Special Publication SJ 90-SP6

TIME DOMAIN ELECTROMAGNETIC TEST SURVEY IN ST. JOHNS RIVER WATER MANAGEMENT DISTRICT

BLACKHAWK GEOSCIENCES, INC.

Special Publication SJ90-SP6

TIME DOMAIN ELECTROMAGNETIC TEST SURVEY IN ST. JOHNS RIVER WATER MANAGEMENT DISTRICT

Prepared For:

St. Johns River Water Management District
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(Contract No. 90D134)

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(BGI Project #90022)

July 26, 1990

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1.0 INTRODUCTION

This report contains the results of a time domain electromagnetic (TDEM) survey performed in east-central Florida for the St. Johns River Water Management District (SJRWMD). The field work was performed by Blackhawk Geosciences, Inc. (BGI) from May 17 to May 22, 1990, and consisted of 12 separate soundings made in four locations.

The objectives of the survey were to

- map the stratigraphy of the geologic section
- determine the depth to saline water.

The present survey was a test of the TDEM geophysical method. The soundings were made in several different areas in which the geology of the subsurface, salinity of the ground water, electrical noise levels and depth to saline waters varied.

2.0 DATA ACQUISITION

2.1 SOUNDING LOCATIONS

The TDEM sounding locations were chosen by SJRWMD. The present survey was a test of the TDEM geophysical method and the sites were chosen so that differing conditions were encountered at the various sites. The four areas surveyed along with the number of soundings in each are

- Osceola Landfill - 3 soundings
- Camp David Hendricks - 2 soundings
- Bull Creek - 5 soundings
- Lake Washington - 2 soundings.

The general locations of the four sites are shown in Figure 2-1.

2.2 FIELD PROCEDURES

The field crew consisted of three people. BGI supplied one geophysicist to operate the equipment and interpret the field data. SJRWMD supplied two field helpers to assist in laying out the transmitter loops and two four-wheel drive vehicles to transport the equipment. The transmitter loops consisted of 12-gauge insulated wire which was laid out in either a square or rectangle. Dimensions of the loops were determined by the depth of exploration required and availability of open land. At the Osceola Landfill and Camp David Hendricks the depth of exploration was less than 500 ft, which required a transmitter loop of 300 ft by 300 ft.

The Bull Creek and Lake Washington areas required exploration depths of greater than 1,500 ft and transmitter loop sizes varied from 1,300 ft by 1,500 ft to 1,000 ft by 2,400 ft. Most of the transmitter loops were square in shape, but in some cases access required that rectangular loops be used. The actual dimensions of the transmitter loops at each sounding location are shown on the location maps in Section 5.2 through 5.5. All loops were surveyed using a compass and measuring string. The locations of the loops were plotted on maps by SJRWMD personnel. Table 2-1 summarizes the daily field activities.

Table 2-1. Daily log of field activities.

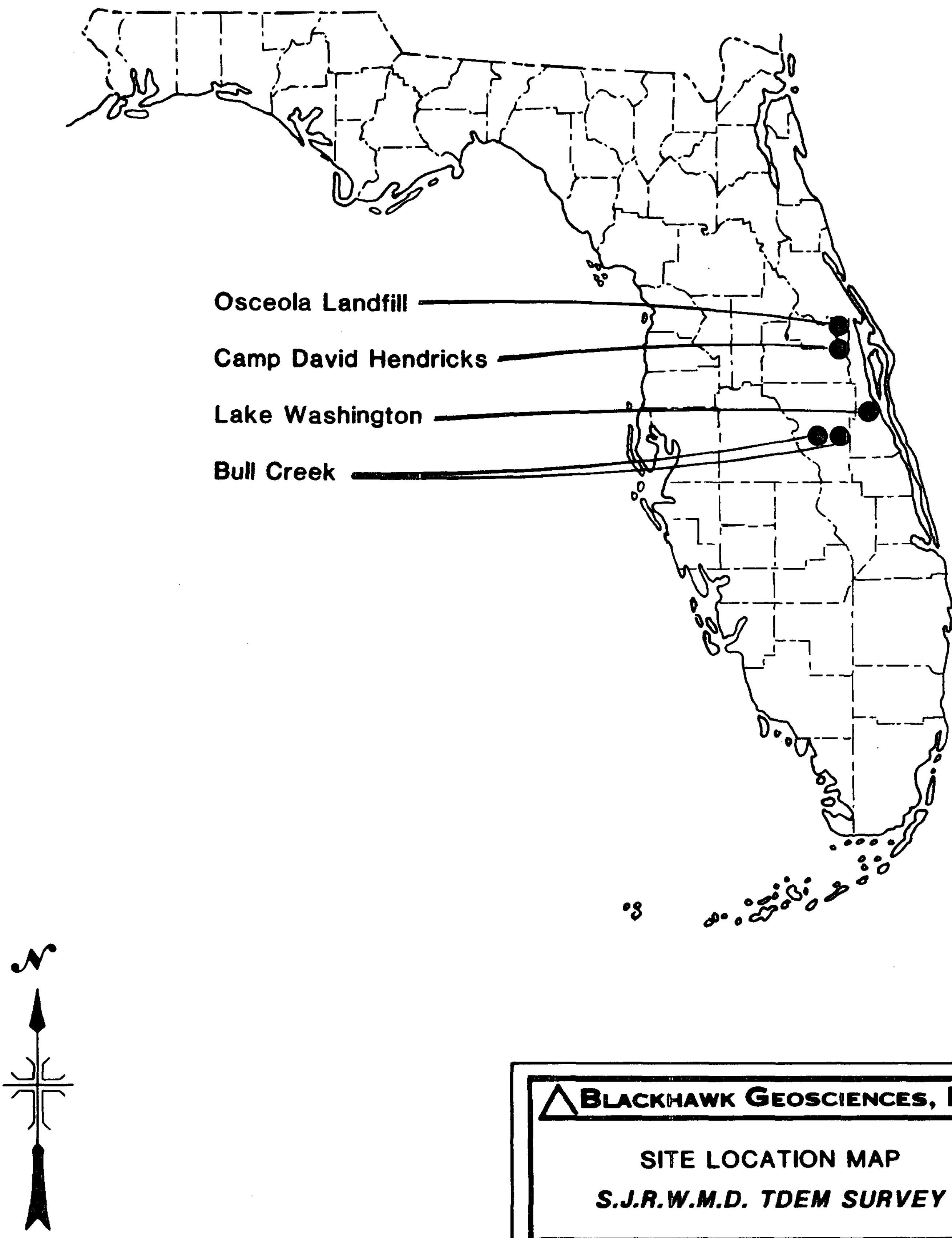
Date (1990)	Activity
May 16	Mobilize from Denver, CO to Sanford, FL.
May 17	Read loops OSL-1, OSL-2 and OSL-3.
May 18	Read loops CDH-1 and CDH-2. Mobilize to Melbourne, FL.
May 19	Read loops BC-1 and BC-2.
May 20	Read loops BC-3, BC-4 and BC-5.
May 21	Read loop LW-1.
May 22	Read loop LW-2. Mobilize to Jacksonville, FL.

At all stations the electromotive force (emf) due to the vertical magnetic field was recorded at several amplifier gains and opposite receiver polarities. Receiver coils with effective areas of 100 m^2 and 1,000 m^2 were employed. The data was recorded at base frequencies of 3 Hz and 30 Hz. The current driven through the transmitter loops varied from 13 to 24 amps, depending on loop size. All data was recorded on a DAS-54 data logger.

2.3 PROCESSING

The data stored in the DAS-54 solid memory logger was transferred to floppy disks on a computer. The first step in data processing was to average the emf's recorded at opposite receiver polarities. Next, the recordings at different amplifier gains and frequencies were combined to produce one transient decay. The emf's in the various time gates of this decay curve are subsequently entered into a ridge regression inversion program to obtain a one-dimensional geoelectric section that matches the observed decay curve.

The inversion program requires an initial model for the geoelectric section. This model is usually derived from approximate matching of apparent resistivity curves with model curves from a series of albums of model curves or from knowledge of the geoelectric section obtained from drill holes. The inversion program is then allowed to adjust the model to improve the fit. This involves the adjustment of resistivities and thicknesses of the layers within the geoelectric model. The inversion program does not change the total number of layers within the model curve but all other parameters float freely, or optionally can be held constant. To determine the influence of number of layers on the solution, separate inversions with a different number of layers are run.



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SITE LOCATION MAP

S.J.R.W.M.D. TDEM SURVEY

PROJECT NO.: 90022

FIGURE 2-1

3.0 GEOLOGY

A description of the geology of the survey area is given in Table 3-1. The Hawthorn formation, when it contains clays, is probably the most electrically distinctive. Classification of geologic units is based on age, and different units may not have different characteristic ranges of physical properties. Moreover, changes in physical properties may be caused by factors (e.g., salinity of pore water, porosity) not reflected in a geologic classification scheme. In electrical resistivity mapping it is likely that characteristic ranges of resistivity are observed for the Recent Pleistocene sediments, the Hawthorn formation, and the Limestone formation. Porosity and salinity variation within the various limestone and dolostone formations makes it unlikely that resistivity techniques can differentiate between various limestone groups.

Table 3-1. Summary of the properties of the geologic formations penetrated by water wells in the Last Central Florida Region

Series	Formation name	Thickness in feet	Description of material	Water bearing properties	Aquifer
Recent Pleistocene, Pliocene, and Miocene	Undifferentiated, may include Caloosahatchee Marl	0-200	Mostly quartz sand with varying amounts of clay and shell.	Varies widely in quantity and quality of water produced	Non artesian
Miocene	Hawthorn	0-250	Gray-green, clayey quartz sand and silt; phosphatic sand; and buff, impure, phosphatic limestone, mostly in lower part.	Generally impermeable except for limestone, shell, or gravel beds.	Secondary artesian, lower limestone beds may be part of Floridan
Eocene	Ocala Group	0-400	Cream to tan, fine, soft to medium hard, granular, porous, sometimes dolomitic limestone	Moderately high transmissibility, most wells also penetrate underlying formations.	Floridan
Eocene	Avon Park Limestone	100-1,000	Upper section mostly cream to tan, granular, porous limestone. Often contains abundant cone-shaped Foraminifers. Lower section mostly dense, hard, brown, crystalline dolomite.	Overall transmissibility very high, contains many interconnected solutions cavities. Many large capacity wells draw water from this formation.	Floridan
Eocene	Lake City Limestone	Over 700 total unknown	Dark Brown crystalline layers of dolomite alternating with chalky fossiliferous layers of limestone	Similar to Avon Park Limestone, Municipal supply of City of Orlando obtained from this formation.	Floridan

4.0 TECHNICAL APPROACH

The surface geophysical method employed in this survey was TDEM. The principles of TDEM are discussed in Appendix A. The TDEM method measures from the surface the bulk electrical resistivity, or its inverse conductivity, of the subsurface. For interpretation purposes the results of the survey are expressed as resistivities. The result of each sounding is an interpreted geoelectric section consisting of the resistivity stratification of the subsurface. For hydrogeologic purposes the resistivity values derived from the TDEM soundings need to be correlated with lithology and/or ground water salinity. The resistivity of a water bearing rock is mainly a function of its clay content, water salinity, and porosity. Most rock forming minerals are essentially insulators and nearly all electrical current is carried over the surface of particles (exchangeable ions) and through pore fluids.

An empirical equation has been derived relating the bulk resistivity of a rock unit to its porosity and water salinity. This relationship is known as Archie's Law and is expressed as follows:

$$F = R_o/R_w = a\Phi^{-m} \qquad \{1\}$$

where F = formation factor

R_o is the bulk resistivity of the rock

R_w is the resistivity of the pore water

Φ is rock porosity expressed as a fraction per unit volume

a, m are empirically derived constants dependent on rock lithology and pore type distribution.

Kwader (1986) found a value of m = 1.6 and a = 1 to best fit his observation in the Floridan aquifer in Seminole County. He also performed an extensive data collection and investigation of the relation between ionic concentration, fluid resistivity, and formation resistivity for the ground water aquifers in Florida. Figure 4-1 shows the relation between chloride concentration and pore fluid resistivity for the Floridan aquifer in Seminole County. The solid line on Figure 4-1 is described by the equation

$$Cl = 3500/Rw - 153 \qquad \{2\}$$

where Cl is chloride concentration in ppm, and
Rw is fluid resistivity in ohm-m.

Data points to a maximum chloride concentration of about 10,000 ppm were available to Kwader (1986), and the relation is untested at higher chloride concentrations. Figure 4-2 shows the computed relation between porosity and formation resistivity at a chloride concentration of 250 ppm (drinking water limit) using equation {1}. Values at other chloride concentration would parallel this line.

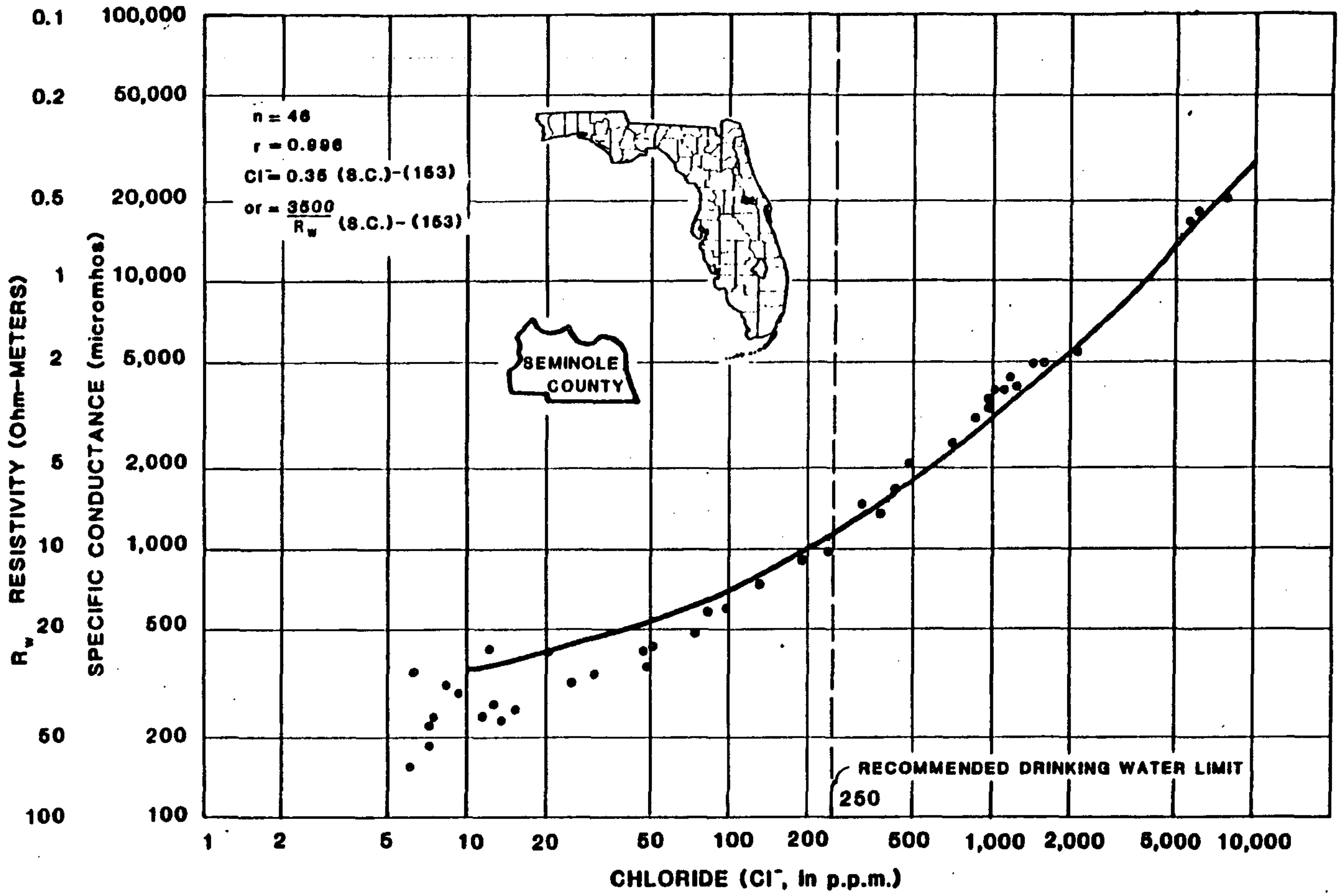
Thus, TDEM measures the bulk resistivity (formation resistivity) of the Floridan aquifer, and bulk resistivity depends mainly on porosity and fluid resistivity. Fluid resistivity in turn is controlled by concentration of dissolved solids (Fig. 4-1). Therefore, from surface electrical measurements alone, salinity or porosity cannot be independently resolved. However, the fact that in limestone aquifers both porosity and salinity influence bulk resistivity does not negate the TDEM method to be an effective tool for mapping water quality for two reasons:

(1) Resistivity changes caused by salinity at the interface between fresh/brackish water and highly saline water may be two orders of magnitude, and those caused by porosity at most a factor 3 or 4. The ability of TDEM to map small changes in salinity in environments where both porosity and salinity change randomly, however, may be limited.

(2) Porosity and salinity seldom change randomly locally, but they generally change along regional trends laterally and with depth. Surface geophysics correlated against occasional well data are often a good tool to interpolate well data over a large areal extent at modest cost.

<u>Reference</u>

Kwader, Thomas 1986. The use of geophysical logs for determining formation water quality, Ground Water, V 24, No. 1, Pg. 11-15.



(AFTER: KWADER, 1986)

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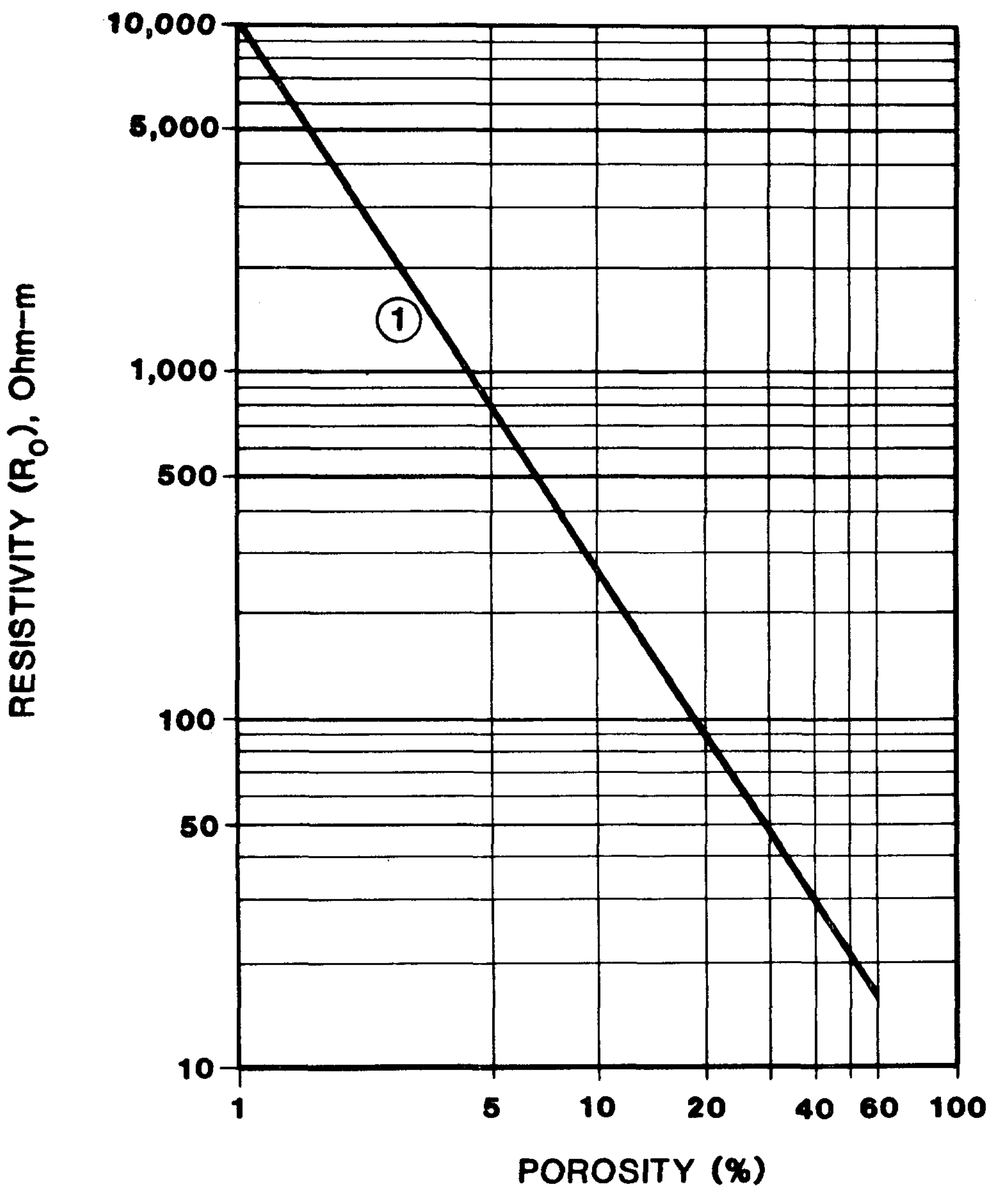
FLUID RESISTIVITY (Rw)
VERSUS CHLORIDE CONCENTRATION
S.J.R.W.M.D. TDEM SURVEY

PROJECT NO.: 90022 FIGURE 4-1



① Floridan Aquifer

$m = 1.6$

$R_W = 7.21$

BLACKHAWK GEOSCIENCES, INC.

RELATION BETWEEN POROSITY AND FORMATION RESISTIVITY AT 250 ppm CHLORIDE

S.J.R.W.M.D. TDEM SURVEY

PROJECT NO.: 90022 **FIGURE 4-2**

5.0 RESULTS

5.1 GENERAL

The results of the 12 soundings are contained in Attachment A. An example of the output of the inversion program for square transmitter loops is given in Figures 5.1-1 and 5.1-2, and Table 5-1. In Figure 5.1-1 the experimentally measured data are superimposed on a solid line. The solid line represents the behavior of the geoelectric section shown on the right. This geoelectric section was derived by inversion. Table 5-1 lists the experimental data, the computed data for the best fit, and the error between experimental and measured data at each time gate. The inversion table and all the inversion tables in Attachment A show a resolution matrix and parameter bounds analysis. The most meaningful table for practical purposes is the parameter bound analysis, which indicate the range of values thicknesses and resistivities can assume within the accuracy of the measured data. Figure 5.1-2 shows an analysis of equivalence which was derived by allowing the inversion program to display the range of resistivities and thicknesses that fit the observed data within an overall RMS error of 3.0%. The resulting ranges of thicknesses and resistivities are plotted on the graph. Thus, the depth to the lower conductive layer may vary between 134 m, ± 2 m, and the resistivity of the lower layer between 2.69 ohm-m, ± 0.2 ohm-m.

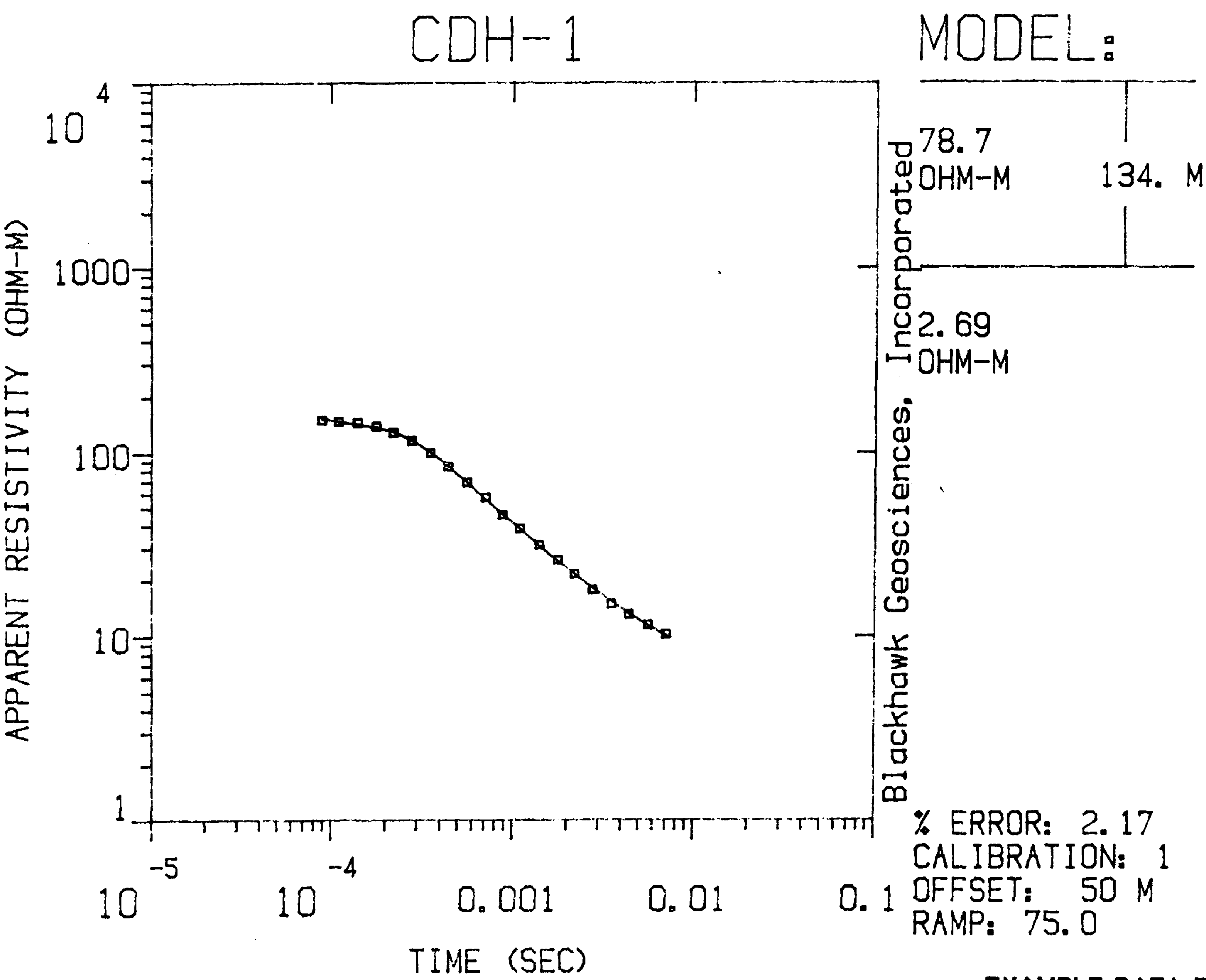
Also, Table 5-2 summarizes the geoelectric section measured for each station. In addition to the parameters that best matches the observed behavior, it also lists the range of equivalence within the inversion error.

The display format for the Lake Washington soundings, LW-1 and LW-2, is slightly different from that shown for the other soundings (Fig. 5.1-3 and Table 5-3). The difference in display is due to the rectangular shape of the transmitter loop which required the use of a different version of the inversion program.

In these test surveys geophysical measurements were made near wells. The purpose of making measurements near wells is to allow a comparison of geophysical interpretations from surface measurements with lithologic and geophysical logs obtained in wells. To understand the validity of such comparisons the difference between surface and downhole electrical measurements is briefly discussed next.

In downhole electrical measurements the geophysical tool measures the variation in bulk resistivity of all geologic units penetrated by the borehole. The vertical resolution of such tools can be on the order of a few feet, and electric logs can display small variations continuously. In surface measurements the resistivities of all layers within the effective exploration depth of the sensor influence the value of the measurement. By making soundings over a range of parametric (or geometric) parameters (e.g., time in TDEM), measurements are obtained at different effective depths of exploration. Computer programs allow deconvolution of surface measurements into layers with distinct resistivities and thicknesses. However, the detail obtainable in downhole geophysics can never be reproduced with surface geophysics. From surface geophysics only boundaries where major changes in resistivity occur can be recognized. In comparing interpretations from surface geophysics with downhole geophysical logs, agreement in general trends are sought rather than in fine detail.

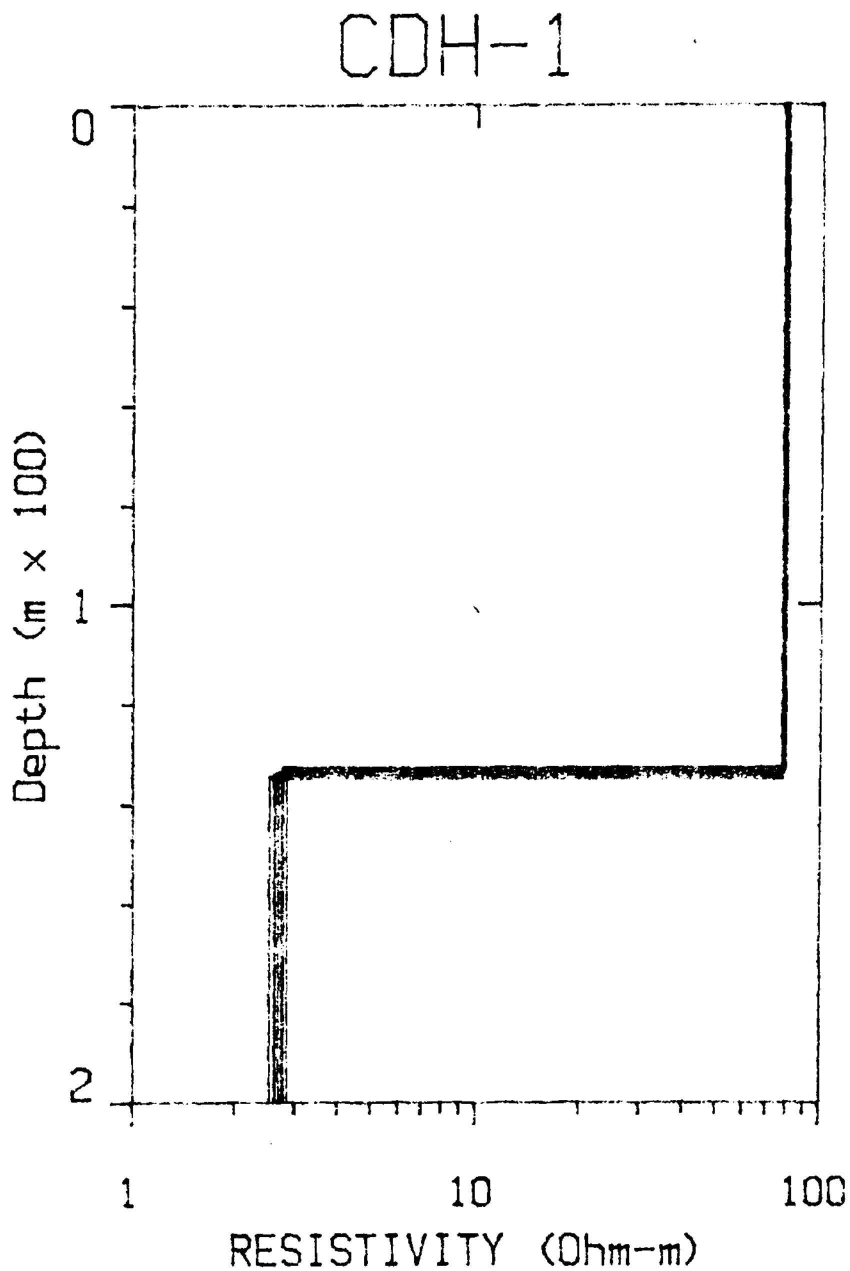
There is one additional difference between downhole and surface geophysics, and that is in the volume of ground averaged in a measurement. The borehole tools sense at most a few feet around the hole, the surface geophysical sensor laterally averages over distances of several hundred feet.



