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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 ($\Delta V = IR$), Equation 1 becomes

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

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

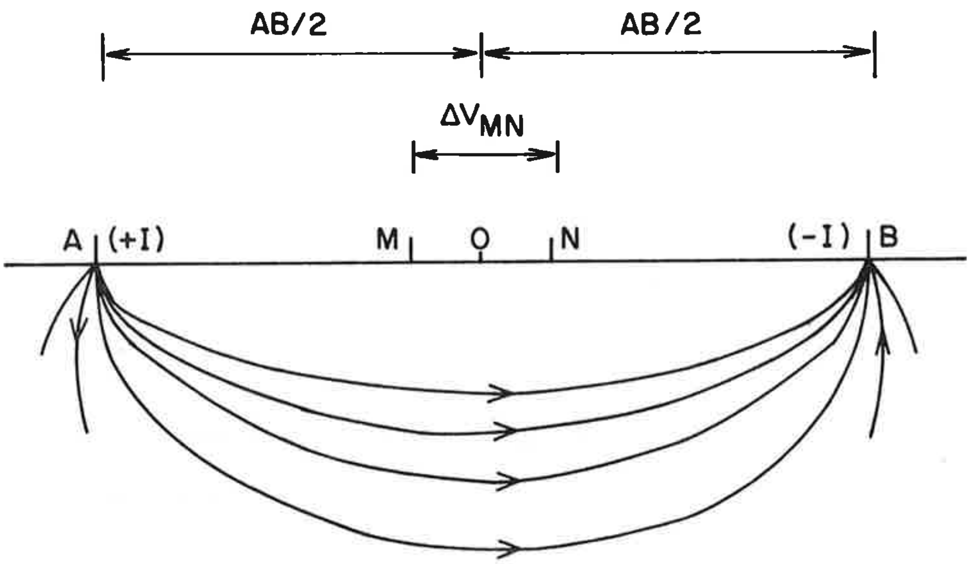
[1] Water temperature and salinity affect its resistivity. Conductivity is the inverse of resistivity.
[2] Telford *et al.* (1976) [3] Roberts (1980) [4] Davidge (1982) [5] Banwell and McDonald (1965)

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

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

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).

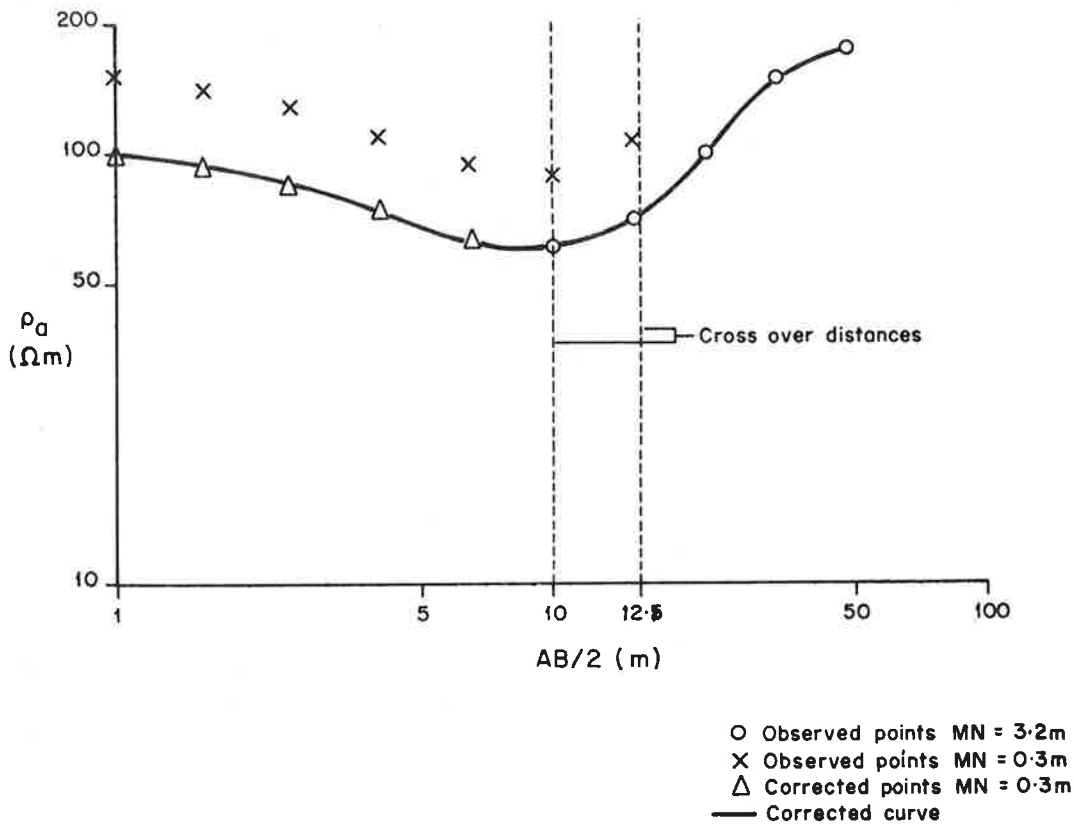


Fig. 2: Illustration of the effect of curve smoothing. In this example, observed resistivities with an MN of 0.3 m were corrected to give the final curve.

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.

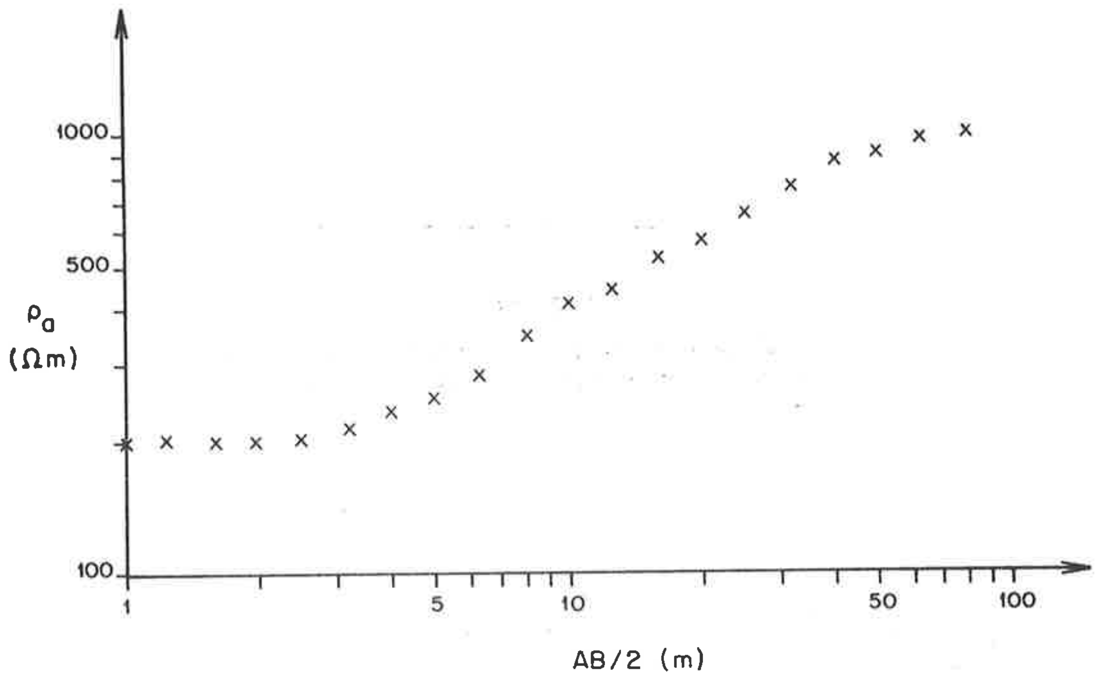


Fig. 3: Sounding curve of corrected resistivity data from Table 2.

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.

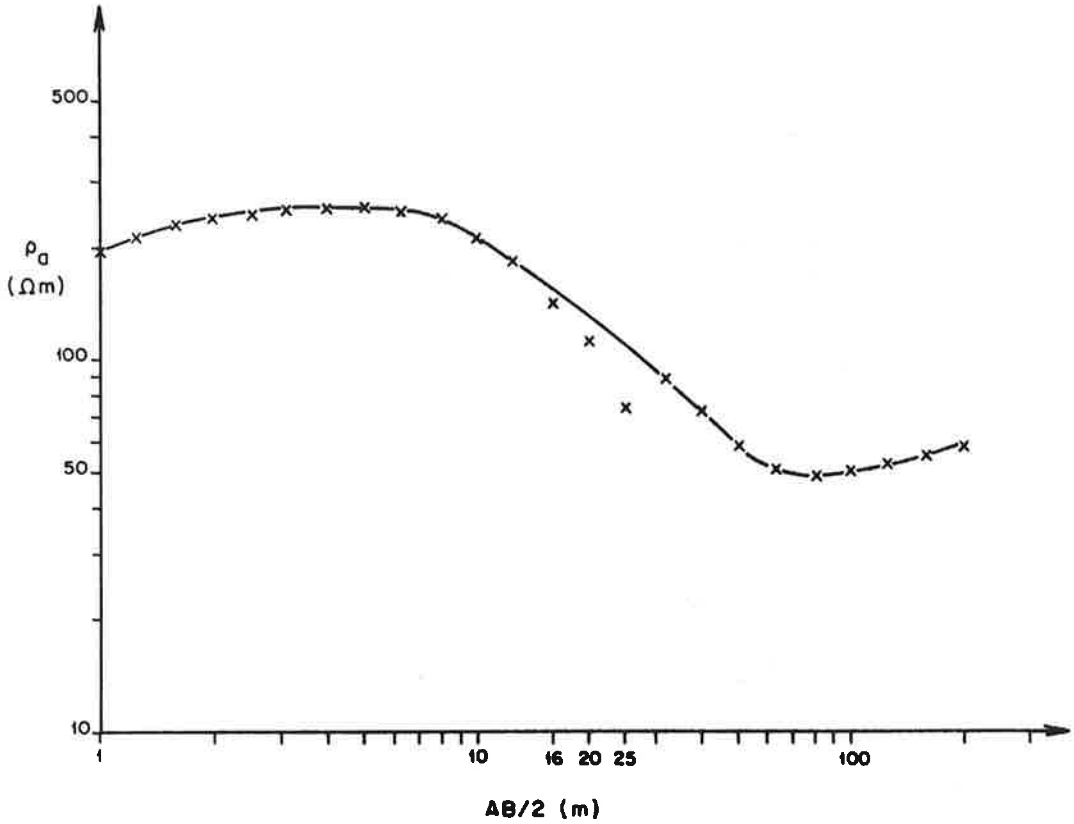


Fig. 4: A sounding curve showing effects of a lateral resistivity variation. Data at AB/2 = 16, 20 and 25 m are affected by the lateral change and are ignored when drawing the 'corrected' curve.

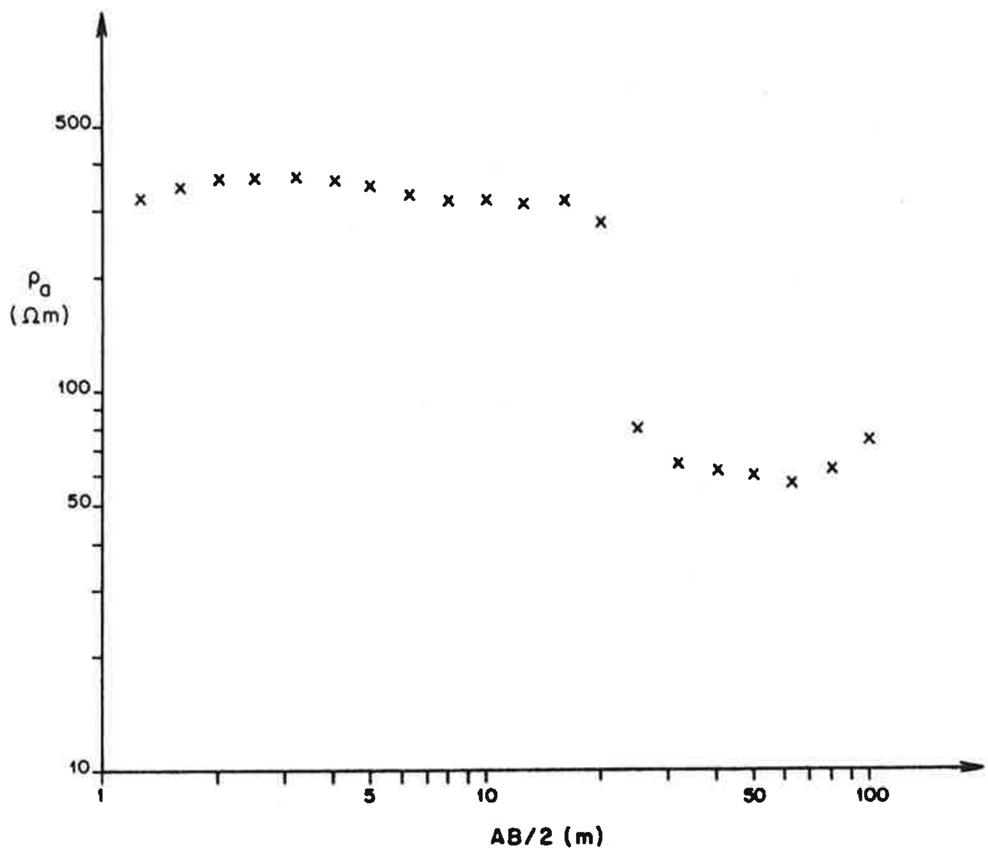


Fig. 5: Sounding curve affected by large scale lateral resistivity variation. This curve is not interpretable purely in terms of resistivity varying with depth under the sounding site.

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.

