GEOPHYSICAL SURVEY
GROUND WATER EVALUATION
ULUPALAKUA RANCH
ISLAND OF MAUI, HAWAII

Prepared For:

Ulupalakua Ranch
Maui, Hawaii 96790

Prepared By:

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(Our Job #90028)

Table of Contents

1.0 INTRODUCTION

This report contains the results of a geophysical survey for ground water resource evaluation on Ulupalakua Ranch Property on the Island of Maui. The work was performed by Blackhawk Geosciences, Inc. (BGI) for Ulupalakua Ranch during May 24 to May 29, 1990.

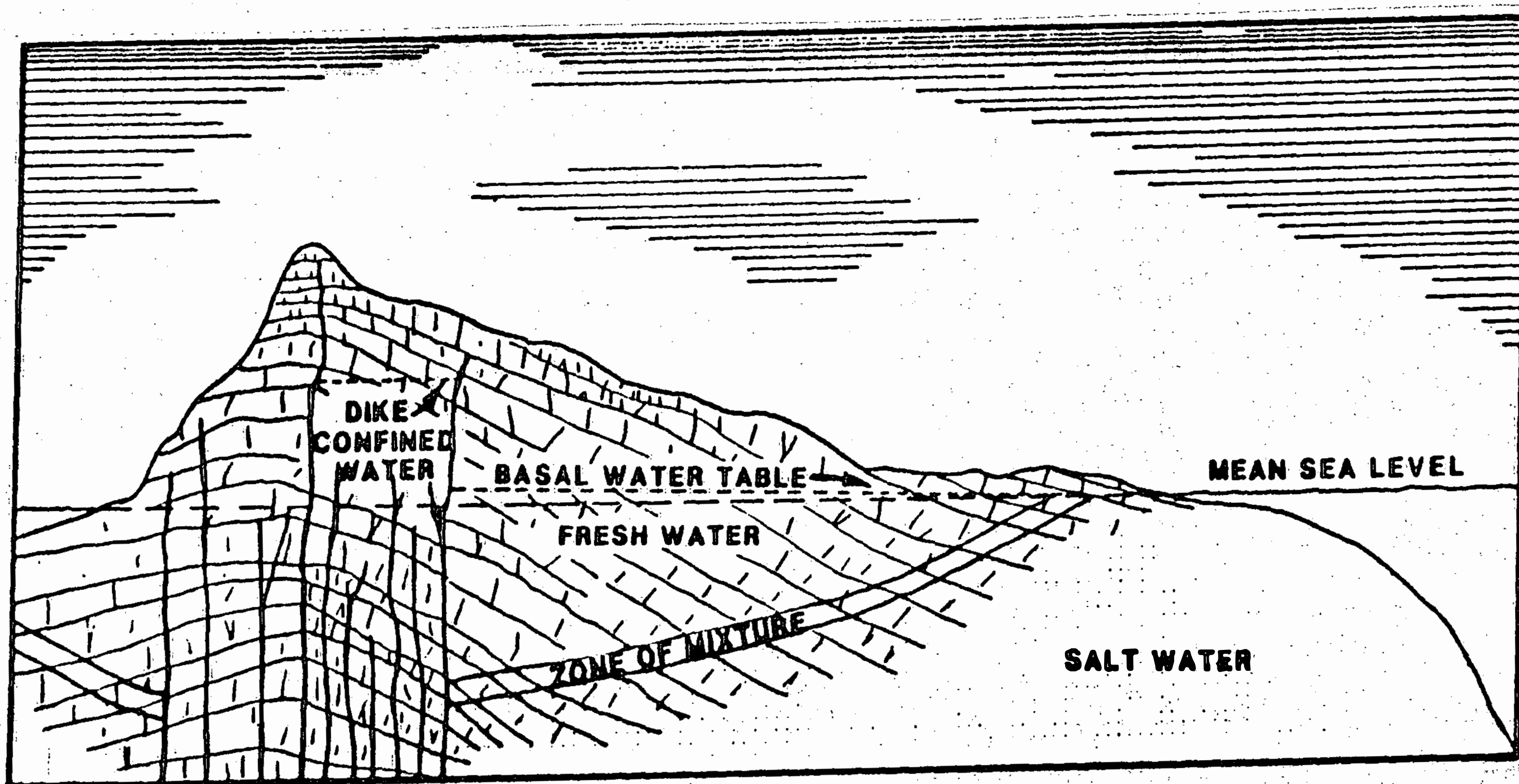
The general objective of the geophysical survey at the Ulupalakua Ranch property was to assist in characterizing the hydrologic regime in the study area. The main objectives for geophysical surveys for ground water evaluations on volcanic islands are illustrated in Figure 1-1. The volcanic rocks are generally highly permeable and this allows rainwater to percolate with little impedance directly downward through the island mass. The fresh water in these island settings is generally found in two environments:

1. Dike-confined waters. Typically, above the rift zone, intrusive dikes originating from a magma source below can form ground water dams, and behind these natural dams significant quantities of ground water can be stored.

2. Basal fresh water. The high permeability of the volcanic rocks allows sea water to enter freely under the island, and a delicate balance is reached where a lens of fresh water floats on sea water. In cases of hydrostatic equilibrium, the Ghyben-Herzberg relation states that for every foot of fresh water head above sea level there will be about 40 ft of fresh water below sea level.

At Ulupalakua Ranch, ground water was expected to occur mainly as basal fresh water. The impetus for using geophysics is that the cost of a geophysical sounding is about one-thousandth the cost of completing a well at elevation above 1,000 ft. Geophysical surveys, combined with other hydrogeologic information, are used to provide optimum locations for well placement and well completion depths.

The geophysical method employed was time domain electromagnetic (TDEM) soundings. This method was selected because it has proven effective in prior surveys in similar settings in Hawaii.



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SCHEMATIC HYDRO-GEOLOGIC CROSS SECTION

ULUPALAKUA RANCH, MAUI, HI

PROJECT NO.: 90028 **FIGURE 1-1**

2.0 LOGISTICS AND DATA ACQUISITION

A brief description of the fundamentals of TDEM are given in Appendix A. Briefly, the logistics of a TDEM measurement consists of:

1. Laying out a square loop of insulated wire. A generator placed in the loop is used to drive current pulses through this closed loop. The dimensions of the square loops employed depend on the exploration depth requirements. The dimensions of the loops used for Ulupalakua Ranch were 1,000 ft by 1,000 ft on each side for 9 loops at higher elevation and 500 ft by 500 ft for 8 loops at lower elevation near the Makena Golf Course.