EXAMPLE DATA FROM SQUARE TRANSMITTER LOOP

S.J.R.W.M.D. TDEM SURVEY

PROJECT NO.: 90022 **FIGURE 5.1-1**



EXAMPLE DATA FROM SQUARE TRANSMITTER LOOP
S.J.R.W.M.D. TDEM SURVEY

PROJECT NO.: 90022 **FIGURE 5.1-2**

CDH-1

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		0.0	0.0		
78.69	134.0	-134.0	-439.7	1.7	1.7
2.69					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	1.51E+02	1.54E+02	-1.940	
2	1.10E-04	1.48E+02	1.48E+02	0.357	
3	1.40E-04	1.46E+02	1.43E+02	2.038	
4	1.77E-04	1.39E+02	1.38E+02	1.263	
5	2.20E-04	1.29E+02	1.31E+02	-1.249	
6	2.80E-04	1.16E+02	1.17E+02	-0.768	
7	3.55E-04	9.97E+01	1.00E+02	-0.449	
8	4.43E-04	8.42E+01	8.51E+01	-1.060	
9	5.64E-04	6.90E+01	6.91E+01	-0.102	
10	7.13E-04	5.70E+01	5.57E+01	2.336	
11	8.85E-04	4.56E+01	4.60E+01	-0.831	
12	1.10E-03	3.83E+01	3.82E+01	0.382	
13	1.41E-03	3.13E+01	3.08E+01	1.384	
14	1.78E-03	2.58E+01	2.54E+01	1.393	
15	2.21E-03	2.17E+01	2.15E+01	0.534	
16	2.80E-03	1.77E+01	1.80E+01	-1.571	
17	3.55E-03	1.48E+01	1.53E+01	-3.255	
18	4.43E-03	1.31E+01	1.32E+01	-0.864	
19	5.64E-03	1.15E+01	1.14E+01	0.790	
20	7.13E-03	1.02E+01	1.00E+01	1.692	

R: 50. X: 0. Y: 50. DL: 100. REQ: 56. CF: 1.0000
CLHZ ARRAY, 20 DATA POINTS, RAMP: 75.0 MICROSEC, DATA: CDH-1

RMS LOG ERROR: 9.33E-03, ANTILOG YIELDS 2.1719 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

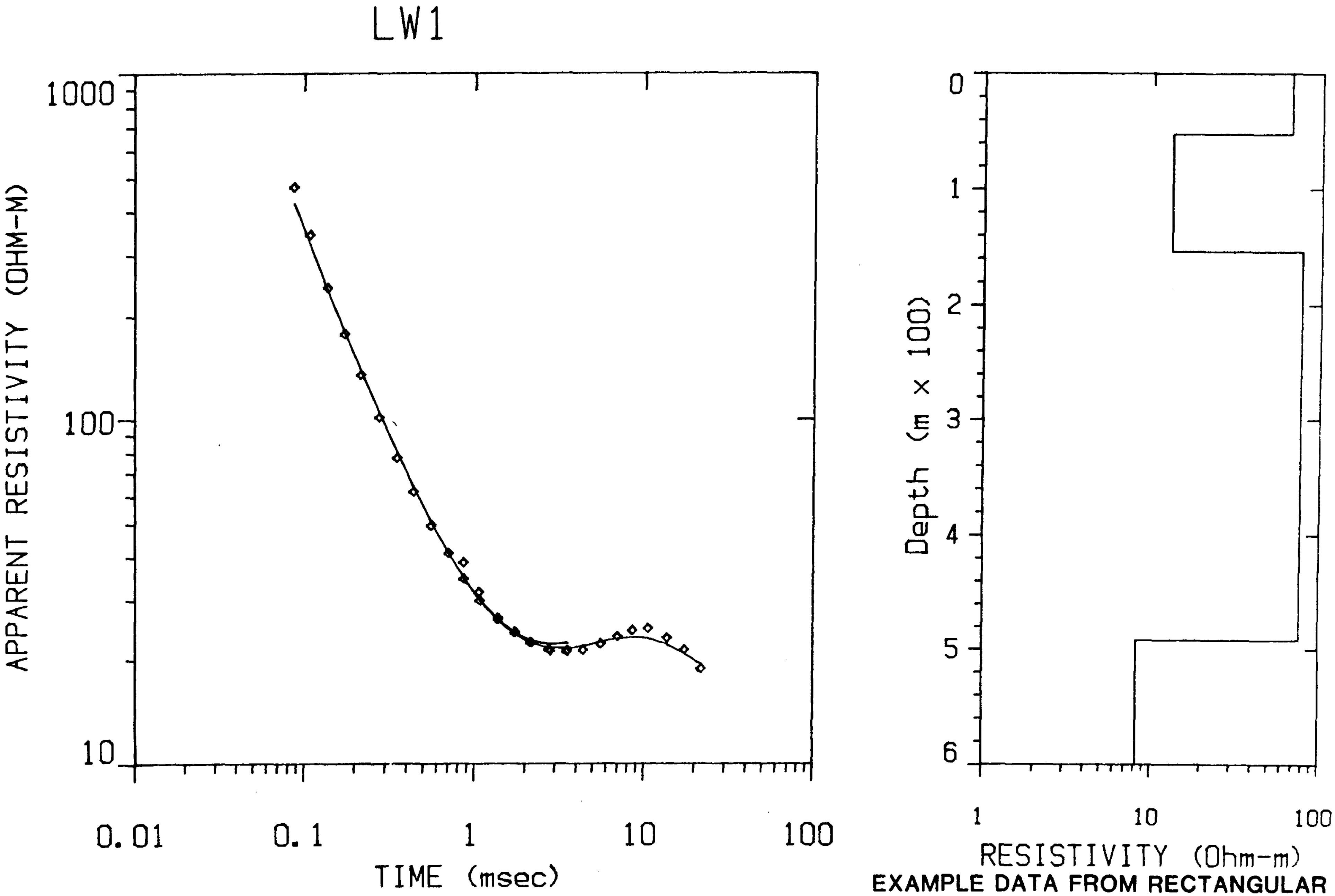
PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

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

EXAMPLE DATA FROM SQUARE TRANSMITTER LOOP
S.J.R.W.M.D. TDEM SURVEY
PROJECT NO.: 90022 **TABLE 5-1**

Table 5-2
Summary of Geoelectric Sections Measured at Various Sites
(The range of equivalence of each site is also shown)

Site Name	Station #	Number of Layers Modeled	ρ_1, ohm-m			h_1 m			ρ_2, ohm-m			h_2 m			ρ_3, ohm-m			h_3 m			ρ_4, ohm-m		
			Min	Best	Max	Min	Best	Max	Min	Best	Max	Min	Best	Max	Min	Best	Max	Min	Best	Max	Min	Best	Max
Osceola	OSL-1	2	74.9	77.3	80.1	91.0	91.9	92.8	2.5	2.5	2.6												
	OSL-2	2	63.7	65.0	66.3	89.7	90.4	91.0	2.5	2.6	2.6												
	OSL-3	2	69.9	71.3	73.0	89.9	90.5	91.1	2.5	2.5	2.6												
Camp David Hendricks	CDH-1	2	78.0	78.7	79.3	133.4	134.0	134.6	2.6	2.7	2.8												
	CDH-2	2	90.0	90.9	91.7	148.9	149.7	150.5	2.9	3.0	3.1												
Bull Creek	BC-1	3	113.6	120.5	157.0	31.6	36.2	37.7	30.1	30.5	31.9	158.2	169.7	195.3	73.8	80.7	92.4						
	BC-2	3	123.4	131.6	137.0	38.7	39.9	42.0	30.0	30.1	31.7	118.5	130.5	141.5	72.0	76.0	82.6	407.8	416.5	427.2	2.6	3.3	3.9
	BC-3	4	92.6	115.0	128.2	39.2	43.4	48.0	22.0	23.4	25.1	98.6	113.4	131.4	110.0	144.6	176.5	344.4	362.2	385.2	10.8	11.7	12.5
	BC-4	4	104.0	117.0	127.8	45.0	46.8	48.4	22.9	23.2	23.5	105.0	108.3	111.5	109.3	118.9	131.7	352.6	360.0	367.5	11.2	11.8	12.4
	BC-5	3	43.9	45.8	48.4	33.6	46.7	66.3	36.9	38.4	39.2	168.0	194.1	217.1	169.6	247.4	607.4						
Lake Washington	LW1	4	61.2	65.5	129.5	41.4	53.0	58.5	11.4	13.0	14.1	83.6	101.7	118.3	55.1	76.9	132.8	311.3	337.8	382.9	3.0	8.3	10.4
	LW2	4	46.3	88.2	275.3	9.6	17.1	23.7	22.8	23.6	24.6	189.4	220.8	264.5	63.0	162.5	454.3	235.1	277.8	325.5	6.1	7.8	10.1



EXAMPLE DATA FROM RECTANGULAR TRANSMITTER LOOP

FIGURE 5.1-3

DATA SET: LW1

CLIENT:	ST. JOHNS RWMD	DATE:	2105
LOCATION:	0011 0000	SOUNDING:	00000
COUNTY:	BREVARD	ELEVATION:	0.00 m
PROJECT:	SJRWMD	EQUIPMENT:	Geonics PROTEM

LOOP SIZE: 304.000 m by 731.000 m
COIL LOC: 0.000 m (X), 0.000 m (Y)
SOUNDING COORDINATES: X: 0.0000 Y: 0.0000

FITTING ERROR: 5.937 PERCENT

L #	RESISTIVITY (ohm-m)	THICKNESS (meters)	ELEVATION (meters)	CONDUCTANCE (Siemens)
			0.0	
1	65.49	53.01	-53.01	0.809
2	13.04	101.6	-154.7	7.79
3	76.88	337.8	-492.5	4.39
4	8.26			

ALL PARAMETERS ARE FREE

PARAMETER BOUNDS FROM EQUIVALENCE ANALYSIS

LAYER		MINIMUM	BEST	MAXIMUM
RHO	1	61.171	65.493	129.503
	2	11.418	13.046	14.101
	3	55.139	76.888	132.801
	4	3.040	8.260	10.364
THICK	1	41.435	53.019	58.544
	2	83.593	101.683	118.256
	3	311.311	337.809	382.946
DEPTH	1	41.435	53.019	58.544
	2	140.587	154.702	168.401
	3	471.398	492.511	542.244

CURRENT: 1.00 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 30.00 Hz GAIN: 0 RAMP TIME: 210.00 muSEC

No.	TIME (ms)	Apparent Res (ohm-m) DATA	SYNTHETIC	DIFFERENCE (percent)

*   Blackhawk Geosciences, Inc.   *

EXAMPLE DATA FROM RECTANGULAR TRANSMITTER LOOP
S.J.R.W.M.D. TDEM SURVEY
PROJECT NO.: 90022 **TABLE 5-3**

5.2 OSCEOLA LANDFILL

Three soundings were made at this location shown on Figure 5.2-1. A two-layer model consisting of an approximately 70 ohm-m layer overlying a 2.5 ohm-m layer characterizes the inversions of the three soundings. The depth to the conductive layer averaged 299 ft. Figure 5.2-2 compares the sounding results with the lithologic and geophysical logs of drill hole S-0087, which is located approximately 150 ft southeast of OSL-1. The boundary shown at 300 ft in the soundings corresponds to the midpoint of the transition zone from fresh water above 250 ft to highly saline water at around 360 ft, and is probably the result of the TDEM method averaging the resistivities between the zones.

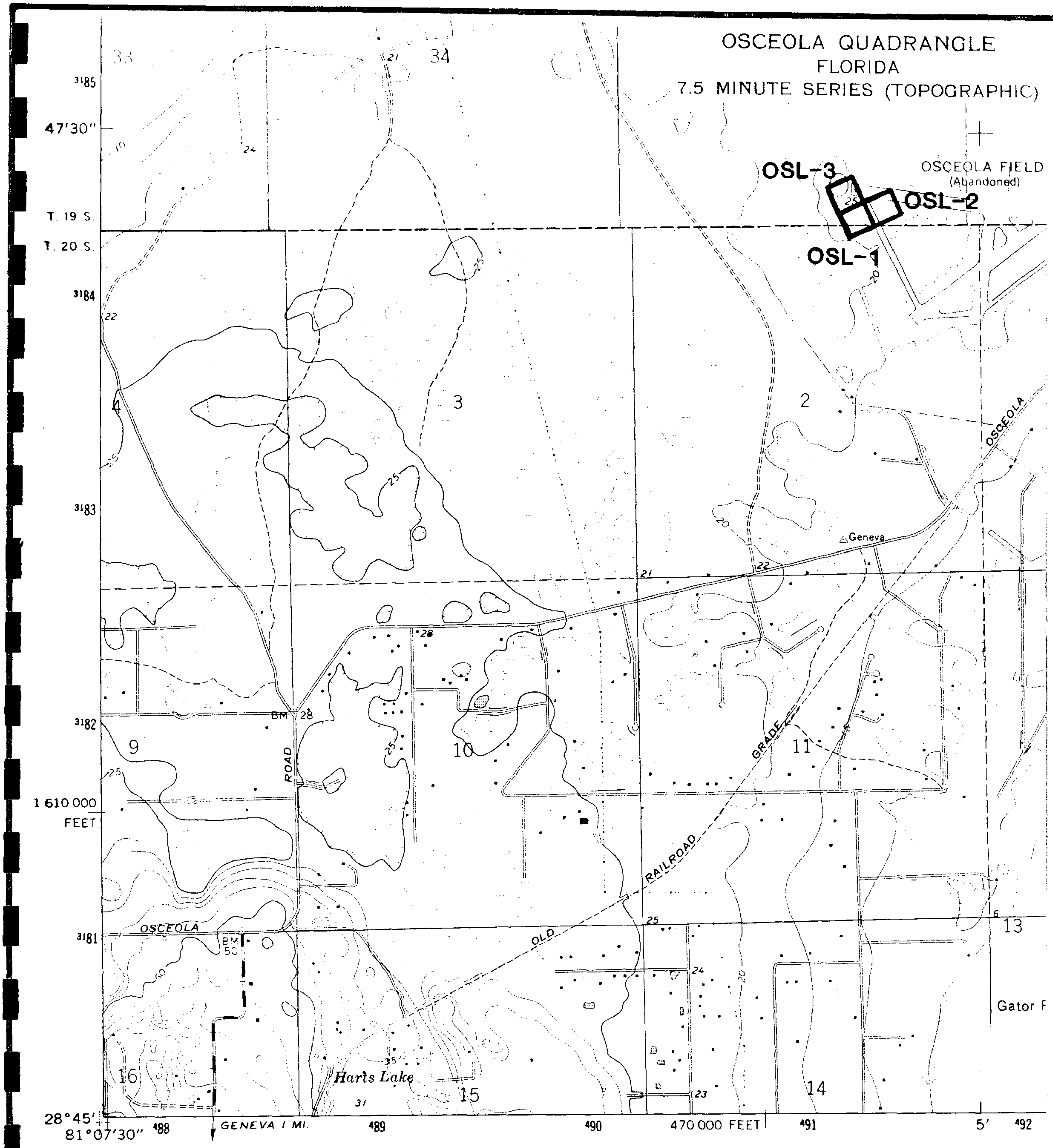
The electrical properties of the fresh water-filled Floridan Aquifer are not shown to be significantly different from the overlying Hawthorn and surficial deposits. This implies that the clay content in these overlying units is low resulting in higher resistivities.

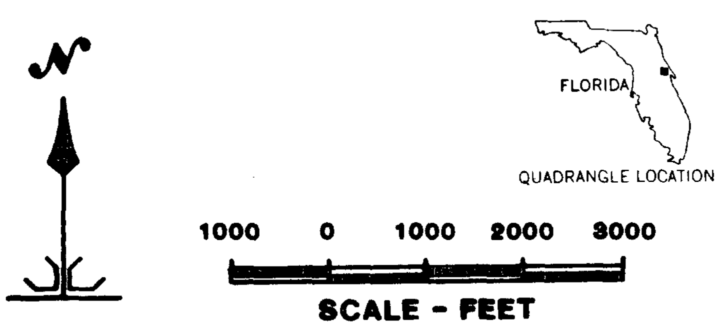
The equivalence models (Attachment A) for the soundings show very little variance. This is normally the case when resistivity contrasts are high and the total number of layers of the models low. The relatively shallow depth of exploration required at this site allowed the use of small transmitter loop sizes (300 ft by 300 ft). The signal strengths were high throughout the time interval in which data needed to be recorded to obtain a sufficient exploration depth. The influence of electrical noise, such as 60 cycle power lines, was negligible at this site.

In evaluating the utility of TDEM surveys in this particular hydrogeologic setting, the following conclusions can be drawn:

(1) TDEM surveys are effective in determining the depth of occurrence of the fresh water - salt water interface. The depth that is determined is about the middle of the transition zone. If this transition zone is consistent within a regional hydrologic setting, then TDEM surveys can be used inexpensively to evaluate variation in depth to saline water in a region. In this particular setting the depth is consistently determined within ± 2 m.

(2) The Hawthorn formation was found to be relatively resistive (70 ohm-m), likely indicating the absence of confining clay layers. TDEM surveys would be effective in delineating areas of prime recharge where clay layers are absent.



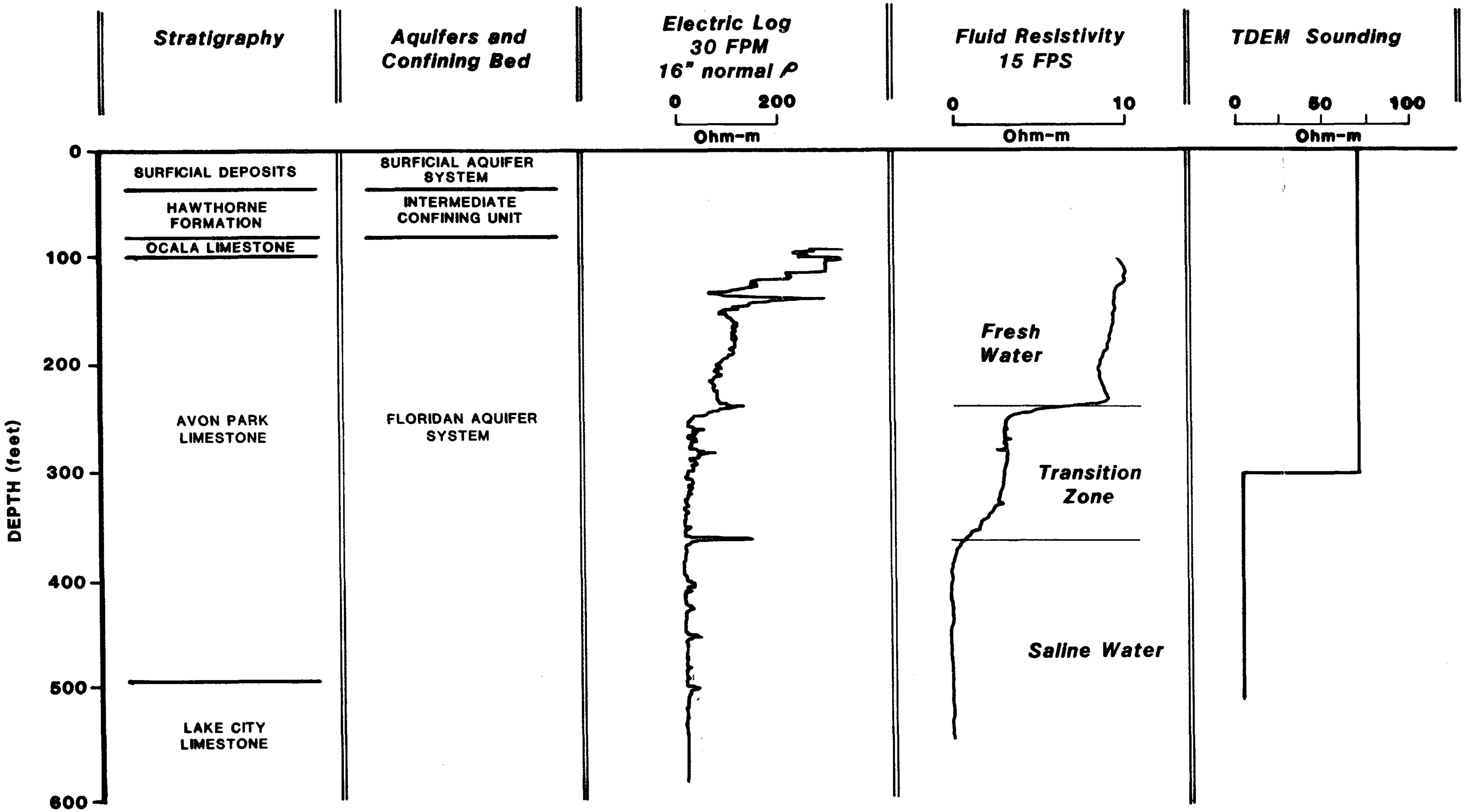


BLACKHAWK GEOSCIENCES, INC.

OSCEOLA LANDFILL LOCATION MAP

S.J.R.W.M.D. TDEM SURVEY

PROJECT NO.: 90022 **FIGURE 5.2-1**



BLACKHAWK GEOSCIENCES, INC.

COMPARISON OF TEST WELL S-0087 AND TDEM SOUNDING OSCEOLA LANDFILL AREA

S.J.R.W.M.D. TDEM SURVEY

PROJECT NO.: 90022 FIGURE 5.2-2

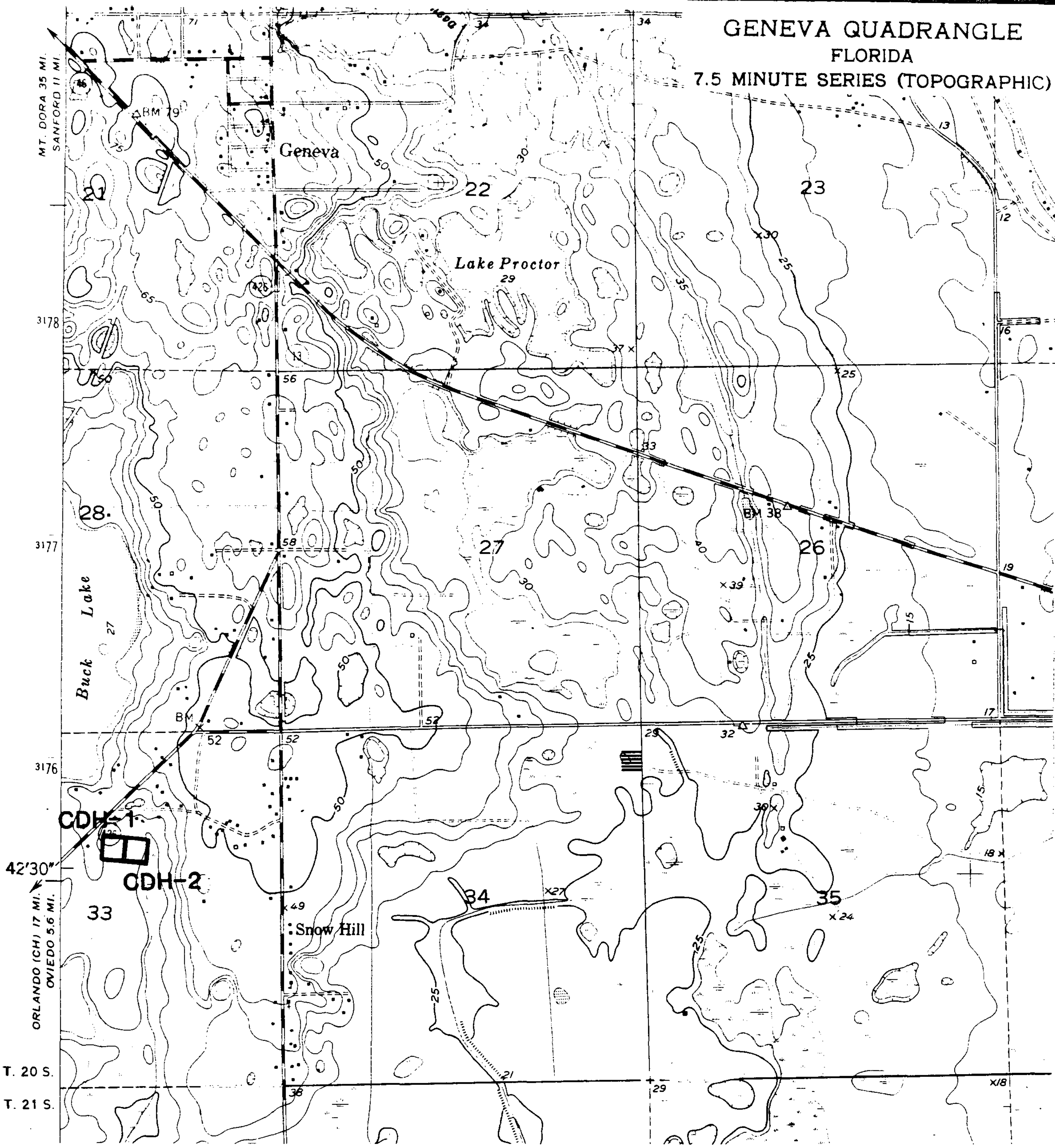
5.3 CAMP DAVID HENDRICKS

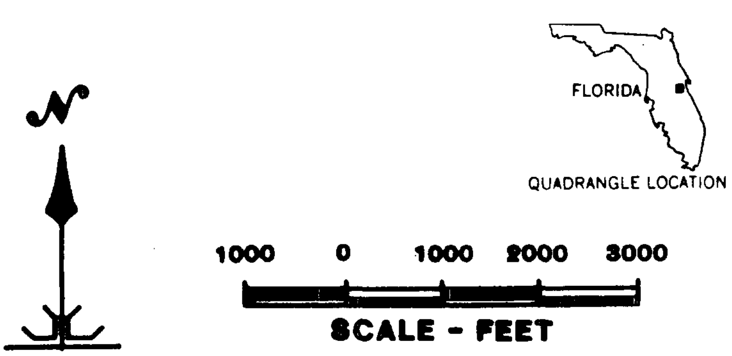
The location of the two soundings made at this site is shown in Figure 5.3-1. The general geoelectric section here is similar to that seen at the Osceola Landfill. A resistive section of 80 to 90 ohm-m overlies a conductive lower layer of 2.5 to 3.0 ohm-m. The data at this location are summarized in Figure 5.3-2. The interface between 450 ft and 500 ft in this geologic setting can confidently be interpreted to be the boundary between fresh water and saline water. Since no wells were available for calibration the thickness of the transition zone cannot be resolved from the TDEM data.

Also in this setting there appears to be no resistivity contrasts between the Hawthorn formation and the limestones of the upper Floridan aquifer. Both units have relatively high resistivities. This again likely indicates the absence of clay confining layers.

Electrical power lines along the main highway and running to houses adjacent to the field where the sounding was made do not appear to affect the data in the time range applicable to the depth of exploration.

In evaluating the utility of TDEM surveys in this particular hydrogeologic setting, the conclusion can be drawn that TDEM surveys are effective in determining the depth of occurrence of the fresh water - salt water interface. Likely, the depth interpreted from the TDEM data is in the transition zone. If this transition zone is consistent within a regional hydrologic setting, then TDEM surveys can be used to inexpensively evaluate variation in depth to saline water.





