ON SCHLUMBERGER SOUNDINGS AND HEAD-ON MEASUREMENTS

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ABSTRACT

The results of the interpretation of three resistivity profiles made for geothermal exploration are presented. Two of the profiles were done using the Head-on array. They are from the Urridavatn low temperature geothermal field in Iceland. The third profile is from the Miravalles high temperature geothermal field in Costa Rica. It was made employing Schlumberger soundings.

For the interpretation of the profiles a program developed by Dey and Morrison (1976) was used. For one-dimensional interpretation of Schlumberger soundings a program developed in Iceland is used.

A low resistivity zone (2 to 25 ohmm) is detected between 50 and 200 m depth at the Miravalles geothermal field. Relatively high resistivity layers are seen both at the top and the bottom. Lateral variations around soundings 20, 31, 54 and 64 divide the low resistivity layer.

Low resistivity blocks in the Urridavatn area are found in the central part of the two lines interpreted. The low resistivity crossover in the Head-on profiles might indicate a thin vertical structure.

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1 INTRODUCTION

1.1 Scope of work

The main purpose for this report as a requirement at the end of the practical training course, is to present the resistivity interpretation the author has done from three profiles, two with Head-on measurements and one with Schlumberger soundings.

The Geothermal Training Programme, which takes six months and is sponsored by the National Energy Authority of Iceland (ORKUSTOFNUN) and the United Nations University (UNU), begins with an introductory lecture course during the first month. This course gives a view over the different sciences involved in geothermal exploration such as Geology, Geophysics, Reservoir Engineering, Drilling Technology, Geochemistry, etc. After the introduction the specific training starts. For the author it involved training in electrical methods for geophysical exploration, applied to geothermal field prospecting. In addition, the UNU Fellows went on excursion (8 days) to the most important geothermal fields in Iceland.

In accordance with the main needs of the home country of the author, Costa Rica, the main objects kept in mind during the geophysical training programme, were numerical interpretation of Head-on measurements and of one- and two-dimensional Schlumberger soundings. Moreover, different aspects to improve the collection of field data were discussed as well as soundings design and the principal aspects to choose the best equipment according to the local conditions.

1.2 Areas considered and methods used

In this report data from two geothermal fields are interpreted i.e. from the Urridavatn low temperature area in Eastern Iceland and from the Miravalles high temperature geothermal field in North-Western Costa Rica.

From Urridavatn there have been interpreted two Head-on profiles of 1200 m length each line (Lines 3 and 5), the AB/2 used was 300 m (only in line 3) and 500 m with MN/2 of 25 m in both cases. From Miravalles eleven Schlumberger soundings with AB/2 of 2000 m and MN/2 of 240 m maximum were interpreted. All of them are set up in one profile which has been called 23.

The Head-on profiles were interpreted by means of the program DIM2K. The Schlumberger soundings were interpreted in two stages, firstly by employing the program ELLIPSE for one-dimensionl interpretation, and secondly through two-dimensional interpretation using the program DIM2. The programs will be explained later, however, it should be mentioned that the program ELLIPSE was developed in Iceland, by the scientific staff of the National Energy Authority (Orkustofnun).

This excercise has given the author a valuable experience in comparing the interpretation of geophysical data using the classical methods and the numerical ones.

2 BASIC THEORY OF SCHLUMBERGER SOUNDINGS AND HEAD-ON MEASUREMENTS

This chapter is presented in order to provide a general idea about the theoretical aspects of the processing data system used for interpreting Schlumberger soundings and Head-On profiles. It is not a detailed theoretical analysis, but the necessary references are given to be consulted in case of a particular subject.

2.1 Schlumberger soundings

2.1.1 One-dimensional interpretation (ELLIPSE)

The potential at a given point on the surface of a homogeneous earth, due to a point source of current can be written as follows:

$$V_p = \rho I / 2\pi r, \qquad (1)$$

where V_p is the potential or the point, ρ is the resistivity of the homogeneous earth, I is the intensity of the current injected at the point source and r is the distance from the point source to the point where the potential is measured.

If we consider a symmetrical linear electrode configuration (Fig. 1) the potential difference between the two measuring electrodes will be given by

$$\Delta V = 2(\rho I / 2\pi) \cdot \left(\frac{1}{s-b} - \frac{1}{s+b}\right) \qquad (2)$$

If we solve the equation for ρ we can get the expression for the apparent resistivity:

$$\rho_a = (\Delta V / I) \cdot 2\pi \cdot s(s^2 - b^2)/(4bs) \qquad (3)$$

where the factor $(s^2-b^2)/(4bs)$ is known as the geometrical factor.

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A                 M     N                 B
X-----------------X---0---X-----------------X
                      +-b-+
                      +----------s----------+
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Fig. 1: Linear symmetrical electrode configuration, Schlumberger array.

According to the Schlichter's kernel function (Koefoed, 1979) the expression for the surface potential due to a point source becomes:

$$V = \frac{\rho_1 I}{2\pi} \int_0^{\infty} K(\lambda) \cdot J_o(\lambda \cdot r)\, d\lambda \qquad (4)$$

Then combining all this equations we get another expression for the apparent resistivity:

$$\rho_a = 2\rho_1 \cdot s\left(\frac{s^2-b^2}{4bs}\right) \int_o^{+\infty} K(\lambda)\left[J_o(\lambda s-\lambda b)-J_o(\lambda s-\lambda b)\right] d\lambda \qquad (5)$$

or using $T(\lambda) = \rho(\lambda)K(\lambda)$:

$$\rho_a = 2s\left(\frac{s^2-b^2}{4bs}\right) \int_o^{\infty} T(\lambda)\left[J_o(\lambda s-\lambda b)-J_o(\lambda s+\lambda b)\right] d\lambda \qquad (6)$$

These two equations (5 and 6) are used to make the program ELLIPSE, which has been used in one-dimensional interpretation.

If $c=b/s$ is arbitrarily defined as the eccentricity the last equation can be rewritten as:

$$\rho_a = 2s\left(\frac{1-c^2}{4c}\right) \int_o^{\infty} T(\lambda)\left[J_o(\lambda s(1-c)) - J_o(\lambda s(1+c))\right] d\lambda \qquad (7)$$

This equation varies with the electrode configuration used (Koefoed, 1979).

The difference between ELLIPSE and the programs already known for one-dimensional interpretation, is that it considers simultaneously the variation of both MN/2 and AB/2 (b and s). In this way it is possible to calculate directly the resistivity at each point taking into account the rate between MN/2 and AB/2 (that is the eccentricity). To correct this effect in ELLIPSE the overlaps have been divided into two types depending on their shapes. If the overlap is convergent, going down in the field curve this is a one-dimensional effect, but if the overlap has any other shape it is considered as a two-dimensional effect. Fig. 2 shows different examples of this effect.

A) ONE-DIMENSIONAL EFFECT. A convergent shape is observed when the eccentricity tends to zero. In that case the value we are measuring tends to be the gradient dV/dx for x=0.

B) TWO-DIMENSIONAL EFFECT. A parallel form is observed when the potential electrodes change their position over different resistivity bodies, in this case a high-resistivity body surrounded by a low resistivity one. In the first part of the curve the measuring electrodes are on the high resistivity body, in the second part they are on the low resistivity one.

C) COMBINED EFFECT. This is observed when the above situations are found at the same time.

