Proceedings World Geothermal Congress 2010
Bali, Indonesia, 25-29 April 2010

How the Use of Tem Changed the Resistivity Model of Oxarfjordur Temperature Field from an Earlier Dc Survey - a Case History

Ragna Karlsdottir and Olafur G Flovenz

Iceland GeoSurvey, Grensasvegi 9, 108 Reykjavik, Iceland.

rk@isor.is and ogf@isor.is

Keywords: DC survey, TEM survey, Resistivity model,

ABSTRACT

A resistivity survey in Oxarfjordur temperature field in north Iceland, performed by the use of the Schlumberger (DC) method showed a resistivity structure interpreted as a high temperature reservoir with temperatures exceeding 240°C. Drilling into the field however did not confirm an active high temperature field nor temperatures exceeding 190 °C. A TEM (Transient Electro Magnetic) survey explained the structure with a better resolution at depth, as a geothermal fracture dominated field within sedimentary surroundings at temperatures as high as 190°C

1. INTRODUCTION

Oxarfjordur geothermal field lies within the northern end of the volcanic zone in Iceland. Georgsson et al. (2000) described the system and the exploration made until 1998, prior to any deep drilling into the system. By definition high temperature fields are geothermal fields where temperature exceeds 200°C at 1 km depth. They are always associated with volcanic systems, and their heat sources are cooling intrusions. Oxarfjordur field lies immediate south of the Tjornes transform fault, that shifts the ridge axis from Öxarfjördur the to the Kolbeinsey spreading ridge. It belongs to the fissure swarm of the Krafla central volcano. The geothermal field is embedded in up to 0,8 km thick sediments in the delta formed by one of the largest glacial rivers in Iceland. Surface manifestations are sparse, only up to 80°C warm ground by the Bakkahlaup river (Georgsson et al., 2000).

2. THE RESISTIVITY STRUCTURE OF HIGH TEMPERATURE FIELDS IN ICELAND

Resistivity methods have been in the main geothermal exploration tool in Iceland. From the mid sixties, DC-methods, mostly Schlumberger soundings, were used to identify and delineate high-temperature systems. In the mid eighties the DC methods were replaced by central-loop TEM-soundings (Transient Electro-Magnetic). The TEM-soundings have proven to be more downward focused and have better resolution at depth than the DC-methods. (Arnason and Flovenz, 1992).

High-temperature systems, within the basaltic crust in Iceland, show similar resistivity structure; characterized by a low resistivity cap at the outer margins of the reservoir, underlain by a more resistive core towards the inner part (Fig. 2).

Due to water-rock interaction and chemical transport by the geothermal fluids, the primary minerals in the host rock matrix suffer alteration and new secondary minerals form. , The alteration process and the resulting type of alteration minerals depend on the type of primary minerals, chemical composition of the geothermal fluid, pressure and temperature. Furthermore, the intensity of the alteration depends on time and the permeability of the host rock. The alteration process and the resulting alteration mineralogy of the basaltic rocks in high-temperature geothermal systems in Iceland have been studied quite extensively. (Kristmannsdóttir, 1979).

Comparison of the resistivity structure with data from wells shows a good correlation between the resistivity the alteration mineralogy (Flovenz et al. 1985, Arnason et.al., 1987 and 2000). The low resistivity in the low-resistivity cap is dominated by conductive minerals in the smectite-zeolite zone formed in the temperature range of 100-220ºC. At temperatures 220-240ºC zeolites disappear and the smectite is gradually replaced by more resistive chlorite. At temperatures exceeding 250ºC chlorite and epidote are the dominant minerals. Thus the observed resistivity structure may be interpreted in terms of temperature distribution, provided there is equilibrium between temperature and the thermal alteration of the rock. This approach is, however only valid for geothermal systems with rather dilute pore fluid (Flóvenz et al., 2005, Kuhlenkampff et. al., 2005).

3. A DC RESISTIVITY SURVEY AT OXARFJORDUR

A resistivity survey was performed at Oxarfjordur in the 19 eighties by the use of Schlumberger DC method (Georgsson et al., 1993) and later a TEM survey was added. Fig. 3 shows the survey area at Oxarfjordur. The Schlumberger survey was made with half current spacing (AB/2) up to 1500m while the TEM survey was made with a transmitter loop of 300x300m.

The Schlumberger survey was interpreted in a two dimensional way (Georgsson et al., 2000. Fig. 4 shows an east west resistivity section (2D) through Bakkahlaup, where the most prominent surface manifestations are. Low resistivity layer is observed at shallow depth with underlying higher resistivity. The low resistivity layer reaches surface at the hot spring area near Bakkahlaup. A map of the resistivity at 500m b.l.s.l. is also shown in Fig. 10. The resistivity structure was interpreted as being that of a typical high temperature field i.e. a low resistivity cap underlain by a high resistivity core. The conclusion was that "Resistivity measurements show an area within the Krafla fissure swarm including the Bakkahlaup geothermal field, at least 10 km^2 in size at 500 m depth, with a resistivity structure typical for high-temperature systems in Iceland. It shows a low-resistivity coat around a resistive core, representing the centre of the system. This high resistivity is associated with alteration minerals such as chlorite and epidote, that form at temperatures around 250°C. This is also supported by the local high-velocity/gravity anomaly in this area"(Georgsson et al., 2000).

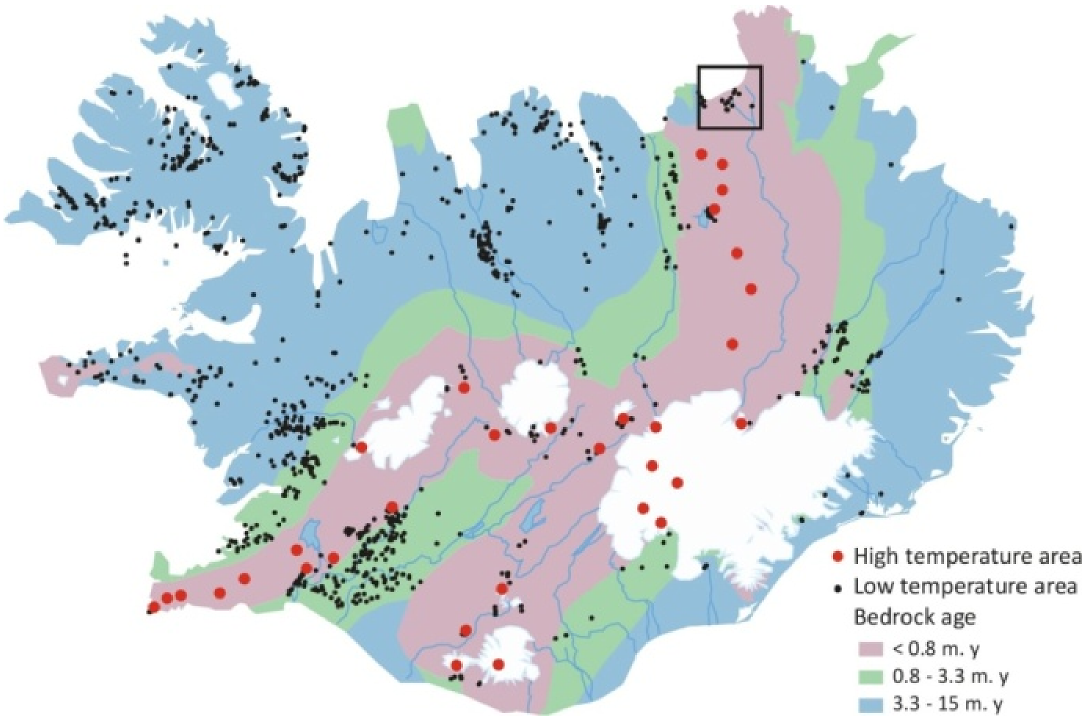

Figure 1. The figure above shows Oxarfjordur temperature field on a simplified geological map of Iceland.

