HEAD-ON PROFILING AND ITS TWO DIMENSIONAL INTERPRETATION BY FINITE ELEMENT METHOD

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ABSTRACT

The objective of this report is to stress on importance of headon profiling as a tool to detect conductive zones for geothermal reservoirs.

An account of geoelectric sounding and profiling theory has been given. Discussion has been made of various methods of interpretation, these include model generations for both one and two dimensional models.

Finite element method as a means of solving potential functions in computer interpretations has been discussed.

Qualitative analysis of headon data from Arbaer low temperature geothermal field in Iceland has been done as an Exercise. Emphasis has been on important role played by various potential and current electrode arm lengths to detect lateral variations of geological structure at various depths.

There is a review of Urriðavatn low temperature geothermal field as case history in relation to headon profiling.

TABLE OF CONTENTS

List of Figures

1. INTRODUCTION

This report is but a portion of what the author has learnt during a six months intensive course in geothermal exploration techniques at United Nations University, Reykjavik, Iceland, during 1986 academic year.

This was an initiative of UNDP who were also the author's sponsors for the course to alleviate future personnel problems in the joint UNDP/MERD project for geothermal energy exploration and exploitation.

The format of the course was as follows, introductory lectures on all disciplines of geothermal explorations including, Borehole geology, Borehole Geophysics, Geology, Reservoir Engineering, Drilling Technology, Geochemistry, Geothermal utilization and Geophysics.

This was followed up by a specialised training during which the author opted for Geophysical Exploration Techniques. Thermal, Magnetic, Gravity, Passive Seismics and Electrical Methods were learnt with much emphasis on electrical methods. Direct current electrical methods play a major role in geothermal systems exploration both at regional and local scale, the author being introduced both to practical and theoretical approaches of the methods.

Field excursion was offered all over Iceland to expose fellows to high and low temperature geothermal fields. Observations were also made of case history fields and exploitations of these fields both at commercial and domestic scale. As computers play an important role in data interpretation in electrical methods the author also had some spell with the computer facilities both at UNU and ORKUSTOFNUN.

In addition to this report there will be another report handed over to MERD, Geothermal Section. This will be a joint report with Mr. Mariita (Kenya) on one dimensional interpretation of

Schlumberger soundings. The data comes in two batches, there is the Suswa data collected by Mr. Baticci, UNDP and Eburru data collected by coauthors with assistance from Mr. Kilele, MERD. Both data are from Kenya and were carried out at regional scale for reconnaissance purposes.

There were also data collected in Iceland in conjunction with Mr. Mulyadi (Indonesia) and Mr. Mariita under supervision of Mr. Eyjólfsson. This was intended to expose the Geophysical Exploration team to practical snags in the field and how to overcome them. Part of this report comprises interpreting this data.

2. Theory of Geoelectric Sounding and Profiling

Resistivity measurements fall under two main categories namely geoelectric sounding and profiling. The difference is not in the actual set up but rather in the way the data is collected. The profiling method is mainly used for investigation of vertical changes in the subsurface whereas the sounding method helps in determination of horizontal changes in a vertical direction of the subsurface strata. Both methods fall under direct current measurement methods.

Suppose now that we have a homogeneous half space earth with resistivity α, and we introduce current I, at a point P, with displacement r, from the current source then the potential V, at position r, is given by equation 1.

$$V(r) = \frac{I\alpha}{2\pi r} \qquad (1)$$

If there are two sources with current +I and -I located at points r_1 and r_2 respectively then V(r) will be given by equation 2.

$$V(r) = \frac{I\alpha}{2\pi(1/r_1 - 1/r_2)} \qquad (2)$$

However the earth is not a homogeneous mass and therefore we have to introduce a new term apparent resistivity α_a, which is a function of a true resistivity structure of the earth and the locations of the electrodes given by equation 3, where δV is the measured potential change.

$$\alpha_a = \frac{\delta V * 2\pi}{I(1/r_1 - 1/r_2)} \qquad (3)$$

The next part of the text discusses the setups and interpretations of the two popular DC methods in geothermal energy explorations that is Schlumberger sounding and Headon profiling. In both methods a transmitter of output range of 100 to 3000 Volts and a receiver to measure potential changes in the range of microvolts to 100 Volts are essential. It should also be noted that high impedance in the receiver minimizes the error in the apparent resistivity measurements.

2.1. Schlumberger Sounding

Schlumberger sounding is the most important electrical method in geothermal exploration. It is usually used to do the initial electrical survey in the areas being explored, but in later stages it is used in conjunction with the other geophysical methods to delineate the geothermal system.
The method gives very valuable information about the physical parameters with depth. The set up is rather simple as depicted in Figure 1.

The apparent resistivity is given by equation 4, on substituting δV for the set up in Figure 1. into equation 3.

$$\alpha_a = \frac{\delta V * k}{I} \qquad (4)$$

Where k, is a geometric factor depending on electrode spacing in this case

$$k = \frac{2\pi}{\{(1/AM - 1/BM) - (1/AN - 1/BN)\}}$$

2.2. Headon Profiling

Here the set up is similar to the Schlumberger setup but with an extra current electrode C, as is illustrated in Figure 2. The electrode C is placed at infinity. In this method one moves the centre of the array at some fixed distance between successive positions on the line.
The set up is a very useful method in detecting concealed faults and dykes a long which thermal fluids ascend to the surface.

On assuming that C, approaches infinity and that equation 2, holds then we obtain equations 5. Note from the setup also that AM = BN and BM = AN.

$$\delta V_{AB} = \frac{I\alpha}{\pi\{1/BN - 1/BM\}}$$

$$\delta V_{AC} = \frac{I\alpha}{2\pi\{1/BN - 1/BM\}} \qquad (5)$$

$$\delta V_{BC} = - \frac{I\alpha}{2\pi\{1/BN - 1/BM\}}$$

From these equations it follows that

$$\delta V_{AB} = \delta V_{AC} + \delta V_{BC} \qquad (6)$$

This means that there are only two independent parameters

Thus both δV_{AC} and δV_{BC} are functions of δV_{AB}.
On using equation 3 in equations 5, we obtain equations 7.

$$\alpha_{AB} = \frac{\delta V_{AB} * \pi}{I\{1/BN - 1/BM\}}$$

$$\alpha_{AC} = \frac{\delta V_{AC} * 2\pi}{I\{1/BN - 1/BM\}} \qquad (7)$$

$$\alpha_{BC} = \frac{\delta V_{BC} * 2\pi}{I\{1/BN - 1/BM\}}$$

The basic principle of headon profiling lies in the theory of potential distributions in the different geological structures with different resistivities in the vicinity of electric field due to the current electrode.
The differences in the above equations 7, are caused by perturbed potential due to inhomogeinities. The data collected includes α_{AC}, α_{AC} and α_{AB}.
On considering Schlumberger array in Figure 1, apparent resistivity α_a is given by

$$\alpha_a = \frac{k*\delta V}{I}$$

Where k, δV and I represent similar physical parameters as

described for Schlumberger array.
Now an electric field $\underline{E}$ between M and N potential electrodes is given by

$$|\underline{E}| = \frac{\delta V}{MN}$$

But $$|\underline{E}| = |\underline{J}|\alpha$$

Where J and α are current density and resistivity respectively in the vicinity of MN.
Thus solving for $\underline{E}$ from the pair of equations above and substituting in the apparent resistivity equation 4, we have

$$\alpha_a = \frac{k*J*\alpha*MN}{I}$$

for Isotropic medium

$$\alpha_a = \alpha \quad \text{and} \quad J = J_0$$

Where J_0 is current density in the Isotropic medium thus substituting this values in the apparent resistivity equation above we obtain

$$\frac{1}{J_0} = \frac{k*MN}{I}$$

or

$$\alpha_a = (J/J_0)\alpha$$

Thus apparent resistivity is a function of current density in the vicinity of potential electrodes M and N.
By using an array in Fgure 2, one measures two potential differences, δV_{AC} and δV_{BC}. In an Isotropic medium $J = J_0$ and $\alpha_{AC} = \alpha_{BC}$. However if the centre of the AB array is near a fault, $J \quad J_0$ and $J_{AC} \quad J_{BC}$ hence $\alpha_{AC} \quad \alpha_{BC}$.

