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Handbook on Hydrogeological Applications of Earth Resistivity Measurements

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HANDBOOK ON HYDROGEOLOGICAL APPLICATIONS OF EARTH RESISTIVITY MEASUREMENTS

by

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This handbook is designed to allow the assessment of the earth resistivity technique for solving ground water problems. Theory and method of earth resistivity measurement are described, together with examples of the application of the resistivity technique to hydrogeological investigations in New Zealand.

Examples are given of the use of resistivity measurements to define basin structure, locate aquifers, map saline water intrusions, detect polluted water and estimate ground water flow direction. A short bibliography is presented.

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1 INTRODUCTION

Electrical resistivity surveying has much to contribute to ground water exploration in New Zealand. It can be used to assess some of the hydrogeological and water quality factors involved in ground water abstraction.

Part A describes basic resistivity theory and provides an introduction to field measurement and interpretation of earth resistivity data. Part B presents brief details of New Zealand case studies representative of a range of ground water problems to which earth resistivity techniques can be applied.

PART A: MEASUREMENT AND INTERPRETATION OF EARTH RESISTIVITY DATA

2 ELECTRICAL RESISTIVITY

The concept of resistivity is introduced by way of the relationship between electrical resistance and resistivity for a wire.

$$R = \rho \frac{L}{A} \qquad \ldots 1$$

where R = electrical resistance of the wire (Ω),
ρ = resistivity (Ω m),
L, A = length and cross-sectional area respectively of the wire (m and m^2).

Applying Ohm's law (ΔV = IR), Equation 1 becomes

$$\rho = \frac{A}{L} \cdot \frac{\Delta V}{I} \, \Omega \, m \qquad \ldots 2$$

where ΔV = potential difference in the wire (volts),
I = current flowing (amps).

Equation 2 shows that resistivity is a function of the ratio of voltage drop to current, and of the dimensions of the wire conductor; the same is true for *any* conductor, including the earth.

Table 1: Resistivities of some rock forming materials and rocks in New Zealand

Material	Resistivity (Ω m)
Sea water[1]	0.2
Typical fresh water	50–100
Quartz[2]	$4 \times 10^{10} - 2 \times 10^{14}$
Dry Canterbury gravels	5000–20000
Saturated Canterbury gravel	500–1000
Sea water saturated gravels	0.5–5
Water saturated clay	2–20
Water saturated basalt (Auckland)[3]	400–2000
Dry basalt (Auckland)[3]	3000–7000
Ignimbrite (water saturated)[4]	100–800
Greywacke (basement)	100–2000
Tertiary mudstone (saturated)	20–50
Hot water saturated rock, Wairakei[5]	5
Limestone	300–10000

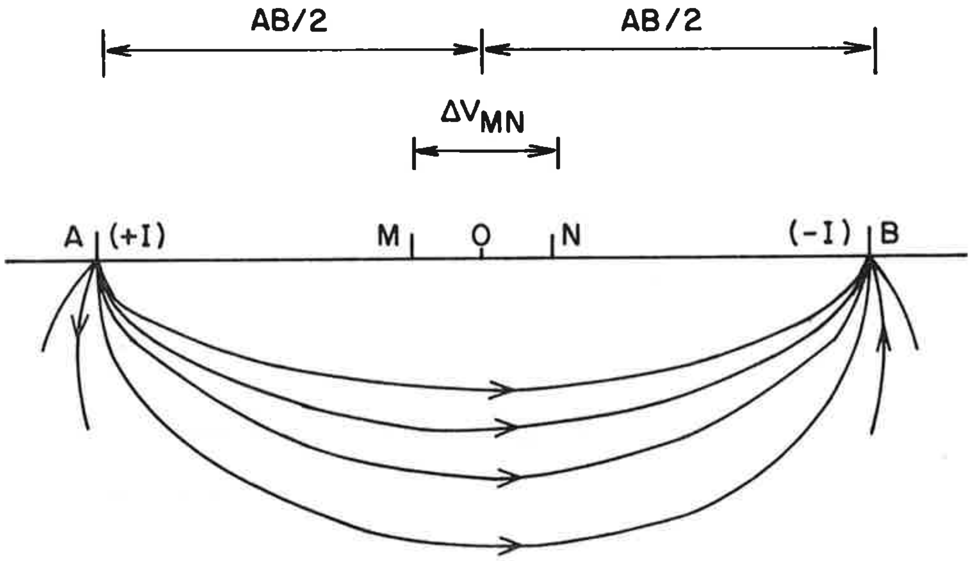
[1] Water temperature and salinity affect its resistivity. Conductivity is the inverse of resistivity.
[2] Telford *et al.* (1976) [3] Roberts (1980) [4] Davidge (1982) [5] Banwell and McDonald (1965)

The resistivity of rocks is highly variable, as shown by Table 1. The principal factors determining the resistivity of a rock or unconsolidated sedimentary material are:

- *The total amount of water present.* The water fraction of most earth materials is more conductive than the solid fraction. Hence the resistivity of a rock tends to decrease with increasing water saturation of the pores. Resistivity tends to decrease with increasing porosity in non clay-bearing rocks.
- *Water salinity.* Dissolved conductive ions in water cause the water's resistivity to decrease markedly.
- *Type of rock.* Clay minerals in a rock reduce its resistivity and hence coarse-grained sediments usually have a higher resistivity than do fine-grained sediments containing similar pore water. Clay also decreases permeability. Both resistivity and permeability are affected by the linkage between rock pores, and for some rock formations a clear relationship exists between resistivity and permeability. Fresh igneous rocks tend to have higher resistivities than metamorphic rocks, which in turn tend to have higher resistivities than sedimentary rocks.

3 EARTH RESISTIVITY MEASUREMENT

Earth resistivity can be measured using an array of electrodes in contact with the ground. The array most widely used in New Zealand is the 'Schlumberger' array, illustrated in Fig. 1. Also in common use is the Wenner array which has four electrodes equally spaced in a line. This report deals exclusively with the Schlumberger array.



O	Mid point of A and B and of M and N	ΔV_{MN}	Voltage drop between M and N
A,B	Current electrodes	→	Lines of current flow within the ground between A and B
M,N	Potential electrodes	I	Current between A and B
AB/2	Distance from centre of array to outside current electrode		

Fig. 1: Schlumberger electrode array and schematic current distribution within the ground.

