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APPLICATION OF THE HEAD-ON RESISTIVITY PROFILING METHOD IN GEOTHERMAL EXPLORATION

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ABSTRACT

The last three years the head-on resistivity profiling method has been tested in geothermal prospecting in Iceland. It has proved extremly useful in detecting and locating subvertical aquifers in low temperature geothermal areas where other methods have failed. The method is a combination of the "half Schlumberger method" and ordinary profiling with Schlumberger arrangement. The principle of the method and interpretation is discussed, and field examples are shown from areas where the model obtained has been confirmed by drilling.

INTRODUCTION

Detection and location of conductive, subvertical faults, dykes or fractures is one of the major tasks in geothermal prospecting, as well as in many other brances of exploration geophysics. In geothermal fields aquifers are commonly connected with fractures and the key to successful drilling is to cut them at a desired depth. Several exploration methods have been used to map subvertical fractures, such as geological mapping, ground magnetic surveys, self potential maesurements, various types of electromagnetic methods and resistivity profiling. Although geological mapping and magnetic measurements are frequently quite useful in detecting faults and dykes they do not distinguish between conductive and nonconductive ones and hence dont indicate if they are waterbearing or not.

Self potential (SP) surveys have been tried with positive results to locate fractures in some geothermal fields in USA (Corwin and Hoover 1979). The experience from SP measurements in geothermal fields in Iceland indicates that self potential anomalies are exceptional. As well the interpretation of SP anomalies are usually troublesome.

The electromagnetic measurements (EM) are of limited use as well, mainly because of how sensitive they are to man-made structures such as pipelines, cables and fences. The depth penetration is also poor in most EM methods. Therfore some kind of resistivity profiling seems to be the most promising way of detecting subvertical, waterbearing fractures.

Profiling methods with several different electrode conifigurations have been tried. Brass et al. (1981) carried out field tests with different electrode configuration over known graphite deposits in Germany and found that the "half-Schlumberger array" gave the most reliable results.

A modified version of the half-Schlumberger method, named the "combined head-on resistivity profiling method", has been used in China since 1958 (Cheng 1980). Originally it was mainly used to detect narrow conducting zones in mining prospecting but since 1965 it has also been used in geothermal prospecting in China.

In the last three years this method has been under test and evolution in prospecting for subvertical faults in low temperature areas in Iceland.

THE PRINCIPLE OF THE METHOD

The electrode arrangement for the head-on resistivity method is shown on fig. 1. An ordinary Schlumberger arangement is set up with current electrodes A and B and potential electrodes M and N. In addition, the third

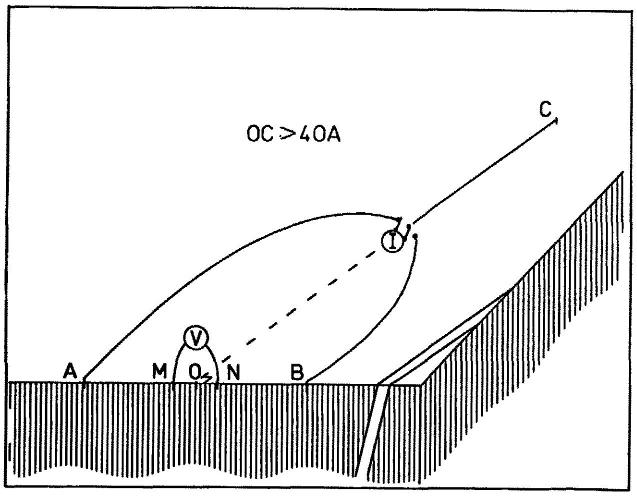

Figure 1. Scematic picture of the electrode arrangement in head-on resistivity profiling.

current electrode, C, is used, placed at "infinity". C is considered to be at infinity when the distance from the potential array MN is large enough to neglect the potential at M and N due to current source at C. It can be shown that the perpendicular distance from the line of the profile to the current source C, has to be four times as great as the distance OA (= OB =AB/2) if the error due to the current from C is to be kept within 2.5%.