The changes in α_{AC} and α_{BC} as the array AB crosses a fault can be assesed by assuming that the potential field at MN is caused by a single electrode that is A or B, since C is far away from A and B. On plotting a_{AC} and α_{BC} against profile distances, the two apparent resistivities would converge or diverge depending on whether the array is approaching a conductive fault or a resistive dyke. Some of the theoretical models for various contacts of headon profiling are given by Abdulkadir, (1984).

When the set up is symmetrical over a resistive or conductive structure there is a cross over and if there is not, there is a change in direction of the curve. In cases of two symmetrical resistivity contrasts there is a semi cross over.

3. Concepts of Data Interpretation in Geoelectric Sounding and Profiling

In data collection, it should be borne in mind that interpretation results would depend on quality of collected data, thus all precautions should be taken during data collection to minimize errors as much as possible. It is also important to have an experienced person taking charge of data collection as he/she would solve problems as they arise, and he/she can also decide on future resitivity survey regions by analyzing the resistivity curves in the field as they are being plotted during the survey work.

However the most important part of geophysical exploration techniques is the manipulation of these data to delineate a geothermal field. Schlumberger sounding is used for regional scale surveys, on the other hand headon profiling in conjunction with Schlumberger would be important in mapping out a two dimensional subsurface structure.

Interpretation then would mean using the field data, to come up with a geological solution of the structure with corresponding apparent resistivities.

A flowchart Figure 3, gives an outline of interpretation of apparent resistivity curves. The results can pinpoint not only a geothermal reservoir but a drilling site as well, if used in conjunction with the engineering and other geosciences interpretations.

There are two main interpretation methods namely, Inversion and Forward Modelling or Trial and Error methods. The latter method is based on Finite Element Method which the author would discuss in due course of the text.

Inversion method is only used for one dimensional Schlumberger sounding interpretations. A model is made from the apparent

resistivity curves and a computer programme(ELLIPSE in case of ORKUSTOFNUN) is used to calculate the response which is then compared with field data until the best fit is achieved.
In Forward Modelling the interpreter predicts the model and a gain a computer programme(TWODIM in case of ORKUSTOFNUN) is used to calculate the response which is then compared with the field until the best fit is obtained.

3.1. Principle of Interpretation by Finite Element Method

On assuming homogeinity and isotropy of the earth, and an infinitesimal potential electrode separation, the potential on the surface of the earth at a distance r, is given by equation 1.

From field data apparent resistivity would be obtained by equation 4, where δV and I can be measured, and **k** the geometrical factor can be calculated. In data interpretation models are made of which would require solutions for apparent resistivity functions. In most cases these functions involve differential equations which are not easy to solve. Numerical methods in mathematics need then to be applied to transform these apparent resistivity functions into resistivity transform functions which can easily be solved by integration.[computer programmes for interpretations are based on this principle of integration.]
Both functions are linearly related which means that we can move either way depending on function of interest.
In the following text the author discusses the Finite Element Method for a generalised one dimensional interpretation.
Let us consider a functional $J[y(x)]$ of a function $y(x)$. An increment (absolute value) in $y(x)$ leads to a variation of the functional given by equation 8 below

$$\delta J = J[y(x) + \delta y(x)] - J[y(x)] \qquad (8)$$

It has been proved mathematically, Xixiang et al, (1986), that a variation of a functional $Jy(x)$ at $y(x)$ would be equal to the time derivative of $J[y(x) + t\delta y(x)]$ at $t = 0$ thus we have the equation below

$$\delta J[y(x)] = \frac{\delta\{J[y(x),\ t\delta y(x)]\}}{\delta t}\Big|_{t=0}$$

condition for J = J[y(x)] to take extremum is given by

$$\delta J = \delta J[y_0(x)]$$

where $y_0(x)$ is the extremum curve or function that J(y) takes as a local maximum or minimum in y(x), also known as the zeroth order function in J(y).

But $$J[y_0(x) + t\delta(x)] = \phi(t)$$

therefore as J(y) takes extremum at $y_0(x)$, $\phi(t)$ takes extremum at t = 0

i.e $$\frac{\delta J[y_0(x) + t\delta y(x)]}{\delta t} = 0$$

or $$\delta J = L[y_0(x),\ \delta y(x)] = 0$$

where $L[y(x) + \delta y(x)]$ is a homogeneous linear function as to $\delta y(x)$ or variation of J[y(x)] at y(x).

Finite element method is based on the fact that extremum of a functional is equivalent to the solution of it's corresponding differential equations. Finite element technique transforms the solutions of differential equations of apparent resistivities as functions of potential changes between potential electrodes into the extremum problem of the corresponding functional. This is done by establishing first the functional expression which is equivalent to the differential equations, that is one is left with an integral problem of an extremum of a functional which would be easily accomplished using numerical relations in mathematics.
Abscissa is divided into many small elements and linear interpolation of the inside of every element as well as

integration of the functional are all taken care of with in the computer programme.

Summation of integrations over all elements is done to transform functional of a continuous function into the functional for the values of the function at discrete nodes. As both functions and functionals are linearly related and an extremum problem is at stake filters are chosen to suit extremum conditions, this is also taken care of with in the computer software. Finally one obtains linear equation system whose function at every node satisfies extremum conditions. Solving the equations system, we obtain the values of the function at all nodes, then these discrete values of the function are the approximate solutions of the differential equation.

The principle of two dimensional interpretation by Finite Element Method is the same as that of one dimensional interpretation. However in two dimensional interpretation the solution of the extremum is obtained by minimising regions by dividing elements into triangular nets, and using double integrals to solve for differential equations at the nodes rather than minimizing lines by linear interpolation and applying single integrals as in one dimensional interpretations. Once again the filters are necessary to transform back the functional into apparent resistivity function and all this is catered for with in the computer programme.

The fundamental differential equation that the transformed potential (ø) function follows under condition of one dimensional geoelectric structure with a point source of current is given by Helmholtz's equation below, Xixiang et al.(1986).

$$\mathrm{Div}(\sigma \mathrm{Grad}\phi) - k^2\sigma\phi = -\tfrac{1}{2}\delta(x - x_0)\delta(z - z_0)$$

where

σ = conductivity of the earth

k = wave number which can be chosen so as to suit the interpretation

ϕ = potential as a function of $r(x,z)$

The solution of this differential equation is

$$LU = -\frac{\delta}{\delta x}\tau\left(\frac{\delta U}{\delta x}\right) - \frac{\delta}{\delta z}\left(\tau\frac{\delta U}{\delta z}\right) + \beta U = f$$

under a given boundary condition this corresponds to the function which minimizes the functional J(U) thus

$$J(U) = \iint_D (U,U',f)\,dxdz + \int_\Gamma (\tau,\ulcorner,U)\,dx$$

Where D is the research region divided into a triangular mesh

Γ is boundary of curve D

U is the target function related to ø by Inverse Fourier Transform function U, is then solved at the nodes of triangles in D, Xixiang et al, (1986).