In order to increase AB/2 it is necessary to increase MN/2 because the potential ΔV, becomes too small to be read on the receiver. This is the reason for the field curve ρ_a versus AB/2 usually being composed of as many segments as the number of different MN/2 that have been used during the data collection (Fig 2). The question in this case is which one of the segments reflects the real conditions in the earth. The variations in the overlaps depend on the eccentricity and on the surface inhomogenities which distort the current distribution pattern.

The problem of the eccentricity can be corrected for by applying linear filter methods. In the case of surface inhomogenities the correction is not well defined yet. Koefoed (1979), suggests an adjustment by multiplying all the apparent resistivity values in a segment (for a given MN/2) by a factor determined by the parallel shift of the whole segment on logarithmic scale.

The program ELLIPSE considers both problems by using linear filter methods. In general terms this program treats the two problems in the field curve by calculating one parameter which varies of the order of the magnitude of the overlap. A least square inversion is subsequently made.

2.1.2 Two-dimensional interpretation

A brief explanation will be given below of how the program DIM2 is used for a quantitative interpretation. For further reading Dey and Morrison (1976) is recommended. An elucidating summary is also given by Mwangi (1982).

Dey and Morrison (1976) developed a numerical technique for three-dimensional potential distribution caused by a single source of current, into a half space with an arbitrary two-dimensional conductivity distribution. The program, considers the distribution of the potential on a rectangular grid nodes by computing the apparent resistivity, and approximating Poisson's equation by using finitedifference equations. Solutions are obtained with a matrix inversion process. The method considers all shapes of two-dimensional geologic bodies with infinite extent along the strike. A theoretical model divided in vertical blocks is given and the size depends on the net previously chosen. The process is repeated as often as necessary depending on the fit between the field curve and the theoretical curve obtained by means of the program. Pseudosections can be made for this purpose to compare the field curve and the model curve.

2.2 Head-on measurements

The theoretical aspects of this method was treated by Cheng (1980) and summaries can be read in Mwangi (1982) and Alhamid (1982). Application of the method in geothermal exploration can be found in Flovenz (1984).

The Head-on array has the same electrode position as the Schlumberger array, with a third current electrode (called C) added at infinity. The current is injected at three different positions AB, AC, and BC. The readings are obtained by the usual MN potential electrodes.

After each set of reading the whole array is moved to the next station and so on. The C electrode can be kept in the same position if AB OC >> 2AB.

The method seems to have a good resolution for locating vertical low and high resistivity bodies such as dykes and faults. The method has been used with success in the People's Republic of China to locate shallow faults in geothermal investigations, and recently also in Iceland (Flovenz, 1984).

The same program is used as in two-dimensional Schlumberger interpretation, the only difference being the (set up to) data collection.

3 THE MIRAVALLES AREA

3.1 Geological setting

The Miravalles Geothermal Field is located on the volcanic ridge of Guanacaste in the North-Western part of Costa Rica. The ridge is mainly composed of volcanics of Quaternary and Tertiary age.

The stratigraphy of the area can be summarized as follows from the top to the bottom (from E.L.C., 1983)

Recent Lavas	(andesites)
Lahares Miravalles Volcano	(pyroxene andesites)
Miravalles Palaeo-volcano	(lavas)
Cabro Muco-La Giganta complex	(andesites and pyroxene basalts)
Volcanic Sediments	(tuffs, clays, and sandstones sometimes with fossils)
Pyroclastic Deposits	(tuffs, ignimbrites and sandstones)
Precaldera Lavas	(pyroxene-andesites and basalts)

The area is cut by two main fracture systems trending N-S and NE-SW, respectively. The Guayabo Caldera is also an important feature as the promising geothermal areas are situated within it. Moreover, some graben structures have also been observed within the caldera.

3.2 Geothermal manifestations

The main geothermal features are fumaroles and hot springs that are controlled by the system of fractures mentioned above. In the Las Hornillas area the geothermal manifestations are perhaps the most evident and geothermal investigations were initiated there.

Geothermal gradients of the order of 200°C/Km were found in an area about 10 Km^2. Geothermometers (SiO_2 and Na-K-Ca) revealed temperatures higher than 200°C. In addition to this the interpretation of electrical soundings showed a resistivity anomaly (less than 10 ohmm) between 400 and 600 m depth, in the Las Hornillas area.

3.3 Schlumbergar soundings interpretation

The Schlumberger soundings dealt with here correspond to profile 23 in Miravalles geothermal field. The profile is located inside the Guayabo caldera about 4 Km SE of the crater of the Miravalles volcano close to the Las Hornillas site. The profile is 5 Km long with 11 soundings of 2000 m AB/2 maximum. The depth of investigation is about 700 m, according to the two-dimensional interpretation. However, one-dimensional interpretation indicated deeper penetration. The separation between individual soundings was 400 to 900 m.

The procedure started with a one-dimensional interpretation by means of the ELLIPSE program. The results are presented in Appendix 1. All the soundings have similar curves, except that the lowest resistivity layer which appears in the whole profile might be cut by lateral thin bodies. Unfortunately the separation between soundings was to long to permit the analyses of thin structures like dykes or faults. The resolution was not good. There might be significant lateral changes between soundings 15 and 20, 26 and 31, in 54, and between 64 and 69. These changes are probably the result of strong variations near the surface, principally in the uppermost 200 m. The main reason is that the profile crosses different geological formations which includes lahares, different kinds of lavas, and geological structures, which affect the shallow resistivity values.

According to the one-dimensional interpretation the layer with the lowest resistivity is between 150 m and more than 1100 m thick (see Appendix 1). The layer is found in the entire profile and its calculated resistivity is in the range of 1 to 10 ohmm.

In all the soundings except in 15 there is a bottom layer with a relatively high resistivity (more than 12 ohmm). Soundings 31 and 35 seems to have the same tendency but the situation is not very clear.

Different two-dimensional effects can be observed in the first part of all the soundings, that is in the first 700 m.

One-dimensional interpretation of the same data does not always correspond with the two-dimensional one. Another trouble that appear in soundings 54 and 59 is the high slope (more than 45 degrees) of the field curve. This effect might be explained by the occurrence of lateral variations, such as vertical contacts or vertical structures.

The two-dimensional interpretation on the other hand showed a high resistivity bottom layer in soundings 20, 26, 31, 59 and 64 (Fig. 3). The thickness of the low resistivity layer is no more than 700 m. This layer is most shallow in the central part of the profile and also on its edges. In the centre of the profile it is at 50 to 75 m depth and at the edges it is at about 200 m depth.

It was observed that an increasing slope in the last part of the field curve does not always indicate a high resistivity layer. This effect might be created by many different reasons, such as higher lateral resistivity blocks in relation to the position of the current electrodes, or ingeneralby any other surface inhomogenities. Soundings 40, 49 and 54 did not reveal the same results as in the one-dimensional interpretation (Fig. 3, model 2). The results showed that the solution is not unique. This is the main reason for not depending completely on a one-dimensional interpretation, but combination of methods.

Interpretation of sounding 64 is the most problematic. It has been treated in many different ways. Fig. 3 shows the 3 models that have been chosen, Fig. 4 shows the pseudosection of the field data, and Fig. 5, 6 and 7 show the pseudosections from three different models. There are three different possibilities. In models 1 and 2 a high resistivity bottom layer appears (400 ohmm). The difference between the models is in the thickness of the second layer. In model 2 the second layer is 100 m thicker than in model 1. The bottom layer does not appear in the third model and thus the thickness of the low resistivity layer is undefined.

