaled 16" and 64" and pseudo logs from 3D TEM/MT in col. 3-5, up scaled 16" and 64" and 1D TEM/MT in col. 6-8 (Scale in Figure 8.) Appearance of alteration minerals as horizontal lines.

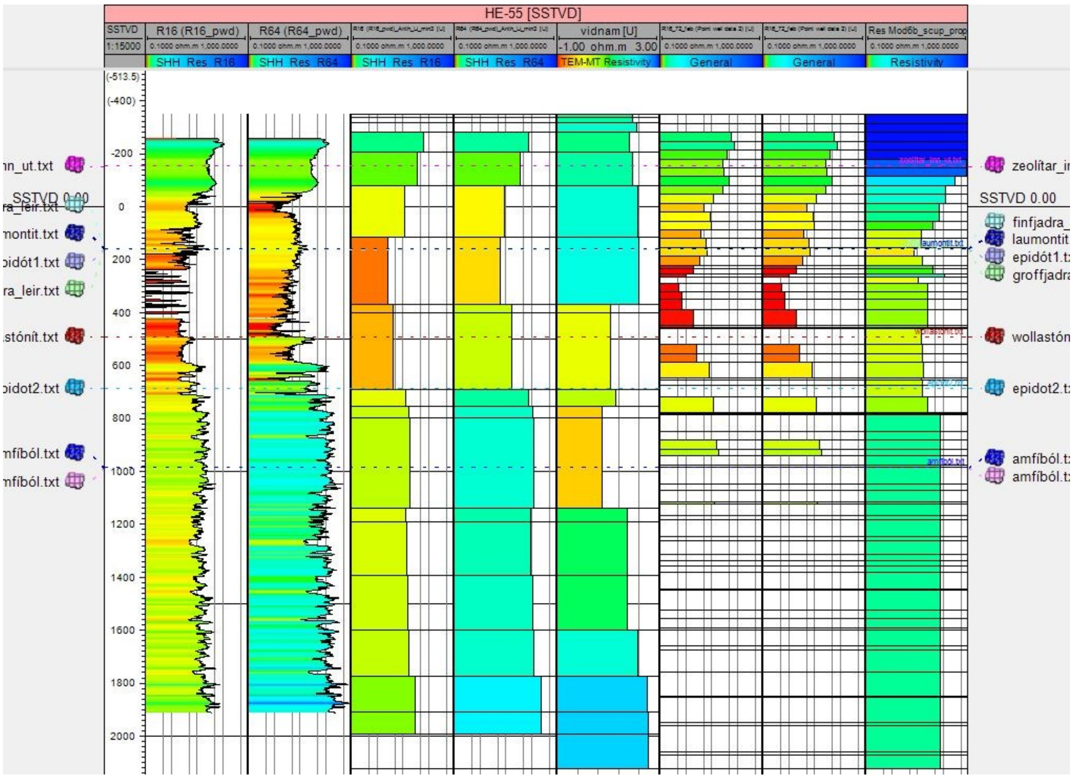

Figure 14. HE-55. Resistivity against vertical depth (m b.s.l.). 16" and 64" resistivity in col. 1-2, up scaled 16" and 64" and pseudo logs from 3D TEM/MT in col. 3-5, up scaled 16" and 64" and 1D TEM/MT in col. 6-8 (Scale in Figure 8.) Appearance of alteration minerals as horizontal lines.

Resistivity: Well logs and TEM/MT

As may be realized by looking at Figures 11-15 that there can not be any exact match between the measured resistivity well logs and the “pseudo logs” from TEM and MT, neither for the 1D inversion nor the 3D inversion. Similar resolution in depth, by up scaling or averaging the measured resistivity logs, clearly helps. The 3D resistivity model, which has lower resolution than was selected in the interpolation of the 1D resistivity, and this gives the latter the benefit of allowing the well logs to keep more resolution, show better e.g. where there are 2 low resistivity zones as in Figure becomes clear in the comparison of the logs in the Figures.

The results based on the 1D inversion have been studied thoroughly (Haraldsdóttir et al., 2012) and show a fairly good connection between the results with respect to the location of the low resistivity layer in both types of methods, and ignoring the difference in resolution gives a better view of the consistency. Often the “pseudo logs” do not show even the major variations at depth, below the low resistivity layer, as could be expected (see Figure 11). Another difference is the scale of the low resistivity, which in most cases is lower in the measured well logs than in the “pseudo logs”.

Often there seems to be a difference in the scale and depth of the low resistivity layer in the well logs and the resistivity from 1D TEM/MT, where the values at the minimum are lower in the measured well logs than the “pseudo logs”.

Significant layers are not seen when the resolution is low, neither in the “pseudo logs” from TEM/MT nor measured 16" and 64" resistivity up scaled to the coarser grid. This applies to both of the sets of similar resolution.

