

# **GROUNDWATER ASSESSMENT KINGDOM OF TONGA**

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## ABSTRACT

This report records the results of a visit to Tonga undertaken in response to a request from the Government of Tonga to provide assistance with the assessment of groundwater resources on small inhabited islands of the Ha'apai Group. The assessment was planned as a training exercise in collaboration with staff of the Ministry of Lands, Survey and Natural Resources (MLSNR). Priorities for assessment were suggested by the Governor of Ha'apai in light of the severe water shortages suffered during the drought of 1998. In addition to the water supply issues the assessment team was requested to examine and comment on reports of coastal erosion on O'ua.

Mr Tevita Fatai was the team leader from MLSNR with Trainees Apai Moala, Akapei Vailea and Siale Vailea. The assessment concentrated on the application of electrical resistivity (ER) and electromagnetic (EM) geophysical methods since the Ministry has the necessary equipment, and previous field experience had demonstrated the effectiveness of these techniques. The training exercise involved field work and data analysis on Lifuka, O'ua and Lofanga, followed by further analysis and interpretation in Nuku'alofa.

Results of the exercise can be summarised as follows:

- MLSNR staff are able to undertake ER and EM field surveys and produce reliable and consistent results.
- MLSNR ER and EM equipment has been maintained in good working order despite having been in storage for several years. The equipment performs well and is a valuable asset for groundwater assessment in Tonga. The software required to use the EM data-logging equipment appears to have been lost, and a replacement should be sought from the manufacturer. It may be desirable for MLSNR to acquire an Offset Wenner Sounding system to supplement the existing Schlumberger system.
- MLSNR staff are able to carry out ER and EM data analysis and undertake interpretations. However, it would be desirable for them to acquire an up-to-date copy of ER analysis software. It would be very helpful for MLSNR staff to have access to external review of any interpretations and reports. This could be provided by SOPAC or by a number of other organisations or individuals with relevant experience and interest in Tongan hydrogeology. Access to Internet e-mail would be extremely useful to facilitate that sort of professional contact.
- Analysis of ER and EM observations on O'ua suggests that it is unlikely to have usable quantities of groundwater. The policy to encourage the development of rainwater catchments on O'ua should be continued.
- The reported erosion on O'ua appears to have been an active feature for many years, and consists of a deep gully which is progressively extending back from the coast. This appears to be a consequence of rapid surface runoff from extensive steep and bare areas where the fine volcanic ash soil forms a relatively impermeable cover. In places where the soil is bare of any vegetation there is clear evidence of surface erosion, and the foundations of some houses are at risk.
- Analysis of ER and EM observations on Lofanga suggests that there is little prospect of finding usable quantities of groundwater. Though this result is less certain than for O'ua, until the exploration drilling problem is solved, the policy to encourage the development of rainwater catchments on Lofanga should be continued.

## **ACKNOWLEDGEMENTS**

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We are pleased to record our appreciation of the assistance provided by Mr Saimone Helu (Manager, Tonga Water Board) and Ms Lesieli Niu (Chief Engineer, Tonga Water Board) for advice on the water supply situation on Lifuka and providing access to data. We are grateful to Mr Tony Falkland (ACTEW) for his advice regarding the planning of the exercise and his willingness to review a draft of this report.

We happily acknowledge the support provided by the Honourable Governor of Ha'apai and his Assistant Secretary in facilitating our transport arrangements within the Ha'apai Group. The Royal Tongan Police Force allowed the use of their patrol boat when the previously assigned boat suffered storm damage - our thanks to the captain and crew for a safe voyage. Village representatives on O'ua and Lofanga provided hospitality, assistance with field work and a generous supply of coconuts.

## INTRODUCTION

The activities described in this report were carried out in response to a request from the Government of Tonga, as part of SOPAC's 1999 approved work programme (Task No. TO 99.01). The objective of that task was to "Assist in the assessment of the water resource and/or water supply of outer islands some of which may have potential for tourism development". Following discussions with the Ministry of Lands, Survey and Natural Resources (MLSNR) it was agreed that the task would be undertaken as a training exercise on selected small islands of the Ha'apai Group. These particular islands were chosen as priority areas for investigation because of the serious effects of the recent drought.

The training aspect of the exercise was emphasised because of the potential for MLSNR to undertake future work of this sort. They already have geophysical survey equipment and some past experience in the field procedures involved.

While in Nuku'alofa the assessment team consulted staff of the Tonga Water Board (TWB) and the MLSNR. Broader issues relating to water resources assessment and legislation were raised in these discussions, and the team was requested to consider future options for addressing these.

## BACKGROUND

Groundwater is a vital resource in the Kingdom of Tonga, and the need to understand and manage the resource has been recognised for many years. Furness and Helu (1993), in their investigation into the hydrogeology and water supply of all inhabited islands in the country, provide a useful review of previous hydrogeological investigations. Understandably, most work has been concentrated on Tongatapu where population growth and development have created the greatest demand for water.

Within the Ha'apai Group most attention has been paid to the islands of Lifuka and Foa where, once again, population density has set a priority, and relative accessibility has made water resource investigation and development feasible. Falkland (1991) carried out an assessment of the water resources of Tonga as part of the Tonga Water Supply Master Plan Project, including preliminary estimates of the sustainable yield of freshwater lenses, and noted that the main islands in the Ha'apai Group show the effects of inappropriate pumping. The on-going development and monitoring of the freshwater lens on Lifuka is now providing useful information about groundwater behaviour in this particular hydrogeological environment (TWB, pers. comm., Falkland, 1999).

The outer islands of the Ha'apai Group have received much less attention. This can in part be attributed to their small populations, but another significant factor must be their relative remoteness and inaccessibility. Furness and Helu (1993) report on visits to all the inhabited islands of the Ha'apai Group and make preliminary assessments of the potential for groundwater development. Their conclusions are summarised in Table 1. It is noteworthy that in many instances Furness and Helu comment that, even where groundwater development may be possible, there would be significant difficulty involved in getting a drilling rig on to the island. This raises a significant question about the strategy for future groundwater exploration and development on small islands.

As noted by Furness and Helu (1993), most of the islands in Tonga fall into the category "very small islands" with an area not greater than 100 km<sup>2</sup> or a width greater than 3 km (Dijon, 1984). Within the Ha'apai Group the islands are all very small, and provide environments where the existence of usable quantities of groundwater is likely to be marginal. In these circumstances it is particularly desirable for any groundwater development to be preceded by a careful assessment

and followed by appropriate monitoring. Unfortunately, the small population base able to derive benefits from any such development is likely to limit the potential for such an ideal approach.

**Table 1. Summary of preliminary assessments of groundwater potential on islands in Ha'apai Group from Furness and Helu (1993).**

Island	Area (km <sup>2</sup> )	Population	Survey Method	GW Potential
Nomuka	6.33	686	ER/EM	Potential brackish groundwater for sanitation
Mango	0.77	83	-	Fresh groundwater possible, solar pump suggested
Fonoifua	0.45	111	-	Little prospect for fresh groundwater, potential brackish groundwater for sanitation
O'ua	0.94	266	EM	Fresh groundwater possible, access for drilling difficult
Ha'afeva	2.00	450	-	Fresh groundwater feasible, EM required, solar pumping suggested
Tungua	1.54	301	-	Scope for fresh groundwater, EM required, solar pumping suggested
Matuku	0.32	142	-	Little prospect for fresh groundwater, potential brackish groundwater for sanitation
Kotu	0.40	233	-	Practically no scope for further groundwater development
Tofua	45.81	89	-	Little scope for improvement, access very difficult
Fotuha'a	1.07	192	-	No prospect for groundwater development because of difficult access
Lofanga	1.51	330	-	Groundwater development likely possible if drilling rig can be landed
'Uiha	5.46	880	EM	3 new wells recommended, low capacity pumps
Lifuka	11.44	2850	ER/EM	New wells and pumping rates recommended
Foa	13.54	1410	ER/EM	New wells and pumping rates recommended
Ha'ano	6.66	727	-	Fresh groundwater development possible
Mo'unga'one	1.38	164	-	Fresh groundwater development possible, drilling rig access difficult

ER indicates that the assessment included electrical resistivity measurements

EM indicates that the assessment included electromagnetic measurements

Strategies for groundwater resource exploration and assessment have been proposed to deal with the conditions encountered on small islands. The REFRESHR method was promoted by Dale et al. (1987) as a rapid method of evaluating freshwater resources on small islands. The method incorporates surface geophysics, well reconnaissance and sampling, pump testing and water balance studies to develop an assessment of groundwater potential. The technique was demonstrated in a workshop conducted on Uoleva Island in the Ha'apai Group (Dale et al., 1988).

Because of the absence of existing wells on O'ua and Lofanga, the current assessment has relied primarily on surface geophysics to identify the presence of freshwater. The use of surface geophysics for groundwater exploration can provide reliable results when supported by independent observations of groundwater condition. However in the absence of such observations, geophysical methods can often produce results that leave room for considerable uncertainty.

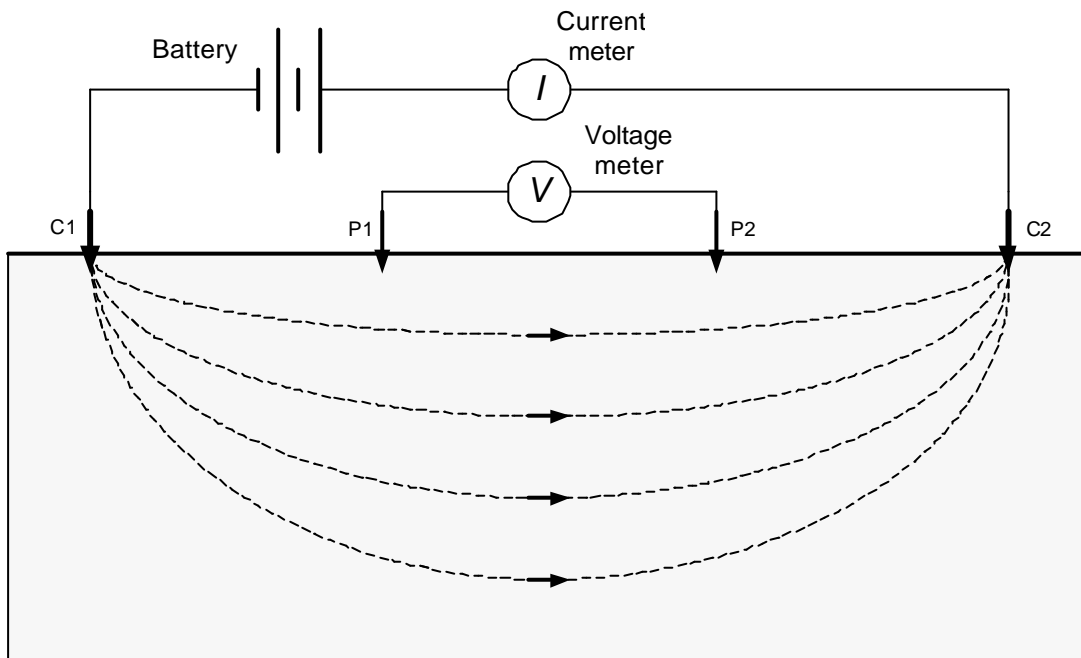


## METHODOLOGY

### Electrical Resistivity (ER) method

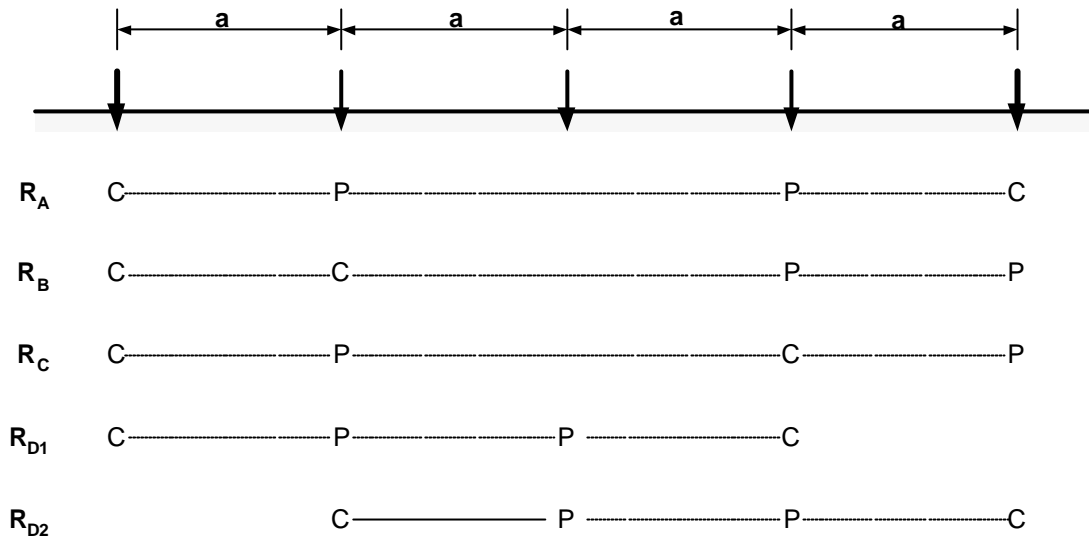
#### *Principles*

Surface resistivity methods are based on the concept that the apparent resistivity of the ground can be measured by inducing an electrical current at the ground surface using a standard array of electrodes (two current and two potential electrodes). Resistivity soundings involve measurements of apparent resistivity over a range of electrode spacings in order to obtain an indication of how resistivity changes with depth. Interpretation of these soundings can establish the depths to a sequence of different layers with different electrical resistivity. Figure 1 provides a schematic view of the basic components involved in making resistivity measurements. A battery is used to generate a measured current ( $I$ ) between two current electrodes (C1 and C2). The resulting voltage difference ( $V$ ) between two potential electrodes (P1 and P2) is then measured to provide a measure of resistance which can be converted into an apparent resistivity depending on the electrode configuration.



*Figure 1 Schematic diagram of resistivity measurement.*

Most of the resistivity soundings undertaken in this assessment used the “Offset Wenner” method (Barker, 1981), which is an improvement on the standard Wenner array. In the Offset Wenner method five electrode positions are used to measure two (offset) Wenner resistances and three additional resistances (see Figure 2). The displacement (offset) of each of the Wenner arrays reduces undesirable spurious effects due to lateral underground resistivity variations. In addition, three additional resistance measurements allow calculation of the observation error, which gives an indication of the reliability of the measurement for each electrode spacing.



*Figure 2 Electrode configurations used in the Offset Wenner array*

C indicates that the electrode is used as a current electrode  
P indicates that the electrode is used as a potential electrode

For the standard Wenner array the apparent resistivity ( $\rho_a$ ) may be determined from the expression:

$$\rho_a = 2\pi a R$$

For the Offset Wenner array this is instead calculated as the mean of the two Offset resistances:

$$\rho_a = 2\pi a (R_{D1} + R_{D2})$$

The offset error ( $e_o$ ) is a function of the difference between the two offset resistances:

$$e_o = \frac{2(R_{D1} - R_{D2})}{R_{D1} + R_{D2}} \times 100\%$$

and the observation error ( $e_{obs}$ ) is determined from a tri-potential check as follows:

$$e_{obs} = \frac{R_A - [R_B + R_C]}{R_A} \times 100\%$$

This observation error should normally fall within the range -5% to 5%. Values outside this range could indicate instrument malfunction, leakage of current from damaged cables or high electrode contact resistances. The Offset Wenner method includes a procedure to extrapolate the measured sounding curve allowing a Wenner resistivity at 256 m spacing to be computed from resistances measured with an electrode spacing of 128 m. However, as demonstrated by White and Scott (1988), these extrapolated points can be unreliable and should be used with considerable caution.

Some soundings were carried out using the Schlumberger array. For this array configuration the potential electrodes are placed close together as shown in Figure 3. Normally the distance between the two current electrodes (AB) is set equal to or greater than five times the distance between the potential electrodes (MN).

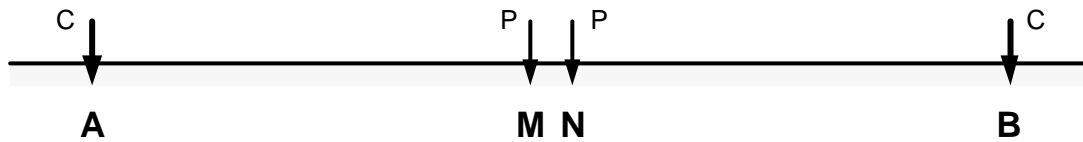


Figure 3 Schlumberger electrode array

C indicates the position of a current electrode  
P indicates the position of a potential electrode

For the Schlumberger array the apparent resistivity ( $\rho_a$ ) may be determined from the expression:

$$\rho_a = \rho \frac{(AB/2)^2 - (MN/2)^2}{MN} \frac{\Delta V}{I}$$

Unlike the Offset Wenner method, the Schlumberger method does not provide a direct measure of observation errors.

### Equipment

ER soundings were carried out using an ABEM Terrameter SAS 300 B. The Offset Wenner array was set up using the BGS-256 switch box and multi-core cable system with steel spikes used as current and potential electrodes. For the Schlumberger array, four single-core cable reels were used with stainless steel current and potential electrodes.

### Procedures

Resistivity methods perform better and give reliable results in a horizontally layered situation. Thus all the resistivity soundings were oriented, as much as possible, parallel to the coastline. The maximum electrode spacing employed with the Offset Wenner method was 128 m (involving a total cable spread of 512 m and 21 electrodes). Following the placing and connection of all electrodes, resistance measurements were made beginning with the smallest spacings and progressing outward. This approach was adopted in order to provide more reliable detection of problems. Observations were recorded on the Offset Wenner Sounding Data Form (Appendix 2), and observation error checked at each setting to ensure that any faults were detected and corrected. In addition, apparent resistivity was calculated and plotted in the field to obtain an initial impression of the sounding results.

For the Schlumberger array the maximum electrode spacing used was 147 m. Standard  $AB/2$  and  $MN/2$  spacings were adopted as shown on the Schlumberger Data Form in Appendix 2. Once again, apparent resistivity was calculated and plotted in the field as an aid to error checking and to determine whether the sounding should be extended to larger electrode spacings.

### Interpretation

Field observations were processed using Excel procedures to calculate apparent resistivities and to produce plots (Appendix 2). The derived resistivity data were then interpreted using the computer program RINVERT (© C Vision). RINVERT is designed for interpreting resistivity sounding data acquired by either Wenner or Schlumberger electrode arrays. The assumed earth model consists of multiple horizontal layers, each of which is described by a thickness and resistivity value. This is often a reasonable approximation to the real earth, especially in shallow environments, as a result of the mechanisms of sedimentation and weathering.

Forward modelling in RINVERT was used to interpret the data. The steps involved in this process are:

- 1) Estimate a model of the local earth
- 2) Compute and display the theoretical sounding curve for this model
- 3) Observe the mismatch with the field sounding data
- 4) Adjust the model parameters to improve the match
- 5) Repeat steps 2 to 4 until a satisfactory match is achieved.