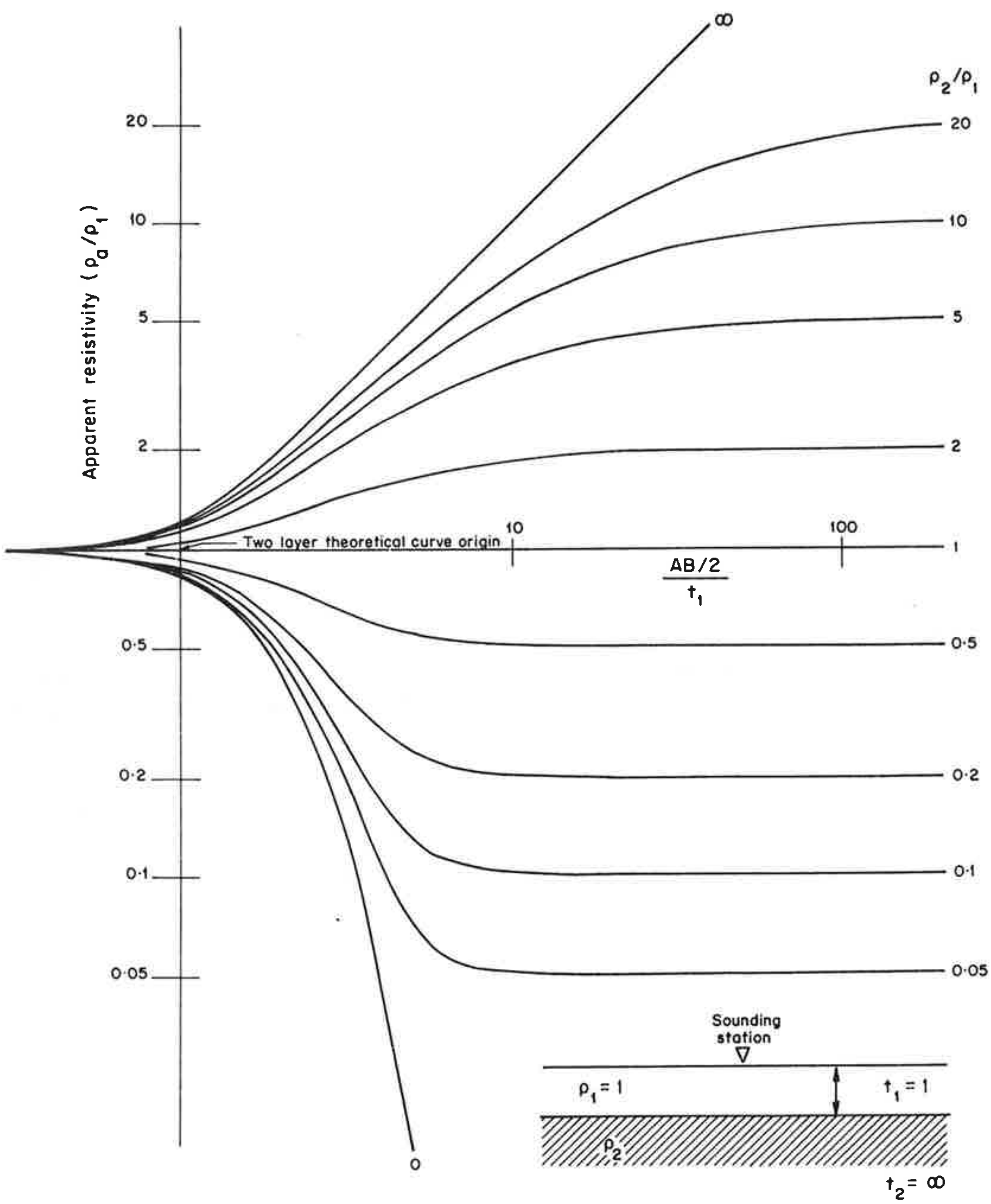


Fig. 6: Theoretical two layer sounding curves for the Schlumberger array (after Orellana and Mooney, 1966).

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'.

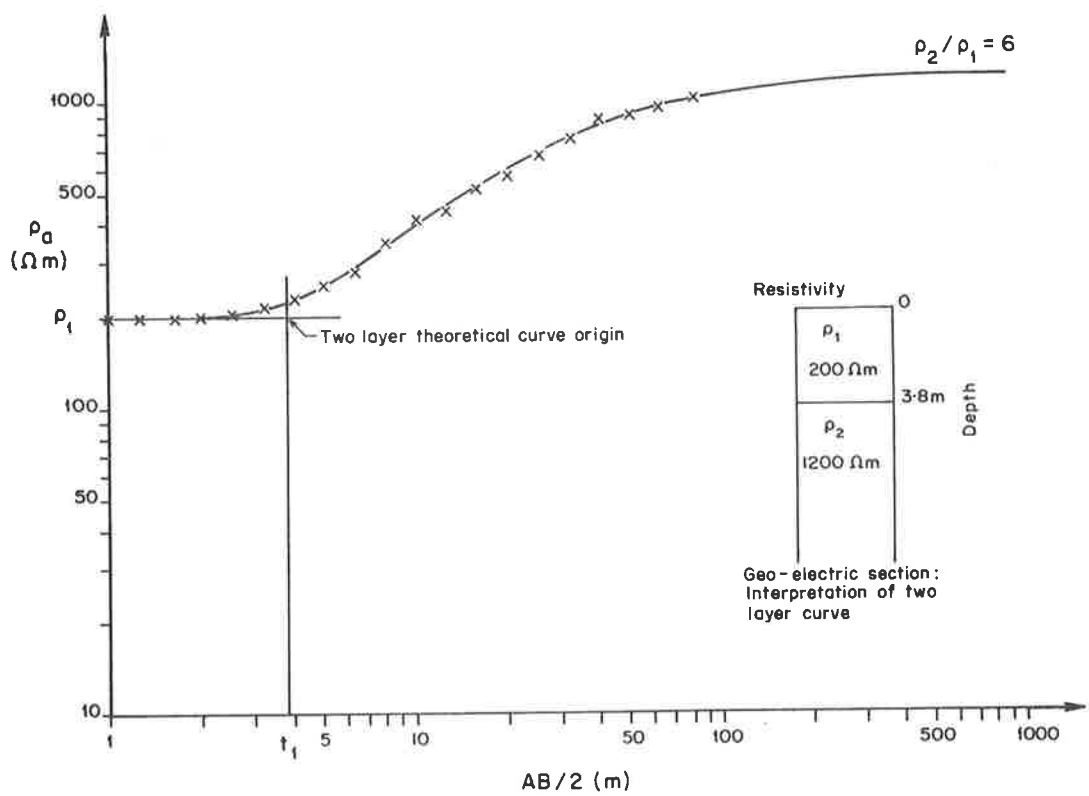


Fig. 7: The field curve of Fig. 3 (crosses) matched to a theoretical two layer curve (solid line) and resulting geo-electric section.

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

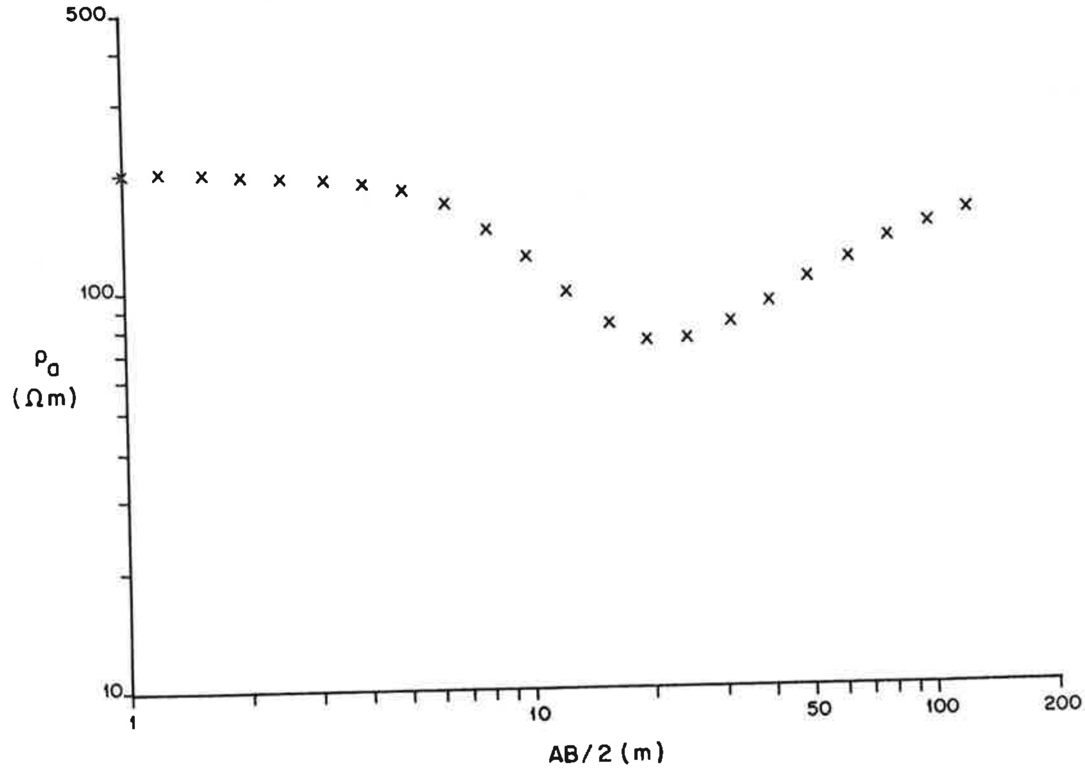


Fig. 8: A three layer sounding curve.

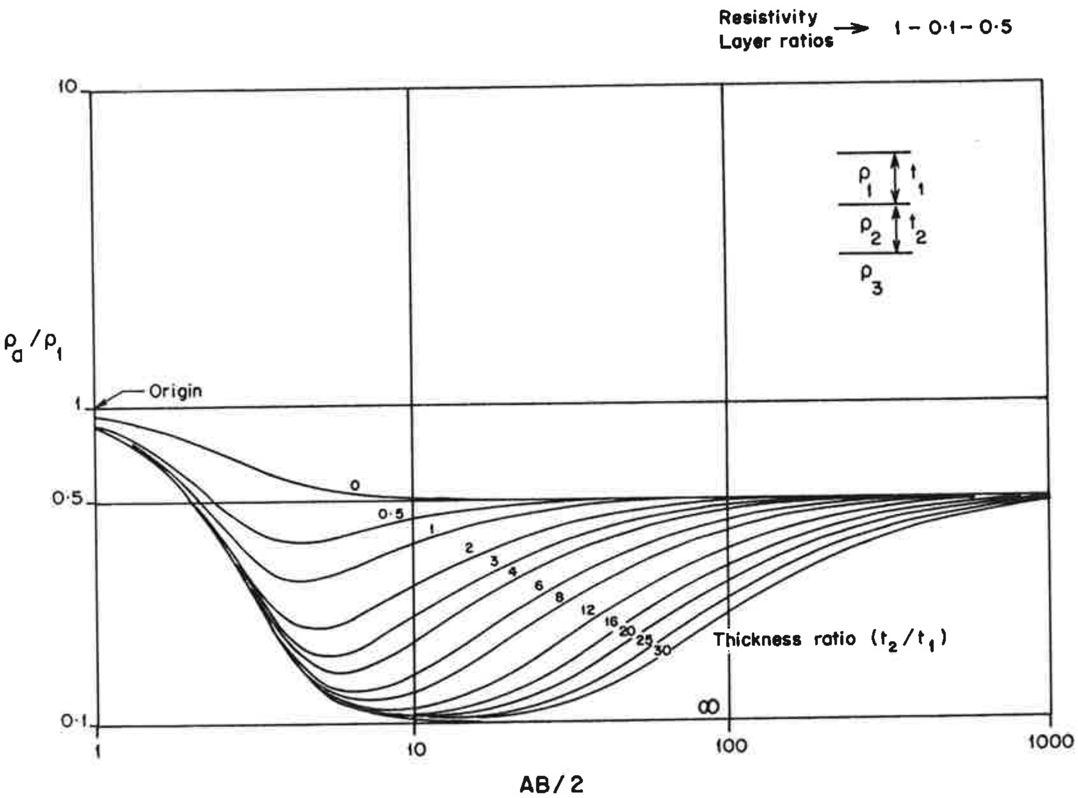


Fig. 9: A group of standard three layer curves for the Schlumberger array (after van Dam and Meulenkamp, 1969).

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.

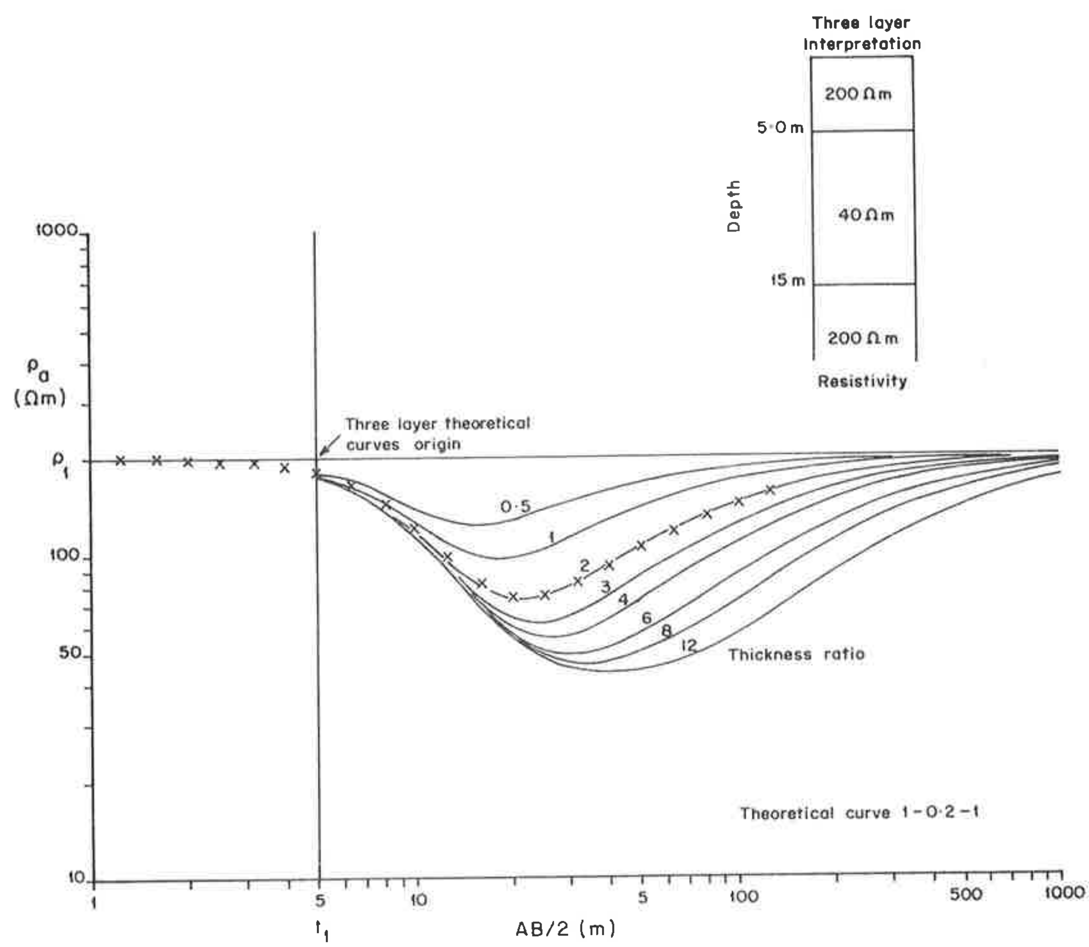


Fig. 10: Illustration of a three layer interpretation by curve matching. The crosses are the field observations. The geo-electric section of the best fit theroetical curve is shown.