The following analysis is from Haraldsdóttir et al. (2012): The resistivity logs do in many wells not cover the whole well, data is lacking, partly because the first section is only logged in one well at a well pad. In the first analysis of the low resistivity layer, too much data was lacking in 15 wells to be able to tell with certainty if the main low resistivity layer was seen and the comparison for these wells could not be performed.

The uppermost part of a well is vertical and the wells on the same well pad are located close to each other, so the uppermost part has been considered as valid for the wells on the same well pad where data has been missing. By regarding the data from the uppermost part in a well at the same well pad to be valid for the one where data was missing only 2 wells lacked too much data to be included in the comparison. With the above conditions a rough estimation of the low resistivity layer (LR) in the well logs from 72 boreholes and in the “pseudo logs” from TEM and MT shows:

- In 26 wells the “pseudo logs” show LR higher up in the strata than the well-logs
- In 31 wells LR appears at approximately at the same depth in both types of data
- In 7 wells LR appears lower in the “pseudo logs” from TEM/MT than in the well logs
- In 6 wells where there are two measured LR zones in the well logs, the LR in the “pseudo logs” from TEM/MT lies between them
- In 2 wells it was not possible to analyse due to insufficient data

The 3D inversion model shows the low resistivity layer generally lower than the 1D model and lower than the low resistivity in the well logs. Even lower than the one father down in the well in case of two low resistivity layers (Figures 11-15)..

Resistivity well logs and alteration minerals

Resistivity in wells and alteration minerals show a clear correlation:

- There is high resistivity in fresh rock formations
- The resistivity generally lowers at the upper limit of zeolites and/or where there are indications of clay in voids
- The resistivity often starts to increase at the upper limit of epidote
- Epidote and chlorite often appear at similar depths

In Figure 15 an example of a combined neutron-neutron log (NN), gamma log (G), and the 16” and 64” resistivity logs as well as the up scaled 16” and 64” resistivity to the same resolution as the “pseudo log” from the 3D inversion and finally the alteration minerals shown as horizontal lines. The first four columns are examples of the available and already depth corrected data where the logs from individual sections of the well have been combined to one log for each type. There is a clear correlation between NN and the 16” and 64” resistivity logs. When these signals are higher than in the surrounding layers it means often lower porosity, with less water, e.g. at 400 to approximately 950 m depth, where fairly similar patterns are seen in these logs. At 1400 m the correlation is clear, increasing in all of the above mentioned well logs as well as in the gamma log, indicating an intrusion or a lava layer with more silica than the basaltic rock above and below and higher NN and resistivity which means less porous rock than above and below.
Some of the well logs have been used to depth correct geological sections found from drill cuttings as well as conformed the analysis or indicated that a further study should be done to find the correct geological model.