All the final models seem to indicate a significant change around sounding 54. Another important change appears between soundings 15 and 20 and between 31 and 35. This might be produced by thin vertical structures which should be analysed by adding some soundings and reinterpreting the profile.

4 THE URRIDAVATN AREA

4.1 Geological setting

There are three rock formations have been observed in Iceland, namely Tertiary rocks, Quaternary rocks and Recent volcanics. The Tertiary rocks are located in eastern and north-western part of the country. The, Quaternary rocks are located between the Tertiary and the central part of the country, and are Quaternary rocks dominated by lava flows and hyaloclastites. The youngest formation is found in The Neovolcanic Zone, which is in fact the surface manifestation of the Mid Atlantic Ridge according to the plate tectonics theory. It crosses Iceland from SW-NE but is divided in several branches. It is easily recognized at the surface because the main characteristics are fissure swarms and active central volcanoes.

Urridavatn, thearea directly involved inthis work, is located entirely in the Tertiary zone, and is dominated by extinct fault swarm and dykes trending NE-SW. The surface rocks are mainly porphyritic basalts and the dykes are finer grained than the lavas. Porphyritic dykes however occur.

According to Einarsson et al. (1983) there are four lithological series in this area :

D: tholeiites
C: porphyritic basalts
B: tholeiites
A: tholeiites and porphyritic basalts

Several dykes appear everywhere cutting the whole geological landscape. The dykes have the same orientation as the fault swarm. The regional dip is very smooth, about 6 degrees in a SW direction. Faulting displacements between 15 and 100 m are, however found.

4.2 Geothermal manifestations

The Urridavatn area is a low temperature geothermal field in the neighborhood of the town Egilsstadir. There 1100 inhabitants live and the purpose of exploiting the geothermal area is to supply water for district heating services. The flow rate and temperature necessary for this purpose is about 35 l/s and > 70°C, respectively.

The known geothermal manifestations are only on the bottom of the Urridavatn lake. These consist mainly of some gas bubbling and water with higher temperatures than the surrounding water. According to an isogradient map the thermal manifestations are oriented SW to NE, i.e. in the same direction as the fault swarm and the dyke system.

Eight wells have been drilled in the lake. The temperature of the aquifers in the wells has been measured about 70°C, and the pumping rate is about 35 l/s. Cooling of the wells is a serious trouble and this is related to the amount of water pumped out of the system. Trace studies have revealed that this problem is caused byinfiltration of cold water from the lake. From the 8 wells drilled only 4 are productive, and two of them are cooling down.

4.3 Head-on profiles interpretation

As an excercise, two lines already interpreted were chosen to learn how to use quantitative methods for interpretation. Both profiles are located on Urridavatn lake. The main reason for locating the lines across the lake was that the geothermal manifestations are confined to the bottom of the lake. Moreover previous work like surface geological mapping, magnetic survey and temperature map showed that the most promissing area was seated in the lake, which is not more than 15 m deep.

It should be mentioned that the method used was adapted for working on the surface of the water. It was necessary to tend the wires over the lake, a rope held the porous pots and the current electrodes and they were pulled for changing stations. The electrodes and the porous pots were kept floating by buoyes.

The lines considered by the author are number 3 and 5. Fig. 8 to 10 show the field data and the models found. The purpose of the profiles was to look for low resistivity zones whichcould be related to geological structures such as dykes, faults, etc., which might indicate acquifers. The prescence of low resistivity crossover in all the Head-on profiles revealed a thin structure that helped to choose the drilling site for a new well.

Line 3 (Fig. 8) shows that the low resistivity crossover appears near the -200 coordinate. The resistivity found is of the order of 15 ohmm, but toward the left side of the profile there appears a low resistivity zone until the coordinate -300 m. The resistivity is 50 ohmm. On the right side of the crossover, two relatively low resistivity areas also appear. They are on the coordinates 100 m and 350 m respectively. However, the second one is not as reliable as the ones which are in the centre of the profile, because the assumed model did not consider any situation beyond the extremes of the profile. The quality of the interpretation is only reliable in the central 400 m of the profile.

The behaviour in line 5 is very similar to that of line 3. A low resistivity block was found in the central part of the profile which can easily be related with line 3. In the central part of the profile a crossover was found as in line 3. However, a high resistivity block in line 5 cuts the low resistivity zone which is in an equivalent position on the left of the crossover of both profiles.

The lines 3 and 5 are only separated by 200 m. The same is true for the rest of the profiles. All of them show that the situation does not change in such a short distance.

5 DISCUSSION

To point out the most interesting part of the practical training this chapter has been divided into three parts. These are considered to be the most useful parts of the training of the author for the home country.

5.1 Field work

This part has been considered carefully by the author because some modifictions can be done in order to improve the field work and to make it more effective. This is important because good field work is one of the main issues to secure success in the final interpretation. Other important factors are how fast the field work can be done and how convenient the data processing system is. This should not be forgotten because all these facts are also important in relation to the cost.

For obtaining the measurements it is usually necessary to take at least 20 readings on each AB/2, but of course that depends on the conditions of the ground. For instance in the Urridavatn area some AB/2 needed up to 200 readings to ensure steady average.

In the case of the Miravalles area 10 readings were taken at each AB/2. This was considered quite enough for the accuracy that can be obtained with manual interpretation.

The set up of the soundings was similar in the Miravalles area to that in Iceland with respect to the selection of AB/2 and the sounding orientation. However, it is interesting to note that the design might be better if two-dimensional effects are roughly located at the beginning of the survey.

For instance the way to treat all the soundings in profile 23 was guessing that a high resistivity layer appeared in the bottom, that is between 400 and 600 m depth according to the surveys made before. But two-dimensional interpretation revealed this was not always certain. However, the question is how to know this prior to the interpretation of the area.

One way to get an idea of the area is to run a quick survey before the principal one through the main routes. In this way one-dimensional and two-dimensional effectscan be roughly discriminated. On the basis of this first interpretation the soundings for the final survey can be better selected and a faster interpretation can be accomplished. It has to be kept in mind that the first interpretation proposed will be strongly dependent on the data processing method selected.

5.2 Data processing

Perhaps this is the most important part of the training according to the needs of the home country of the author. Up to now data processing in the Miravalles geothermal project has been done on basis of the master curve collection of Orellana and Money (1966). During the last 5 months the author has had the opportunity to work with numerical methods and in this way it has been possible to compare the interpretation and accuracy achieved with manual procedures and those obtained by means of the computer programs used in Iceland.

The method developed by Dey and Morrison (1976) is as good as the filter used (Eyjolfsson, pers. comm.). The rest dependsonthe grid file selected, which of course is a function of the geological features looked for. It has been an interesting experience to work with DIM2 because this program gives the model and at the same time the data to be checked. In this way a reference is used. In manual interpretation on the other hand there is no control on how accurate the final interpretation is, except for the experience of the interpretor.

The last topic to be commented on is the Head-on interpretation. In this case the model selected is certainly better in the central part of the profile. This method can not consider structures thinner than 25 m, if for instance the gridfile sets up measurements on the surface every 25 m. This means that vertical structures less than 25 m thick will be treated as if they had that thickness.

There is no doubt that numerical methods lead to better interpretation than the manual ones.

5.3 Equipment

The equipment is very important accuracy and improvements of the interpretation. For instance the Icelanders have already reached a very high level regarding the quality of the equipment by making their own equipment to cope with their practical needs.