## Electromagnetic (EM) method

### Principles

The electromagnetic method for the measurement of terrain resistivity uses induced current as illustrated in schematic form in Figure 4. A transmitter coil (Tx), energised with an alternating current at an audio frequency, is placed on the earth (assumed uniform) and a receiver coil (Rx) is located a short distance  $S$  away. The time-varying magnetic field arising from the alternating current in the transmitter coil induces very small currents in the earth. These currents generate a secondary magnetic field ( $H_s$ ) which is sensed together with the primary field ( $H_p$ ) by the receiver coil.

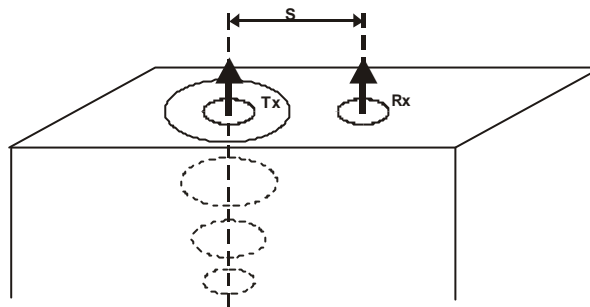


Figure 4 Schematic diagram of the EM method.

In general, this secondary magnetic field is a complicated function of the intercoil spacing ( $S$ ), the operating frequency ( $f$ ) and the ground conductivity ( $s$ ). However, under certain constraints the secondary magnetic field is a simple function of these variables. These constraints are incorporated into the design of the EM 34-3 instrument used for this survey and allow the calculation of apparent conductivity  $s_a$  from the ratio of the secondary to the primary magnetic field as:

$$s_a = \frac{4}{2\pi f \mu_0 S^2} \left( \frac{H_s}{H_p} \right)$$

where:

- $s_a$  = apparent ground conductivity (mho/m)
- $H_s$  = secondary magnetic field at the receiver coil
- $H_p$  = primary magnetic field at the receiver coil
- $f$  = frequency (Hertz)
- $\mu_0$  = permeability of the free space
- $S$  = intercoil spacing (m).

In the horizontal dipole mode (coils vertical coplanar) the response is a maximum for near-surface material, decreasing monotonically with depth. Conversely, in the vertical dipole (coils horizontal coplanar) the relative response is zero for near-surface material, increasing with depth to become a maximum at a depth approximately 40% of the intercoil spacing, and decreasing slowly thereafter.

At high values of terrain conductivity the indicated conductivity is no longer linearly proportional to the actual conductivity. This effect is more severe for the vertical dipole than for the horizontal dipole. A correction is needed if the vertical dipole value exceeds 40 millimhos/m, whereas the horizontal dipole shows an acceptable linearity between measured conductivity and true ground conductivity for values up to 100-120 millimhos/m.

### *Equipment*

The instrument used in this survey was the Geonics EM 34-3 DL. Three different intercoil cable lengths (10, 20 and 40 m) were used to connect the transmitter coil with the receiver coil.

The EM 34-3 instrument uses electromagnetic induction to provide a direct measure of the conductivity of the ground without the need for electrodes. Separate portable transmitter and receiver coils can be aligned vertically or horizontally at up to 3 different spacings, along a pegged line or track, to give a conductivity profile. The different orientation and spacing of the coils effectively provide a range of exploration depths. A different signal frequency is used at each spacing which, in principle, gives a depth of investigation independent of the conductivity of the ground provided it is horizontally stratified, with no lateral variation.

Data recording was carried out manually, because the Programmable Digital Data Recorder was not functioning.

Further details about EM methods in general and about the Geonics EM 34-3 in particular can be found in a series of Technical Notes produced by Geonics Ltd, e.g. McNeill (1980).

### *Procedures*

Before each EM survey, a quick on-the-spot inspection was carried out to decide where to run the profile line. The profile is carried out taking readings at each 10 metres (station) till the end of the line. Each reading consists of two values measured for horizontal dipole (coils vertical coplanar) and vertical dipole (coils horizontal coplanar). The same procedure is repeated for the 10, 20 and 40 m cable length spacing. An offset of -5 and -15 metres is applied respectively to the beginning of the 20 m and the 40 m profile, in order to superimpose the centre-point of the station for each spacing.

### *Interpretation*

For each station, the Geonics EM 34-3 measures the relative response (as conductivity) for the horizontal dipole and the vertical dipole. However, these two readings can be referred to an exploration depth that is a function of the intercoil distance. The factor linking exploration depth and intercoil distance ranges from 0.4 to 0.75 for the horizontal dipole and is 1.5 for the vertical dipole.

When investigating terrains with relatively high conductivity (saltwater-saturated sediment, clayey deposits, etc.) there are some advantages in operating with the horizontal dipole. First, compared to the vertical dipole, the indicated apparent conductivity measured with the horizontal dipole stays linear with true conductivity over a wider range of values. Secondly, since for the horizontal dipole the secondary magnetic field is in maximum coupling with the receiver coil, the measurement is relatively insensitive to misalignment of the two coils.

For these reasons only the horizontal dipole readings were used for the interpretation. The three spacings were plotted together in a graph to illustrate the profile of the conductivity at three different depths.

## **RESULTS**

### **Lifuka**

Geophysical observations were undertaken on Lifuka in order to test the equipment, provide introductory training in its application and, most importantly, to correlate the results against measured salinity profiles. Figure 5 shows the location of the geophysical observations and the TWB multi-piezometer observation bores.

## Lifuka

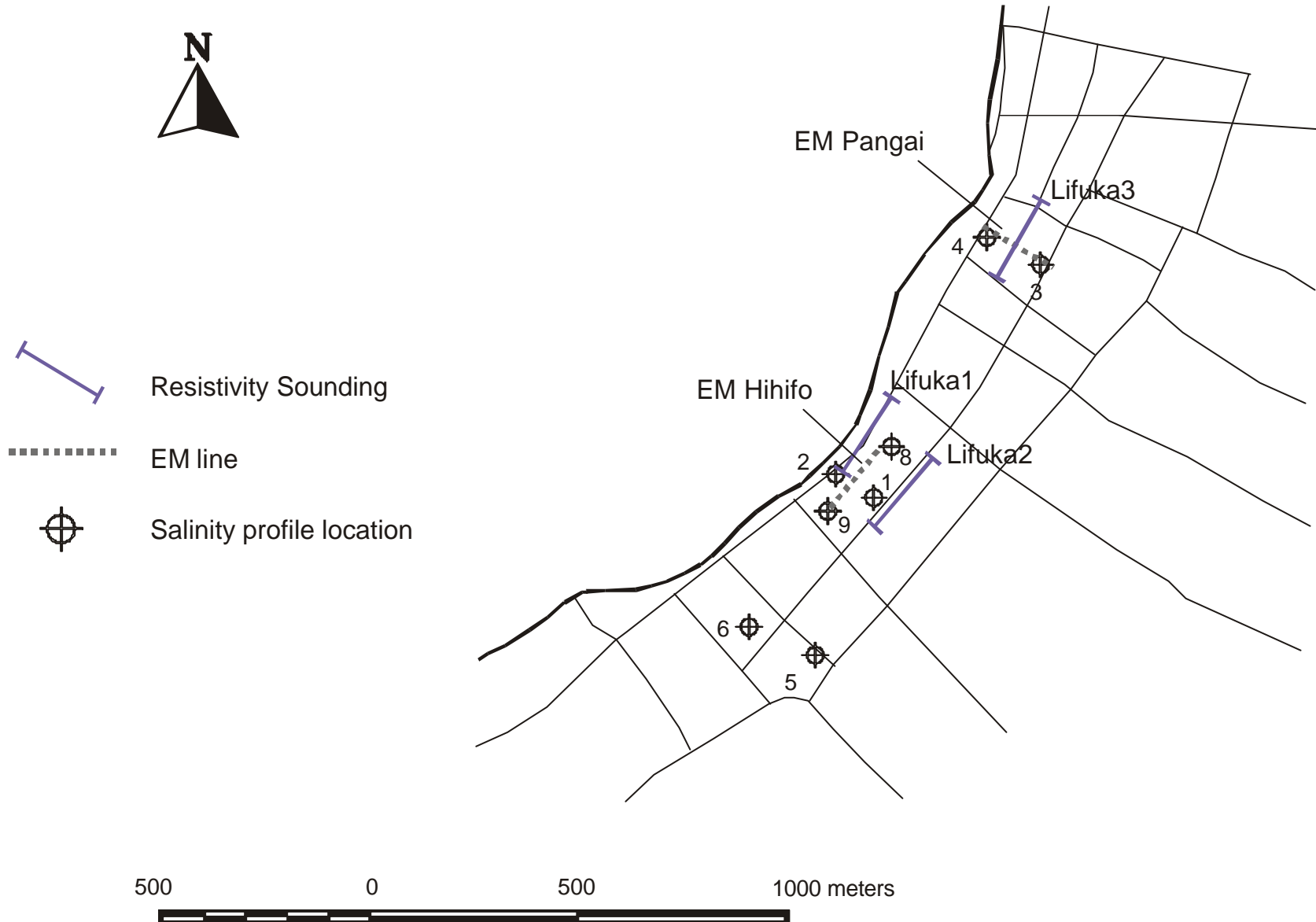


Figure 5 Location of observations on Lifuka

### *ER soundings*

Three resistivity soundings were carried out adjacent to the west coast on Lifuka. Details of the observations are listed in Appendix 2. The Offset Wenner array was employed for the Lifuka 1 and Lifuka 2 soundings on and adjacent to the Hihifo rugby field, while the Schlumberger array was used for the Lifuka 3 sounding on the Pangai rugby field. The Lifuka 1 sounding had particularly low observation errors, with an RMS error of 1.58% for all 8 settings and a single maximum absolute error of 4.05%. The offset errors are acceptably low as shown by the small spread between plotted Offset Wenner resistivities. The Lifuka 2 sounding also had very low observation errors (<0.6%) except for the two outer spacings where lateral errors were also significant. As a result, the indicated sharp increase in resistivity at the end of the curve may not be reliably interpreted with a horizontal layer model. A stable negative resistance was observed for the  $R_B$  array configuration at setting 8. The Schlumberger array was used for the Lifuka 3 sounding and so no error measures can be reported. However, the overlapping segments of the curves (for different values of  $MN/2$ ) show good agreement and so require no adjustment.

The measured and simulated apparent resistivities for the Lifuka soundings, together with the derived resistivity-depth models, are illustrated in Figure 6, Figure 7 and Figure 8. The depth to water table and thickness of freshwater inferred from the TWB salinity profile observations as measured in January 1999 (Appendix 4) have been used to constrain the range of possible solutions. The resistivity results are summarised in Table 2 along with the inferred lithology for each model layer. The results are consistent with the measured salinity profiles and allow determination of resistivity values for sand-saturated with freshwater, brackish water and seawater as shown in Table 3.

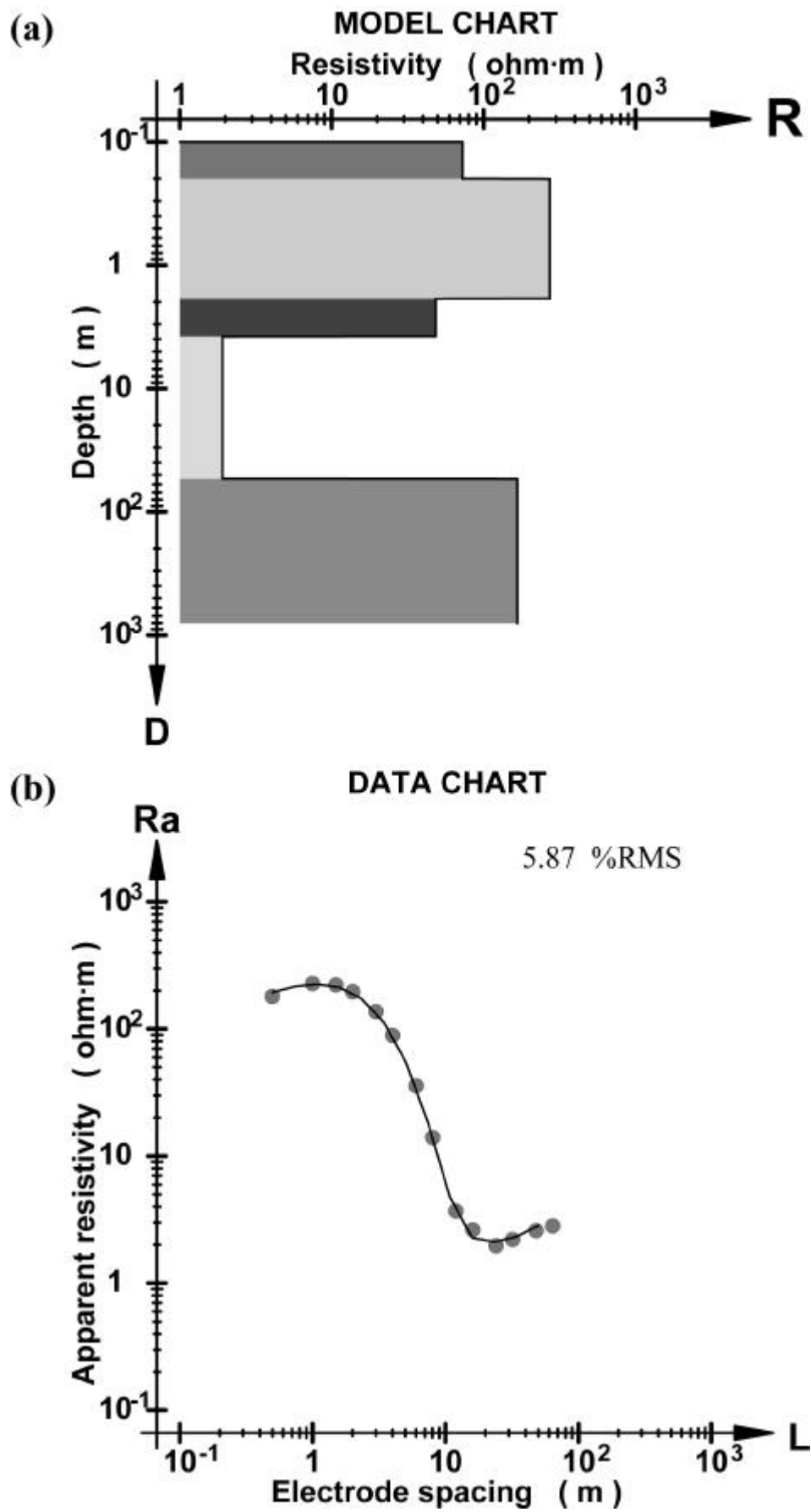


Figure 6 Interpretation of Lifuka 1 resistivity sounding.



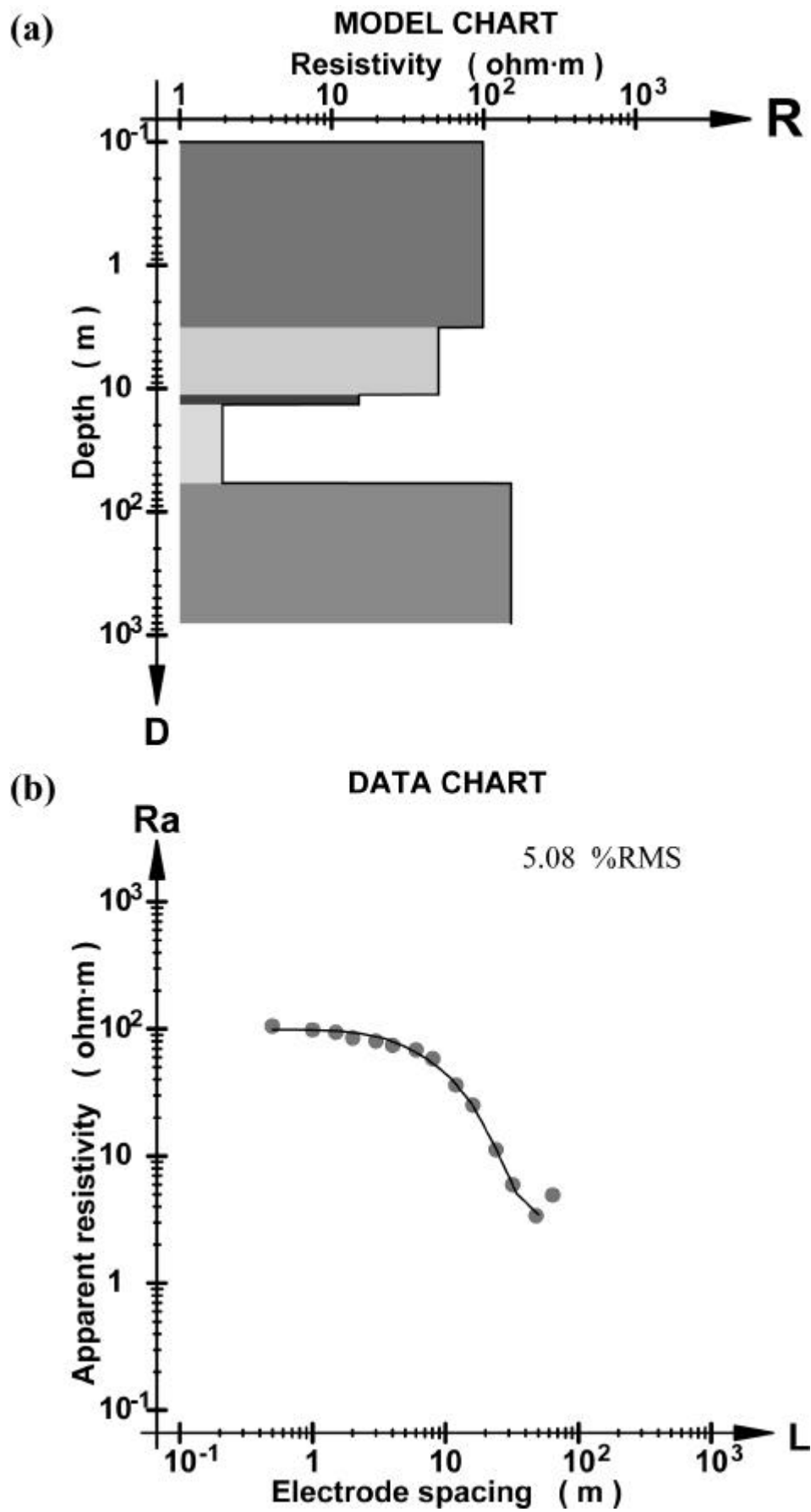


Figure 7 Interpretation of Lifuka 2 resistivity sounding.