4. Two Dimensional Headon Interpretation of Arbaer Geothermal Field

4.1. Introduction

Headon profiling method has been introduced in the previous parts of the text and the set up given. The method is used to locate faults, dykes and fractures with their dips. This is so because intensive drilling say in Iceland, has proved that aquifers are mostly associated with these structures. It is also a common fact that most of the hot springs are found at intersections between such structures where one acts as an aquifer and the other as an aquiclude.

In this part of the text the author tries to analyse data from Arbaer Field as an exercise to understand the method of determining these structures from the apparent resistivity curves of headon profiling.

Arbaer field lies with in the extinct Hveragerði volcanic system, which is part of Hengill Volcanic system in South West Iceland. It is a low temperature field with no surface manifestations. The potential of the field is untapped, and the only exploitation currently going on is confined to the local farmers in the area for domestic purposes. Work is currently going on in this area by ORKUSTOFNUN Geophysical Exploration Team. The map Figure 4, Flóvenz, (1985), shows some of the profile lines carried out in the author's absentia and those in which the he participated.

4.2. Data Interpretation

The map on Figure 4, shows locations of profile lines in Arbaer Field. ORKUSTOFNUN carried out measurements on lines 1, 2 and 3 in September, 1985. The author and the other Geophysical Exploration Technique Fellows Mr. Mariita (Kenya) and Mr. Mulyadi (Indonesia) carried out measurements on lines 4 and lines 5 in June, 1986 under supervision of Mr. Eyjólfsson. This practical approach was intended to act as an aid in understanding the theory of headon profiling. On completion of data collection the author made it his responsibility to interpret these data as part of his project as the rest set on various topics for their projects. As the author was writing this report, the profile lines 4 and 5 had not been entered into the map (Figure 4), and therefore had to approximate these positions on the map.

Potential electrode arm lengths MN/2 = 25m, current electrode arm lengths AB/2 = 500m and 300m were in use. Forward Modelling by Finite Element Method has been used in the interpretation. Both data were collected with electrode B as the minimum centre of measurement though the programme assumes electrode A as the minimum centre of measurement. Lines 4 and 5 are not drawn to scale, and the array displacement was 25m.

4.3. Line 4, Headon Data Analysis

Looking at Figure 5. the calculated apparent resistivity curves tend to fit well with the calculated response from the model Figure 6. On considering AB/2 = 300m curve, there are two cross overs of low resistivity contrasts, these cross overs don't appear on the AB/2 = 500m set up an indication that these cross overs are superficial. Further changes in the model on the first stratum (Figure 5), could not effect these cross overs. A solution to this snag could be a use of shorter electrode arm lengths.

The central part of the line could be considered a low apparent resistivity zone probably due to highly thermally altered rocks an indication of fractures or any other conductive media. As can be observed in Figure 4, this is in agreement with previous interpretations of lines 1 and 2 by Flóvenz, (1985).

4.4. Line 5, Headon Data Analysis

Looking at the model for this line[Figure 7], there is an indication of high resistivity zone at around 1600m, this could be so due to dense and fresh unaltered intrusions with low porosity, probably a dyke, and another one is at around 1000m.

However at around 1100m, there exists a conductive zone which could be an extension of the fracture in lines 1 and 4 in Figure 4. As can be observed in Figure 8, the patterns for both current electrodes of 300m and 500m tend to agree. Nevertheless the measured resistivities seem to be a bit higher in magnitude as compared to the response values. A modification of the model in the upper two layers could not effect any change on these resistivity magnitudes. This could be due to an underground telephone line which was crossed by current electrode A. The effect is more pronounced on AB/2 = 500m set up. As AB/2 = 500m is only effective for analysis up to 100m depth, probably a verification of this theory by wider electrode arm lengths would be crucial for future and further investigations. Measurable data can only be obtained reasonably up to a depth of about (AB/4) Mwangi,(1982).

4.5. Conclusion

As there aren't any surface manifestations in Arbaer, geothermal water here is meteoric and is probably heated up by heatflow on penetrating into the bed rocks. The fractures in the models, Figures 5 and 6, act as aquifers forming an interlacing mesh with the several dykes detected by proton magnetometer.
The intersection zones of the fractures and dykes play an important role in geothermal fields as they form the path for geothermal fluid conduction onto the surface. However it

would be too soon to jump to conclusions as at times dips might occur in these resistivity contrasts and be misinterpreted as vertical contrasts with displacements. In this connection it would be a commendable idea for those who would be involved in future geophysical exploration in this field to correlate, their results not only with Schlumberger soundings but with extended arm lengths both current and potential electrodes in headon profiling. As for line 4, it is important to reduce the arm lengths as well to determine how far the intrusions penetrate into the substratum layer.

The underground telephone line or any other form of conductive media should be avoided in future as these would keep giving spurious results resulting in misinterpretations and eventually capital cost in the exploration.

5. Urriðavatn Geothermal Field Case History

Urriðavatn low temperature geothermal field in Eastern Iceland, lies outside the neovolcanic zone and therefore has no surface manifestations just like the Arbaer Field. However during winter seasons holes form on ice an indication that there is some sort of heating going on from with in the substrata. The field shown in Figure 9, Einarsson,et al. (1983), lies below the lake bed. The map in the figure also shows the location of the field and some of the profile lines carried out in 1982 by ORKUSTOFNUN Geophysical Team.

The map in Figure 10, Einarsson et al. (1983) shows some dykes and faults which had been detected prior to headon profiling. As can be observed from the map, the dykes and faults form such a complicated mesh that it would be very difficult not only to determine the dips of the structures but also to locate the aquifers.

The geophysical exploration and geological mapping was made even more difficult by the fact that the reservoir lies deep below the lake. These difficulties led into a failure of the original model, for instance well numbers 4 and 6 which were sunk on assumption that the dykes responsible for the aquifer were tilting westwards. Well numbers 2, 3, 4, 5 and 6 never struck main aquifers and their temperatures were soon dropping with a gradual drop in production rate. The cooling could also have something to do with the lake as the aquifers in the wells were only about 0.2km to 0.5km in depth.

In the initial model, the assumption was that the dykes controlled the water flow, however drill hole cutting analyses have demonstrated that the dykes were intersected by the wells, but no major aquifers were connected to these intersections. This left only one option of conduction by fractures.
Headon profiling was thus introduced in 1982, to locate this conductive structures. As observed from the map Figure 9, the area surrounding the geothermal field shown hatched, has high

resistivity which could mean impermeable dykes or faults.
On interpreting these data a low resistivity wall was located marked with broken lines on the map. This wall could be the fracture responsible for conduction of hot water to the thermal area. An exploratory well number 7, was sunk to determine the dip of this wall and it was found to be about 5° to 9° towards east.

From these headon interpretations well number 8, was sunk and proved very successful in its production.

