*Proceedings World Geothermal Congress 2000*
*Kyushu - Tohoku, Japan, May 28 - June 10, 2000*

# TEM-RESISTIVITY IMAGE OF A GEOTHERMAL FIELD IN N-ICELAND AND THE RELATION OF THE RESISTIVITY WITH LITHOLOGY AND TEMPERATURE

Olafur G. Flovenz and Ragna Karlsdottir
Orkustofnun, Grensasvegi 9, 108 Reykjavík, Iceland

**Keywords:** Resistivity, lithology, temperature

## ABSTRACT

In Eyjafjordur in N-Iceland several small hot springs were found. Drilling at the various hot springs has shown that the geothermal activity is mainly connected to fractures in the basaltic pile of very low permeability but there are also indications of some near horizontal flow. TEM resistivity soundings have been used to create a resistivity image of the basaltic pile in the area to improve the older resistivity picture obtained by Schlumberger soundings. The TEM soundings were initially inverted to give a layered resistivity model without considering any other geological knowledge. This was done to avoid biasing during interpretation. The result shows several layers of high and low resistivity with southerly dip. This pattern was not resolved in the previous Schlumberger soundings. An additional local low-resistivity zone is observed. Comparison of the TEM result with borehole- and surface data shows that the resistivity layering coincides with the lithological layering. The low resistivity layers coincide with series of 20-30m thick phorphyritic tholeiitic lavas interbedded with several metres thick sedimentary layers and also with series of thick olivine tholeiitic lava. The higher resistivity coincides with series of compound basaltic lavas. The low resistivity anomaly coincides with a temperature anomaly which is interpreted as the main upflow zone of the geothermal activity. After the interpretation in terms of lithology, the borehole data were used to fix the thickness of each lithological unit to give more exact information on the resistivity of that individual layer. Since the layers dip aproximately 6° dip, each resistivity layer descends progressively towards south and the temperature therefore increases. Correlation between the resistivity and the temperature is in agreement with relations between these parameters proposed by Flovenz et al. 1985. Feedzones in boreholes and geohydrological observations show that the series of the thick phorphyritic tholeiites have higher permeability than the surrounding lava pile. In the boreholes the hot water feed zones tend to be within this formations and cold springs are observed where the same formation emerges in the nearby mountain sides. A model, where the local resistivity anomaly denotes the main upflow zone, is proposed. The geothermal fluid migrates laterally away from the upflow zone along thick tholeiitic layers, from where it ascends to the surface in hot springs along some of the numerous dykes and faults in the area and their intersection.

## INTRODUCTION

Eyjafjordur is a 40 km long fjord in central north Iceland surrounded by 600 - 1200 m high mountains. The town of Akureyri with its 15000 inhabitants is located at the bottom of the fjord. In addition there are several fishing villages with 300 - 1500 inhabitants. Figure 1 shows a simplified geology of the area. The geological formation of the area consists of 6-9 m.y. classical tertiary flood basalts embedded with thin sequences of sediments and few layers of acidic rocks associated with extinct volcanic centres. The main basaltic lava units are: a) 20-30m thick tholeiitic lavas, sometimes interbedded with few metres of scoria and inter-eruptional sediments, b) compound lavas, c) olivine tholeiites and d) phorphyric basalts. To the north of Akureyri, the lava pile is generally dipping 3-6° towards south but an eastward component of the dip increases slightly southwards. The strike is almost 90° north of Akureyri but turns to 55° a few km south of the town (Bjornsson and Saemundsson, 1975).

