PROCEEDINGS, Thirty-Seventh Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 30 - February 1, 2012
SGP-TR-194

PRELIMINARY STUDY OF DOWN-HOLE RESISTIVITY FROM 72 BOREHOLES IN THE S-HENGILL GEOTHERMAL FIELD, SW-ICELAND, WITH RESPECT TO SURFACE RESISTIVITY DATA AND ALTERATION MINERALS

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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) are compared. The resistivity is also compared with the uppermost appearance of alteration minerals with special emphasis on clay minerals. The available resistivity logs from each section of drilling are combined for each well and inserted into Petrel, a 3D visualization software, for geological and geophysical data. A 3D model of resistivity was also made in Petrel based on 1D resistivity found previously from TEM and MT data by doing a joint inversion. The resistivity well logs are averaged to the same resolution as the TEM and MT data. Previous TEM and MT resistivity models show high-resistivity formations underlain by low-resistivity ones below which resistivity increases again. This variation was interpreted as being due to the different conductivity of alteration mineral assemblages. Low resistivity was linked with zeolites and smectite and higher resistivity with chlorite deeper down in the wells. The comparison between the resistivity from the surface TEM and MT soundings and the resistivity logs shows a good match in many of the wells. 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.

INTRODUCTION

The purpose 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 three data sources are combined, i.e. two types of resistivity surveys done in the Hengill reservoir and their relation to changes in hydrothermal alteration.

Figure 1 shows the location of the central volcano and geothermal complex of Hengill, in SW-Iceland. Hengill is located in the Reykjanes-Langjökull volcanic rift zone.

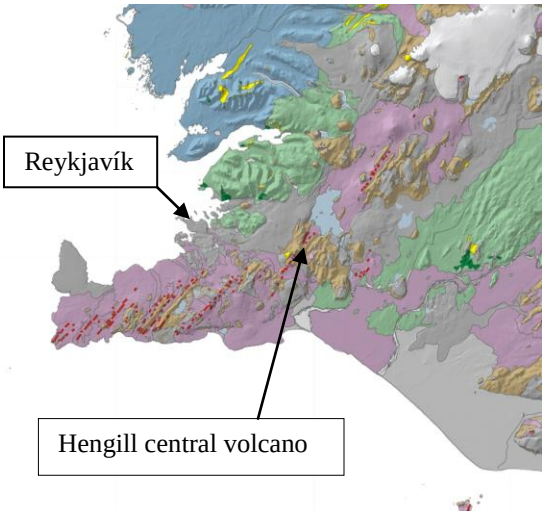

Figure 1. Geological map of SW-Iceland and location of Hengill central volcano and the Reykjavík capital.

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.

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 ranges from around 1000 to 3300 m.

This paper first describes the relevant earlier studies in the Hengill area followed by the methodology of data preparation and lastly the results and conclusions are presented.

PREVIOUS STUDIES OF THE S-HENGILL AREA

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 investigations in the Hengill area with respect to geothermal activities were made during the years 1947-1949 (Einarsson et al., 1951, Böðvarsson, 1951). Sæmundsson (1994) mapped the surface geology and tectonic features 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. Lastly, a comparison between TEM/MT, borehole resistivity and alteration was done in nine wells as a prelude to this study (Haraldsdóttir et al., 2010).

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.