A direct current generator is used to pass a current, I_{AB}, between the current electrodes A and B (Fig. 1.) The resulting potential difference, ΔV_{MN}, is measured between potential electrodes M and N.

When the measurements are made on a flat surface over ground of variable resistivity and the electrodes are point contacts, then **apparent resistivity** is related to ΔV_{MN} and I_{AB} by the expression

$$\rho_a = \frac{\Pi}{MN}\left[\left(\frac{AB}{2}\right)^2 - \left(\frac{MN}{2}\right)^2\right]\frac{\Delta V_{MN}}{I_{AB}}\ \Omega\,\mathrm{m} \qquad \ldots 3$$

where MN $\leqslant$ AB/5

AB, MN = distance (m) between A and B, and M and N respectively.

Apparent resistivity represents a complex average of the resistivities in the ground. Measured apparent resistivity is equal to true ground resistivity when the ground is of uniform resistivity.

The depth and lateral extent of the sample of ground which contributes significantly to apparent resistivity increases as the spacing between the current electrodes increases. Variations of apparent resistivity with electrode spacing can be interpreted in terms of a subsurface distribution of true resistivities.

Earth resistivity measuring equipment essentially consists of a voltmeter, current generator and ammeter. A high impedance voltmeter is used to avoid current flowing in the potential circuit, causing false measurements of potential difference. Potential electrodes are usually of a 'non-polarising' type which contain copper sulphate solution. These electrodes are advantageous when measuring small potential differences.

The current generator usually runs off portable 12 V batteries and contains 'constant current' circuitry. Synchronised reversing contacts between current and potential circuits allow the elimination of the effects of potential differences unconnected with the generated current. Current is introduced into the ground by way of metal electrodes.

3.1 Resistivity Sounding

An electrical resistivity sounding is a series of apparent resistivity measurements which can be used to estimate subsurface resistivities and the depths at which they occur. The subsurface distribution of resistivities are then used to estimate subsurface geology.

Table 2: Example of resistivity sounding data with MN spacings of 0.3, 3.2 and 10 m

AB/2 (m)	ΔV (mV)	I (mA)	ρ_a (Ω m)	ρ_a (corrected)
(MN = 0.3 m)				
1	434	20	222	200
1.25	277	20	223	201
1.6	168	20	223	201
2	109	20	227	204
2.5	71	20	232	209
3.2	45	20	241	217
4	31	20	259	233
5	21.3	20	279	251
6.3	15	20	312	281
8	10.8	20	362	326
*10	8.7	20	455	
*12.5	5.5	20	450	
(MN = 3.2 m)				
*10	79	20	378	378
*12.5	58	20	438	438
16	41.6	20	518	518
20	30	20	585	585
25	21.9	20	669	669
*32	15.1	20	757	757
*40	11.7	20	917	917
(MN = 10 m)				
*32	48	20	753	
*40	33.6	20	831	
50	22	20	855	898
63	7.4	10	917	963
80	4.9	10	981	1030

*Cross-over measurements for curve smoothing purposes. Values of AB/2 at 10 and 12.5 m were used for both MN = 0.3 and 3.2 m, and an AB/2 of 32 and 40 m were used for both MN = 3.2 and 10 m.

Measurements of ΔV_{MN} and I_{AB}, or their quotient ($\Delta V/I$) are made for a sequence of increasing current electrode spacings. The Water and Soil Directorate, Ministry of Works and Development uses a sequence, shown in Table 2, in which each spacing is $10^{0.1}$ times the preceding one. Apparent resistivity is calculated for each current electrode spacing, using Equation 3, and the values of ρ_a are plotted against electrode spacing (AB/2) on graph paper with logarithmic axes. The curve resulting from joining the plotted points is termed an electrical sounding curve.

To keep the voltage ΔV_{MN} at a measurable level, the potential electrode spacing MN has to be increased from time to time as the spacing of the current electrodes is increased. Typically, MN is increased at AB/2 values of about 10 m, 30 m and 100 m (Table 2).

The curve segments produced using different MN distances do not usually join (Fig. 2) and a curve smoothing technique must be used. Resistivity 'cross-over' measurements are made at two values of AB/2 whenever MN is increased (see Table 2).