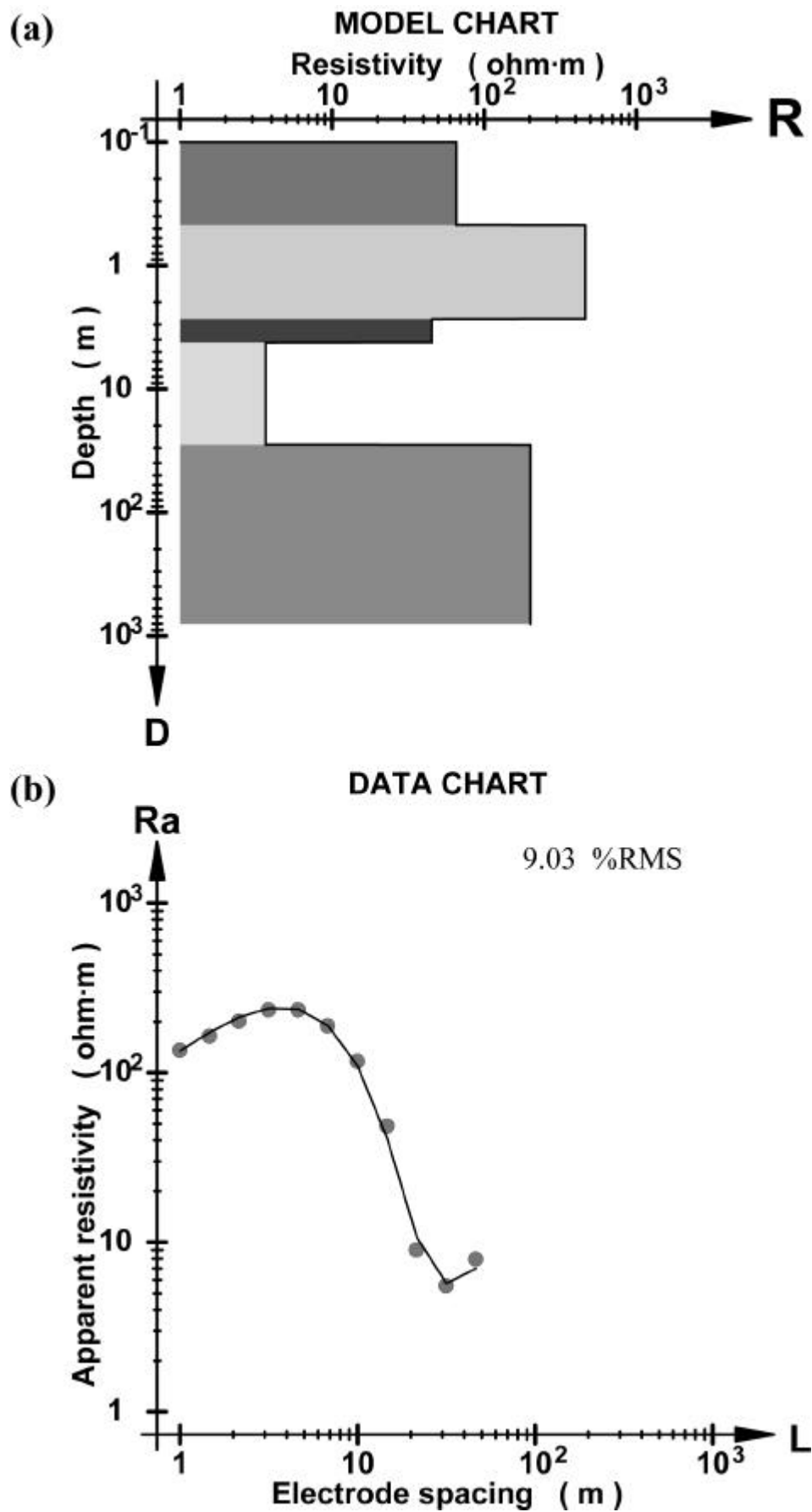


Figure 8 Interpretation of Lifuka 3 resistivity sounding.

Table 2 Interpretation of Lifuka ER soundings.

Sounding (RMS error)	Depth (m)	Thickness (m)	Resistivity (ohm•m)	Lithology	WT depth (m)
<b>Lifuka 1</b>	0	0.1	72	Top soil	1.77
(5.87%)	0.1	1.67	270	Unsaturated sand	
	1.77	1.9	48	Freshwater-saturated sand	
	3.67	50	1.9	Seawater-saturated sand	
	53.67	∞	165	Basement (?)	
<b>Lifuka 2</b>	0	3.1	98	Unsaturated sand	3.1
(5.08%)	3.1	8	50	Freshwater-saturated sand	
	11.1	2.2	15	Brackish-water-saturated sand	
	13.1	45	1.9	Seawater-saturated sand	
	58.3	∞	150	Basement (?)	
<b>Lifuka 3</b>	0	0.37	65	Top soil	2.61
(9.03%)	0.37	2.24	458	Unsaturated sand	
	2.61	1.5	45	Freshwater-saturated sand	
	4.11	24	3.65	Seawater-saturated sand	
	28.11	∞	200	Basement (?)	

Table 3 Inferred relationship between conductivity and apparent resistivity.

	Conductivity reading (water)	Apparent resistivity (terrain)
Freshwater	up to 3000 uS/cm	40-50 ohm•m
Brackish water	From 3000 to 9000 uS/cm	10-15 ohm•m
Seawater	From 25 000 uS/cm	2-4 ohm•m

Interpretation of the results demonstrates the difficulty of clearly identifying an intermediate layer of freshwater when its thickness is less than (or approximately the same as) the thickness of the overlying unsaturated zone. For both Lifuka 1 and Lifuka 3 it is possible to obtain a reasonable model fit without including the thin freshwater layer. However, for Lifuka 2 the greater thickness of freshwater is clearly required in order to obtain a satisfactory fit.

A puzzling feature of each of the interpreted models is the relatively high resistivity that has had to be assigned to the basement layer. That resistivity (150-200 ohm-m) is not consistent with a salt-water-saturated material, and there is no drilling to the required depth (30-60 m) to provide an explanation.

### EM profiles

Two EM (electromagnetic) profiles were conducted adjacent to the resistivity soundings on the Hihifo and Pangai rugby fields. The profile on the Hihifo field was oriented parallel to the coastline, while the one in the Pangai field was perpendicular to the coast (bearing 110 degrees) in order to profile across the thickening of the freshwater lens.

Full details of the EM observations are provided in Appendix 3. For the purpose of calibration the horizontal dipole readings have been compared with the measured salinity profiles. The EM profiles for Hihifo and Pangai, for the three inter-coil spacings, are shown in Figure 9 and Figure 10.

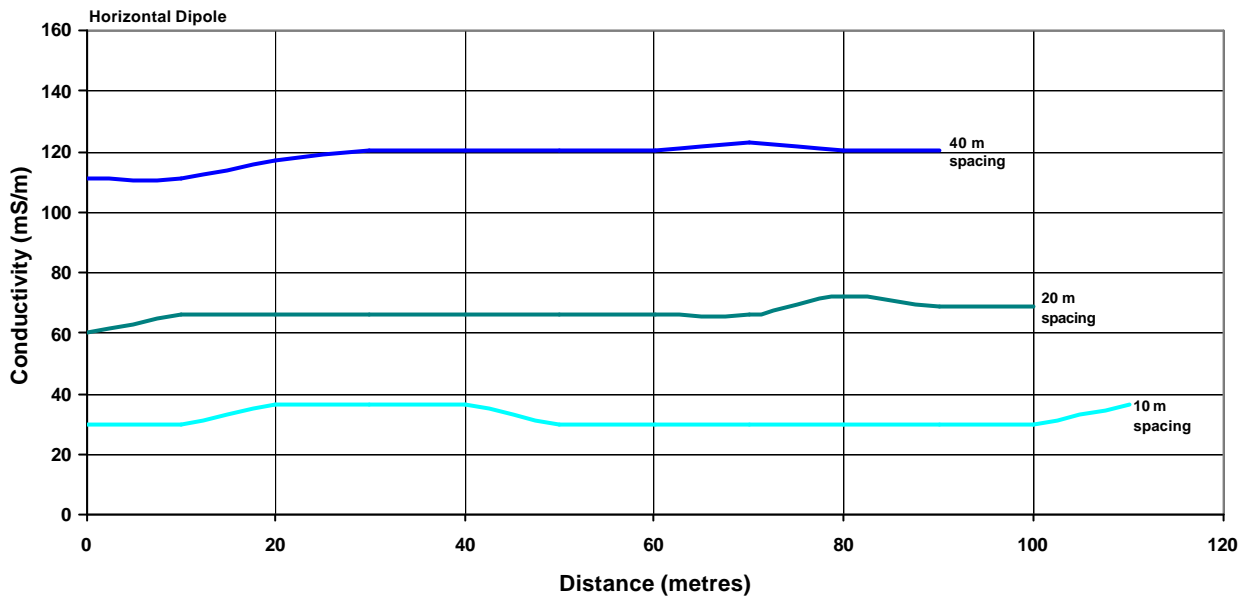


Figure 9 EM observations at Hihifo Rugby Field (Profile parallel to the coast).

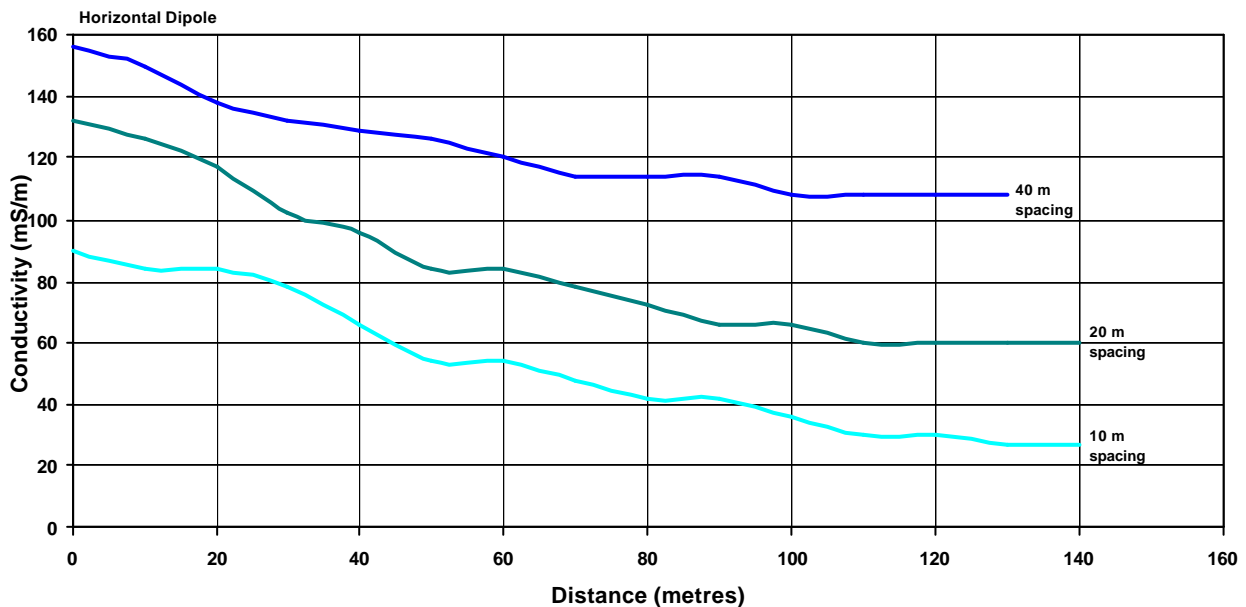


Figure 10 EM observations at Pangai Rugby Field (Profile perpendicular to the coast).

As can be observed from the two figures the EM profiles quite reliably represent the geometry of the freshwater lens. At Hihifo (Figure 9), where the profile was parallel to the shoreline, the three curves indicate relative uniform conductivity at each depth. In contrast, the profile at Pangai (Figure 10), being at right angles to the shoreline, shows the conductivity increasing as the freshwater lens thickens inland.

Comparison of the EM readings with the TWB salinity profiles suggests that, in this case, the exploration depth appears to be approximately 0.4 to 0.5 times the inter-coil spacing. If we adopt a factor of 0.4, the readings at 10, 20 and 40 metres spacing can be taken to refer respectively to 4, 8 and 16 metres exploration depth. On that basis a relationship between water and terrain conductivity (for a sand matrix) can be inferred as shown in Table 4:

*Table 4 Inferred relationship between conductivity and EM conductivity.*

	<b>Conductivity reading (water)</b>	<b>EM Conductivity reading (terrain)</b>
Freshwater	up to 1500 uS/cm	30 mS/m
Brackish water	6000 uS/cm	60 mS/m
Seawater	35 000 uS/cm	100-120 mS/m

## **O'ua**

### **General Observations**

O'ua is a roughly circular coral limestone island reaching a maximum elevation of approximately 25 metres above sea level. Figure 11 shows a plan view of the island together with a vertical profile showing the steep slopes around the island perimeter.

A thick layer of volcanic ash soil covers the limestone cropping out over most of the island. This pyroclastic sediment consists of alternations of yellow-brown or reddish-brown clay, with coarser beds of fragments of andesitic lava and glass (Cunningham and Anscombe, 1985). The ash layer appears to be relatively impermeable, since there is clear evidence of surface runoff and erosion in areas wherever the vegetation has been removed. In places the erosion has developed distinct gullies which are actively eroding. In one area close to the southern landing point a gully has extended inland to the extent that the foundations of one house are soon likely to be at risk.

O'ua was visited in 1992 and an EM survey conducted, which Furness and Helu (1993) interpreted as indicating that fresh to brackish water exists under the island. They concluded that, considering the size of the island, groundwater development should be possible. However, people living on the island reported that a hand-dug well on the southern flank had produced only brackish water. It is not clear whether that attempt was undertaken before or after the 1992 visit. No other wells or traditional practices involving groundwater use were reported.

O'ua

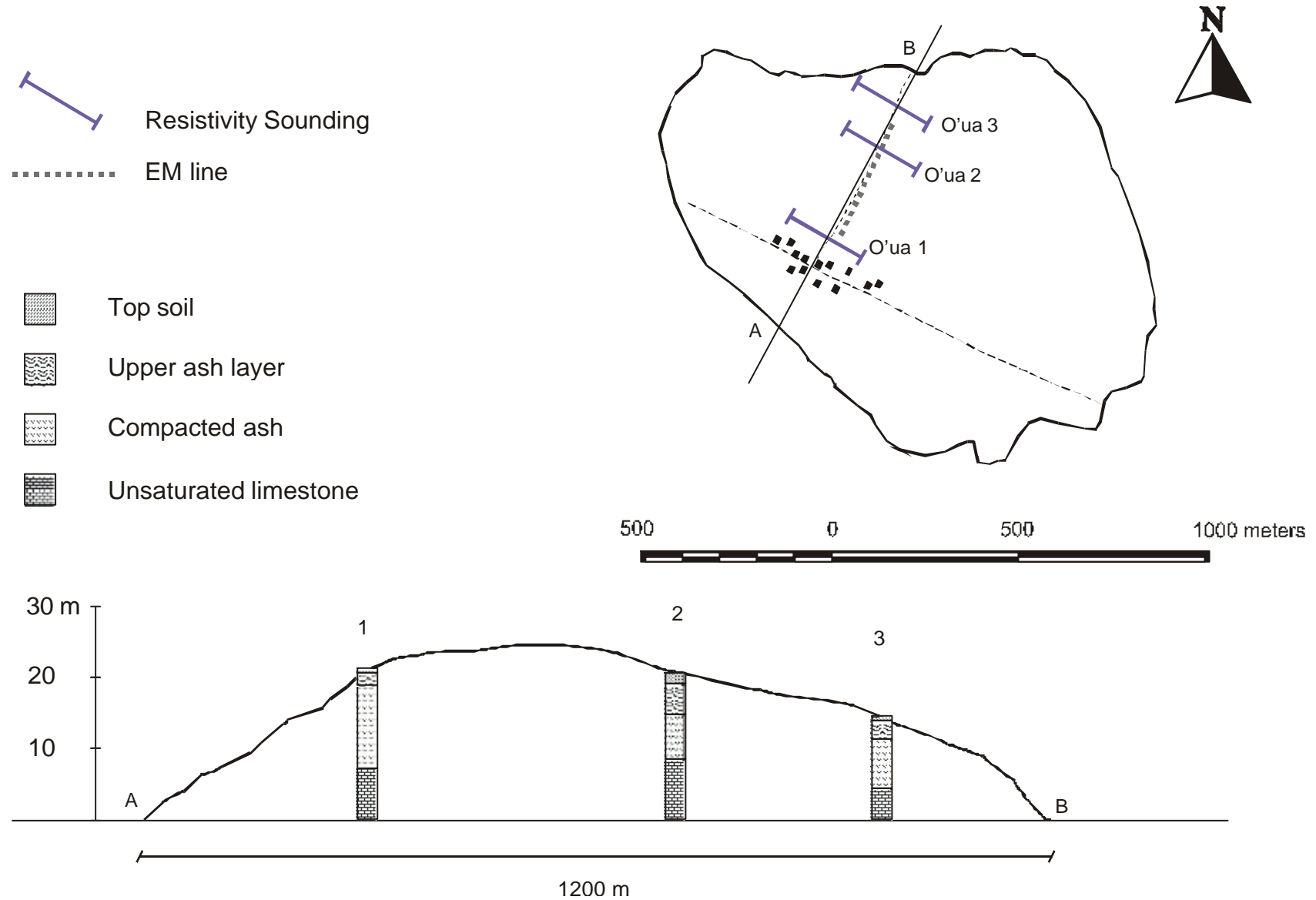


Figure 11 Map of O'ua showing location of ER and EM measurements

### *ER Soundings*

Three resistivity soundings (O'ua 1, O'ua 2 and O'ua 3) were carried out on O'ua, all using the Offset Wenner system. Details of the observations are listed in Appendix 2. The soundings were oriented at right angles to the foot track running roughly north-south across the island (see Figure 11). Because of the island profile it was possible to carry out each sounding at a distinctly different elevation. However, for each sounding, the elevation along the cable spread was also variable, with outer electrodes being generally at a lower elevation than the centre-line of the array. The O'ua 1 sounding shows very low observation errors, with an RMS error of 0.33% and a maximum absolute error of only 0.57%. Offset errors were also low apart from the final spacing. Since all 9 electrode spacings were used for this sounding, the extrapolated values have been calculated and plotted indicating a continuing increase in apparent resistivity with depth. The O'ua 2 sounding shows low observation errors and unremarkable offset errors. The O'ua 3 sounding, while generally showing low observation errors, has consistent offset errors ( $RD1 > RD2$ ) for spacings greater than 4 m. This may be a result of the ground slope along the cable spread. The D1 offset, to the west of the centre-line, was along falling ground while the ground to the east was relatively flat.

The ER sounding results together with the interpretations are shown in Figure 12, Figure 13 and Figure 14. The results are quite similar and show a general increase in resistivity with depth. The interpretations were based on the following assumptions:

- the island's limestone basement is almost certainly permeable and will be saltwater saturated at some depth below sea level. A resistivity of around 5 ohm\*m could be expected at or below sea level.
- Apart from the uppermost soil layer, the bulk of the island is likely to have similar electrical resistivity properties at the same elevation. At some depth below ground level the island is expected to be relatively homogeneous horizontally, and so there should be correlation of model resistivity values between each sounding interpretation.

The results were interpreted with the RINVERT package using the approach described earlier. If a seawater-saturated limestone layer is specified as the lowest layer, the interpretation of the sounding curves requires the insertion of a layer of high resistivity just above the saturated limestone. This layer of high resistivity is interpreted as unsaturated limestone. The interpretations for all three soundings are summarised in Table 5.