6. Conclusion on Headon Profiling Method

Headon profiling method came into limelight in early eighties as a technique in geothermal exploration. Schlumberger sounding is very important in geophysical exploration for geothermal systems. Nevertheless it does not have enough resolutions for lateral variation in the subsurface strata. This is where the headon method has become a very important tool not only in giving a lateral variation of the strata but also locates dykes, faults and fractures. In geothermal reservoirs structures play an important role as they are responsible for conduction of the geothermal fluid which is eventually utilized in the exploitation of the resources.

The importance of the method can be observed in the application of the method to locate drill sites after the other methods both geological and geophysical had proved fruitless in Urriðavatn Geothermal Field in Iceland. Used effectively with high impedance equipments and avoiding cultural noises the method is quite an asset in geothermal explorations, and can reduce drilling costs due to faulty interpretations when used in conjunction with Schlumberger sounding as this would effect a two dimensional interpretation. The method has been quite a success in Iceland and can no doubt be spread in other geothermal systems the world over as they all have common parameters.

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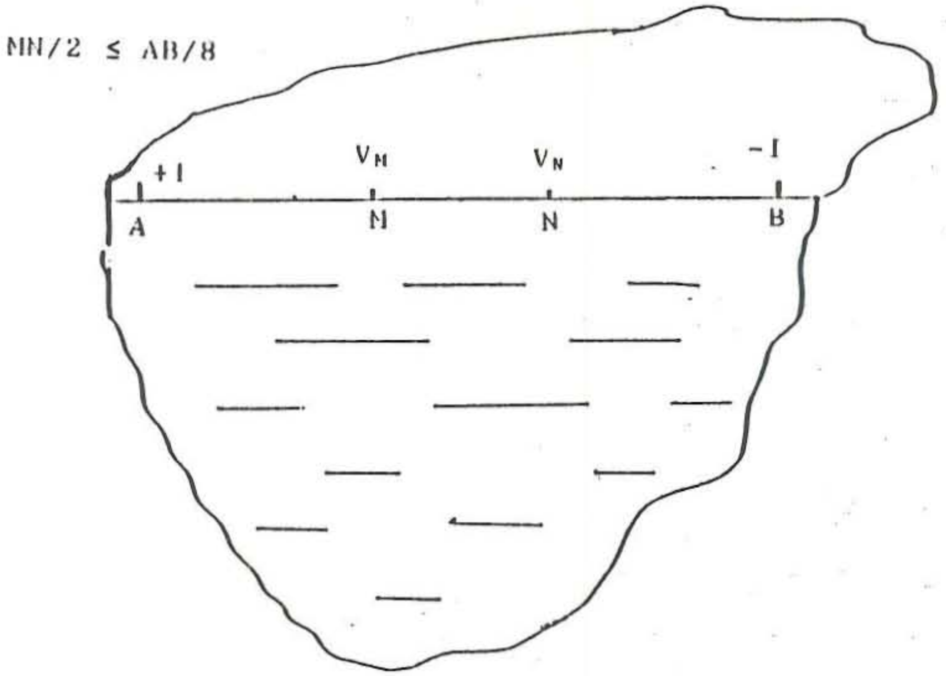

Figure 1. A cross section of the Earth being investigated by Schlumberger Sounding