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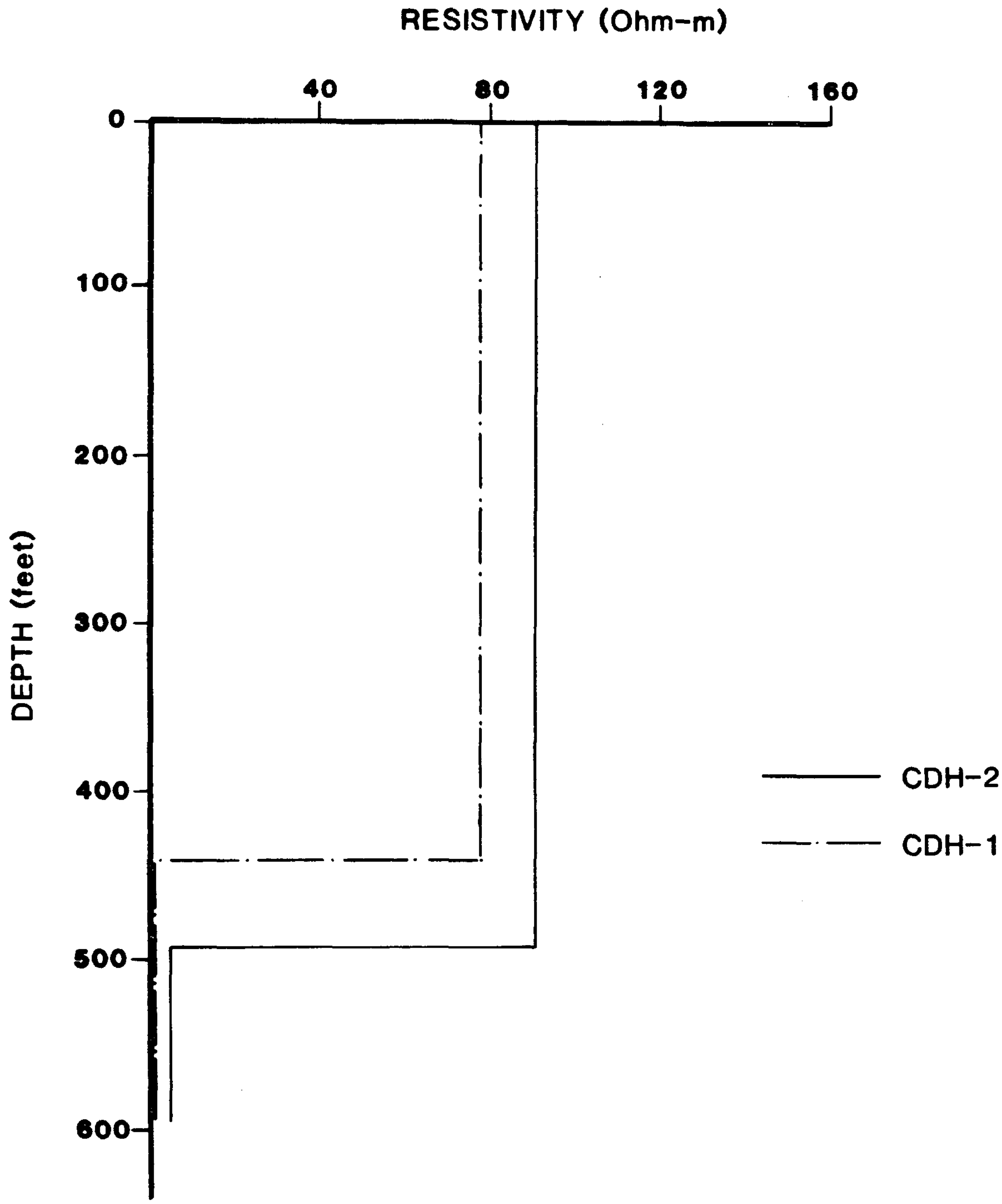
CAMP DAVID HENDRICKS
LOCATION MAP

S.J.R.W.M.D. TDEM SURVEY

PROJECT NO.: 90022 FIGURE 5.3-1



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TDEM GEOELECTRIC SECTIONS
CAMP DAVID HENDRICKS AREA
S.J.R.W.M.D. TDEM SURVEY

PROJECT NO.: 90022 FIGURE 5.3-2

5.4 BULL CREEK

A total of five soundings were made in the Bull Creek area and their locations are given in Figures 5.4-1 and 5.4-2. The required depth of exploration in this area is 1,500 ft to 2,000 ft and to accomplish this transmitter loop sizes with dimensions of 1,500 ft by 1,300 ft for BC-1 and BC-2, and 1,500 ft by 1,500 ft for BC-3 and BC-4 were used. Sounding BC-5 was measured to investigate the upper section immediately adjacent to the Bull Creek Test Monitor Well and employed a smaller loop size of 500 ft by 500 ft.

The Bull Creek test well was located in the northwest corner of soundings BC-1 and BC-5. A comparison of an interpretation (smoothing) of the electric log from the well and these two soundings is shown in Figure 5.4-3. The following observations can be made from the comparison.

1. BC-5 utilized a smaller transmitter loop and was designed to check the dolomitization change which occurs at 750 ft in the well. Moreover, measurements with a smaller transmitter loop are more representative of the subsurface immediately adjacent to the well. The depth to an increase in resistivity in BC-5 is at 790 ft which is in close agreement with the well's depth of 750 ft. In sounding BC-1 the increase in resistivity is observed at 675 ft.

2. Resistivities observed in the upper Floridan aquifer (above about 650 ft) in the geophysical log and the TDEM sounding show good agreement. Salinity values of approximately 440 ppm Cl are reported for the Floridan aquifer to a depth of 1,483 ft. These relatively high salinity values are also reflected in the resistivity values of the upper 600 ft. The resistivity values measured at BC-1 and BC-5 are about 30 ohm-m, considerably lower than e.g., measured at the Osceola Landfill (greater than 70 ohm-m).

Sounding BC-2 is adjacent to BC-1 and of similar transmitter loop size. Figure 5.4-4 compares the geoelectric section from both soundings. BC-2 is, however, 1,500 ft further from the power line which lies along the east side of BC-1. This lessened the effect of the electrical noise from the line and increased the depth of exploration for the sounding. The geoelectric section of BC-2 is similar to BC-1 except it detects a conductive, saline unit at a depth of 1,925 ft. The thickness of dolomitization appears substantial (greater than 1,200 ft).

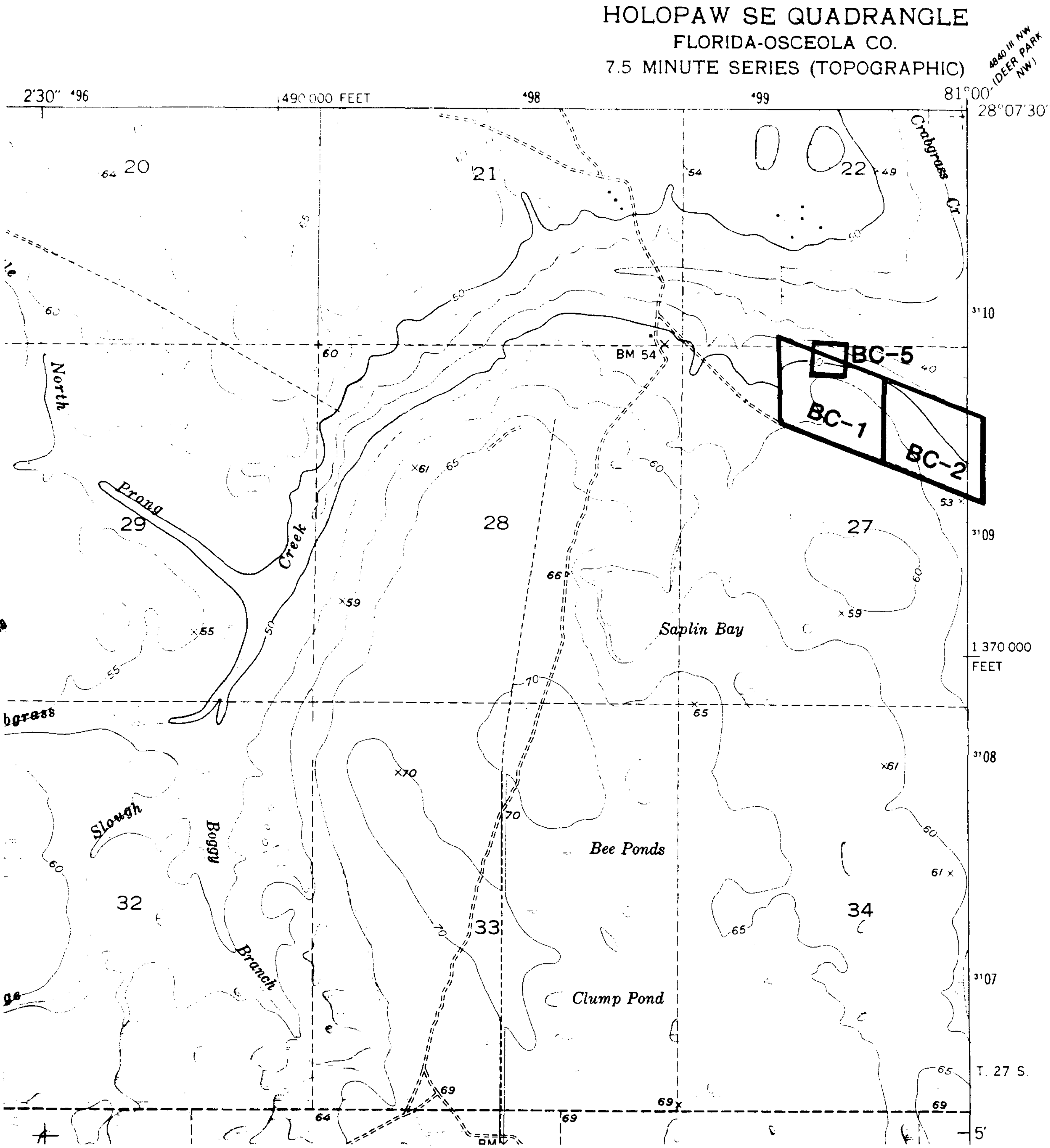
The location of soundings BC-3 and BC-4 are shown in Figure 5.4-2. They are separated by several miles from the Bull Creek test well and are contiguous loops utilizing 1,500 ft by 1,500 ft transmitter loops. The geoelectric sections from the two soundings are nearly identical (Fig. 5.4-5). Moreover, the geoelectric sections and, therefore, probably the geologic sections are similar to soundings BC-1, BC-2 and BC-5, although the depths of occurrence of individual units are different. The resistivity between 150 ft and about 700 ft is about 30 ohm-m. It is unlikely that the Hawthorn Formation extends to 700 ft, so that it is reasonable to assume that formation resistivities in the upper 700 ft of the Floridan aquifer is 30 ohm-m. Again, for resistivity values of 30 ohm-m in the upper 700 ft, chloride concentrations in excess of 400 ppm can be expected. Soundings BC-3 and BC-4 identify the suspected dolomitization porosity change at 503 ft which is shallower than that seen in the previously discussed soundings.

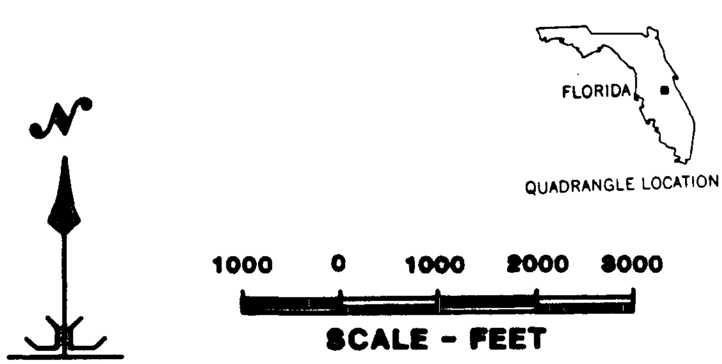
In evaluating the utility of TDEM surveys in this particular hydrogeologic setting the following conclusions can be drawn:

(1) The limestone aquifer is not of uniform hydraulic character. Dolomitization, which likely results in a decrease in porosity and permeability, is reflected by an increase in resistivity in both the downhole geophysical log and the geoelectric section derived from TDEM data. It appears that TDEM surveys can detect this change in aquifer characteristics consistently.

(2) The resistivity values in the upper 500 ft are generally below 30 ohm-m, indicative of ground water with high concentrations of dissolved solids, and consistent with a water quality in excess of 400 ppm measured in the well.

(3) The interface between ground water of salinities of about 400 ppm Cl and ground water of high salinities occur at depths in excess of 1,500 ft, and was determined in several soundings.





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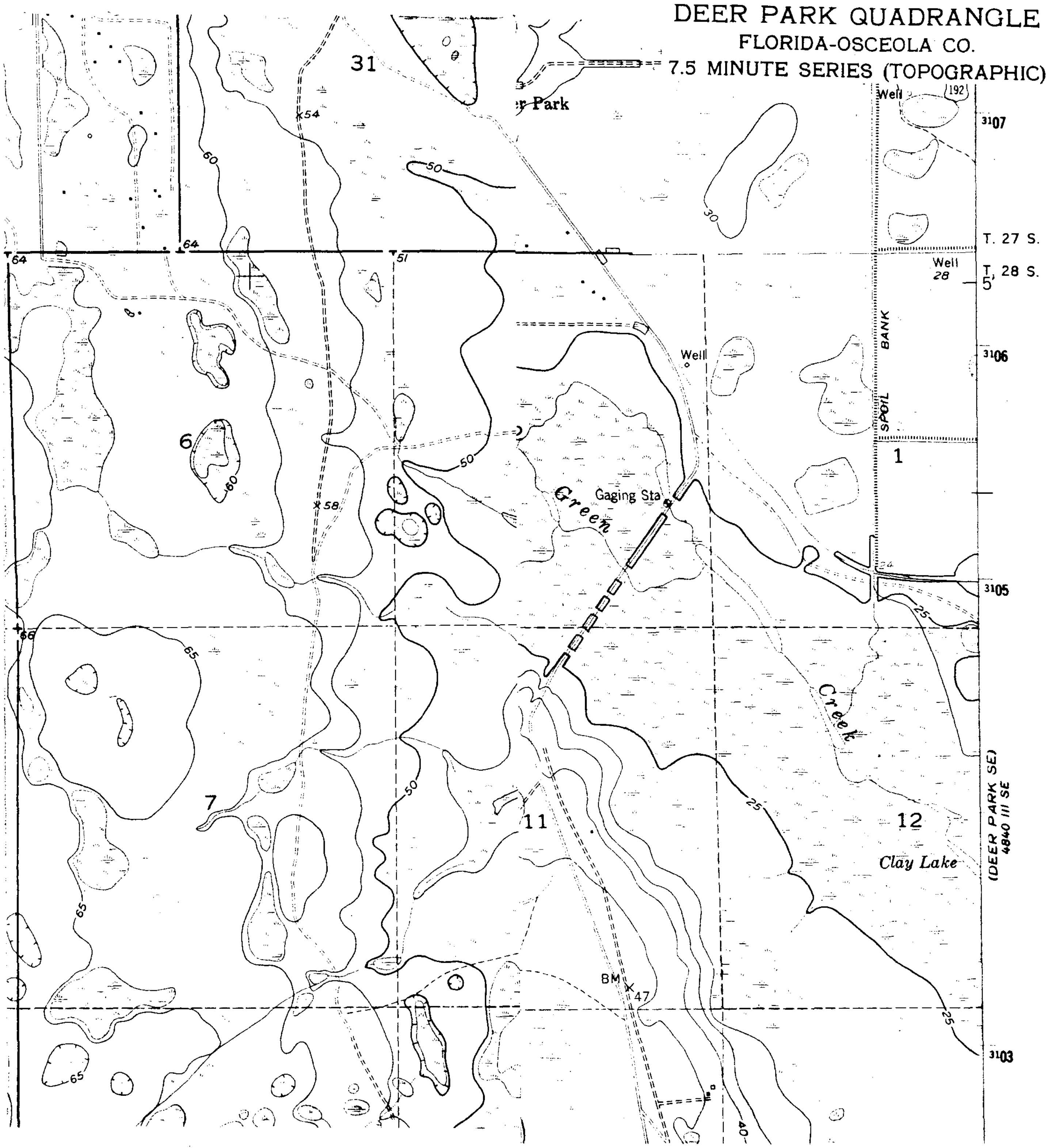
BULL CREEK LOCATION MAP

S.J.R.W.M.D. TDEM SURVEY

PROJECT NO.::90022 **FIGURE 5.4-1**

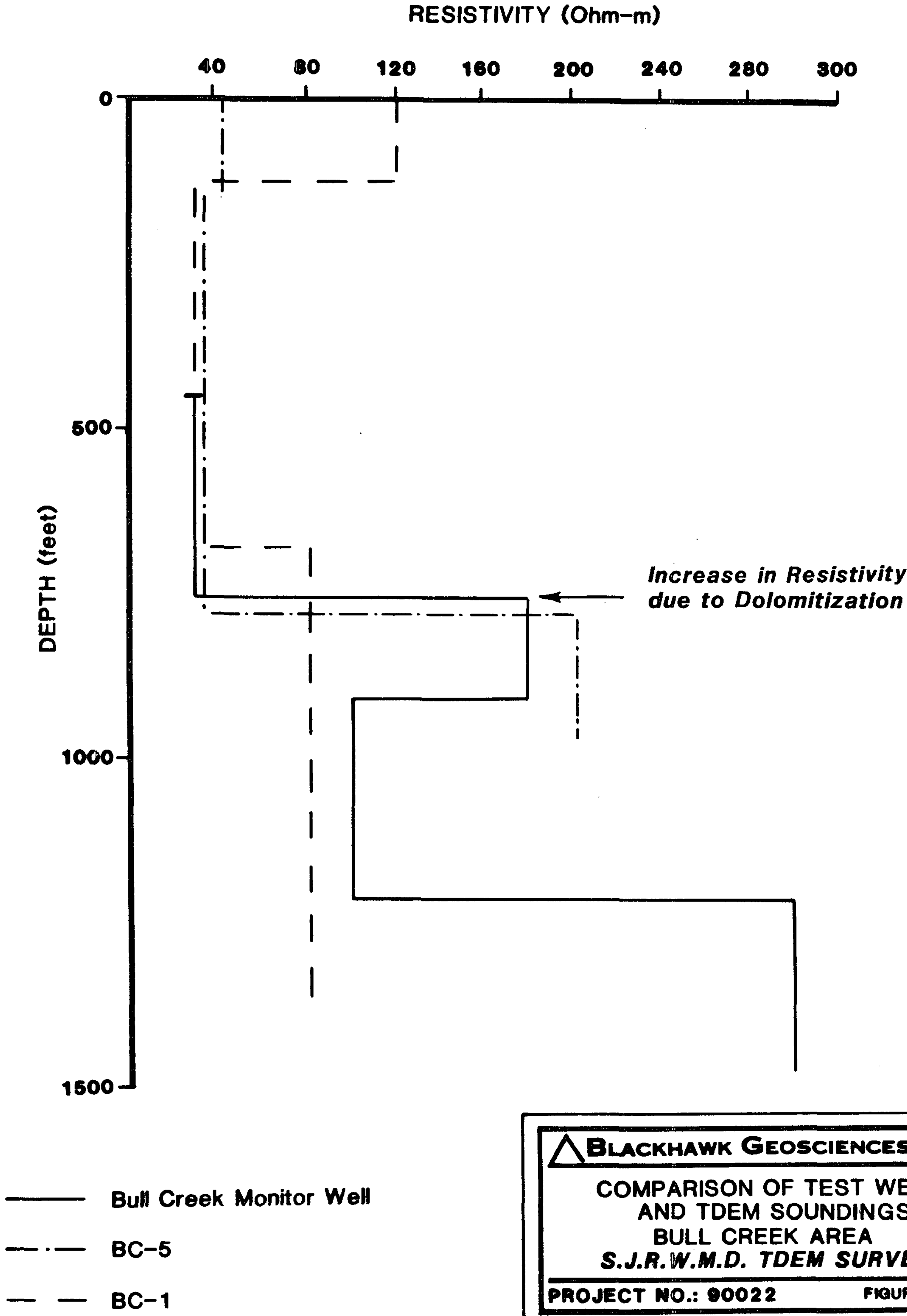


BLACKHAWK GEOSCIENCES, INC.

BULL CREEK LOCATION MAP

S.J.R.W.M.D. TDEM SURVEY

PROJECT NO.: 90022 **FIGURE 5.4-2**



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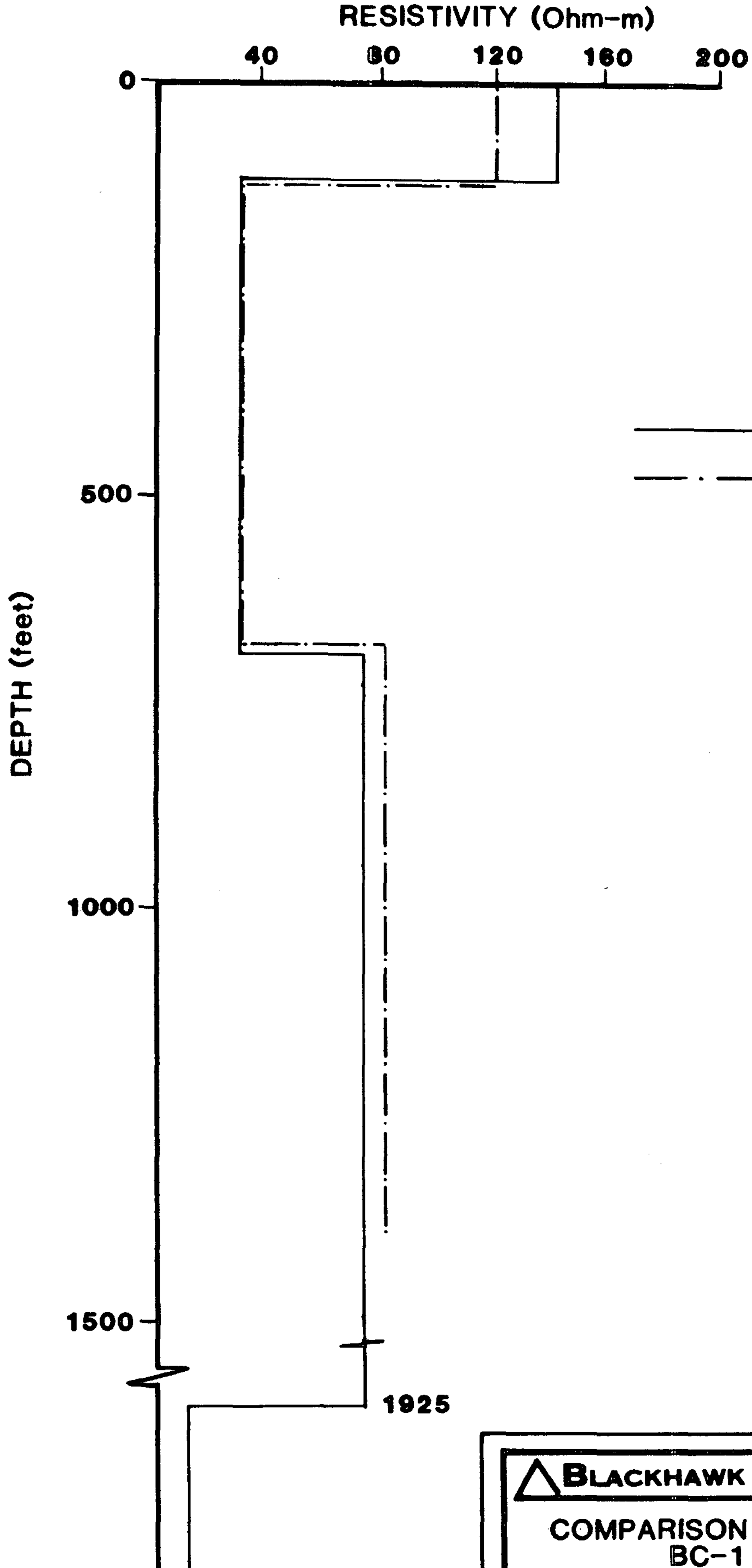
COMPARISON OF TEST WELL
AND TDEM SOUNDINGS
BULL CREEK AREA
S.J.R.W.M.D. TDEM SURVEY

PROJECT NO.: 90022

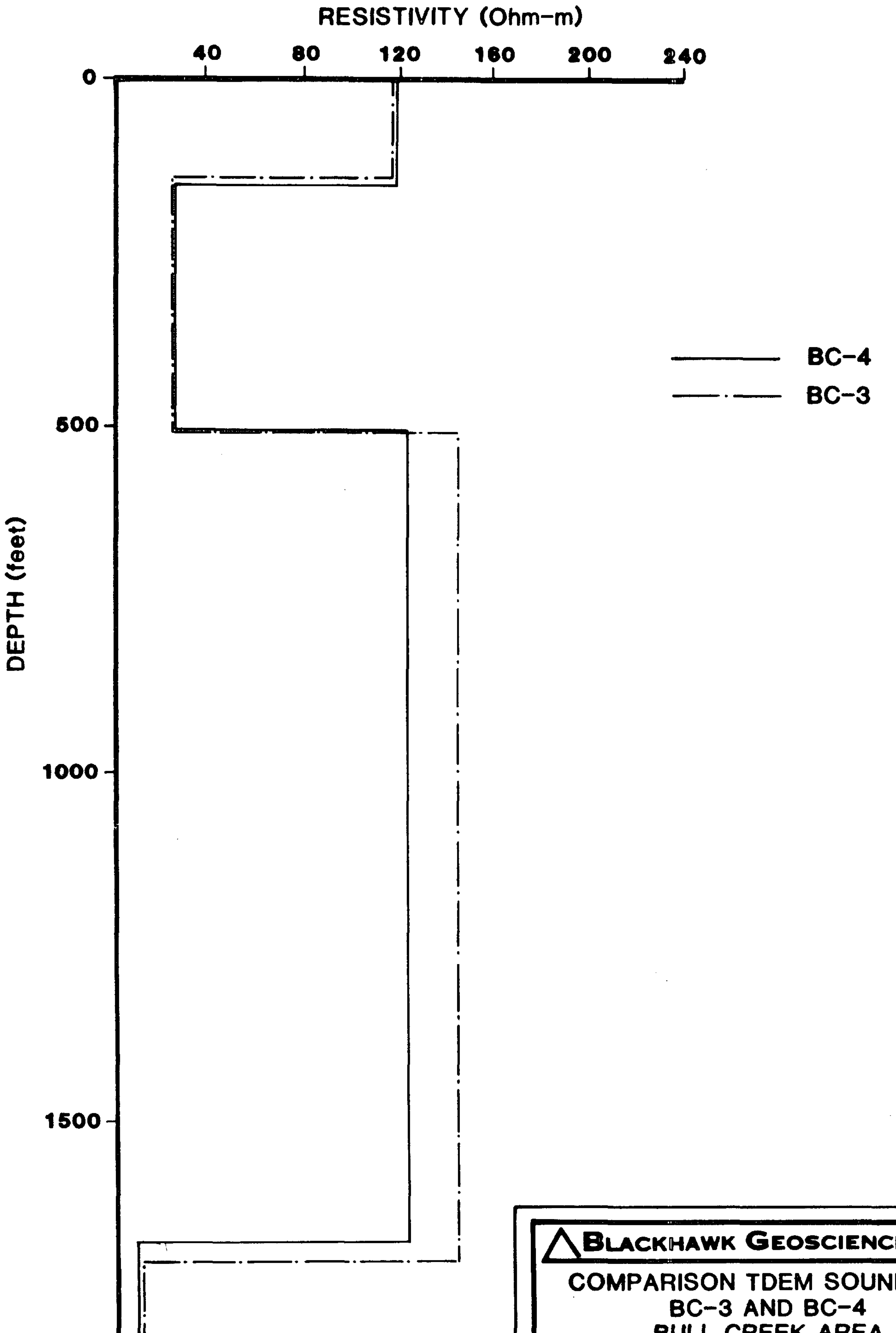
FIGURE 5.4-3



BLACKHAWK GEOSCIENCES, INC.

COMPARISON TDEM SOUNDINGS
BC-1 AND BC-2
BULL CREEK AREA
S.J.R.W.M.D. TDEM SURVEY

PROJECT NO.: 90022 **FIGURE 5.4-4**



BLACKHAWK GEOSCIENCES, INC.

COMPARISON TDEM SOUNDINGS
BC-3 AND BC-4
BULL CREEK AREA
S.J.R.W.M.D. TDEM SURVEY

PROJECT NO.: 90022 **FIGURE 5.4-5**

5.5 LAKE WASHINGTON

The location of the two soundings at Lake Washington is given in Figure 5.5-1. The Lake Washington Road Test well was located several hundred feet southwest of LW-1. The required depth of exploration was from 1,500 to 2,000 ft. Due to access restrictions rectangular loops were utilized. LW-1 was 1,000 ft by 2,400 ft and LW-2 was 1,300 ft by 2,000 ft.

A comparison of the geoelectric section derived at sounding LW-1 and an interpretation of the resistivity log of Lake Washington Road Test Well are shown in Figure 5.5-2. In comparing the two data sets the following common features are observed:

(1) In the upper Floridan aquifer between about 200 ft and 550 ft the resistivities derived from TDEM soundings (13 ohm-m) are relatively low, indicating ground water of relative high salinity. A salinity of 600 ppm chlorides was measured in the well.

(2) An increase in resistivity is observed in the TDEM derived section at 528 ft, and in the borehole resistivity log at 560 ft. The detail in resistivity variation observed in the borehole resistivity log is not measured in the TDEM geoelectric section for the reasons explained in Section 5.1. The cause for the increase in formation resistivity at about 550 ft is likely due to a change from limestone to dolomite, similar to that observed at Bull Creek.

(3) The interface between brackish water (600 ppm chlorides) and highly saline water is observed at a depth of 1,600 ft in the TDEM geoelectric section. The drill hole was terminated at a depth of about 1,000 ft.

(4) The top 173 ft resistive zone in the TDEM derived geoelectric section probably represents sand-rich surficial deposits and upper Hawthorn material.