(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:

$$\rho_1 = 200\,\Omega\,\text{m}$$
$$t_1 = 5\,\text{m} = d_1.$$

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 $\rho_2 = 40\,\Omega\,\text{m}$ and $\rho_3 = 200\,\Omega\,\text{m}$.

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.

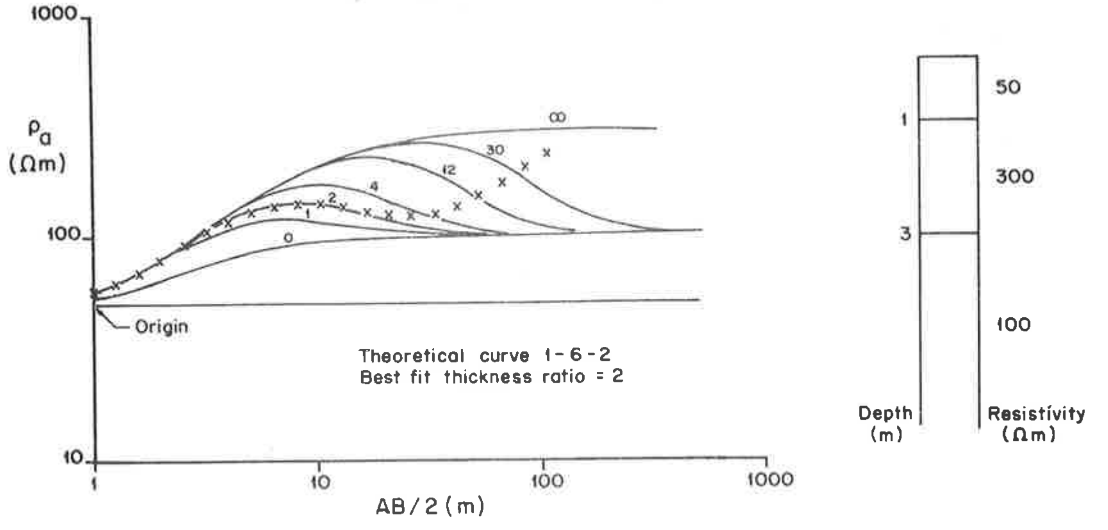
When analysing soundings, some discretion must be exercised as to the number of layers in an interpretation; only obvious trends should be analysed. As a guide, six layers should be the maximum number of layers for soundings up to an AB/2 of 125 m.

Interpretation using a computer

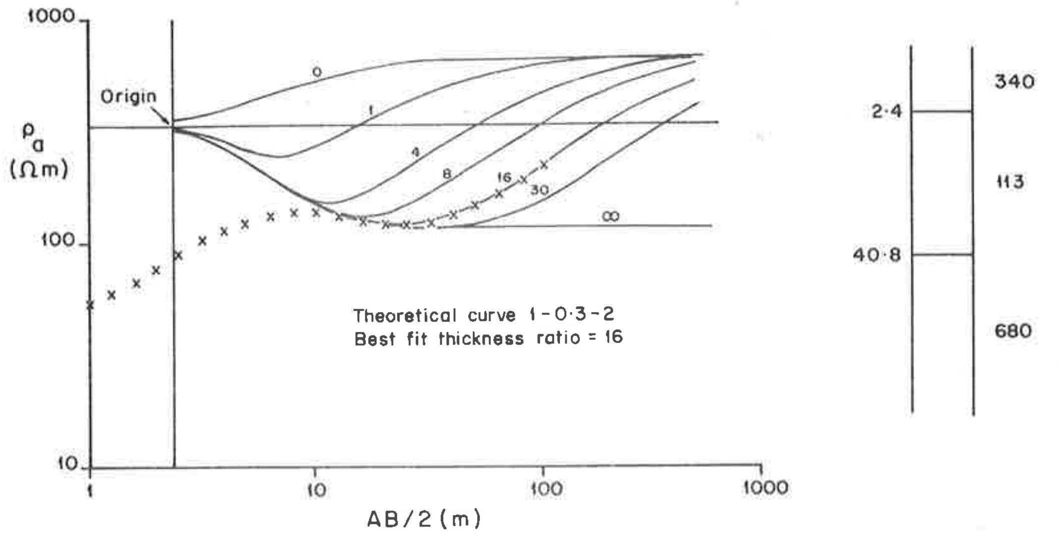
Computer interpretations often result in more exact geo-electric sections than graphical curve matching.

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 with the field data. This process is repeated until a geo-electric section is obtained that produces a sounding curve which corresponds to the field data as closely as possible.

Step 1. Match the upper three layers to a standard curve and produce interpretation



Step 2. Match the lower three layers to a standard curve and produce interpretation



Step 3. Interpretations from steps 1 and 2 are combined to give the final interpretation

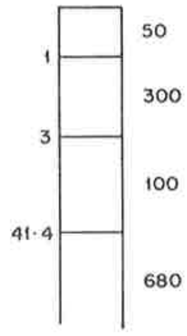


Fig. 11: Interpretation of a four layer field curve using three layer standard curves. Crosses are field data and the solid lines are the theoretical curves.

The computer interpretation process, using the data and graphical solution of Fig. 11, is illustrated in Fig. 12. Agreement between field data and data calculated for the trial geo-electric section (Fig. 12a) is poor for AB/2 less than 2 m and greater than 25 m, demonstrating the approximations made by graphical interpretation.

A comparison of field data and theoretical sounding curve after optimisation (Fig. 12b) shows the ability of computer methods to produce a more exact solution. Optimisation has, in this case, reduced the resistivity and changed the thickness of all layers.

More detailed accounts of computer based methods of interpretation are given by Koefoed (1979).

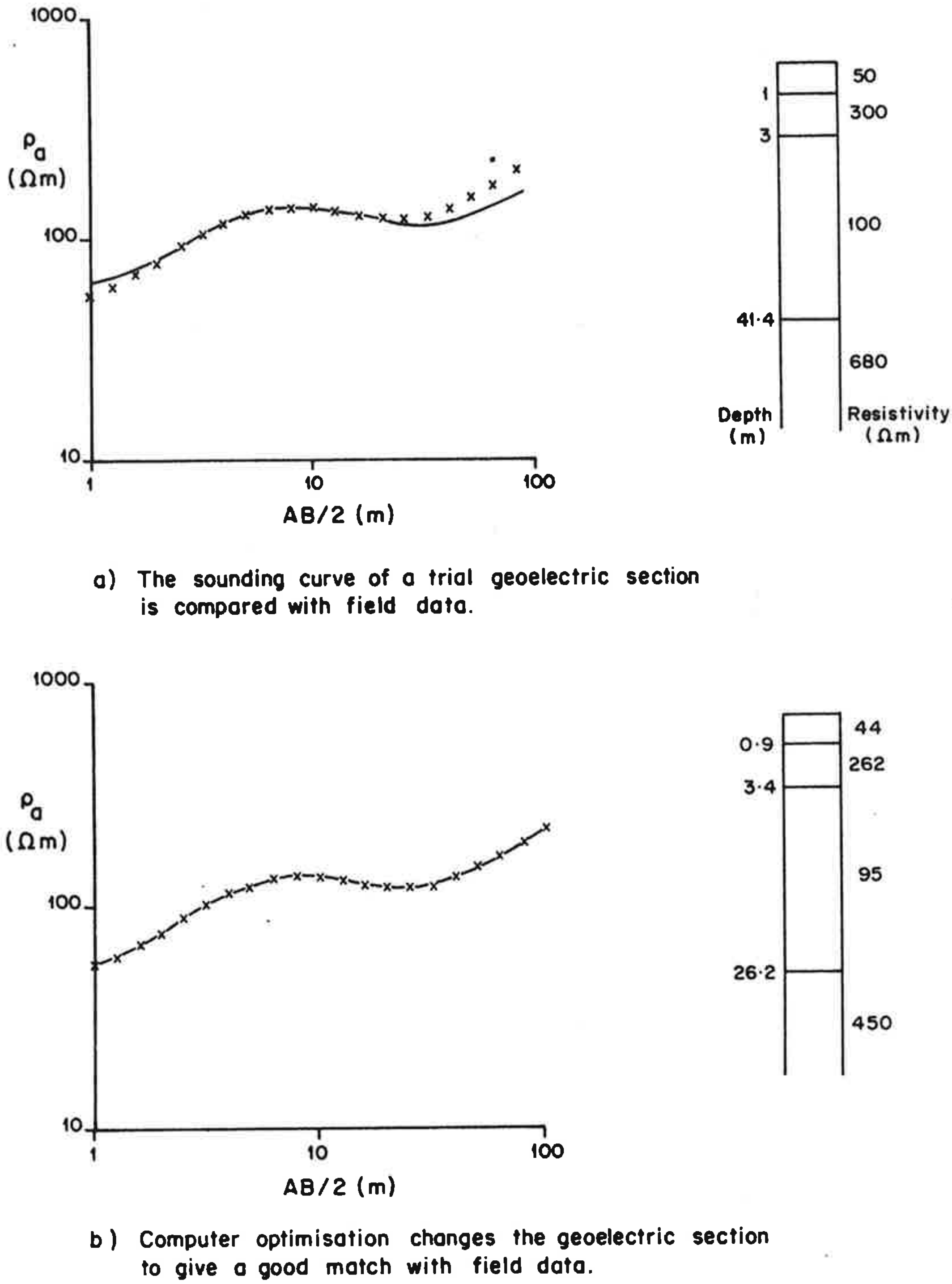


Fig. 12: Computer interpretation of a sounding curve. The data and trial geo-electric section come from Fig. 11. Crosses are field data and the solid lines are geo-electric section curves.

(a) The sounding curve of a trial geo-electric section is compared with field data.

(b) Computer optimisation changes the geo-electric section to give a good match with field data.

Non-uniqueness of sounding interpretations

The ambiguity of sounding curve interpretation is manifested by two phenomena called 'equivalence' and 'suppression'. In both, a range of layer resistivities and thicknesses can produce the same sounding curve, this range being dependent on the curve shape.

Equivalence conditions are usually encountered when a layer has a large resistivity contrast with its neighbours and a thickness which is small relative to its depth. Figure 13 illustrates an example of sounding interpretation equivalence.

When the effect of a lithological layer is not identifiable, the layer is said to be 'suppressed'. Suppression occurs, for example, when a thin layer is sandwiched between layers of greatly differing resistivities.

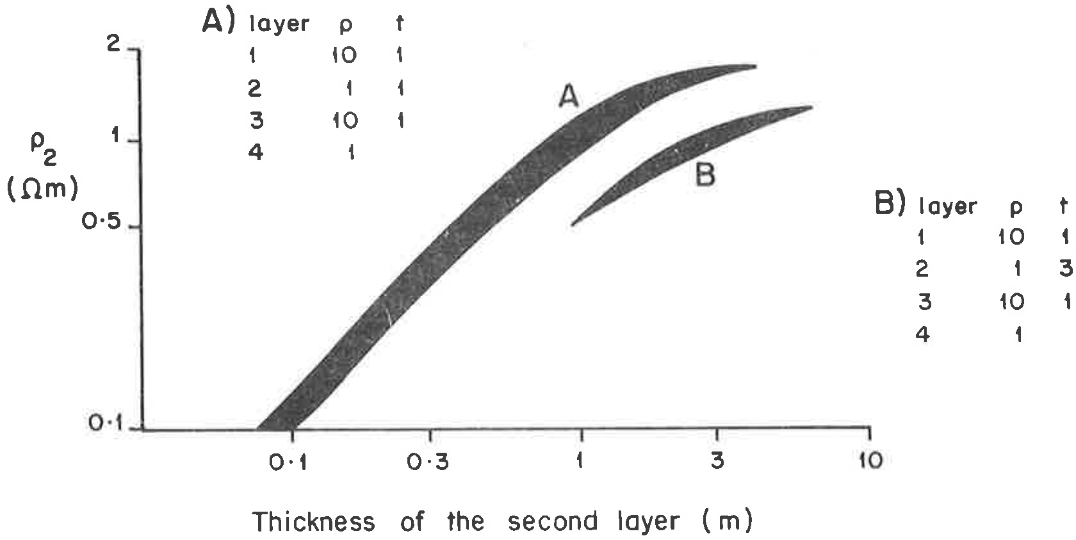


Fig. 13: Equivalent interpretations of two sounding curves (after Koefoed, 1979). The areas in black represent the range of second layer resistivity and thickness that produce sounding curves indistinguishable from those of the respective models.