Table 5 Interpretation of O'ua ER soundings.

Sounding (RMS error)	Depth (m)	Thickness (m)	Resistivity (ohm•m)	Lithology	Altitude (m)
<b>O'ua 1</b>	0	0.6	12.2	Top soil	22
(7.61%)	0.6	1.8	5.1	Upper ash layer	
	2.4	12	50	Compacted ash	
	14.4	7.5	5900	Unsaturated limestone	
	22	∞	5	Seawater saturated limestone	
<b>O'ua 2</b>	0	1.3	12.3	Top soil	17
(3.70%)	1.3	3.57	5.4	Upper ash layer	
	4.8	5.3	50	Compacted ash	
	10	7	5900	Unsaturated limestone	
	17	∞	5	Seawater saturated limestone	
<b>O'ua 3</b>	0	0.7	17.8	Top soil	13.6
(3.58%)	0.7	2.3	4.3	Upper ash layer	
	3.1	6.5	50	Compacted ash	
	9.5	4	4500	Unsaturated limestone	
	13.6	∞	5	Seawater saturated limestone	



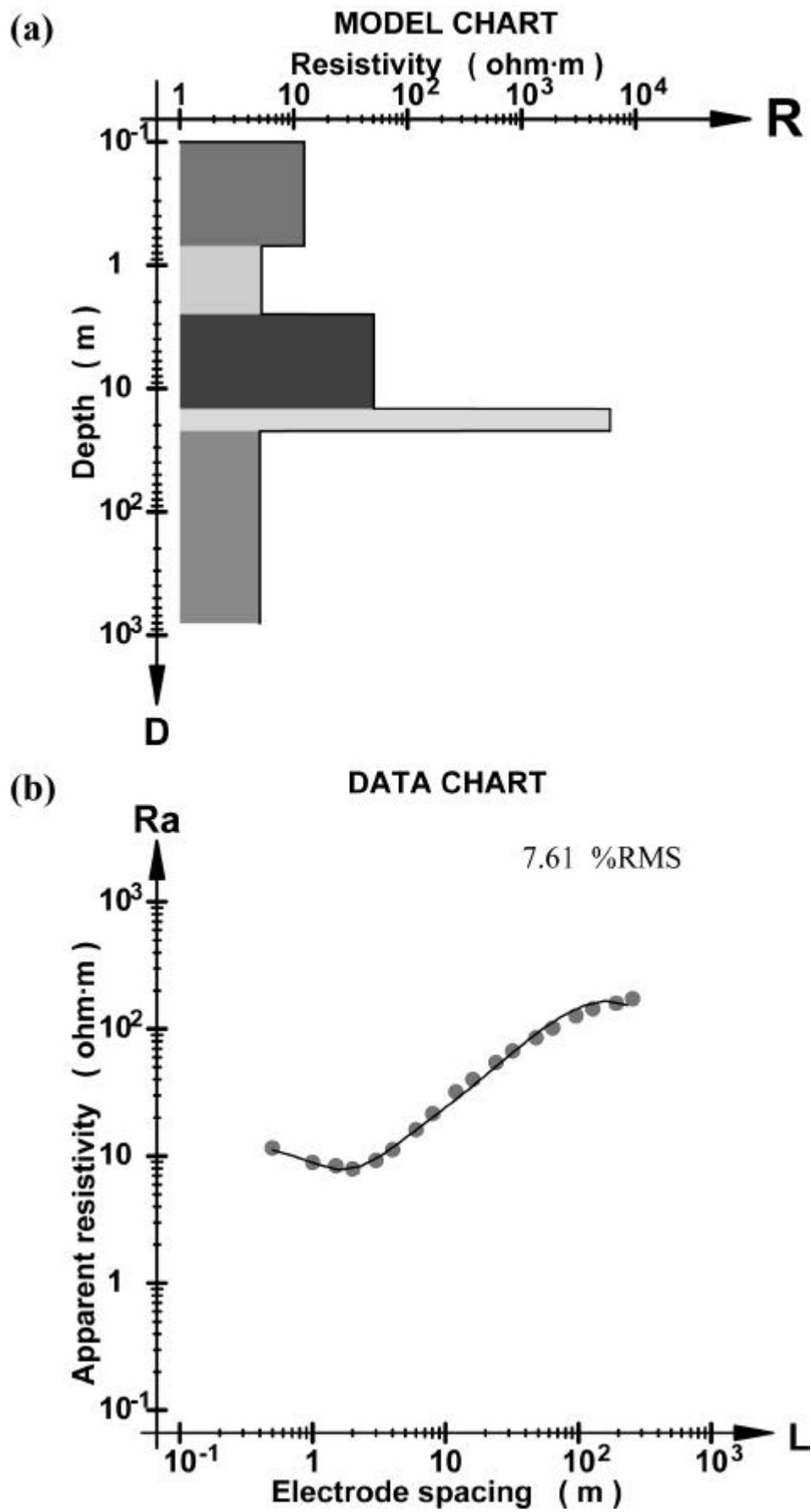


Figure 12 Interpretation of O'ua 1 resistivity sounding.

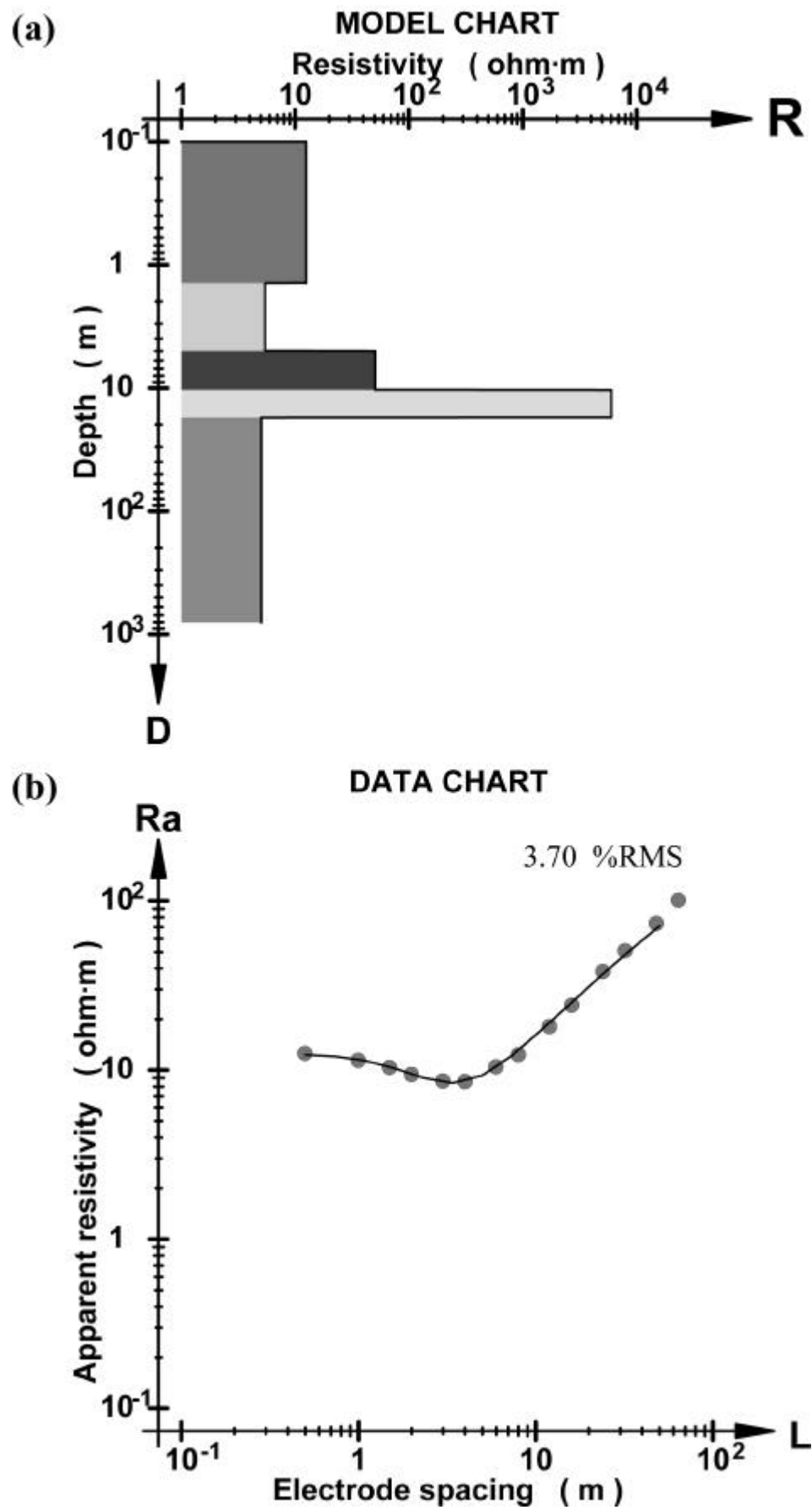


Figure 13 Interpretation of O'ua 2 resistivity sounding.

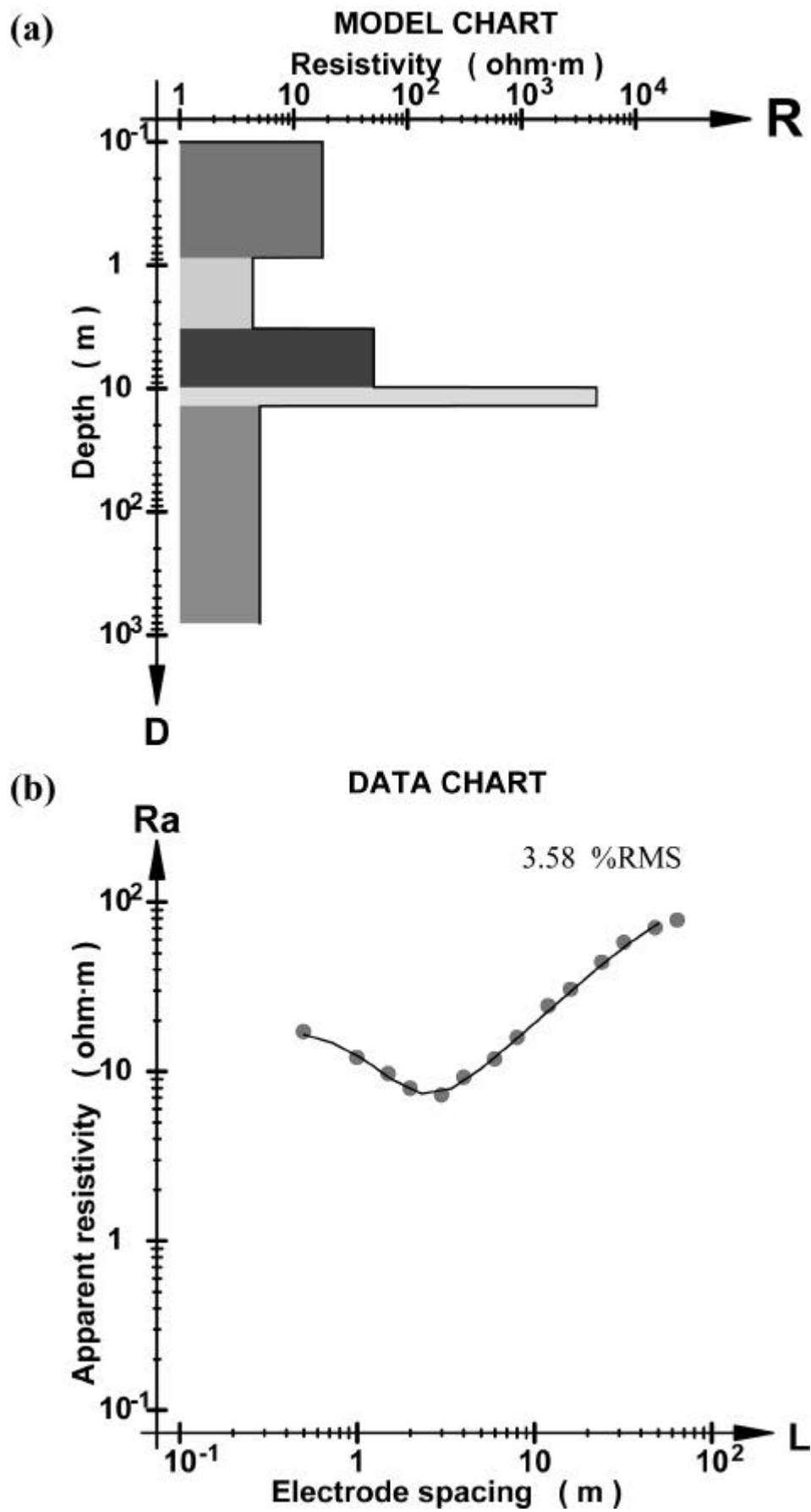


Figure 14 Interpretation of O'ua 3 resistivity sounding.

### EM Profile

The EM profile was conducted on the same foot track as the ER soundings. The altitude of the profile ranges from approximately 22 metres to 16 metres above sea level. Conductivities measured for three inter-coil spacings (10, 20 and 40 m) with the horizontal dipole have been plotted in Figure 15, giving profiles representing depths of 4, 8 and 16 metres. The results confirm the indication obtained from the resistivity soundings, where a more resistive layer (compacted ashes - 20 m spacing) underlies a shallow conductive layer (ash top layer - 10 m spacing). The profile for the 40-m spacing suggests the presence of seawater at around sea level. This is particularly evident at the end of the profile (Distance > 250 m) where conductivity increases to almost 100 mS/m.

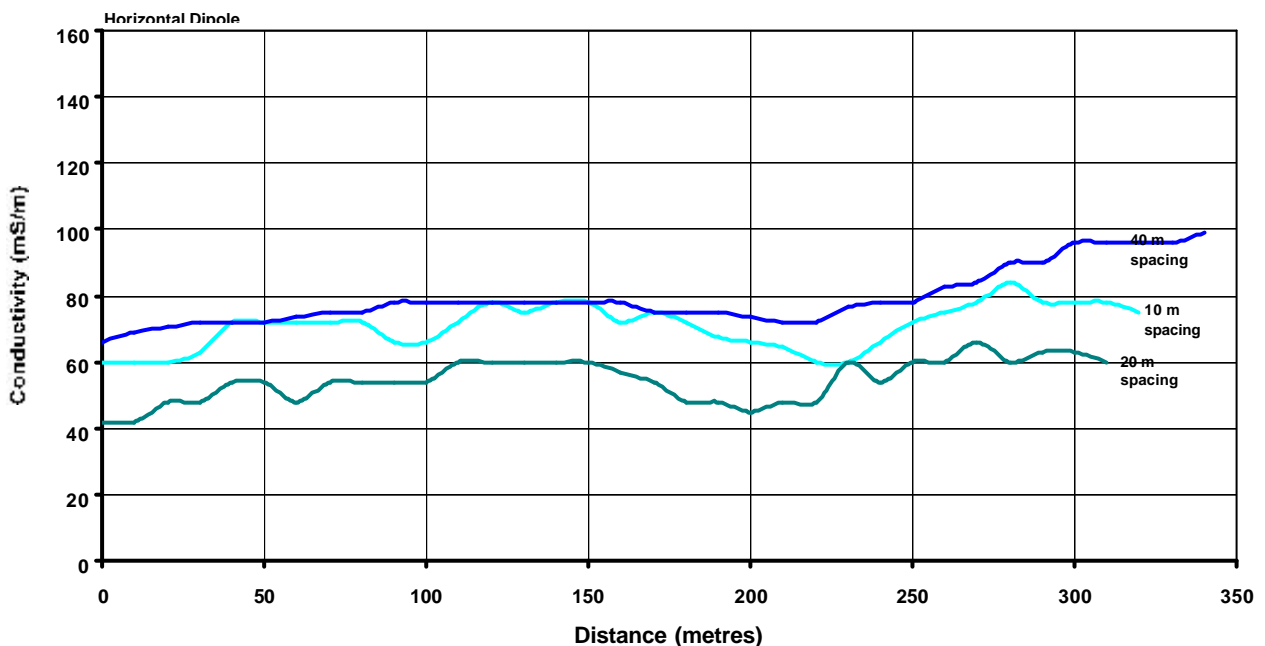


Figure 15 EM observations on O'ua.

### Interpretation

There are several indications that, despite its size, the island O'ua is unlikely to have developed a permanent freshwater reservoir. Both geophysical methods indicate the presence of a thick layer beneath the island (compacted ash). At a greater depth it appears likely that permeable limestone is saturated in seawater at around sea level. Interpretation of the ER soundings, though somewhat speculative, is not consistent with the formation of a significant thickness of freshwater.

The relatively impermeable topsoil favours run-off rather than infiltration. Also the thickness of the compacted ash limits percolation of water even where infiltration occurs. Possibly the most reliable indication is provided by the report of a dug well reaching brackish water.

## **Lofanga**

### *General Observations*

Lofanga is a raised coral island with an elevation near the centre of the island of approximately 15 metres above sea level (see Figure 16). As in O'ua, a thick ash deposit covers the limestone over most of the island. However, the slopes around the island perimeter are less steep, and narrow sandy beaches have developed around the coast (sand deposits do not extend more than 10-15 metres from the coast). A brief hydrogeological reconnaissance was undertaken in 1992 after which Furness and Helu (1993) reported that suitable drilling sites were available in the middle of the island. They considered that the island is large enough for a freshwater lens to have developed. However, they also noted the difficulty of getting a drilling rig on to the island.

A large pit has, at some stage, been excavated on the southern flank of Lofanga in an attempt to find usable groundwater. As on O'ua, this was unsuccessful, though it is unclear whether this was because of a lack of freshwater or the result of low permeability. Nevertheless, it does provide a storage pond for rainfall, and this provides further evidence of the relative impermeability of the volcanic ash deposits.