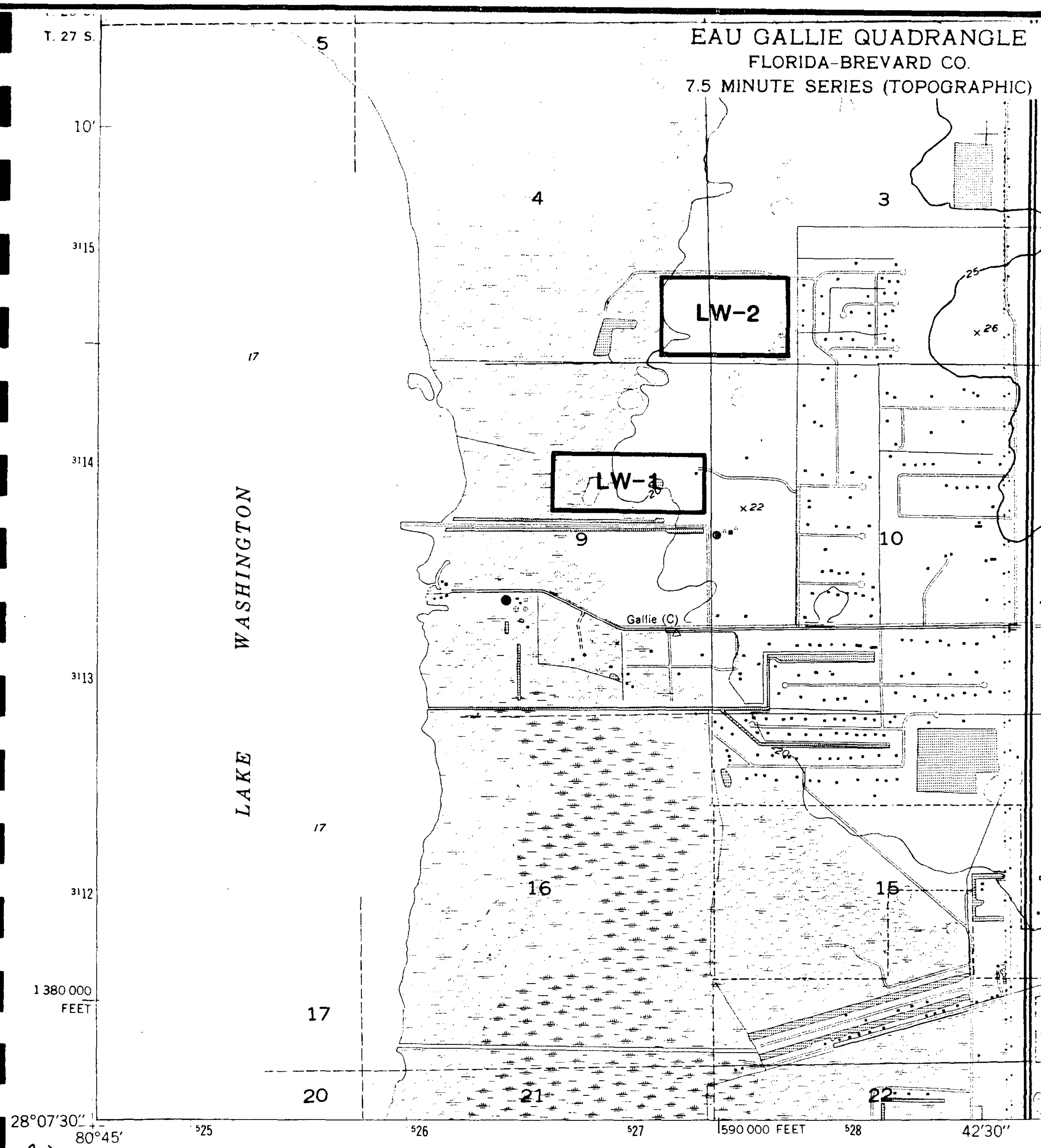
Figure 5.5-3 compares the geoelectric sections derived from TDEM soundings LW-1 and LW-2. The two soundings are separated by about 3,000 ft. The geoelectric section of the two soundings is very similar. In both soundings relative low resistivities are observed in the upper Floridan aquifer, and the aquifer's characteristics change at about 550 ft.

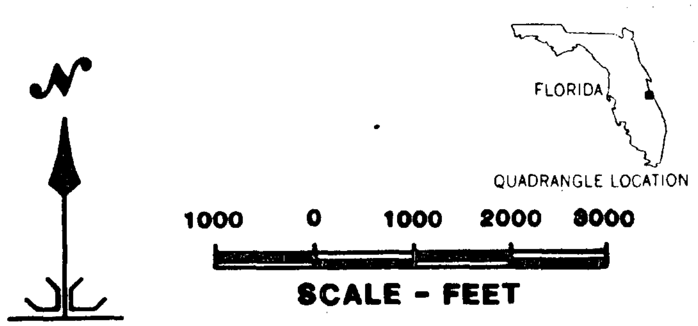
In evaluating the utility of TDEM surveys in this particular hydrogeologic setting the following conclusions can be drawn:

(1) The limestone aquifer is not uniform in hydraulic character. Dolomitization, which likely results in a decrease in porosity and permeability is reflected by an increase in resistivity in both the downhole geophysical log and the geoelectric section derived from TDEM data. It appears that TDEM surveys can detect this change in aquifer characteristics consistently.

(2) The resistivity values in the upper Floridan aquifer measured with TDEM are below 20 ohm-m, indicative of ground water with high concentration of dissolved solids, and consistent with a water quality in excess of 600 ppm measured in the well.

(3) The interface between ground water of salinities about 600 ppm Cl and ground water of high salinity occurs at a depth of about 1,600 ft and was determined in several soundings.





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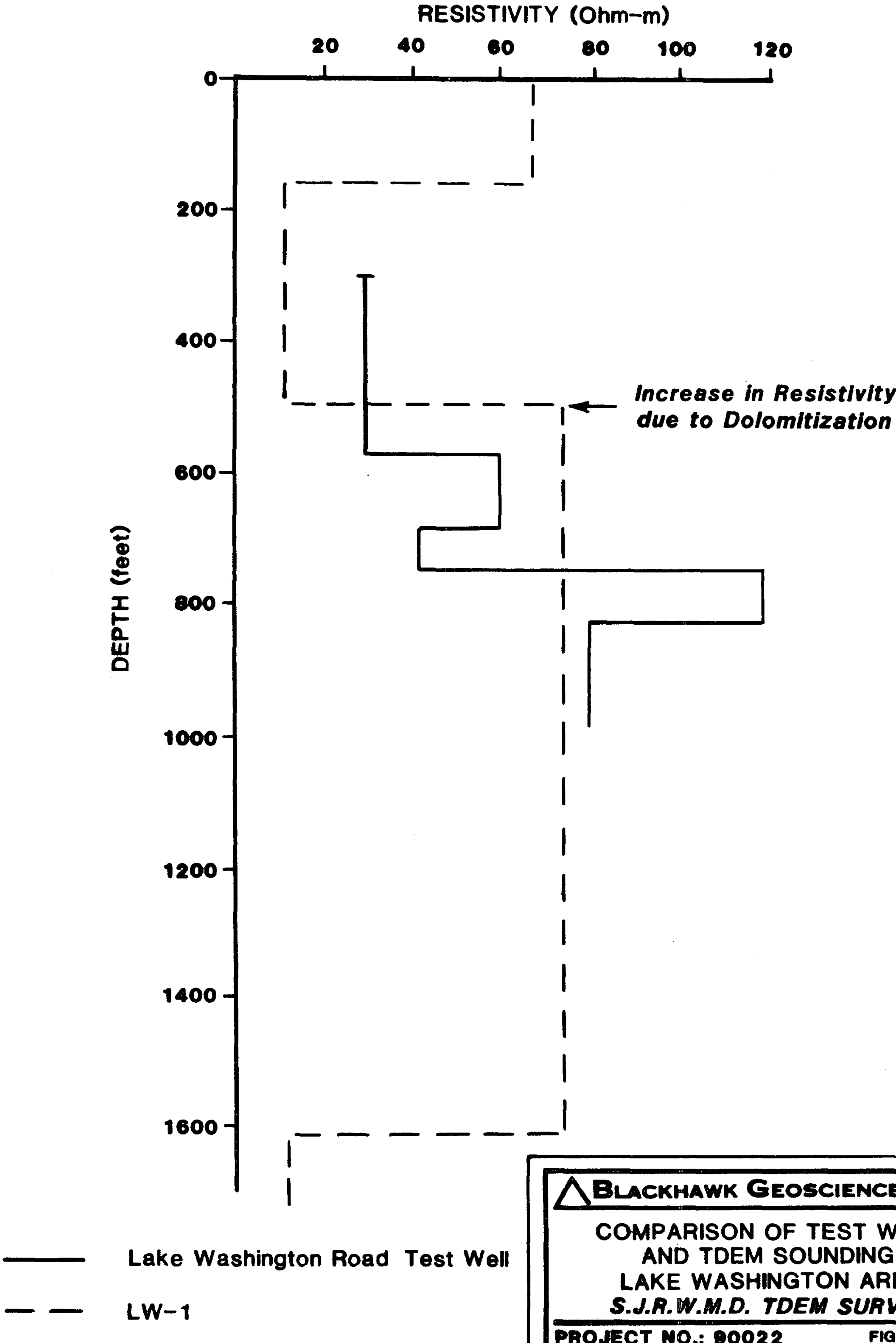
LAKE WASHINGTON LOCATION MAP

S.J.R.W.M.D. TDEM SURVEY

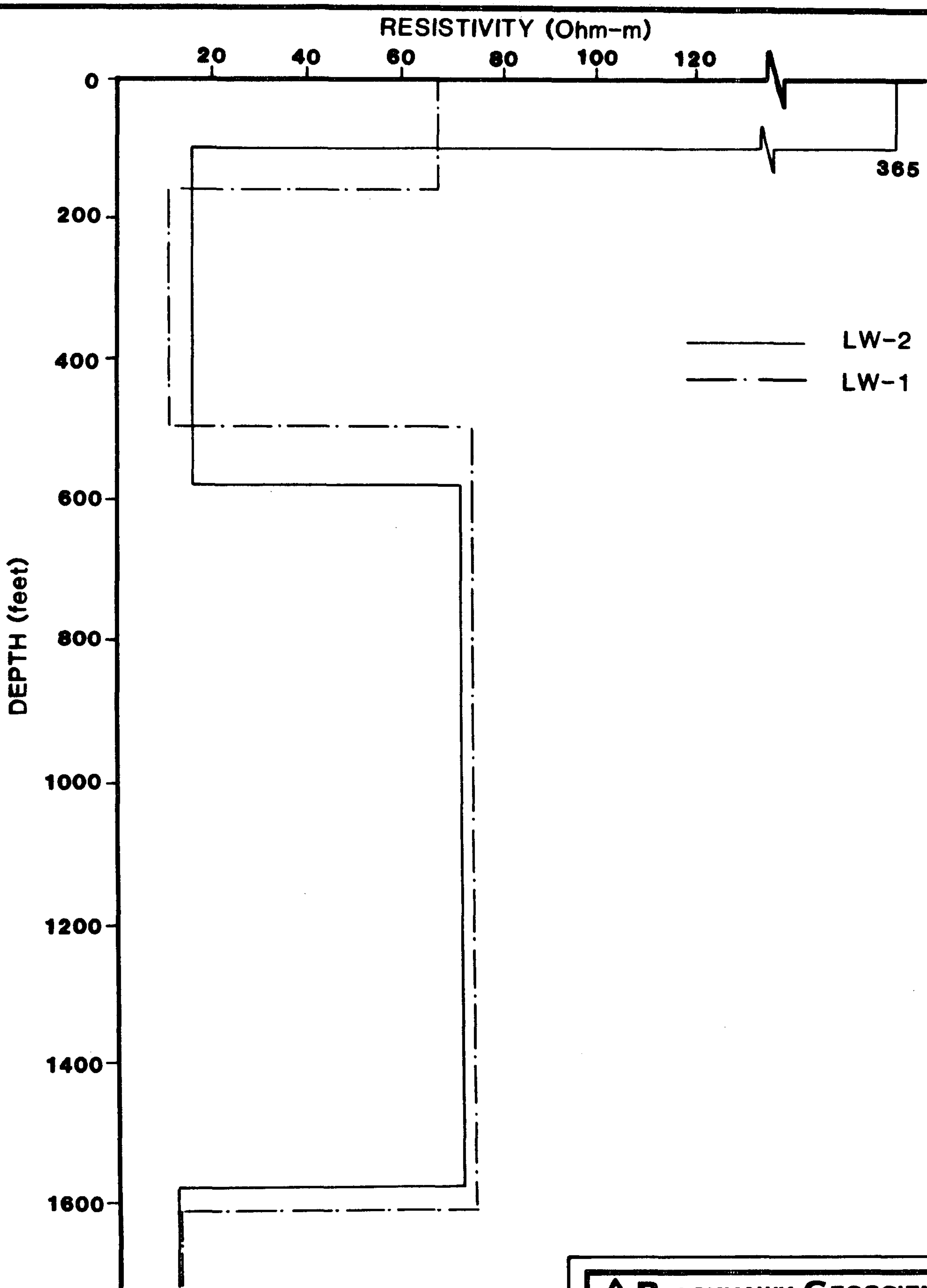
PROJECT NO.: 90022 **FIGURE 5.5-1**



BLACKHAWK GEOSCIENCES, INC.

COMPARISON OF TEST WELL
AND TDEM SOUNDING
LAKE WASHINGTON AREA
S.J.R.W.M.D. TDEM SURVEY

PROJECT NO.: 90022 FIGURE 5.5-2



BLACKHAWK GEOSCIENCES, INC.

COMPARISON TDEM SOUNDINGS
LW-1 AND LW-2
LAKE WASHINGTON AREA
S.J.R.W.M.D. TDEM SURVEY

PROJECT NO.: 90022 FIGURE 5.5-3

6.0 CONCLUSIONS AND RECOMMENDATIONS

From the tests of the TDEM survey at four sites throughout the SJRWMD, the following conclusions can be drawn about the utility of TDEM to derive hydrogeologic characteristics.

Water Quality

Information about water quality in the Floridan aquifer was available at three sites. In Table 6-1 the resistivities derived from the TDEM survey and chloride concentration from wells for the upper Floridan aquifer are listed. The reason for comparing the results for the upper aquifer is that dolomitization appears to change aquifer characteristics at several sites at greater depths. In the upper 500 ft porosities may be similar.

Table 6-1

Comparison of the resistivities for the upper Floridan aquifer derived from TDEM data and Cl concentration measured in wells

Site	Chloride Concentration	R_w (ohm-m)	Formation Resistivity Derived from TDEM (ohm-m)
Osceola Landfill	150*	10*	65-77
Bull Creek	475	5.58	23-35 (30)**
Lake Washington	896	3.34	13-20 (18)**

* From fluid resistivity log.
** (Values used in calculations).

Assuming a porosity of 35 percent for the upper Floridan aquifer, the fluid resistivity, R_w, was computed using equation {1}. Subsequently, chloride concentrations were derived using equation {2}. The values in Table 6-1 are plotted on the data set of Kwader in Figure 6-1. Since these data points represent measurements at stations separated by tens of miles, it must be concluded that TDEM can be used as a rough indicator of water quality in the upper Floridan aquifer. Particularly when measurements are made in a more confined area, where porosity variation may be limited, TDEM derived resistivities likely will be a good indicator of water quality.

Aquifer Characteristics

Major changes in resistivity with depth in the Floridan aquifer were measured in the geoelectric section at Bull Creek and Lake Washington. At Bull Creek these changes are known to relate to a decrease in porosity due to dolomitization. Assuming that the salinity of pore water remains similar, the expected decrease in porosity can be computed by using equation {1}, assuming a porosity of 35% in the upper Floridan aquifer. The computed values are listed in Table 6-2.

Table 6-2

Computation of Expected Change in Porosity with Depth in Floridan Aquifer from TDEM Derived Geoelectric Section

Site	Depth of Change (ft)	Chloride Concentration (ppm)	Computed Change in Porosity (%)
Bull Creek	515	400	10
Lake Washington	575	600	21

* * *

Approximate knowledge about changes in aquifer characteristics is clearly important for well placement and design.

Mapping Interfaces Between Fresh/Brackish Water and Saline Water

At all sites a low resistivity layer (< 4 ohm-m) was measured at depth. Table 6-3 lists the first depth of occurrence of that layer and its resistivity. In the limestone aquifers of Florida there is little question that this layer represents the interface between fresh/brackish and highly saline water. The salinity of the lower layer can be estimated by assuming a certain porosity, and validity of equation {2} at higher chloride concentration. In Table 6-3 salinities have been computed for three values of porosity - 10%, 20% and 30%. It appears that a porosity of 20% and 30% results in more realistic chloride concentrations than 10%.

Table 6-3

First Depth of Occurrence of Low Resistivity Layer (Interface Between Fresh/Brackish and Highly Saline Water)*

Sounding	Formation Resistivity Lower Layer (ohm-m)	First Depth of Occurrence Highly Saline Layer (ft)	Computed Chloride Concentration (ppm)		
			Porosity		
			10%	20%	30%
Osceola Landfill					
OS-1	2.5	302	55,000	18,200	9,460
OS-2	2.6	296	53,400	17,500	9,090
OS-3	2.5	297	55,000	18,200	9,460
Camp David Hendricks					
CDH-1	2.7	440	51,450	16,870	8,750
CDH-2	3.0	491	46,300	15,170	7,860
Bull Creek					
BC-1	(Not Detected)				
BC-2	3.3	1,926	42,070	13,780	7,130
BC-3	11.7	1,703	11,760	3,780	1,900
BC-4	11.8	1,689	11,660	3,740	1,880
BC-5	(Not Detected)				
Lake Washington					
LW-1	8.3	1,614	16,630	5,380	2,740
LW-2	7.8	1,689	17,710	5,740	2,930

*The expected concentration of chloride in ppm is calculated (i) assuming porosity values of 10%, 20% and 30%, (ii) validity of Archie's Law, and (iii) the relation, Cl (ppm) = 3500/Rw - 153.

* * *

Table 6-3 shows that this information can be obtained with TDEM surface measurements to large depth (2,000 ft) with the equipment employed (Geonics EM-37), and it can be obtained to greater depth (7,500 ft) with other equipment. The depth to highly saline water is one component necessary for evaluating the quantity of fresh water/brackish water available.

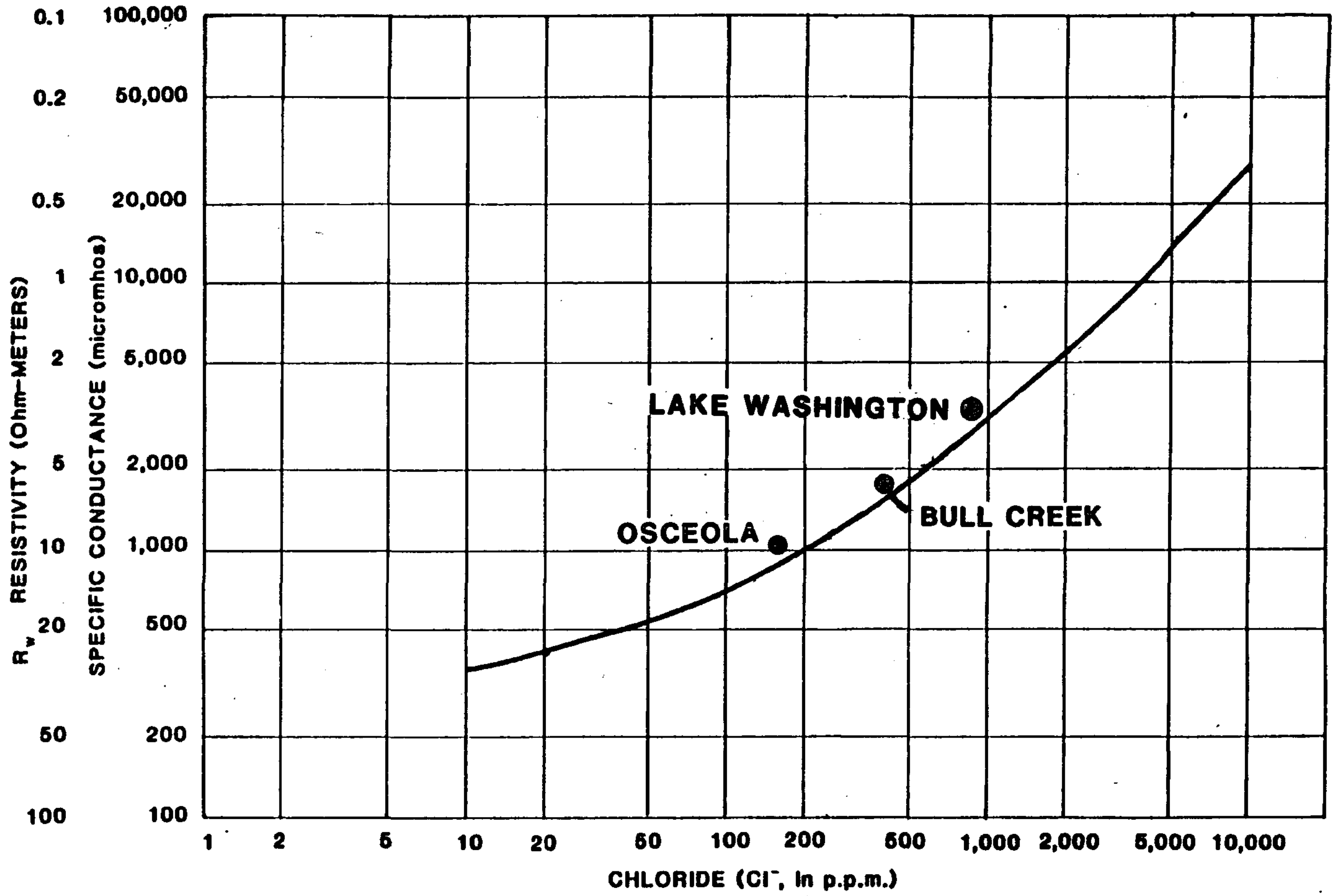
Logistical Comments

The measurements were often taken in areas with substantial culture (power lines, roads, fences). Although some data were affected by culture most were not. With proper site selection TDEM surveys can be effectively performed in urban settings.

References

Kwader, T., 1986. The use of geophysical logs for determining formation water quality, Ground Water, V. 24, No. 1, pg. 11-15.

Northwest Florida Water Management District, 1983. Interpretation of borehole geophysical logs and their application to water resources investigations, Water Resources Assessment 83-1, 176 p.



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DATA FROM TABLE 6-1
SUPERIMPOSED ON KWADER DATA
S.J.R.W.M.D. TDEM SURVEY

PROJECT NO.: 90022

FIGURE 6-1

Appendix

The Use of Geophysical Logs for Determining Formation Water Quality

by Thomas Kwader[a]

ABSTRACT

In situ water-quality measurements, with respect to various ion and dissolved solids concentrations, have been closely approximated using open-hole borehole geophysical logs. Analyses have shown good correlation between water resistivity (R_w, as determined from the logs) and dominant ion concentrations sampled from a wide range of water quality in Tertiary carbonate and granular formations.

R_w can be accurately determined by cross-plotting saturated formation resistivity (R_o), obtained from normal or lateral resistivity logs, against formation bulk porosity from neutron, density, or acoustic velocity logs. Plotting these data on Hingle Resistivity-Porosity Cross Plot (RPCP) paper with the proper matrix cementation factor (m, commonly 1.4 for unconsolidated sands or 1.6 for noncompacted Tertiary carbonates), will yield a graphical solution for R_w based upon the relationship $R_w = \phi^m R_o$. The graphical technique also provides information concerning water-quality variations with depth, true matric resistivity, location of confining beds, and vertical changes in formation porosity.

Once R_w has been determined, other ion concentrations can be estimated based upon chemical analyses of water samples from adjacent wells tapping a similar type water mass (i.e., calcium-bicarbonate, sodium-chloride water, etc.). Total dissolved solids (TDS), chloride, sulfate, potassium, sodium, magnesium, and hardness (as $CaCO_3$) concentrations have consistently shown a high correlation with R_w.

INTRODUCTION

An important and often expensive aspect of water-resources investigations is the drilling of test wells for determining formation water quality. Another problem associated with wells used for water-quality sampling is the pumped sample obtained may represent only one discrete zone or consist of a composite sample containing unknown mixed proportions and water qualities from multiple producing zones. Geophysical logs, on the other hand, can provide a continuous quantitative record of in situ formation water quality throughout the entire length of the open borehole.

This paper is a summary of an extensive research project where numerous porosity and resistivity logs were compared with actual cores and water-quality samples from wells completed in Tertiary carbonate aquifers of the southeastern Coastal Plain of the United States.

SATURATED FORMATION RESISTIVITY, POROSITY, AND MATRIX CEMENTATION RELATIONSHIPS

Archie (1942) first recognized that formation resistivity (often called the formation resistivity factor, F) is directly influenced by the bulk formation porosity (ϕ), the degree of matrix cementation (m), and a pore geometry coefficient (a), dependent upon the type of porosity present (fracture, intergranular, intragranular, etc.). This relationship is expressed as:

$$F = a/\phi^m \qquad \text{(Archie equation)} \qquad (1)$$

where:

F = formation resistivity factor (dimensionless);

a = the pore geometry coefficient, a is assumed to be equal to 1 for most Tertiary carbonates and granular systems;

ϕ = porosity (in percent) from neutron, density, or acoustic velocity logs, and

m = cementation factor (dimensionless, empirically derived).

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Discussion open until July 1, 1986.

It also has been widely recognized that the formation resistivity factor (F) is equal to the saturated formation resistivity R_o, obtained from electrical resistivity logs, divided by the reduction in resistance due to pore-water resistivity (R_w), or

$$F = R_o/R_w \quad (2)$$

where R_o = resistivity of the saturated formation, from deep resistivity log (in ohmmeters); and R_w = resistivity of the formation pore water (in ohmmeters). Note: specific conductance (in micromhos) = $10{,}000/R_w$.

Combining, we have:

$$R_w = \phi^m R_o \quad (3)$$

DETERMINING SATURATED FORMATION RESISTIVITY AND POROSITY

Although R_w is not a direct measurement of water quality, the calculated value can be directly related to most of the dominant ions present in ground water (discussed later). Porosity (ϕ) and saturated formation (R_o) resistivity values can be derived from geophysical logs currently used in water-resources investigations. Porosity values are most often obtained from neutron or density logs (compensated or uncompensated and corrected with a caliper log). Normal resistivity (16" or 64") or 6' lateral logs commonly are utilized to obtain saturated formation resistivity (R_o). Induction logs are rarely used in water-resources investigations since they have severe limitations in fresh-water environments. Ideally, the resistivity log should be reading saturated formation resistivity (R_o; note: $R_o = R_t$ in water-saturated formations) beyond the mud cake and flushed zones. Optimum results are obtained in small-diameter, mud-filled, smooth boreholes in order to minimize rugosity effects. Consideration also should be given to analyzing lithologically thick zones at least twice the probe's radius of investigation.

CEMENTATION FACTOR (m)

Although the ages of the carbonates studied range from Eocene to Upper Miocene, in all cases the limestones and dolomites are considered to be poorly cemented and relatively uncompacted. For log interpretation purposes, these carbonates respond as granular systems as opposed to carbonates commonly referred to in the petroleum literature. This observation has considerable significance in the interpretation of geophysical logs since many of the logging principles (particularly resistivity) are based upon the fact that the formations analyzed are of a granular nature. For example, the cementation factor (m) for many oil field carbonates is often assigned a value of 2.0 or more. The cementation factor for most of the Tertiary carbonates analyzed in the Coastal Plain is commonly in the range of 1.4 to 1.8 as derived by empirical methods. A cementation factor of 1.3 to 1.4 appears to fit best for most unconsolidated quartz sand aquifers (Table 1). Although this difference may not appear to be significant compared to values traditionally used, the slight reduction is critical since m is expressed as an exponent [as in equations (1) and (3); see Pickett, 1973, for a more complete discussion on derivation of m]. Another problem with earlier attempts to derive R_w from resistivity/porosity relationships has been the use of uncalibrated and/or uncompensated porosity-type logs. Many of these logs were assigned a porosity too low for Tertiary formations. Borehole compensated logs, now available for water-resources investigations and numerous porosity tests run on cores, indicate carbonate porosities are often in the 25 to 50 percent range, and although rare, may attain as much as 70 percent in some moldic porosity-type intergranular dolomites.