The voltage between M and N is measured when current is transmitted between A and C, B and C and A and B, and three corresponding values of the apparent resistivity calculated, AC, BC and ρ_{AB}. The array AMNB is then moved gradually along the profile and new values of the resistivity are calculated. The resistivity is plotted as a function of the location of the center of arrangement O.

Only two of the three resistivity values are independent. The ρ_{AB} is just an average of the two other resisivity and could just be calculated from them. On the other hand since ρ_{AB} can be measured very quikly, it is trongly recommended as it provides information on the quality of the measurements.

When presenting data from head-on resistivity profiling, it is more clear to plot the ρ_{AB} and the differences $\rho_{AC} - \rho_{AB}$ and $\rho_{BC} - \rho_{AB}$ (denoted as ρ_{AC-AB} and ρ_{BC-AB}) along the profiles, since large variations in ρ_{AB} are common.

In case of homogeneous isotropic earth, all the three resistivity values are idendical. But in presence of vertical resistivity contrasts they become different. The electric current always tends to flow along a conductive fracture. Therefore the current density will increase, compared to homogeneous earth, in the area between the current source (A or B) and the conductive fracture, but decrease elsewhere. Since the electric field is proportional to the current density by Ohm's law and the apparent resistivity is proportional to the electric field in the vicinity of the potential array MN, an elevated apparent resistivity will be measured when MN are between the current source and the conductive fracture, but decreased elsewhere.

In fig. 2 a theoretical model for a profile crossing conductive dyke is shown. When the array AMNB (fig. 1) is approching a conductive fracture from left with B leading, the value of ρ_{BC} will decrease ($\rho_{BC}-\rho_{AB}$ negative) since the potential array MN is not between B and the fracture. On the other hand MN is between A and the fracture so the value of ρ_{AC} will be incresed ($\rho_{AC} - \rho_{AB}$ will be positive). When MN crosses the fracture the situation is reversed, i.e. ρ_{BC-AB} becomes negative and ρ_{AC-AB} positive. Just above the fracture ρ_{AC} and ρ_{BC} will be equal, i.e. the curves for ρ_{AC-AB} and ρ_{BC-AB} will cross each other. Therefore it is easy in simple cases to find the strike of the conductive fracture by mapping the crossover point on several lines.

INTERPRETATION OF HEAD-ON DATA

Unfortunately, the real earth is seldom as simple as demontrated in the theoretical examples in fig. 2. Large near surface resistivity anomalies frequently occur and especially in areas of high dyke density or strongly faulted areas considerable vertical resistivity contrasts are observed. In such complicated cases, the curves for ρ_{AC} and ρ_{BC} do not neccessary cross above conductive fractures, and detailed modelling is needed.

At the National Energy Authority in Iceland the modelling is done by a finite difference program, based on Dey (1976). An initial model is made by looking at the data and the program calculates the model response, which is then manually compared to the original data. The model is then adjusted until a satisfactory fit is obtained. In such interpretaion one must keep in mind that the model obtained is not an unique solution.

Figs. 2 and 3 both show theoretical curves for a model containing a 25 m, conductive dyke in a homogeneous medium. The dyke in fig. 2 reaches to the surface. The curves for ρ_{AC-AB} and ρ_{BC-AB} cross just above the dyke and an anomaly of approximately 30 Ohmm is found, which is approximately 30% of the resistivity in the homogeneous media. Also a low resistivity anomaly of about 50 Ohmm is found in the ρ_{AB} curve just above the dyke. The dyke on fig. 3 is buried at 200 m depth. As before the curves for ρ_{AC-AB} and ρ_{BC-AB} cross each other just above the dyke and the amplitude of the anomaly is approximately 12 Ohmm. The curves for ρ_{AB} show now a maximum value above the conductive dyke with minimum values on both sides. This suggests that resistivity profiles with Schlumberger arrangement can easily be misinterpreted.

Fig. 4 shows a theoretical curves for a 25 m thick, low resistivity surface anomaly in homogeneous medium. Comparison with fig. 2 shows that similar anomaly in the ρ_{AB} curves are obtained indicating that the ρ_{AB} curve primarily reflects near surface structures. The curves for ρ_{AC-AB} and ρ_{BC-AB} show considerably less anomaly, both in amplitude and horizontal extent. This suggests that it is possible by modelling work to distinguish between low resistivity anomalies caused by dykes and those which are caused by surface phenonmena.