## Lofanga

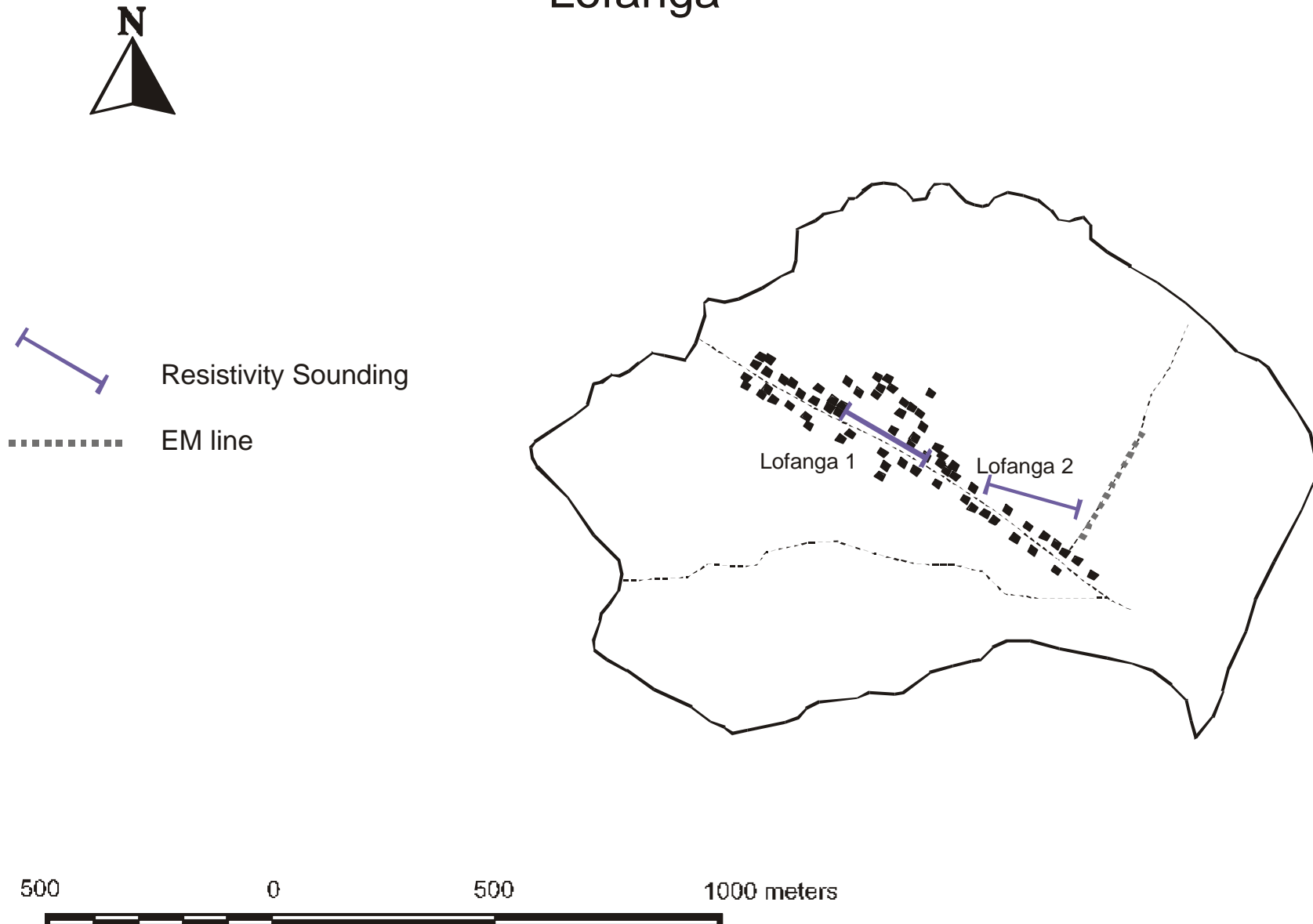


Figure 16 Map of Lofanga showing location of ER and EM measurements.

### *ER Soundings*

Two resistivity soundings were carried out on the island. The first (Lofanga 1) was along the central foot track in the village while the second (Lofanga 2) was to the North-East (see **Figure 16**). Details of the observations are listed in Appendix 2. The Schlumberger array was used for both soundings, and in both cases problems were encountered, with inconsistent resistances being measured at higher  $AB/2$  values. These inconsistent measurements were found to be stable. In the case of Lofanga 1 an additional electrode position was used ( $AB/2 = 147$  m) to check the sudden drop measured at  $AB/2 = 100$  m. This check suggested that the intermediate value was anomalous and, since it could not be explained by a horizontal layered model, was excluded from the interpretation. For the Lofanga 2 sounding, anomalies were encountered at the final spacing for  $MN/2 = 2$  m and  $MN/2 = 4$  m. Again these values were checked and found to be stable. Nevertheless they have been excluded from the interpretation on the grounds that they appear inconsistent with the other observations.

The interpretation of the first sounding (Lofanga 1) shows a situation similar to that of O'ua. A thick layer of ashes overlies the limestone layer. Given the high resistivity value (around  $2200 \text{ ohm}\cdot\text{m}$ ) this limestone layer must be unsaturated. At about sea level the same limestone is saturated by seawater showing a resistivity value of  $5 \text{ ohm}\cdot\text{m}$ .

The interpretation of Lofanga 2 presents a different situation. Under the thick layer of ashes there is a thin layer ( $\sim 1$  metre) with a resistivity of  $220 \text{ ohm}\cdot\text{m}$  which could be interpreted as a freshwater-saturated layer. The seawater-saturated layer lying below the limestone has a resistivity value that could indicate an intermediate situation between brackish and seawater saturated. This interpretation is non unique. Unlike the interpretation of Lofanga 1 it does not rule out the possible presence of freshwater. However, by itself it is not enough to give real and convincing evidence of the existence of freshwater.

The interpretations for both soundings are summarised in Table 6.

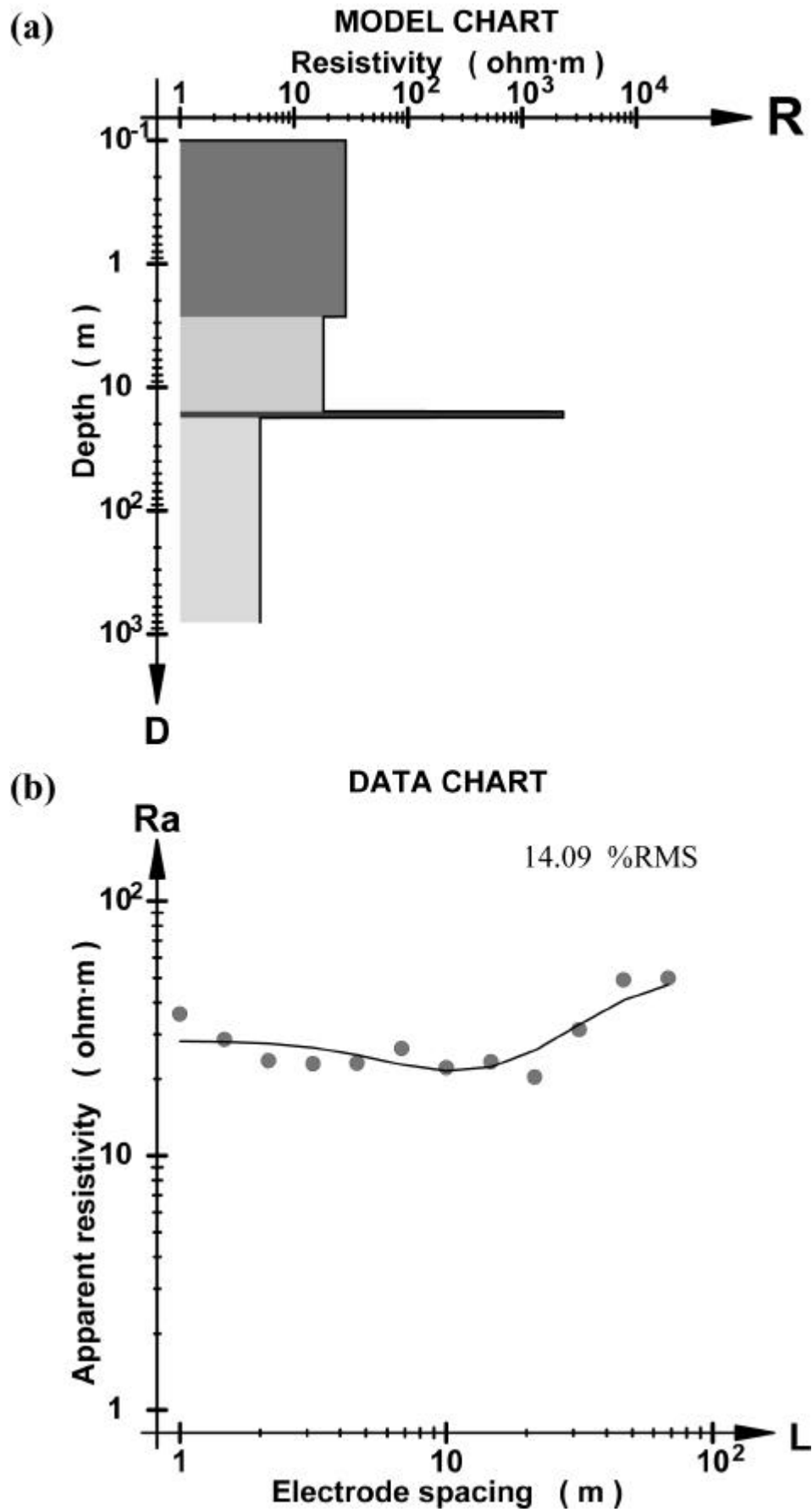


Figure 17 Interpretation of Lofanga 1 resistivity sounding.



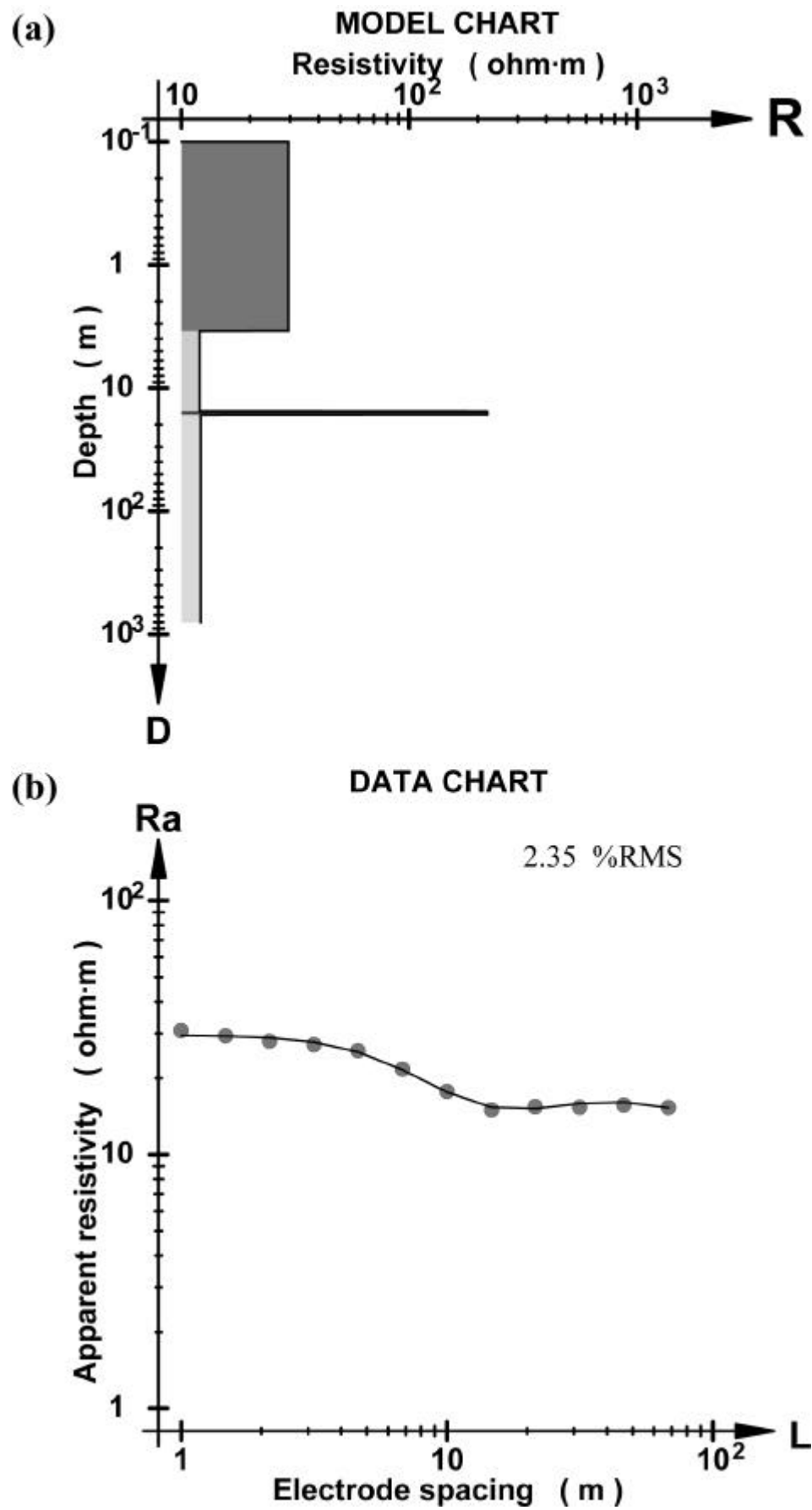


Figure 18 Interpretation of Lofanga 2 resistivity sounding.

Table 6 Interpretation of Lofanga ER soundings.

Sounding (RMS error)	Depth (m)	Thickness (m)	Resistivity (ohm•m)	Lithology	Altitude (m)
<b>Lofanga 1</b>	0	2.58	28.12	upper ash layer	15-16
(14.09%)	2.58	13	18	compacted ash	
	15.58	1.8	2256	unsaturated limestone	
	17.38	$\infty$	5	Seawater-saturated limestone	
<b>Lofanga 2</b>	0	3.345	23.41	upper ash layer	15-16
(2.35%)	3.345	12	12	Compacted ash	
	15.345	1	220	Freshwater-saturated limestone	
	16.345	$\infty$	12.14	brackish/seawater-sat. limestone	

### EM Profile

The EM profile was conducted on the track that leads from the village to the north coast. The results indicated that the conductivity of the soil increases with depth (see Figure 19). The 40-m spacing curve, which represents an exploration depth of approximately 16 m depth, remains above 110 mS/m. This suggests that that seawater saturates the limestone at about sea level.

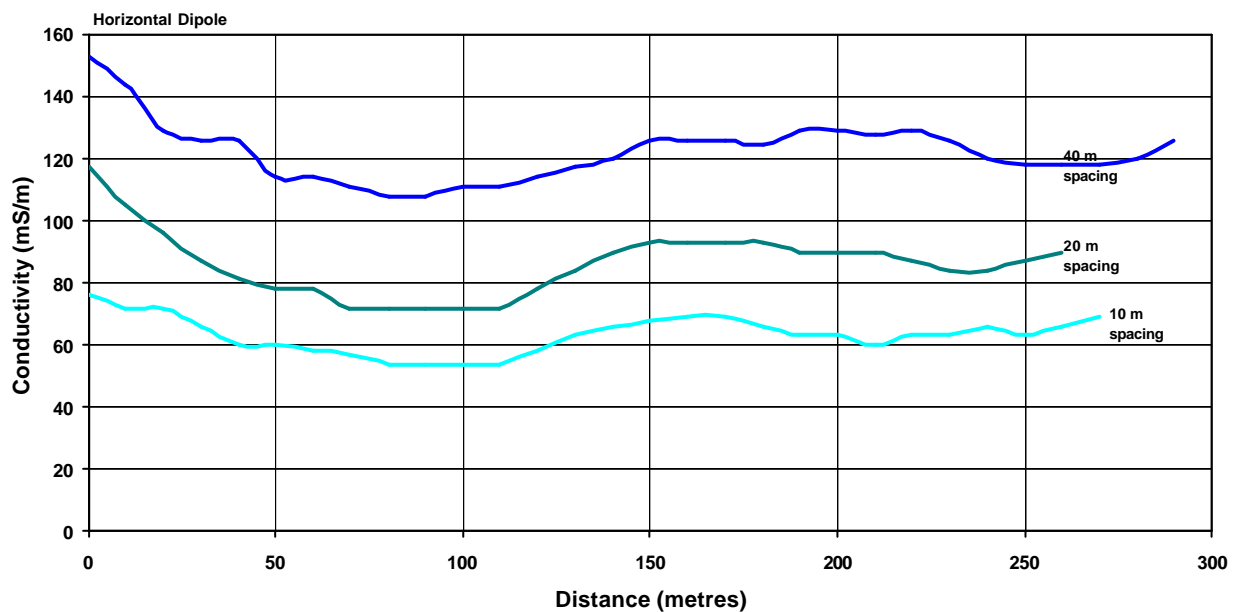


Figure 19 EM observations on Lofanga.

### Interpretation

The resistivity soundings and EM profile results suggest that there is little prospect of a freshwater lens being found on Lofanga. The fact that a dug pit was unable to find usable freshwater confirms that impression. Nevertheless, the second ER sounding indicated the possibility of a very thin lens. If exploratory drilling could be undertaken without much difficulty, further exploration might be justified. However, given the access difficulties presented by Lofanga this is probably not justified at present.

## DISCUSSION

The work described in this report had two parallel aims:

- to make an initial assessment of groundwater resources on small islands in the Ha'apai Group by attempting to identify the presence of freshwater, and
- provide training in the use of the electrical resistivity and electromagnetic geophysical methods.

In addition, the exercise provided an opportunity to assess the basic rationale for the survey. This raises an important issue and it is helpful to consider that before discussing the more direct outcomes of the exercise. The difficulty of getting a drilling rig on to the small, remote and relatively inaccessible outer islands of the Ha'apai Group presents a significant constraint to effective groundwater assessment and development. Without the independent observations made possible by drilling there is a risk that further geophysical surveys will provide inconclusive results. In turn, inconclusive results are unlikely to provide the basis for a successful proposal for the funding necessary for drilling. One way out of that impasse would be to obtain alternative exploratory drilling equipment that would be relatively cheap and significantly more portable than the existing equipment. The technologies and mechanisms for undertaking this deserve further consideration.

The outcome of the resource assessment aspect of the exercise can be summarised as follows:

- Analysis of observations on O'ua suggests that it is unlikely to have usable quantities of groundwater. The policy to encourage the development of rainwater catchments on O'ua should be continued.
- The reported erosion on O'ua appears to have been an active feature for many years, and consists of a deep gully which is progressively extending back from the coast. This appears to be a consequence of rapid surface runoff from extensive steep and bare areas where the fine volcanic ash soil forms a relatively impermeable cover. In places where the soil is bare of any vegetation there is clear evidence of surface erosion, and the foundations of some houses are at risk.
- Analysis of observations on Lofanga suggests that there is little prospect of finding usable quantities of groundwater. Though this result is less certain than for O'ua, until the exploration drilling problem is solved, the policy to encourage the development of rainwater catchments on Lofanga should be continued.

Results of the training aspect of the exercise can be summarised as follows:

- MLSNR staff are able to undertake ER and EM field surveys and produce reliable and consistent results.
- MLSNR ER and EM survey equipment has been maintained in good working order despite having been in storage for several years. The equipment performs well and is a valuable asset for groundwater assessment in Tonga. The software required to use the EM data logging equipment appears to have been lost, and a replacement should be sought from the manufacturer.
- Experience with the Offset Wenner and Schlumberger methods for electrical resistivity sounding has demonstrated some of the advantages of the Offset Wenner method. In particular, non-specialists can gain re-assurance in the field about the quality of their observations by using the error-checking procedures provided by the Offset Wenner method. It may be desirable for MLSNR to acquire an Offset Wenner Sounding cable system to supplement the existing Schlumberger system.
- MLSNR staff are able to carry out ER and EM data analysis and undertake interpretations. However, it would be desirable for them to acquire an up-to-date copy of ER analysis software. It would be very helpful for Ministry staff to have access to external review of any interpretations and reports. This could be provided by SOPAC or by a number of other organisations or individuals with relevant experience and interest in Tongan hydrogeology.

Access to Internet e-mail would be extremely useful to facilitate that sort of professional contact.