Up to now we have been working in the Miravalles area with an equipment which has 20 µV accuracy theoretically. But in the field it hasbeen observed that measurements lower than 100 µV are not reliable. One trouble is how to filter the noise. It is too difficult to get clear measurement if the wind is blowing strongly, or if it is raining. The same effect is caused by electrical storms. The record is graphycally registered and the voltage manually calculated.

One way to control the quality of the data is incorporating a processor to the receiver. In this way a faster record can be realized. On the other hand if the ampermeter can control the output current, more reliable measurements can be expected.

It is necessary to have a clear idea about the response of the ground to the current injection, this means the maximum and the minimum voltage expected, the maximum current needed, the noise nature and so on.

It might be more expensive to manufacture equipment but in that way we can be sure that it will be the most appropriate for the local conditions and a more reliable interpretation can be expected.

6 CONCLUSIONS

Considering the manual interpretation and the numerical methods, there is no doubt that computer procedures give better results. They offer the chance to control the accuracy of the interpretation by using different techniques. Manual interpretation depends fundamentally on the experience of the interpretor, there is no change to control the quality of the interpretation and, it may not be possible to analyse two-dimensional effects even if they are observed.

Even if the procedures for interpreting are good an apropiate equipment is required. Therefore it is very important to have a clear idea about the ground conditions,in order to select equipment for a survey.

ACKNOWLEDGEMENTS

The autor whises to express his deep aknowledgement to the staff of the National Energy Authority of Iceland (ORKUSTOFNUN) and to the United Natios University (UNU), for awarding him to participate in the Geothermal Training Programme, Iceland, 1984. The gratefulness is extended to the scientist who gave lectures during the introductory lecture course and all the persons who cooperated with the author in different ways.

Special gratefulness are for Dr. Ingvar Birgir Fridleifsson director of the UNU Geothermal Training Programme and Brynjolfur Eyjolfsson for his guidance during the practical training. This is extended to Grimur Bjornson for his gentle cooperation in Head-on interpretation.

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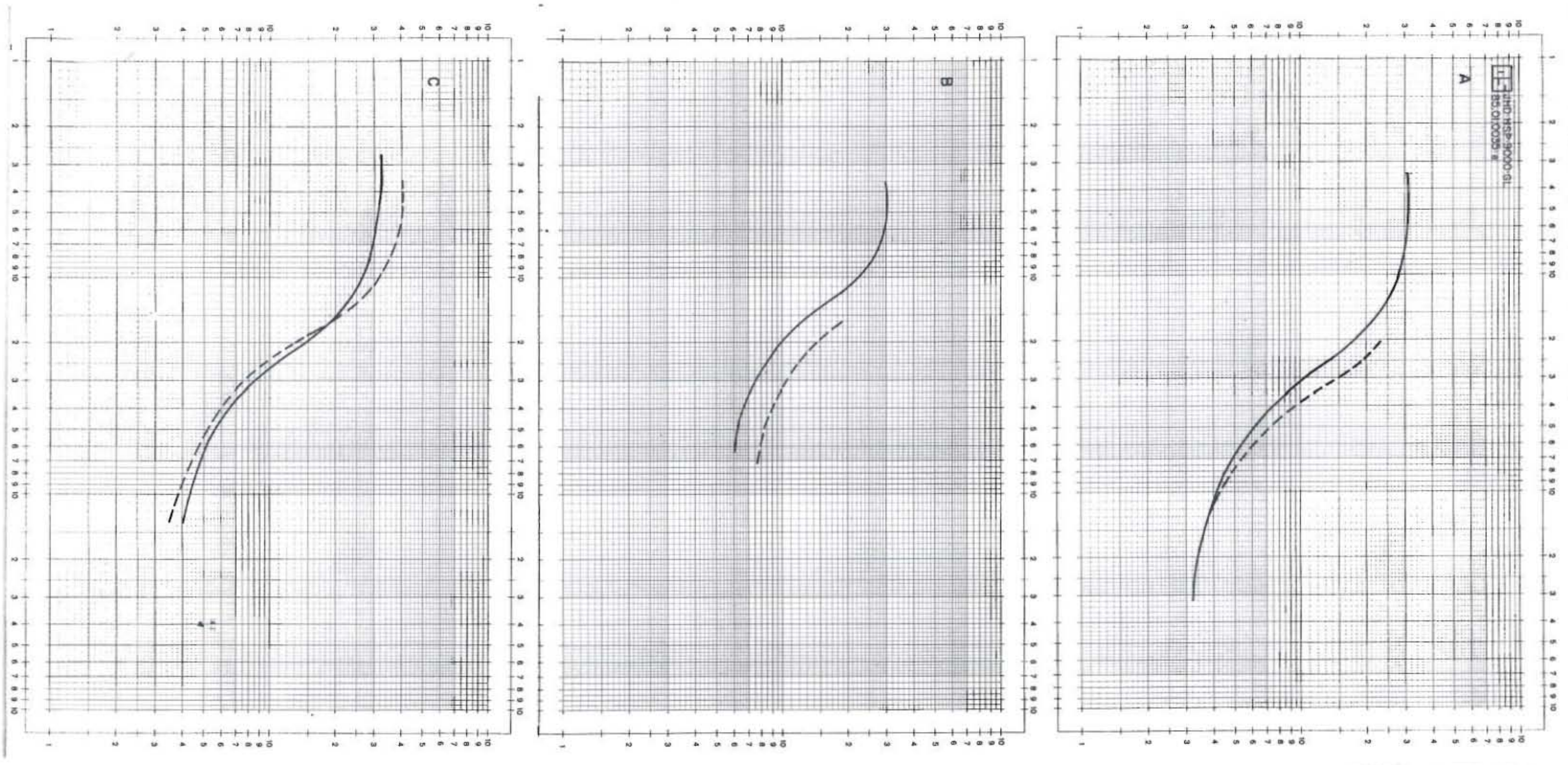
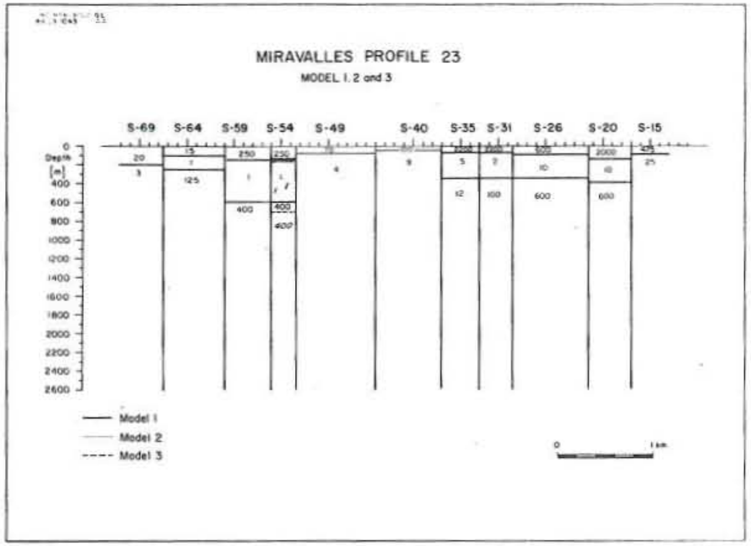
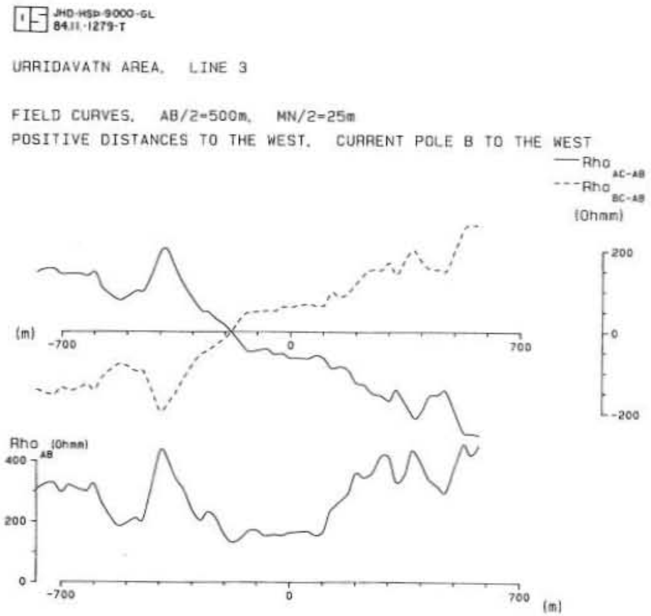