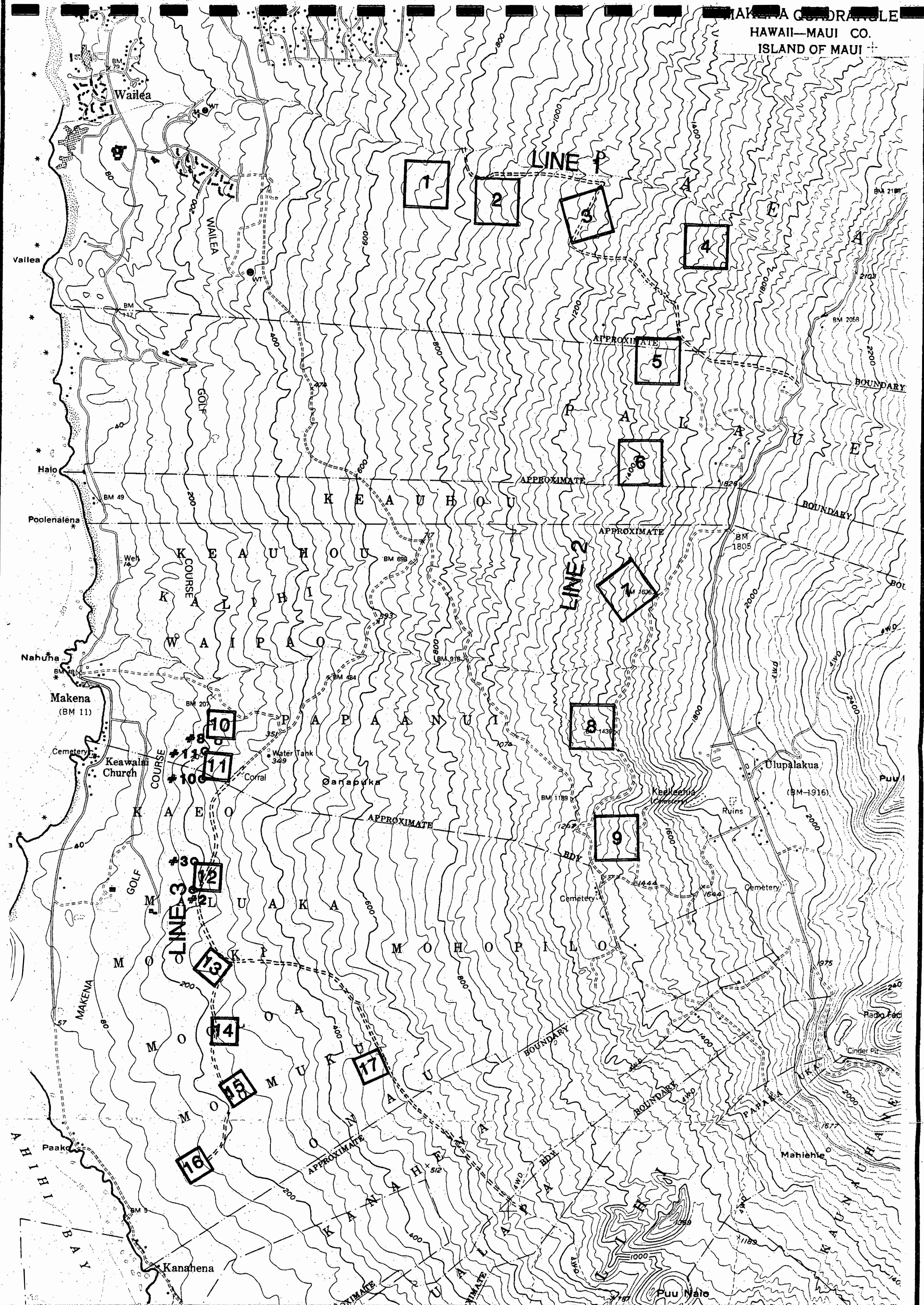
2. Making a measurement with a receiver in the center of the loop. The data acquired at each station was stored in the field on a solid state data logger and subsequently dumped to a computer at the end of each field day. The data acquired at each station usually consisted of measurements at several receiver gain settings and transmitter frequencies in order to assure data quality and to obtain data over the largest time range possible. Data quality was generally very good.

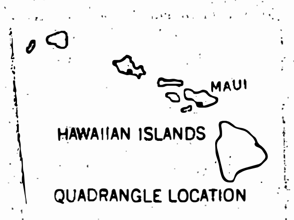
During the six days of field work, 17 soundings were completed. A daily log of field activity is given in Table 2-1. The location of the soundings for Ulupalakua Ranch are shown in Figure 2-1.

The elevation of sounding centers were measured using a Lietz Air Barometer/Altimeter, Model AIR-HB-1L. The Ulupalakua benchmark (elev. 1916 ft) was used for calibration of the altimeter for measurements of soundings at higher elevations, while the Makena benchmark (elev. 11 ft) was used for soundings at lower elevations. The repeatability of the benchmark readings varied from approximately ± 20 ft. throughout an average day.

Table 2-1. Daily log of field activity

Date (1990)	Activity
May 21	BGI personnel mobilize from Golden, CO to Honolulu, HI in conjunction with other surveys.
May 23	Meet with Ulupalakua Ranch personnel and pick up EM-37 equipment from storage at ranch.
May 24	Check survey areas with C. Pardee Erdman. Data taken on soundings 1 and 2.
May 25	Data taken on soundings 3, 4 and 5.
May 26	Data taken on soundings 6, 7 and 8.
May 27	Data taken on soundings 9, 10 and 11.
May 28	Data taken on soundings 12, 13 and 14.
May 29	Data taken on soundings 15, 16 and 17.
May 30	Demobilize to other Hawaii geophysical surveys.