The issue of water-resources legislation and administrative arrangements in Tonga was raised in discussions with officials from TWB and MLSNR. On the basis of the very short-term exposure to the situation in Tonga it would be presumptuous for the assessment team to propose specific recommendations. Nevertheless, it is probably worth noting the recommendation made by Falkland (1991) that “comprehensive water resources legislation in the form of a Water Resources Act should be drafted and introduced for the proper planning, assessment, development, control, monitoring and protection of water resources throughout the Kingdom of Tonga.” The need for such measures is probably more compelling now than it was in 1991. The recommended approach of separating the administration of issues relating to water resources management from those relating to water supply is sound in principle. There is potential for conflict of interest if a single authority is charged with responsibility for water resource assessment, monitoring and regulation along with carrying out the responsibilities for water supply.

## **RECOMMENDATIONS**

In relation to the specific hydrogeological investigations on O'ua and Lofanga:

- The policy to encourage the development of rainwater catchments on O'ua should be continued.
- Measures to control surface water drainage should be implemented in areas on O'ua where surface erosion is having unacceptable effects. This could involve revegetation of some areas or the construction of simple cut-off drains.
- Though the survey results for Lofanga were less certain than for O'ua, the policy to encourage the development of rainwater catchments on Lofanga should be continued.

In relation to an on-going programme of investigations for small-island resource assessment and development:

- The development of rainwater catchments should be promoted as the preferred approach to water supply on all the small elevated islands of the Ha'apai Group. That policy could be reviewed once an appropriate technique for groundwater exploratory drilling has been established.
- An appropriate approach to groundwater exploratory drilling should be identified and evaluated in a pilot project. Light-weight portable drilling equipment may make it possible to conclusively demonstrate the feasibility of groundwater development on islands such as Lofanga.
- The established capacity within MLNSR to undertake and interpret ER/EM soundings should be maintained and developed by further field exploration. In the first instance this should be undertaken in situations where exploratory drilling would be feasible. It would be desirable for MLNSR to develop the existing system by obtaining updated copies of data-processing and interpretation software. If possible, the suite of existing equipment should be extended to incorporate an Offset Wenner sounding system.
- Subject to the development of suitable drilling techniques for exploration and development, and dependent on the outcome of a feasibility study, field exploration could be extended to less accessible islands.

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## **APPENDICES**

**Appendix 1: Diary of Activities**

**Appendix 2: Electrical resistivity field data**

**Appendix 3: Electromagnetic field data**

**Appendix 4: Salinity profile data**

### Appendix 1: Diary of Activities

Saturday 13 Feb	Suva to Tongatapu via Nadi
Sunday 14 Feb	Rest day
Monday 15 Feb	MLNSR met with Dr Savae Latu (Secretary, MLNSR), assessment team members, other staff from Geology & Hydrogeology Section. Examined ER and EM equipment. Visit to TWB, met with Saimone Helu and discussed broad objectives and TWB collaboration.
Tuesday 16 Feb	Obtained provisions, rainfall data, tide tables, TWB for salinity profile data, fly to Lifuka. Met Governor of Ha'apai and discussed priorities and logistics.
Wednesday 17 Feb	Three trainees and equipment arrive by ferry. Introduction to theory of ER & EM and brief field trial. Weather worsening with high wind warnings.
Thursday 18 Feb	No field work possible because of high wind and heavy rain
Friday 19 Feb	ditto
Saturday 20 Feb	Calibration ER & EM surveys on Lifuka. Travel plans further disrupted by storm damage to boat. With Governor's assistance made alternative plan to use the Police Vessel to visit O'ua and Lofanga
Sunday 21 Feb	Rest day
Monday 22 Feb	Travel to O'ua. General inspection, ER & EM survey work on island. Stayed overnight on O'ua
Tuesday 23 Feb	Further ER sounding. Travel to Lofanga. General inspection, ER & EM survey. Travel on to Lifuka
Wednesday 24 Feb	Pack up, fly to Tongatapu. Data analysis
Thursday 25 Feb	Data interpretation and synthesis of results.
Friday 26 Feb	Equipment & trainees return by ferry. Packing of equipment for return to Suva. Visits to Dr Savae Latu, Australian High Commission (Mr Ray Lloyd, First Secretary), TWB (Saimone Helu)
Saturday 27 Feb	Tongatapu to Suva via Nadi

## **Appendix 2: Electrical resistivity field data**

This appendix provides copies of the standard data forms for the Offset Wenner and Schlumberger methods and full details of the resistivity measurements made on Lifuka, O'ua and Lofanga.

The plotted Wenner Sounding curves show three different resistivity values for each array setting. The Wenner resistivity calculated from the RD1 and RD2 configurations are shown by a solid diamond (◆) and a circle (●) respectively. The mean value is shown by a solid square (■). For observations with low offset errors these different symbols are so close that they are indistinguishable.



**OFFSET WENNER SOUNDING DATA FORM**

Site:			Ref No:			Weather:				
Observers:			Bearing:			Topography:				
Date:			Soil:			Geology:				
SETTING (n)	OBSERVED MEASUREMENTS					ERRORS			SPACING (metres)	WENNER RESISTIVITY
	RA	RC	RD1	RD2	RB	OBS	OFFSET	LATERAL		
1						N/A	N/A		0.5	
2						N/A	N/A	N/A	1.0	
									1.5	
3						N/A	N/A	N/A	2.0	
									3.0	
4						N/A	N/A	N/A	4.0	
									6.0	
5						N/A	N/A	N/A	8.0	
									12.0	
6						N/A	N/A	N/A	16.0	
									24.0	
7						N/A	N/A	N/A	32.0	
									48.0	
8						N/A	N/A	N/A	64.0	
									96.0	
9						N/A	N/A	N/A	128.0	
RMS Error:						#DIV/0!	#DIV/0!	#DIV/0!	192.0	
									256.0	

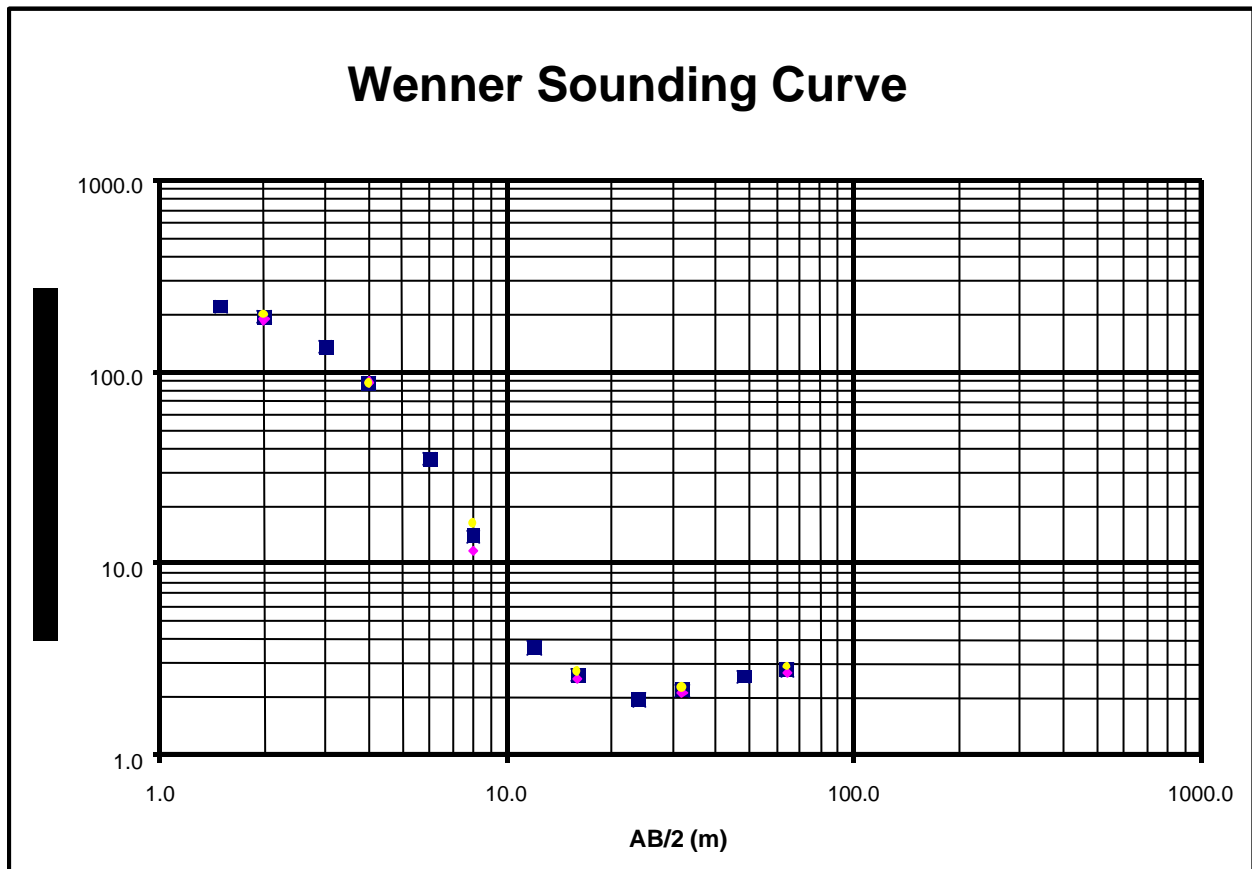
**Comments:**

## SCHLUMBERGER SOUNDING DATA FORM

No. Location: Elevation			Date: Coordinates Bearings:		
AB/2 (m)	MN/2 (m)	Resistanc (ohm)	k	Apparent Resistivit (ohm*m)	Apparent Resistivit (ohm*m)
1.00	0.4		3.30		
1.47	0.4		7.85		
2.15	0.4		17.52		
3.16	0.4		38.57		
4.64	0.4		83.88		
6.81	0.4		181.40		
4.64	2		13.76		
6.81	2		33.27		
10.00	2		75.36		
14.70	2		166.49		
21.50	2		359.73		
31.60	2		780.73		
46.40	2		1686.93		
31.60	4		385.65		
46.40	4		838.76		
68.10	4		1813.98		
100.00	4		3918.72		
147.00	4		8475.25		

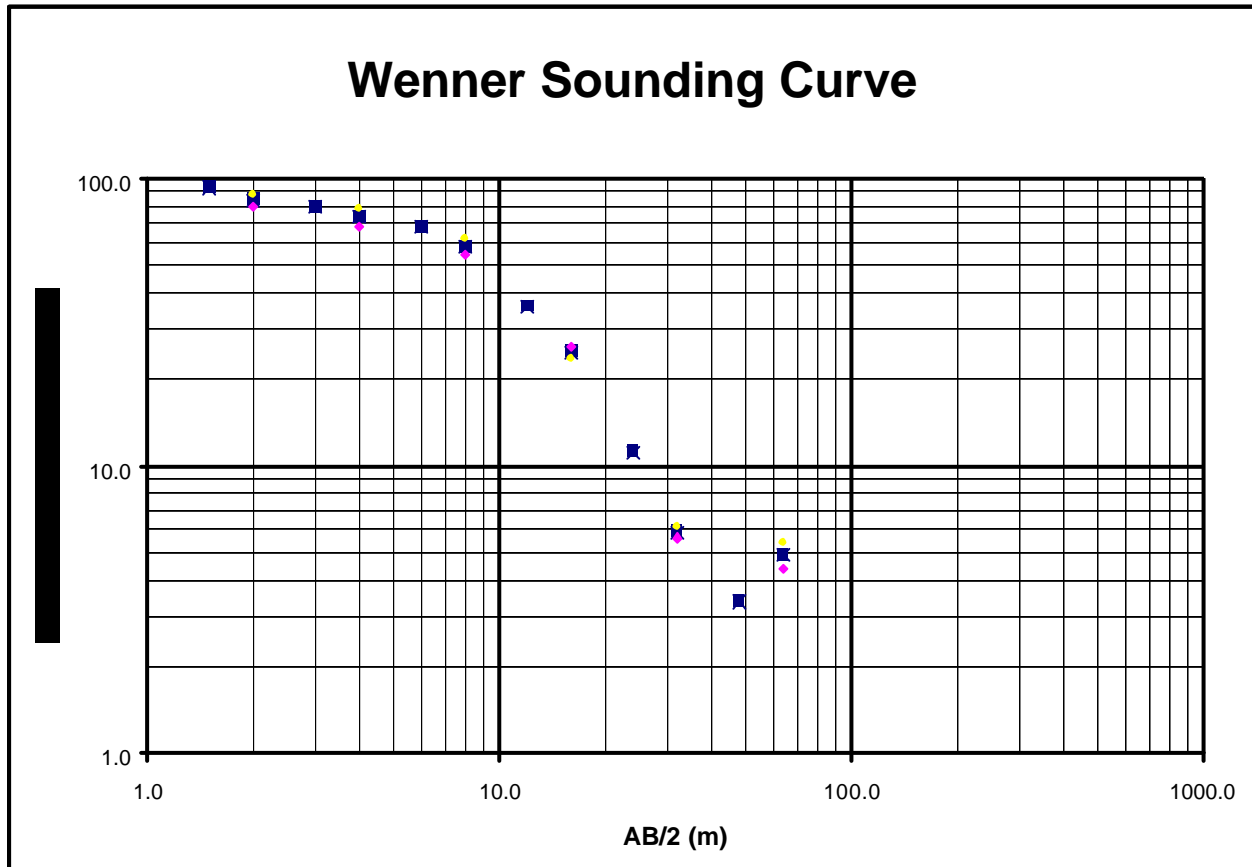
Site: Hihifo Rugby Field					Ref No: Lifuka 1		Weather: Hot			
Observers: David Apai					Bearing: D1 North		Topography: Flat			
Date: 20/2/99					Soil:		Geology:			
SETTING (n)	OBSERVED MEASUREMENTS					ERRORS			SPACING	WENNER
	RA	RC	RD1	RD2	RB	OBS	OFFSET	LATERAL	(metres)	RESISTIVITY
1	80.6	74.8	58.8	54.7	5.6	0.25	7.22		0.5	178.29
2	48	44.6	35.5	36.4	3.33	0.15	-2.50	-0.93	1.0	225.88
									1.5	220.57
3	18.15	17.07	14.97	15.84	1.06	0.11	-5.65	-12.72	2.0	193.58
									3.0	135.30
4	3.9	3.79	3.53	3.46	0.1093	0.02	2.00	4.18	4.0	87.84
									6.0	35.22
5	0.271	0.262	0.232	0.32	0.00669	0.86	-31.88	-114.01	8.0	13.87
									12.0	3.65
6	0.0328	0.0319	0.0248	0.0272	0.001232	-1.01	-9.23	199.07	16.0	2.61
									24.0	1.95
7	0.01659	0.01509	0.0105	0.01122	0.000842	4.05	-6.63	-5.70	32.0	2.18
									48.0	2.57
8	0.0101	0.00944	0.00669	0.00719	0.000531	1.29	-7.20	-30.70	64.0	2.79
									96.0	
9						N/A	N/A	N/A	128.0	
RMS Error:						1.58	12.71	81.99	192.0	
									256.0	

**Comments:** Visited by Governor of Hapai'i during sounding.

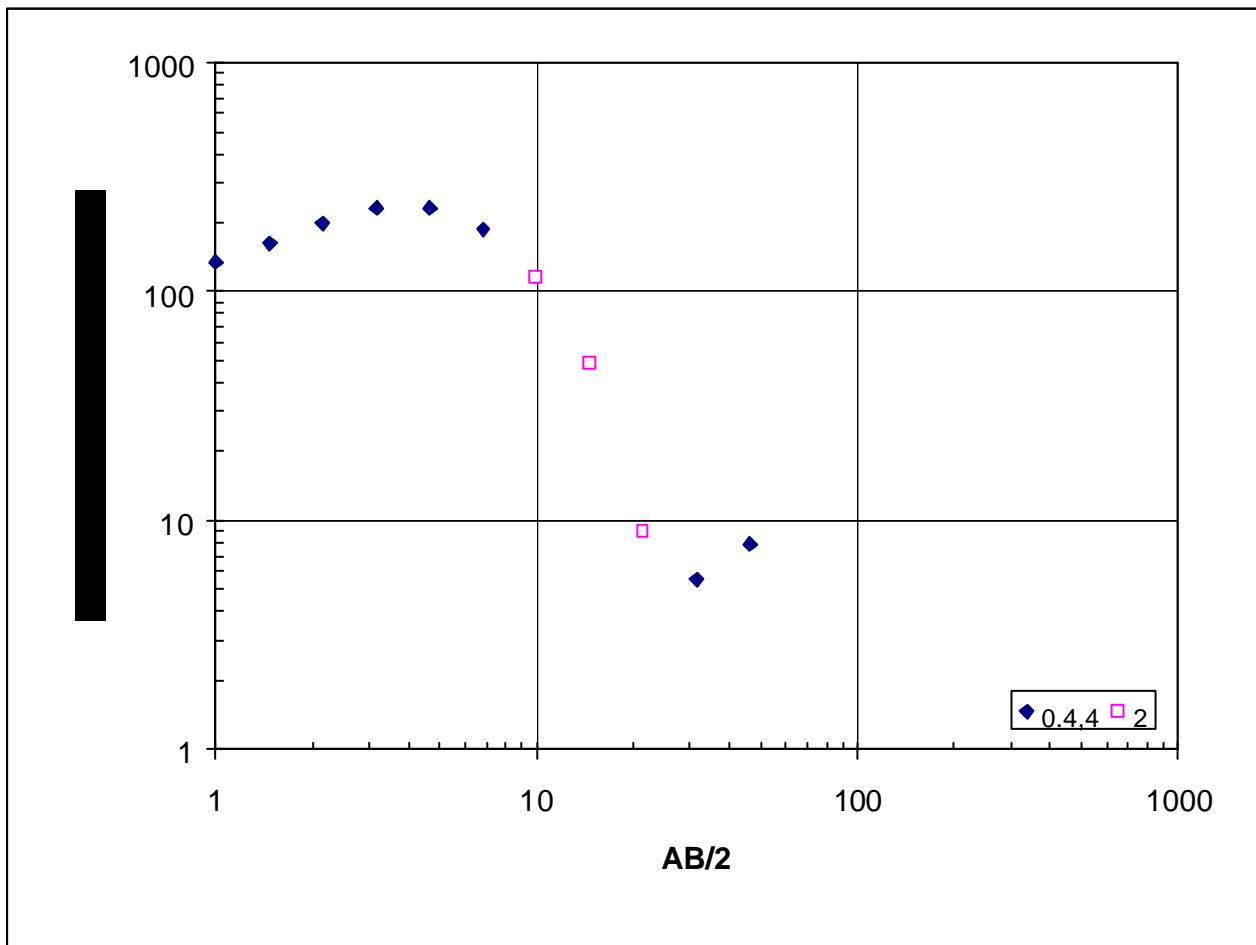


Site:		East of Hihifo Rugby Field				Ref No:		Lifuka 2		Weather:	
Observers:		David. Apai				Bearing:		D1 North		Topography:	
Date:		20/2/99				Soil:				Geology:	
SETTING (n)	OBSERVED MEASUREMENTS					ERRORS			SPACING	WENNER	
	RA	RC	RD1	RD2	RB	OBS	OFFSET	LATERAL	(metres)	RESISTIVITY	
1	45	42.6	35.2	31.2	2.36	0.09	12.05		0.5	104.30	
2	20.3	19.22	15.45	15.63	1.11	-0.15	-1.16	-21.22	1.0	97.64	
									1.5	92.93	
3	8.79	8.24	6.37	7	0.538	0.14	-9.42	-9.67	2.0	84.01	
									3.0	79.77	
4	3.63	3.32	2.71	3.13	0.298	0.33	-14.38	-6.89	4.0	73.39	
									6.0	67.66	
5	1.351	1.274	1.076	1.222	0.0762	0.06	-12.71	29.42	8.0	57.75	
									12.0	35.89	
6	0.228	0.215	0.26	0.235	0.01172	0.56	10.10	-1.32	16.0	24.88	
									24.0	11.14	
7	0.0344	0.0364	0.0279	0.0306	0.00238	-12.01	-9.23	318.08	32.0	5.88	
									48.0	3.37	
8	0.01765	0.0224	0.01087	0.01344	-0.00032	-22.58	-21.14	18.20	64.0	4.89	
									96.0		
9						N/A	N/A	N/A	128.0		
RMS Error:						9.05	12.44	113.45	192.0		
									256.0		