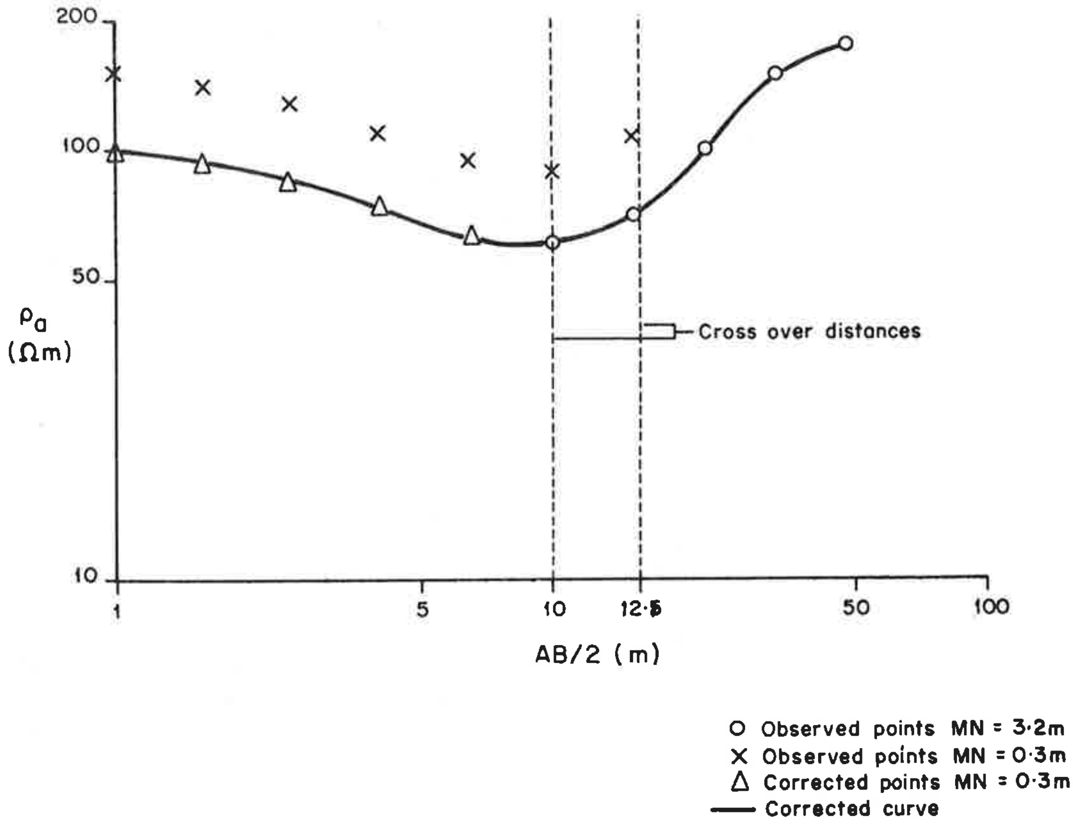


Fig. 2: Illustration of the effect of curve smoothing. In this example, observed resistivities with an MN of 0.3 m were corrected to give the final curve.

If the values of AB/2 used for 'cross-over' measurements are 10 m, 12.5 m, 32 m and 40 m then the sounding curve is smoothed as follows:

(i) Calculate the ratio

$$\frac{\rho_a\,(MN = 3.2\text{ m})}{\rho_a\,(MN = 0.3\text{ m})}$$

for AB/2 = 10 m and for AB/2 = 12.5 m. Usually these two ratios will be similar and in the range 0.8 to 1.2. If they are quite different (say 0.5 and 1.9) then some or all of the calculated resistivities could be in error. Perhaps a change in surface resistivity occurred near the potential probe. In these circumstances, caution should be exercised when interpreting the measurements in terms of a resistivity depth distribution.

(ii) Multiply all the apparent resistivity values measured with MN = 0.3 m by the average of the two ratios calculated in part (i).

(iii) Calculate the ratio

$$\frac{\rho_a\,(MN = 3.2\text{ m})}{\rho_a\,(MN = 10\text{ m})}$$

at AB/2 = 32 and 40 m and take the average. (Again, the two ratios should be similar.)

(iv) Multiply all the apparent resistivity values measured with MN = 10 m by the average from part (iii).

If more than three spacings of potential electrodes are used then each curve segment is often smoothed to agree with the corrected resistivities of the immediately lesser MN spacing, following a procedure similar to steps (iii) and (iv). Other similar smoothing procedures can be used.

Corrected resistivities are then plotted to give a sounding curve. Figure 3 is a plot of corrected resistivities given in Table 2.

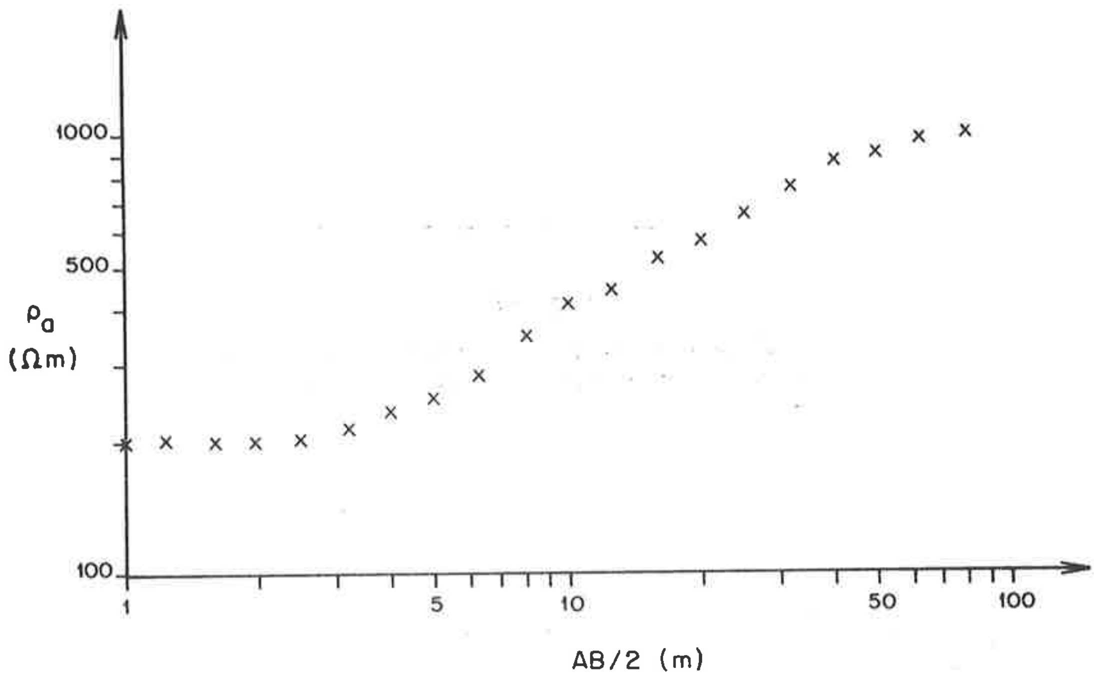


Fig. 3: Sounding curve of corrected resistivity data from Table 2.

A resistivity sounding usually plots as a smooth curve although occasionally a few points distort the smooth trend. A common form of curve distortion, illustrated in Fig. 4, is that caused by the presence of resistivity variations in a horizontal direction (lateral resistivity change). Three points are 'displaced' downwards from the smooth trend, indicating that the current probe(s) passed over a relatively conductive body. The calculated resistivities at AB/2 = 16, 20 and 25 m were ignored when the curve was drawn. If the inhomogeneity had been highly resistive, then the displacement of the data would have been upwards. The sounding curve may still be interpretable if the curve distortion is relatively minor.

Large scale lateral variation in resistivity can make theoretical interpretation of a sounding curve difficult, and sometimes impossible. However, parts of the curve may be interpretable, as for example the left hand part of the curve in Fig. 5. Lateral variation in resistivity is shown when the ascending gradient of a sounding curve exceeds 45° or the descending gradient exceeds 80°. Data associated with such gradients should not be interpreted purely in terms of resistivity varying with depth.

Pairs of orthogonal soundings at one site are often made so that lateral and anisotropic effects can be identified.