[1] Transmitter Loop Locations

+1o Well Locations

2000 0 2000
SCALE FEET

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TDEM SOUNDING LOCATION MAP

ULUPALAKUA RANCH, MAUI, HI

PROJECT NO.: 90028 **FIGURE 2-1**

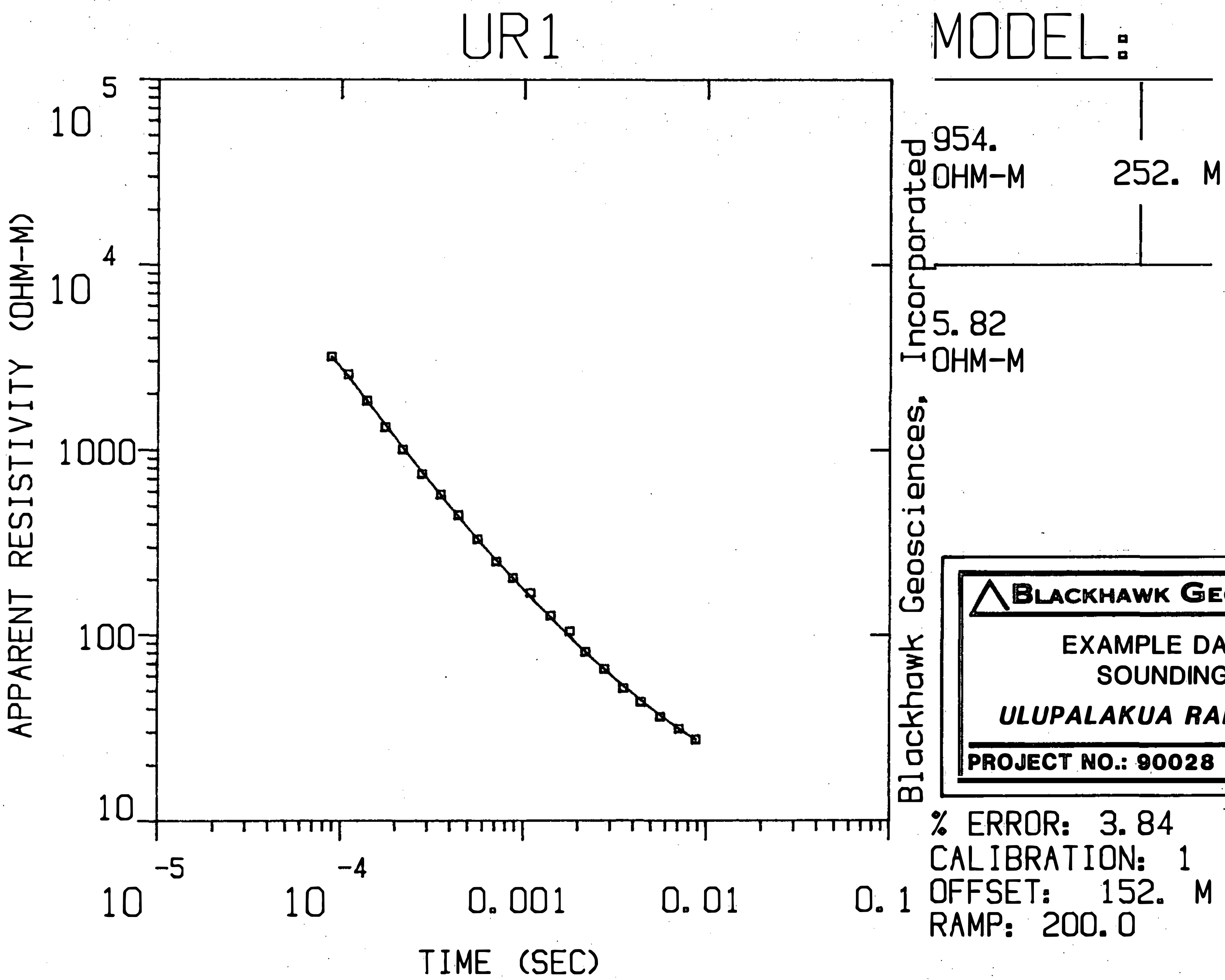
3.0 DATA PROCESSING

The field data acquired each day was transferred from the DAS-54 data logger to a microcomputer. The data for each sounding location is edited and combined (both 3 Hz and 30 Hz frequencies) to produce a transient decay curve. This decay curve is transformed into an apparent resistivity curve, which is entered into an Automatic Ridge Regression Transient Inversion Program. From the apparent resistivity curve a one-dimensional model of resistivities and thicknesses is calculated.

The inversion program requires an initial estimate of the geoelectric section, including the number of layers, and the resistivities and thicknesses of each of the layers. The program then adjusts these parameters so that the model curve converges to best fit the curve formed by the field data set. The inversion program does not change the total number of layers within the model, but allows all other parameters to float freely.

An example data set is given in Figures 3-1 and 3-2 for sounding UR1. Figure 3-1 shows the measured data points (in terms of apparent resistivity) superimposed on a solid line. The solid line represents the computed behavior of the true resistivity layering shown on the right. Figure 3-2 lists in column 4 the error between measured and computed data in each time gate.

The apparent resistivity curves and data sheets for all soundings are contained in the attachment.



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EXAMPLE DATA SET
SOUNDING UR1

ULUPALAKUA RANCH, MAUI, HI

PROJECT NO.: 90028 **FIGURE 3-1**

UR1

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		222.5	730.0		
953.73	252.3	-29.8	-97.7	0.3	0.3
5.82					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	3.17E+03	3.16E+03	0.127	
2	1.10E-04	2.54E+03	2.48E+03	2.499	
3	1.40E-04	1.83E+03	1.83E+03	-0.137	
4	1.77E-04	1.32E+03	1.36E+03	-3.116	
5	2.20E-04	1.01E+03	1.04E+03	-2.906	
6	2.80E-04	7.46E+02	7.69E+02	-2.999	
7	3.55E-04	5.79E+02	5.76E+02	0.506	
8	4.43E-04	4.48E+02	4.43E+02	1.195	
9	5.64E-04	3.32E+02	3.34E+02	-0.640	
10	7.13E-04	2.51E+02	2.57E+02	-2.090	
11	8.81E-04	2.04E+02	2.04E+02	0.365	
12	1.10E-03	1.69E+02	1.61E+02	5.204	
13	1.41E-03	1.27E+02	1.24E+02	2.123	
14	1.80E-03	1.05E+02	9.81E+01	6.744	
15	2.20E-03	8.10E+01	8.10E+01	0.047	
16	2.80E-03	6.57E+01	6.53E+01	0.520	
17	3.55E-03	5.16E+01	5.32E+01	-3.035	
18	4.43E-03	4.36E+01	4.46E+01	-2.272	
19	5.64E-03	3.64E+01	3.72E+01	-1.975	
20	7.13E-03	3.14E+01	3.14E+01	0.003	
21	8.81E-03	2.76E+01	2.74E+01	0.370	

R: 152. X: 0. Y: 152. DL: 305. REQ: 169. CF: 1.0000
CLHZ ARRAY, 21 DATA POINTS. RAMP: 200.0 MICROSEC, DATA: UR1
ULUP RANCH
LINE 1
RMS LOG ERROR: 1.64E-02, ANTILOG YIELDS 3.8426 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	1.00		
P 2	0.00	1.00	
T 1	0.00	0.00	1.00
	P 1	P 2	T 1

BLACKHAWK GEOSCIENCES, INC.

EXAMPLE DATA SET
SOUNDING UR1

ULUPALAKUA RANCH, MAUI, HI

PROJECT NO.: 90028 **FIGURE 3-2**

4.0 INTERPRETATION RESULTS

4.1 GENERAL

The main objective of the geophysical survey is not to obtain the resistivity layering of the subsurface, but to infer from the resistivity layering information about the elevation and thickness of the fresh water resource. The translation of resistivity layering into meaningful hydrogeologic information is generally accomplished in two ways:

1. Using available knowledge about the relation between resistivity values and hydrogeology. For example, in the volcanic rocks of Hawaii, rocks saturated with salt water will generally have resistivities less than 5 ohm-m. On the other hand, dry and fresh water/brackish water saturated volcanic rocks and intrusives can have very high resistivities (greater than 1000 ohm-m).

2. Calibrating the geophysical interpretation at a well. In this case several wells were available for comparison above the Makena Golf Course. The approximate location of these wells are shown in Figure 2-1. The three wells (#8, #11 and #10), located at about the 210-260 ft elevation level, had measured static water levels (heads) of 1 ft above sea level, but proved to be less successful wells after pump tests. Wells #2 and #3, located at about the 200 ft elevation level, also had heads of 1 ft above sea level and proved to be successful wells.

Where a very conductive layer (less than 5 ohm-m) is detected below sea level in the TDEM interpretation, this layer is interpreted to be caused by salt water saturated volcanics. Static water levels (heads) can be calculated from these soundings by using the Ghyben-Herzberg relation. This relation however, assumes hydrostatic equilibrium and is not expected to apply to soundings in close proximity to major geologic structures (rifts, dikes, altered zones, etc.) which act to dam ground water flow.