Fig. 2. Illustration of the overlaps in an apparent resistivity curve with symmetrical configuration.





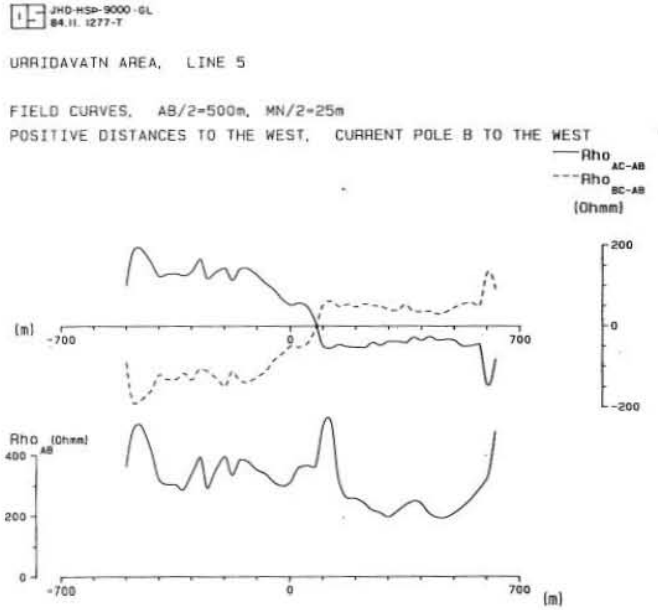


Fig. 3. Profile 23 Miravalles geothermal field, two-dimensional interpretation.

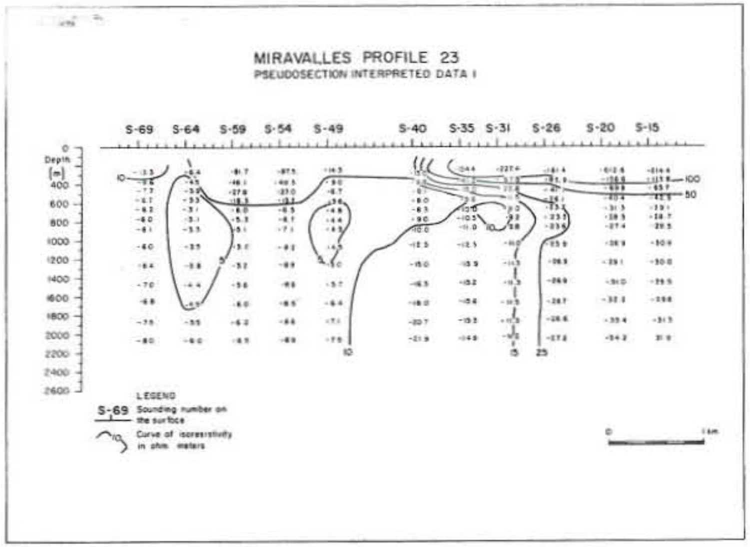


Fig. 4. Profile 23 Miravalles geothermal field, pseudosection field data.

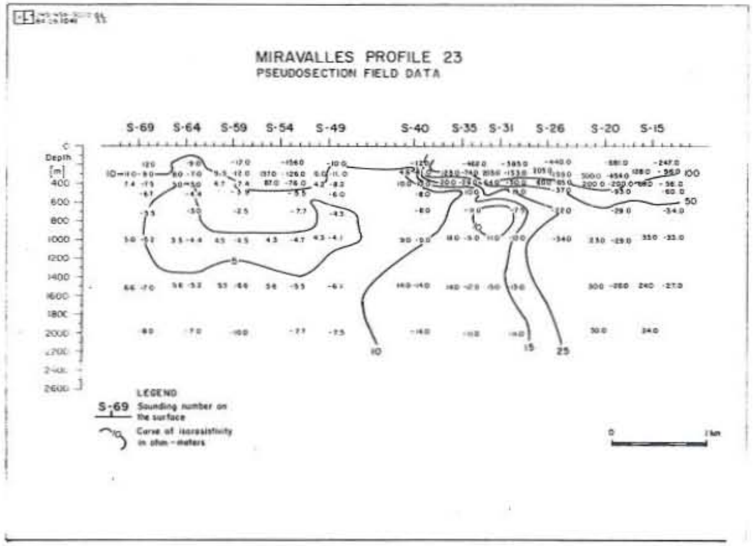


Fig. 5. Profile 23 Miravalles geothermal field, pseudosection computer model 1.

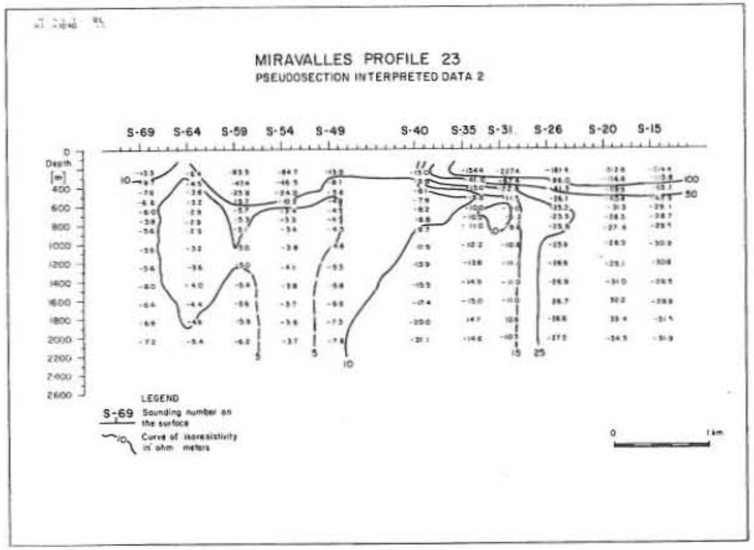


Fig. 6. Profile 23 Miravalles geothermal field, pseudosection computer model 2.