In fig. 5 theoretical curves for a high resistivity dyke in homogeneous earth is shown. The curve for ρ_{AB} shows very strong and narrow anomaly just above the dyke, but the anomalies in the ρ_{AC-AB} and ρ_{BC-AB} curves are complicated and of low amplitude.

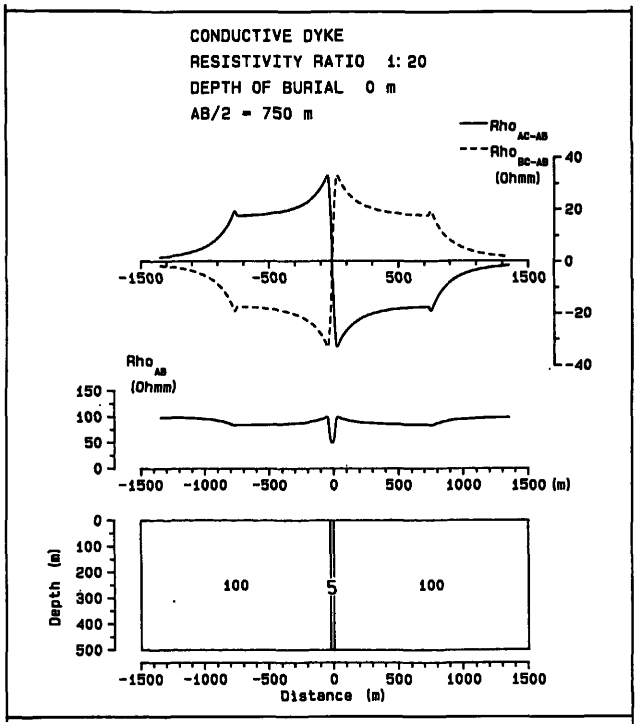

Figure 2. Calculated curves for head-on anomaly over a 25 m wide conducting dyke in homogeneous half space

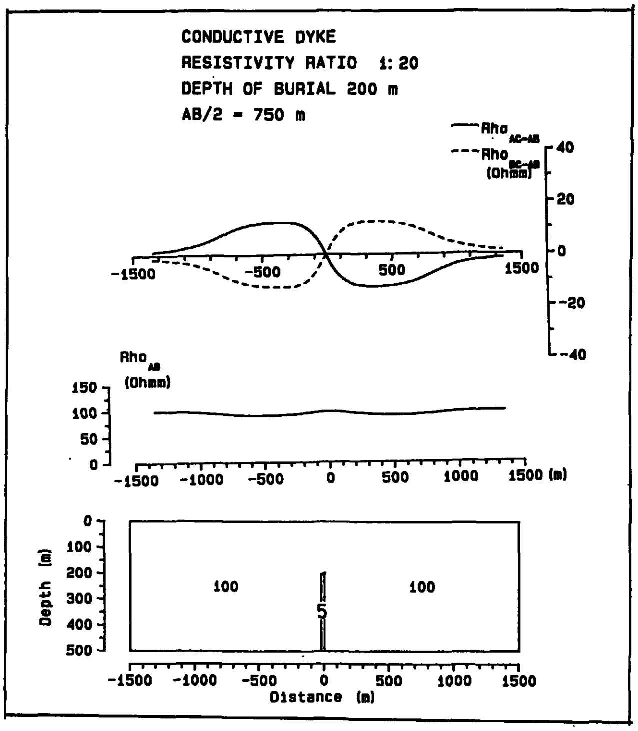

Figure 3. Calculated curves for head-on anomaly over a 25 m wide conducting dyke burried at 200 m depth in homogeneous half space