The uppermost 1-2 km of the original lavas have been removed by glacial erosion. The alteration of the lava increases progressively with depth (figure 1). The alteration zones are almost horizontal in the area. The top of the mesolite/scolesite alteration-zone is at 200-300m elevation (Bjornsson and Saemundsson, 1975) while the top of the laumontite- zone is at approximately 500m depth below sea level, and the top of the epidote zone is at 2200m depth below sea level (Palmason et al, 1978). Thus the primary porosity and the permeability of the lava is quite low. The temperature gradient in the area is also low outside geothermal fields, ranging between 40 - 60 °C/km. In spite of low temperature gradient and permeability, hot springs are found at many places in Eyjafjordur (figure 1). These are believed to be partly associated with recent fracturing of the formation caused by the highly seismic active Tjörnes fracture north of Eyjafjordur and probably partly by glacial rebound (Bodvarsson 1982). The geothermal fields are low temperature geothermal fields with reservoir temperatures in the range of 50 - 100 °C. Many of them are exploited for househeating and at the present all, except one small village in Eyjafjordur, are heated with geothermal water. The Akureyri District Heating and Water Works is by far the largest utility in the area, providing a population of 16000 people in Akureyri and its vicinity with hot water for space heating as well as drinking water. (Olafur G. Flovenz et al., 1995). The hot water comes from five small geothermal fields within 15 km from the town while the majority of the cold water comes from springs associated with near horizontal boundary in the lava pile in a mountainside close to Akureyri.

The crust in Eyjafjordur is intersected by many near vertical dykes and normal faults. The dykes tend to be in swarms which were most likely formed as vertical intrusions, laterally intruded into the crust from a magma chamber during rifting periods. The dykes are usually normal to the layering. Figure 1 shows a rose diagram of the faults and dykes that have been mapped by ground magnetic surveys in the area between Reykhus and Botn (Bjorgvinsdottir, 1982). It reveals that the dominant strike of the normal magnetized dykes (a) and the normal faults (c) are NNE while the reverse magnetised dykes (b) tend to have NNW strike, NNE strike and in few cases NE to ENE strike. The relative age of the dykes is unknown, but they clearly reflect different stress regimes with time.

The geothermal exploration in the area was mainly carried out by Schlumberger resistivity surveys in the seventies, followed by intensive drilling supported by local geological and geophysical considerations. After the invention of the TEM survey method (Arnason and Flovenz, 1992) it was decided to get more detailed picture of the resistivity structure by a TEM survey in the hillsides south of Akureyri. The purpose was an attempt to understand the complicated pattern of the geothermal fields in that area and to test the quality of the information obtained by TEM soundings.

Figure 1 shows the location of the TEM soundings as well as the hot springs in the area and the main geological units (Hjartarson, 1998). As can be seen from the figure, hot water is produced at four places in the area, at Botn, Laugaland, Ytri-Tjarnir and Reykhus. All the geothermal fields are fracture dominated fields, the feedzones are usually northerly striking dykes or faults. However, a NE-SW fracture, connecting Botn and Laugaland has been suggested as the main upflow zone of these geothermal fields.

Due to the pumping the water level in the boreholes is presently at 200 - 300 m depth below the well head compared to initial overpressure of 20 bar. In order to get a free flow from the wells again, it would require a year or more of recovery, without pumping from Laugaland, Ytri-Tjarnir and Reykhus. Botn, however, shows basically different behaviour. If pumping there is turned off the pressure builds so rapidly up that a free flow starts within a few days. This indicates the presence of a nearby constant pressure boundary, probably a strong geothermal field which has not yet been affected by the 18 years of production.

Only minor hot springs existed originally in the area and most of the original hot springs in the area disappeared as soon as production started. However, three of the hot springs in the area, at Kristnes, Stokkahladir and Gryta have after more than 20 years of production not yet been affected by this great pressure fall within the geothermal systems. This is interpreted as an evidence of independent geothermal fields which, if found, could be used to increase the production in the area. The purpose of the TEM soundings was an attempt to discover the geothermal reservoirs feeding these still remaining hot springs.