4.2 GEOELECTRIC CROSS SECTIONS

The results of the interpretation of individual TDEM soundings is the resistivity layering as a function of depth. Where soundings are acquired relatively close together along a survey line, the results of the individual soundings can be plotted to form a geoelectric cross section. In the cross sections, layers with similar resistivities have been linked together. A total of three cross sections were constructed from the Ulupalakua Ranch data.

Line 1

The geoelectric cross section for line 1 is shown in Figure 4-1. In the west to east geoelectric section each sounding is interpreted to be a two layer sequence. The upper surface layer with resistivities of 876 to 1675 ohm-m is interpreted to represent unweathered volcanics. The portions of the layer which occur below sea level are expected to contain fresh or brackish water. The deeper layer in the section (3.1 to 11.6 ohm-m) is interpreted to represent salt water saturated volcanics. Generally, it is difficult to discriminate between dry volcanics grading into fresh water or brackish water saturated volcanics. The reason is, that in addition to salinity, changes in porosity and lithology also influence formation resistivity.

Line 2

The results of the TDEM interpretations for line 2 are shown as a south to north geoelectric cross section in Figure 4-2. Soundings were positioned at or about the 1,500 ft elevation level due to client request and available road access. In the cross section each sounding is interpreted as two-layer sequences as in line 1. The upper layer, which exhibits resistivities from 1399 to > 5000 ohm-m throughout the cross section is interpreted as a zone of unweathered volcanics. The lower layer in the section with resistivities of 2.8 to 4.8 ohm-m is interpreted to be salt water saturated volcanics. Beneath soundings 6, 7, 8 and 9 the salt water interface is detected at or close to sea level. In the geoelectric section soundings 4 and 5 (to the north) show more potential for a thicker zone of fresh or brackish water below sea level.

Line 3

The geoelectric cross section for line 3 is shown in Figure 4-3. In the geoelectric section a two-layer sequence is interpreted for each sounding. The near surface layer (107 to 737 ohm-m) is interpreted to represent unweathered volcanics. The portions of this layer which are below sea level are expected to contain fresh to brackish water saturated volcanics. The lower layer in the section (3.0 to 3.6 ohm-m) represents salt water saturated volcanics.

Soundings 10, 11 and 12 were positioned near existing producing and non-producing wells (Fig. 2-1) above the Makena Golf Course, for comparison to measured head levels. Soundings 10 and 11, located along the power line road and about 20 ft higher in elevation than the #8 and #11 non-producing wells, showed an approximate 52 and 40 ft, respectively, thickness of fresh/brackish water lens. If we can assume this water is at hydrostatic equilibrium, then the static water level (head) can be calculated using the Ghyben-Herzberg relation. This relation states that for every foot of fresh water head above sea level, there will be about 40 ft of fresh water below sea level. The calculated heads for soundings 10 and 11 would be approximately 1 ft. Sounding 12, located about 15 ft higher in elevation than producing wells #2 and #3, showed an approximate 19 ft of fresh/brackish water lens, which would calculate to about 0.5 ft head when using the Ghyben-Herzberg relation. These values are in good general agreement with the 1 ft heads measured from pump tests conducted during June 1989 on these wells.

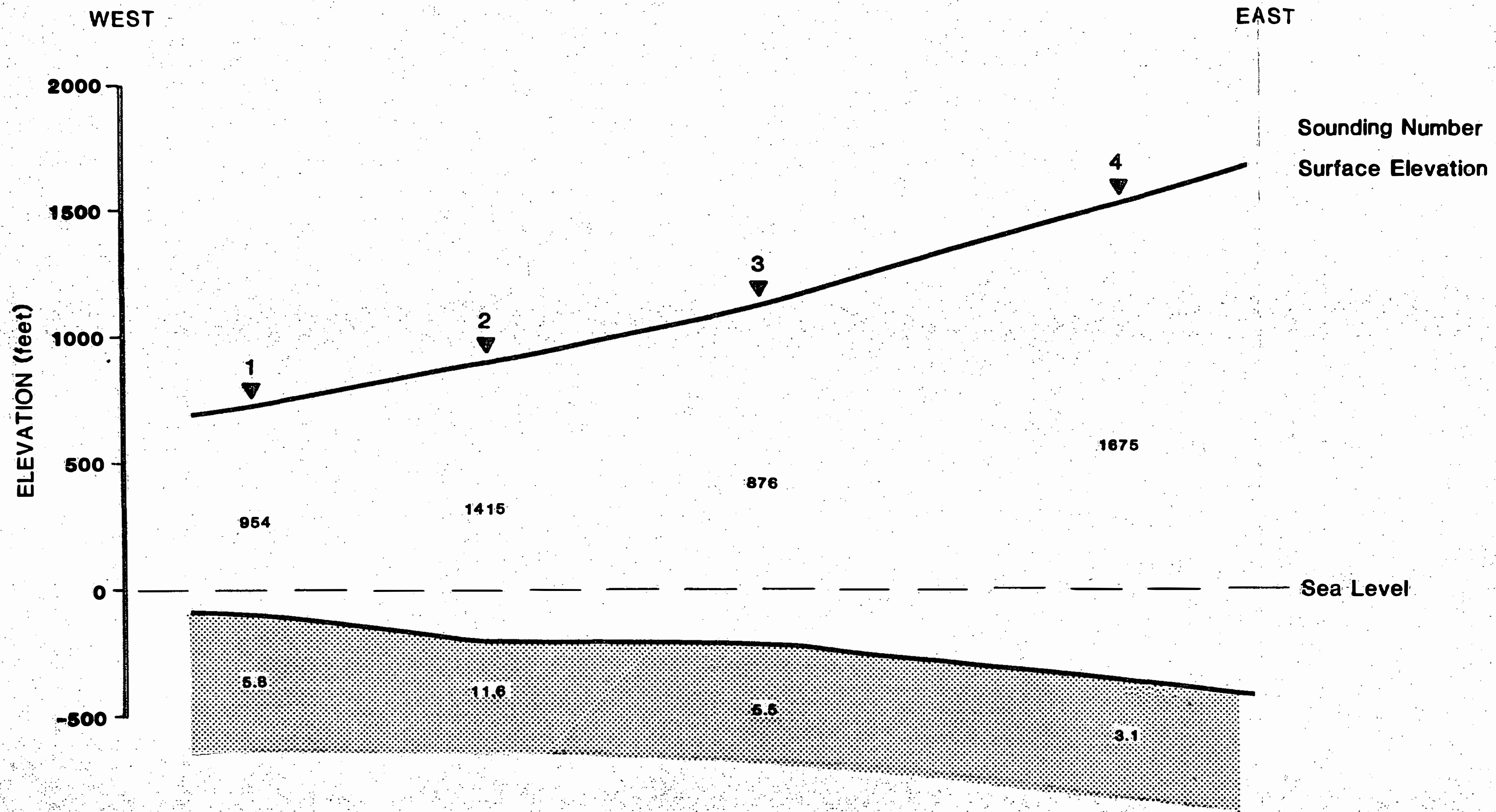
Using the Ghyben-Herzberg relation for the results of soundings 13, 14, 15 and 16 we calculate heads varying from near zero at sounding 14 to approximately 1 ft head at sounding 16.