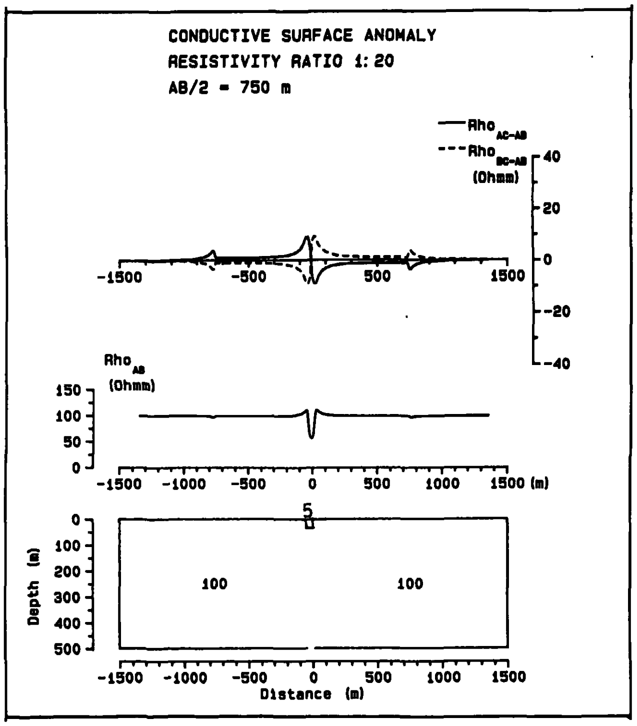

Figure 4. Calculated curves for head-on anomaly over a 25 m wide and 25 m thick conducting surface anomaly in homogeneous half space

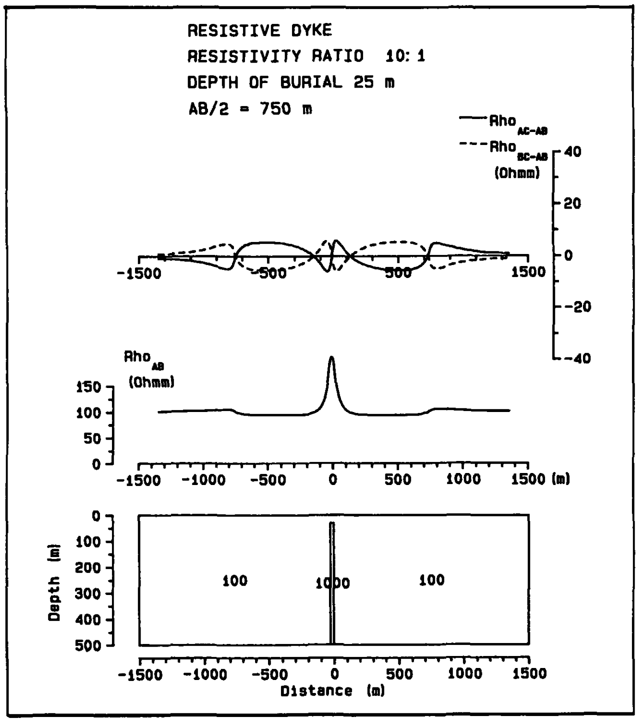

Figure 5. Calculated curves for head-on anomaly over a 25 m wide resistive dyke burried at 25 m depth in homogeneous half space

EQUIPMENT AND FIELD PROCEDURE

The head-on resistivity profiles in Iceland are usually 1-3 km long. The instruments used are designed and produced by Microprocessor Technology Ltd. in Reykjavík, in cooperation with the electrical laboratory of the National Energy Authority. The equipment is composed of two units, a 500W constant current transmitter driven by a 24 V car battery and a microprocessor contolled receiver unit. The signal from the transmitter has a form close to a square wave with period 4, 8, or 16 sec. Maximum output current is 1 Amper and maximum output voltage is 1000 Volt. Each time the polarity of the signal changes a syncronizing puls and the value of the transmitted current is sent through a fiber optic cable to the receiver. The input sensitivity of the receiver is 5 V. It measures the voltage difference, integrated over a short period of time, between the positive and the negative part of the incoming signal. Thus both high frequency noise and drift in the self potential are ignored. The microprocessor calculates the average value of the current and the voltage signal, the apparent resistivity and its standard deviation and numbers of readings. The data, the calculated values and some information on the geometry appears on a digital display. It is also possible to connect a printer and a data logger to the receiver and store all measured values.