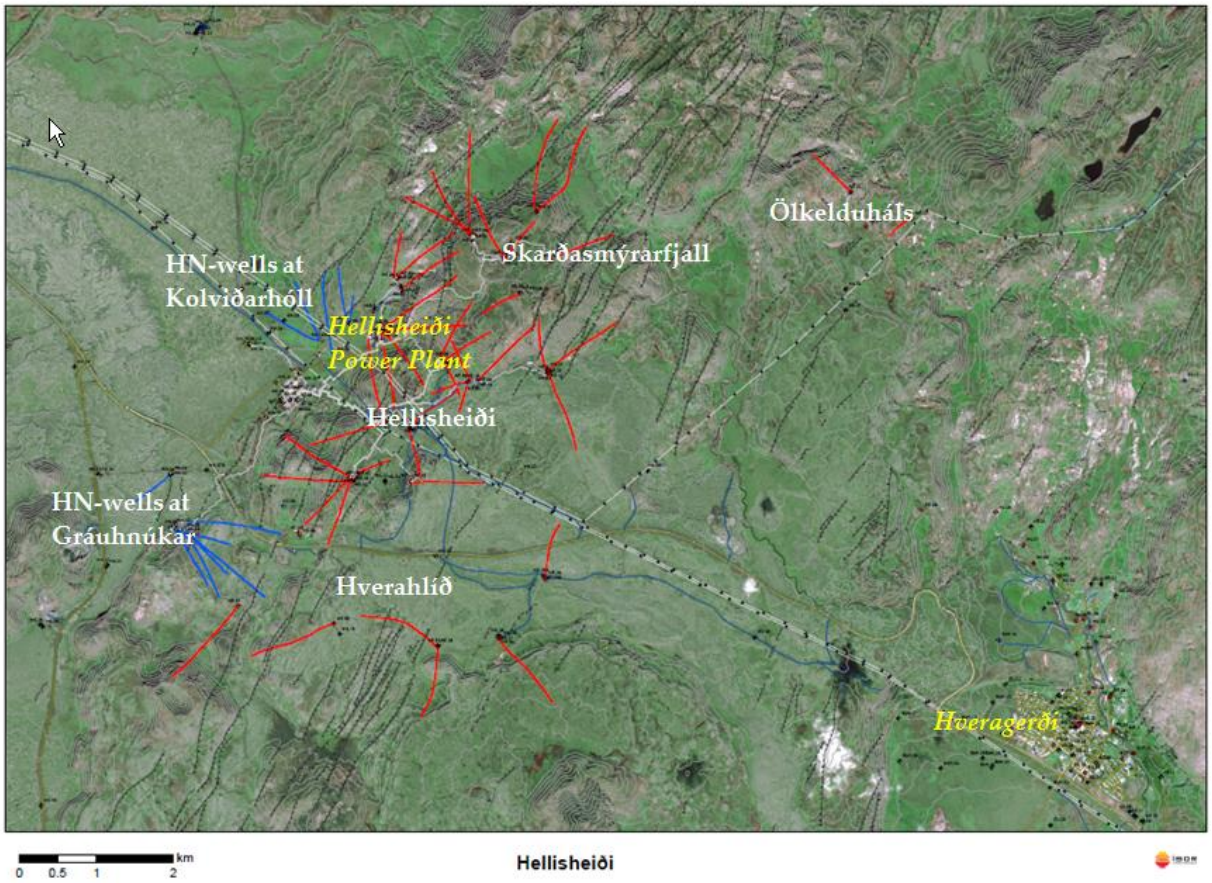

Figure 2. South-Hengill. Boreholes are projected on the surface, red: research and production wells, blue: reinjection wells. Note that the lines indicate directional wells, while vertical wells appear only as a dot.

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.

Alteration

Figure 3 shows schematically the relation between zones of hydrothermal alteration, rock alteration and temperature (Franzson, 1994).

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

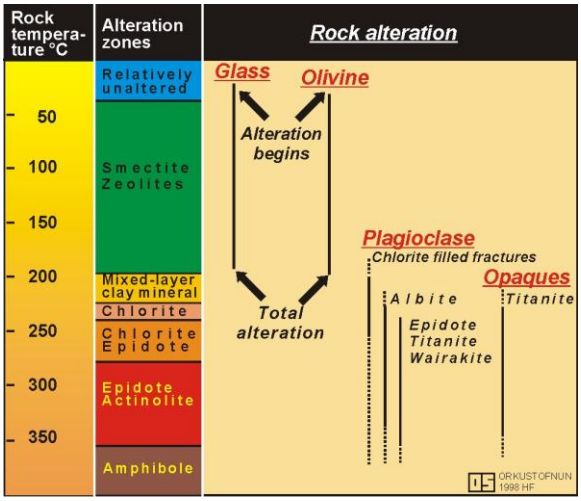

Figure 3. Zones of alteration and the corresponding rock alteration (Franzson, 1994).