Inherent error in sounding interpretation

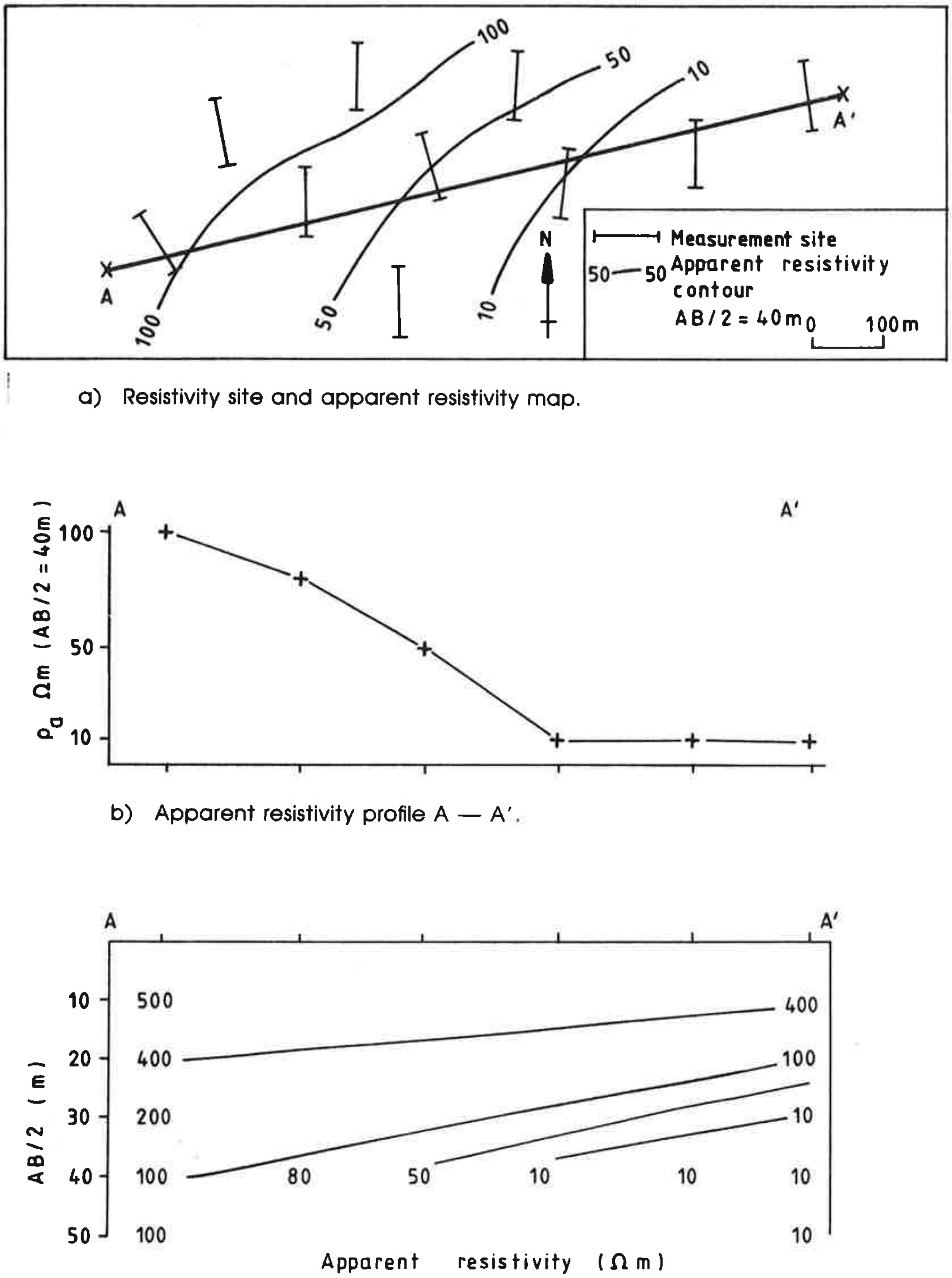
Errors inherent in sounding measurement and interpretation result in a depth determination accuracy of about $\pm 10\%$ under favourable conditions for the technique, namely all the interpretation assumptions are satisfied and good resistivity contrasts exist between the layers. Equivalence of sounding interpretations can result in larger errors (Fig. 13). The absolute error of depth determination increases with depth.

4.2 Horizontal Profiling Interpretation

The interpretation of horizontal profiles is qualitative. Field data are usually presented as apparent resistivity maps, profiles or pseudosections (Fig. 14). All three methods of plotting indicate how the resistivity at depth is varying horizontally, and allow the identification of geological features such as faults, dipping strata and aquifers.

Contoured apparent resistivity maps and graphs of resistivity profiles are useful in displaying and interpreting the horizontal variation of resistivity.

A pseudosection is a cross section showing the variation of apparent resistivity with array location and AB/2. Apparent resistivity is plotted on a linear AB/2 spacing scale to emphasise resistivity changes at depth. This presentation technique usually contains both profiling and sounding information.



a) Resistivity site and apparent resistivity map.

b) Apparent resistivity profile A — A'.

c) Apparent resistivity pseudosection. Profile measurements are used to fill in gaps between soundings measured near A and A'.

Fig. 14: Presentation of horizontal profiling data. Apparent resistivity is decreasing towards the south-east as shown by the map (a). The profile A-A[1] (b) indicates apparent resistivity decreasing towards the east. These measurements reflect resistivity changes 10-13 m below ground level-probing depth is between approximately one third and one quarter of AB/2. The pseudosection (c) shows that the higher resistivity surface layer is thinning towards the east.

5 GENERAL EXPLORATION STRATEGY

In all resistivity surveys the usual exploration strategy consists of the following steps:

(i) Definition of the ground water problem to be solved.

(ii) Collection of all relevant borehole information, particularly lithological logs and water level and water conductivity data. This information is often crucial to the successful interpretation of any resistivity survey.

(iii) Assessment of the applicability of the resistivity technique to the solution of the problem, by either a library study of previous applications to similar problems and/or by making initial measurements. For the latter, resistivity soundings near wells are useful so that layer resistivity may be compared with known lithology, allowing evaluation of the technique to detect layers of interest.

(iv) The survey

A combined sounding/profiling survey is usually the best method of investigation. Soundings give details of resistivity depth structure while profile measurements efficiently measure horizontal variations of resistivity. When great detail is required a survey may consist entirely of a grid of sounding measurements with perhaps orthogonal measurements to identify anisotropy, lateral effects and other sources of error (Section 3.3). No rule can be given on the density of surface measurements because this depends on the nature and difficulty of the problem.

It is useful to interpret data as the survey proceeds so that desirable sites for future measurement can be located.

6 GROUND WATER BASIN STRUCTURE

The identification of the thickness of an aquifer system is often required for the assessment of regional ground water resources. The resistivity method can successfully define the depth to impermeable basement when the basement is within the depth-probing range of the equipment and a good resistivity contrast exists between aquifer system and basement. If this contrast is small then the method should not be pursued.

Resistivities typical of the basement and the aquifer system can be established from measurements taken on suitable outcrops, the comparison of sounding interpretations with borelogs, or library studies.

6.1 Mt Wellington

In order to prevent flooding problems during periods of sustained rainfall in parts of Mount Wellington Borough, Auckland (Fig. 15), it was proposed that soakage boreholes should be drilled into the underlying Quaternary basalt flows. To assess the feasibility of this proposal, the thickness of the flows was determined using a variety of geophysical techniques, including resistivity measurements.

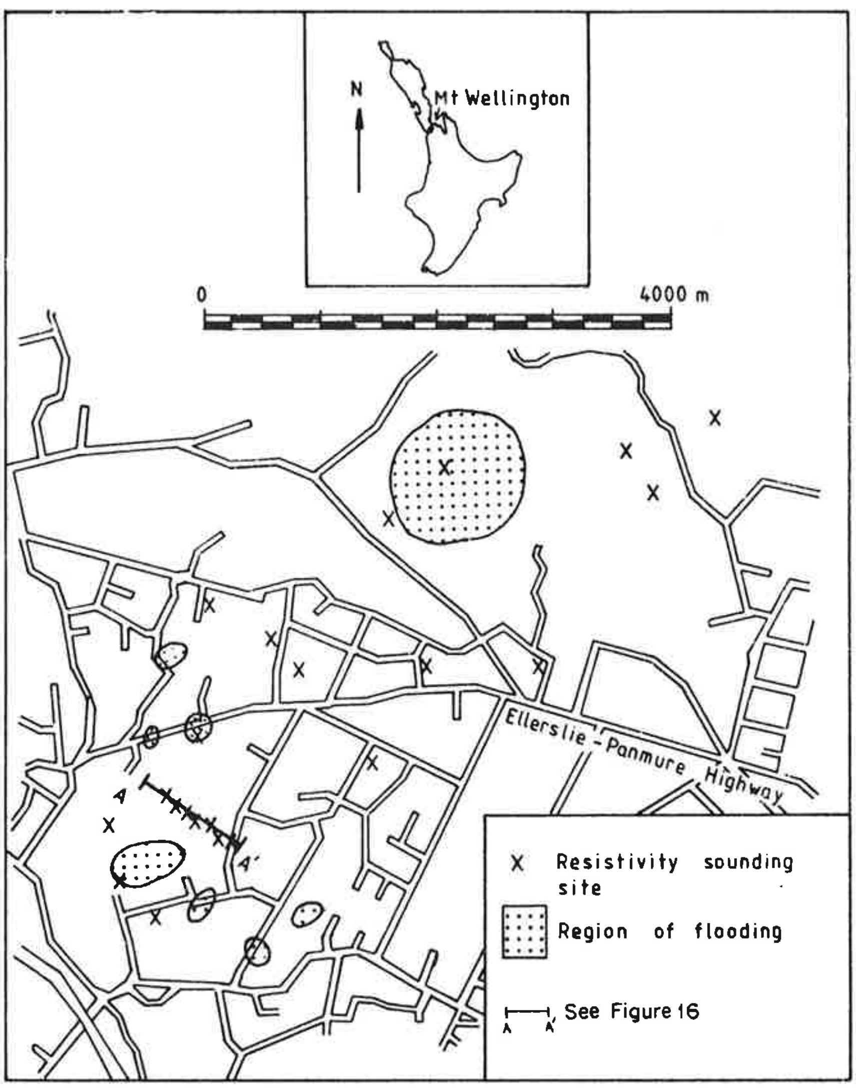


Fig. 15: Mt Wellington—location of sounding sites (after Roberts, 1980). Resistivity measurements were used to estimate the thickness of basalt.

Aquifers occur within the basalts in thin zones at the boundaries of basalt flow units. The underlying weathered Waitemata sediments are impermeable and constitute 'basement' for this investigation (Roberts, 1980).

Schlumberger resistivity soundings were made at thirty-two sites (Fig. 15) but ten were uninterpretable because of disturbances caused by dwellings, buried pipes and roads. The interpreted resistivity values of the different rocks were:

Soil or weathered basalt	60–400 Ω m
Dry basalt	3000–7000 Ω m
Saturated basalt	400–2000 Ω m
Waitemata sediments	10–150 Ω m

A good resistivity contrast exists between the basalt and sediments and interpretation of basalt thickness generally showed good agreement with thickness measured from boreholes. Figure 16 shows one of the sounding curves together with its interpretation

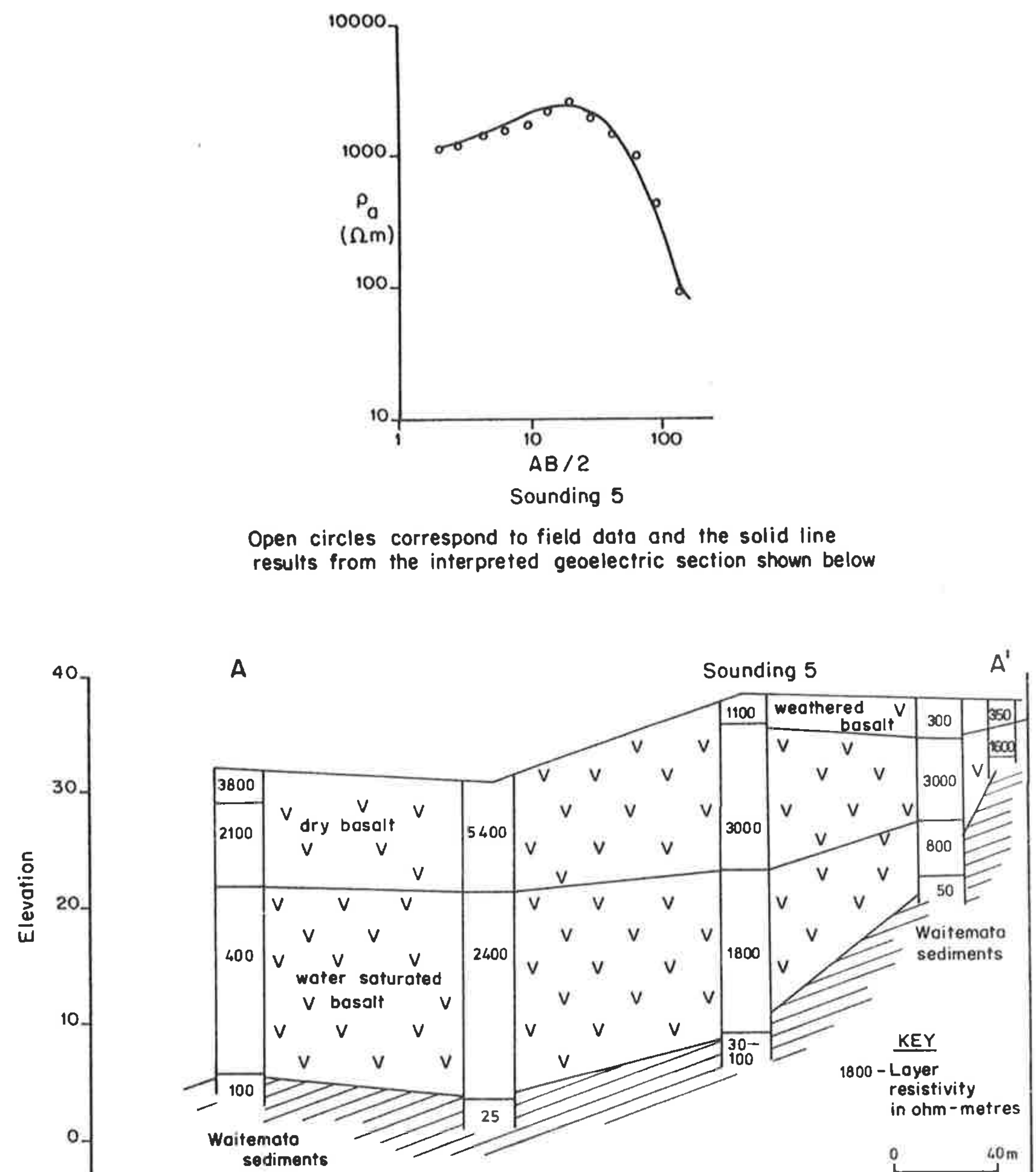


Fig. 16: Mt Wellington sounding curve and geo-electric cross section (after Roberts, 1980). The interpretation of sounding 5 is incorporated in section A–A[1] of Fig. 15. Measurements show the variation of basalt thickness.

and correlation with other geo-electric sections. All interpreted basalt thicknesses were presented in the form of an isopach map which identified an ancient valley filled with basalt; a likely 'drain' for the flooded areas. Soakage boreholes were subsequently drilled into the basalt in an effort to alleviate flooding.