Comments: Along road



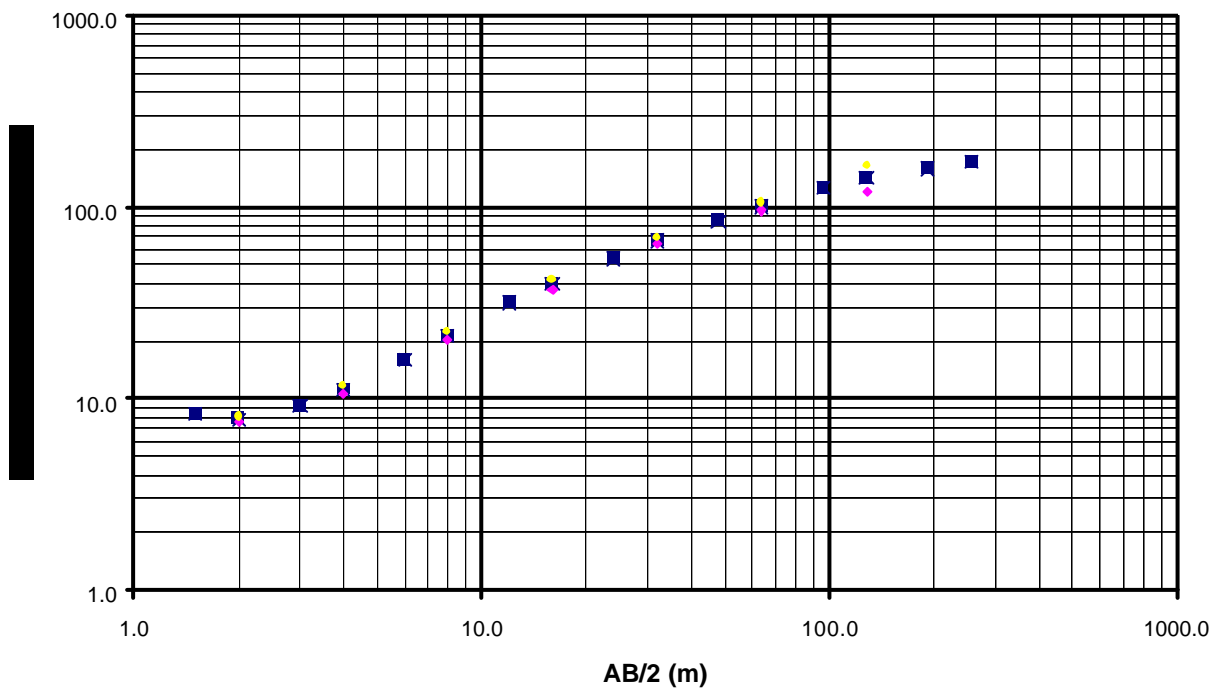
No. Location: Elevation:	Lifuka 3 Panqaia Rugby Field		Date: Coordinates: Bearings:	20/02/99	
AB/2 (m)	MN/2 (m)	Resistance (ohm)	k	Apparent Resistivity (ohm*m)	Apparent Resistivity (ohm*m)
1.00	0.4	40.7	3.30	134.19	
1.47	0.4	20.7	7.85	162.57	
2.15	0.4	11.35	17.52	198.80	
3.16	0.4	6.02	38.57	232.16	
4.64	0.4	2.77	83.88	232.34	
6.81	0.4	1.03	181.40	186.84	
4.64	2	15.79	13.76		
6.81	2	5.74	33.27		
10.00	2	1.532	75.36		115.45
14.70	2	0.289	166.49		48.12
21.50	2	0.0249	359.73		8.96
31.60	2	0.0102	780.73		
46.40	2	0.0139	1686.93		
31.60	4	0.0143	385.65	5.51	
46.40	4	0.0094	838.76	7.88	
68.10	4	-0.02	1813.98	?	
100.00	4	-0.00265	3918.72	?	
147.00	4		8475.25		



Site: Ou'a along fence line behind village					Ref No: O'ua 1		Weather:			
Observers: David, Tevita, Siale					Bearing: D2 towards west		Topography:			
Date: 22/2/99					Soil:		Geology:			
SETTING (n)	OBSERVED MEASUREMENTS					ERRORS			SPACING	WENNER
	RA	RC	RD1	RD2	RB	OBS	OFFSET	LATERAL	(metres)	RESISTIVITY
1	4.91	4.68	3.66	3.65	0.22	0.20	0.27		0.5	11.48
2	1.859	1.766	1.419	1.391	0.0913	0.09	1.99	-46.59	1.0	8.83
									1.5	8.33
3	0.896	0.853	0.602	0.641	0.0449	-0.21	-6.28	-16.43	2.0	7.81
									3.0	9.16
4	0.703	0.67	0.424	0.463	0.0342	-0.17	-8.79	-3.99	4.0	11.15
									6.0	15.92
5	0.653	0.606	0.404	0.441	0.0467	0.05	-8.76	-6.95	8.0	21.24
									12.0	31.75
6	0.594	0.554	0.371	0.418	0.0401	-0.02	-11.91	6.90	16.0	39.66
									24.0	53.70
7	0.489	0.457	0.318	0.344	0.0292	0.57	-7.85	3.65	32.0	66.55
									48.0	84.43
8	0.359	0.337	0.238	0.263	0.0239	-0.53	-9.98	-1.65	64.0	100.73
									96.0	125.55
9	0.242	0.23	0.1484	0.205	0.01317	-0.48	-32.03	3.10	128.0	142.11
RMS Error:						0.33	13.02	16.92	192.0	157.98
									256.0	171.47

Comments:

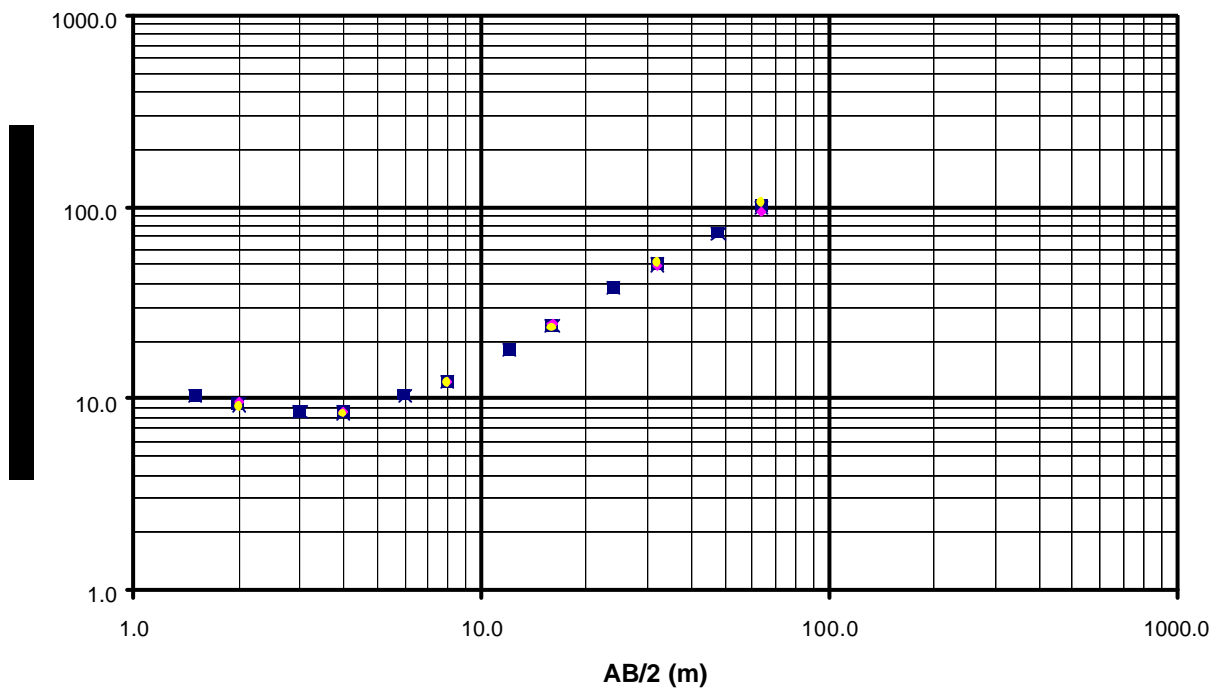
## Wenner Sounding Curve



Site: O'ua - parallel to O'ua 1					Ref No: O'ua 2		Weather:			
Observers: David, Tevita, Siale					Bearing: D1 towards west		Topography:			
Date: 22/2/99					Soil:		Geology:			
SETTING (n)	OBSERVED MEASUREMENTS					ERRORS			SPACING (metres)	WENNER RESISTIVITY
	RA	RC	RD1	RD2	RB	OBS	OFFSET	LATERAL		
1	5.49	5.19	3.64	4.27	0.307	-0.13	-15.93			0.00
2	2.43	2.3	1.784	1.812	0.1262	0.16	-1.56	-37.01	1.0	11.30
									1.5	10.27
3	1.002	0.963	0.763	0.723	0.0386	0.04	5.38	-35.61	2.0	9.34
									3.0	8.53
4	0.481	0.459	0.342	0.332	0.0234	-0.29	2.97	-30.68	4.0	8.47
									6.0	10.36
5	0.381	0.363	0.245	0.241	0.01972	-0.45	1.65	0.14	8.0	12.21
									12.0	17.87
6	0.387	0.364	0.243	0.234	0.0269	-1.00	3.77	0.06	16.0	23.98
									24.0	37.86
7	0.374	0.36	0.245	0.254	0.01895	-1.31	-3.61	0.86	32.0	50.16
									48.0	72.70
8	0.387	0.362	0.236	0.261	0.0289	-1.00	-10.06	12.97	64.0	99.93
									96.0	
9						N/A	N/A	N/A	128.0	
RMS Error:						0.71	7.29	21.64	192.0	
									256.0	

**Comments:** East-west sounding at right angles to EM survey. NB location on EM profile noted as 310m from gate.

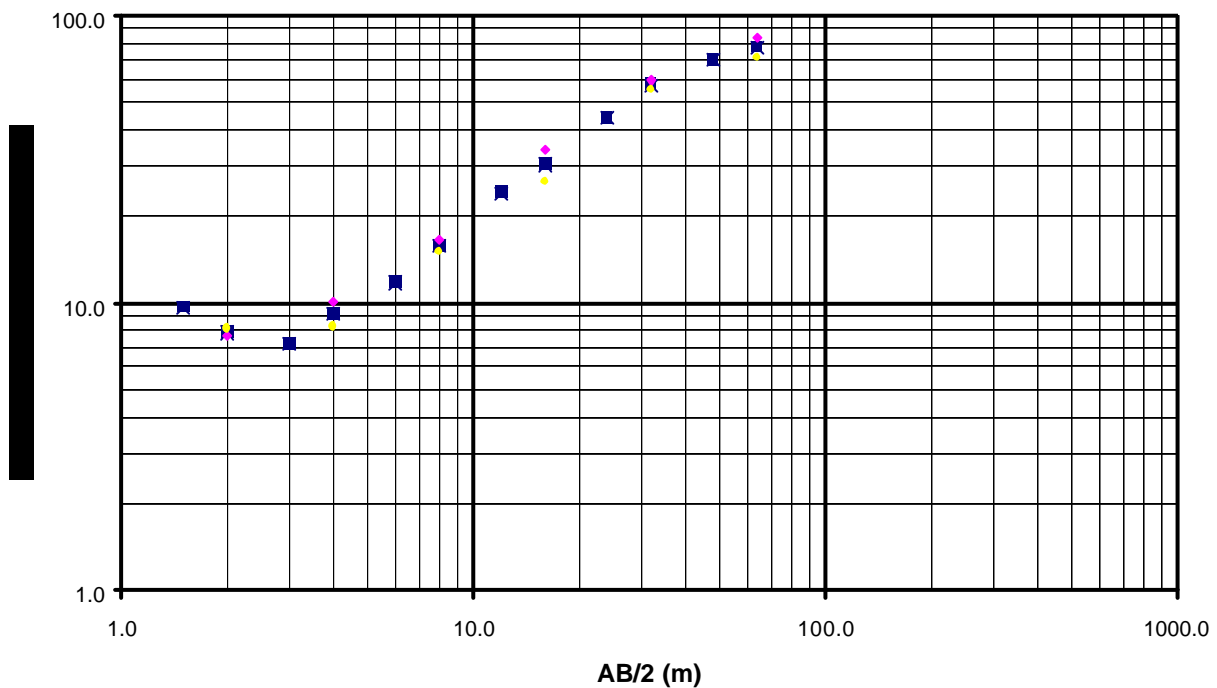
## Wenner Sounding Curve



Site: O'ua - parallel to O'ua 2					Ref No: O'ua 3		Weather:			
Observers: David, Tevita, Siale					Bearing: D1 to west		Topography:			
Date: 23/2/99					Soil:		Geology:			
SETTING (n)	OBSERVED MEASUREMENTS					ERRORS			SPACING (metres)	WENNER RESISTIVITY
	RA	RC	RD1	RD2	RB	OBS	OFFSET	LATERAL		
1	7.61	6.82	5.47	5.35	0.404	5.21	2.22		0.5	17.00
2	2.12	1.964	1.86	1.957	0.1671	-0.52	-5.08	-66.36	1.0	11.99
									1.5	9.62
3	0.785	0.73	0.61	0.646	0.0525	0.32	-5.73	83.96	2.0	7.89
									3.0	7.21
4	0.561	0.536	0.402	0.328	0.0246	0.07	20.27	43.47	4.0	9.17
									6.0	11.73
5	0.491	0.455	0.329	0.298	0.037	-0.20	9.89	-9.21	8.0	15.76
									12.0	24.10
6	0.47	0.435	0.339	0.263	0.035	0.00	25.25	6.29	16.0	30.26
									24.0	43.85
7	0.439	0.403	0.295	0.274	0.028	1.84	7.38	5.80	32.0	57.20
									48.0	69.87
8	0.261	0.243	0.208	0.1766	0.0265	-3.21	16.33	-27.10	64.0	77.33
									96.0	
9						N/A	N/A	N/A	128.0	
RMS Error:						2.27	13.83	42.18	192.0	
									256.0	

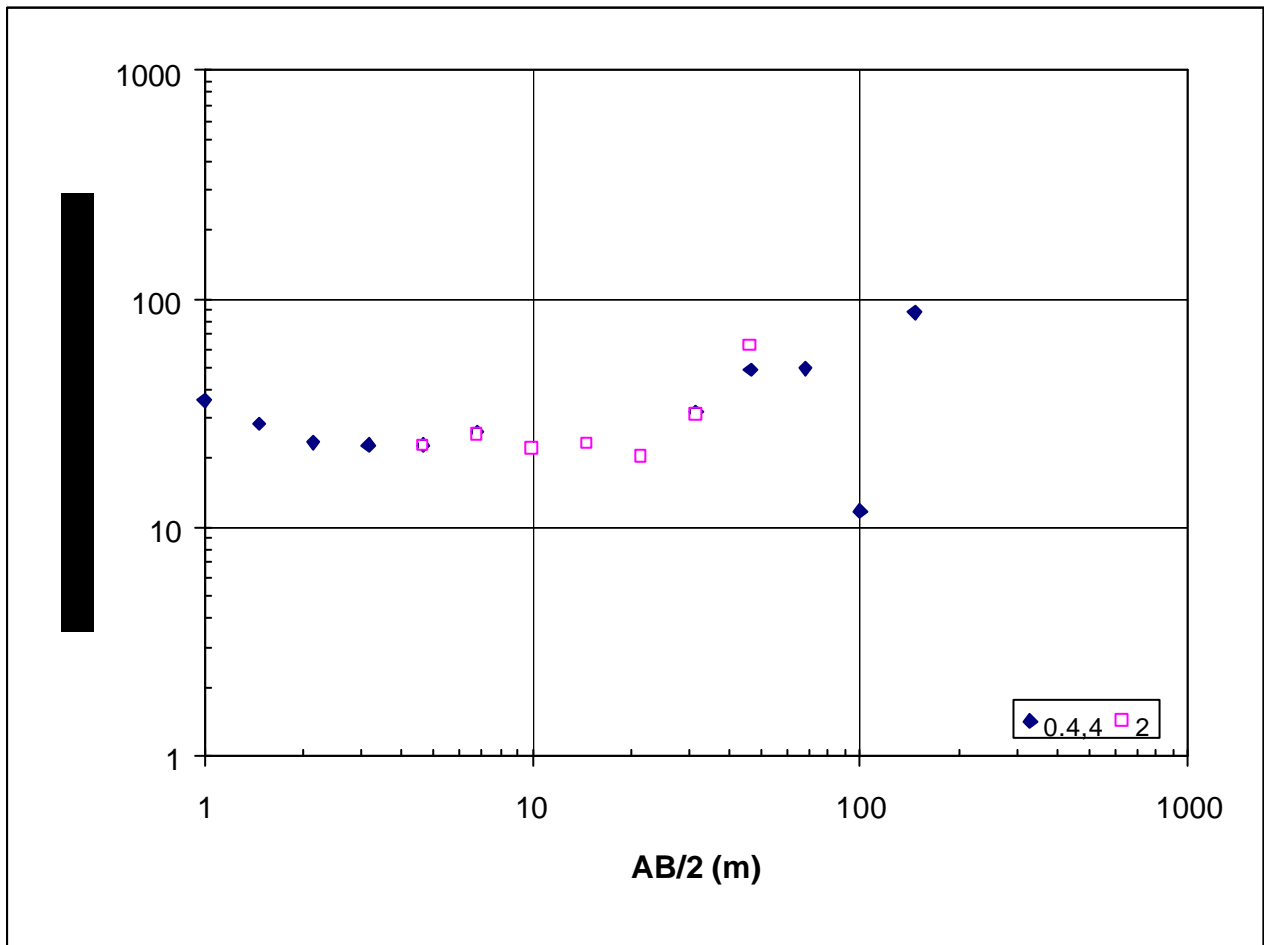
**Comments:** East-west sounding near top of slope down to shore (estimated as approx 50m from shore).