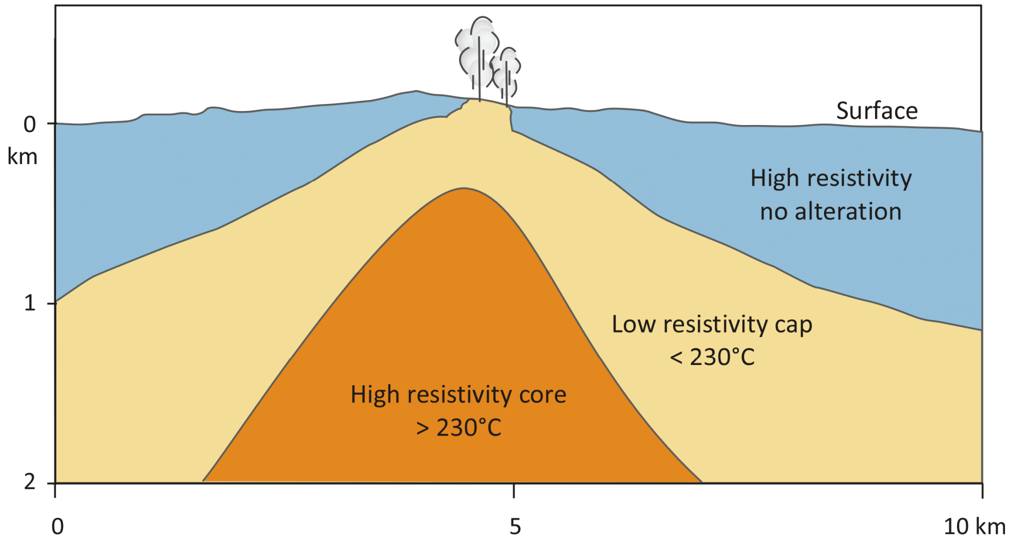

Figure 2. A simplified resistivity cross section through a high temperature field.

This conclusion was further strengthened by general geological consideration and geochemical results.

During an volcanic episode in the Krafla central volcano 1975 – 1984, intrusions were repeatedly injected from the magma chamber under Krafla, along the fissure swarm towards the Oxafjordur geothermal field. That supported the conclusions that Oxarfjordur is a high temperature field.

Geothermometers, based on the chemical content of the geothermal water were used to estimate the temperature in the reservoir. The silica content in the waters from Oxarfjordur, implied temperatures 200 – 230 °C in the reservoir, provided there is an equilibrium between the silica to quarts in a high temperature field. An equilibrium to chalcedony as would be the case in a low temperature field would lead to a lower temperature estimate. The presumption of silica to quarts equilibrium was used here as other research results indicated a high temperature field.

4. DRILLING

Based on the results from the resistivity survey, supported by the estimated temperature from chemical geothermometers it was decided to drill a high temperature exploratory well in the area. The selection of the drilling site was mainly based on the Schlumberger resistivity section in Fig. 4 but also on measurements of seismic noise in the area and the presence of nearby geothermal activity on the surface (Georgsson et al., 2000). According to the interpretation of the resistivity structure it was expected to reach temperature up to 230°C at shallow depth, i.e. close to the top of the resistive core at roughly 300m depth.
The borehole BA02 was drilled in 1999. Temperature logs from the well are shown in Fig. 5. Until the depth of 370 meters, the well cut through sediments where the basaltic basement was reported (Fridleifsson et al, 1999A, Richter et al., 1999). The texture of the lava pile implies that it is a basement of tertiary age contrary to what was expected in the middle of the riftzone (Fridleifsson et al, 1999 B).