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.

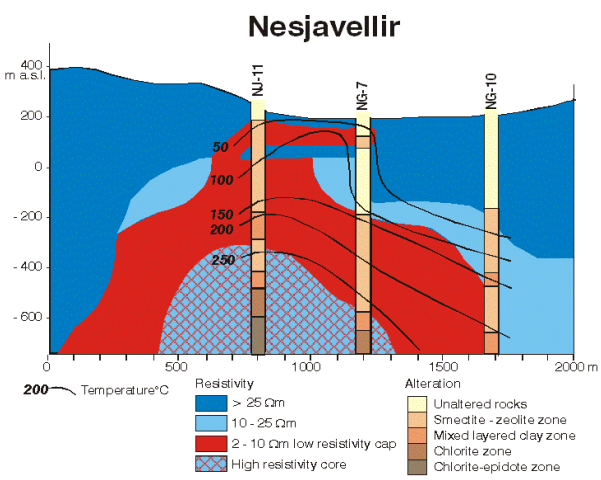

Figure 4. The relation between resistivity, temperature and alteration (Árnason et al., 1987).

The changes in resistivity were explained by different conduction of alteration minerals. These results were confirmed and reviewed in a recent paper about 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.
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 tinner 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).

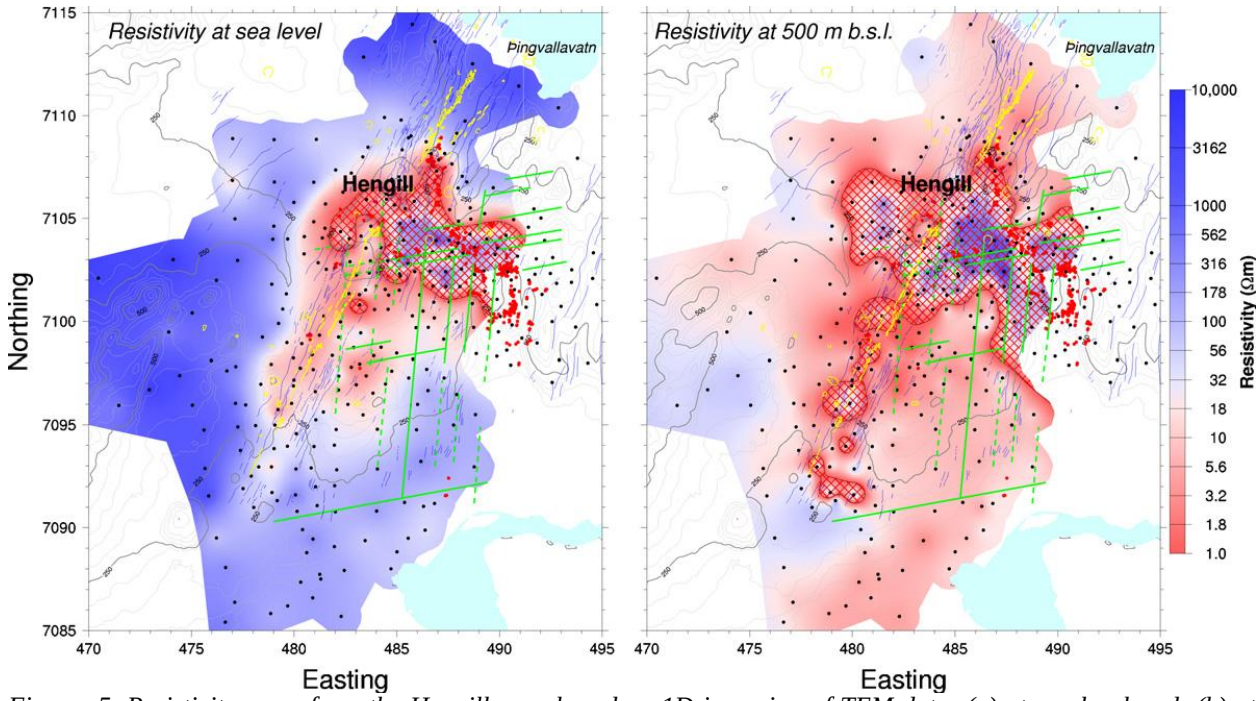

Figure 5. Resistivity maps from the Hengill area based on 1D inversion of TEM data: (a) at sea level and (b) at 500m b.s.l. Geothermal activity at the surface is shown as red dots, faults and fractures mapped on the surface are shown in blue, faults inferred from seismicity are shown in green and volcanic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