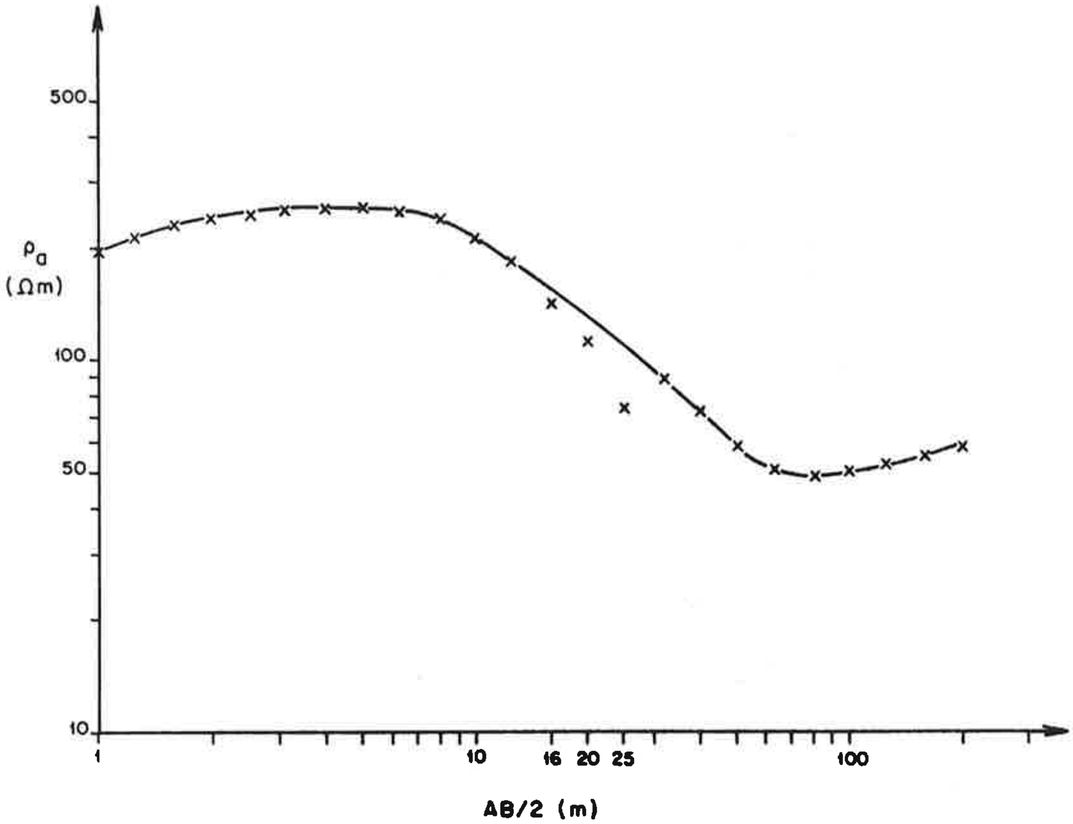


Fig. 4: A sounding curve showing effects of a lateral resistivity variation. Data at AB/2 = 16, 20 and 25 m are affected by the lateral change and are ignored when drawing the 'corrected' curve.

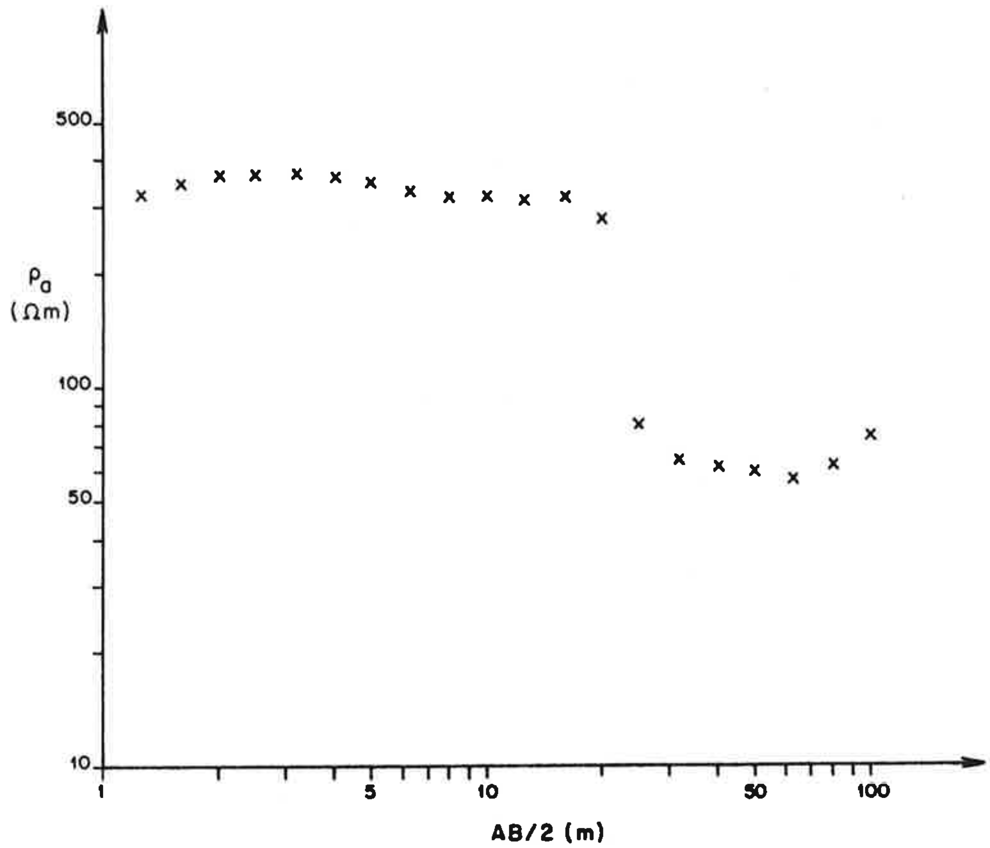


Fig. 5: Sounding curve affected by large scale lateral resistivity variation. This curve is not interpretable purely in terms of resistivity varying with depth under the sounding site.

Lateral changes in near-surface resistivity close to the potential probe can affect the sounding curve. These changes are often visible when cross-over points are calculated.

3.2 Horizontal Profiling

Horizontal profiling (or 'traversing') consists of making repeated resistivity measurements over a region with a few selected AB/2 spacings. The aim of profiling is to detect lateral resistivity changes within a particular depth range, the range being dependent on the AB/2 spacing chosen. Large areas can be covered in a relatively short time.