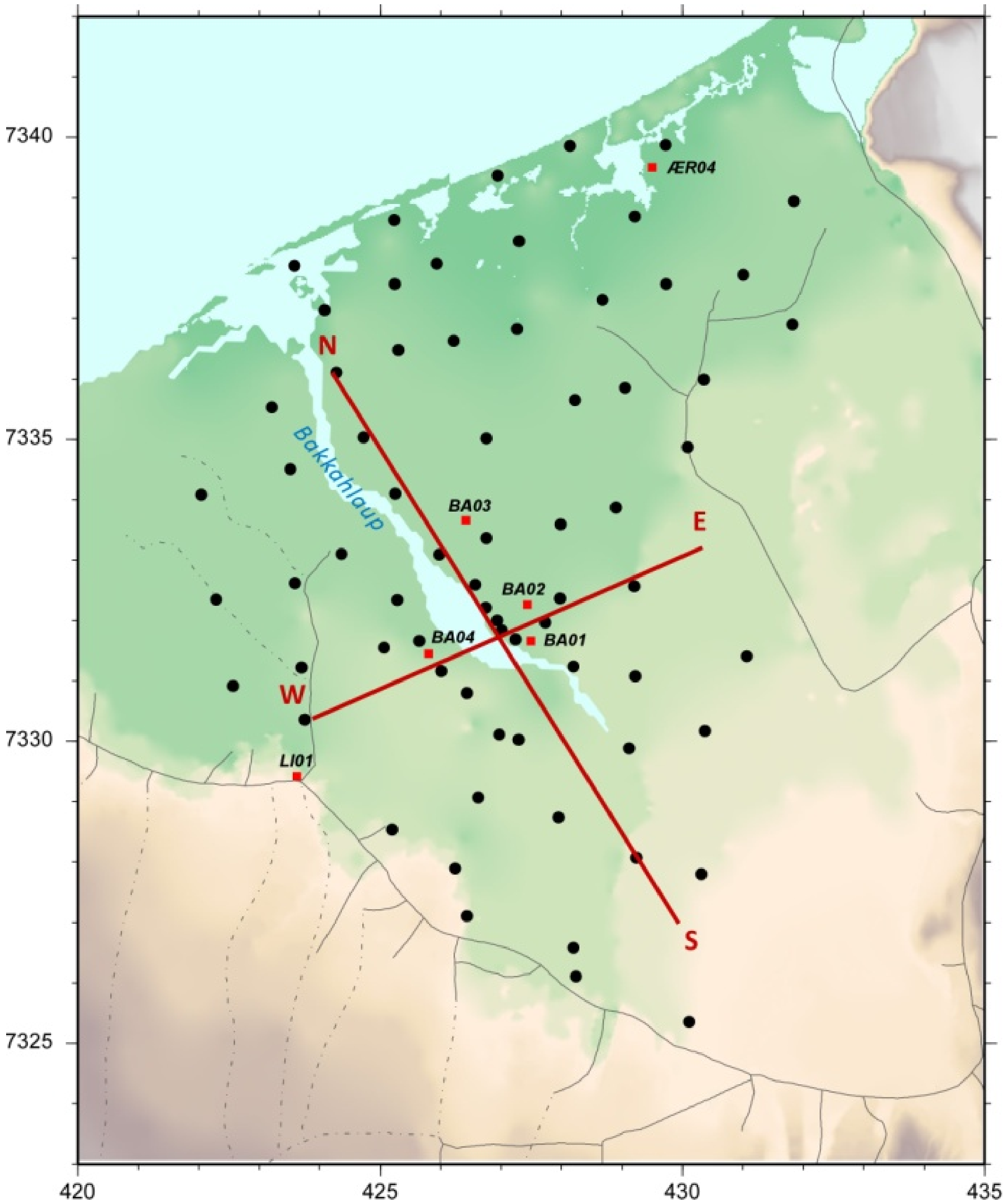

Figure 3. The survey area in Öxarfjördur. Location of TEM soundings are shown by black dots. The coverage of Schlumberger soundings was similar. The red dots are boreholes.

In the depth interval 300-500m feed zones were observed and the temperature reaches 180-190°C. The maximum value is just below the top of the basalts (Fridleifsson et al., 1999 B). This depth interval was cased off, as higher temperatures were anticipated at depth. Contrary to expectations, the temperature lowered with depth below 500m and at the bottom at 1962m the temperature was down to 115 – 120°C. At 500m the alteration mineral epidote appears and is found more or less continuously to the bottom of the well and clear signs of overprinting of low temperature alteration minerals were not found. (Fridleifsson, 2001, Fridleifsson et al 1999, 2000). However, some overprinting of anhydrite and wairakite were observed that could indicate slight cooling. This means that the temperature has reached at least 240°C at 500m depth but has obviously cooled down later, probably due to repeated recent faulting with invasion of cold groundwater into the geothermal system. It should also be pointed out that the amount of alteration minerals is low compared to classical high temperature fields and could be of regional origin since the system is emplaced in an old tertiary lave pile but not in a newly formed volcanic system as is usually the case in Icelandic high temperature systems (Fridleifsson et al 1999B).

It was also concluded that the 190°C water-flow of, at 300 – 500 meters depth, was a lateral flow from an up-flow zone at some distance or alternatively, the up-flow zone being a very narrow fracture, almost a pipe. That up flow was considered to be at temperatures exceeding 200°C as the water most likely cools when it flows laterally along the horizontal aquifers close the the sediment/basement boundary. Fridleifsson et.al., (1999a, 1999B); Richter et.al. (1999),

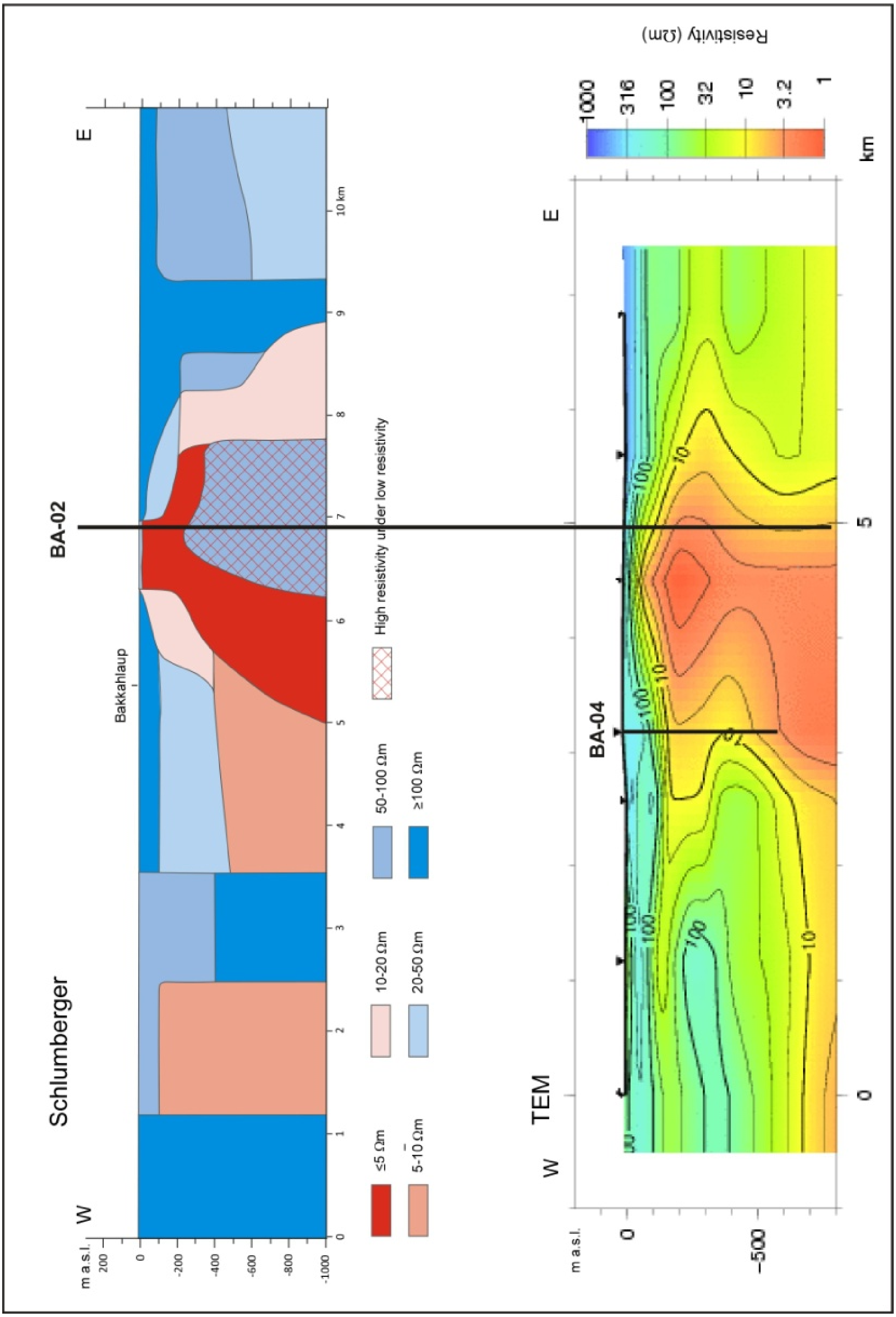

Figure 4. An E-W resistivity cross section through the Öxarfjaördur high temperature field. The surface manifestations of geothermal activity are where the low resistivity layer reaches the surface. The upper section shows the result of 2D interpretation of Schlumberger soundings, while the lower one shows the result of the 1D interpretation of TEM soundings. The location of the well BA-02 is also shown.