## Wenner Sounding Curve

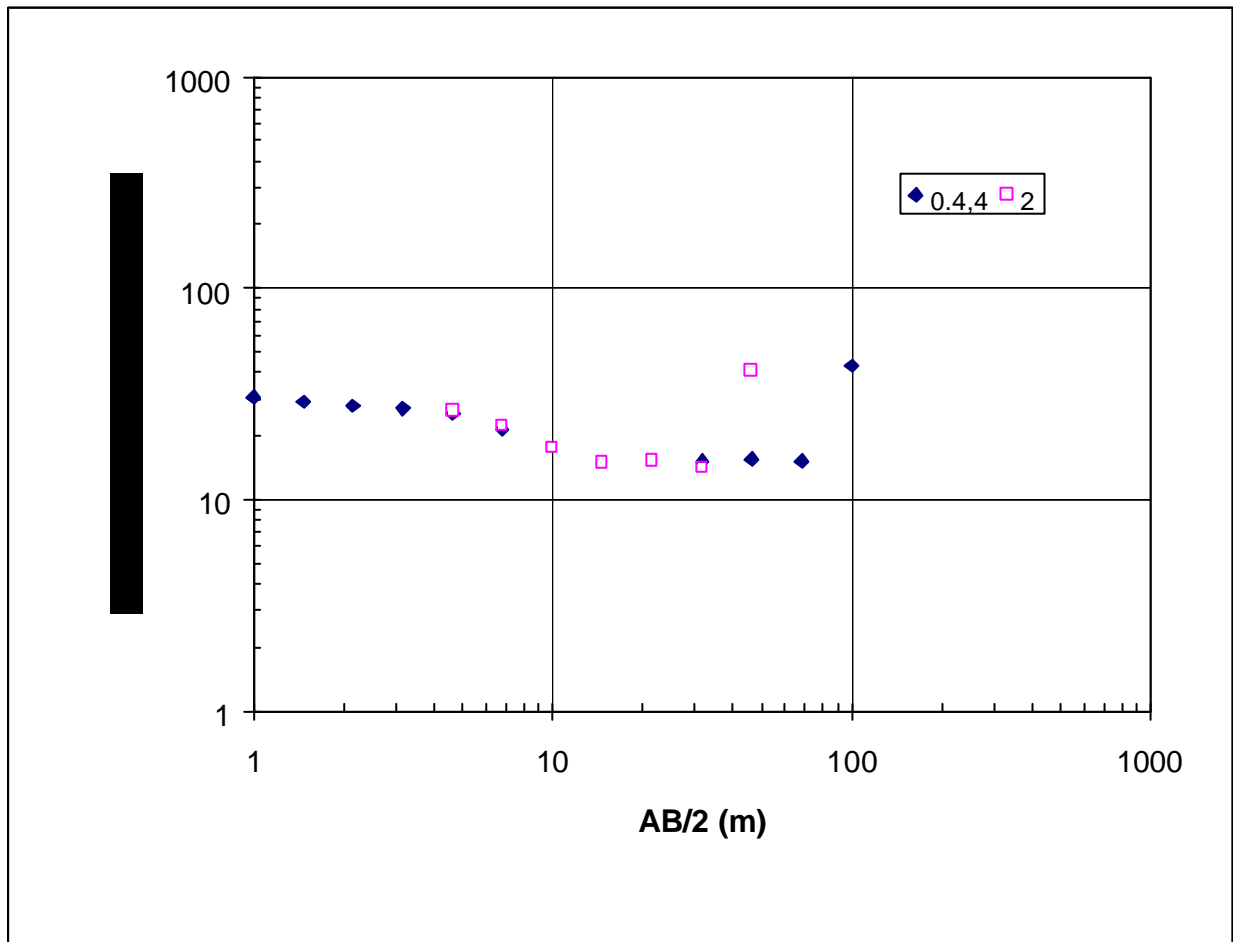




Ref No: Site: Elevation:	Lofanqa 1		Date: Coordinates: Bearings:	23/2/99	
AB/2 (m)	MN/2 (m)	Resistance (ohm)	k	Apparent Resistivity (ohm*m)	Apparent Resistivity (ohm*m)
1	0.4	10.9	3.30	35.94	
1.47	0.4	3.63	7.85	28.51	
2.15	0.4	1.341	17.52	23.49	
3.16	0.4	0.593	38.57	22.87	
4.64	0.4	0.274	83.88	22.98	
6.81	0.4	0.1445	181.40	26.21	
4.64	2	1.652	13.76		22.73
6.81	2	0.761	33.27		25.31
10	2	0.293	75.36		22.08
14.7	2	0.1397	166.49		23.26
21.5	2	0.0563	359.73		20.25
31.6	2	0.0399	780.73		31.15
46.4	2	0.037	1686.93		62.42
31.6	4	0.0832	385.65	32.09	
46.4	4	0.0582	838.76	48.82	
68.1	4	0.0273	1813.98	49.52	
100	4	0.003	3918.72	11.76	
147	4	0.0103	8475.25	87.30	



Ref No: Site: Elevation:	Lofanqa 2		Date: Coordinates: Bearings:	23/2/99	
AB/2 (m)	MN/2 (m)	Resistance (ohm)	k	Apparent Resistivity (ohm*m)	Apparent Resistivity (ohm*m)
1	0.4	9.28	3.30	30.60	
1.47	0.4	3.72	7.85	29.22	
2.15	0.4	1.587	17.52	27.80	
3.16	0.4	0.698	38.57	26.92	
4.64	0.4	0.304	83.88	25.50	
6.81	0.4	0.119	181.40	21.59	
4.64	2	1.915	13.76		26.35
6.81	2	0.672	33.27		22.35
10	2	0.234	75.36		17.63
14.7	2	0.0896	166.49		14.92
21.5	2	0.0427	359.73		15.36
31.6	2	0.0181	780.73		14.13
46.4	2	0.0242	1686.93		40.82
31.6	4	0.0396	385.65	15.27	
46.4	4	0.0186	838.76	15.60	
68.1	4	0.0084	1813.98	15.24	
100	4	0.011	3918.72	43.11	
147	4		8475.25		



### Appendix 3: Electromagnetic field data

This appendix provides full details of the electromagnetic measurements made on Lifuka, O'ua and Lofanga. Though measurements were made using both the vertical and horizontal dipoles only the horizontal dipole values have been included in the main body of the report.

Lifuka Hihifo	Dir 220 degrees				19/02/1999	
Spacing Point (m)	10 m		20 m		40 m	
	horizontal (mS/m)	vertical (mS/m)	horizontal (mS/m)	vertical (mS/m)	horizontal (mS/m)	Vertical (mS/m)
0	30	36	60	66	111	72
10	30	36	66	66	111	56
20	36	42	66	66	117	66
30	36	42	66	63	120	66
40	36	42	66	69	120	72
50	30	42	66	69	120	66
60	30	42	66	66	120	60
70	30	42	66	66	123	48
80	30	42	72	72	120	72
90	30	42	69	72	120	66
100	30	42	69	72		
110	36	42				

Lifuka Pangai	Dir 110 degrees				19/02/1999	
Spacing Point (m)	10 m		20 m		40 m	
	horizontal (mS/m)	vertical (mS/m)	horizontal (mS/m)	vertical (mS/m)	Horizontal (mS/m)	vertical (mS/m)
0	90	78	132	66	156	30
10	84	78	126	66	150	24
20	84	78	117	60	138	30
30	78	72	102	60	132	42
40	66	72	96	75	129	60
50	54	66	84	75	126	69
60	54	60	84	60	120	66
70	48	60	78	60	114	66
80	42	54	72	66	114	60
90	42	48	66	66	114	60
100	36	48	66	63	108	60
110	30	42	60	72	108	72
120	30	42	60	78	108	69
130	27	42	60	54	108	75
140	27	24	60	60		

O'ua	Dir 15 degrees 20 m past the gate				22/02/99	
Spacing Point (m)	10 m		20 m		40 m	
	horizontal (mS/m)	vertical (mS/m)	horizontal (mS/m)	vertical (mS/m)	horizontal (mS/m)	vertical (mS/m)
0	60	33	42	18	66	66
10	60	24	42	18	69	57
20	60	33	48	24	71	57
30	63	27	48	18	72	60
40	72	30	54	18	72	51
50	72	36	54	18	72	51
60	72	36	48	18	74	54
70	72	36	54	24	75	57
80	72	36	54	36	75	57
90	66	30	54	30	78	63
100	66	36	54	24	78	62
110	72	42	60	30	78	60
120	78	42	60	30	78	54
130	75	51	60	24	78	54
140	78	48	60	30	78	60
150	78	51	60	30	78	57
160	72	42	57	27	78	54
170	75	48	54	24	75	54
180	72	36	48	30	75	54
190	68	39	48	36	75	59
200	66	41	45	24	74	60
210	65	24	48	27	72	66
220	60	39	48	24	72	66
230	60	33	60	30	77	60
240	66	36	54	24	78	60
250	72	42	60	24	78	60
260	75	54	60	30	83	60
270	78	36	66	27	84	42
280	84	48	60	36	90	60
290	78	45	63	39	90	60
300	78	54	63	39	96	60
310	78	48	60	33	96	51
320	75	54			96	78
330					96	53
340					99	66

Lofanga	Dir 20 degrees 80 m after the fence				23/02/99	
Spacing	10 m		20 m		40 m	
Point (m)	horizontal (mS/m)	vertical (mS/m)	horizontal (mS/m)	vertical (mS/m)	horizontal (mS/m)	vertical (mS/m)
0	77	59	117	48	153	48
10	72	60	105	60	144	54
20	72	60	96	66	129	51
30	66	60	87	51	126	69
40	60	57	81	60	126	60
50	60	60	78	60	114	78
60	59	54	78	60	114	72
70	57	48	72	54	111	66
80	54	57	72	66	108	66
90	54	48	72	54	108	60
100	54	51	72	60	111	69
110	54	54	72	66	111	66
120	59	54	78	60	114	60
130	63	57	84	57	117	66
140	66	60	90	60	120	56
150	68	57	93	54	126	54
160	69	56	93	63	126	60
170	69	59	93	60	126	63
180	66	57	93	54	125	51
190	63	59	90	66	129	48
200	63	60	90	60	129	57
210	60	51	90	54	128	57
220	63	59	87	57	129	57
230	63	57	84	69	126	54
240	66	54	84	60	120	51
250	63	63	87	54	119	45
260	66	59	90	54	119	57
270	69	60			119	54
280					120	60
290					126	59

**Appendix 4: Salinity profile data  
(Provided by Tonga Water Board)**

<b>Borehole:</b> LIF1 <b>Location:</b> East side of Hihifo rugby field <b>Type:</b> Nylon tubes (for pumping with electric Flojet pump) <b>Operator(s):</b> Montiveti & Sione Hala								
Date	Time of day	Tube No.	Tube Depth (m)	Conductivity readings			Temp (deg C)	Depth to water table (m)
				1 (uS/cm)	2 (uS/cm)	3 (uS/cm)		
11/01/99	14:52	PVC	4.1	929	904	771	30.7	3.2
	15:02	1	4.5	977	922	798	28.3	
	15:07	2	6.5	1.087	962	836	27.3	
	15:15	3	8.5	1.289	1.016	844	26.9	
	15:20	4	10.5	2.525	1.887	1.625	26.3	
	15:25	5	12.5	8.330	8.680	7.378	26.3	
	15:32	6	14.7	32.400	34.100	28.305	26.4	
	15:44	7	18.0	42.300	43.300	36.890	27.2	

\*\*\*3rd readings are reduced by 15% due to calibration error. all readings should be reduced

<b>Borehole:</b> LIF2 <b>Location:</b> West side of Hihifo rugby field <b>Type:</b> Nylon tubes (for pumping with electric Flojet pump) <b>Operator(s):</b> Sione Hala, Sione Fotu								
Date	Time of day	Tube No.	Tube Depth (m)	Conductivity readings			Temp (deg C)	Depth to water table (m)
				1 (uS/cm)	2 (uS/cm)	3 (uS/cm)		
12/01/99	10:53	PVC	3.0	1.790	1.785	1.637	28.5	2.1
12/01/99	10:59	1	3.5	2.520	2.264	1.848	27.1	
12/01/99	11:08	2	5.5	9.070	9.110	7.760	27.4	
12/01/99	11:16	3	7.5	9.700	9.480	7.998	26.8	
12/01/99	11:22	4	9.5	14.900	15.800	12.852	26.7	
12/01/99	11:27	5	12.0	21.100	21.620	18.793	26.4	
12/01/99	11:31	6	15.6	39.700	40.800	35.275	26.2	

\*\*\*only the 3rd reading is reduced by 15%

<b>Borehole:</b> LIF3 <b>Location:</b> East side of Pangai rugby field <b>Type:</b> Nylon tubes (for pumping with electric Flojet pump) <b>Operator(s):</b> Sione Fotu, Sione Hala								
Date	Time of day	Tube No.	Tube Depth (m)	Conductivity readings			Temp (deg C)	Depth to water table (m)
				1 (uS/cm)	2 (uS/cm)	3 (uS/cm)		
12/01/99	11:56	PVC	4.0	578	889	723	32.6	3.6
	12:11	1	4.5	1.889	1.608	1.284	27.0	
	12:05	2	6.5	3.620	3.650	2.992	27.7	
	15:45	3	8.5	6.980	7.670	6.647	28.8	
	15:52	4	10.5	12.970	17.460	16.949	27.7	
	15:56	5	12.2	16.560	23.390	20.000	28.8	
	15:59	6	14.2	26.270	30.700	26.690	26.3	

\*\*3rd reading was reduced by 15%

<b>Borehole:</b>		<b>LIF4</b>						
Location:		West side of Pangai rugby field						
Type:		Nylon tubes (for pumping with electric Flojet pump)						
Operator(s):		Montiveti & Sione Hala						
Date	Time of day	Tube No.	Tube Depth (m)	Conductivity readings			Temp (deg C)	Depth to water table (m)
				1 (uS/cm)	2 (uS/cm)	3 (uS/cm)		
12/01/99	16:12	PVC	2.5	3.270	3.180	3.187	29.3	2.2
13/01/09	09:42	1	3.5	10.880	10.400	8.823	27.1	
	09:48	2	4.5	12.100	12.420	10.650	26.5	
	09:53	3	5.5	12.640	12.640	10.786	26.2	
	09:59	4	6.5	12.890	12.830	11.135	25.8	
	10:05	5	8.0	15.310	15.700	13.515	22.7	

\*\*3rd readings are reduced by 15%

<b>Borehole:</b>		<b>LIF5</b>						
Location:		North side of Moa Rd, Hihifo, between Lotokolo Rd and Tu'akolo Rd						
Type:		PVC tubes with slots at base (for bailing or pumping by hand)						
Operator(s):		Montiveti & Sione Hala						
Date	Time of day	Tube No.	Tube Depth (m)	Conductivity readings			Temp (deg C)	Depth to water table (m)
				1 (uS/cm)	2 (uS/cm)	3 (uS/cm)		
11/01/99	09:48	1	4.5	593	586	507	28.2	3.9
	09:52	2	6.0	795	866	777	27.6	
	09:56	3	7.5	3.100	3.030	2.643	27.3	
	10:00	4	9.0	5.170	6.670	5.125	27.4	
	10:04	5	12.0	19.600	22.960	19.711	27.5	

\*\*3rd readings are reduced by 15%

<b>Borehole:</b>		<b>LIF6</b>						
Location:		North side of Moa Rd, Hihifo, between Holopeka Rd and Lotokolo Rd						
Type:		Nylon tubes (for pumping with electric Flojet pump)						
Operator(s):		Montiveti & Sione Hala						
Date	Time of day	Tube No.	Tube Depth (m)	Conductivity readings			Temp (deg C)	Depth to water table (m)
				1 (uS/cm)	2 (uS/cm)	3 (uS/cm)		
11/1/99	10:29	PVC	3.0	2.405	1.525	1.283	29.7	2.9
	10:30	1	4.0	1.607	1.973	1.286	27.2	
	11:12	2	5.5	3.230	3.240	2.856	28.4	
	11:19	3	7.0	3.620	3.630	3.102	28.2	
	11:24	4	8.5	6.820	6.850	5.933	27.7	
	11:46	5	11.0	14.640	14.460	12.359	27.7	
	11:36	6	13.3	30.300	31.600	27.285	28.1	

\*\*3rd readings were reduced by 15%

<b>Borehole:</b>		<b>LIF7</b>						
Location:		Koulo, west side of road just south of airstrip						
Type:		PVC tubes with slots at base (for bailing or pumping by hand )						
Operator(s):		Sione Hala & Sione Fotu						
Date	Time of day	Tube No.	Tube Depth (m)	Conductivity readings			Temp (deg C)	Depth to Water table (m)
				1 (uS/cm)	2 (uS/cm)	3 (uS/cm)		
13/01/99	11:27	1	5.0	8.300	9.500	7.905	31.6	5.2
	11:32	2	6.0	10.200	11.400	9.775	26.6	
	11:37	3	7.0	15.600	15.400	13.260	25.4	
	11:42	4	9.0	23.100	23.200	20.655	26.0	

**\*\*3rd readings was reduced by 15%**

Depth to water table is deeper than tube depth as from the data; need check this

<b>Borehole:</b>		<b>LIF8</b>						
Location:		North side of Hihifo rugby field						
Type:		Nylon tubes (for pumping with electric Flojet pump)						
Operator(s):		Sione Hala & Sione Fotu						
Date	Time of day	Tube No.	Tube Depth (m)	Conductivity readings			Temp (deg C)	Depth to water table (m)
				1 (uS/cm)	2 (uS/cm)	3 (uS/cm)		
11/01/99	16:00	PVC	3.0	-	-	-	-	2.54
	16:05	1	4.0	2.311	1.926	1.559	26.7	
	16:10	2	5.0	1.454	1.362	1.138	26.9	
	16:15	3	6.0	1.679	1.682	1.424	26.6	
	16:24	4	8.0	2.586	2.581	2.197	27.1	

**\*\*3rd readings was reduced by 15%**

<b>Borehole:</b>		<b>LIF9</b>						
Location:		South side of Hihifo rugby field						
Type:		PVC (numbers 1, 2 & 3) and nylon tubes (numbers 4 & 5)						
Operator(s):		Monitiveti & Sione Hala						
Date	Time of day	Tube No.	Tube Depth (m)	Conductivity readings			Temp (deg C)	Depth to water table (m)
				1 (uS/cm)	2 (uS/cm)	3 (uS/cm)		
11/01/99	14:22	1	2.8	1.365	1.332	1.114	30.1	2.6
	14:25	2	5.0	1.378	1.615	1.376	28.8	
	14:29	3	6.0	1.722	1.738	1.496	27.5	
		4	7.0	blocked				
		5	8.0	blocked				

**\*\*3rd readings are reduced by 15%**