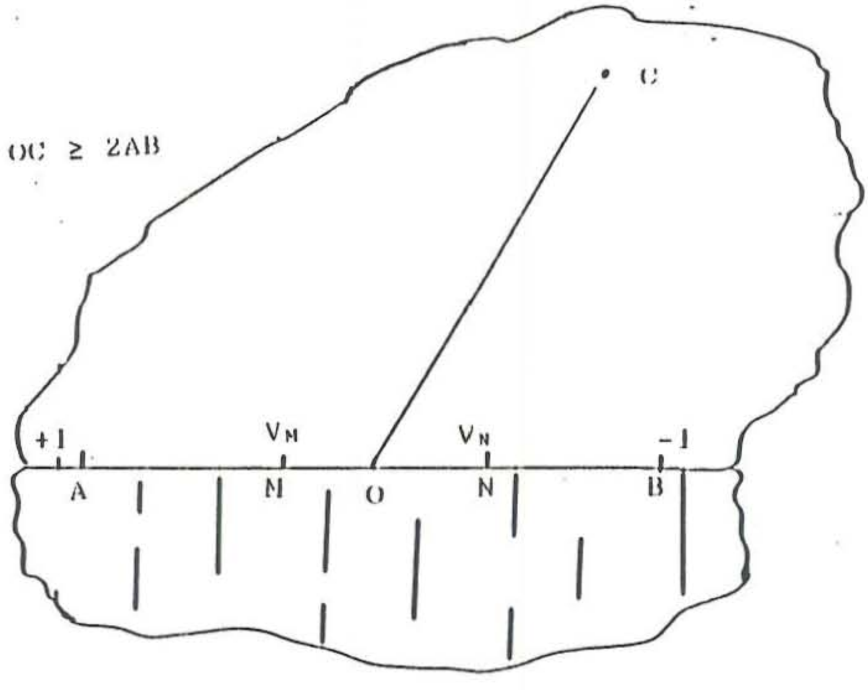

Figure 2. A cross section of the earth being investigated by Headon Profiling

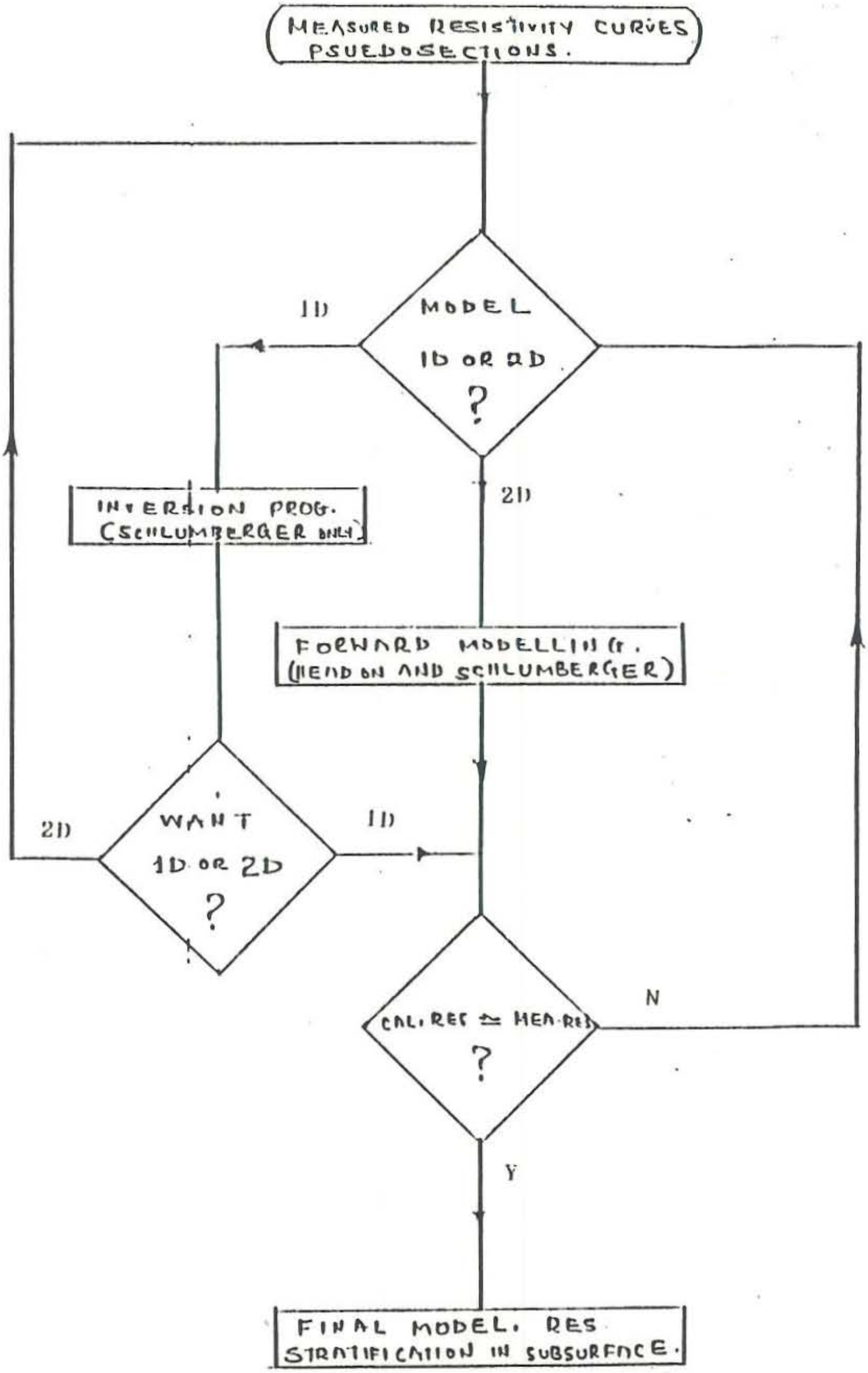

Figure 3. Flow chart for Data Interpretation of Geoelectric Sounding and Hendon Profiling Methods.