As a general rule, the AB/2 spacing should be chosen as approximately three to four times the depth of interest. Resistivity sounding interpretation is the best way of determining the relation between depth of interest and AB/2 spacing. Soundings should therefore be measured in conjunction with profiling surveys.

3.3 Choice of Measurement Site

Generally, the following features should be avoided when making resistivity measurements.

(a) Fence lines

Fence lines which are close to and near parallel with the electrode array can produce misleading measurements of apparent resistivity, particularly in damp surface conditions. Therefore measurements should generally be taken as far away from fences as possible. Measurements may be taken with fence lines crossing the line of electrodes at right angles, but the fences should not pass between potential electrodes. Junctions of fence lines should be avoided. Electric fences should be turned off because small varying voltages can be set up in the ground which can make the voltage resulting from the instrument unreadable.

(b) Buried pipes

Positioning an electrode above a horizontal metal pipe will lead to a misleading measurement of apparent resistivity. The vertical steel casing of a well, however, has little effect on resistivity measurement, unless an electrode is positioned immediately adjacent to it.

(c) Power lines

Power lines, other than those for normal domestic and light industrial supply, can create large voltages in the ground around them and swamp the voltage induced by the instrument.

(d) Highly variable surface conditions near the array centre

All potential electrode positions at a site should encounter the same surface conditions if possible. Roadsides and boundaries between dry and irrigated paddocks are examples of localities where variation could affect resistivity measurements. The curve adjustment technique described in Section 3.1 corrects for minor variations in surface conditions.

(e) Large changes in topography

Equation 3, from which apparent resistivity is calculated, is derived assuming measurements are made on a flat surface. Large changes in topography, for example, narrow, steep-sided valleys or ridges, should be avoided. Small topographical changes, such as low banks and ditches, are not of major concern.

(f) Lateral changes in resistivity

An assumption in the commonly used resistivity sounding interpretation method is that the subsurface can be represented by horizontal layers which have a large lateral extent relative to the distance between the current electrodes. Where major departures from this assumption occur, depth interpretations should be avoided.

(g) Weather

Wet surface conditions can cause current circuit shorting and severe errors in potential measurement. This situation is worsened if there are any faults with cable insulation. Avoid resistivity measurement whilst it is raining.

4 RESISTIVITY INTERPRETATION

4.1 Sounding Interpretation

Resistivity sounding interpretation analyses surface measurements of **apparent** resistivity to deduce the subsurface distribution of **actual** resistivity. The methods of sounding interpretation that this report describes are graphical curve matching, a relatively simple and convenient method for field use, and computer analysis.

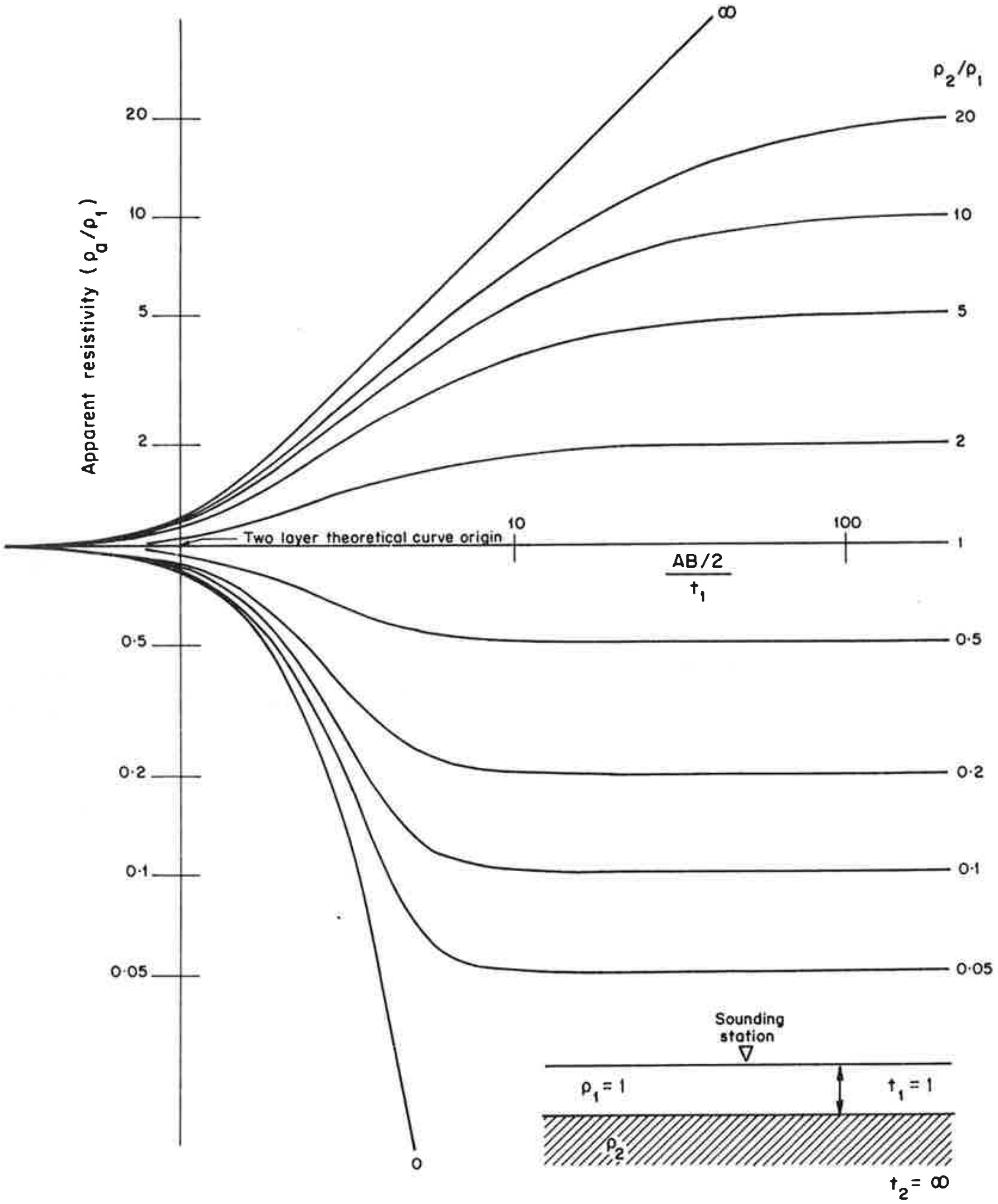


Fig. 6: Theoretical two layer sounding curves for the Schlumberger array (after Orellana and Mooney, 1966).