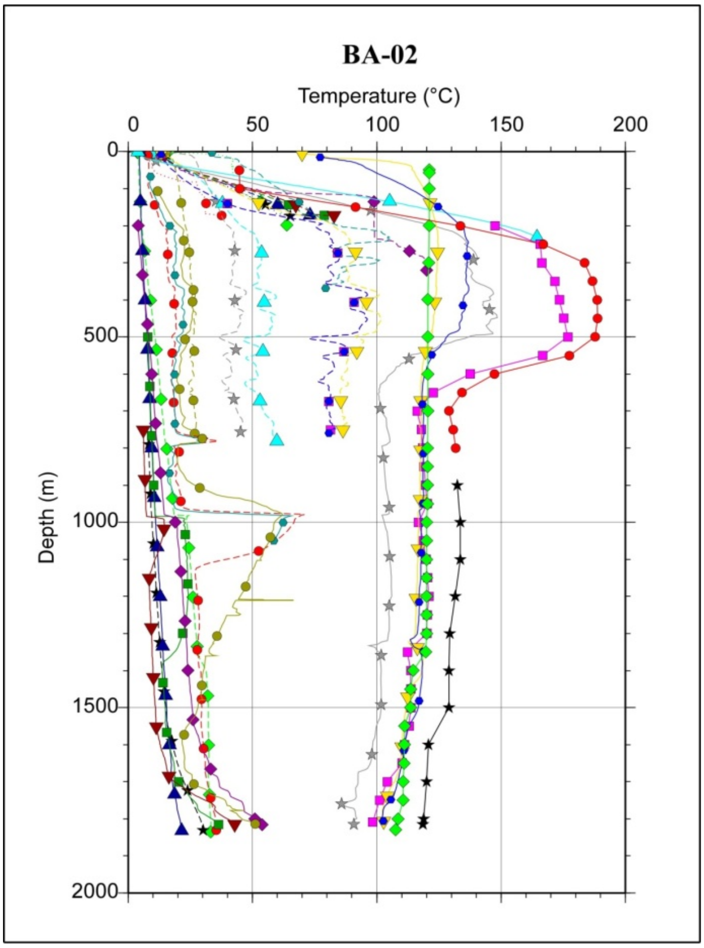

Figure 5. Temperature logs from the well BA-02 at different times during and after drilling. Note that some of the logs are run during a flow test. The log to the far right are made in the well in no-flow condition after it has equilibrized and should represent the true formation temperature.

These results were quite discouraging. The strong temperature reversal at 500m depth shows that the well did intersect a lateral flow of about 190°C water between 300 and 500m depth, so it was assumed that the system did not held temperatures above 200°C or hardly high enough to be considered as a high temperature system. It was at that time decided to drill a new borehole BA03, now into the top of the low resistivity anomaly (Fig. 10) approximately 1500 meters to the north of BA02, to see if higher temperatures were found in the alleged high resistivity core in that area.

Now the results were even more discouraging. The borehole BA03 was very permeable but only contained 80°C hot water and the bottom temperature at 700 meterss depth did not exceed 100°C (Fig. 6). No indications of higher temperatures pointing at a high temperature reservoir, were seen in the rock alteration minerals. Fridleifsson et.al. (2000).

At this point, all the exploration results were reviewed. Oxarfjordur temperature field was evidently not a large active high temperature field. The interpretation of the resistivity structure was obviously not correct and not reflecting a high temperature field i.e. the high resistivity core below the shallow low resistivity cap was not caused by high temperature alteration. The explanation could be of lithological origin, i.e. basaltic lava pile under thick sediments could cause the higher resistivity at depth. The overall results of the revision now suggested a highly permeable geothermal field, with reservoir temperatures of 80 – 200 °C but the hot up-flow zone had not been discovered as of yet.

It was therefore decided to perform a TEM resistivity survey of the area, in order to explain the resistivity structure with a better resolution method and to try to detect the up-flow of geothermal water into the sediments.

5. THE TEM SURVEY AND COMPARISON WITH BOREHOLE LOGS

The TEM resistivity survey was performed in the years 2003 and 2004 (Karlsdottir, 2005, Karlsdottir and Flovenz, 2005) covering the same area as the previous DC-survey (Fig. 3). Compared to the Schlumberger soundings the TEM method is more downward focused and has much better resolution at depth and usually a greater depth penetration. The experience in Iceland indicates that a 1D interpretation of TEM soundings gives even better resolution than 2D interpretation of Schlumberger soundings. The results of the TEM survey in Öxarfjördur are shown as E-W cross section in the lower part of Fig 4 and as N-S cross section in Figure 7. The sections cross each other close to well BA02. The interpretation of the TEM methods is done with Occam inversion based on ISOR´s software by Knutur Arnason and Hjalmar Eysteinsson. The Occam method assumes 1D continuous variation of resistivity with depth below each sounding and the 2D section is made by contouring the results from soundings. Note that the interpretation of the Schlumberger soundings in Fig. 4 is made with a finite difference code that is based on regular boxes of constant resistivity.

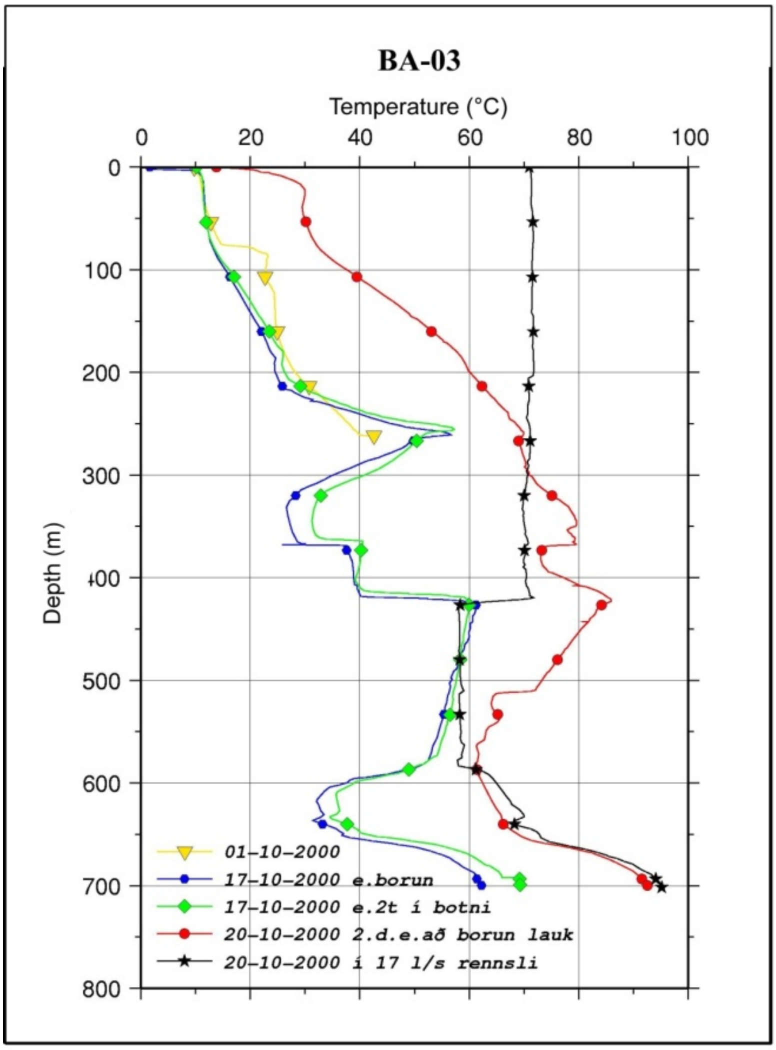

Figure 6. Temperature logs from the well BA-03.