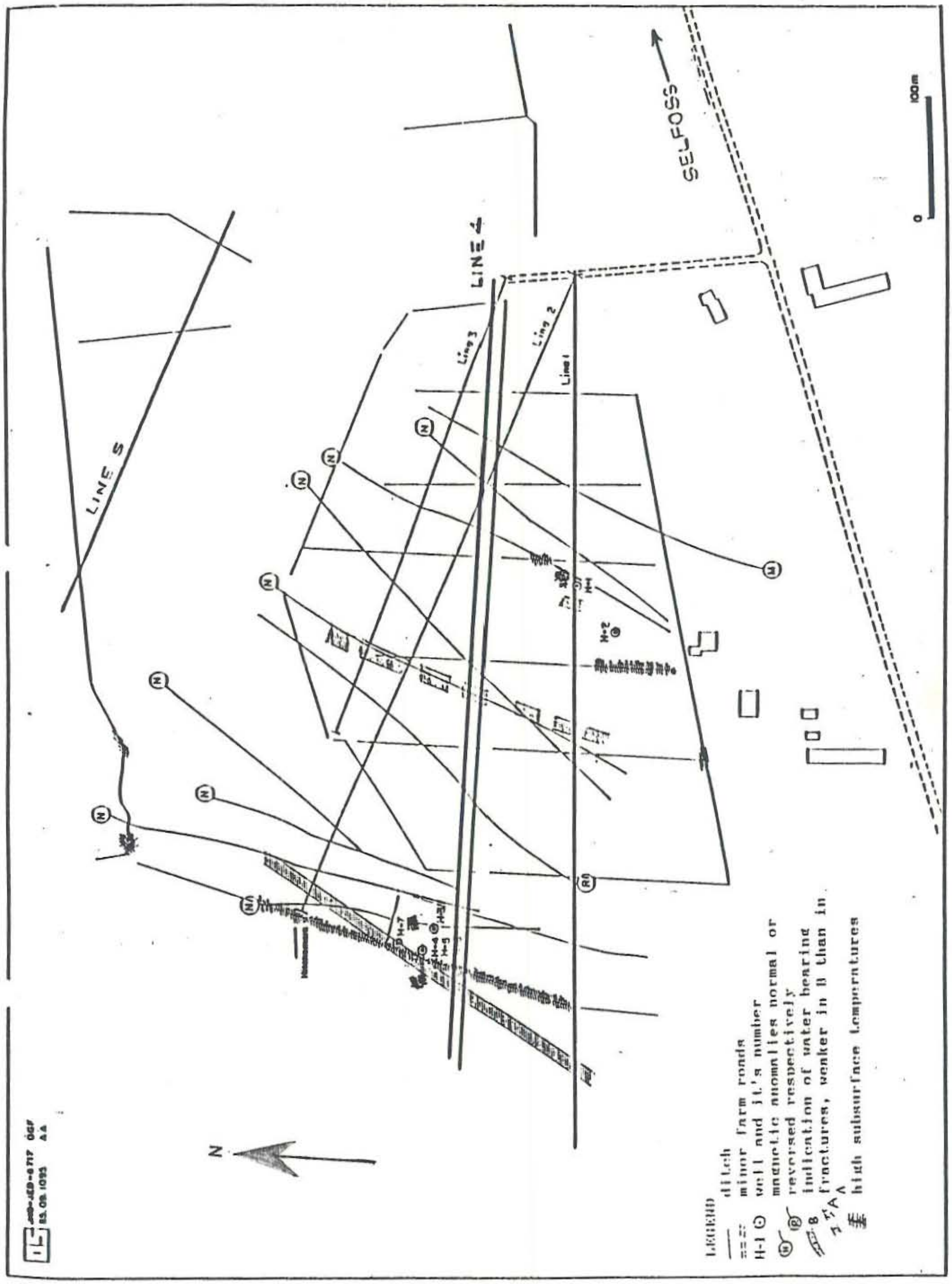

Figure 4. Locations of Profile Lines in Arbaer Field Iceland

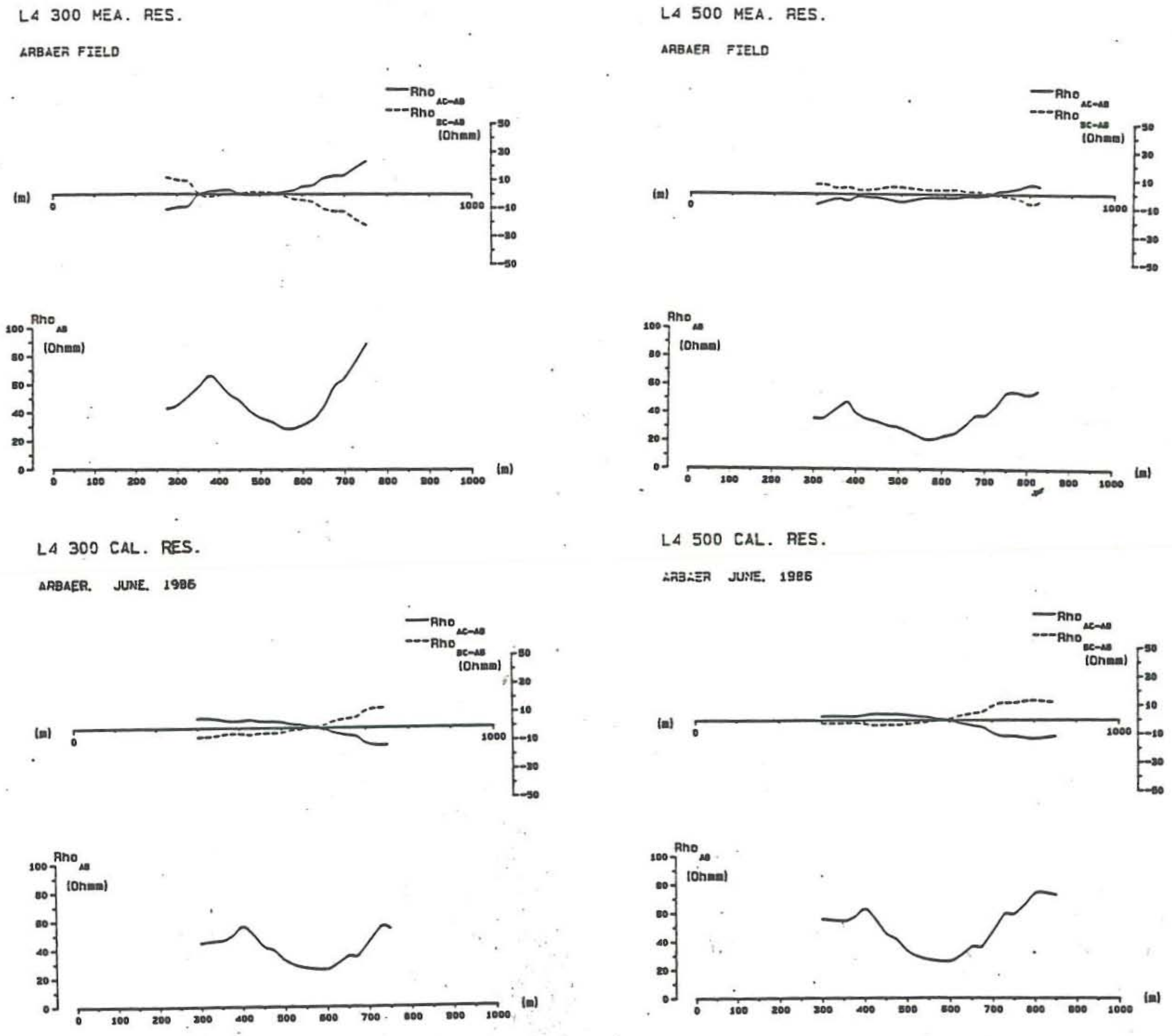

Figure 5. Line 4, Measured Resistivities and Calculated Resistivities from Model