A sounding curve is interpreted as representing a discrete number of horizontal layers of differing true resistivities. Assumptions are made that the layers are homogeneous, isotropic, of infinite horizontal extent and that the lowest layer extends to infinite depth. Sounding interpretation is likely to be less reliable when field conditions deviate from these ideals.

Procedure for interpretation in terms of two layers

Theoretical Schlumberger array curves for ground consisting of two layers of various resistivity ratios and depths are shown in Fig. 6. The greater the resistivity contrast of the two layers, the greater the gradient on the theoretical curve. A two layer interpretation is made as follows:

(i) Plot the smoothed resistivity sounding data on transparent log-log graph paper at the same scale as the standard theoretical curves.

(ii) Superimpose the observed curve (Fig. 3) on the theoretical curve and match the two as well as possible (e.g., Fig. 7), keeping the axes of the field and theoretical curves parallel.

(iii) When the best fit has been obtained, mark the origin of the theoretical curve on the transparent field data sheet and note the resistivity ratio of the lower layer to the upper layer (ρ_2/ρ_1) for the matching theoretical curve.

(iv) The horizontal co-ordinate of the marked origin on the field curve is equal to the thickness of the first (surface) layer, with the vertical co-ordinate giving the true resistivity of the layer. The second (lower) layer true resistivity is calculated from the resistivity ratio of the best matched theoretical curve.

In the example (Fig. 7) $\rho_1 = 200\ \Omega$ m and the thickness, t_1, is 3.8 m. As $\rho_2/\rho_1 = 6$, then $\rho_2 = 1200\ \Omega$ m.

Resistivity interpretations are conventionally written as a column, or 'geo-electric section'.

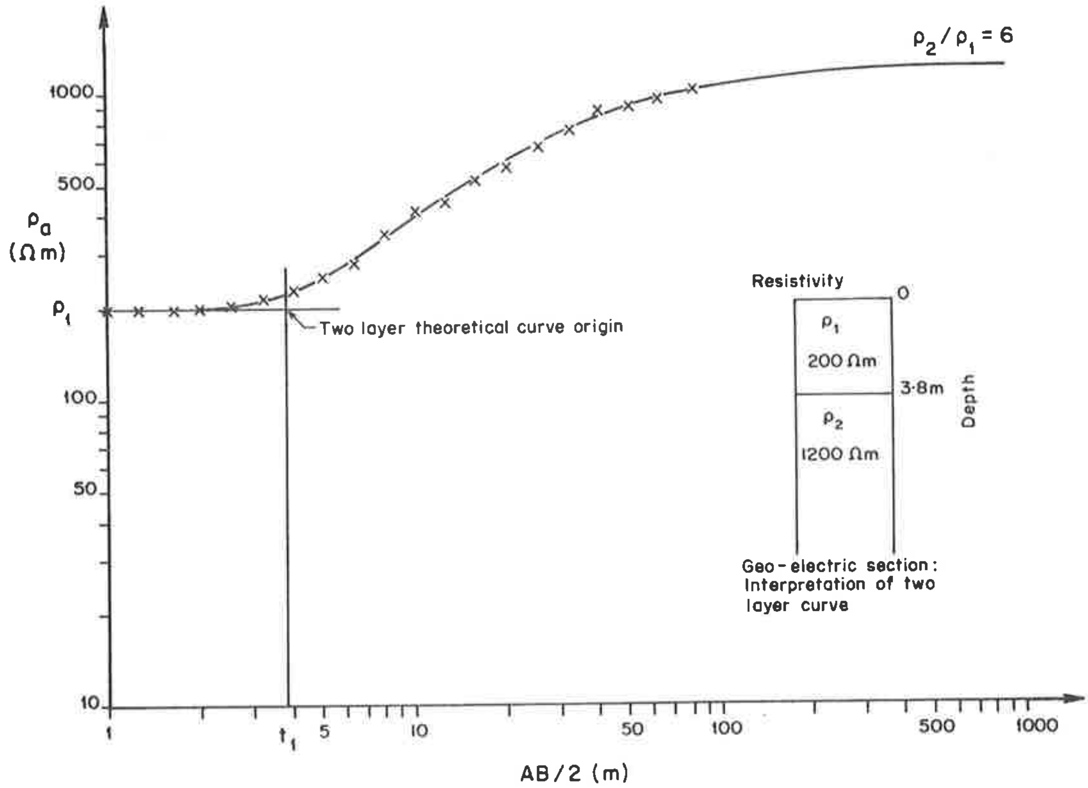


Fig. 7: The field curve of Fig. 3 (crosses) matched to a theoretical two layer curve (solid line) and resulting geo-electric section.

Procedure for interpretation in terms of three layers

Sounding data which suggest a three layer geo-electric section (e.g., Fig. 8) are interpreted using an appropriate set of theoretical curves, such as those in Fig. 9 (see van Dam and Meulenkamp, 1969). Three layer theoretical curves are arranged for different resistivity ratios 1:X:Y, with the resistivity of the first layer (ρ_1) normalised