The resistivity section based on the TEM soundings in Figs 4 and 7 show different picture compared to the Schlubemrger soundings although the general resistivity section is similar. The TEM resistivity section do not show the typical characteristics of a high temperature field, i.e. a resistive core with a conductive cap but rather a diapir of low resistivity rising through a more resistive basement.

Fig. 8 shows a resistivity log from the well BA-02 for comparison with the TEM soundings. The resistivity is quite low (<5 Ohm-m) in the sediments according to both the exploration methods (Schlumberger and TEM) and the borehole resistivity log. At the top of the basement at 370m the log shows sharp increase in the resistivity to 15-20 Ohm-m. This is in good accordance with the results from the Schlumberger soundings but the resistivity increase in the TEM soundings is not as sharp due to the assumptions used in the Occam method.

The low resistivity layer with a higher resistivity layer below, was obviously misinterpreted in the DC survey since it is according to the drilling and the well logging caused by the sediment-basement boundary rather than a change to high temperature alteration. Higher resistivity below denotes here lava flows under the sediments and not high temperature alteration. The top of the epidote zone was found at 500m depth but the degree of high temperature alteration is low. No clear increase in resistivity is associated with it, neither in the logs nor in the soundings. Possible explanation is that the lowering of the temperature counteracts the increase due to the change in the mineralogy or low temperature clays might have formed again in the rock as a consequence of the cooling.

The resistivity log from well BA-03 in Fig. 9 shows similar feature as can be read from the resistivity section in Fig.7. Relatively high resistivity (50Ωm) is observed close to the surface in the section and in the log. In the lowest part of the sediments the resistivity lowers sharply in the log from 50Ωm to 3Ωm and corresponding lowering is seen on the section. When basement is reached at 330m the resistivity increases again in the log to 20-30Ωm and an increase is also seen in the section. Below 370m the log shows fluctuating resistivity around 10Ωm with strong lowering at the bottom. The overall resistivity of the basement is lower below 500m in BA-03 compared to BA-02 possibly reflecting the fact that BA-03 has not yet reached the epidote zone.

The north south TEM resistivity section on the east bank of Bakkahlaup River (Fig. 7) shows the diapiric structure like in Figure 4. The most likely interpretation of this diapir is that the column reflects temperature variation in the basement caused by up-flow of geothermal water. The head of the diapir is thus most likely reflecting lateral flow of the hot water within the sediments and at the sediment/basement boundary. The borehole BA-03 cuts through this head at the depth of 200–300 metres revealing a flow of water at 80°C temperature

Chemical composition of the water in BA-03 also revealed that the geothermal water is mixed with seawater coming in from the shore along the sediments. The distinctive lower temperature in BA03 tells that the off flow of geothermal water is at a considerable distance from the drill hole and is more likely to be found in the vicinity of BA-02.

In continuation of the TEM survey a new well, BA-04 was drilled at the western side of the river Bakkahlaup. The purpose of that well was to search for hot water supply for district heating in residences to the west of the river. The well was drilled in 2006 down to 600m depth. A temperature log from BA-04 is shown in Fig. 10. The low temperature at only 80°C shows that the borehole is at considerable distance from the up flow of 200°C. At 550 – 600m depth the temperature rises to about 90°C, where the borehole reaches the off flow zone indicated by the low resistivity in the TEM survey as seen on resistivity section in Fig. 4.

6. DISCUSSIONS AND CONCLUSIONS

A Schlumberger resistivity survey at Oxarfjordur led to the conclusion that the geothermal field was a high temperature field with anticipated temperatures exceeding 230°C in the reservoir. This conclusion was supported by the fact that the geothermal field lies within the fissure swarm extending to the north from the Krafla central volcano. Wells based on these conclusions showed a different picture.

A more detailed TEM survey showed together with the drilling results that Oxarfjordur geothermal field is a fracture dominated field with the main up flow along a fissure under the river Bakkahlaup. From the up flow along the fissure at Bakkahlaup the geothermal water flows laterally along a sediment layer at 300 – 500 metres depth The uppermost part of geothermal field is imbedded in sediments overlying a tertiary lavapile, quite unusual geological settings for a high temperature geothermal field in Iceland.

The results also show that in fact that the Schlumberger survey only has a downward resolution of 300 – 400 metres in these conditions i.e. the soundings can only detect the resistivity increase at sediment/basement boundary but not the actual value or further resistivity changes downwards. A comparison of resistivity maps in Fig 11 shows that the resistivity at 500 m.b.sl. in the Schlumberger survey shows approximately the same results as the TEM survey at 200 m.b.s.l., i.e. a geothermal up flow at Bakkahlaup and off-flow towards north along sediments, where it meets and mixes with saline water from the sea.

The TEM has the resolution to see through the low resistivity layer and considerably into the underlying resistive basement. The map of the TEM-resistivity at 500m is interpreted as lateral flow of geothermal water and saline water within the sediments. The map at 800 meters depth in Fig. 11 reveals the fracture dominated area within the basement where the resistivity lows are most likely representing local up-flow zones of 100-200°C hot water along the fissures with the most prominent one, at Bakkahlaup geothermal field. The other part of the fissures from the Krafla volcano within the Oxarfjordur region, seems however to be filled with cold ground water above 800 meters as no low resistivity is bound to the fissures, as drawn on the resistivity map at 800 meters depth (Fig 11, bottom right).

The fact, that Oxarfjordur geothermal system lies within the extension of the volcanic zone led to the presumption of it being a high temperature field. Drilling into the field showed quite interesting settings of the geothermal field. It lies within the extension of the fissure swarm from Krafla central volcano but cuttings from the boreholes revealed tertiary bedrock and not recent lavas as characteristic for a rifting zone. As mentioned earlier, Oxarfjordur field lies immediate south of the Tjornes transform fault that shifts the ridge axis from Öxarfjördur to the Kolbeinsey spreading ridge.

The Krafla fissure swarm has cut its way into tertiary bedrock at the junction of the transform fault and the extension of the volcanic zone. At some time lava intrusions have made their way along the fissures and at Bakkahlaup enough heat has managed to produce high temperature alteration, epidote that is formed at temperatures about 250°C. As epidote is not found in other boreholes than BA-02 it is bound to be anomalous at Bakkahlaup and not a part of regional alteration.