The current electrodes are approximately 50cm long steel or aluminium rods. In areas of high contact resistivity several parallel connected rods are used. The potential electrodes consist of a copper rod in a $CuSO_4$ solution.

The distance between the potential electrode, M and N, is usually 50 m. The distance from the center of array to the current sources A (OA) and B (OB) is between 250 m and 750 m. Each line is usually measured for two or three different values of OA. When deciding the distance OA several things must be taken in to account. Firstly we want to minimize effects from near surface inhomogeneities. This can be done by having OA large, but that means lower voltage signal and increased electromagnetic coupling between current and potential wires. Obviously we need some sort of compromise. Fig. 6 shows the maximum amplitude curves of the ρ_{AC-AB} for three different values of the distance OA as a function of the depth to the top of a conductive dyke in homogeneous media. The resistivity contrast is 5:100. In all cases a considerable anomaly is found when the dyke reaches the surface although it is much lower for the largest spacing then for the shortest one. When the depth of burial is close to 75 m the anomalies are similar for all the three cases and below 130 m the anomaly is largest for the greatest spacing OA. The difference between the curves for OA=500 m and OA=750 m is relatively small so it seems resonable not to choose the largest spacing used more than 500 - 750 m. According to fig. 6 we could expect, under favorable circumstances, to be able to detect a low resistivity dyke if the depth of burial is not more than 200 - 300 m.

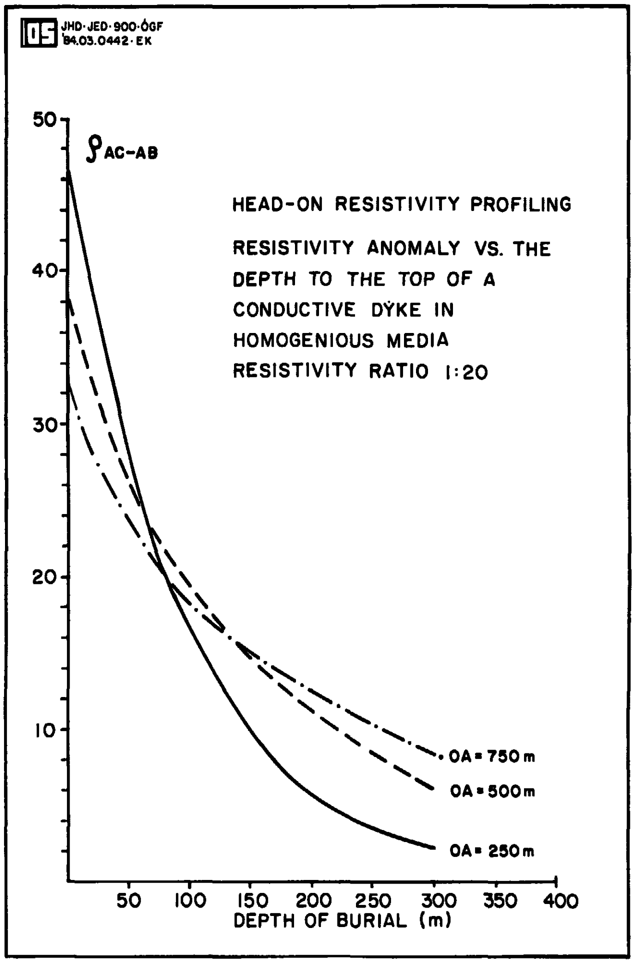

Figure 6. Maximum amplitude in the ρ_{AC-BC} curves as function of the depth of burial of a conductive dyke in homogeneous medium.

In Iceland a field crew of 5-6 is commonly used to carry out head-on resistivity measurements. The resistivity is measured for only one current arm simultaniously, which means that the array AMNB has to be moved three times along the profiling line if three different distances, OA, are to be measured. One person operates the instruments, which are mounted in a four wheel drive truck. Cables are led from the truck to the current and potential electrodes. Two assistants are needed to move the current electrodes and one person moves both the potential electrodes. The fifth person acts as an assistant in the truck. His job is to assist the operator.

It takes, on the average, 1 day to carry out 1 km of head-on resistivity profile and the cost is close to 1000 $ per day. The processing cost is estimated to be close to 700 $ per kilometre.