## DATA AQUISITION AND PROCESSING

The location of the TEM soundings in the hillside of the western part of the valley was constrained by an electrical power line and low resistivity postglacial clays within the 100m thick sediments covering the bottom of the valley. The electrical current can disturb the TEM method seriously and highly conducting near surface sediments act as a non transparent shield for soundings located above them. Measuring a TEM sounding to the side of such conducting near surface body but too close to it can cause 3-D effects in the sounding which gives errors in 1-D interpretation. The distance from the power line was kept over 500m and the distance from the boarders of the conducting sediments exceeding 1000m.

The measurements were carried out in March 1995, while the area was covered by snow. Two persons carried out the measurements by using snowmobiles. The instrument used were the Protem 67-D (transmitter) and Protem 37-D (receiver) from Genoics. The number of datasets sampled, always depends on the situation at each site. In low-resistivity areas, the signal is stronger and less quantity of data is required, than in high-resistivity areas. Datasets are sampled at frequencies 25, 2.5 and 0.25 Hz for 4 seconds each set (high freq.) and 15, 30 or up to 60 seconds for the lowest frequencies. During a sampling period the data are stacked. Minimum of four sets are taken for each frequency, often at different magnitudes. This gives a good overlap from different frequencies and good constraints on the datacurve.

Figure 2 shows an example of an apparent resistivity curve after processing. The interpretation of the data was made in the following way: Each sounding was interpreted separately by the program TINV (Arnason 1987). The program inverts for the apparent resistivity in a given number of layers and compares the response from the model to the data curve. Each curve is inverted by using different number of layers and the model with the least chi-square from the inversion is selected. The inversion was made, completely without any prior assumptions from the geological or geophysical knowledge of the area. After the inversion of individual sounding was completed, the result from the soundings were presented on pseudosections, showing the resistivity as function of depth along three N-S striking profiles. One of these is shown in figure 3.

The section shows, in general, layered structure where two layers with relatively low resistivity are embedded in an environment of 100-250 Ohmm. The resistivity layers have apparent dip close to 7° towards south. Two main deviations from this layering are observed. At the south of the profile, a deep low resistivity body emerges and under the northern part of the profile, a body with decreased resistivity is observed below the lower conducting layer and it seems to dip down towards north.

The section shows that both the low resistivity layers emerge at the surface in the mountainside. By comparison with the geological map (Hjartarson, 1998) it turns out that the upper layer consists of a series of olivine basalts while the lower layer is made of series of thick phorphyritic lavas interbedded with few meter thick sediments The higher resistivity material in which the low resistivity layers are embedded consists mainly of ordinary tholeiites of varying thickness, usually with relatively thin scoria and sediments in-between.

From these observations it is clear that the resistivity structure is reflecting the lithology in the basaltic lava pile. The low resistivity is found in the thick phorphyritic units and the olivine basalts while the higher values are associated with ordinary tholeiites.

It is of interest to compare the result of the TEM soundings to the previous Schlumberger data. We have a number of sites, where both types of soundings are performed. A typical example of the result is shown in Figure 4. It shows the result of one dimensional layered inversion of a TEM sounding compared to a 1-D inverted Schlumberger sounding. The comparison shows clearly how the TEM sounding gives better resolution and greater depth penetration. Comparison with borehole and surface geology also confirms that the inversion of TEM soundings better corresponds to the main layering of the lava column. The Schlumberger soundings on the other hand have a better resolution at shallow depth or down to approximately 100 metres depth, mainly because of the high frequency limits of the TEM-transmitter used.