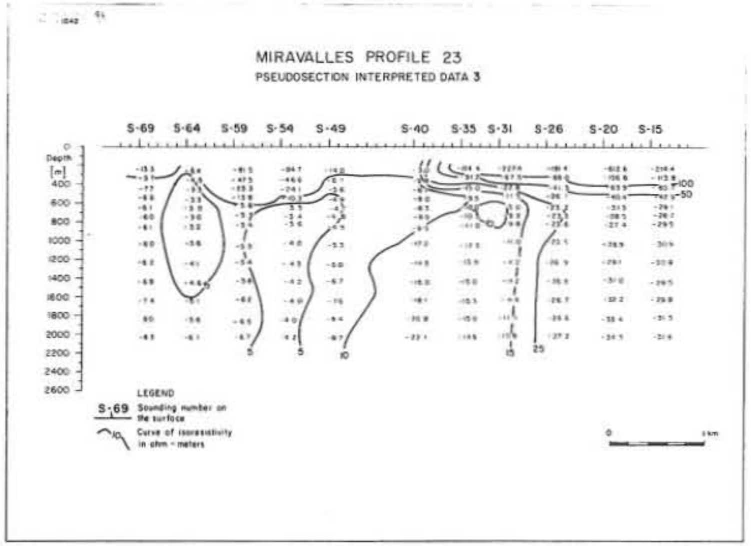


Fig. 7. Profile 23 Miravalles geothermal field, pseudosection computer model 3.

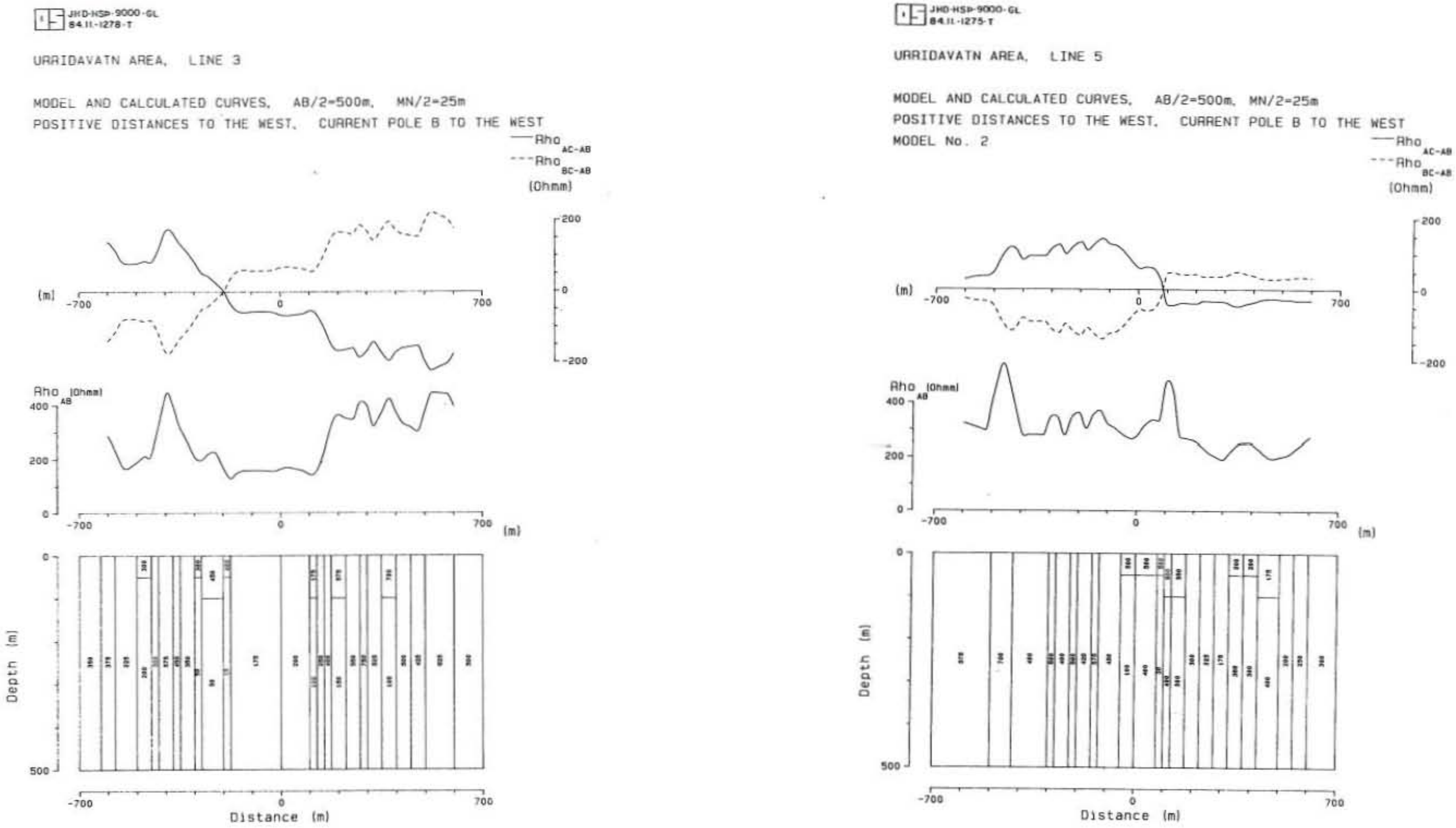
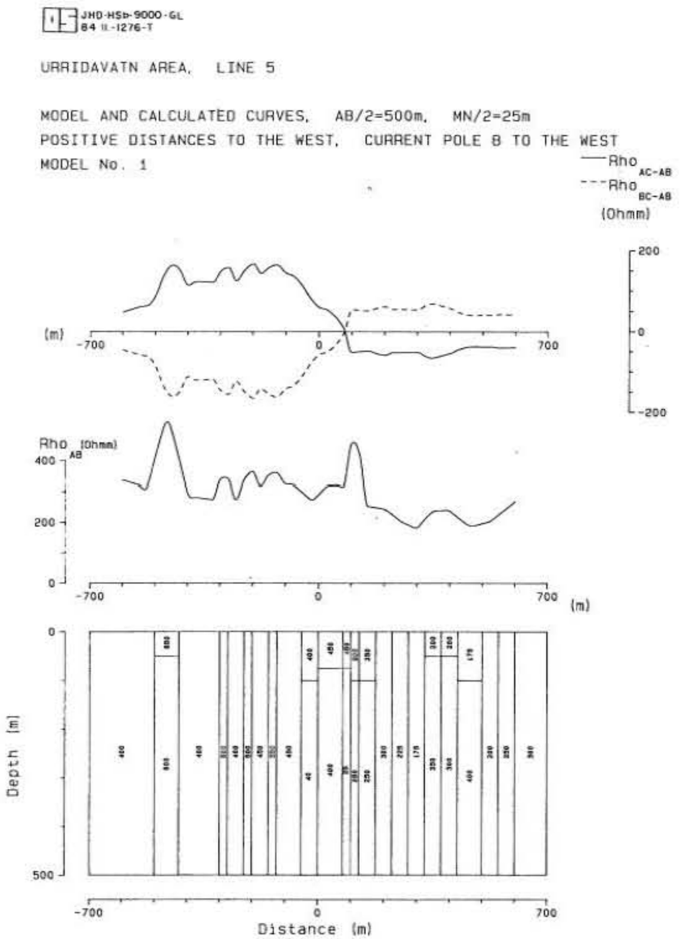


Fig. 8. Line 3 Urridavatn low temperature geothermal field, field curve and computer model.