EXAMPLE 1: GLERÁRDALUR NORTH-ICELAND

In the Glerárdalur low temperature field in North Iceland, warm water emerges from an exposed dyke in a 50 m deep gully in a mountain side at elevation about 200 m above sea level. The hot spring is only 2-3 km away from Akureyri, a town of 13000 people. Drilling of several boreholes close to this dyke before 1970 gave negative result. The deepest well was 647 m and showed relatively low thermal gradient. Further research was abandonned until 1980 when detailed geological mapping and a resistivity survey with Schulmberger soundings were carried out.

In the summer 1981 the first head-on survey in Iceland was made at Glerárdalur along several lines perpendicular to the strike. Each line was measured by two different spacings, OA (fig.1), 200 m and 400 m. The distance between the potential electrodes M and N was 50 m and the resistivity was measured every 25 m along the prospecting line. Fig. 7 shows an example of the data and its interpretation. Two low resistivity fractures were observed, interpreted to be permeable fractures. Several thermal gradient wells (100-300 m) were drilled in the area and a high thermal gradient was observed above these fractures. This was followed by drilling of 793 m deep production well, sited over the left low resistivity anomaly on fig. 7. A permeable dyke was cut in this well and approximately 30 l/s of 62°C water is now pumped to Akureyri where it is used for space heating.

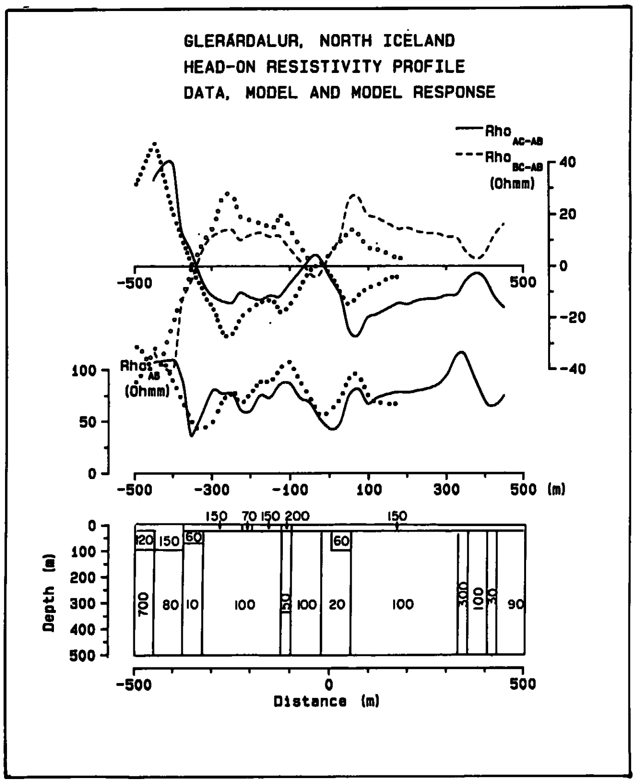

Figure 7. A head-on resistivity model and calculated model response of the Glerárdalur geothermal field in North Iceland compared to the field data (dotted lines). Drilling into the 10 Ohmm low resistivity anomaly was successful.

The total cost of all the prospecting surveys was 54000$, and the total drilling cost was 367000$. The mean annual energy production from the area is now 32.3 GWh. If the area has a life time of 25 years and the interests are 8% per year the then the part of the energy price which is due to prospecting and drilling is as low as 1.2 mills per KWh.

EXAMPLE 2: URRIÐAVATN, EASTERN ICELAND

At the bottom of lake Urriðavatn in Eastern Iceland hot water emerges from the basement at depth of 10-20 m. Detailed investigation of the geothermal system is described by Einarsson et al.(1983) Ground magnetic surveys and geological mapping shows several dykes and faults crossing the upflow area. Six wells were drilled, either from the shore or from a narrow protrusion which was built for the purpose of drilling. The only success was that several aquifers at shallow depth (100-300 m) were found. Only minor aquifers were observed in connection with the dykes. The deepest well is close to 1800 m and four wells are deeper then 600 m. The temperature of the water from these wells was only around 60°C, but temperature profiles in the deeper wells indicated a geothermal system of 70 -80°C. Therefore it was concluded that the wells had not cut the main aquifers. Nevertheless approximately 30 l/s of the water from these wells was pumped to the village Egilsstaðir, 5 km away and used there for space heating. Shortly after the pumping began, the water from the wells started to cool. The only way to solve this problem was to find the main aquifers, which were belived to be subvertical fractures.