## BOREHOLE DATA

Many boreholes have been drilled within the research area. The locations of several boreholes deeper than 1000m are shown in Figure 1 as well as the location of a few shallow boreholes used for heat flow measurements. Geological sections exist for all the boreholes based on analysis of drill cuttings and lithological well logging, mostly by neutron-neutron and natural-gamma logs. The similarity between the boreholes is obvious, apart from the depth intervals where the boreholes intersect near vertical dykes. Lava groups, and in many cases separate lava flows, can be traced over the whole area. Three different boundaries, easy to identify, are traced in 6 or 7 boreholes and used to fit the best plane through them and by this calculate the dip and the strike of the lava pile. The dip for these three surfaces, varies from 8.5° to 9.7°, the average being 9.0°. The strike varies between 59.2° and 61.0°, the average being 60.9°. The average RMS deviation of the depth to each layer from the best plane varies between 14m and 24m for the three planes, the average being 19m. The extreme deviations are 35m for a single depth value. There are no obvious regularities in the distribution of the deviations which could imply a major fault in-between the boreholes and the values of the dip and strike are similar to previous estimates of 6° and 55° based on surface investigations (Bjornsson and Saemundsson, 1975). The observed deviations in our data are most likely caused by variations in thickness of the individual lavas or minor faults in-between the boreholes.

Because of the dip, the formation observed in the boreholes can be traced up to the surface and correlated with the geological map. Figure 6 shows an example of the stratigraphical correlation.

## TEMPERATURE RESISTIVITY RELATIONSHIP

Having come to the conclusion that the resistivity layering corresponds to the stratigraphical layering, the stratigraphical layering being well defined in the boreholes, it is possible to improve considerably the interpretation of the resistivity data. In the resistivity measurements there is a trade off between the thickness and the resistivity of each layer, the inversion process can not distinguish between a relatively thin layer with low resistivity and a slightly thicker layer with a slightly higher resistivity. This means that the thickness and the resistivity values are not well determined while the ratio between the two parameters is well constrained. The borehole data, as well as the geological mapping, suggest that there are only small variations in the thickness of the lava units that the low resistivity layer consists of. Based on the resistivity profile on figure 4, the average thickness is around 270m.

Since the resistivity layers are dipping with 7° from the surface down to a depth of almost 1 km within the research area, the temperature within in this layer increases correspondingly from 4-5°C at the surface to 90 °C at 1 km depth. This opens the possibility of investigating the effect of the temperature on the resistivity. In the southern part of the area the temperature is known from direct measurements within the layers in deep boreholes but in the northern part we have to estimate the temperature by extrapolation of the near surface temperature gradient.

Figure 5 shows a plot of the resistivity to the temperature for the second low resistivity layer. The resistivity values are obtained by calculating the ratio of the measured resistivity to the measured thickness and multiply the ratio by the average thickness of the layer. This is equivalent to fixing the depth of the layer but assuming the same conductance. The temperature is estimated from the borehole temperature-logs in the area and interpolation between them. Compared to the data, there are the empirical relation between the resistivity of altered basalts and temperature by Flovenz et al. (1985) ;

$$\rho_T = \rho_0 / \{ ( 1+ \alpha (T - T_0) (1 + \beta (T - T_0)) \} \qquad (1)$$

and the curve for resisitiviy of an electrolyte as function of temperature (Dakhnov, 1962).

$$\rho_T = \rho_0 / ( 1+ \alpha(T - T_0 )) \qquad (2)$$

where $\rho_T$ and $\rho_0$ are the resistivities at the temperature T and reference temperature $T_0$, and $\alpha$ and $\beta$ are empirical constants, refering to $T_0$ .

The empirical relationship of Flovenz et al. shows about twice as much dependence of the resistivity on temperature as could be expected for electrolytic conduction alone. It was explained as an effect of interface conduction along very thin but highly conductive layers of clay minerals covering the interconnected fractures in the microcracks of the rock. Our result on figure 5 appear to be in good agreement with the empirical relation or show slightly less temperature dependence with the exception of two of the northernmost soundings. At these two sites direct measurements on temperature are missing and our estimate is obtained from interpolation of data from the nearest boreholes which are few kilometres away. In this area, however, there is a 48°C hot spring not so far from the two soundings, indicating that there might be higher subsurface temperature than we get from interpolation of the available data.