4.3 HYDROGEOLOGIC INTERPRETATION

TDEM soundings in the survey area were able to detect salt water saturated volcanics below sea level. In the areas interpreted to be represented by basal water resources, the fresh water resource can be estimated by the volume between sea level and the interpreted elevation of salt water. Table 4-1 shows the thickness of the fresh/brackish water lens interpreted directly from the model results for each sounding.

Table 4-1. <u>Hydrogeologic information derived from TDEM soundings</u>

Sounding #	Surface Elevation (ft)	Approximate Thickness of Fresh/Brackish Water Lens (ft)
1	730	98
2	900	202
3	1115	223
4	1520	363
5	1520	134
6	1390	36
7	1475	85
8	1440	0
9	1430	57
10	220	52
11	275	40
12	215	19
13	280	25
14	270	6
15	255	44
16	190	53
17	535	38



LEGEND

5.5 Values in Ohm-m

Unweathered Volcanics

Salt Water Saturated Volcanics

HORIZONTAL EXAGGERATION 2 TO 1

0 1000 2000

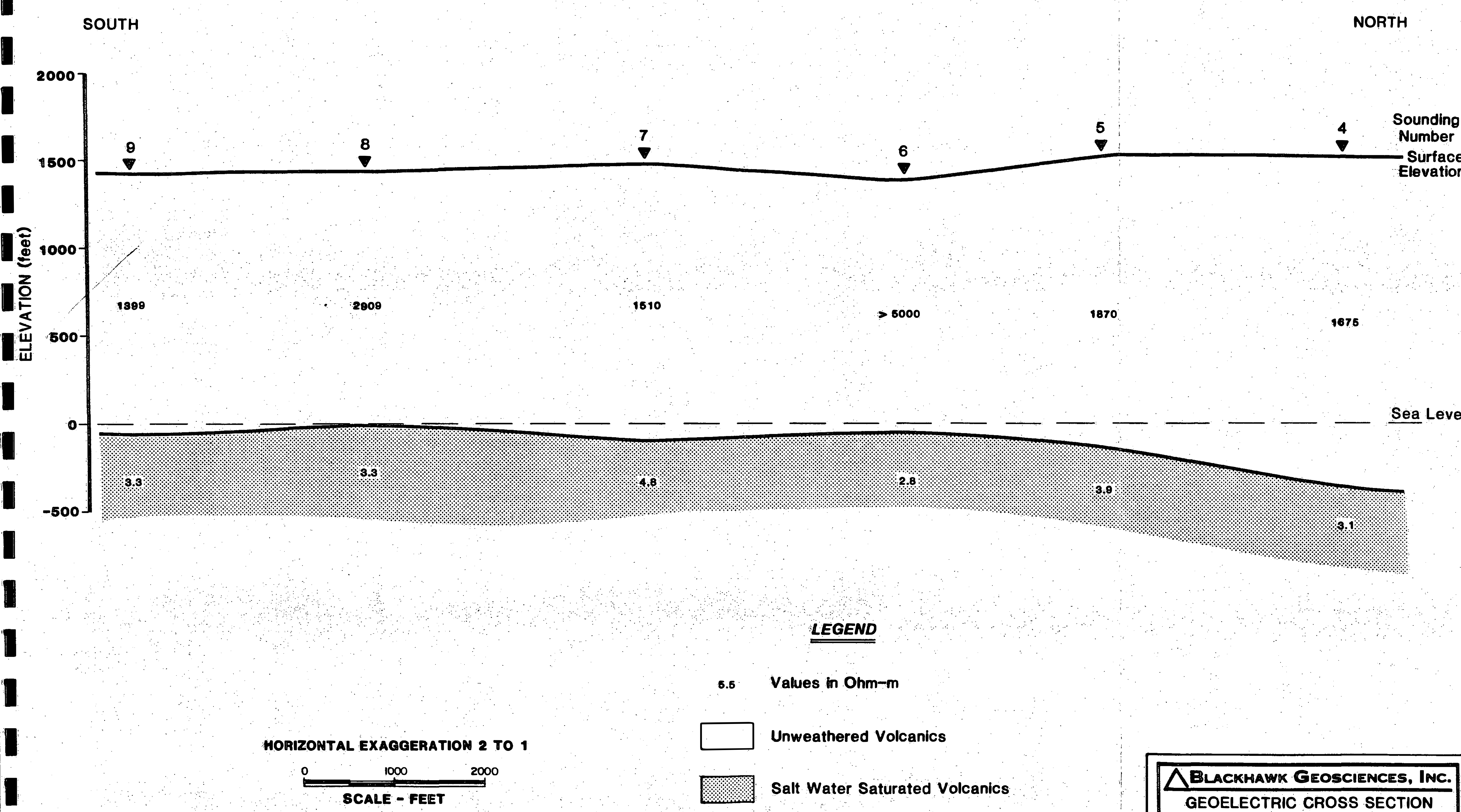
SCALE - FEET

BLACKHAWK GEOSCIENCES, INC.