In the summer 1983 a head-on resistivity survey was carried out across the 500-700 m wide lake Urriðavatn. Since the lake contains only fresh water the resistivity of it is of the order 100 Ohmm, which is similar to the near surface resistivity around the lake. Fig. 8 shows the result from a typical head-on resistivity profile across the lake, in the vicinity of the hot springs, and a model which fits the data. Two low resistivity fractures were observed, the one with lower resistivity is close to the area of the main upflow at the bottom of the lake. Note that even thought very clear intersection of the curves for ρ_{AC-AB} and ρ_{BC-AB} is observed, almost no anomaly in the curve for ρ_{AB} is seen. By comparing the models from individual lines it was easy to trace the strike of the conducting fracture. The dip of it was estimated from the temperature profiles in wells and a new production well was sited. At depth between 500 and 700 m, several aquifers were cut. After completing the drilling there was a free discharge of approximately 14 l/s of 76°C water in spite of a drawdown close to 100 m in the nearby pumping wells.

DISCUSSION

The examples above are choosen from several cases where the method has been tried in prospecting for subvertical aquifers in low temperature geothermal areas in Iceland. In all the cases when it has been possible to find a low conductivity fracture by this method and have it tested by drilling the results has been positive. The main reason for the efficiency of the method in low temperature fields in Iceland is that large contrast in resistivity is between the water bearing fractures and the surrounding rocks. In high temperature geothermal areas this contrast is much lower and hence the anomalies caused by subvertical fractures are small. However, data from the Olkaria high temperature geothermal field in Kenya indicates that head-on resistivity profiling may be of great importance there in locating fractures (Mwangi 1982). The method is now under test in high temperature areas in Iceland.

ACKNOWLEDGEMENT

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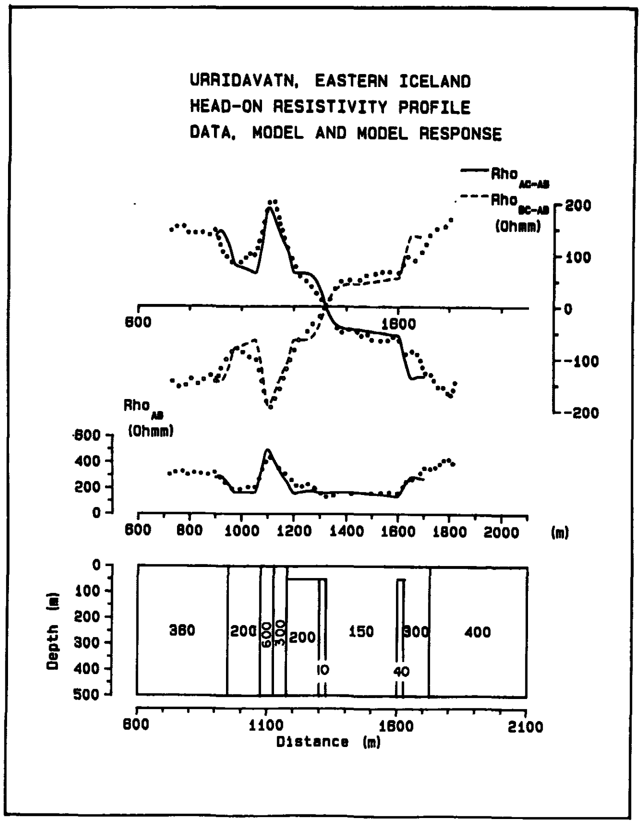

Figure 8. A model and calculated model responses compared to the field data (dotted lines) from the Urriðavatn geothermal field in Esatern Iceland. Drilling into the 10 Ohmm fracture was successful.

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