One might ask if change in the chemical composition could be the reason for this observed dependence on temperature. It is not the case since the chemical composition of the geothermal water is very similar to local ground water with exception of the silica content. Water sample from a feedzone at 450m depth in the borehole RWN-7 has nearly the same conductivity as the geothermal water at Botn which comes from around 1700m depth. However it should be noted that as the layer is buried to a greater depth and brought to higher temperatures within hydrothermal fields, it could be expected that the porosity is somewhat reduced due to precipitation of hydrothermal minerals within the microfractures. This effect would then counteract the reduction in resistivity with increased temperature in our data. Therefore we can conclude that the resistivity is at least as temperature dependent as suggested by the empirical relation.

## GEOLOGICAL INTERPRETATION

Figures 6 and 7 show combined cross sections based on the geological and geophysical observations in the area. The figures show the dipping basaltic lava pile and how the low resistivity phorphyritic basaltic layer extends from around 1 km depth in the southern part of the section toward the surface in the central part of the section (figure 6) and how it further appears in the mountain north of Akureyri (figure 7). It is also interesting to notice that the main cold water supply in Akureyri is found where the down dip part of the layer emerges in the mountain side which means that a cold water aquifer is associated with the layer.

Figure 6 also shows the two main low resistivity regions, which cannot be correlated with the stratigraphy of the lava pile. One of them is at the southern end of the section, just below the Botn geothermal field. The inferred isotherms from the boreholes also show how the temperature maximum is observed at the same place, indicating the geothermal field to be the source of the low resistivity region, either due to the elevated temperature or porosity effects. An indication of a temperature anomaly is observed over the northern low resistivity region but reliable data are lacking from this area. The origin of this anomaly is therefore unknown.

By examining the isotherms on the figure we can see how the isotherms follow the low resistivity phorphyritic unit upwards from the Botn geothermal field. This implies that that there has been a flow of hot water from the Botn field along this low resistivity layer towards the surface. This is further supported by the fact that the main feed zones in the boreholes are usually found within or close to this layer (figure 6).

Based on the above considerations we propose the following model of the geothermal activity in the area:

At the Botn geothermal field in the southern end of the section a fracture dominated geothermal field is found. The proposed strike of the main fracture is NE-SW. It is a high pressure geothermal field with reservoir temperature close to 100°C below 1 km depth. It is almost completely sealed off from the surface by low permeability cap rock, probably due to secondary mineralisation caused by the escaping hydrothermal fluid. Due to the high pressure and the dense cap rock the geothermal fluid is forced into the slightly permeable sequence of the thick phorphyritic basalts along which it flows laterally towards the north where it ascends to the surface along narrow fractures created by the intersecting dykes. Since the main upflow is at Botn and the hot springs north of Botn are a consequence of lateral flow, drilling close to these hot springs has not, and is unlikely ever to give significant yield.

Furthermore, the presence of the cold groundwater springs in the mountainside close to Akureyri is easily understood with reference to figure 7. Since the lava pile in the mountain contains less secondary minerals than the lava at deeper levels, the rain water can penetrate the bedrock directly, or through fissures until it reaches the relatively highly permeable phorphyritic series. Due to gravitational effects, the water follows this sequence downdip until it can escape at the surface where the layers appear in the mountainside.

**CONCLUSIONS**

The result of the TEM survey in the basaltic crust in Eyjafjordur, N-Iceland shows that the TEM method has both greater vertical resolution and penetration than the Schlumberger method. The joint interpretation of the TEM resistivity data and borehole data shows that different sequences of basalts have different resistivity by factor 2 or 3. Furthermore, comparison of resistivity data and temperature within the same stratigraphic unit shows close agreement with the empirical relations between resistivity and temperature, proposed by Flovenz et al. (1985). The resulting resistivity cross section explains the nature of the geothermal fields in the Eyjafjordur valley. A single high pressure fractured upflow zone generates lateral flow along a slightly permeable and dipping sequence of phorphyritic tholeiites interbedded with scoria and sediments.

**ACKNOWLEDGEMENT**

The authors express their thanks to Einar Kjartansson and Hjalmar Eysteinsson for undertaking the field work; Helga Sveinbjornsdottir for assisting in the layout of figures; The Akureyri District Heating and Water Works are also acknowledged for allowing publication of their data.