GEOELECTRIC CROSS SECTION
TDEM RESULTS FOR LINE 1

ULUPALAKUA RANCH, MAUI, HI

PROJECT NO.: 90028 **FIGURE 4-1**



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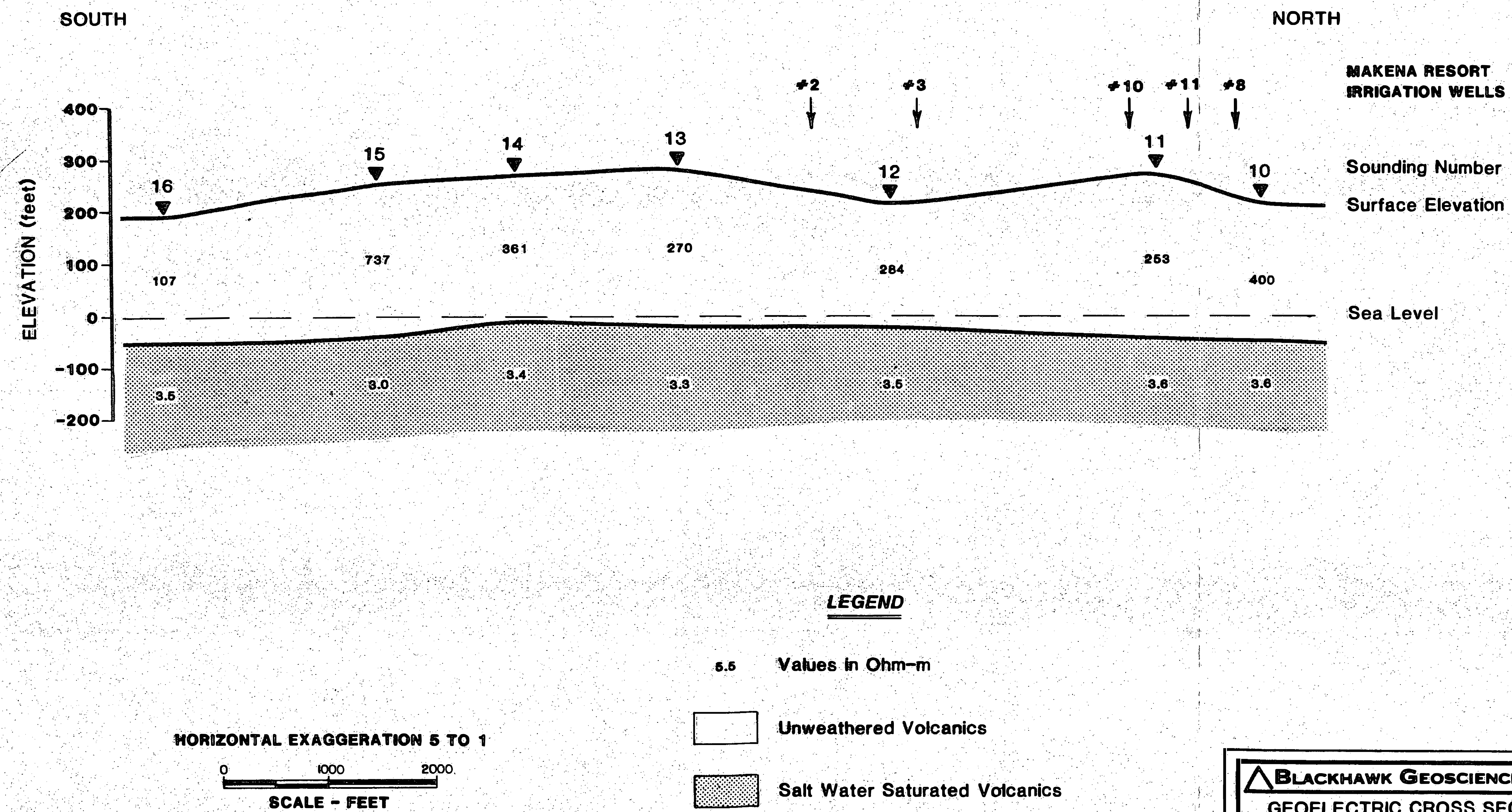
GEOELECTRIC CROSS SECTION
TDEM RESULTS FOR LINE 2

ULUPALAKUA RANCH, MAUI, HI

PROJECT NO.: 90028 FIGURE 4-2



BLACKHAWK GEOSCIENCES, INC.

GEOELECTRIC CROSS SECTION
TDEM RESULTS FOR LINE 3

ULUPALAKUA RANCH, MAUI, HI

PROJECT NO.: 90028 FIGURE 4-3

5.0 CONCLUSIONS AND RECOMMENDATIONS

The results of the TDEM survey for Ulupalakua Ranch indicate that in the areas covered at higher elevation (lines 1 and 2) the potential for the thickest lens of fresh/brackish water occurs towards the northeast direction of these two lines, beneath sounding 4. At this sounding the thickness of the fresh/brackish basal water lens is expected to be approximately 360 ft.

The geoelectric cross section for line 2 (Fig. 4-2) shows that beneath soundings 6, 7, 8 and 9 a very thin basal water lens was detected. This rapid decrease in basal lens thickness, from sounding 4, may be the result of lava flows associated with the nearby rift zone, which may have affected the porosity of the ground water regime in this area of the ranch. The application of the Ghyben-Herzberg relation in this area is expected to be marginal.

In the Makena Golf Course area (Fig. 4-3) soundings 10, 11 and 12 of line 3, taken near existing producing and non-producing wells, show good comparisons of calculated (using Ghyben-Herzberg relation) static head levels of approximately 1 ft to measured 1 ft heads in wells #2 and #3.

Pump tests conducted on the Makena irrigation wells during June 1989 proved wells #8, #10, and #11 to be less successful (in maintaining water level, chloride ions, and pumping rate) than wells #2 and #3. This is probably due to the type of lava the wells were completed in. Wells #2 and #3 were probably completed in a relatively permeable lava flow with some lateral continuity, which allowed for more basal water flow during pump tests. TDEM soundings generally cannot detect minor permeability changes in lava flows, but when combined with other hydrogeologic information, are useful in determining optimum locations for well placement and well completion depths. Soundings 13 through 17 on line 3, taken at about the 200 ft elevation level, show potential for some basal lens water to exist.

To help confirm the existence of geologic structures, additional soundings on lines parallel and perpendicular to the expected structures are recommended.

PRINCIPLES OF
TIME DOMAIN EM

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Question.-- What is TDEM?

Answer.-- TDEM is a surface geophysical method for determining the lateral and vertical resistivity variation (geoelectric section) in the subsurface.

Question.-- What useful information can be derived from the geoelectric section?

Answer.-- Electrical resistivity can be used as an indicator for mapping several important objectives in the subsurface, such as:

1. Presence of contaminants. Dissolved solids in ground water decrease formation resistivities, so that industrial contaminant plumes and differences in salinity (e.g., salt water intrusion) can often be delineated from geoelectric sections.

2. Soil and rock types. Clays and clay shales, and formations of low hydraulic permeability, have lower resistivities than formations of high hydraulic permeability, such as sands and gravels, sandstones, basalts, and high porosity limestones. The geoelectric section can, therefore, be used to map continuity of clay and clay shale lenses.

3. Fractures and shear zones. Such zones are conduits for ground water flow and contaminant migration, and they are often characterized by zones of low resistivity. The reasons for the lower resistivities of these zones are infilling of the fracture zones by clay gouge, alteration of wall rock, and higher water contents.

Question.-- What advantages does TDEM have over other electrical and electromagnetic methods, such as resistivity (direct current) and electromagnetic conductivity profiling with the Geonics EM-31 and EM-34?

Answer.-- The advantages of TDEM over other electrical and electromagnetic methods are

- better vertical and lateral resolution
- lower sensitivity to geologic noise (see page 5)
- the ability to explore below highly conductive layers (e.g., brine saturated layers and clay lenses).

Some of the most frequently asked questions about TDEM and their answers are given below.

Question.-- Are the principles of TDEM similar to electromagnetic induction profiling, such as used in the Geonics EM-31 and EM-34?

Answer.-- Yes, the principles of electromagnetic induction profiling in the frequency domain (FDEM), used in the Geonics EM-31 and EM-34, are in many ways similar to the principles of TDEM.

An important difference between FDEM and TDEM is the current waveform driven through the transmitter loops. It is a continuous, harmonic-varying current in FDEM, and a half-duty cycle waveform in TDEM.

Question.-- Why does the current waveform of the transmitter make a large difference?

Answer.-- The large difference results from the fact that in FDEM the secondary magnetic field due to ground currents is measured when the transmitter current is on, and in TDEM when the transmitter current is off. In both cases the time-variant current driven through the transmitter causes a time-variant primary magnetic field. Associated with this primary magnetic field is an induced electromotive force (emf) that causes eddy current flow in the subsurface. The intensity of these currents is used to determine subsurface conductivities. The induced emf is a harmonic-varying function in FDEM and consists of narrow pulses in TDEM.