6.2 Heretaunga Plains

The resistivity method was used to measure the depth to impermeable bedrock as part of an investigation of the ground water resource of the Heretaunga Plains.

The Plains consist of a series of alluvial floodplains covering a total area of approximately 260 km^2. The bedrock is composed of intercalated mudstones and limestones of marine origin deposited in the East Coast Geosyncline. In the early Pleistocene, the syncline was infilled by coarse sediment derived from the rapidly eroding greywacke mountains of the Main Divide. During orogenic and climatic fluctuations in sea level, inter-bedded layers of clay, silt and sand were deposited, and some beds now form aquicludes beneath the eastern part of the Plains (Grant-Taylor, 1957; Kingma, 1971).

Resistivity sounding sites in the Ngatarawa Valley (Hawkins, 1978) were selected on a grid basis with 10 cross sections and 4 long sections covering the area (Fig. 17). Soundings were made with a Schlumberger array at AB/2 spacings of up to 200 m. Bedrock relief was identified by the strong resistivity contrast between saturated gravels (150–300 Ω m) and intercalated mudstones or limestone bedrock (10–30 Ω m). The resistivity soundings indicated a central bedrock basement depth of 40–45 m along the length of the valley, flanked by a deeper valley (60–70 m) to the north and a terrace (30–35 m) on the southern boundary (Fig. 18). Comparison of the resistivity data with borelogs from nearby wells suggested an average uncertainty in the depth estimates of ±8%.

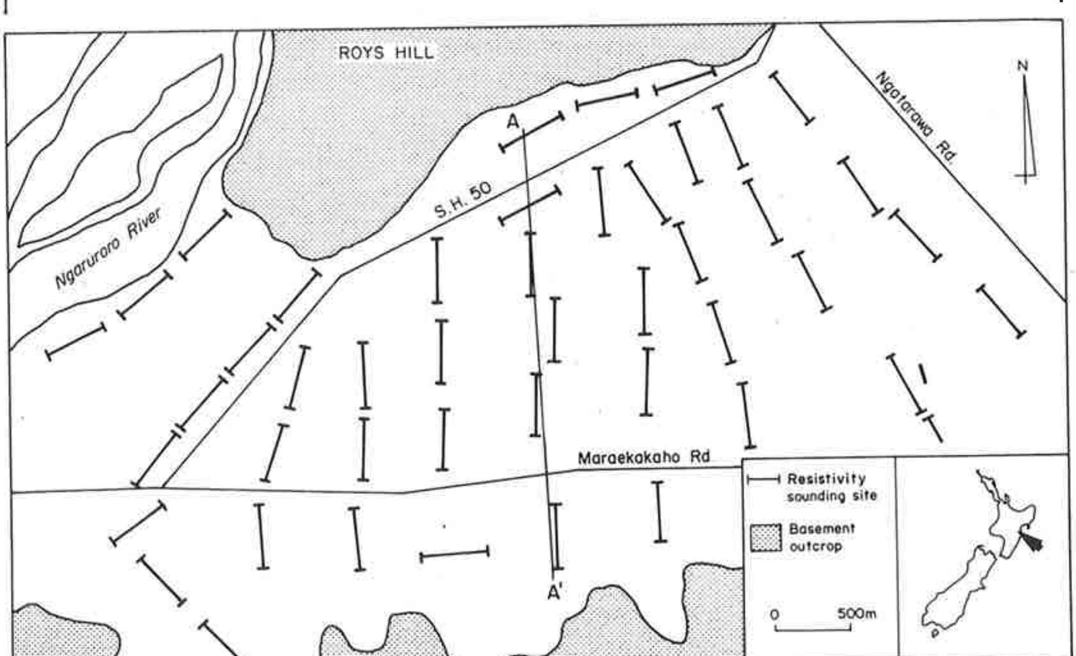


Fig. 17: Heretaunga Plains resistivity sounding sites (after Hawkins, 1978).

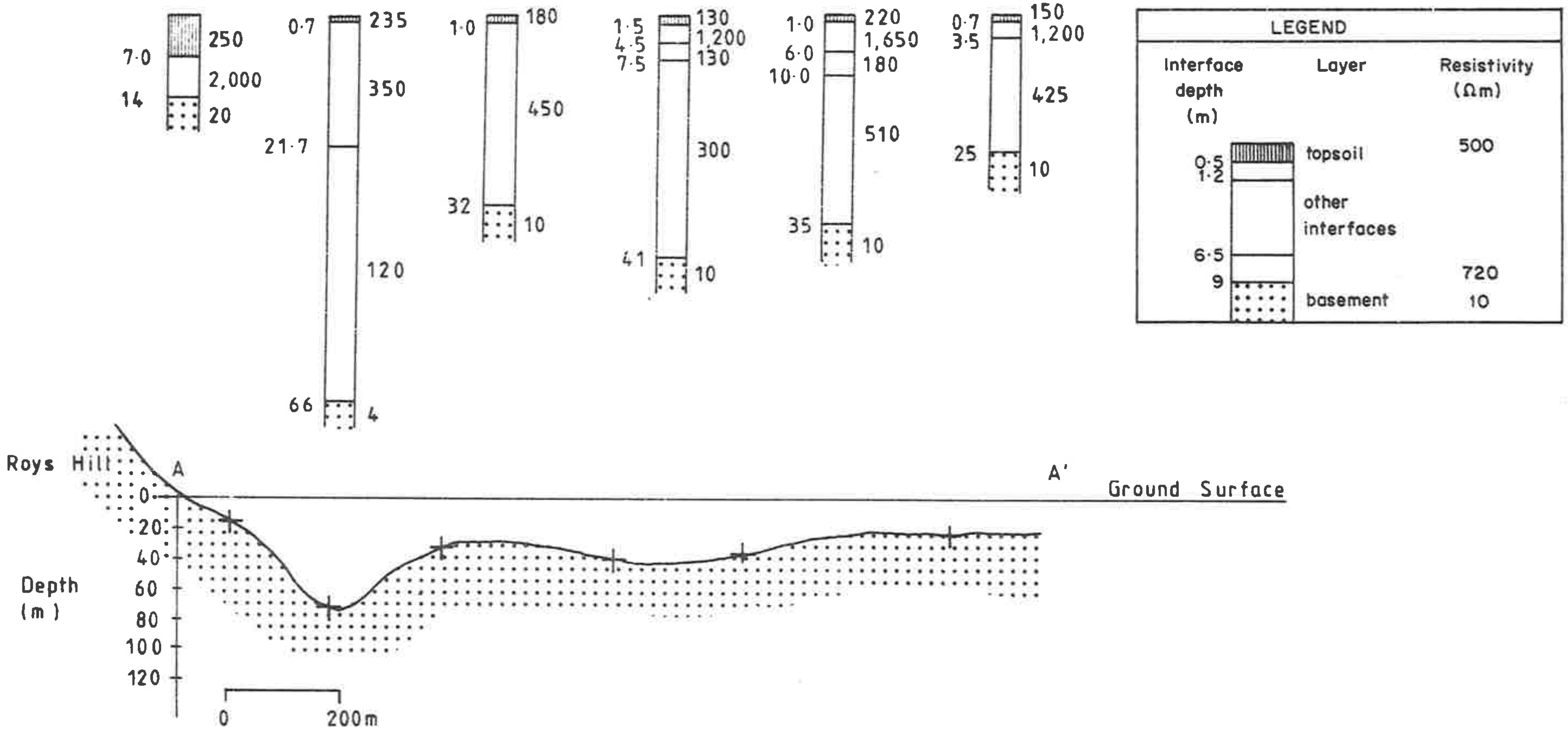


Fig. 18: Heretaunga Plains sounding interpretation of section A–A[1] in Fig. 17 (after Hawkins, 1978). Resistivity interpretations show the variation of Tertiary basement depth.

7 AQUIFER LOCATION

The resistivity technique is useful for locating aquifers, and hence well siting, because regions of high saturated layer resistivity are often related to regions of high permeability. Although the resistivity method may not detect individual aquifers within a lithologic unit, it is usually able to measure the unit's bulk resistivity which can relate to water yielding characteristics.

7.1 Darfield

Several unsuccessful attempts had been made in the past to improve the water supply of Darfield township on the Canterbury Plains. The water level in most wells in the area is more than 70 m below ground and varies considerably throughout the year (Brown, 1966). Ground water occurs in alluvial deposits of sand, gravel and silt. The electrical resistivity method was used to determine depth to water table and to assess aquifer permeability (Risk, 1967).

Twenty electrical soundings were made near the township using the Schlumberger electrode arrangement (Fig. 19). It was not obvious which of the interpreted resistivity boundaries corresponded to the water table, but several boundaries did exist at depths close to the depth of water table as measured in wells at Darfield and Kirwee (60–80 m).

Aquifer resistivities in the region decrease towards the north. Lower aquifer resistivities were interpreted as indicating higher contents of fine sediments. The highest resistivity aquifer was postulated to also have the highest permeability, and to thus be the best source of water supply in the area surrounding the township. Soundings C and D yielded unusually high values (1000 Ω m) of aquifer resistivity.

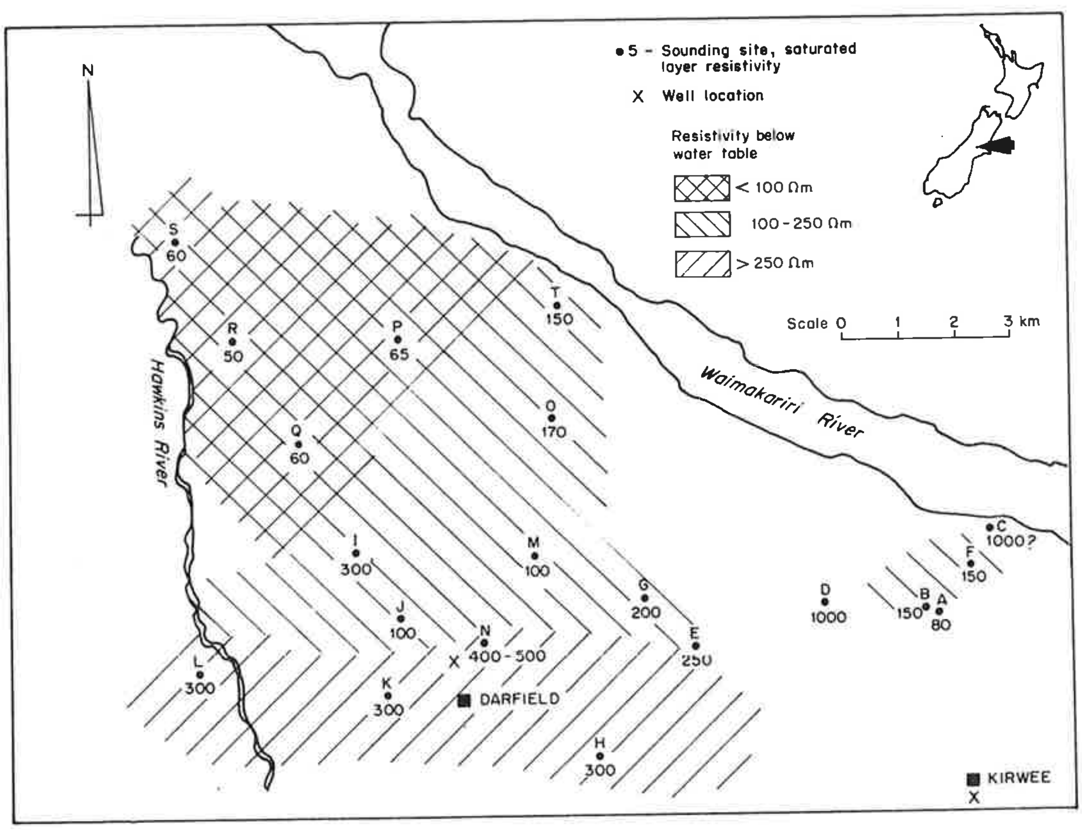


Fig. 19: Resistivity of aquifers near Darfield (after Risk, 1967).

7.2 Kihikihi

Kihikihi is an expanding township in Waipa County. A well drilled in 1980, to augment an existing water supply well for the township, produced an unacceptably low water yield. The earth resistivity method was used to locate a site for a more productive well (Roberts, 1979).

The geology of the area consists mainly of alluvial sediments and air-fall volcanics which occur as complex interbedded lenses. The existing production bore (bore 2, Fig. 20) draws water from a screened section of the aquifer at a depth of 90 to 110 m.