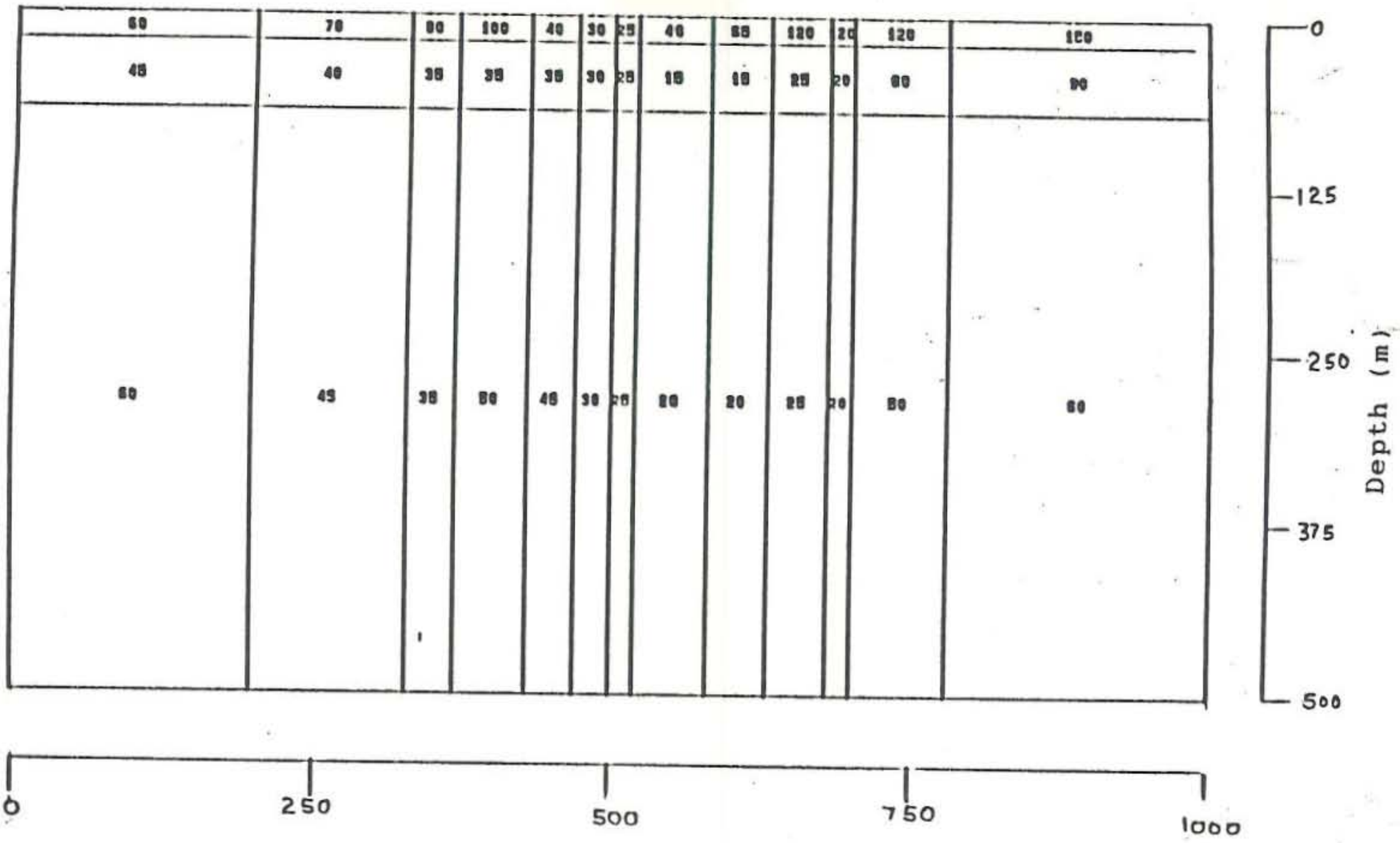

Figure 6. Model for Headon Profile Line 4, Arbaer Field

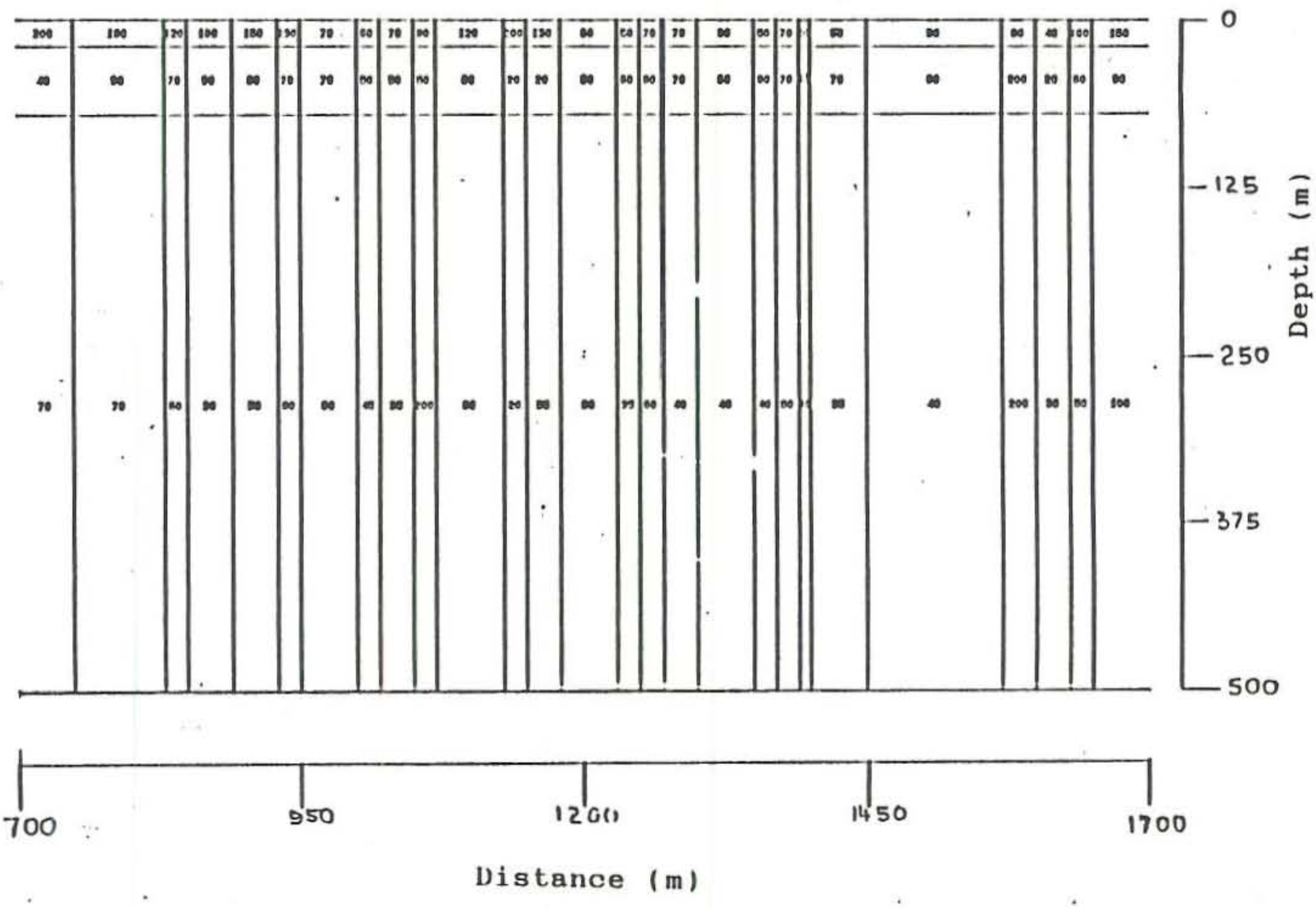

Figure 7. Model for Headon Profile Line 5, Arbaer Field

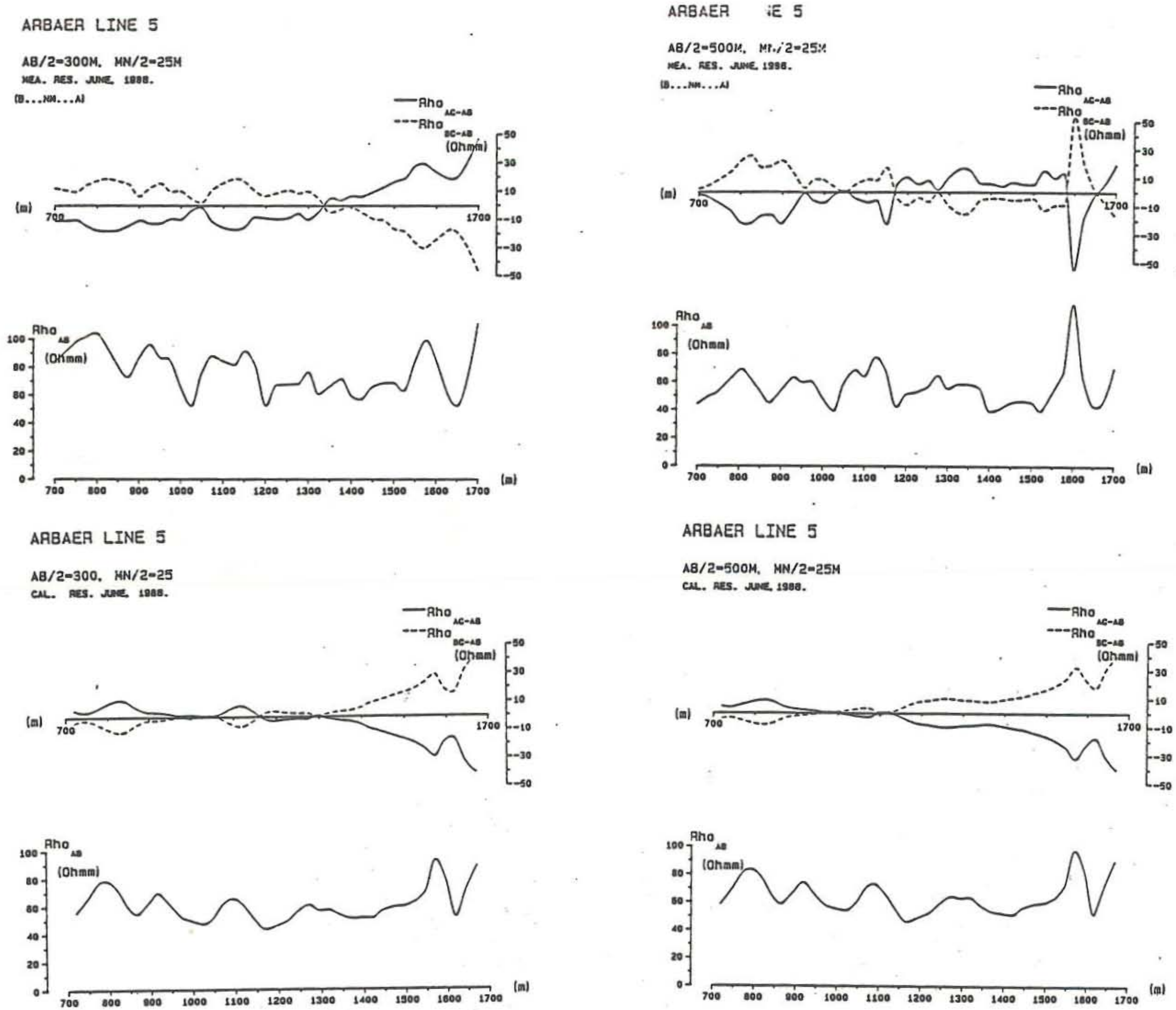