**REERENCES**

Arnason, K. (1987). *Central loop transient electromagnetic soundings over a horizontally layered earth*. Orkustofnun report OS-89032/JHD-06, 128p. (in Icelandic).

Arnason, K. and Flovenz O.G. (1992). *Evaluation of physical methods in geothermal exploration of rifted volcanic crust.* Geothermal Resources Councils Transactions vol. 16 pp 207-214.

Bjorgvinsdottir, B. (1982). *Ground magnetic survey in the Hrafnagil community in Eyjafjordur.* Orkustofnun report OS82100/JHD15 19p. 6 maps (in Icelandic).

Bjornsson, A. and Saemundsson K. (1975). *Geothermal fields around Akureyri.* Orkustofnun report OS-JHD 7557 53p. (in Icelandic)

Bodvarson, G. (1982). *Terrestrial energy currents and heat transfer in Iceland*. In: Palmason, G. (ed), Continental and Oceanic Rifts. AGU Geodyn. Ser. 8.

Dakhnov, V.N. (1962). *Geophysical well logging*. Quart. Colorado Sch. Mines vol 57 no. 2 445p.

Hjartarson, A. (1998*). Geol. map of Akureyri and neighbourhood in 1:50.000).* Orkustofnun, Reykjavik, report in Icelandic, AH-98-02, 6p and 2 maps.

Flovenz, O.G., Arnason, F., Finsson, M. and Axelsson, G. (1995). *Direct utilization of geothermal water for space heating in Akureyri N-Iceland*. Proceedings of the World Geothermal Congress, 1995 Florence Italy pp. 2233-2238.

Flovenz, O.G., Georgsson, L.S., and Arnason, K. (1985). *Resistivity of the upper crust in Iceland*. J. Geophys. Res. 90, pp. 10,136-10,150.

Palmason, G., Arnorsson, S., Fridleifsson, I.B., Kristmannsdottir, H., Saemundsson, K., Stefansson, V., Steingrimsson, B., Tomasson, J. and Kristjansson, L. (1978). *The Iceland Crust: Evidence from drillhole data on structure and and processes.* Second Maurice Ewving Symposium AGU pp. 43-65.

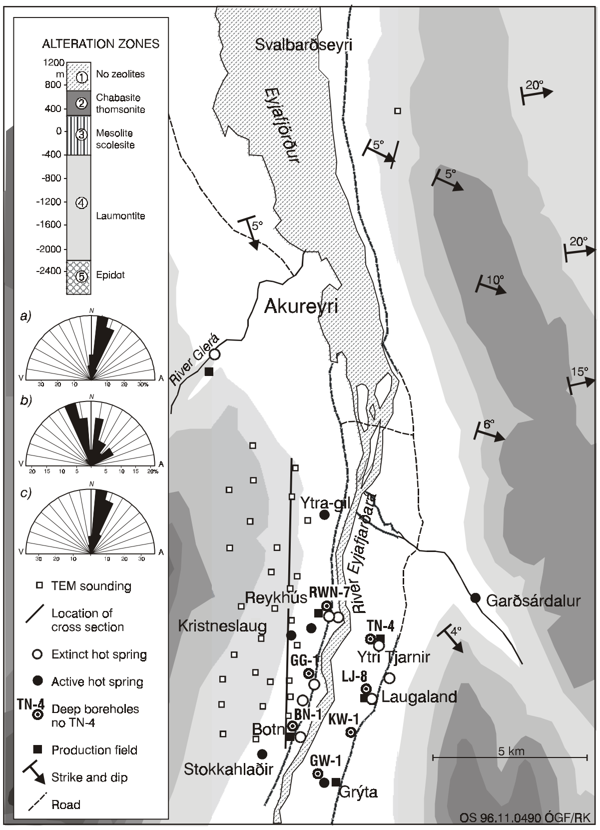


*Figure 1. Map showing the distribution of the hot springs; production fields; location of the TEM soundings and the resistivity section in figure 3; the typical alteration zones of the lava pile and rose diagrams for dykes ((a) normal magnetized) ((b) reverse magnetized) and faults (c).*