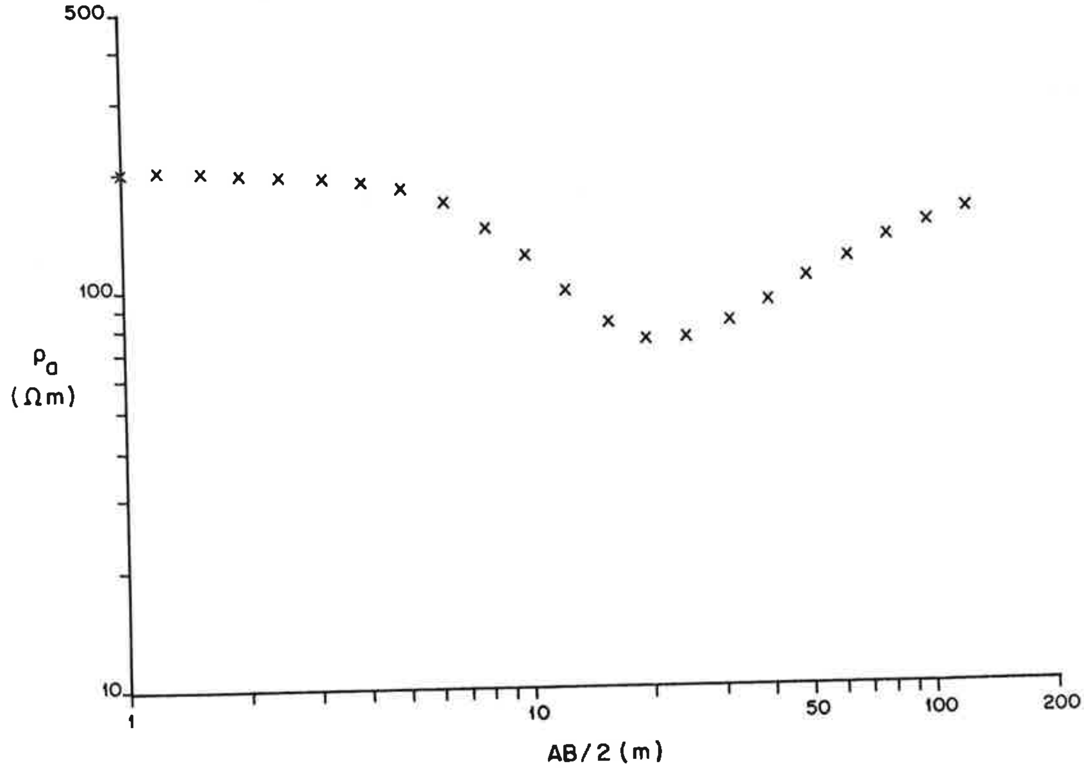


Fig. 8: A three layer sounding curve.

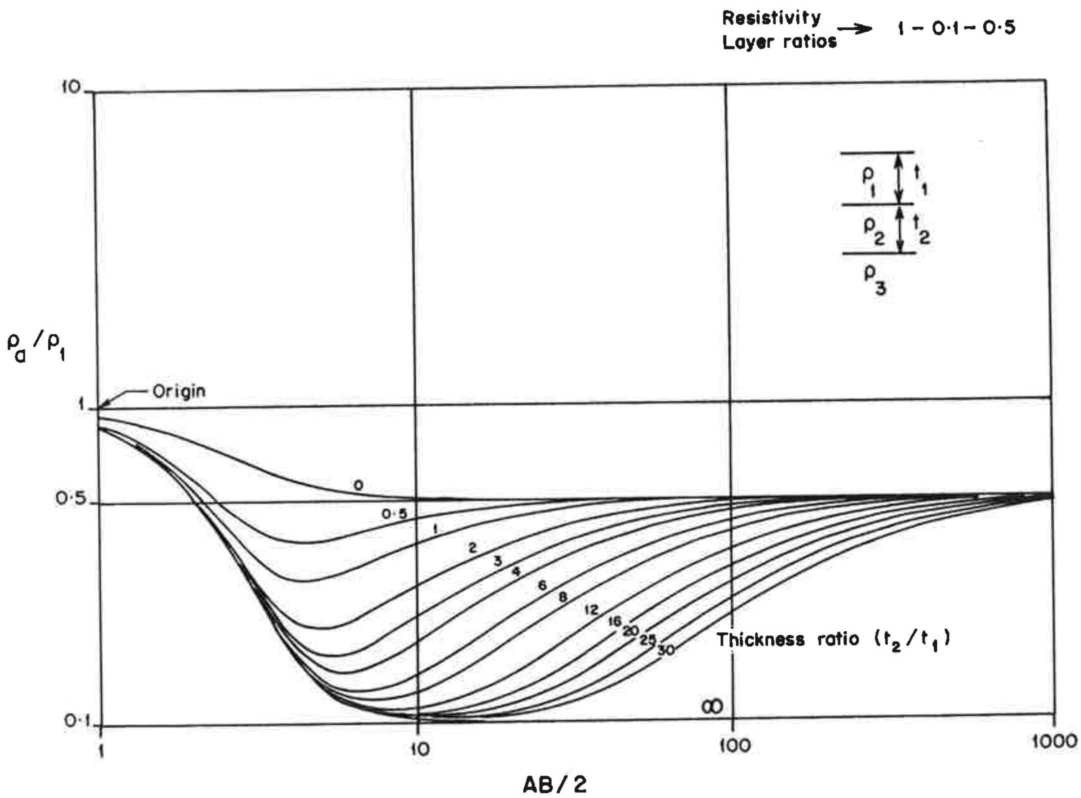


Fig. 9: A group of standard three layer curves for the Schlumberger array (after van Dam and Meulenkamp, 1969).

to 1, $X = \rho_2/\rho_1$ and $Y = \rho_3/\rho_1$. The various curves within each group are labelled in terms of the ratio of the thickness of the second layer to that of the surface layer, t_2/t_1. The third layer is assumed to be infinitely thick. These theoretical curves can be used as two layer curves when either $t_2 = \infty$ or $\rho_2 = \rho_3$.

A three layer interpretation is made as follows:

(i) As for two layer interpretation, plot the sounding data on transparent log-log graph paper at the same scale as that used for the theoretical curves.

(ii) From visual inspection of the field curve choose a likely resistivity ratio of the second and surface layer. Curve gradient is a measure of departure of the ratio from 1. In the example (Fig. 8) a first guess of the ratio ρ_2/ρ_1 would be 0.375, i.e., the minimum value (75 Ω m) divided by the resistivity representative of the first layer (approximately 200 Ω m). Similarly ρ_3/ρ_1 can be estimated as 160/200 = 0.8.

(iii) The theoretical curves are arranged in groups firstly by increments of 1:X and, for each of these, by increments of 1:Y. Using the values of ρ_2/ρ_1 estimated in (ii) as a starting point, find appropriate theoretical curves. Superimpose the field curve on the theoretical curves, keeping both sets of axes parallel, until a match is found.

It is possible that two or more theoretical curves will fit the field curve equally well. Proceed through the following steps using all good fits.