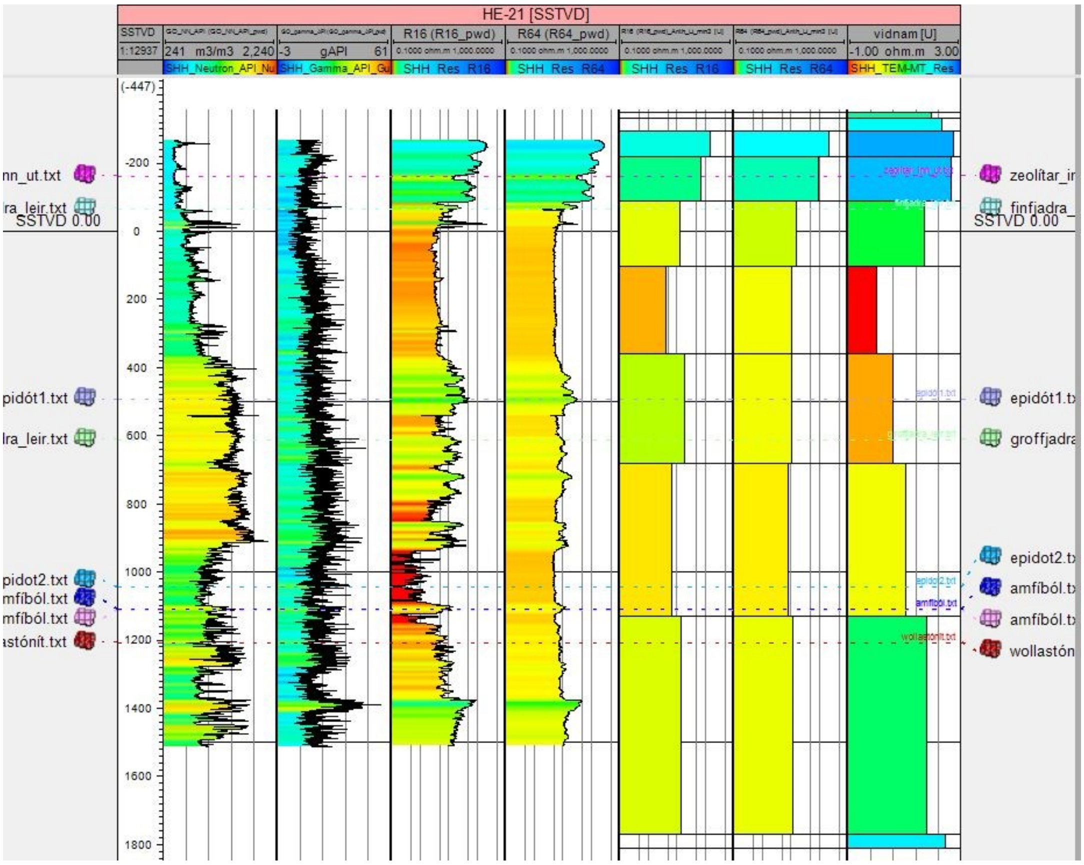

Figure 15. HE-55. Neutron-neutron, natural gamma and 16” and 64” resistivity against vertical depth (m b.s.l.) in col. 1-4, up scaled 16" and 64" and pseudo logs from 3D TEM/MT in col. 5-7. (Scale in Figure 8.) Appearance of alteration minerals as horizontal lines.

FURTHER STUDIES

Measured resistivity and alteration

The relation between increasing resistivity and clay alteration zones needs to be investigated i.e. how gradual or sudden the transformation of smectite to mixed layer to chlorite is in connection with resistivity changes.

It is important to investigate more samples e.g. with XRD-research and the correlation between resistivity and dehydration of alteration minerals.

Resistivity logs and pseudo logs from TEM/MT, neutron-neutron and gamma logs

The resistivity in the 3D inversion model deduced from TEM/MT has not been compared as thoroughly to the well logs as the 1D model. The few examples in the study indicate that it could be worth while to compare the different TEM/MT models as “pseudo logs” projected on the well paths, in addition to comparing to the in-situ measurements with the resistivity well logs. Such studies should help to improve the ideas and the software to make such models.

The neutron-neutron and gamma logs have been prepared as depth corrected logs combined into one log of each kind for each well. They have only been partly used for comparison and combined studies of geological section from drill cuttings. An interesting project would be to analyse all the dataset at S–Hengill for combined interpretation and compare to the model of the geology of the area which can be confirmed or adjusted to the results of further analysis. Possibly some of the parameters for reservoir modelling could be reviewed as well.

In the future a combined study of well logs is recommended such as resistivity, NN, gamma, sonic-logs, video-logs of geological structure, intrusions, alteration minerals with extended XRD-analysis as well as the temperature, feed points, pressure and to use the already available 3D inversion method to estimate the resistivity from the TEM and MT data. This would be of great value and increase the confidence in the knowledge of the geothermal system at the S-Hengill area.

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REFERENCES

Árnason, K., Eysteinsson, H. and Hersir, G.P.: Joint 1D inversion of TEM and MT data and 3D inversion of MT data in the Hengill area SW Iceland, *Geothermics,* **39**, (2010), 13-34.

Árnason, K., Karlsdóttir, R., Eysteinsson, H., Flóvenz, Ó.G., Gudlaugsson, S.Th.: The resistivity structure of high-temperature geothermal systems in Iceland, *Proceedings of the World Geothermal Congress 2000*, Kyushu-Tohoku, Japan, (2000), 923-928.

Árnason, K., Haraldsson, G.I, Johnsen, G.V., Thorbergsson, G., Hersir, G.P., Sæmundsson, K., Georgsson, L.S., Rögnvaldsson, S.Th. and Snorrason, S.P.: Nesjavellir –Ölkelduháls. Surface exploration in 1986, *Orkustofnun*, Report nr. OS-87018/JHD-02, A report in Icelandic, Reykjavík, Iceland, (1987), 112 pp.

Árnason, K. and Magnússon, I.Th.: Geothermal activity at Hengill and Hellisheiði. Results of electromagnetic soundings, *Orkustofnun*, Report nr. OS-2001/091, A report in Icelandic, Reykjavík, Iceland, (2001), 250 pp.

Böðvarsson, G. "*A report about geothermal research at Hengill, Hveragerdi and surroundings, during the years 1947-1949. – First part*", The journal of The engineer society of Iceland, 3-4 volume, A report in Icelandic, Reykjavík, Iceland, (1951), 1-48.

Deer, W.A., Howie, R.A., Zussman, J. *Rock-Forming Minerals, Vol. 3*, Sheet silicates. Longmans, Green and Co. Ltd., London, UK, (1962), 270 pp. (Cited by Árnason et al., 2010.)