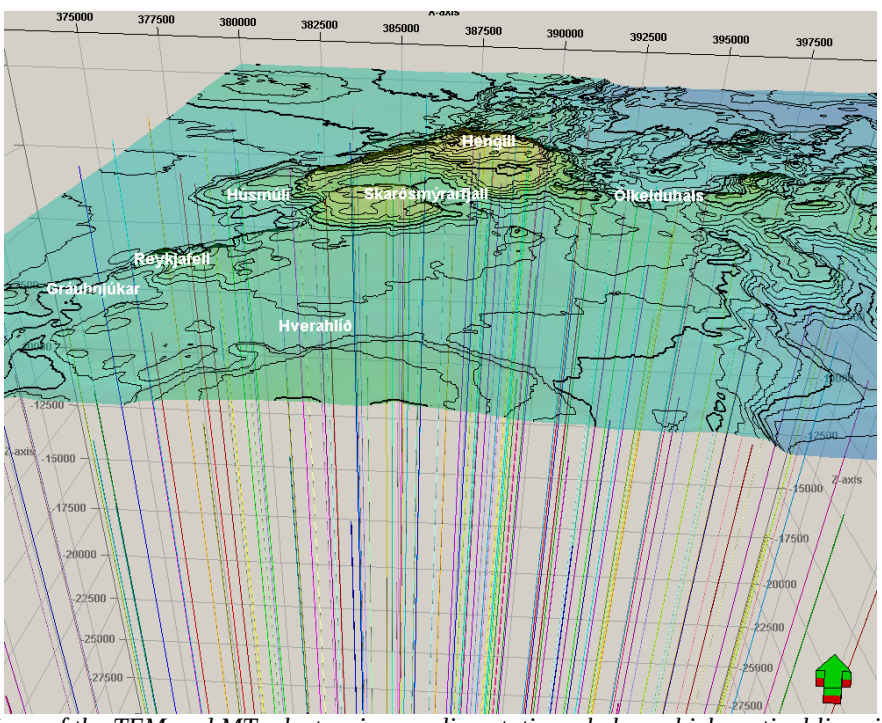

Figure 6: Locations of the TEM and MT electronic sounding stations, below which vertical lines indicate locations for 1D interpretations. The north arrow is at bottom right.