Figure 8. Line 5, Measured Resistivities and Calculated Resitivities from Model

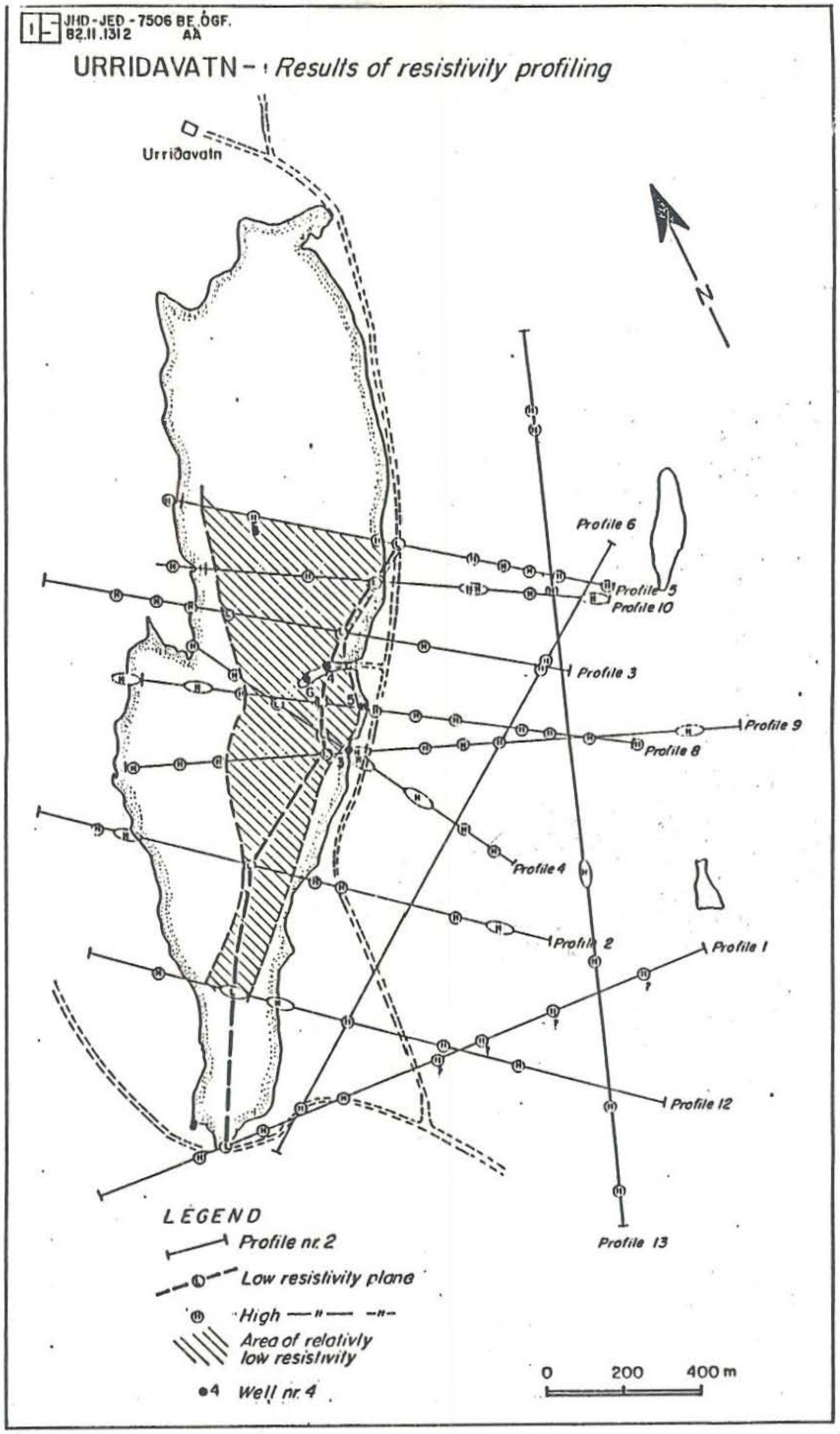

Figure 9. Results of Urriðavatn Resistivity Profiling, 1982

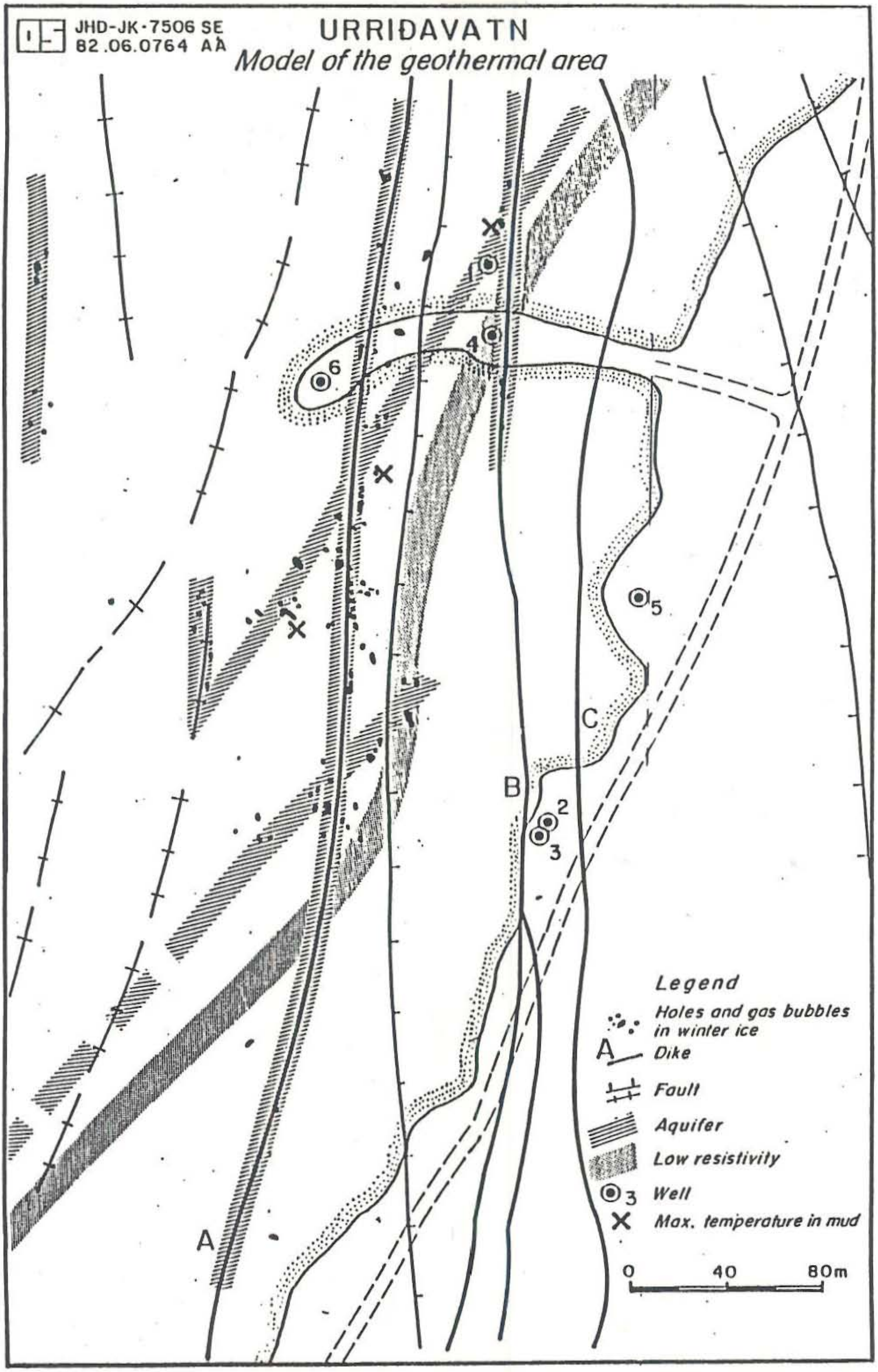

Figure 10. Model of Urriðavatn Geothermal Field, 1982