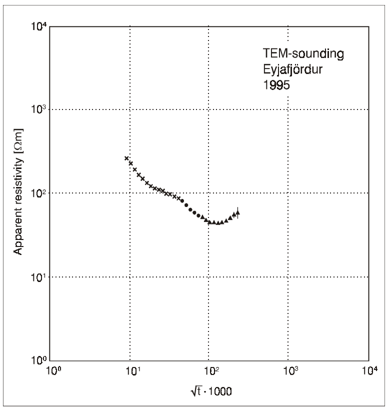


*Figure 2. Example on a TEM apparent resistivity curve (resistivity with depth) after pre-processing of data.*

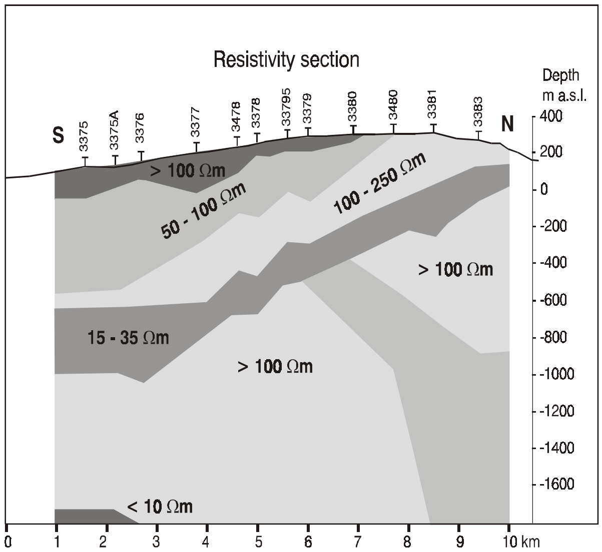


*Figure 3. Resistivity cross section based on one dimentional inversion of the TEM data.*

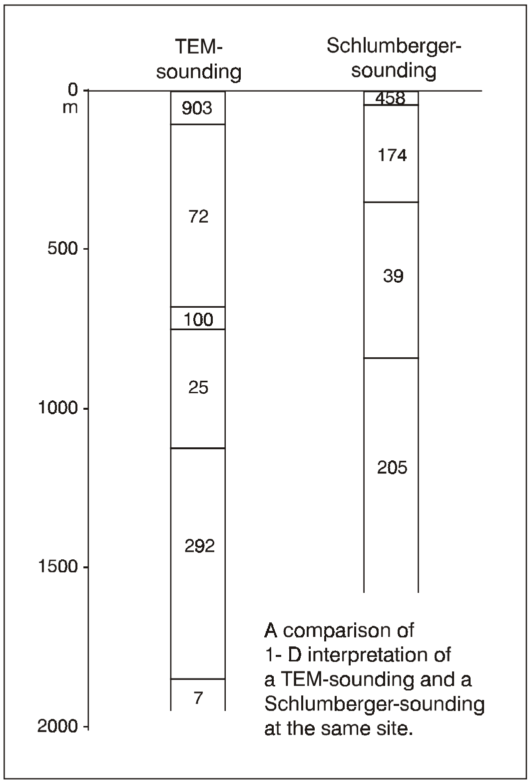


*Figure 4. Comparison of 1-D interpretation of TEM and Sclumberger soundings showing greater vertical resolution and depth penetration of the TEM soundings.*