Five pairs of orthogonal soundings were made using the Schlumberger array. Correlation of the resistivity data with borelogs from the two existing wells indicated that the higher yields in bore 2 were associated with resistivities greater than 100 Ω m

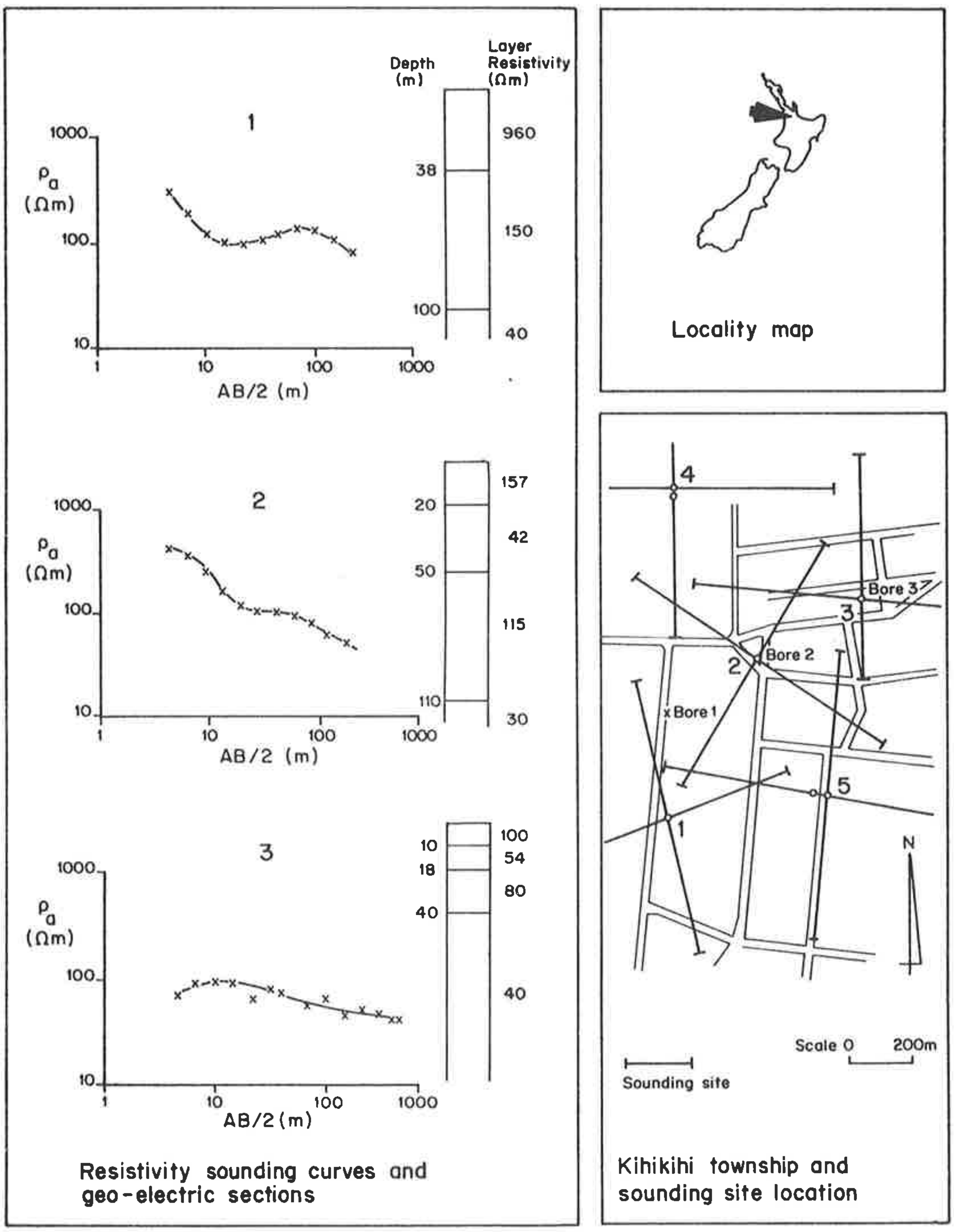


Fig. 20: Kihikihi resistivity sounding sites and interpretations (after Roberts, 1979).

at 20–110 m depth, whereas lower yields (defunct test bore 3) were associated with resistivities less than 50 Ω m in the same depth range. From this observation the best site for drilling was predicted to be site 1, where high resistivities were measured with both soundings.

Subsequent drilling between sites 1 and 2 (bore 1) showed that the geology was the same as that at bore 2 and the new well proved to be a good producer.

8 SALINE WATER INTRUSION

Excessive ground water abstraction can lead to movement of the boundary between saline and fresh water in coastal regions, and ultimately to salt water contamination of wells. The resistivity technique can be used to delineate areas of saline encroachment because of the large contrast in electrical properties between fresh and saline water.

Conclusions about the depth of intrusion and the variation of salinity can be drawn from the interpretation of soundings, although there are difficulties. The lateral proximity of highly conductive sea water can cause low apparent resistivity readings at large electrode spacings which are not representative of conditions at depth. This effect becomes apparent where the electrode array is less than AB/2 away from the sea. Another difficulty is associated with deviation from horizontal layering. Where measurements are taken over an inclined boundary between saline and fresh water, the interpreted resistivities cannot be taken as representative of the actual value below the centre point of the array. It will not generally be possible to establish an accurate correlation between layer resistivity and salt concentration although general trends should be apparent.

Resistivity surveys can also be used to suggest suitable sites for observation bores to monitor movements of the boundary between saline and fresh water and repeat surveys can show if any movement of the boundary has taken place.

8.1 Waimea Plains

Proposals for a new pulpmill in Eves Valley to abstract water from the Appleby Gravels aquifer on the Waimea Plains near the Waimea River mouth led to a ground water survey of the area. The unconfined Appleby Gravels aquifer consists of coarse gravels, which in the delta zone overlie a confined aquifer (Dicker, 1980). The electrical resistivity method was used to locate the interface between fresh and saline water, from which the total abstractable ground water resource could be calculated. Seasonal changes of this interface were also measured.

Apparent resistivities of the unconfined aquifer were greater than 100 Ω m away from the estuary (Fig. 21) and increased landward. Low resistivity (< 10 Ω m) indicated the presence of salt water in the unconfined aquifer. Two saline intrusions were identified, one on Rough Island and the other just to the east of the Waimea River outlet.

The latter zone gave cause for concern because it was within 300 m of a water supply bore operated by the Waimea County Council. Because landward movement of the salt water interface would threaten the fresh water aquifer, the original survey was repeated at the end of the following summer to see whether there had been any such movement.

The measured apparent resistivities at all AB/2 spacings were generally higher in the summer, reflecting higher surface resistivities resulting from drier ground. Several sites showed a decrease in apparent resistivity which was interpreted as resulting from an increase in ground water salinity although saline water did not intrude further south than site 14. Because the boundary had moved only slightly, the water supply bore can be assumed to be safe from the threat of salt water contamination. However, an observation bore at site 14, monitoring water conductivity and level, will give early warning of any salt water flow towards the supply bore.

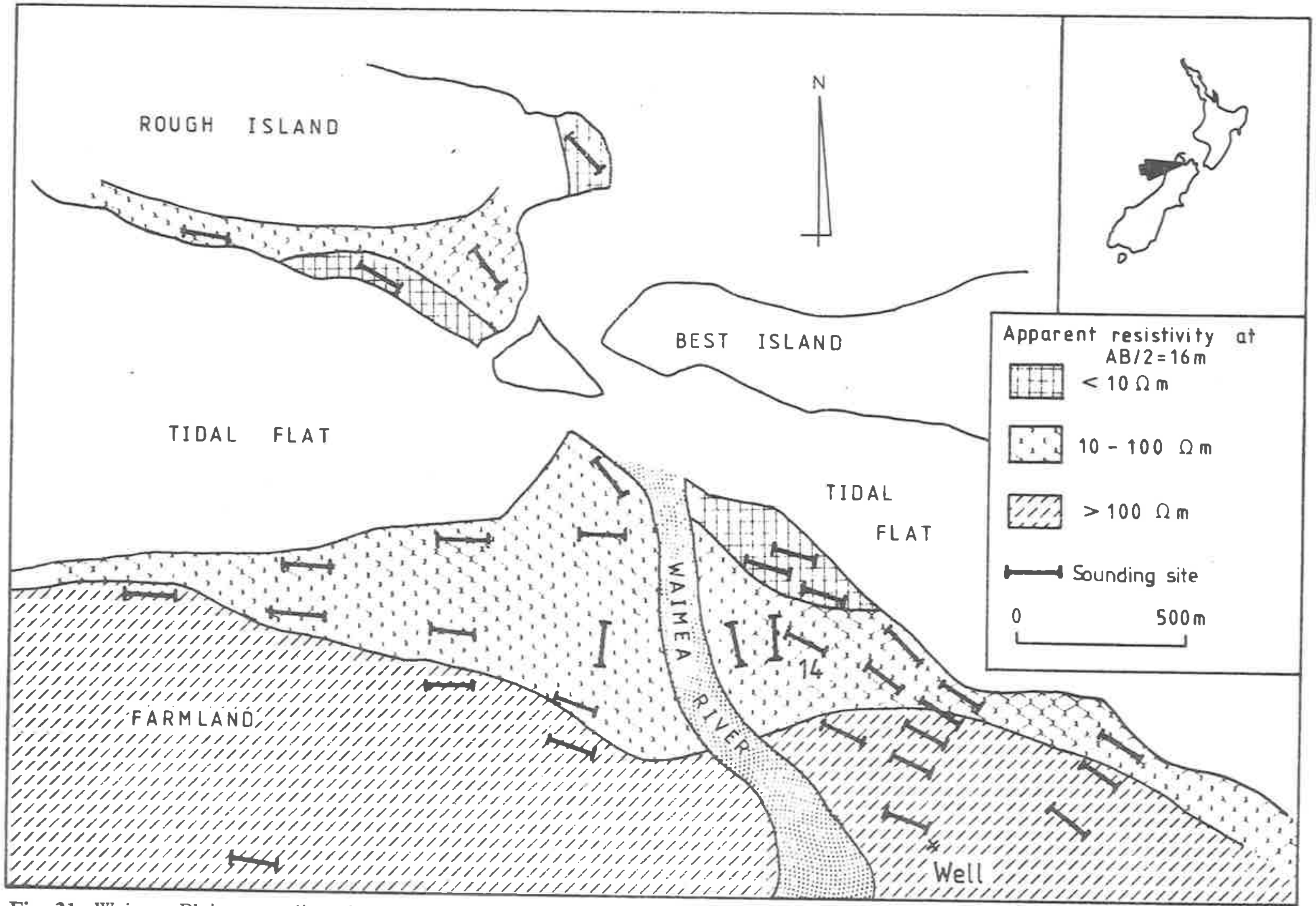


Fig. 21: Waimea Plains sounding sites and apparent resistivity map. Saline intrusion occurs in those regions of less than 10 Ω m.

8.2 Tiwai Peninsula

Tiwai Peninsula, near Bluff, is about 12 km long, 1–3 km wide, and separates the deep inlet of Awarua Bay to the north from the open sea to the south. Ground water beneath the Peninsula is abstracted by an aluminium smelter at a rate of about 3000 m^3 per day. A hydrogeological assessment of the Peninsula indicated that it would be unwise to place further demands on the ground water resource until more was known about the potential for salt water intrusion (Wilson, 1976). The earth resistivity method was used in an attempt to identify regions of salt water intrusion (Risk, 1977).

Coarse Quaternary gravels extend to a depth of about 12 m below sea level. In the western part of the peninsula the gravels overlie a peat layer that may act as an aquitard. At greater depth, sand and silt deposits are common (Wilson, 1976). Recharge of shallow (< 12 m) ground water is by rainfall and upward leakage through the peat layer (Hunt, 1978).

Four Schlumberger resistivity soundings were made on a line across the peninsula (Fig. 22) with the electrode arrays parallel to the coast and AB/2 spacings ranging from 1 to 200 m. Soundings S_1 and S_3 were located 80 and 100 m inland from the shore.

Sounding interpretations indicated a tongue of low resistivity, 1.5–2.5 Ω m, on the northern side of the peninsula. Such a resistivity is close to that expected for sea water saturated gravel and strongly suggested saline intrusion. Risk (1977) considered that the proximity of the sea was unlikely to have caused a false indication of low resistivity at depths of less than 20 m. However, given the maximum electrode spacing

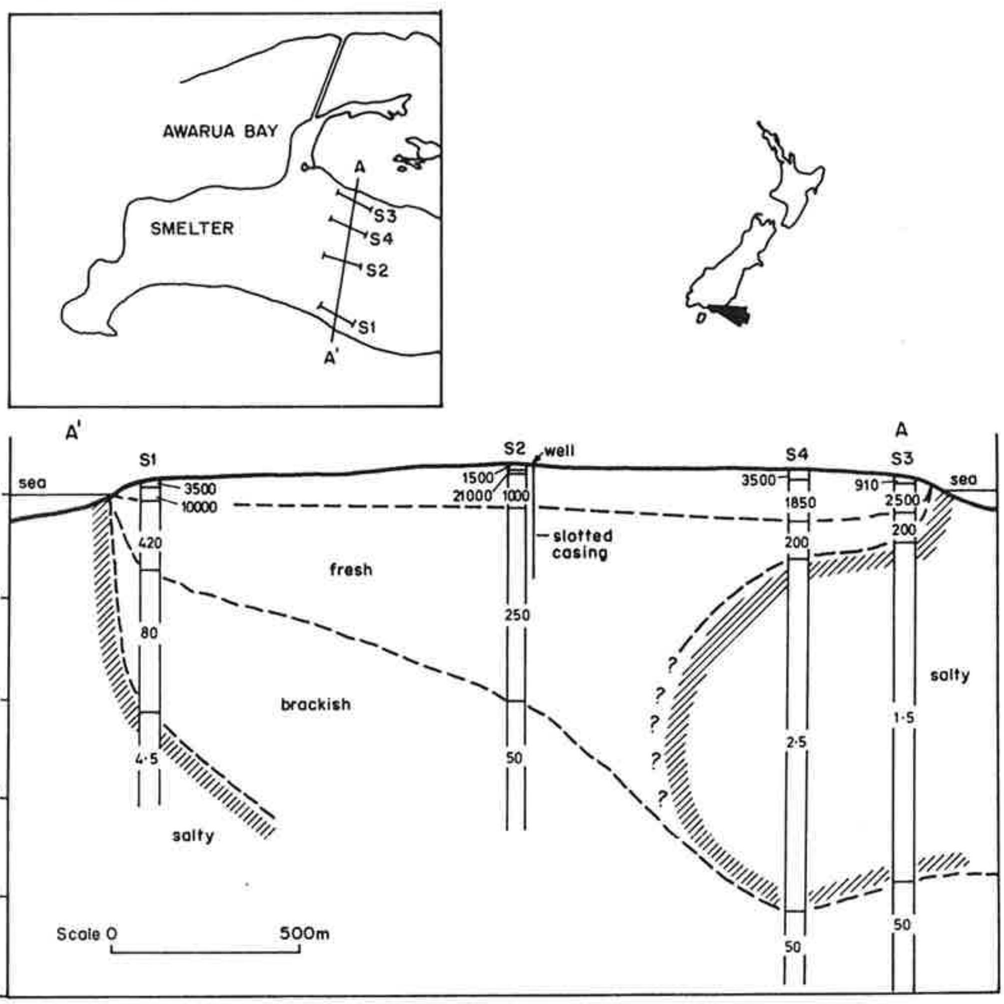


Fig. 22: Tiwai Point—location of soundings and geo-electric section A–A[1] (after Risk, 1977). Resistivity soundings show the depth to the salt water interface.

used, the soundings should have been at least 150 m from the shore to eliminate the effects of the sea.

A low resistivity layer of 4.5 Ω m indicated salt water intrusion on the south side of the peninsula at about 45 m depth. Risk had reservations about this interpretation because the assumption of horizontal layering was unlikely to be strictly valid as close as 100 m to the sea.