The borehole design

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

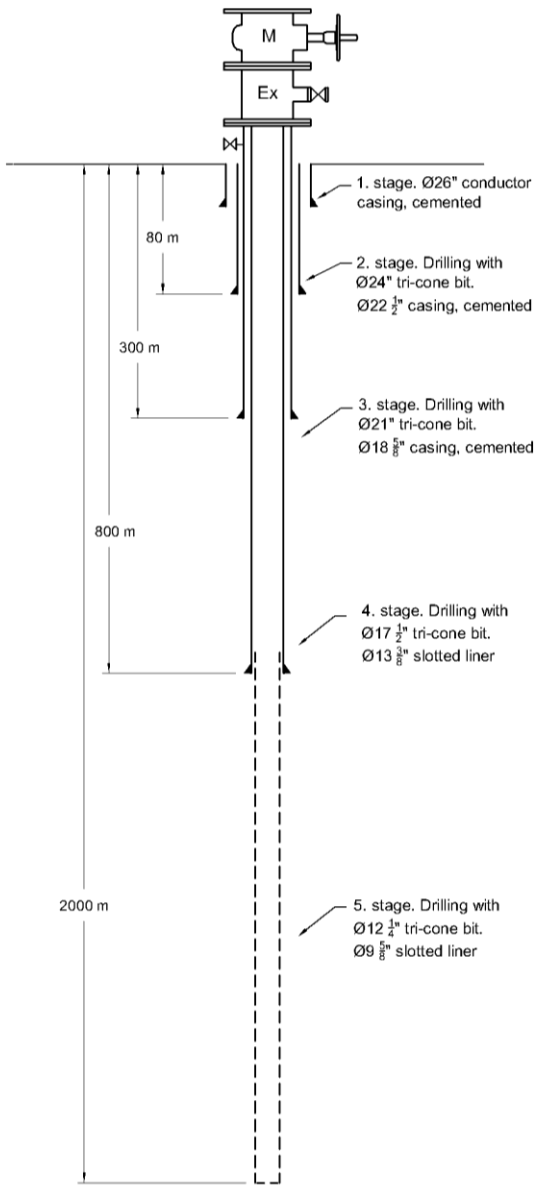

Figure 7. A typical design of a large, vertical well.

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 wallrock 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 blue colour indicates low resistivity which increases in green, yellow and the red 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.

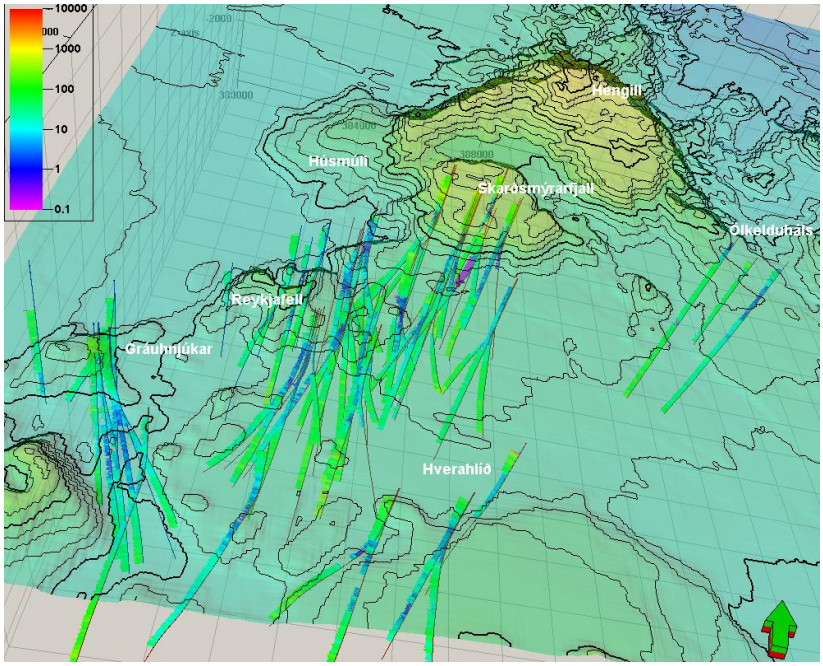

Figure 8. Boreholes south of Hengill with measured 16" resistivity. The resistivity scale (Ωm) is logarithmic and shown in the upper left corner.

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).

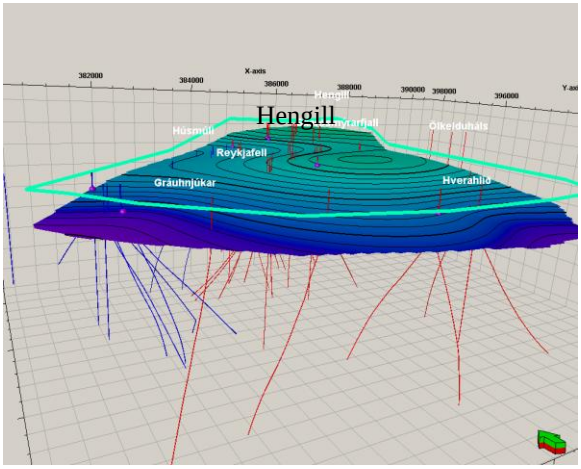

Figure 9: A depth contoured map of S-Hengill showing the upper boundary of smectite based on borehole data. North arrow at bottom right.

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).