Einarsson, T. Sigurgeirsson, Th., Tryggvason, T., Rist, s., Líndal, B. and Schwabe, H.: A report about geothermal research at Hengill, Hveragerdi and surroundings, during the years 1947-1949. – Second part, *The journal of The engineer society of Iceland*, 3-4 volume, A report in Icelandic, Reykjavík, Iceland, (1951), 49-82.

Franzson, H.: Nesjavellir. Details about alteration in a geothermal system, *Orkustofnun*, Report nr. OS-94021/JHD-06, A report in Icelandic, Reykjavík, Iceland, (1994), 34 pp.

Franzson, H.: Hydrothermal Evolution of the Nesjavellir High-temperature System, Iceland, *Proceedings of the World Geothermal Congress 2000*, Kyushu-Tohoku, Japan, (2000), 2075-2080.

Fanzson, H., Kristjánsson, B.R., Gunnarsson, G., Björnsson, G., Hjartarson, A., Steingrímsson, B., Gunnlaugsson, E. and Gíslason, G.: The Hengill-Hellisheidi Geothermal Field. Development of a Conceptual Geothermal Model, *Proceedings World Geothermal Congress 2005*, Antalya, Turkey, (2005), 7 pp, Electronic version.

Franzson, H., Árnason, K., Sæmundsson, K. and Gunnlaugsson E.: The Hengill geothermal system, *Proceedings of the World Geothermal Congress 2010*, Bali, (2010), 9 pp, Electronic version.

Gunnarsdóttir, S.H: Geology and alteration in the vicinity of Reykjavell, Hellisheidi. *University of Iceland*, MSc thesis in Icelandic, (2012), 199 pp.

Haraldsdóttir, S.H., Franzson, H., Árnason, K., Einarsson, G.M. and Björnsson, H.: Comparison of Down-Hole and Surface Resistivity Data from the Hellisheidi Geothermal Field, SW-Iceland, *Proceedings of the World Geothermal Congress 2010,* Bali, (2010), 12 p, Electronic version.

Helgadóttir, H.M. (2011), "*The Gráuhnúkar geothermal system, Hellisheiði, SW-Iceland: Bedrock and hydrothermal alteration*", The Department of Geosciences, University of Iceland, MSc thesis in Icelandic, Reykjavík, Iceland, 185 pp.

Helgadóttir, H.M., Snæbjörnsdóttir, S.Ó., Níelsson, S. Gunnarsdóttir, S.H., Matthíasdóttir, T., Hardarson, B., Einarsson G.M., and Franzson, H.: Geology and Hydrothermal Alteration in the Reservoir of the Hellisheidi High Temperature System, SW-Iceland", *Proceedings of the World Geothermal Congress 2010*, Bali, (2010), 10 pp, Electronic version.

Hersir, G.P., Björnsson, G., Björnsson, A.: Volcanos and geothermal activity at the Hengill area: geophysical exploration, *Orkustofnun*, Report nr. OS-90031/JHD-06, A report in Icelandic, Reykjavík, Iceland, (1990), 93 pp.

Kristmannsdóttir, H.: Types of clay minerals in hydrothermally altered basaltic rocks, Reykjanes, Iceland, *Jökull*, (1977).

Nielsson, S.: Geology and alteration at the geothermal system at Hverahlíð, Hellisheiði, *The Department of Geosciences, University of Iceland*, MSc thesis in Icelandic, Reykjavík, Iceland, (2011), 208 pp.

Nielsson, S. and Franzson, H.: Geology and Hydrothermal alteration of the Hverahlid HT-system, SW-Iceland, *Proceedings of the World Geothermal Congress 2010*, Bali, (2010), 6 pp, Electronic version.

Schlumberger (2008). Petrel Introduction Course, 555 pp.

Serra, O.: *Fundamentals of well-log interpretation. 1. the acquisition of logging data*, Elsevier science Publishers *B.V*., (1984), 423 pp.

Snæbjörnsdóttir, S.Ó.: Geology and geothermal alteration at the western part of the Hengill graben, *The Department of Geosciences, University of Iceland*, MSc thesis in Icelandic, A report in Icelandic, Reykjavík, Iceland, (2011), 241 pp.

Stefánsson, V., and Steingrímsson, B.S.: Geothermal logging I, an introduction to techniques and interpretation, 3rd edition. *Orkustofnun*, Report nr. OS-80017/JHD-09, A report in Icelandic, Reykjavík, Iceland, (1990), 117 pp.

Sæmundsson, K.: A geological map of the Hengill area (bed rock) 1:50000, *Orkustofnun, Hitaveita Reykjavíkur og Landmælingar Íslands*, An Icelandic map, Reykjavík, Iceland, (1994).