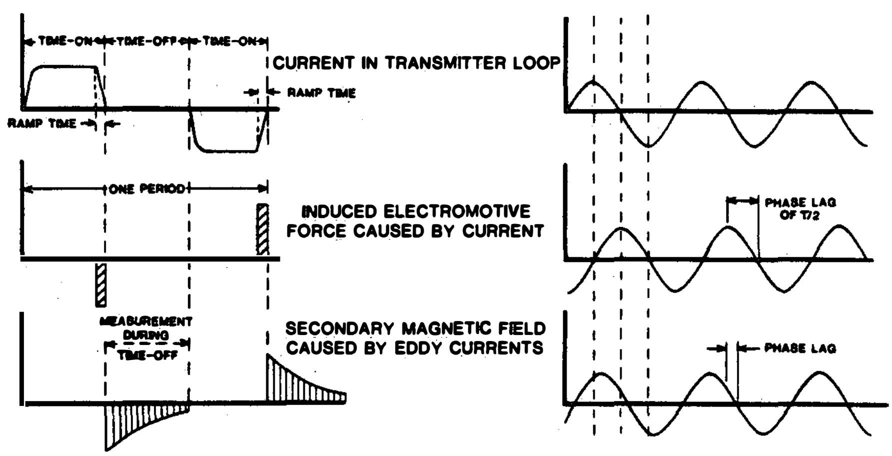

Fig. 1. System waveforms in time domain EM (TDEM) and frequency domain EM (FDEM).

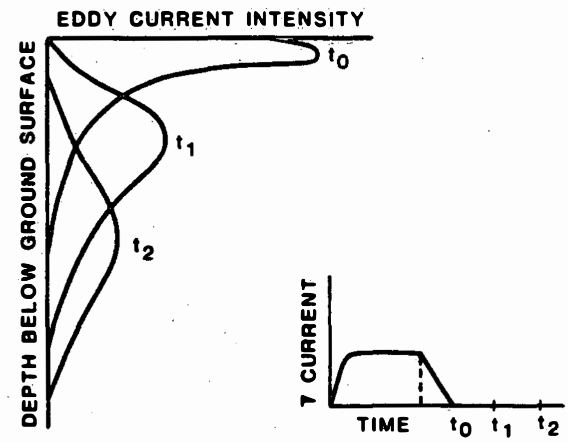

Fig. 4. Schematic illustration of eddy current distribution at different times after turn-off.

Another useful presentation of distribution of current intensity as a function of time is given in Figure 4. At early time, t_0, all currents are concentrated near the surface. At later times (e.g., t_3) the current maxima occur at increasingly greater depth. Thus, from measurements of the decay of emf at one location, the geoelectric section to a substantial depth is obtained.

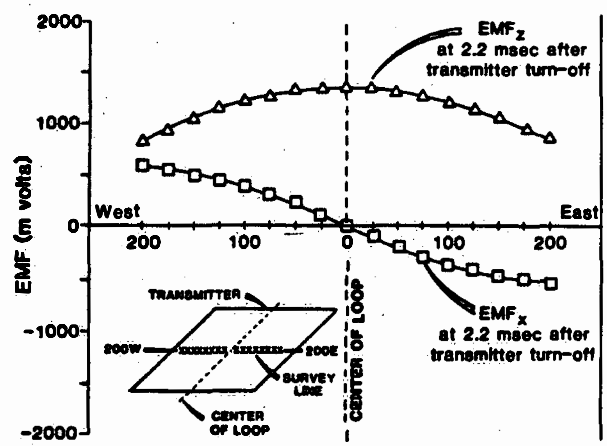

Fig. 5. Spatial behavior of emfs due to vertical (emf_z) and horizontal (emf_x) magnetic field on a profile through the center of square transmitter loop at one time (2.2 millisec) after turn-off.

The emfs caused by square transmitter loops vary with time and distance from the center. Figure 5 shows a typical measured behavior of emfs at a certain time (2.2 milliseconds) after turn-off. At other times the amplitudes will be different, but the spatial behavior is similar. The spatial behavior of the emf_z is relatively flat about the center so that measurements of emf, due to the vertical magnetic field, are relatively insensitive to errors in surveying the center of the loop, or to deviations from a square loop. This is clearly of practical value because it (1. reduces the cost of land surveys and measurement errors, and (2) allows for some flexibility in the field in positioning the measurement stations.

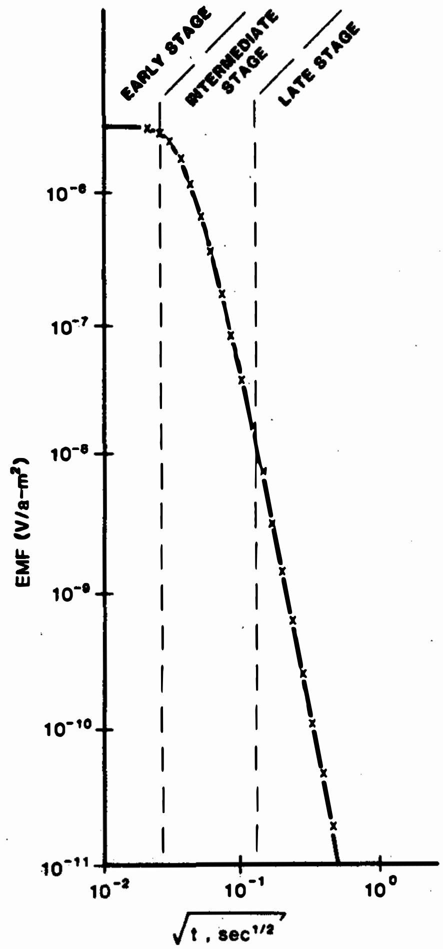

Fig. 6. Typical transient behavior of emf_z in center of square transmitter loop.

Thus, in TDEM soundings, the geoelectric section is derived from measurement of the emf due to the vertical magnetic field (emf_z) as a function of time during the period the transmitter is off. Figure 6 shows a typical behavior of emf_z as a function of time. Emf_z can be seen to decay rapidly with increasing time. One transient decay recorded over a few tens of milliseconds contains information about resistivity layering over a significant depth range.

The emfs, due to the decay of the ground eddy currents, must be measured in the presence of ambient noise sources, such as geomagnetic storms, lightning, 60 hertz powerlines, and other man-made sources. It is common to stack several hundred transient decays to improve signal to noise. Stacking of several hundred transient decays requires only a few seconds, and multiple data sets can be quickly obtained.

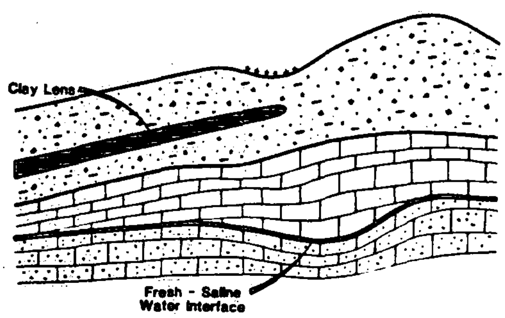

Fig. 9. Schematic geologic section of Floridan aquifer.