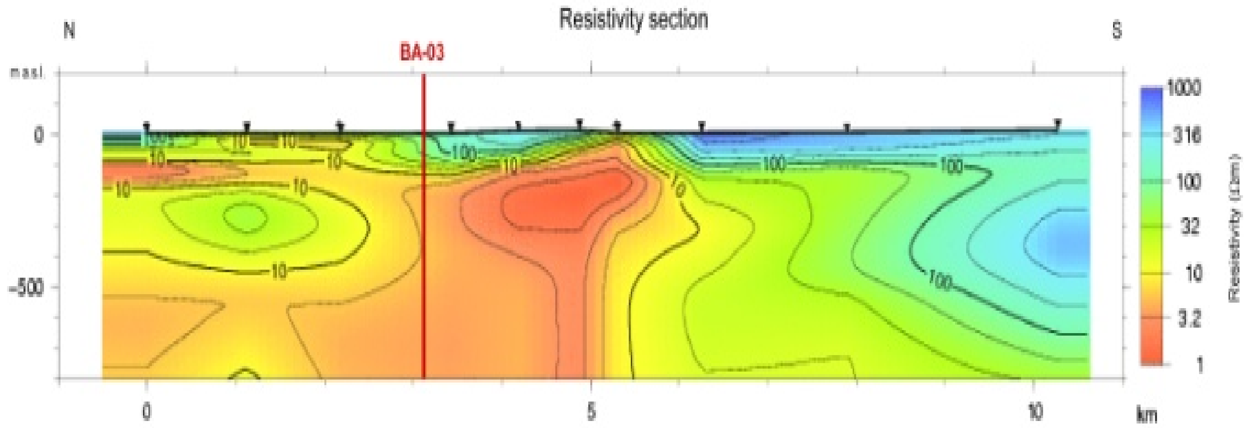

Figure 7 A N-S resistivity section on the eastern bank of Bakkahlaup. BA-03 is projected onto the section from a distance of 500 metres.