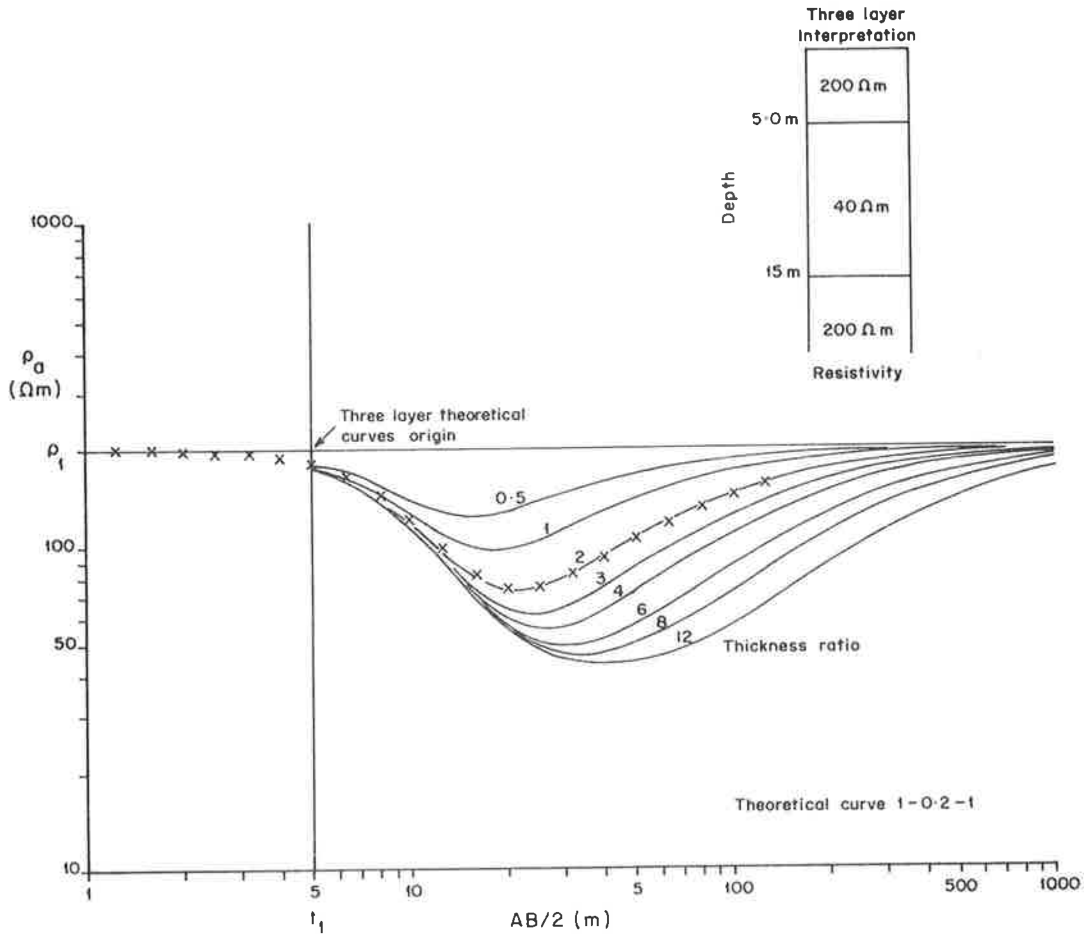


Fig. 10: Illustration of a three layer interpretation by curve matching. The crosses are the field observations. The geo-electric section of the best fit theroetical curve is shown.

(iv) The first layer resistivity ρ_1 and thickness t_1 are derived as for the two layer interpretation by marking the theoretical curve origin on the field sheet and reading the vertical and horizontal co-ordinates. In the example shown in Fig. 10:

$$\rho_1 = 200\ \Omega\ m$$
$$t_1 = 5\ m = d_1.$$

where d_1 = depth to base of the first layer.

Second and third layer resistivities follow from the X and Y ratios of the best fit curves. For Fig. 10, 1:X:Y is 1:0.2:1 so that $\rho_2 = 40\ \Omega$ m and $\rho_3 = 200\ \Omega$ m.

The thickness ratio of the matched curve (t_2/t_1) is used to calculate the thickness of the second layer and hence the depth to its base, i.e.

$$d_2 = t_2 + t_1$$

For the example in Fig. 10, $t_1 = 5$ m, the thickness ratio = 2 and hence $d_2 = 15$ m.

(v) Record the interpreted geo-electric sections in terms of resistivities and depths, as shown in Fig. 10.

Examples of two and three layer sounding data are presented in the Appendix, together with interpretations. The reader may work through these examples to confirm understanding of the interpretation procedures just described.

Procedure for interpretation in terms of more than three layers

Usually the observed sounding curve will represent more than three layers. There are many methods of graphical interpretation of such curves. The method described here is one of the simplest because it uses theoretical three layer curves, but only produces an approximate interpretation. The example referred to below has a four layer interpretation but the technique is much the same for more layers. The procedure is as follows:

(i) Match the left hand side of the field curve as well as possible to a three layer theoretical curve (Fig. 11, step 1). Record the corresponding geo-electric section.

(ii) Ignore that part of the field curve which is dominated by the effect of the first layer and interpret the remaining part in terms of the underlying three layers (Fig. 11, step 2). Record the corresponding geo-electric section.

(iii) The thickness of layer three from step 2 (38.4 m) is added to the depth to layer three from step 1 (3 m), giving a layer four depth of 41.4 m. The resistivity of the fourth layer is that from step 2. The final interpretation for the example is shown in Fig. 11, step 3.

If there are five layers then that part of the curve dominated by the top two layers is ignored and a three layer interpretation sought for the next section of the curve to the right. The third layer is considered as 'surface' and the thickness of the fourth layer is derived together with the resistivity of the fifth layer. This procedure of taking successively deeper three layers is repeated for curves indicating more than five layers.

When analysing soundings, some discretion must be exercised as to the number of layers in an interpretation; only obvious trends should be analysed. As a guide, six layers should be the maximum number of layers for soundings up to an AB/2 of 125 m.

Interpretation using a computer

Computer interpretations often result in more exact geo-electric sections than graphical curve matching.

Most computer interpretation methods are based on the calculation of resistivity sounding curves by linear filter techniques (Ghosh, 1971). Program inputs are a trial geo-electric section, usually derived by graphical techniques, and field measurements. A resistivity sounding curve is calculated for this trial section and compared with field data. Computer optimisation techniques then change the resistivities and thicknesses of the trial section, deriving a new model which agrees more accurately