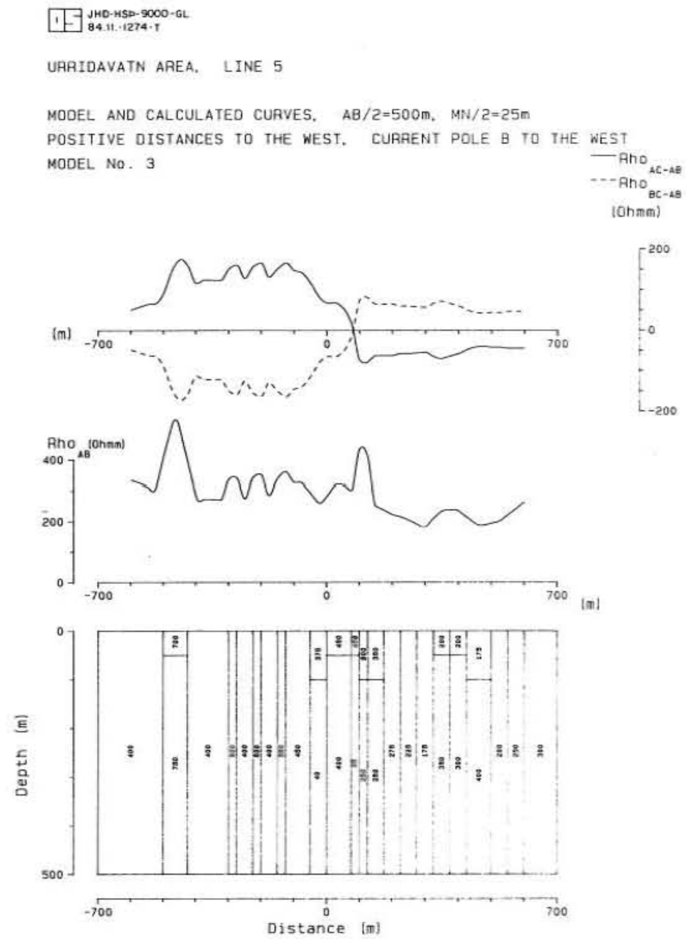
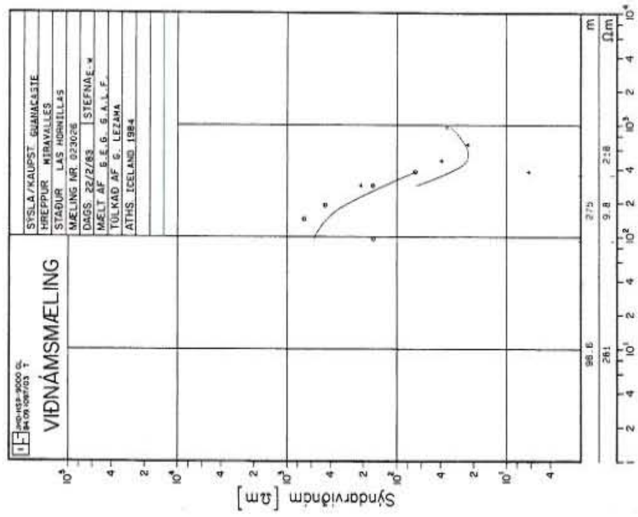
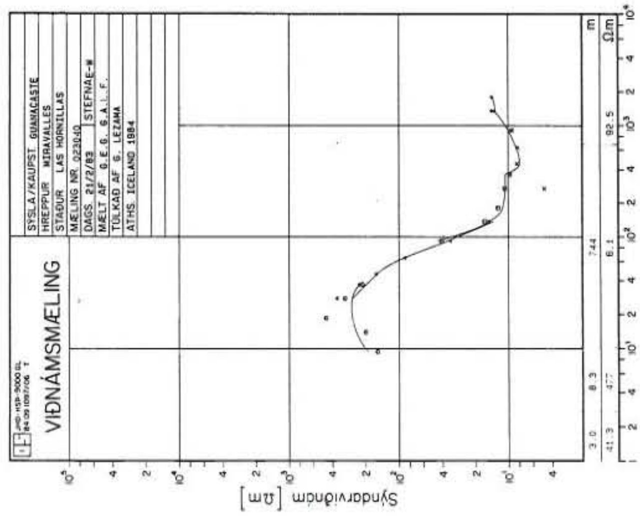


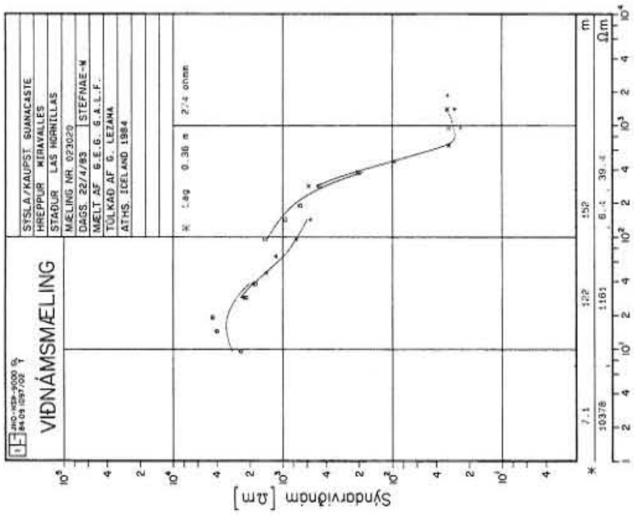
Fig. 9. Line 5 Urridavatn low temperature geothermal field, field curve and computer model 1.

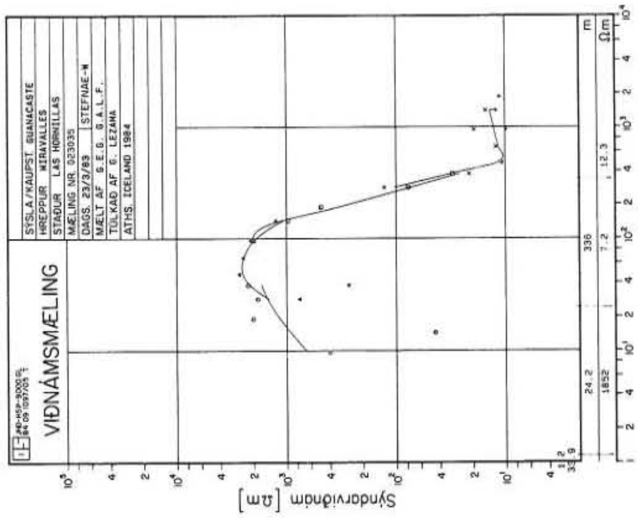
APPENDIX 1

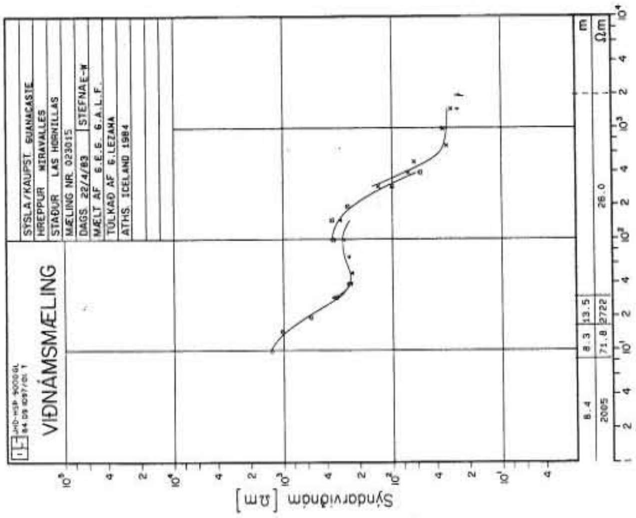
GRAPHICS OF THE SCHLUMBERGER ONE-DIMENSIONAL INTERPRETATION FROM MIRAVALLES GEOTHERMAL FIELD.