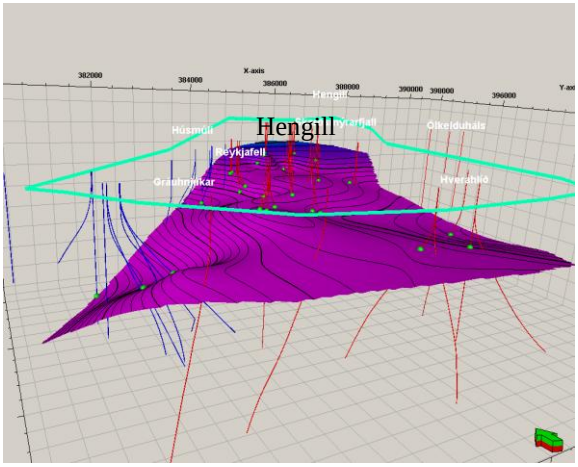

Figure 10. A depth contoured map of S-Hengill showing the upper boundary of chlorite based on borehole data. North arrow at bottom right.

The measured depth to the uppermost appearance of the relevant mineral where 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 inserted as MD and value and linked to the well paths.

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 and MT.

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

1b) 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.

The measured 16" and 64" resistivity well logs and the "pseudo logs" 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.

RESULTS AND CONCLUSIONS

Graphical presentation of the results

Figures 11-15 show examples of the results where the scale for the resistivity is logarithmic as in Figure 8, the range is 0.1-10000 Ωm and colours range from bluish for the low values to green, yellow and red for the higher values. The scale was suggested in Petrel, but this is opposite to the colour scheme for the TEM and MT resistivity in Figure 3.

The first column from left is 16" resistivity, the second 64" resistivity, the fifth is the "pseudo log" from 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. 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.

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

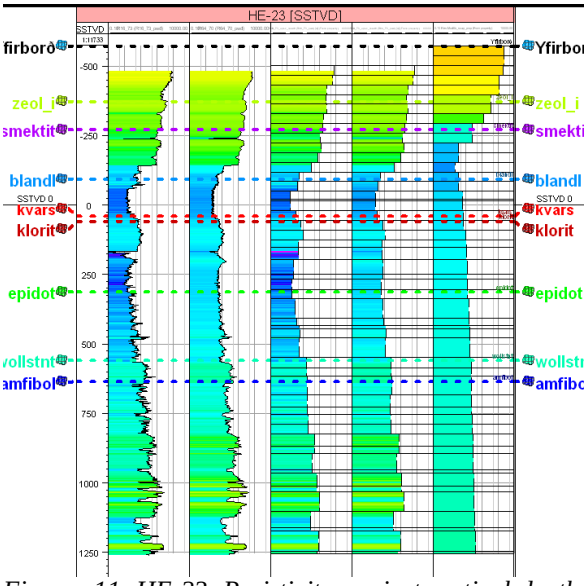

Figure 11. HE-23. Resistivity against vertical depth (m b.s.l.). 16" and 64" resistivity in col. 1-2, up scaled 16" and 64" in col. 3-4 and "pseudo logs" from TEM and MT in col. 5. (Scale in Figure 11.)