9 WATER QUALITY

Resistivity surveys can be used to indicate water quality when there is a relationship between water chemistry and water resistivity. This relationship should be established before the resistivity survey commences by measuring the resistivity of well water samples. The technique is suitable for mapping regions of potable water where a sufficient resistivity contrast exists between potable and unpotable ground water.

9.1 Southern Wairarapa

Farmland in the Pouawha region of southern Wairarapa has been largely reclaimed from a marsh that was once tidal. The region is underlain by silts, sands and gravels. Silts to a depth of around 35 m form an aquiclude overlying a gravel artesian aquifer which was penetrated by five water wells. Three of these produced unpotable, moderately saline water, with total dissolved solids of 400–1400 g. m^{-3}. The earth resistivity method was used to delineate the area of unpotable water before a further water well was drilled.

Resistivity soundings were made at 12 sites using the Schlumberger electrode array (Fig. 23). Soundings were measured adjacent to wells producing unpotable water (A, B and C) and those producing acceptable water (D and E). It was found that the resistivity of the overlying aquiclude, measured by sounding, correlated with aquifer water resistivity measured on samples. On this basis a boundary was drawn between unpotable and potable water.

Sounding curves showed equivalent interpretations (Fig. 24). The range of equivalent solutions was limited by constraint of the aquifer depth to that given by geological logs, but even so, the uncertainty in the resistivity meant that no relationship could be derived between aquifer resistivity and ground water resistivity.

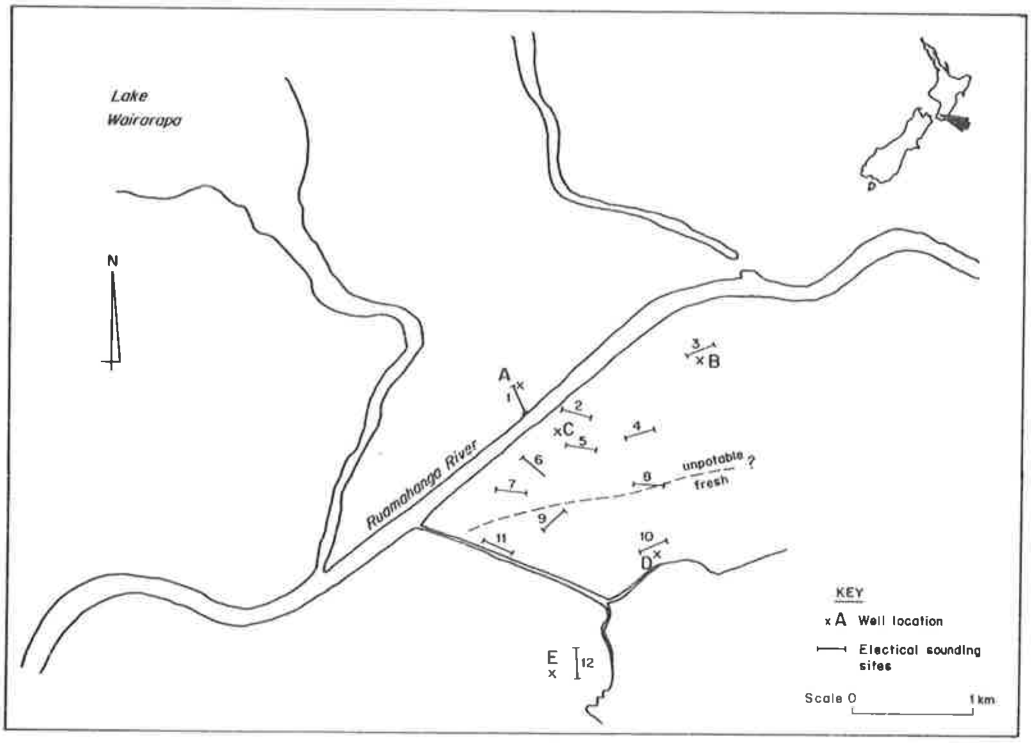


Fig. 23: Wairarapa sounding sites.

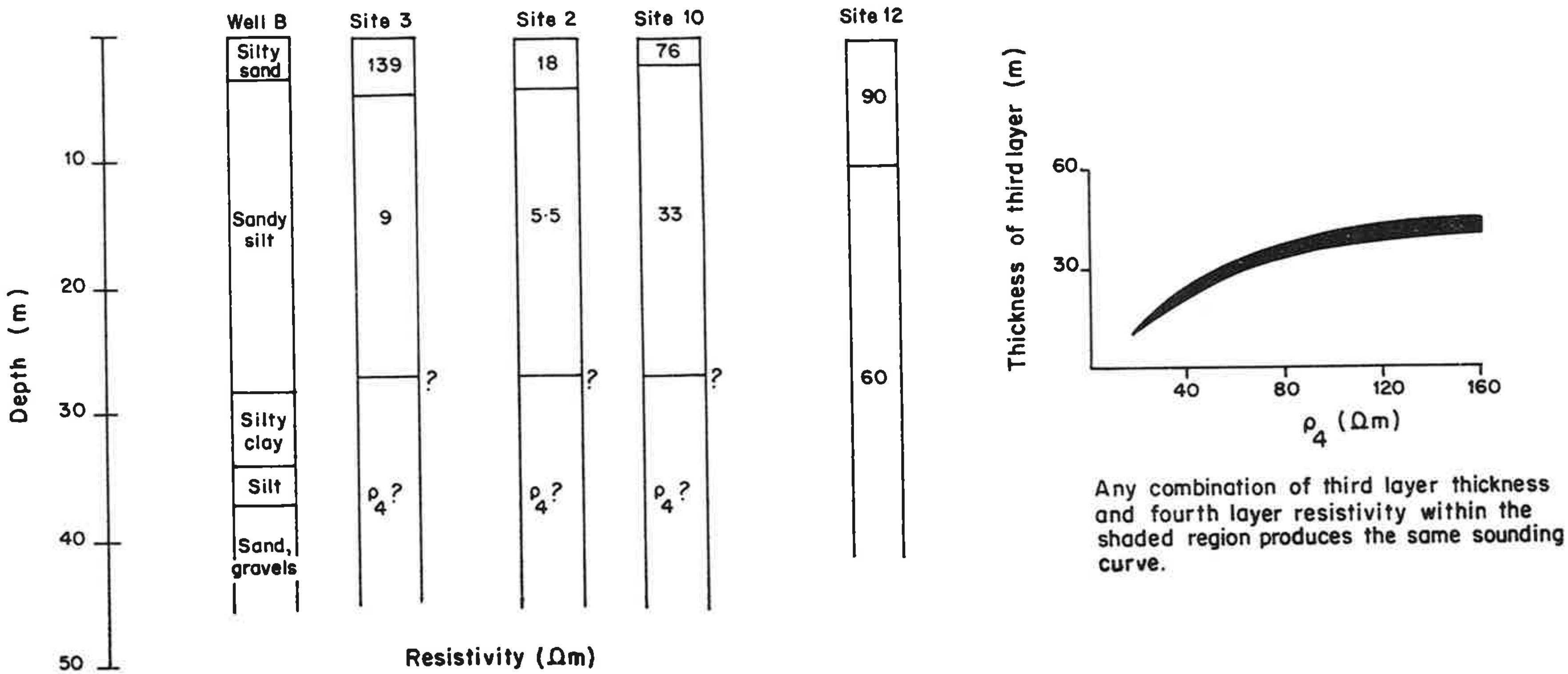


Fig. 24: Wairarapa sounding curve interpretations. Geo-electric sections for sites 2, 3, 10 and 12 of Fig. 23, and inset showing equivalent solutions for site 3. Fourth layer equivalence means that the resistivity method is, in this case, a relatively poor predictor of aquifer resistivity.

9.2 Kinleith

A portion of the effluent from the New Zealand Forest Products' pulp and paper mill at Kinleith is discharged via seepage ponds (Fig. 25) into the local ground water at a rate of about 10 000 m³ per day. The area surrounding the seepage pond is underlain by ignimbrite sheets which are relatively permeable in their more fractured central zones, but have impermeable basal layers (Houghton, 1977).

Ground water is a source of domestic water for many local farms and for Tokoroa township, located about 6 km to the north of the seepage ponds. The possibility of pollution to wells was of concern. Earth resistivity was used in an attempt to map the extent of contaminated ground water (Risk, 1980).

Resistivity soundings, using the Schlumberger electrode arrangement, were made at 13 sites (Fig. 25). Correlation between ignimbrite sheets and resistivity layers was generally poor, suggesting that individual aquifers had not been located.

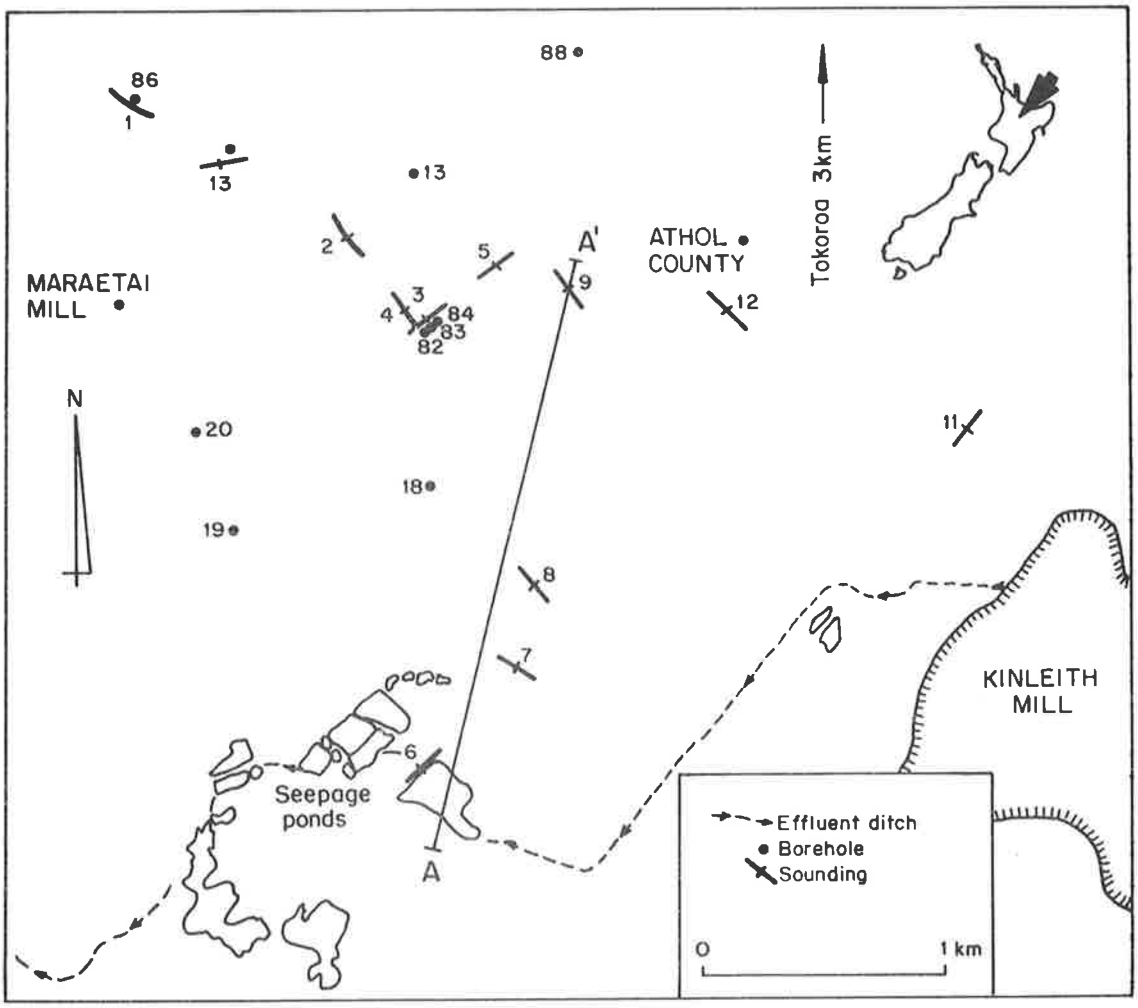


Fig. 25: Kinleith sounding sites and borehole locations (after Risk, 1980).

Downhole conductivity measurements showed contamination of wells 83, 86 and at Maraetai Mill although soundings positively identified effluent only at site 6, on the margin of a seepage pond. Relatively low resistivities in the depth range 20–60 m at sites 7 and 8 suggested possible contamination (Fig. 26).

The survey failed to positively detect ground water contamination at the majority of sites. The transition from dry to saturated ignimbrite causes apparent resistivity to decrease markedly with increasing spacing, suppressing the effect of the conducting effluent. A theoretical test indicated that a contaminated ignimbrite with resistivity 20% less than uncontaminated rock, a thickness of 13 m, and depth below ground of 26 m, was unlikely to be detected.