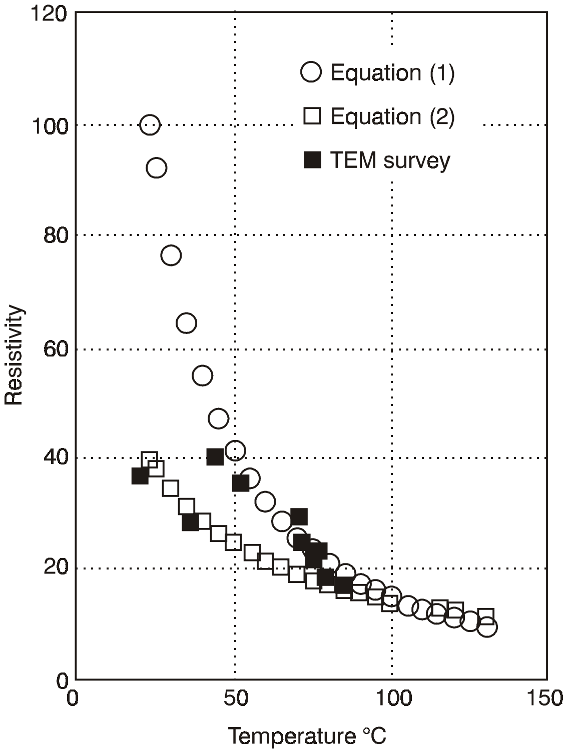


*Figure 5. Resistivity of the low resistivity porphyritic basaltic lava sequence from the TEM-survey as a function of temperature compared to theoretical values from equations 1 and 2 in chapter 4.*

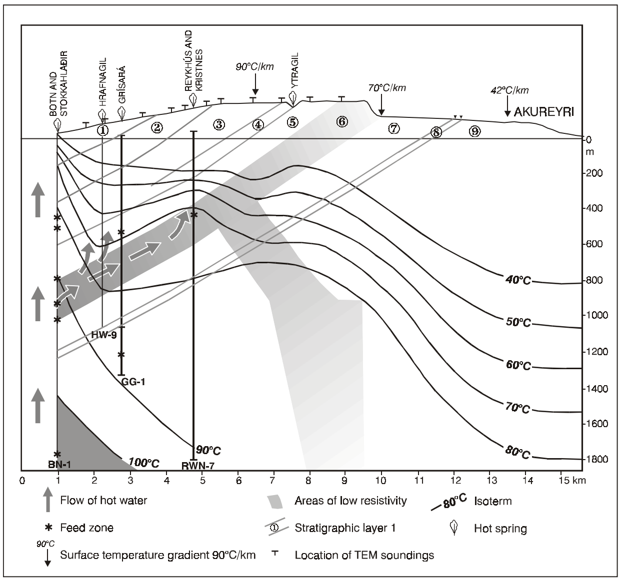


*Figure 6. Geological and geothermal interpretation of the data.*
*The numbers on circles denote the different geological units according to the geological map of Hjartarson (1998), 1) is phorphyritic basalts, 2) is phorphyritic compound lavas, 3),5),7) and 9) are ordinary tholeiites, 4) is olivine basalt and 6) is the thick phorphyritic basalts with few meters of scoria and sediments in-between. The isotherms are from deep boreholes in the southern part but extrapolated from shallow boreholes in the northern part The location of the profile is shown in figure1.*

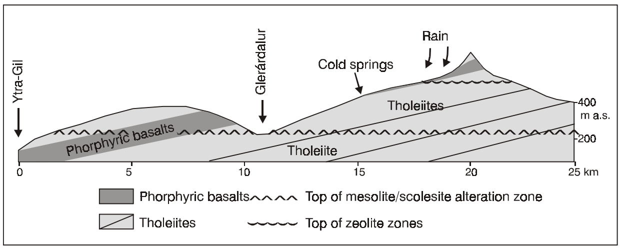


*Figure 7. Geological cross section showing the northward continuation of the section in figure6 in the mountains west of Akureyri. The section shows how the low resistivity phorphyritic basalt unit appears in the mountains and how the cold springs are found on the down dip side at the base of the layer where it comes to the surface in the mountainside.*