Table 1. Typical Cementation Factor (m) Values for Tertiary Lithologies

	m
Miocene-Pliocene unconsolidated surficial sands	1.3-1.4
Slightly consolidated sands	1.4-1.5
Argillaceous limestones	1.4-1.6
"Shelf-type" poorly consolidated limestones	1.5-1.7
Clean "platform-type" limestones	1.6-1.8
Dolomitic limestones	1.8-2.0
Sucrosic dolomites	2.0-2.2
Crystalline dolomites	2.2-2.4

PORE-WATER RESISTIVITY (R_w) FROM RESISTIVITY-POROSITY CROSS PLOTS

Although pore-water resistivity (R_w) can be solved numerically by substituting values into equation (3), a graphic solution developed by Hingle (Hilchie, 1982) clearly shows water-quality trends throughout the borehole. If saturated formation resistivity measurements (R_o) are plotted against porosity measurements on the correct Resistivity-Porosity Cross Plot (RPCP) paper (determined by degree of cementation, m), R_w can be determined by plotting a straight line from the matrix resistivity intercept (at zero

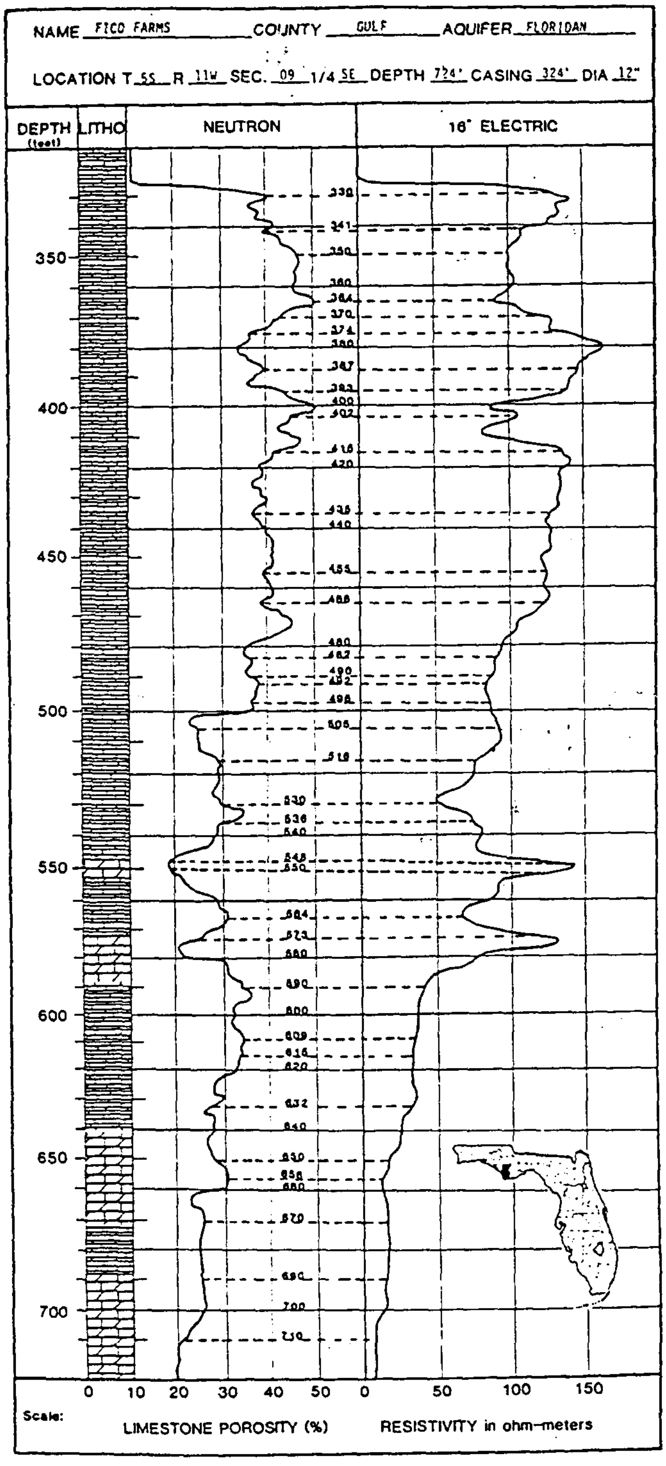

Fig. 1. Neutron and short normal (16") resistivity log from a test well in the coastal area of northwest Florida.

porosity), through the saturated formation resistivity (R_o), and read at the y-intercept at 100 percent porosity. The resistivity reading at the 100 percent porosity will represent the resistivity of the water (R_w). Three major assumptions are made using the RPCP procedure: (1) m does not change appreciably throughout the zones analyzed; (2) all pore spaces are completely saturated with water (as opposed to hydrocarbons); and (3) the formations analyzed are clean quartz sands or carbonates, relatively free of clays, with very high matrix resistivities. R_w cannot be obtained in marls or clays due to the additional reduction in resistivity from ionic structural bonding, a characteristic of clay minerals.

RESISTIVITY-POROSITY CROSS PLOT EXAMPLE

Neutron and resistivity logs (Figure 1) were run in a test hole drilled in the coastal area of panhandle Florida. Forty-seven depths were selected for analyses in the open portion of the borehole between the bottom of the casing (324′) and the total depth of the well (724′). Figure 2 illustrates a method for obtaining R_w by the RPCP method. Porosity and saturated formation resistivity values were then plotted on the RPCP paper (Figure 2) with m = 1.6 to determine R_w for the various depths analyzed. The cementation value of m = 1.6 was based upon cuttings which consisted of a slightly argillaceous, poorly-indurated micritic limestone. Several hydrogeologic and water-quality

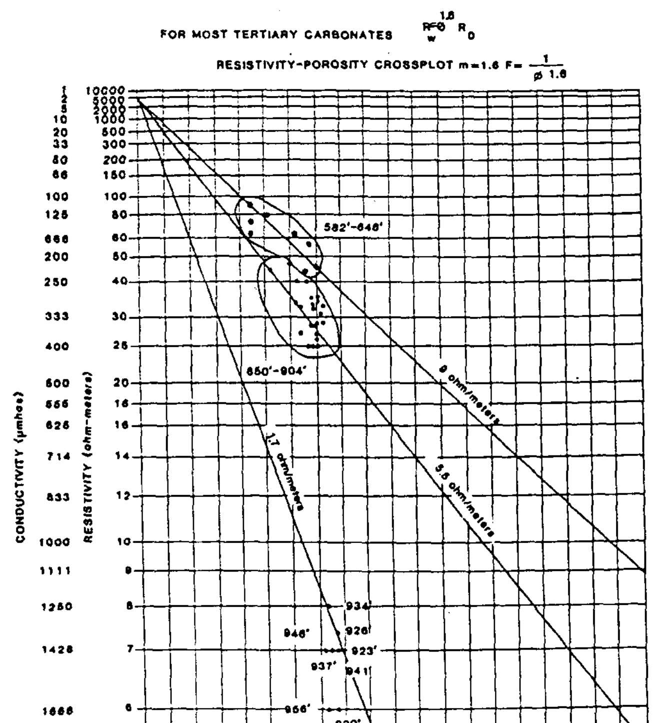

Fig. 2. Resistivity-Porosity Cross Plot (RPCP) for selected depths from logs in Figure 1.

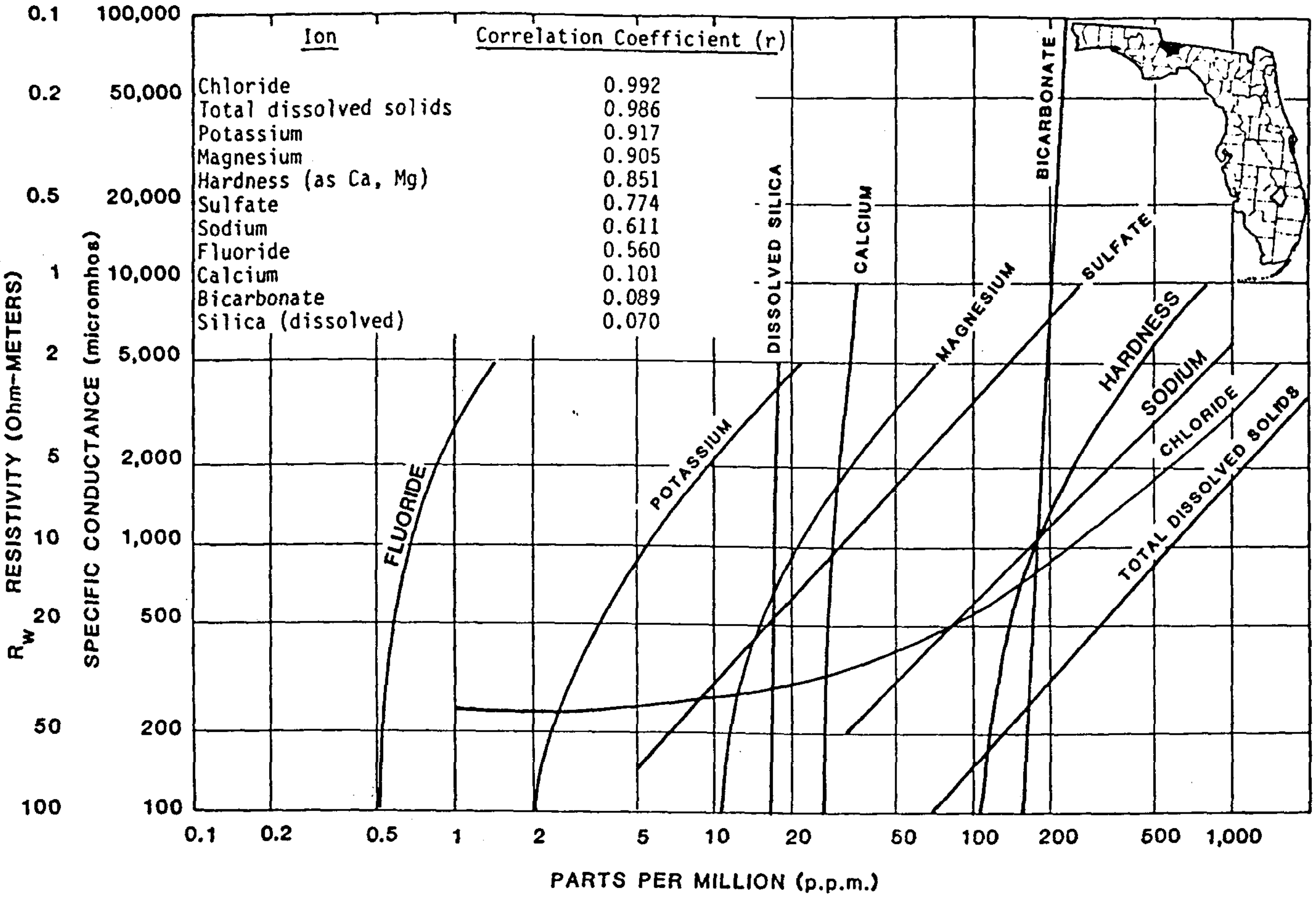

Fig. 3. Approximate relationship between R_w and various ions for wells tapping the Floridan Aquifer in Gadsden County, Florida. The table inset shows the approximate Pearson correlation coefficient (r) for each of the ions, as plotted against R_w.

inferences can be made based upon the data plotted: (1) at least three distinct water-quality zones appear to be present below the bottom of the casing to 580 feet—Zone 1: 330′-468′, R_w = 30 ohmmeters; Zone 2: 480′-498′, R_w = 18 ohmmeters; Zone 3: 505′-580′, R_w = 10 ohmmeters; below 580′, continuing to the total depth of the well, the water resistivity continuously decreases with depth (an increase in the slope of line indicates "poorer" quality water). At depth 710′, R_w declines to less than 0.4 ohmmeters [derived from equation (3)]. The apparent stratification of the upper three zones may be attributed to the presence of a "low"-permeability layer separating these zones. A second observation: (2) relating to the "low"-matrix resistivity (R_{ma}) (5,000 ohmmeters at zero porosity) coincides with observations from the cuttings which show an "impure" fine-grained limestone. "Pure" limestones, dolomites, and quartz sands have a matrix resistivity near infinite ohmmeters.

RELATIONSHIP BETWEEN WATER RESISTIVITY AND WATER QUALITY

As mentioned earlier, water resistivity is not a direct indicator of water quality, but there usually exists a strong correlation between water resistivity and ion concentration, for the major ions present within a particular water mass type (calcium carbonate, sodium chloride, etc.). Ions consistently showing a good correlation with R_w include chloride, sulfate, potassium, sodium, magnesium, hardness ($CaCO_3$), and total dissolved solids. Figure 3 illustrates this relationship for wells tapping the Floridan Aquifer (limestone) in Gadsden County along the northern portion of panhandle Florida. The lines on the figure are based on approximately 30 laboratory analyses throughout a wide range of water resistivity. Some ions exhibit a high degree of correlation (see table inset in Figure 3) while some of the "minor" constituents show a poor correlation. Chloride, commonly the first ion to render ground water

Table 2. Estimated Chloride Concentration (ppm) as Calculated from R_w for Well Analyzed in Figures 1 and 2

Zone	*Depth(s)*	R_w	*Approximate chlorides (ppm)*
1	330'-468'	30	15
2	480'-498'	18	84
3	505'-580'	10	222
–	690'	1.0	3,012
–	710'	0.4	7,662

unpotable, fortunately has a high degree of correlation to R_w for all water masses studied throughout the southeastern Coastal Plain of the United States.

A general equation relating R_w to chloride concentration (ppm) for wells tapping the Floridan Aquifer in areas where the water type is predominantly calcium bicarbonate may be expressed as:

$$\text{Chlorides (ppm)} = \frac{3{,}100}{R_w} - 88 \qquad (4)$$

Using this equation, the chloride concentrations can be estimated from R_w as determined by the RPCP in Figure 2. Table 2 shows the results of a few of these chloride calculations. Since drinking water standards usually limit chloride concentrations to 250 ppm, the lower limit of potable water in this example appears to be at a depth of about 580 feet. Chloride concentrations also appear to increase dramatically below this depth, with the bottom of the borehole probably exceeding 7,000 ppm chloride.

SUMMARY

Accurate water-quality measurements, with respect to various dominant ion concentrations, can be closely approximated, in situ, using open-hole borehole geophysical logs currently available to water-resources investigations for a wide range of Tertiary carbonate and granular formations. Some of the earlier problems associated with this method were related to the assumptions that: (1) Tertiary carbonates are well-cemented ($m \geq 2$), and (2) porosities were generally underestimated. The latter problem has largely been resolved with the introduction of compensated logs to water-resources investigations. This information is urgently needed by hydrogeologists charged with the responsibility of evaluating and protecting the ground-water resources.

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* * * * *

Thomas Kwader has logged over 500 wells while employed at the Northwest Florida Water Management District since 1976. In 1982, he received his Ph.D. in Geology from Florida State University with his primary research in, and dissertation entitled: "The Interpretation of Borehole Geophysical Logs in a Freshwater Carbonate Environment and Their Application to Water Resources Investigations." He also has taught numerous graduate courses and workshops on geophysical logging. Currently, he supervises the borehole geophysical logging program for Woodward-Clyde Consultants in Tallahassee, Florida.

PRINCIPLES OF TIME DOMAIN EM

BLACKHAWK GEOSCIENCES, INC.

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.

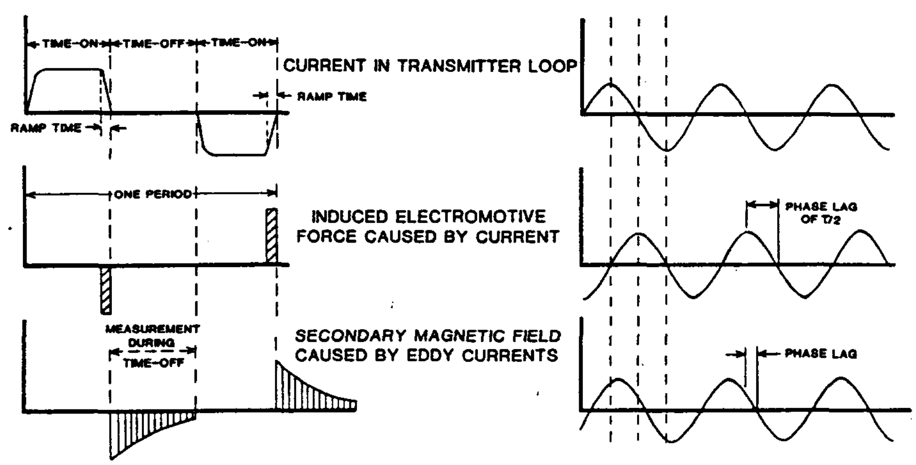


Fig. 1. System waveforms in time domain EM (TDEM) and frequency domain EM (FDEM).

The receiver measures the emf due to the secondary magnetic field of these eddy currents induced in the subsurface, and in the case of FDEM, the emf measured by the receiver is the sum of (1) the primary magnetic field (emf_p due to currents in the transmitter), and (2) the secondary magnetic field (emf_s due to eddy current flow in the ground). Thus,

$$emf_t = emf_p + emf_s$$

where subscript t, p and s refer to total, primary, and secondary magnetic field, respectively. Clearly, emf_s is the only component containing information about the subsurface. Unfortunately, in most situations, the amplitude of emf_s is only one part in 10^4 parts of emf_p. Thus, in FDEM, a small component of emf containing all the useful information about the subsurface must be measured in the presence of a large component containing no information.

In the EM-31 and EM-34 ground conductivity is determined by measuring only the component of emf_s that is in quadrature phase (90^o out-of-phase) with emf_p. Unfortunately, theory shows that the in-phase component is more sensitive to ground conductivity. Measuring only the quadrature phase component limits the accuracy, exploration depth, and utility of FDEM systems.

TDEM improves the situation, because measurements are made during the time the transmitter is off. During off-time the only component of emf measured by the receiver is emf_s. Emf_s is determined in the absence of emf_p, greatly improving its accuracy of measurements.

Question.-- Briefly explain how subsurface resistivities are derived from TDEM measurements.

Answer.-- A TDEM system consists of a transmitter and a receiver. The transmitter configuration often used in ground water and environmental applications is a square loop of insulated wire laid on the ground surface (Figure 2). A multi-turn air coil receiver (about 1 m diam) is placed in the center of the loop. The sizes of the transmitter loops employed are mainly dependent upon the required exploration depth and geoelectric section. Typically, the side of a square is about one-half to two-thirds of the required exploration depth. Thus, for exploration depths to about 200 ft, 75 ft by 75 ft transmitter loops may be employed.

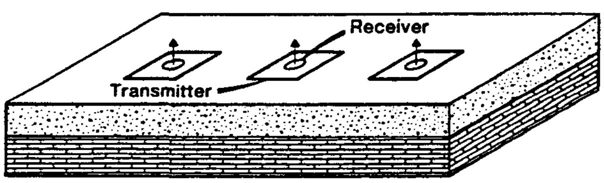


Fig. 2. Transmitter-receiver array in TDEM.

The current waveform driven through th transmitter loops is shown in Figure 1. The waveform consists of equal periods of time-on and time-off. The base frequencies employed in the Geonics instru mentation we employ can be varied from 300 hz, 30 hz 3 hz and 0.3 hz. These frequencies result in on/off intervals of 0.833, 8.33, 83.3 and 833 msec, respectively.

The current driven through the transmitter loops creates a primary magnetic field. During the rapid current turn-off this primary magnetic field is time variant and in accordance with Faraday's Law ther will be an electromagnetic induction during this time (Figure 1b). This electromagnetic induction in turn results in eddy current flow in the subsurface. Th intensity of these currents at a certain time an depth depends on ground conductivity.

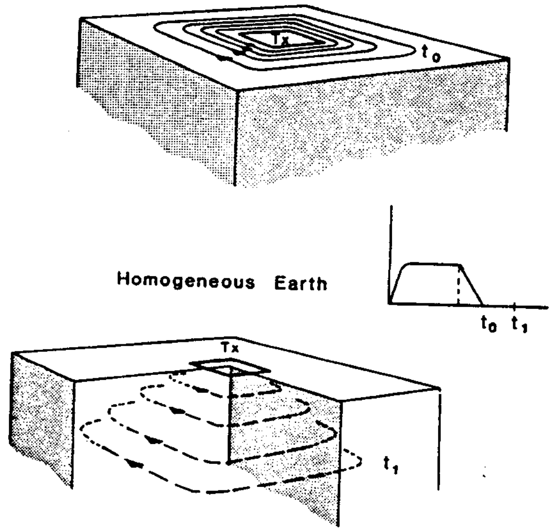


Fig. 3. Current distribution in FDEM at two time after current turn-off.

In near horizontally layered ground, the eddy currents are horizontal closed rings concentric about the center of the transmitter loop. A schemati illustration of these currents is shown in Figure 3 Immediately after turn-off (t_0) the currents are concentrated near the surface, and with increasing time currents are induced at greater depth (t_1).

The receiver measures the emf due the secondary magnetic field caused by these ground eddy currents (Figure 1c). At early time, when the currents ar mainly concentrated near the surface, the emf measure will mainly reflect the electrical resistivity of nea surface layers. With increasing time, as currents are induced at greater depth, the emf measured wil progressively be more influenced by properties c deeper layers. Thus, in TDEM exploration, depth is mainly a function of time of measurement after turn-off.

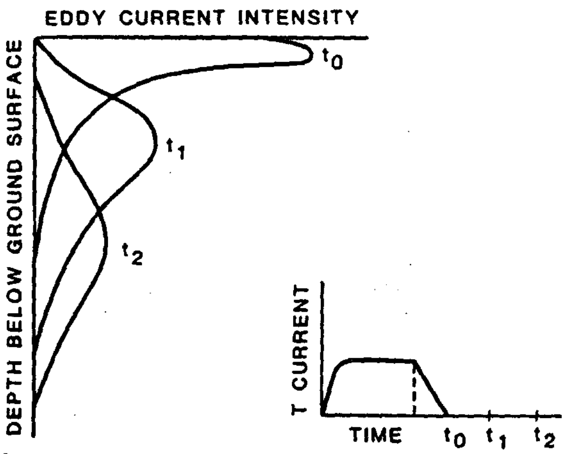


Fig. 4. Schematic illustration of eddy current distribution at different times after turn-off.

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.

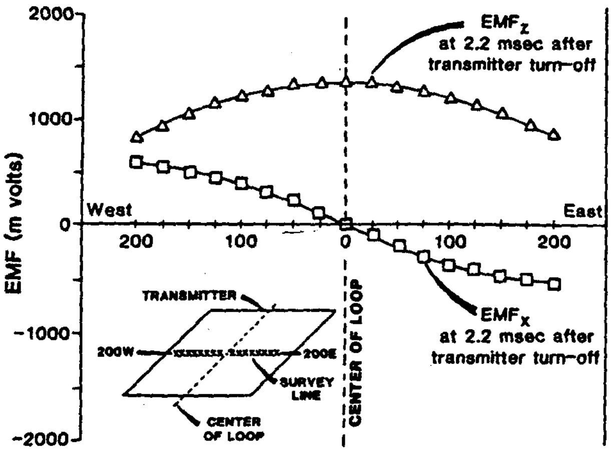


Fig. 5. Spatial behavior of emfs due to vertical (emf_z) and horizontal (emf_x) magnetic field on a profile through the center of square transmitter loop at one time (2.2 millisec) after turn-off.

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 va because it (1, reduces the cost of land surveys measurement errors, and (2) allows for some flexib ity in the field in positioning the measurement s tions.

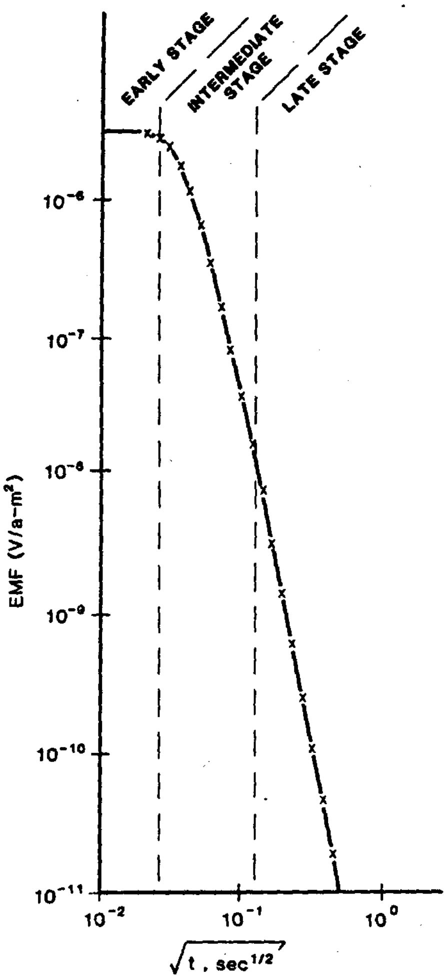


Fig. 6. Typical transient behavior of emf_z in center of square transmitter loop.

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.

The processing and display of TDEM data is in many respects similar to that used in other electrical and electromagnetic methods. The objective of processing TDEM data is to obtain a solution for the resistivity stratification of the subsurface that matches the observed transient.

L022S001

MODEL: 5 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)
2.81	9.3
17.77	33.1
3.01	46.1
39.42	44.8
6.76	

TIMES	DATA LATE MEASURED	CALC LATE	% ERROR
8.90E-05	7.23E+01	7.87E+01	-8.071
1.10E-04	4.75E+01	5.11E+01	-6.997
1.40E-04	3.30E+01	3.38E+01	-2.527
1.77E-04	2.39E+01	2.45E+01	-2.280
2.20E-04	1.83E+01	1.91E+01	-4.201
2.80E-04	1.49E+01	1.55E+01	-3.952
3.55E-04	1.28E+01	1.35E+01	-5.770
4.43E-04	1.13E+01	1.22E+01	-7.412
5.64E-04	1.02E+01	1.05E+01	-3.135
7.13E-04	9.22E+00	9.31E+00	-0.981
8.85E-04	8.14E+00	8.43E+00	-3.402
1.10E-03	7.39F+00	7.52E+00	-1.740
1.41E-03	6.83E+00	6.72E+00	+1.519
1.78E-03	6.36E+00	6.36E+00	+0.002
2.21E-03	6.02E+00	6.06E+00	-0.722
2.83E-03	5.82E+00	5.86E+00	-0.728
3.57E-03	5.80E+00	5.87E+00	-1.050
4.46E-03	5.74E+00	5.82E+00	-1.432
5.67E-03	5.83E+00	5.92E+00	-1.612
7.16E-03	6.01E+00	5.98E+00	+0.543
8.81E-03	5.98E+00	6.05E+00	-1.133
1.10E-02	6.26E+00	6.17E+00	+1.339

RMS ERROR: 5.7275%

Table 1. Inversion table.

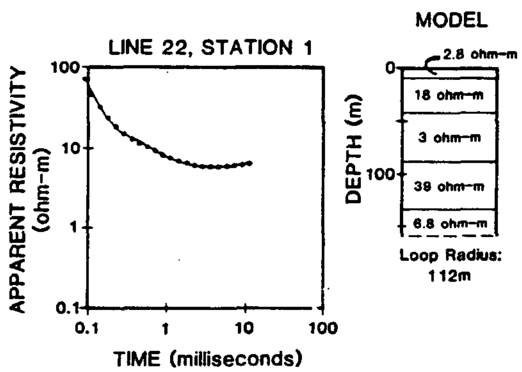


Fig. 7. Example of TDEM apparent resistivity curve and inverted geoelectric section.

The inversion of measured TDEM data into vertical resistivity stratification can be performed on a PC. An example of a data set derived for a sounding is given in Figure 7 and Table 1. In the apparent resistivity curve shown on the left (Figure 7) the measured data at each time gate is superimposed on a model curve of the geoelectric section shown on the right. This geoelectric section represents the best one-dimensional match to the experimental data. In addition to this visual display, an inversion table (Table 1) is obtained that lists (column 4) the error between measured and computed emf at each time gate, as well as an overall RMS error. The data shown on Figure 7 are typical of data quality common to TDEM soundings. Typically, 20 to 30 data points are obtained equally spaced on a logarithmic scale of time. Thus, clearly there is a major difference between TDEM soundings and profiling with the EM-31 and EM-34 (where only a few data points at different effective depths are obtained).

Question.-- If TDEM is a major improvement i electrical geophyics, why has it not been extensively used in ground water and environmental applications?

Answer.-- TDEM has been in common use in thi search for base and precious metals, and for deep electrical soundings in support of hydrocarbon and geothermal exploration for about 15 years. The reasoi for its sparse use so far in ground water and environmental investigations was that no equipment was heretofore available for the often shallow depth (< 100 ft) requirements, common to environmental investigations.

Equipment for shallow exploration recently became available, opening a whole new range of applications for this powerful electrical measurement technique. Figure 8 shows the exploration depth range covered by various instruments.

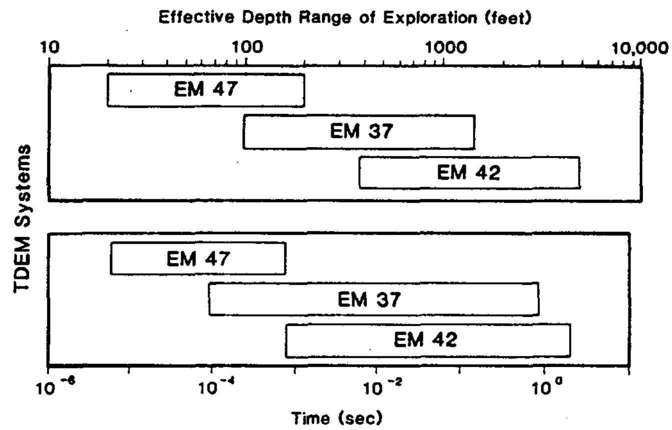


Fig. 8. Effective depth range of exploration and time range of measurement of various TDEM systems.

Question.-- What is geologic noise and why is TDEM less sensitive to such noise?

Answer.-- We define geologic noise as variation in subsurface conditions that obscures the exploration objective. Consider the schematic geologic cross section of the Floridan aquifer (Figure 9). The limestones may be overlain by overburden, likely varying laterally and vertically in soil type and thickness. At some depth in the aquifer an interface between saline and fresh water may occur, and an important exploration objective could be the mapping of this interface. Geologic noise for this objective is the change in soil type and thickness of the overburden. This noise can be very large in direct current resistivity, CSAMT and electromagnetic induction profiling.

Geologic noise is a function of the exploration objective. For example, if the objective in the setting of Figure 9 would have been the mapping of overburden thickness and type (e.g., to delineate areas of prime aquifer recharge), then what was geologic noise before becomes the exploration objective. Geologic noise is often the major cause of poor data quality in geophysical surveys for environmental and ground water applications.

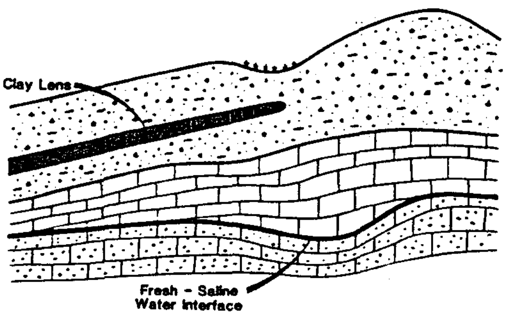


Fig. 9. Schematic geologic section of Floridan aquifer.

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.