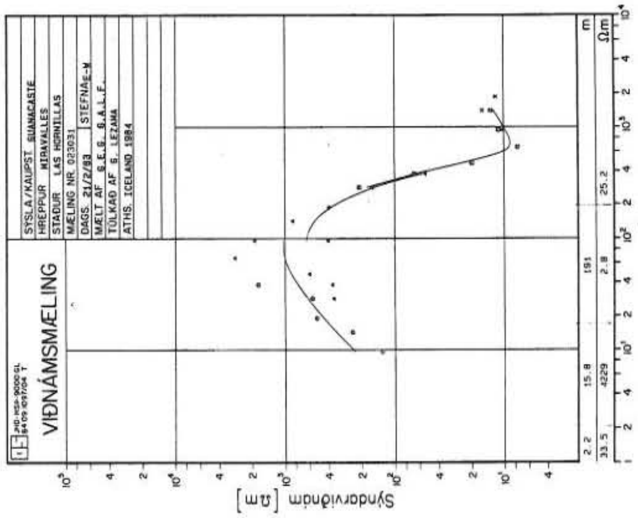


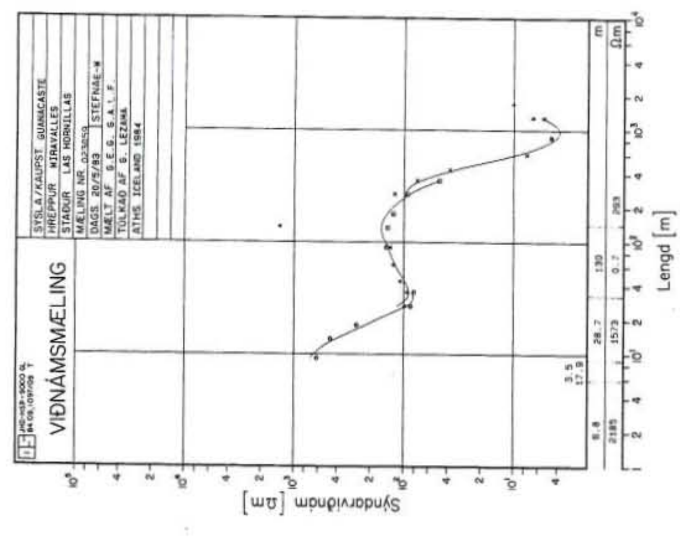








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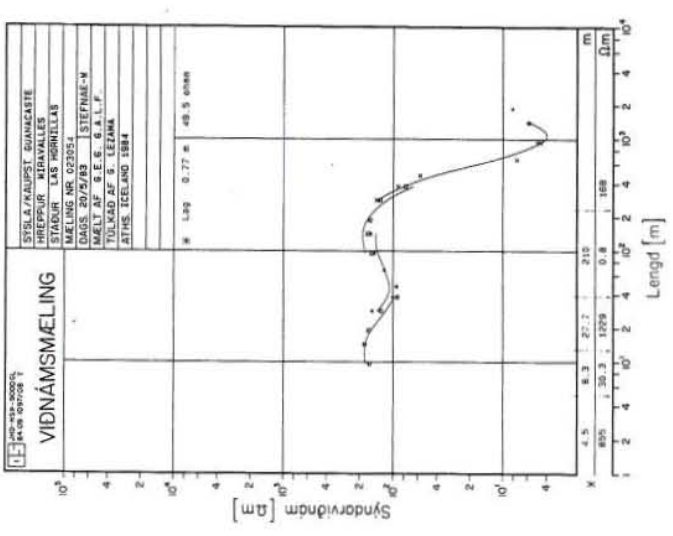
Sýndarviðnám [Ωm]
Lengd [m]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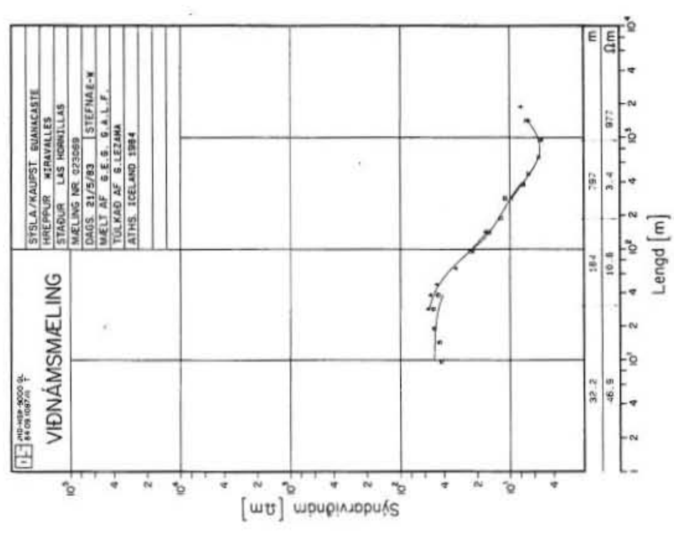
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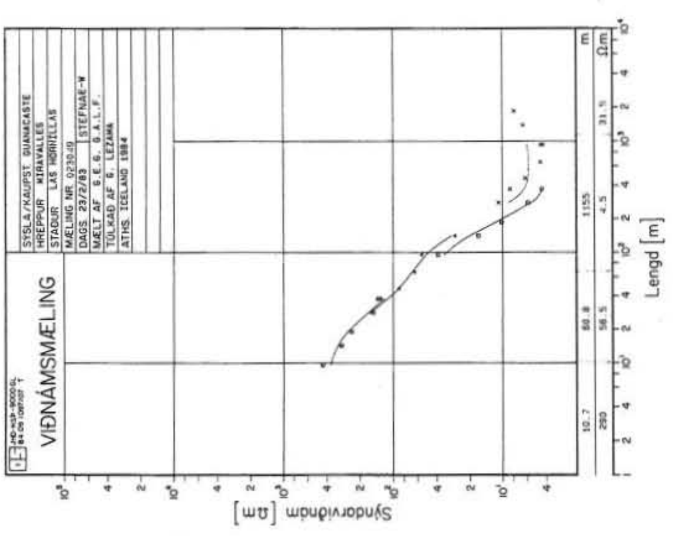
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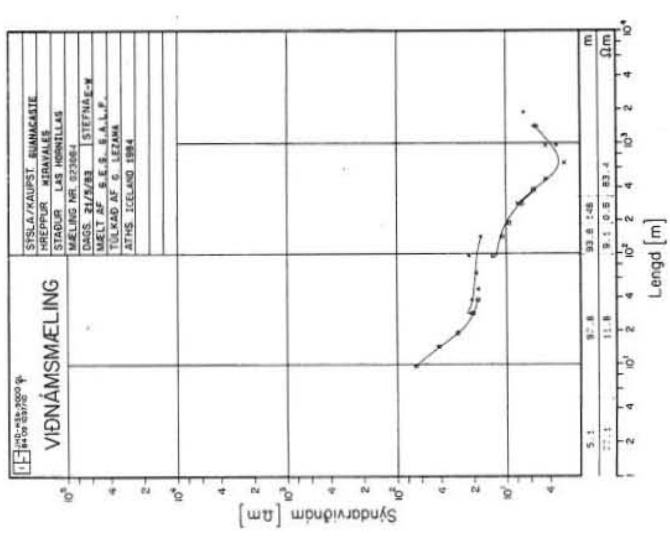
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