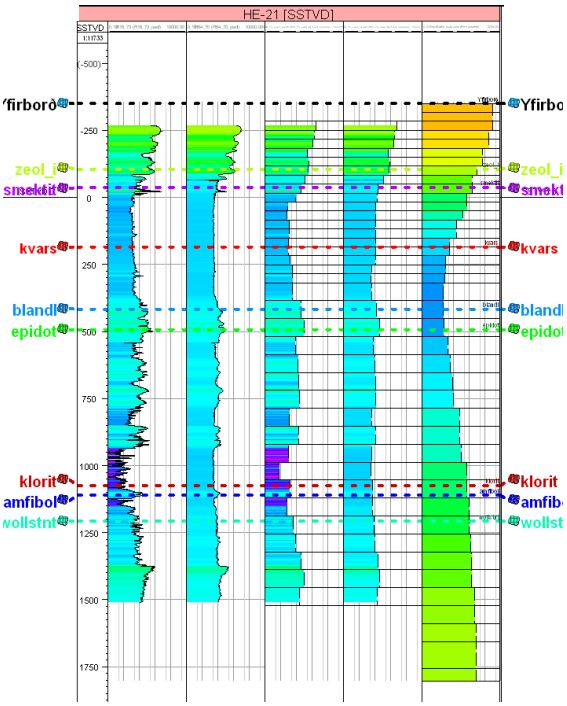

Figure 12. HE-21. Resistivity against vertical depth (m b.s.l.). 16" and 64" resistivity in col. 1-2, up scaled 16" and 64" in col. 3-4 and "pseudo logs" from TEM and MT in col. 5. (Scale in Figure 8).

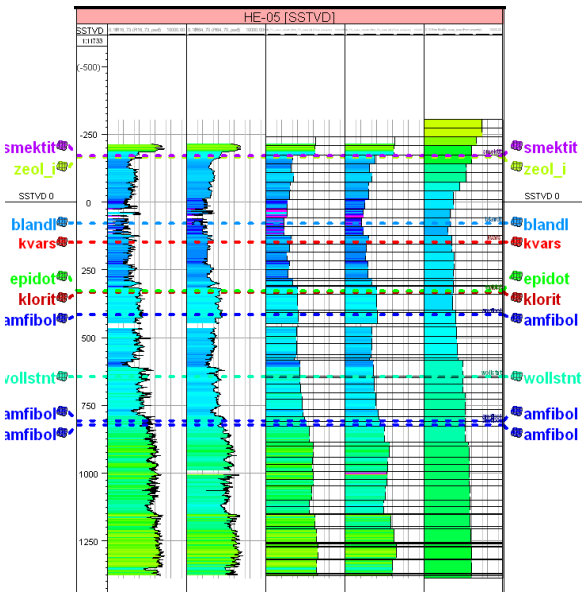

Figure 13. HE-05. Resistivity against vertical depth (m b.s.l.). 16" and 64" resistivity in col. 1-2, up scaled 16" and 64" in col. 3-4 and "pseudo logs" from TEM and MT in col. 5. (Scale in Figure 8.)

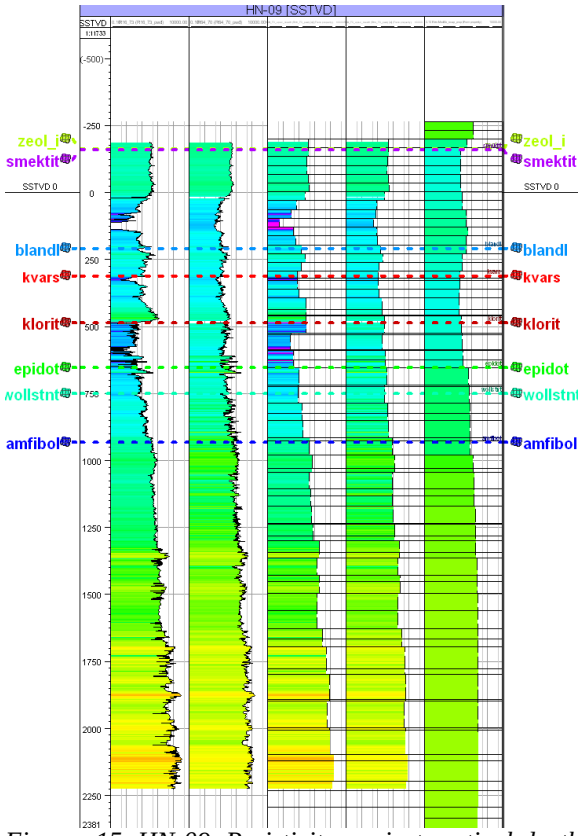

Figure 15. HN-09. Resistivity against vertical depth (m b.s.l.). 16" and 64" resistivity in col. 1-2, up scaled 16" and 64" in col. 3-4 and "pseudo logs" from TEM and MT in col. 5. (Scale in Figure 8.)