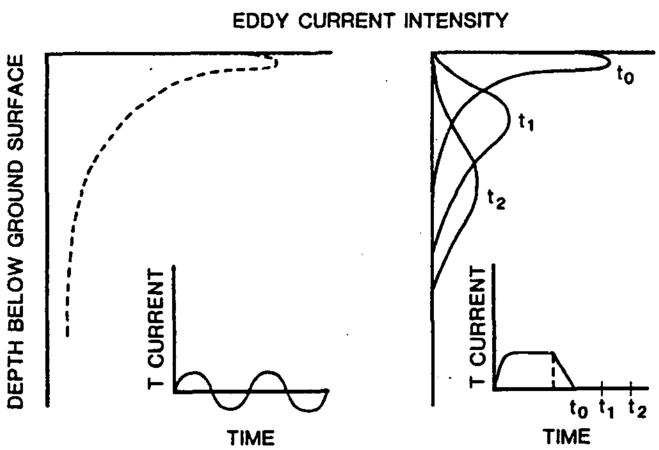


Fig. 10. Eddy current intensity in FDEM and TDEM.

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.

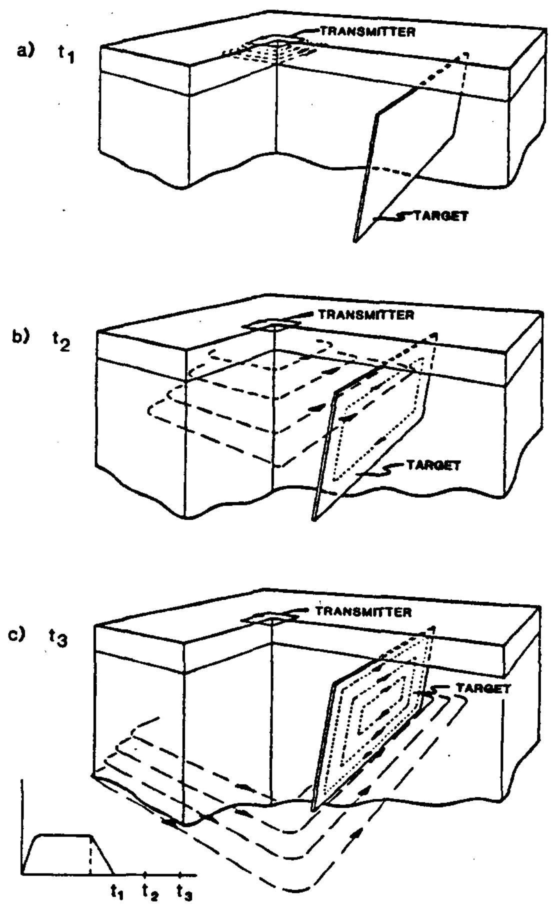


Fig. 11. Illustration of eddy current flow induced in overburden, host rock, and fracture or shear zones at different times.

Thus, in all electrical and electromagnetic methods the geoelectric section is derived by measuring resistance to current flow. We cannot selectively cause current flow in fractures and shear zones, but currents will also be induced in overburden, host rock, fractures and shear zones. The challenge is to isolate the response due to a fracture from the total response, which also contains contributions due to current flow in overburden and host rock.

TDEM is the most effective method for recognizing fractures and shear zones under overburden cover. Figure 11 conceptually explains the physical principles involved. It schematically shows a near vertical fracture zone below overburden cover, and a nearby TDEM source loop induces eddy current flow in the subsurface. At early time (t_0) eddy currents are dominantly situated in the overburden because current flow has not yet reached the fracture. Therefore, a measurement of emf at time, t_0, will not reflect the presence of a fracture zone. At later time currents are induced in the fracture, and because the fracture zone is likely less resistive than adjacent host rock, currents will be preferentially oriented in the fracture plane. In this intermediate time range the emf will contain major contributions due to currents in overburden, host rock and fractures. Currents in overburden may still dominate and fracture zones may be barely detectable. Since the fracture is less resistive than adjacent host rock, currents will decay faster in host rock than in the fracture, and there will be a time range where the fracture has maximum detectability.

To map fractures and shear zones, often different modes of surveying are employed than for determining vertical resistivity stratification (soundings). Figure 12 shows several survey modes. If the strike of the fracture is known a long transmitter loop may be laid out, and profiles are run with a receiver across the fracture zone. Also, a loop-loop array may be employed.

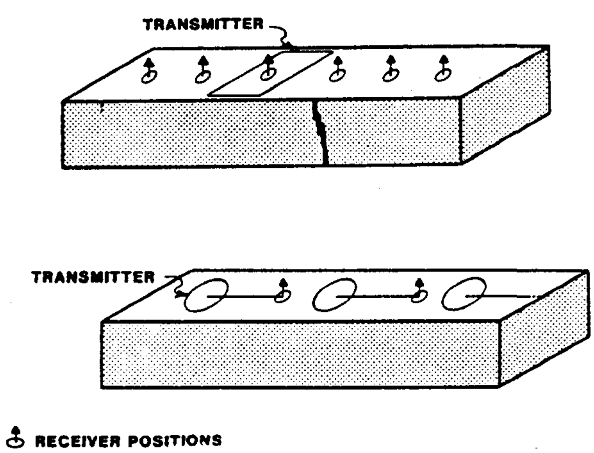


Fig. 12. Transmitter-receiver arrays useful in fracture mapping.

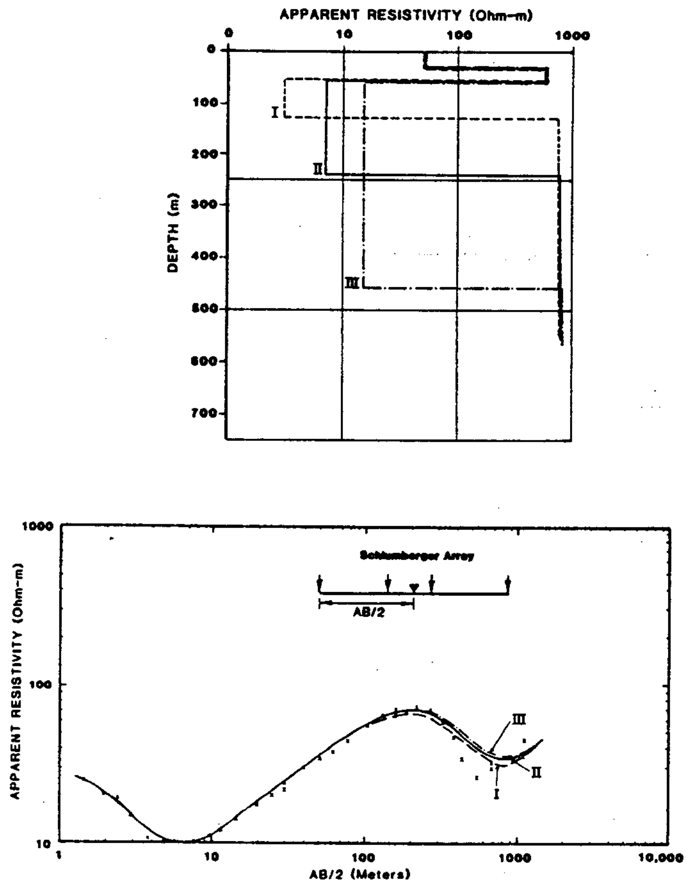


Fig. 13. Schlumberger measured apparent resistivities (a) superimposed on three one-dimensional geoelectric sections (b).

Question.-- I am from Missouri. Show me an example comparing TDEM with another electrical measurement technique next to a drill hole.

Answer.-- In a ground water survey on the coastal plain in Israel, one of the exploration objectives was to map the thickness of alluvium overlying a carbonate bedrock. A drill hole at the survey site showed depth to bedrock at about 168 m (550 ft).

The Institute of Petroleum Research and Geophysics, prior to the arrival of our TDEM crew, conducted a Schlumberger resistivity sounding near the drill hole. The results are given in Figure 13. Measurements were made to AL/2-spacing of 2,000 m (an array length of 4,000 m). The measured apparent resistivity data are superimposed on the forward models of three geoelectric sections. The three geoelectric sections are shown on the right. Clearly the data can be fitted to any of the three models. Yet, depth to bedrock between the three sections was varied by more than 300 m. The Institute, therefore quickly decided that Schlumberger resistivity soundings were not a viable method, because not only was a large effort required to explore to a depth of 168 m (4,000 m of line length), but its vertical resolution was meaningless.

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.

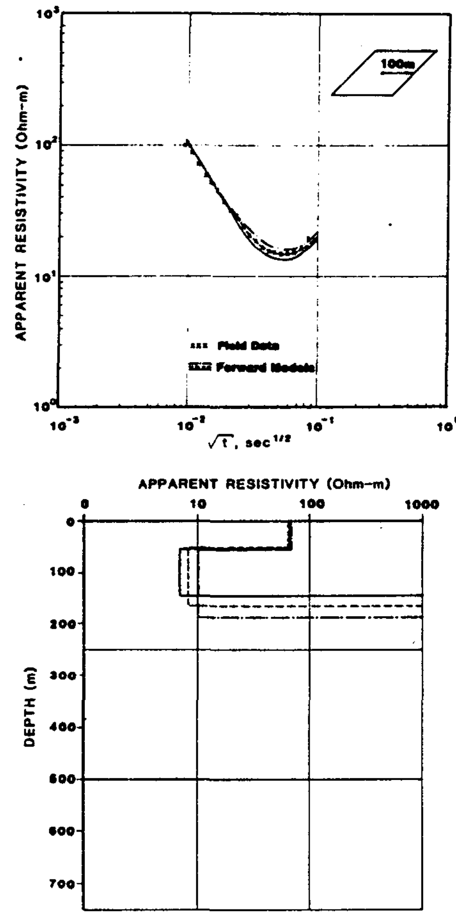


Fig. 14. TDEM measured apparent resistivities (a) superimposed on three one-dimensional geoelectric sections.

ATTACHMENT A

TIME DOMAIN ELECTROMAGNETIC TEST SURVEY IN ST. JOHNS RIVER WATER MANAGEMENT DISTRICT

Prepared For:

St. Johns River Water Management District
Post Office Box 1429
Palatka, Florida 32178-1429

(Contract No. 90D134)

Prepared By:

Blackhawk Geosciences, Inc.
17301 West Colfax Avenue, Suite 170
Golden, Colorado 80401

(BGI Project #90022)

July 26, 1990

FORWARD

This Attachment A contains the inversion figures and tables of all stations. The meaning of these plots and tables are explained in the body of the report.

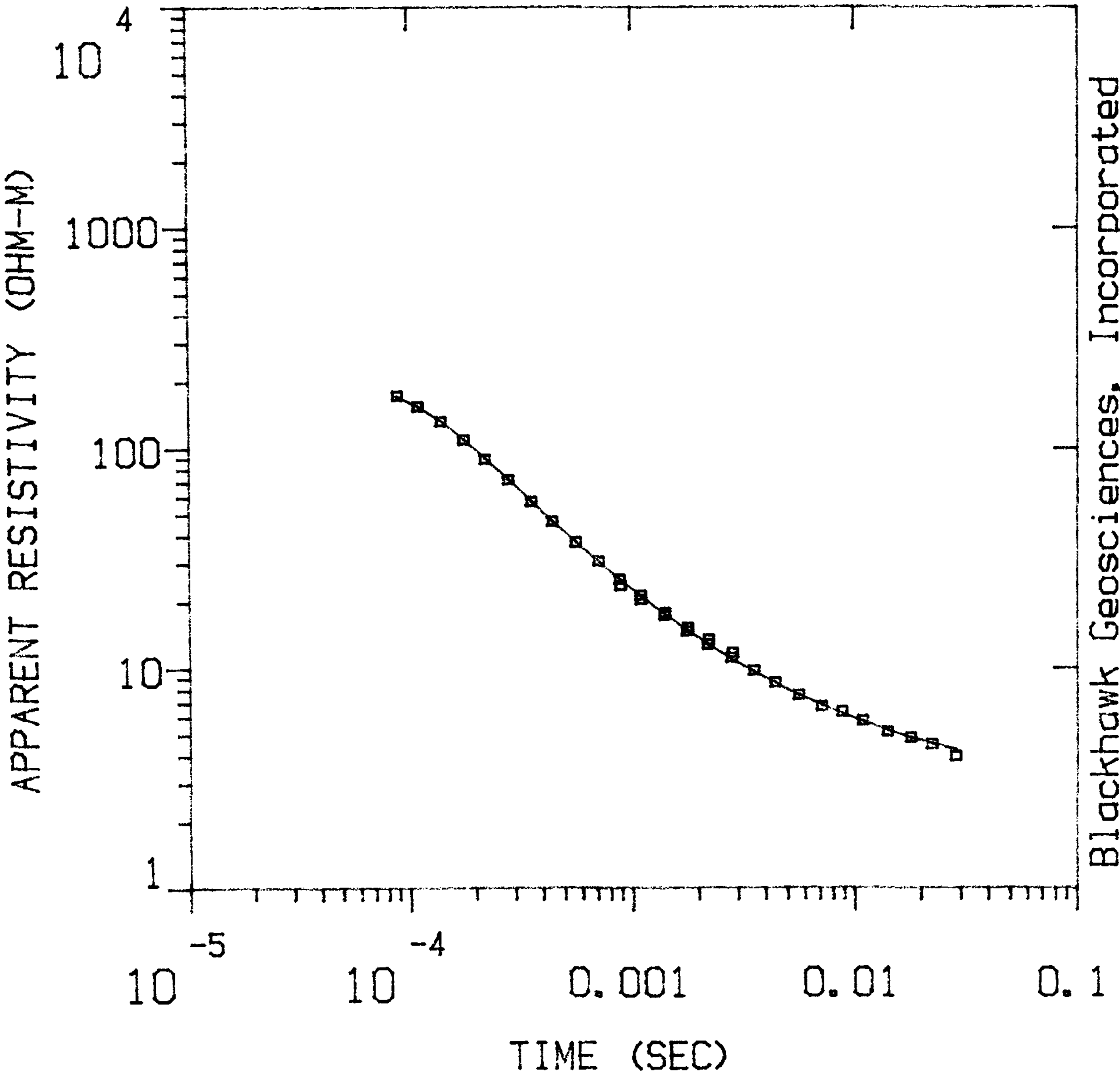
In some cases, e.g., sounding BC-1, two curves are shown on the plot. The meaning of these two curves is as follows:

1. The definition of apparent resistivity in TDEM is complex, and several definitions are in use. The selection of one or the other does not effect inversion or interpretation, but results in different displays.

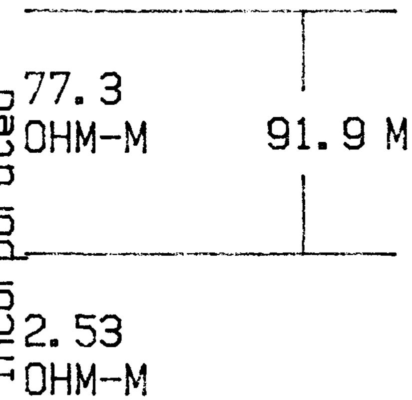
2. The lower curve on some figures represents display of an additional definition of apparent resistivity.

For most soundings, in addition to plots of apparent resistivity curves, plots are also given for the ranges of equivalence, with the exception of LW-1 and LW-2. The program used for rectangular loops at the present time does not allow us to make these plots. The parameter bounds, however, are listed in the inversion tables.

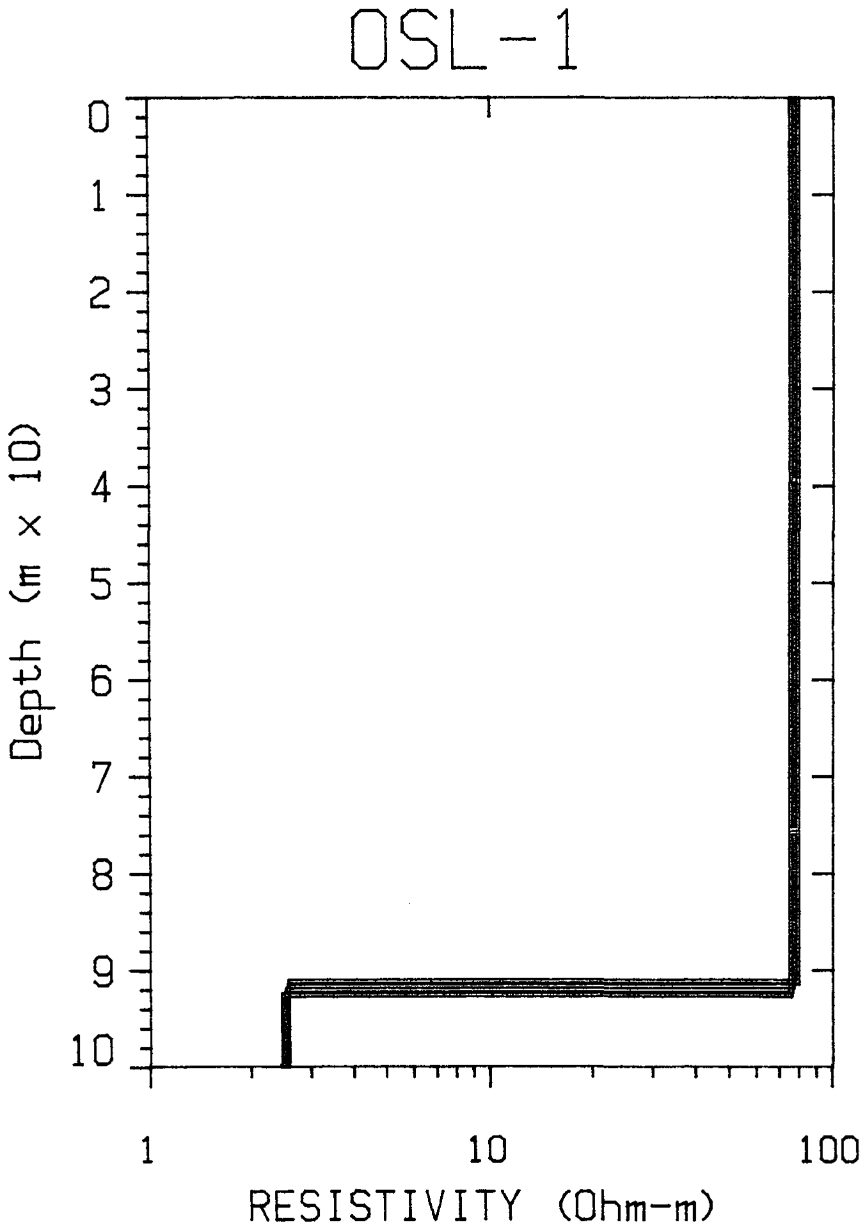
OSL-1



MODEL:



% ERROR: 3.90
CALIBRATION: 1
OFFSET: 50 M
RAMP: 75.0



OSL-1
0
1
2
3
4
5
6
7
8
9
10
Depth (m x 10)
1
10
100
RESISTIVITY (Ohm-m)

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		0.0	0.0		
77.33	91.9	-91.9	-301.5	1.2	1.2
2.53					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	1.73E+02	1.72E+02	0.882	
2	1.10E-04	1.55E+02	1.55E+02	-0.053	
3	1.40E-04	1.32E+02	1.33E+02	-0.418	
4	1.77E-04	1.09E+02	1.10E+02	-0.420	
5	2.20E-04	8.91E+01	9.02E+01	-1.231	
6	2.80E-04	7.17E+01	7.24E+01	-0.941	
7	3.55E-04	5.72E+01	5.75E+01	-0.515	
8	4.43E-04	4.65E+01	4.66E+01	-0.083	
9	5.64E-04	3.73E+01	3.75E+01	-0.366	
10	7.13E-04	3.06E+01	3.04E+01	0.597	
11	8.81E-04	2.54E+01	2.53E+01	0.094	
12	8.90E-04	2.37E+01	2.51E+01	-5.556	
13	1.10E-03	2.14E+01	2.13E+01	0.251	
14	1.10E-03	2.05E+01	2.13E+01	-3.446	
15	1.40E-03	1.73E+01	1.76E+01	-1.643	
16	1.41E-03	1.78E+01	1.75E+01	1.727	
17	1.77E-03	1.48E+01	1.49E+01	-0.789	
18	1.80E-03	1.52E+01	1.47E+01	3.364	
19	2.20E-03	1.28E+01	1.29E+01	-0.591	
20	2.22E-03	1.35E+01	1.28E+01	5.342	
21	2.80E-03	1.11E+01	1.10E+01	1.204	
22	2.85E-03	1.17E+01	1.09E+01	7.538	
23	3.55E-03	9.71E+00	9.61E+00	0.984	
24	4.43E-03	8.56E+00	8.51E+00	0.681	
25	5.64E-03	7.54E+00	7.52E+00	0.248	
26	7.13E-03	6.69E+00	6.79E+00	-1.587	
27	8.81E-03	6.33E+00	6.18E+00	2.378	
28	1.10E-02	5.76E+00	5.69E+00	1.191	
29	1.41E-02	5.13E+00	5.21E+00	-1.594	
30	1.80E-02	4.84E+00	4.82E+00	0.365	
31	2.22E-02	4.51E+00	4.55E+00	-0.788	
32	2.85E-02	3.97E+00	4.25E+00	-6.526	

R: 50. X: 0. Y: 50. DL: 100. REQ: 56. CF: 1.0000
TDHZ ARRAY, 32 DATA POINTS, RAMP: 75.0 MICROSEC, DATA: OSL-1

RMS LOG ERROR: 1.66E-02, ANTILOG YIELDS 3.8997 %
LATE TIME PARAMETERS

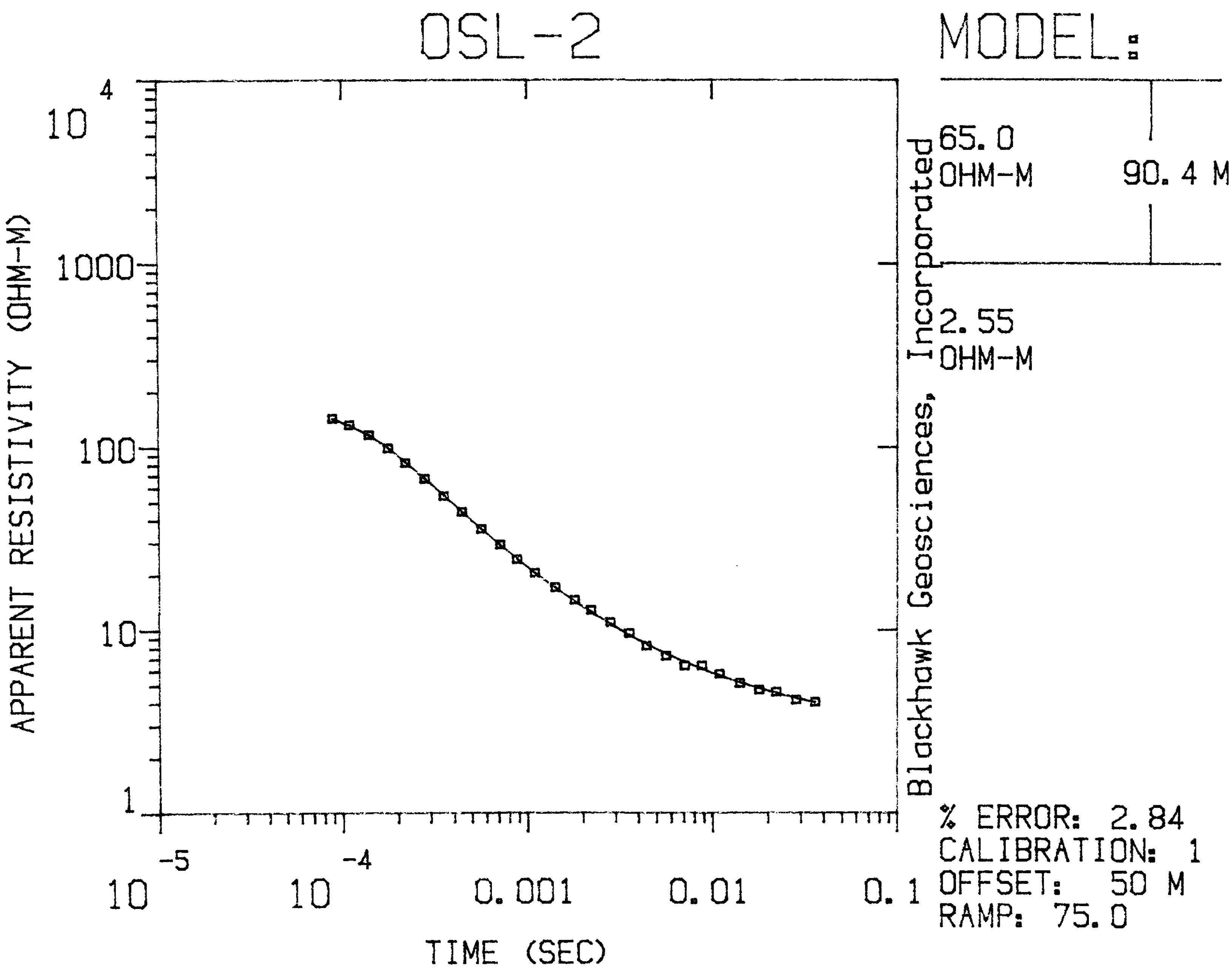
* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

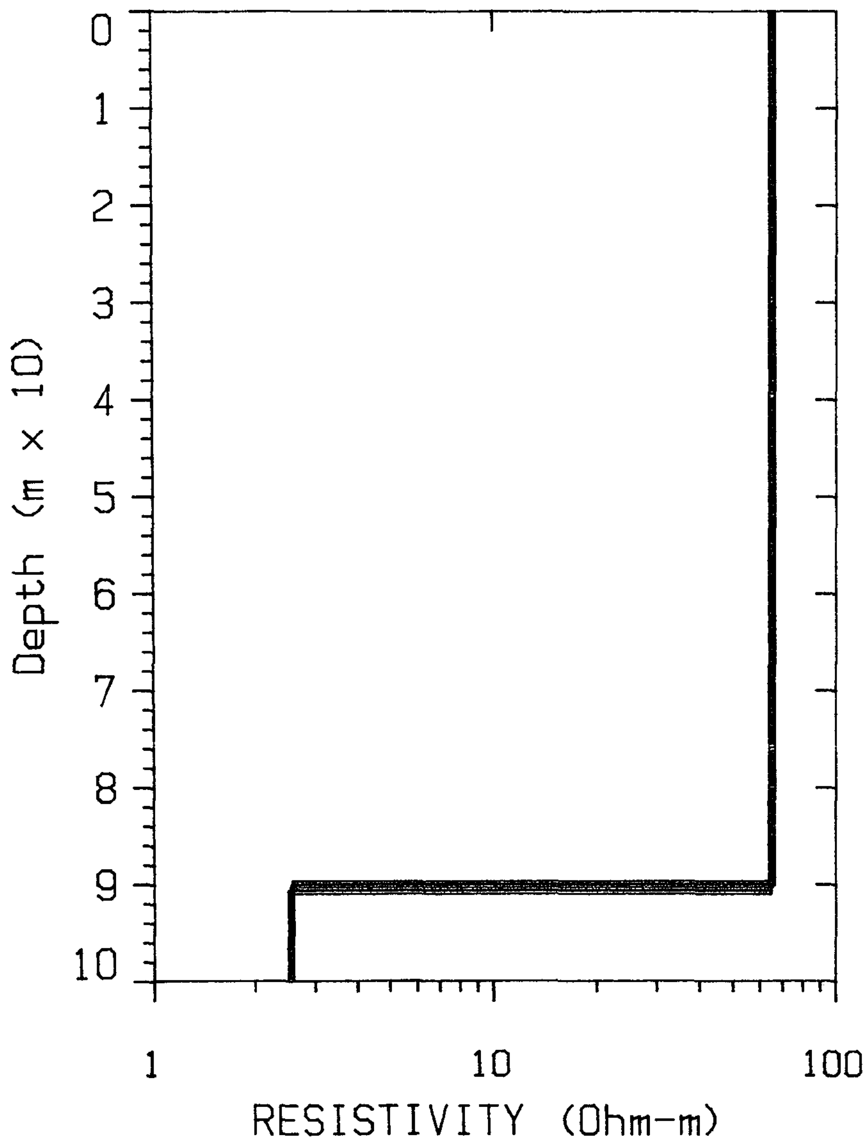
P 1	1.00		
P 2	0.00	1.00	
T 1	0.00	0.00	1.00
	P 1	P 2	T 1

PARAMETER BOUNDS FROM EQUIVALENCE ANALYSIS

LAYER		MINIMUM	BEST	MAXIMUM
RHO	1	74.871	77.327	80.080
	2	2.457	2.529	2.598
THICK	1	91.009	91.903	92.777
DEPTH	1	91.009	91.903	92.777


OSL-2
MODEL:
65.0
OHM-M
90.4 M
2.55
OHM-M
APPARENT RESISTIVITY (OHM-M)
TIME (SEC)
Blackhawk Geosciences, Incorporated
% ERROR: 2.84
CALIBRATION: 1
OFFSET: 50 M
RAMP: 75.0

OSL-2



OSL-2

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		0.0	0.0		
65.00	90.4	-90.4	-296.5	1.4	1.4
2.55					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	1.43E+02	1.43E+02	0.284	
2	1.10E-04	1.32E+02	1.31E+02	0.555	
3	1.40E-04	1.16E+02	1.16E+02	0.125	
4	1.77E-04	9.85E+01	9.93E+01	-0.806	
5	2.20E-04	8.19E+01	8.28E+01	-1.111	
6	2.80E-04	6.69E+01	6.72E+01	-0.401	
7	3.55E-04	5.39E+01	5.44E+01	-0.947	
8	4.43E-04	4.41E+01	4.42E+01	-0.321	
9	5.64E-04	3.56E+01	3.56E+01	-0.013	
10	7.13E-04	2.92E+01	2.92E+01	0.181	
11	8.81E-04	2.43E+01	2.44E+01	-0.692	
12	1.10E-03	2.04E+01	2.05E+01	-0.140	
13	1.41E-03	1.70E+01	1.70E+01	0.123	
14	1.80E-03	1.45E+01	1.43E+01	1.760	
15	2.21E-03	1.28E+01	1.25E+01	2.803	
16	2.83E-03	1.09E+01	1.07E+01	2.077	
17	3.57E-03	9.60E+00	9.33E+00	2.923	
18	4.43E-03	8.18E+00	8.37E+00	-2.199	
19	5.64E-03	7.20E+00	7.40E+00	-2.652	
20	7.13E-03	6.38E+00	6.67E+00	-4.423	
21	8.81E-03	6.38E+00	6.13E+00	4.103	
22	1.10E-02	5.75E+00	5.62E+00	2.351	
23	1.41E-02	5.11E+00	5.17E+00	-1.179	
24	1.80E-02	4.70E+00	4.79E+00	-1.881	
25	2.22E-02	4.58E+00	4.51E+00	1.528	
26	2.85E-02	4.15E+00	4.24E+00	-2.200	
27	3.60E-02	4.03E+00	4.01E+00	0.344	