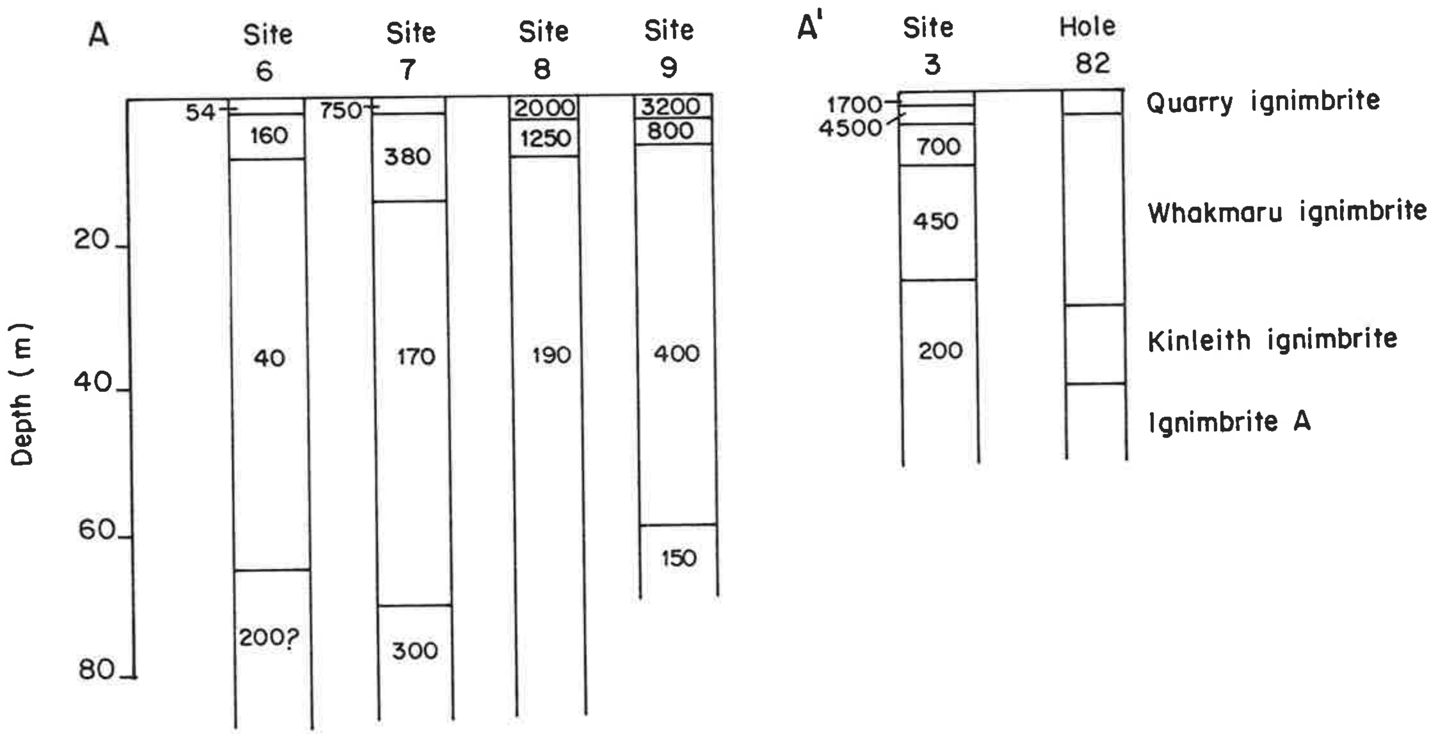


Fig. 26: Kinleith sounding curve interpretations along section A–A[1] of Fig. 25 (after Risk, 1980). Polluted ground water is indicated by low third layer resistivity of site 6, and possibly sites 7 and 8.

10 GROUND WATER FLOW DIRECTION AND VELOCITY

Surface resistivity measurements can be used to estimate the flow direction and velocity of ground water in shallow aquifers.

Salt water is injected into ground water through a well or excavated pit and then traced by surface resistivity measurements in the vicinity of the injection point. The direction of greatest resistivity decrease, subsequent to injection, identifies ground water flow direction. Ground water velocity is estimated by measuring the elapsed time of maximum resistivity decrease at those arrays in the direction of flow.

Current electrode spacings are chosen to allow measurement of resistivity changes at the depth of injection. Electrode spacing is preferably selected from sounding curve analysis, although AB/2 can be estimated as three times the injection depth.

Measurement of ground water velocity by surface resistivity is clearly impractical where flow depths are great. This method is generally limited to flow direction and velocity measurements of unconfined aquifers, where ground waters are within ten metres of the surface. The technique may be useful for up to twenty metres depth in good resistivity conditions.

The method will not work where ground water is saline or where the surface layers are highly conductive.

10.1 Rakaia River

Rakaia River gauging measurements show that approximately 20 $m^3 . sec^{-1}$ or 10% of mean annual flow is lost from surface channels between the Rakaia Gorge and the coast (Fig. 27). This lost water is travelling either within the gravel river bed as underflow, or recharging aquifers under neighbouring farm land. Calculation of underflow allows estimation of river recharge to the nearby ground water systems.

The volume of underflow can be estimated from gravel porosity, cross-sectional area of ground water flow and ground water velocity. Drilling at six locations in the river bed showed that permeable gravels extend to 15 m, hence defining the cross section. Ground water velocity in the bed was estimated by resistivity methods.

Velocity measurements were made in the vicinity of several 4 m deep injection wells, where water depth was 2 m below ground level. The wells were screened throughout the 2 m section below water table.

Radial resistivity arrays covering a wide arc were located near the injection well to ascertain ground water flow direction. The arrays are labelled 1 to 10 in Fig. 27, with A to D being the centres of arrays 6A to 6D. Resistivity sounding curve analysis showed that a salt water slug travelling in the depth range 2–3 m would cause the greatest resistivity decrease at an AB/2 of 10 m and this spacing was used for all resistivity measurements.

Injection of 4000 litres of pre-mixed saline water at 14 wt% NaCl took 18 minutes. Resistivity changes were monitored for a period of four hours following injection. Figure 28a presents maximum resistivity change, by site, within that four hour period. Injected salt water was found to flow in the direction of sites 5 and 6A.

Resistivity changes at four sites (Fig. 28b) along the flow path out to site 6D, 60 m from the injection well, demonstrated the passage of salt water. All sites exhibited rapid resistivity decreases, followed by a relatively slow increase. Velocity was estimated at 720 ± 140 $m.day^{-1}$ from these measurements.

Several wells were subsequently sited on the flow path shown by resistivity. Well to well tracer measurements confirmed surface resistivity results of both flow direction and velocity.

Total underflow was estimated by various velocity measurements as 50% of the Rakaia River's losses below the gorge. River recharge to adjacent ground water systems is therefore approximately 10 $m^3.sec^{-1}$ (Scott and Thorpe, 1985).

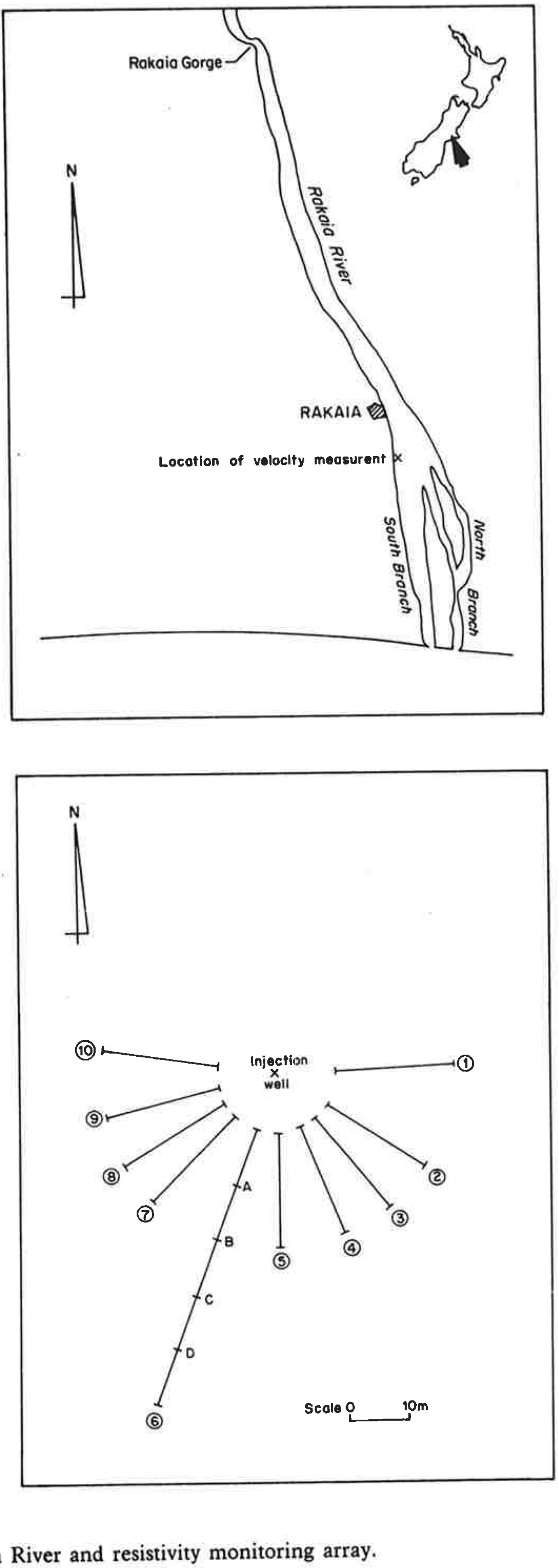
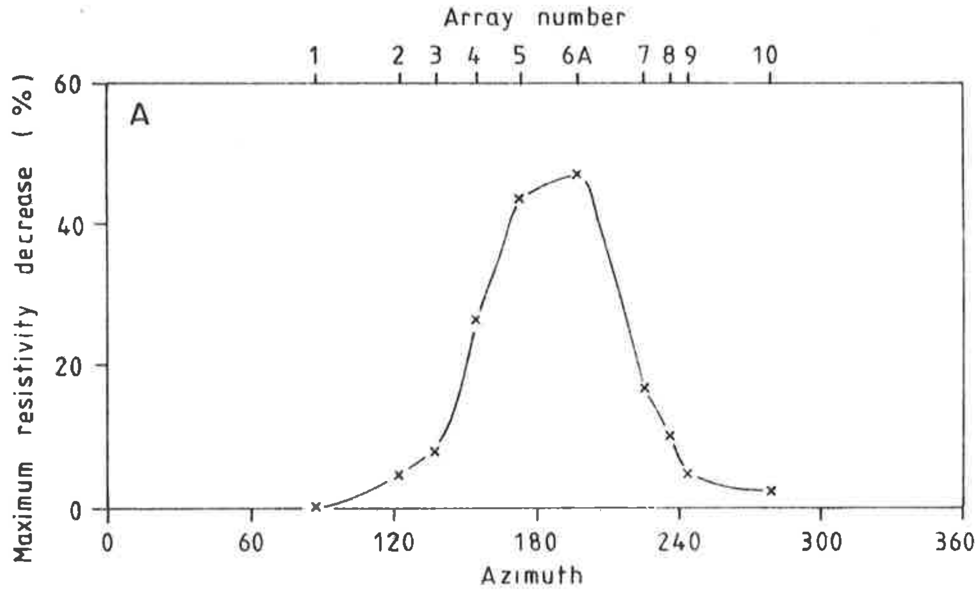
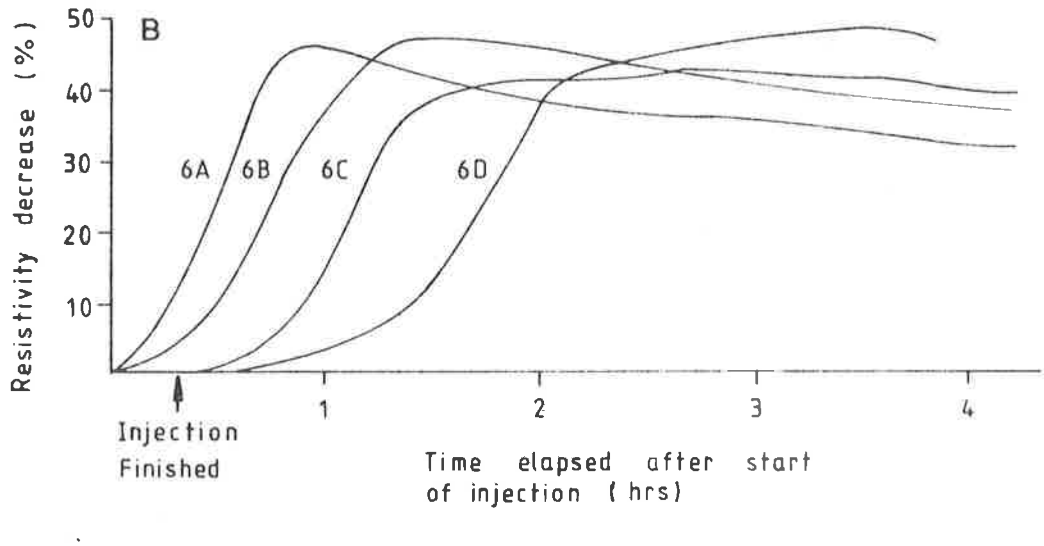


Fig. 27: Rakaia River and resistivity monitoring array.



a) Maximum resistivity decrease within a four hour period after injection. Salt water is travelling in the direction of arrays 5 and 6A (Fig 27)



b) Resistivity changes in the flow direction. The salt waters movement is seen as progressively later arrivals at downstream resistivity sites

Fig. 28: Rakaia River resistivity changes after salt water injection.

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APPENDIX—EXAMPLES OF SOUNDING DATA

Two layer sounding data and interpretation

AB/2 (m)	ρ_a (Ω m)
1	297
1.25	294
1.6	290
2	283
2.5	271
3.2	254
4	234
5	213
6.3	193
8	177
10	166
12.5	160
16	155
20	153
25	152
32	151
40	150
50	150
63	150
80	150

Depth (m)

0.0

Layer 1
300 Ω m

0.2

Layer 2
150 Ω m

AB/2 (m)	ρ_a (Ω m)
1	20
1.25	20
1.6	20
2	20
2.5	20
3.2	20
4	20
5	20
6.3	20
8	20
10	21
12.5	23
16	25
20	28
25	32
32	37
40	43
50	49
63	56
80	63

Depth (m)

0.0

Layer 1
20 Ω m

12.0

Layer 2
100 Ω m

Three layer sounding data and interpretation

AB/2	ρ_a (Ω m)	AB/2 (m)	ρ_a (Ω m)	AB/2 (m)	ρ_a (Ω m)
1	125	1	114	1	50
1.25	102	1.25	124	1.25	50
1.6	81	1.6	141	1.6	50
2	68	2	161	2	51
2.5	59	2.5	186	2.5	52
3.2	54	3.2	217	3.2	53
4	52	4	246	4	56
5	52	5	273	5	59
6.3	51	6.3	295	6.3	64
8	52	8	307	8	70
10	53	10	304	10	75
12.5	55	12.5	285	12.5	82
16	58	16	249	16	89
20	62	20	210	20	97
25	67	25	172	25	105
32	73	32	140	32	116
40	78	40	121	40	127
50	82	50	111	50	138
63	87	63	105	63	149
80	90	80	103	80	160

	Depth (m)		Depth (m)		Depth (m)
	0.0		0.0		0.0
Layer 1 200 Ω m		Layer 1 100 Ω m		Layer 1 50 Ω m	
	0.50		1.0		3.0
Layer 2 50 Ω m		Layer 2 600 Ω m		Layer 2 100 Ω m	
	10.5		5.0		15.0
Layer 3 100 Ω m		Layer 3 100 Ω m		Layer 3 200 Ω m	

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