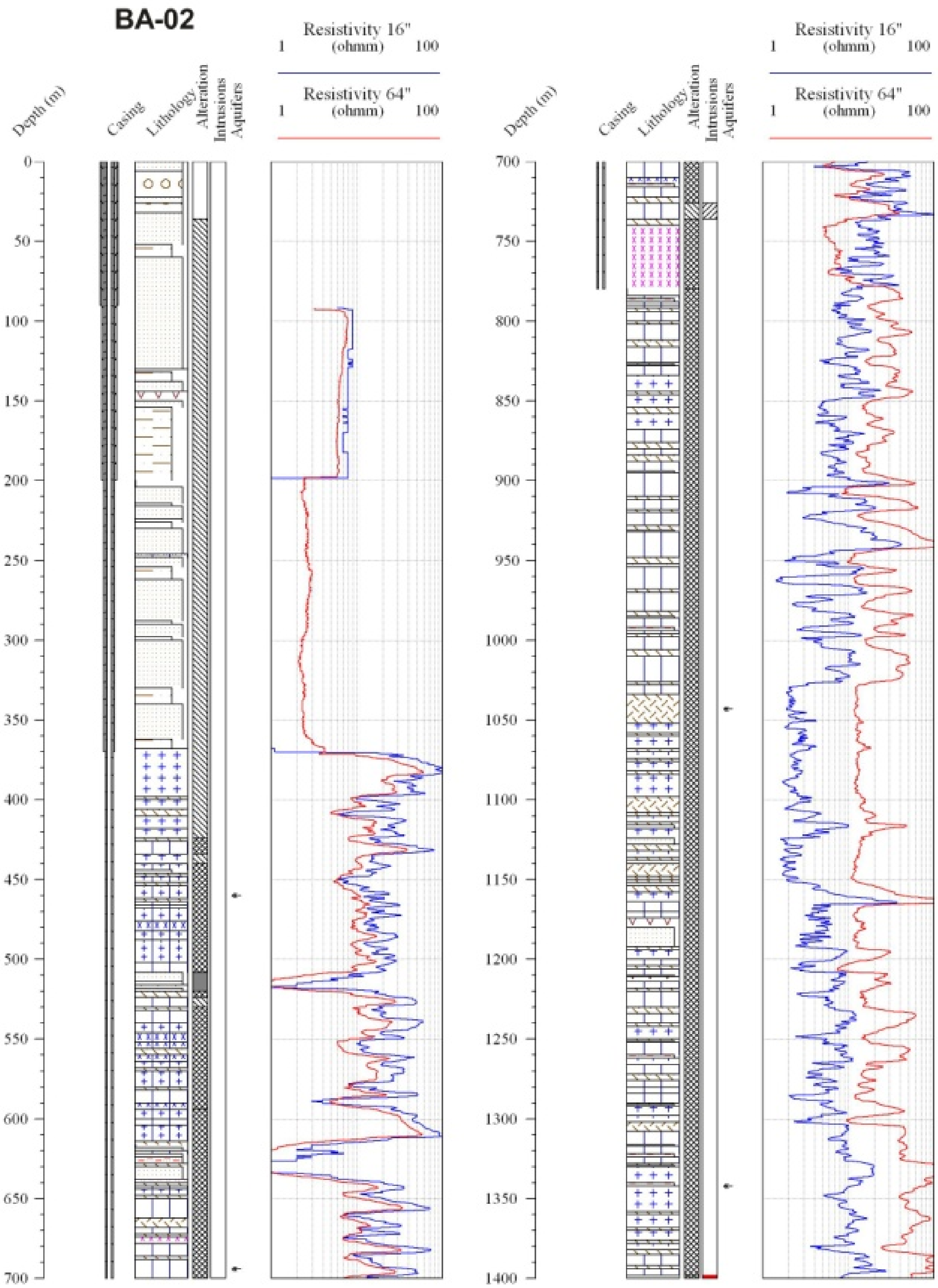

Figure 8. Resistivity log from the well BA-02

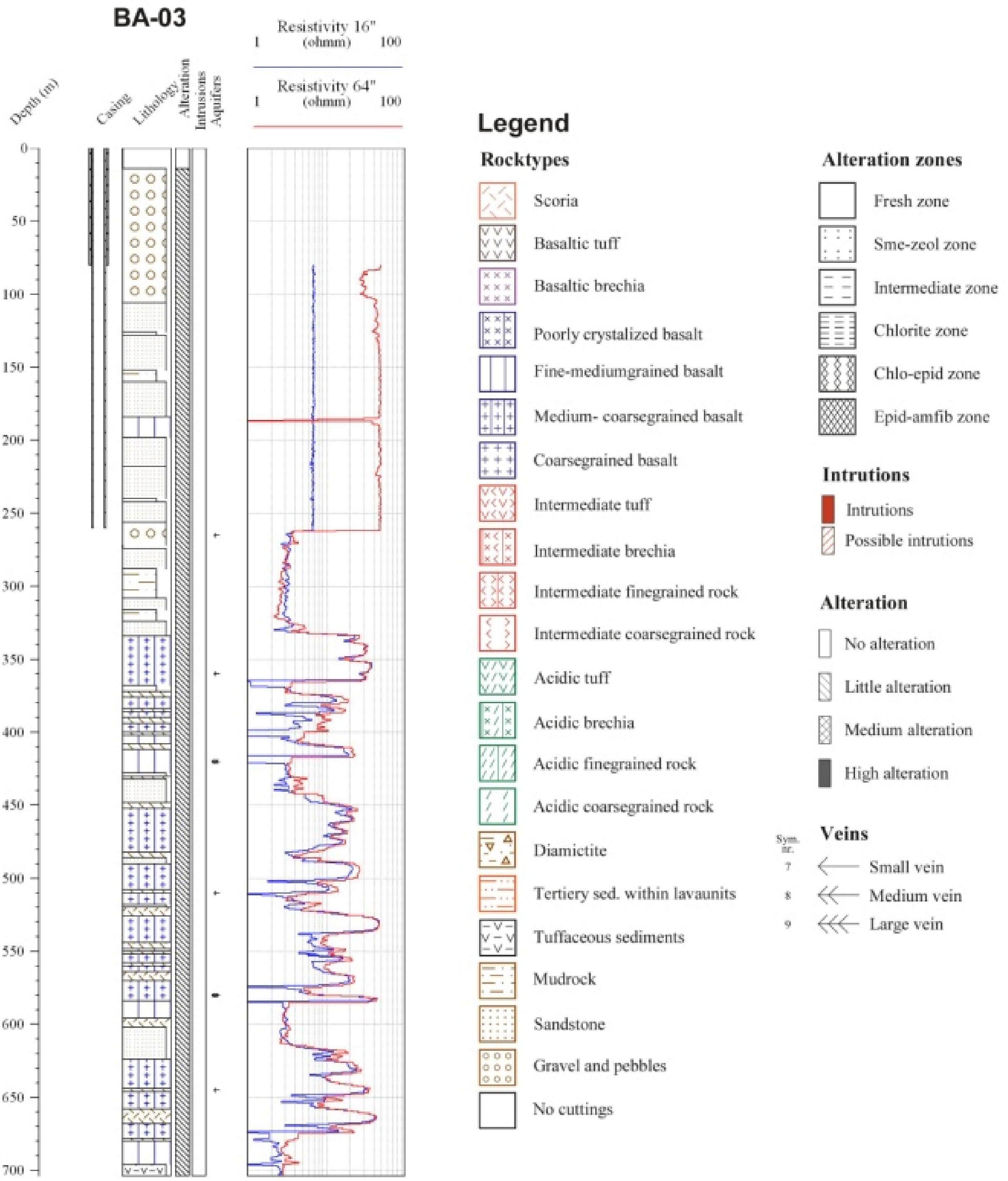

Figure 9. Resistivity log from the well BA-03

The main conclusions are as follows:

1) The difference in resistivity methods

The Schlumberger survey does not resolve the resistivity value in the resistive zone below the conductor close to surface, in conditions as here, with geothermal and saline lateral flow at shallow depth. Misinterpretation of a DC survey, however justified, led to the incorrect conclusions that Oxarfjordur was an extensive high temperature reservoir.

The TEM survey has more downward resolution, seeing through the low resistivity layer at shallow depth and resolving resistivity features below that. The geothermal system is a fracture dominated system with up flow along a few fractures and temperature up to 200°C. The main up flow is under the river Bakkahlaup. Within the range of the TEM survey, down to 800 meters depth there is no indication of the existence of a high temperature system in Oxarfjordur.

The main parameter controlling the resistivity structure in Oxarfjordur geothermal system is temperature and the sediment/bedrock boundary.

2) Geological setting of Oxarfjordur

Oxarfjordur geothermal area is a fracture dominated field, embedded in sediments over tertiary bedrock. It has the character of a low to medium temperature field. It lies within the fissure swarm of the Krafla central volcano where the fissures have made their way into the older rock, immediate south of the junction between the volcanic rift zone and the Tjornes transform fault.

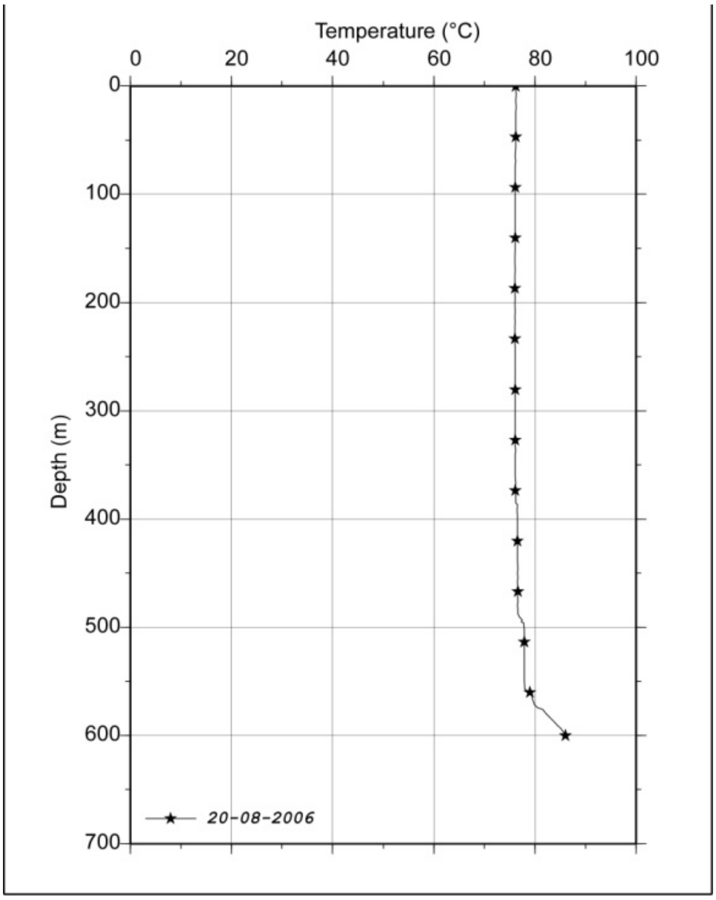

Figure 10. Temperature log from the well BA-04. There is a flow of 70°C-80°C hot water from feed zones from 490-580m depth. Below a strong temperature gradient is observed.