R: 50. X: 0. Y: 50. DL: 100. REQ: 56. CF: 1.0000
TDHZ ARRAY, 27 DATA POINTS, RAMP: 75.0 MICROSEC, DATA: OSL-2

RMS LOG ERROR: 1.21E-02, ANTILOG YIELDS 2.8356 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

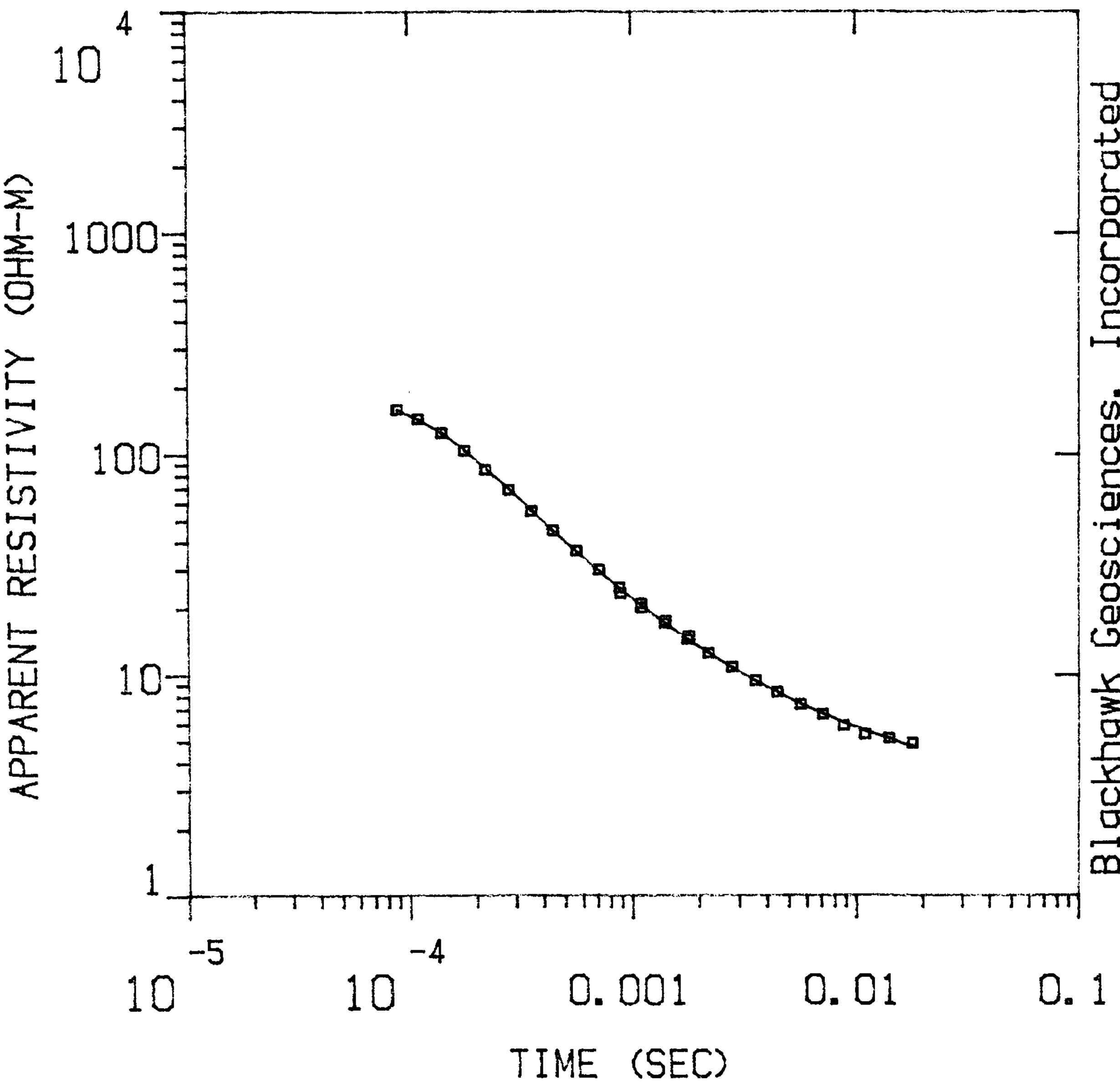
PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	0.99		
P 2	0.00	0.99	
T 1	0.00	0.00	1.00
	P 1	P 2	T 1

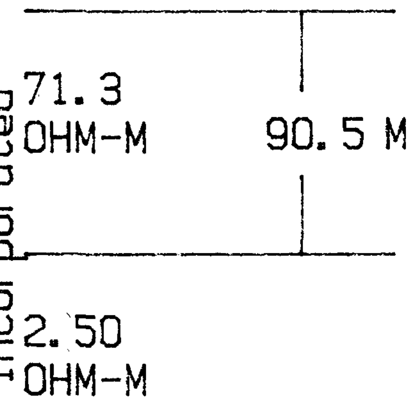
PARAMETER BOUNDS FROM EQUIVALENCE ANALYSIS

	LAYER	MINIMUM	BEST	MAXIMUM
RHO	1	63.731	65.003	66.308
	2	2.511	2.553	2.599
THICK	1	89.741	90.374	91.026
DEPTH	1	89.741	90.374	91.026

OSL-3

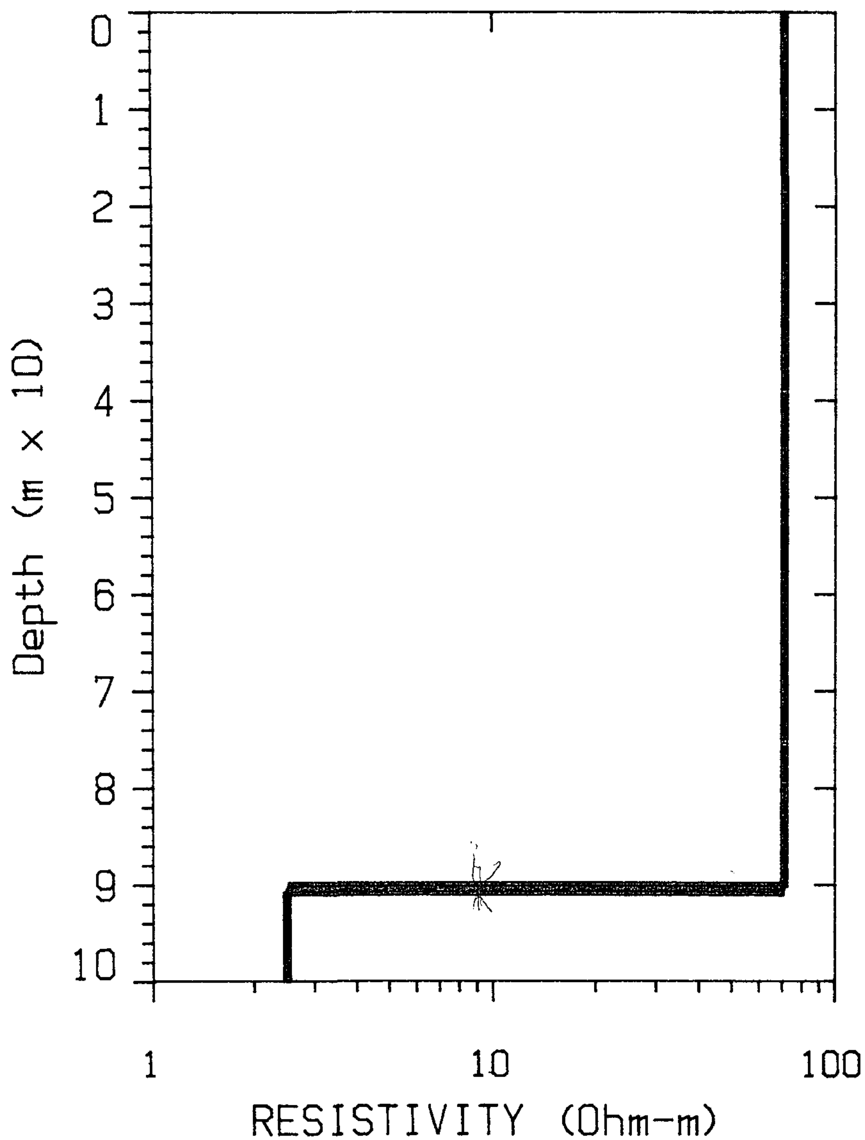


MODEL:



% ERROR: 2.79
CALIBRATION: 1
OFFSET: 50 M
RAMP: 75.0

OSL-3



MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		0.0	0.0		
71.34	90.5	-90.5	-296.9	1.3	1.3
2.50					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	1.59E+02	1.58E+02	0.471	
2	1.10E-04	1.44E+02	1.44E+02	0.347	
3	1.40E-04	1.25E+02	1.25E+02	-0.171	
4	1.77E-04	1.03E+02	1.04E+02	-0.653	
5	2.20E-04	8.49E+01	8.59E+01	-1.166	
6	2.80E-04	6.87E+01	6.93E+01	-0.931	
7	3.55E-04	5.51E+01	5.54E+01	-0.640	
8	4.43E-04	4.50E+01	4.49E+01	0.199	
9	5.64E-04	3.63E+01	3.61E+01	0.591	
10	7.13E-04	2.99E+01	2.95E+01	1.427	
11	8.81E-04	2.49E+01	2.46E+01	1.263	
12	8.90E-04	2.34E+01	2.44E+01	-3.953	
13	1.10E-03	2.10E+01	2.06E+01	1.678	
14	1.10E-03	2.02E+01	2.06E+01	-1.998	
15	1.40E-03	1.71E+01	1.72E+01	-0.505	
16	1.41E-03	1.75E+01	1.71E+01	2.561	
17	1.77E-03	1.45E+01	1.44E+01	0.436	
18	1.80E-03	1.49E+01	1.43E+01	4.275	
19	2.20E-03	1.25E+01	1.25E+01	-0.219	
20	2.80E-03	1.08E+01	1.07E+01	0.879	
21	3.55E-03	9.39E+00	9.36E+00	0.340	
22	4.43E-03	8.32E+00	8.34E+00	-0.189	
23	5.64E-03	7.33E+00	7.35E+00	-0.392	
24	7.13E-03	6.61E+00	6.64E+00	-0.483	
25	8.81E-03	5.88E+00	6.07E+00	-3.198	
26	1.10E-02	5.36E+00	5.57E+00	-3.782	
27	1.41E-02	5.15E+00	5.12E+00	0.527	
28	1.80E-02	4.90E+00	4.73E+00	3.599	

R: 50. X: 0. Y: 50. DL: 100. REQ: 56. CF: 1.0000
TDHZ ARRAY, 28 DATA POINTS, RAMP: 75.0 MICROSEC, DATA: OSL-3

RMS LOG ERROR: 1.20E-02, ANTILOG YIELDS 2.7935 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

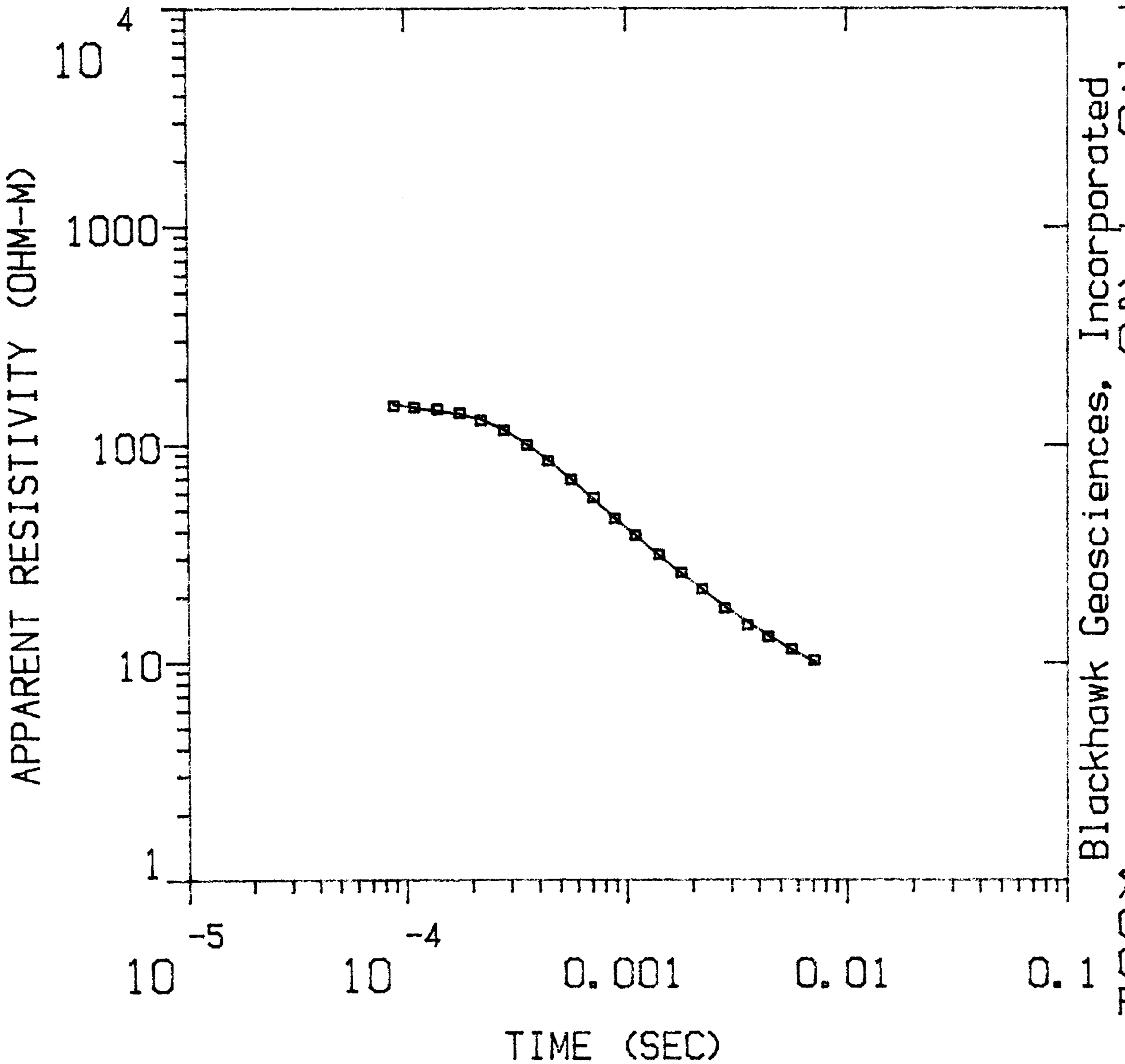
PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

	P 1	P 2	T 1
P 1	0.69		
P 2	-0.07	0.69	
T 1	0.04	0.05	0.96

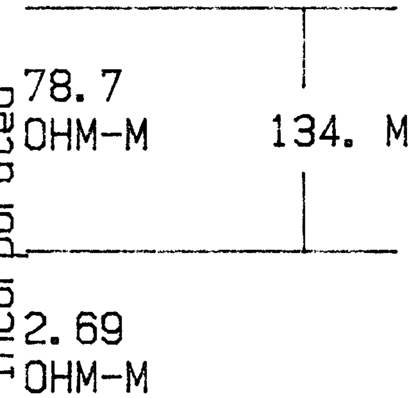
PARAMETER BOUNDS FROM EQUIVALENCE ANALYSIS

	LAYER	MINIMUM	BEST	MAXIMUM
RHO	1	69.854	71.341	72.961
	2	2.451	2.503	2.560
THICK	1	89.882	90.486	91.108
DEPTH	1	89.882	90.486	91.108

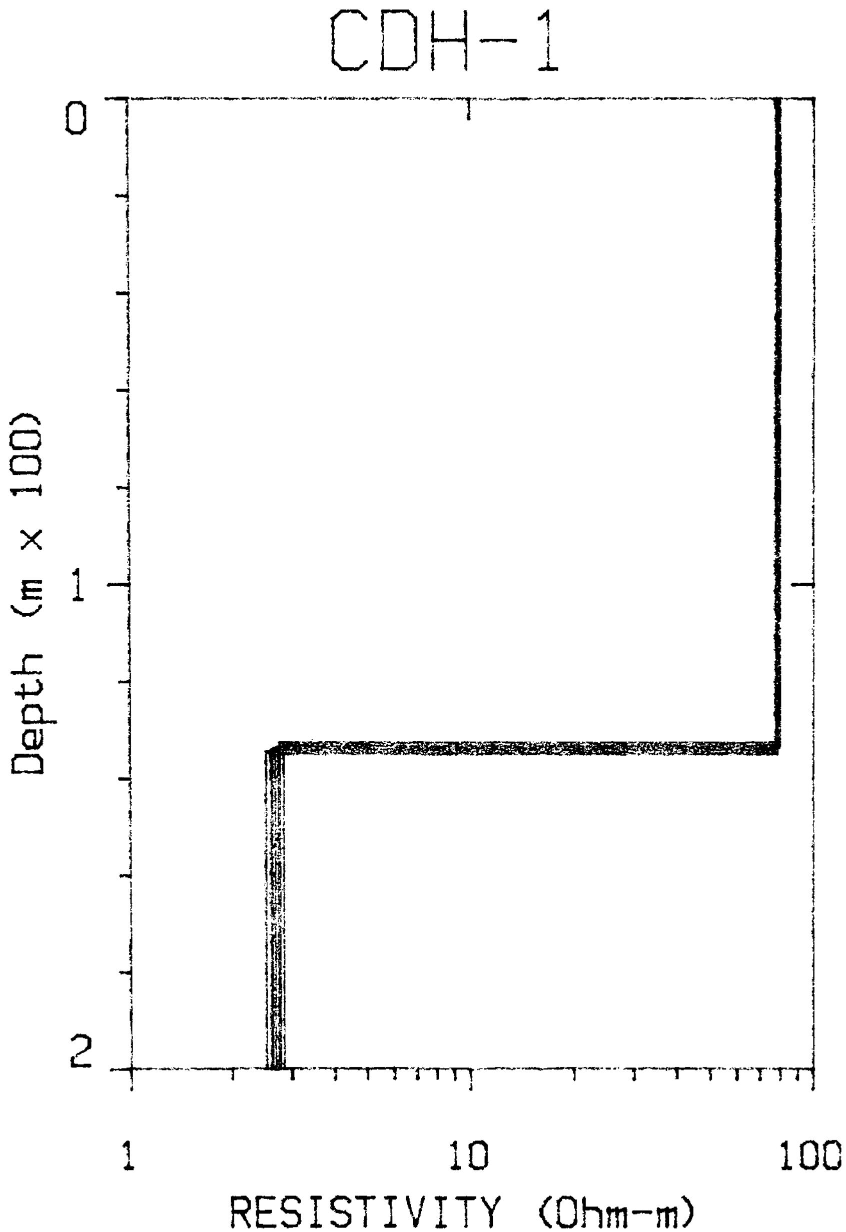
CDH-1



MODEL:



% ERROR: 2.17
CALIBRATION: 1
OFFSET: 50 M
RAMP: 75.0



CDH-1
0
1
2
Depth (m x 100)
1
10
100
RESISTIVITY (Ohm-m)

CDH-1

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		0.0	0.0		
78.69	134.0	-134.0	-439.7	1.7	1.7
2.69					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	1.51E+02	1.54E+02	-1.940	
2	1.10E-04	1.48E+02	1.48E+02	0.357	
3	1.40E-04	1.46E+02	1.43E+02	2.038	
4	1.77E-04	1.39E+02	1.38E+02	1.263	
5	2.20E-04	1.29E+02	1.31E+02	-1.249	
6	2.80E-04	1.16E+02	1.17E+02	-0.768	
7	3.55E-04	9.97E+01	1.00E+02	-0.449	
8	4.43E-04	8.42E+01	8.51E+01	-1.060	
9	5.64E-04	6.90E+01	6.91E+01	-0.102	
10	7.13E-04	5.70E+01	5.57E+01	2.336	
11	8.85E-04	4.56E+01	4.60E+01	-0.831	
12	1.10E-03	3.83E+01	3.82E+01	0.382	
13	1.41E-03	3.13E+01	3.08E+01	1.384	
14	1.78E-03	2.58E+01	2.54E+01	1.393	
15	2.21E-03	2.17E+01	2.15E+01	0.534	
16	2.80E-03	1.77E+01	1.80E+01	-1.571	
17	3.55E-03	1.48E+01	1.53E+01	-3.255	
18	4.43E-03	1.31E+01	1.32E+01	-0.864	
19	5.64E-03	1.15E+01	1.14E+01	0.790	
20	7.13E-03	1.02E+01	1.00E+01	1.692	

R: 50. X: 0. Y: 50. DL: 100. REQ: 56. CF: 1.0000
CLHZ ARRAY, 20 DATA POINTS, RAMP: 75.0 MICROSEC, DATA: CDH-1

RMS LOG ERROR: 9.33E-03, ANTILOG YIELDS 2.1719 %
LATE TIME PARAMETERS

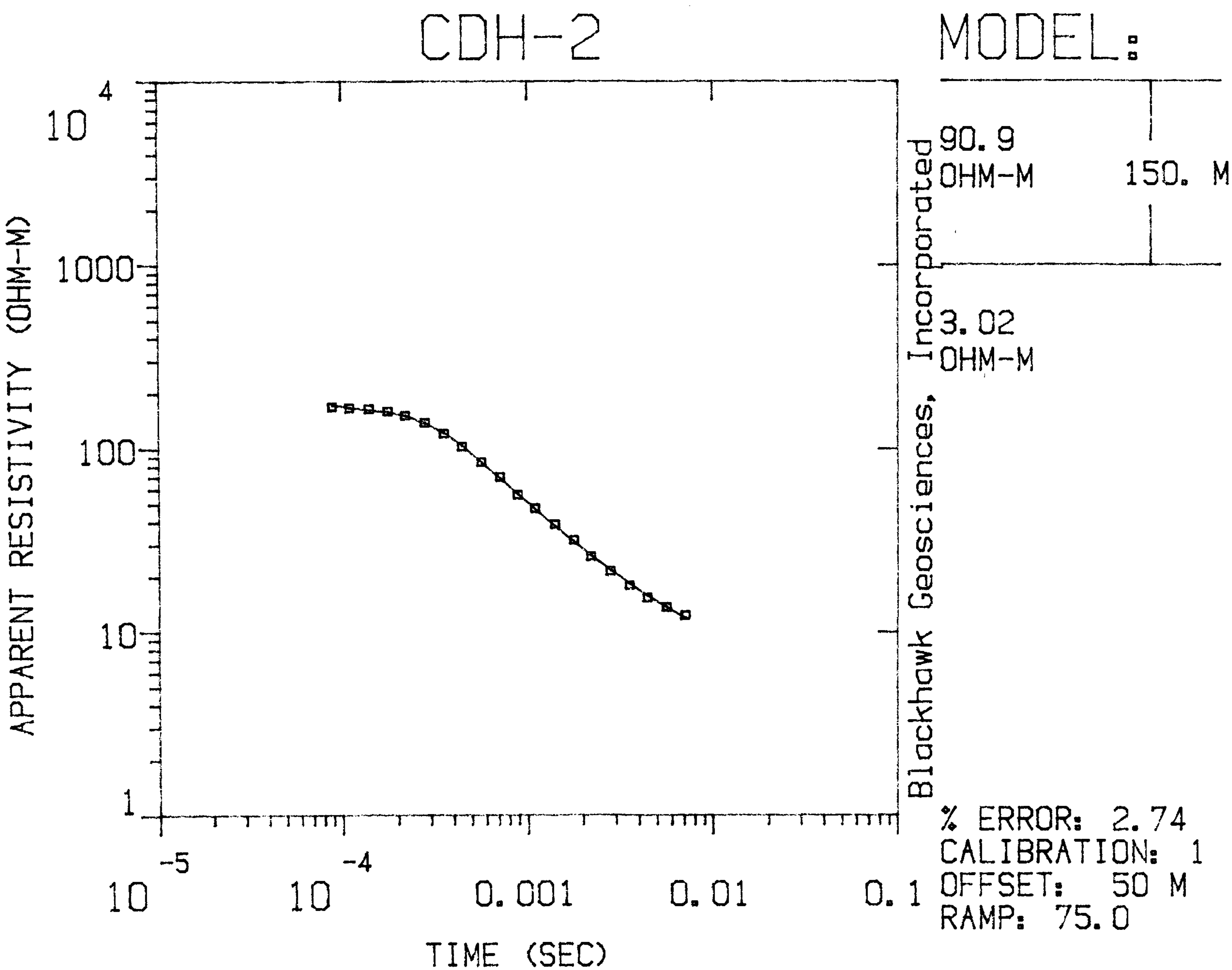
* Blackhawk Geosciences, Incorporated *

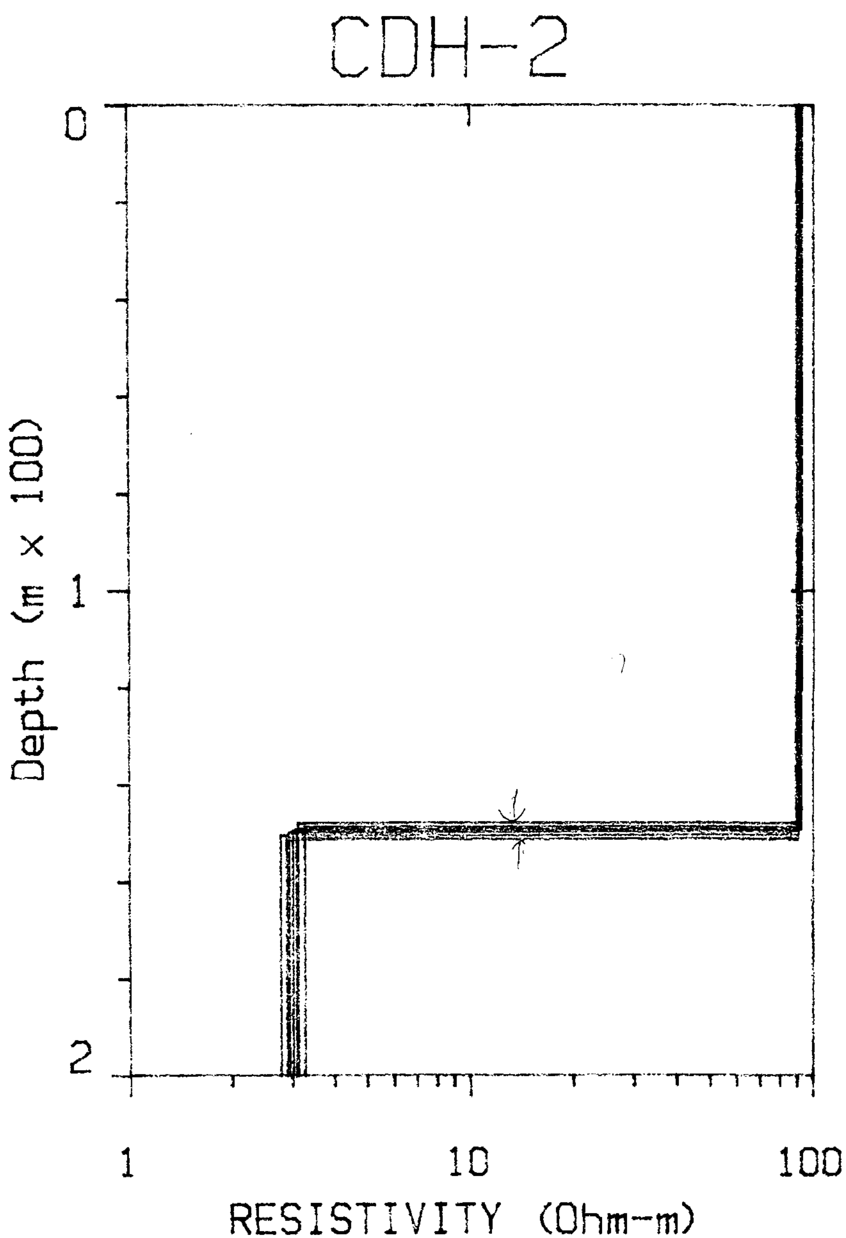
PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

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

PARAMETER BOUNDS FROM EQUIVALENCE ANALYSIS

	LAYER	MINIMUM	BEST	MAXIMUM
RHO	1	78.049	78.686	79.316
	2	2.609	2.691	2.769
THICK	1	133.419	134.013	134.573
DEPTH	1	133.419	134.013	134.573


CDH-2
MODEL:
APPARENT RESISTIVITY (OHM-M)
10^4
1000
100
10
1
10^-5
10^-4
0.001
0.01
0.1
TIME (SEC)
90.9
OHM-M
150. M
3.02
OHM-M
Blackhawk Geosciences, Incorporated
% ERROR: 2.74
CALIBRATION: 1
OFFSET: 50 M
RAMP: 75.0


CDH-2
0
1
2
Depth (m x 100)
1
10
100
RESISTIVITY (Ohm-m)