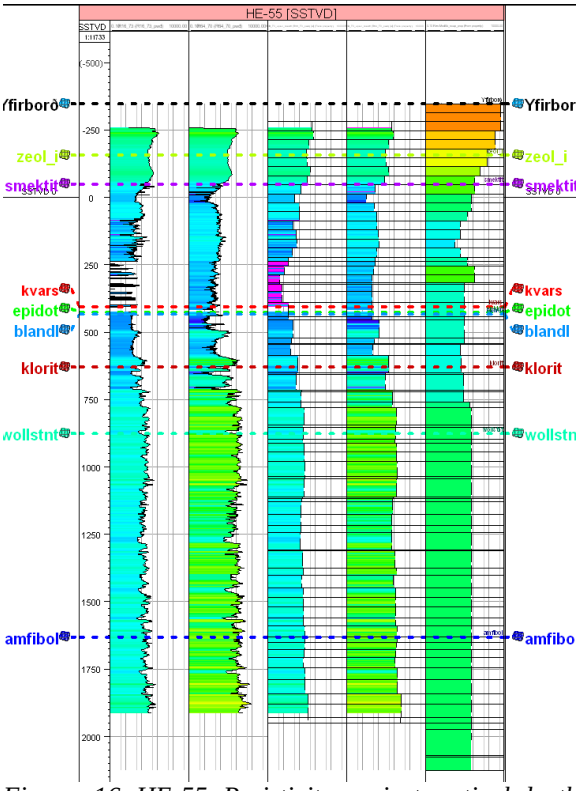

Figure 16. HE-55. Resistivity against vertical depth (m b.s.l.). 16" and 64" resistivity in col. 1-2, up scaled 16" and 64" in col. 3-4 and "pseudo logs" from TEM and MT in col. 5. (Scale in Figure 8.)

Resistivity: Well logs and TEM/MT

As may be realized by looking at the pictures there can not be any exact match between the measured resistivity well logs and the "pseudo logs" from TEM and MT which are in the last column. Similar resolution in depth, by averaging the measured resistivity logs, clearly helps.

The results 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 much 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 TEM and MT, where the values at the minimum are much 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 and MT nor measured 16" and 64" resistivity averaged to the coarser grid.

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 analyze due to insufficient data

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

FURTHER STUDIES ON RESISTIVITY

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, well logs and TEM and MT

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.

ACKNOWLEDGEMENTS

Reykjavík Energy (Orkuveitan) supported the project. We are also grateful to Gudni Axelsson for his comments and assistance. The project is based on work of many colleagues at Iceland Geosurvey, e.g. well logging, corrections of data and preparing the data on alteration minerals in Petrel.

REFERENCES

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

Árnason, K., Karlsdóttir, R., Eysteinsson, H., Flóvenz, Ó.G., Gudlaugsson, S.Th. (2000), "The resistivity structure of high-temperature geothermal systems in Iceland", *Proceedings of the World Geothermal Congress 2000*, Kyushu-Tohoku, Japan, 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. (1987), "Nesjavellir – Ölkelduháls. Surface exploration in 1986", Orkustofnun, Report nr. OS-87018/JHD-02, A report in Icelandic, Reykjavík, Iceland, 112 pp.

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

Böðvarsson, G. (1951), "*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, 1-48.

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

Einarsson, T. Sigurgeirsson, Th., Tryggvason, T., Rist, s., Líndal, B. and Schwabe, H. (1951), "*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, 49-82.

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

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

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

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

Gunnarsdóttir, S.H, (in preparation 2012), MSc thesis in preparation from the University of Iceland.

Haraldsdóttir, S.H., Franzson, H., Árnason, K., Einarsson, G.M. and Björnsson, H. (2010), "Comparison of Down-Hole and Surface Resistivity Data from the Hellisheidi Geothermal Field, SW-Iceland", *Proceedings of the World Geothermal Congress 2010,* Bali, 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. (2010), "Geology and Hydrothermal Alteration in the Reservoir of the Hellisheidi High Temperature System, SW-Iceland", *Proceedings of the World Geothermal Congress 2010*, Bali, 10 pp, Electronic version.

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

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

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

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

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

Snæbjörnsdóttir, S.Ó. (2011). "*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, 241 pp.

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

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