Question.-- How does TDEM reduce geologic noise?

Answer.-- This fact can be conceptually explained from Figure 10 where the intensity of eddy current distribution is schematically illustrated as a function of time for the FDEM and TDEM method. At early time (t_0) in TDEM all currents are concentrated near the surface, and near surface formations will largely determine the emf measured. At later time, for example, t_3, currents have largely decayed in near surface layers, and currents dominantly flow at greater depth. The emf measured at time t_3 is near transparent to near surface layers, so that their influence is greatly reduced at time t_3 and later times.

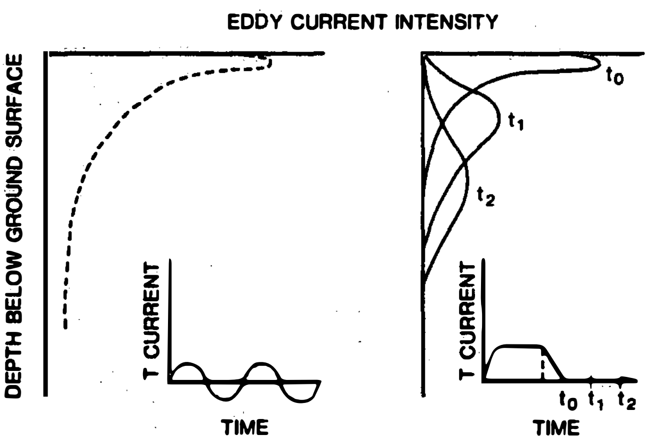

Fig. 10. Eddy current intensity in FDEM and TDEM.

In the FDEM method current intensity is always highest near the surface amplifying the influence of near surface layers.

In summary, geologic noise due to lateral and vertical resistivity variation in TDEM is reduced because:

(a) Exploration depth is mainly a function of time rather than transmitter-receiver separation. The transmitter-receiver separation need not be altered to change exploration depth as is the case in FDEM (EM-31 and EM-34), and direct current resistivity methods.

(b) Relatively small transmitter-receiver separations compared to effective exploration depth are employed.

(c) Measurements at later times are nearly transparent to near surface layers, because eddy currents at later times dominantly flow at greater depth.

Question.-- Can TDEM surveys be effective in mapping fractures and shear zones?

Answer.-- Yes, TDEM can detect contacts, fractures, and shear zones below considerable overburden thickness. The physical concepts of fracture and shear zone mapping are briefly explained.

Electrical and electromagnetic methods are often effective in mapping fractures and shear zones, because fractures and shear zones often are zones of low resistivity in more resistive host rocks. These lower resistivities are generally caused by clay gouge, higher water contents, and alteration in wall rocks. The mapping of fractures and shear zones becomes increasingly more difficult with increasing overburden thickness where outcrops are limited. It is in these situations that geophysical surveys can play an important role.

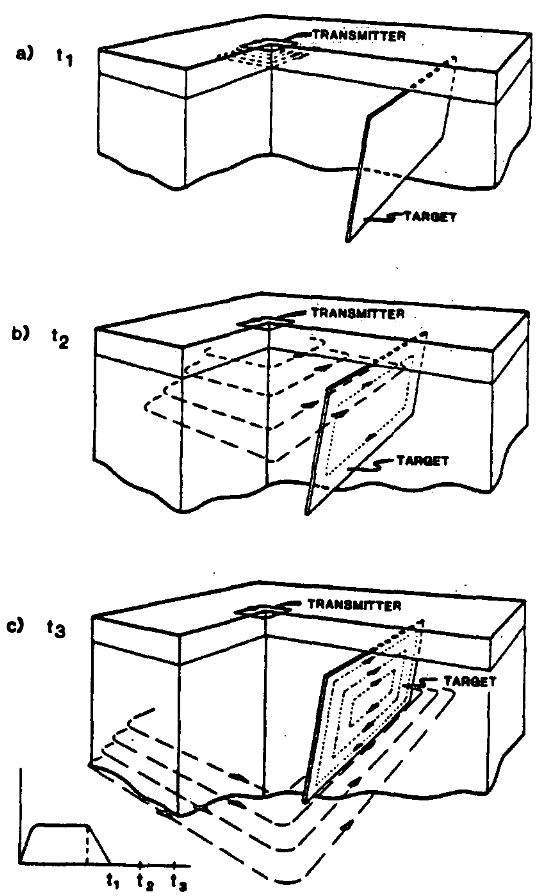

Fig. 11. Illustration of eddy current flow induced in overburden, host rock, and fracture or shear zones at different times.

Measurements at the same location were made with TDEM in 200 m by 200 m transmitter loops, and the results of central-loop TDEM soundings are shown in Figure 14. Again, the measured apparent resistivity curves are superimposed on three forward model curves, and the geoelectric sections of the three model curves are shown on the right. Depth to bedrock in the models is varied by 20 m. It is evident that vertical resolution of determining depth to bedrock is now ± 10 m.

Thus, not only was the physical effort required to sound to a depth of 168 m greatly reduced - only 800 m (4 x 200 m) of wire needed to be laid out, - but the vertical resolution was greatly improved.

Question.-- Summarize for me the potential of TDEM in environmental and ground water geophysics.

Answer.--Electrical surface geophysical methods are an important tool because (1) electrical resistivity is the only readily measureable physical property highly dependent of concentration of dissolved solids (water quality), and (2) electrical resistivity often closely relates to clay content and hydraulic permeability. In the past the vertical and lateral resolution of electrical methods was poor. TDEM techniques are changing that reputation.

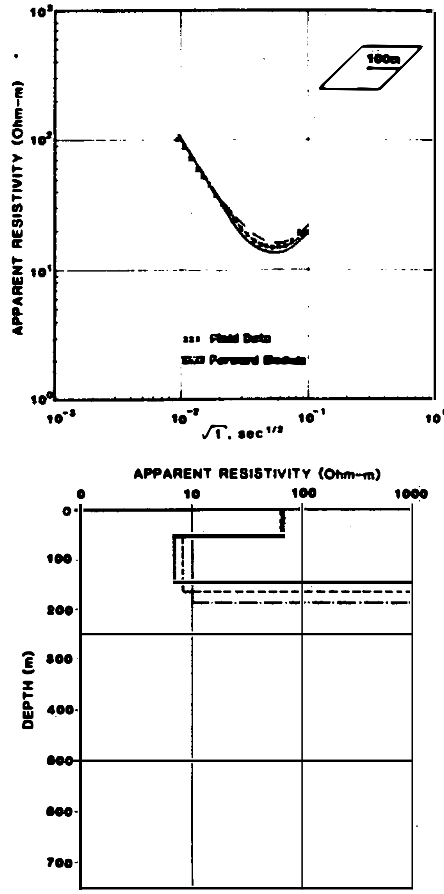

Fig. 14. TDEM measured apparent resistivities (a) superimposed on three one-dimensional geoelectric sections.