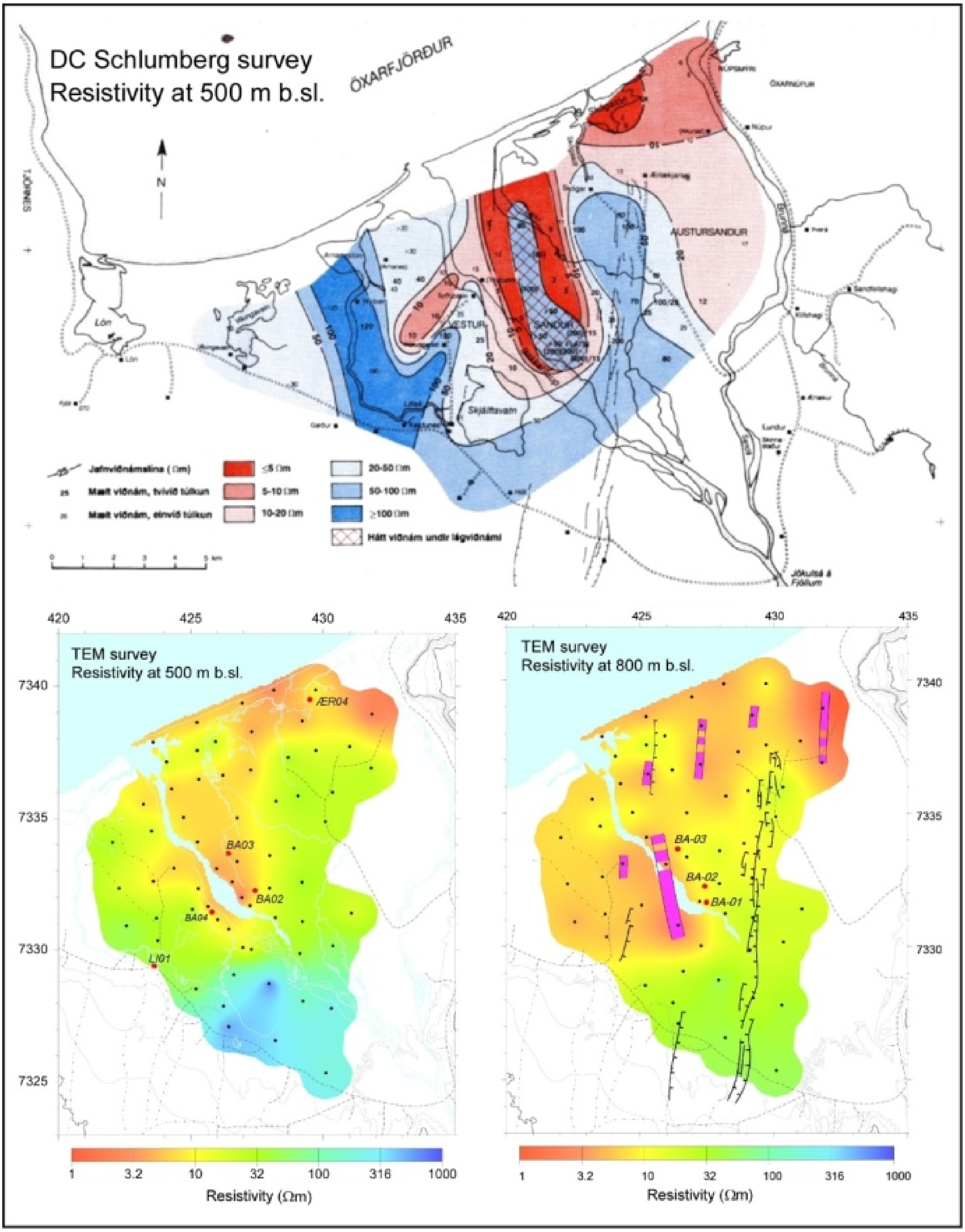

Figure 11. A resistivity map at 500m bl.sl. from the Schlumberger survey (top), shows good correlation to a resistivity map at 200m bl.sl from the TEM survey (bottom left).

REFERENCES

Arnason, K., Flovenz, O.G., Georgsson, L.S. and Hersir, G.P.: Resistivity structure of high-temperature geothermal systems in Iceland. *Abstracts V.2 (International Union of Geodesy and Geophysics XIX General Assembly in Vancuver Canada p447* (1987).

Arnason, K. and Flovenz, O.G. Evaluation of physical methods in geothermal exploration of rifted volcanic crust. *GRC transactions, vol.16 October 1992. 207-217,*(1992).

Arnason, K., Karlsdottir, R., Eysteinsson, H., Flóvenz, O.G., and Gudlaugsson, S.T.: The Resistivity Structure of High-Temperature Geothermal Systems in Iceland. *Proceedings, World Geothermal Congress, Kyushu - Tohoku, 923-928,* (2000).

Flovenz, O.G., L.S. Georgsson and K. Arnason,: Resistivity structure of the upper crust in Iceland. *J. Geophys. Res., 90, 10136-10150* (1985).

Flovenz, O.G., Spangenberg, E., Kulenkamff, J., Arnason, K., Karlsdottir, R., Huenges, E.: The role of electrical interface conduction in geothermal exploration. *Proceedings World Geothermal Congress*, (2005).

Fridleifsson, G.O., Richter, B., Hermannsson, G., Birgisson, K., Sigurdsson, O., Thordarson, S., Thorhallsson, S., Thorisson, S.: Bakkahlaup Öxarfirði. Hola BA-02. Report 1. Drilling 1st 2nd 3rd section. *OS-99064 28p.* (1999 A)

Fridleifsson, G.O., Bjornsson, G., Richter, B., Birgisson, K., Thorhallsson, S., Thorisson, S.: *Bakkahlaup Öxarfirði. Well BA-02. Drilling report.* OS-99079 24p (In Icelandic). (1999 B)

Fridleifsson, G.O., Richter, B., Birgisson, K., Hjartarson, A., Gudlaugsson, S. Th., Bjornsson, G., Thorhallsson, S., Thorisson, S.: *Bakkahlaup Öxarfirði. Hola BA-03. Report. Drilling, geology and logging.* OS-2000/058 20p. (2000)

Fridleifsson, G.O.: Geothermal research at Bakkahlaup. Orkustofnun: Grg. GOF-2001-03 4p. (2001)

Georgsson, L.S., Fridleifsson, G.O., Olafsson, M., Flovenz, O.G., Haraldsson, G.I., Johnsen, G.V.: Research on geothermal activity and sediments in Oxarfjordu/Kelduhverfi area. *OS-93063/JHD-15 63p* (1993)

Georgsson, *L.S., Fridleifsson, G.O., Olafsson, M., Flovenz, O.G.: The Geothermal Exploration of the Öxarfjördur High-temperature Area, NE-Iceland.* Proceedings, World *Geothermal Congress*, Kyushu-Tohoku, 1157-1162, (2000).

Karlsdottir, R. and Flovenz, O.G.: TEM-survey in Oxarfjordur 2004. *ISOR-2005/020 67p* (2005).

Karlsdottir, R.: TEM survey at Bakkahlaup in Oxarfjordur 2005. Grg ISOR-05165 9p.

Kulenkampff, J., Spangenberg, E., Flovenz, O., Raab, S., Huenges, S.: Petrophysical parameters of rocks saturated with liquid water at high temperature geothermal reservoir conditions. *Proceedings World Geothermal Congress*, (2005).

Kristmannsdottir, H.: The role of minerals in geothermal energy research. *From: Uppsala Symposium Clay Minerals-Modern Society 1985. p125-13* (1985)

Kristmannsdottir, H.: Alteration of basaltic rocks by hydrothermal activity at 100-300°C. International clay conference 1978. Elsevier Sci. Publ. Company, Amsterdam 1979, 277-288 (1979).

Richter, B., Fridleifsson, G.O, Hermannsson, G., Birgisson, K., Thordarson, S., Thorhallsson, S., Thorisson, S.: Bakkahlaup Öxarfirði. Hola BA-02. Report 2. Drilling 4th section. *OS-99074 21p* (1999)