CDH-2

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		0.0	0.0		
90.86	149.7	-149.7	-491.1	1.6	1.6
3.02					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	1.69E+02	1.73E+02	-2.350	
2	1.10E-04	1.67E+02	1.66E+02	0.021	
3	1.40E-04	1.64E+02	1.62E+02	1.627	
4	1.77E-04	1.60E+02	1.58E+02	1.043	
5	2.20E-04	1.51E+02	1.51E+02	-0.018	
6	2.80E-04	1.38E+02	1.38E+02	0.401	
7	3.55E-04	1.20E+02	1.22E+02	-1.047	
8	4.43E-04	1.02E+02	1.04E+02	-1.571	
9	5.64E-04	8.42E+01	8.40E+01	0.234	
10	7.13E-04	7.00E+01	6.86E+01	2.107	
11	8.85E-04	5.58E+01	5.66E+01	-1.303	
12	1.10E-03	4.71E+01	4.66E+01	1.128	
13	1.41E-03	3.85E+01	3.76E+01	2.309	
14	1.78E-03	3.16E+01	3.10E+01	1.987	
15	2.20E-03	2.58E+01	2.61E+01	-1.447	
16	2.80E-03	2.14E+01	2.18E+01	-1.868	
17	3.55E-03	1.79E+01	1.84E+01	-2.530	
18	4.43E-03	1.54E+01	1.58E+01	-2.600	
19	5.64E-03	1.36E+01	1.36E+01	0.023	
20	7.13E-03	1.23E+01	1.18E+01	4.086	

R: 50. X: 0. Y: 50. DL: 100. REQ: 56. CF: 1.0000
CLHZ ARRAY, 20 DATA POINTS, RAMP: 75.0 MICROSEC, DATA: CDH-2

RMS LOG ERROR: 1.17E-02, ANTILOG YIELDS 2.7368 %
LATE TIME PARAMETERS

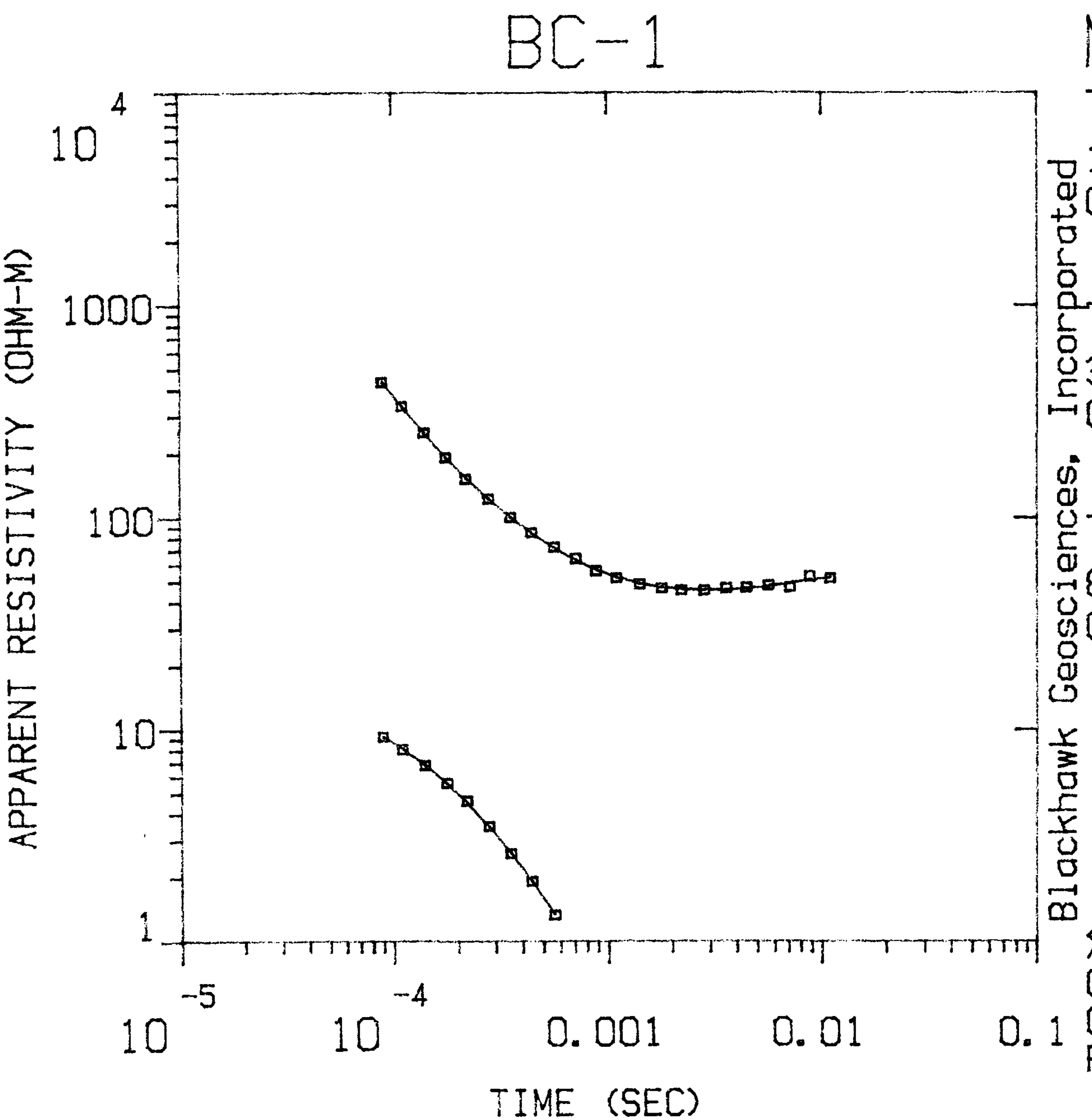
* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	1.00		
P 2	0.00	0.96	
T 1	0.00	0.00	1.00
	P 1	P 2	T 1

PARAMETER BOUNDS FROM EQUIVALENCE ANALYSIS

LAYER		MINIMUM	BEST	MAXIMUM
RHO	1	89.979	90.863	91.714
	2	2.904	3.023	3.135
THICK	1	148.878	149.684	150.458
DEPTH	1	148.878	149.684	150.458



MODEL:

120. OHM-M	36.2 M
30.5 OHM-M	170. M
80.7 OHM-M	

% ERROR: 2.34
CALIBRATION: 1
OFFSET: 206. M
RAMP: 200.0

MODEL: 3 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		0.0	0.0		
120.46	36.2	-36.2	-118.7	0.3	0.3
30.52	169.7	-205.9	-675.5	5.6	5.9
80.68					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	4.33E+02	4.33E+02	-0.140	
2	1.10E-04	3.33E+02	3.32E+02	0.353	
3	1.40E-04	2.50E+02	2.49E+02	0.374	
4	1.77E-04	1.92E+02	1.92E+02	-0.196	
5	2.20E-04	1.52E+02	1.54E+02	-1.193	
6	2.80E-04	1.22E+02	1.23E+02	-0.130	
7	3.55E-04	1.00E+02	1.00E+02	0.100	
8	4.43E-04	8.49E+01	8.45E+01	0.459	
9	5.64E-04	7.24E+01	7.18E+01	0.923	
10	7.13E-04	6.38E+01	6.27E+01	1.663	
11	8.85E-04	5.59E+01	5.66E+01	-1.246	
12	1.10E-03	5.17E+01	5.22E+01	-0.909	
13	1.41E-03	4.84E+01	4.87E+01	-0.609	
14	1.78E-03	4.63E+01	4.66E+01	-0.615	
15	2.21E-03	4.53E+01	4.56E+01	-0.519	
16	2.83E-03	4.53E+01	4.52E+01	0.082	
17	3.57E-03	4.65E+01	4.55E+01	2.056	
18	4.43E-03	4.66E+01	4.62E+01	0.825	
19	5.64E-03	4.78E+01	4.75E+01	0.599	
20	7.13E-03	4.68E+01	4.90E+01	-4.428	
21	8.81E-03	5.26E+01	5.06E+01	4.054	
22	1.10E-02	5.17E+01	5.24E+01	-1.376	

R: 206. X: 0. Y: 206. DL: 412. REQ: 229. CF: 1.0000
CLHZ ARRAY, 22 DATA POINTS, RAMP: 200.0 MICROSEC, DATA: BC-1

RMS LOG ERROR: 1.01E-02, ANTILOG YIELDS 2.3420 %
LATE TIME PARAMETERS

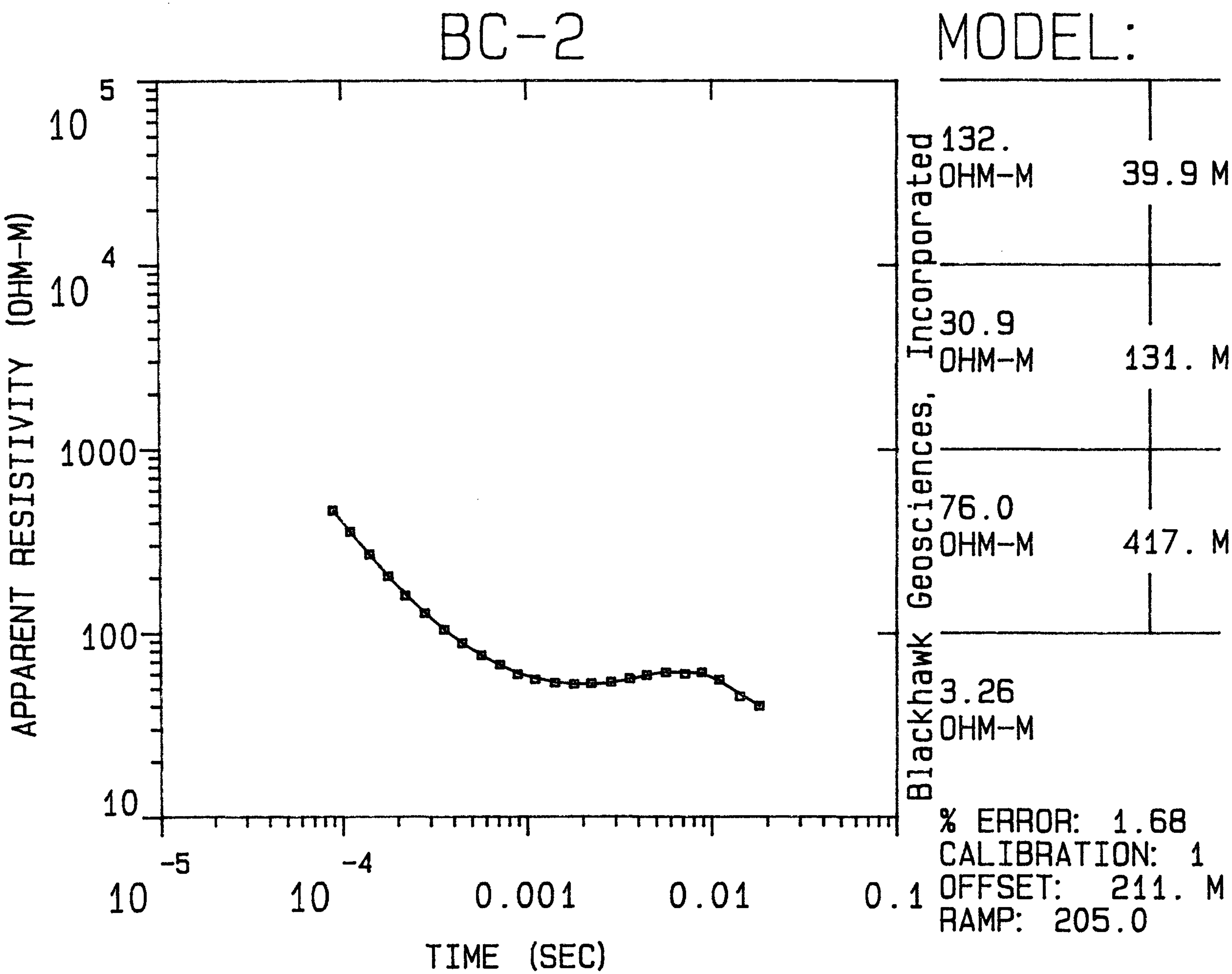
* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

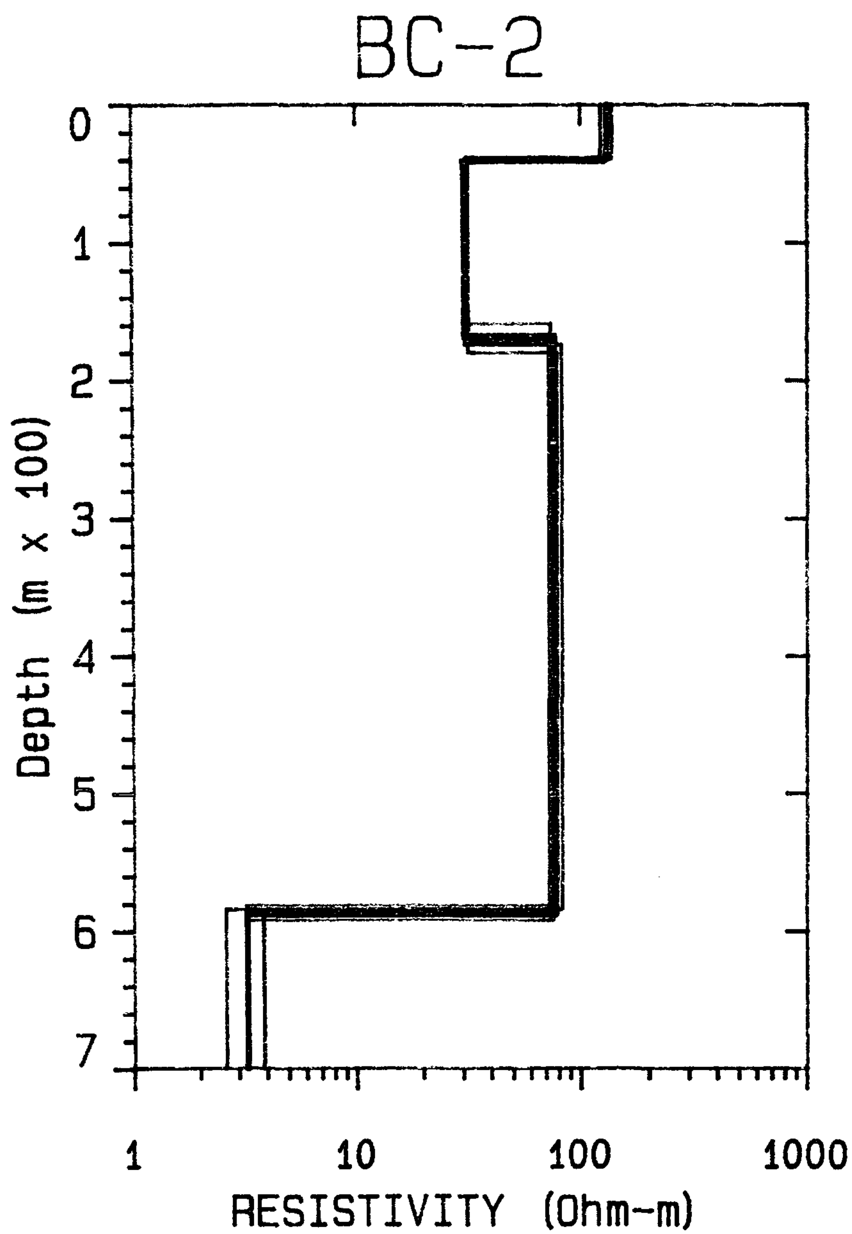
	P 1	P 2	P 3	T 1	T 2
P 1	0.25				
P 2	-0.03	0.99			
P 3	-0.02	-0.01	0.92		
T 1	0.32	0.02	0.02	0.84	
T 2	-0.12	-0.02	-0.06	0.07	0.92

PARAMETER BOUNDS FROM EQUIVALENCE ANALYSIS

LAYER		MINIMUM	BEST	MAXIMUM
RHO	1	113.566	120.462	156.997
	2	30.133	30.517	31.850
	3	73.785	80.680	92.413
THICK	1	31.606	36.191	37.672
	2	158.158	169.691	195.304
DEPTH	1	31.606	36.191	37.672
	2	195.242	205.882	227.351



BC-2
APPARENT RESISTIVITY (OHM-M)
10^5
10^4
1000
100
10
10^{-5}
10^{-4}
0.001
0.01
0.1
TIME (SEC)
Blackhawk Geosciences, Incorporated
MODEL:
132.
OHM-M
39.9 M
30.9
OHM-M
131. M
76.0
OHM-M
417. M
3.26
OHM-M
% ERROR: 1.68
CALIBRATION: 1
OFFSET: 211. M
RAMP: 205.0


BC-2
Depth (m x 100)
0
1
2
3
4
5
6
7
1
10
100
1000
RESISTIVITY (Ohm-m)

MODEL: 4 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		0.0	0.0		
131.57	39.9	-39.9	-131.0	0.3	0.3
30.89	130.5	-170.5	-559.2	4.2	4.5
75.96	416.5	-587.0	-1925.8	5.5	10.0
3.26					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	4.65E+02	4.64E+02	0.229	
2	1.10E-04	3.56E+02	3.55E+02	0.536	
3	1.40E-04	2.67E+02	2.65E+02	0.563	
4	1.77E-04	2.04E+02	2.04E+02	0.151	
5	2.20E-04	1.60E+02	1.62E+02	-1.295	
6	2.80E-04	1.28E+02	1.28E+02	-0.111	
7	3.55E-04	1.04E+02	1.04E+02	0.294	
8	4.43E-04	8.84E+01	8.78E+01	0.606	
9	5.64E-04	7.57E+01	7.53E+01	0.528	
10	7.13E-04	6.72E+01	6.63E+01	1.356	
11	8.85E-04	5.96E+01	6.02E+01	-1.050	
12	1.10E-03	5.59E+01	5.67E+01	-1.437	
13	1.41E-03	5.35E+01	5.38E+01	-0.547	
14	1.78E-03	5.26E+01	5.22E+01	0.776	
15	2.21E-03	5.31E+01	5.29E+01	0.303	
16	2.83E-03	5.42E+01	5.40E+01	0.436	
17	3.57E-03	5.68E+01	5.63E+01	0.950	
18	4.43E-03	5.93E+01	5.94E+01	-0.068	
19	5.64E-03	6.11E+01	6.18E+01	-1.159	
20	7.13E-03	6.00E+01	6.11E+01	-1.941	
21	8.81E-03	6.12E+01	6.00E+01	2.011	
22	1.10E-02	5.57E+01	5.45E+01	2.216	
23	1.41E-02	4.52E+01	4.62E+01	-2.278	
24	1.80E-02	4.01E+01	3.99E+01	0.360	

R: 211. X: 0. Y: 211. DL: 422. REQ: 235. CF: 1.0000
CLHZ ARRAY, 24 DATA POINTS, RAMP: 205.0 MICROSEC, DATA: BC-2

RMS LOG ERROR: 7.24E-03, ANTILOG YIELDS 1.6806 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

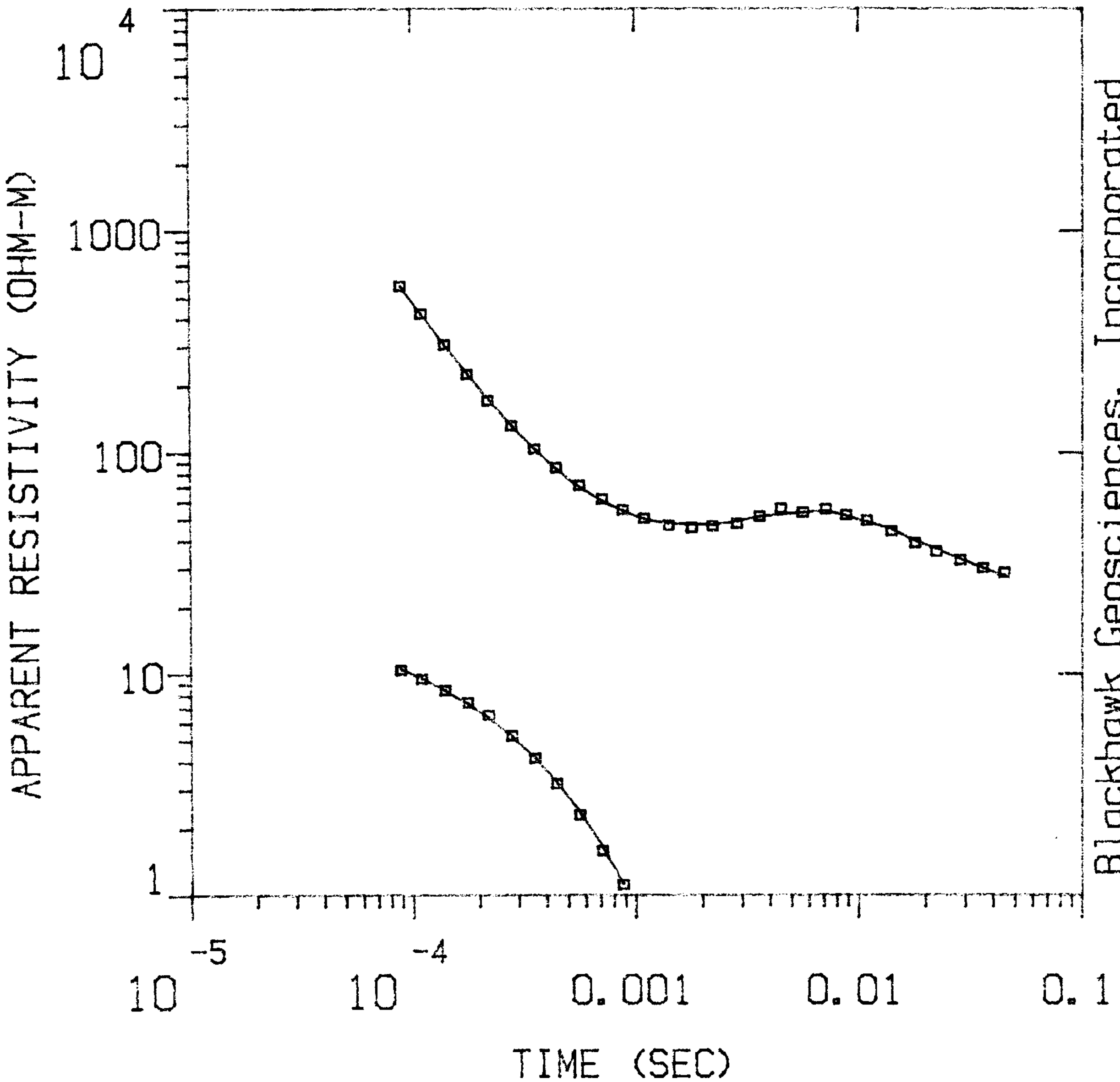
PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

	P 1	P 2	P 3	P 4	T 1	T 2	T 3
P 1	0.24						
P 2	0.04	0.85					
P 3	0.00	0.07	0.31				
P 4	-0.01	-0.01	-0.09	0.05			
T 1	0.15	0.15	-0.06	0.00	0.55		
T 2	0.01	-0.19	-0.23	0.04	0.17	0.39	
T 3	-0.02	0.03	0.13	-0.04	0.00	0.16	0.85

PARAMETER BOUNDS FROM EQUIVALENCE ANALYSIS

	LAYER	MINIMUM	BEST	MAXIMUM
RHO	1	123.367	131.570	136.975
	2	29.952	30.885	31.685
	3	72.011	75.956	82.551
	4	2.627	3.260	3.856
THICK	1	38.666	39.914	42.013
	2	118.519	130.540	141.491
	3	407.799	416.526	427.240
DEPTH	1	38.666	39.914	42.013
	2	159.502	170.455	180.535
	3	581.669	586.981	592.549

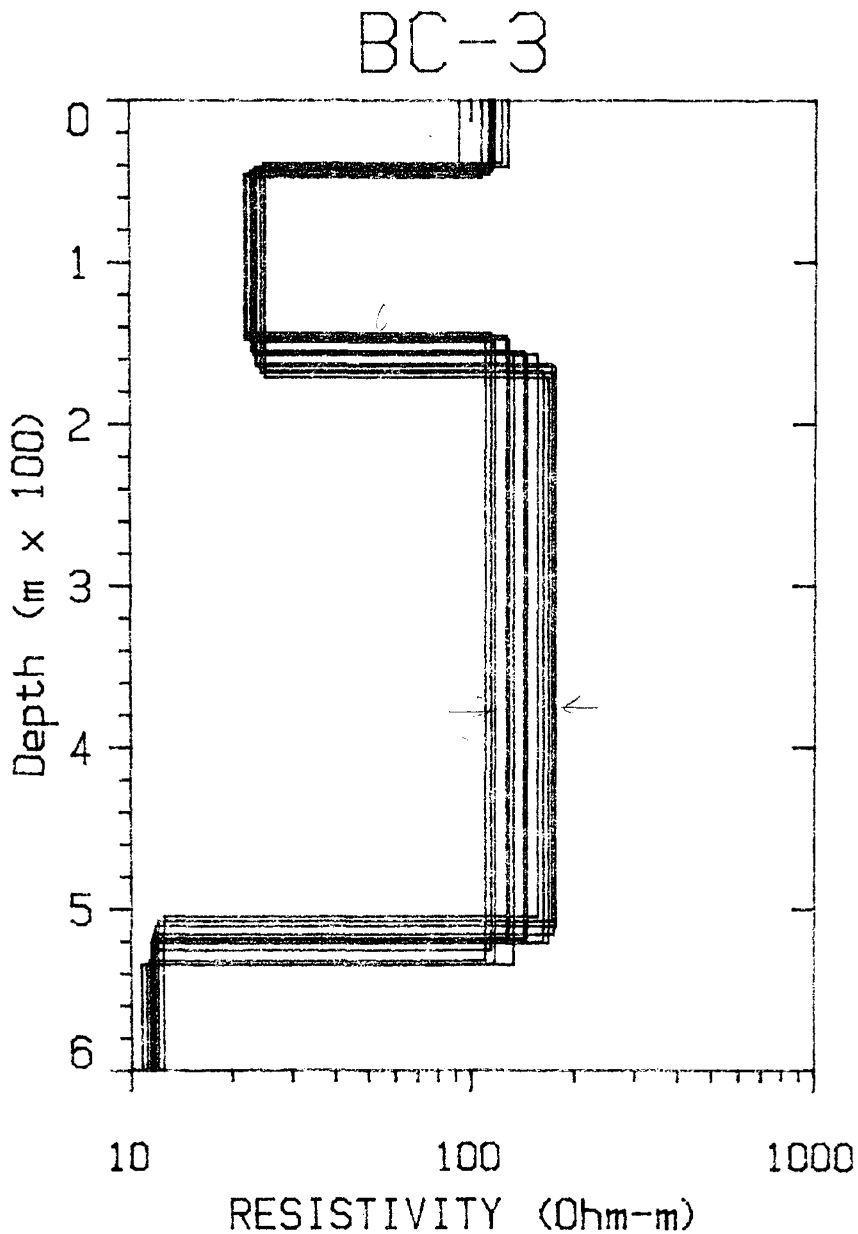
BC-3



MODEL:

115. OHM-M	43.4 M
23.4 OHM-M	113. M
145. OHM-M	362. M
11.7 OHM-M	

% ERROR: 3.09
CALIBRATION: 1
OFFSET: 229. M
RAMP: 205.0



BC-3
Depth (m x 100)
0
1
2
3
4
5
6
10
100
1000
RESISTIVITY (Ohm-m)

MODEL: 4 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		0.0	0.0		
115.00	43.4	-43.4	-142.3	0.4	0.4
23.36	113.4	-156.8	-514.4	4.9	5.2
144.64	362.2	-519.0	-1702.9	2.5	7.7
11.66					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	5.64E+02	5.62E+02	0.470	
2	1.10E-04	4.22E+02	4.21E+02	0.140	
3	1.40E-04	3.05E+02	3.06E+02	-0.182	
4	1.77E-04	2.25E+02	2.27E+02	-1.070	
5	2.20E-04	1.71E+02	1.74E+02	-2.088	
6	2.80E-04	1.32E+02	1.32E+02	-0.583	
7	3.55E-04	1.04E+02	1.04E+02	0.055	
8	4.43E-04	8.53E+01	8.43E+01	1.187	
9	5.64E-04	7.10E+01	6.95E+01	2.095	
10	7.13E-04	6.16E+01	6.01E+01	2.527	
11	8.81E-04	5.48E+01	5.43E+01	0.914	
12	1.10E-03	5.03E+01	4.98E+01	0.863	
13	1.41E-03	4.68E+01	4.74E+01	-1.272	
14	1.80E-03	4.57E+01	4.72E+01	-3.232	
15	2.22E-03	4.64E+01	4.68E+01	-0.947	
16	2.85E-03	4.76E+01	4.88E+01	-2.479	
17	3.60E-03	5.14E+01	5.13E+01	0.209	
18	4.49E-03	5.59E+01	5.26E+01	6.166	
19	5.64E-03	5.35E+01	5.37E+01	-0.310	
20	7.13E-03	5.54E+01	5.46E+01	1.399	
21	8.81E-03	5.21E+01	5.15E+01	1.216	
22	1.10E-02	4.92E+01	4.83E+01	1.960	
23	1.41E-02	4.41E+01	4.50E+01	-1.978	
24	1.80E-02	3.90E+01	3.98E+01	-2.070	
25	2.22E-02	3.56E+01	3.67E+01	-2.849	
26	2.85E-02	3.26E+01	3.30E+01	-1.232	
27	3.60E-02	3.00E+01	3.00E+01	0.126	
28	4.49E-02	2.87E+01	2.76E+01	3.895	

R: 229. X: 0. Y: 229. DL: 457. REQ: 254. CF: 1.0000
CLHZ ARRAY, 28 DATA POINTS, RAMP: 205.0 MICROSEC, DATA: BC-3

RMS LOG ERROR: 1.32E-02, ANTILOG YIELDS 3.0911 %
LATE TIME PARAMETERS

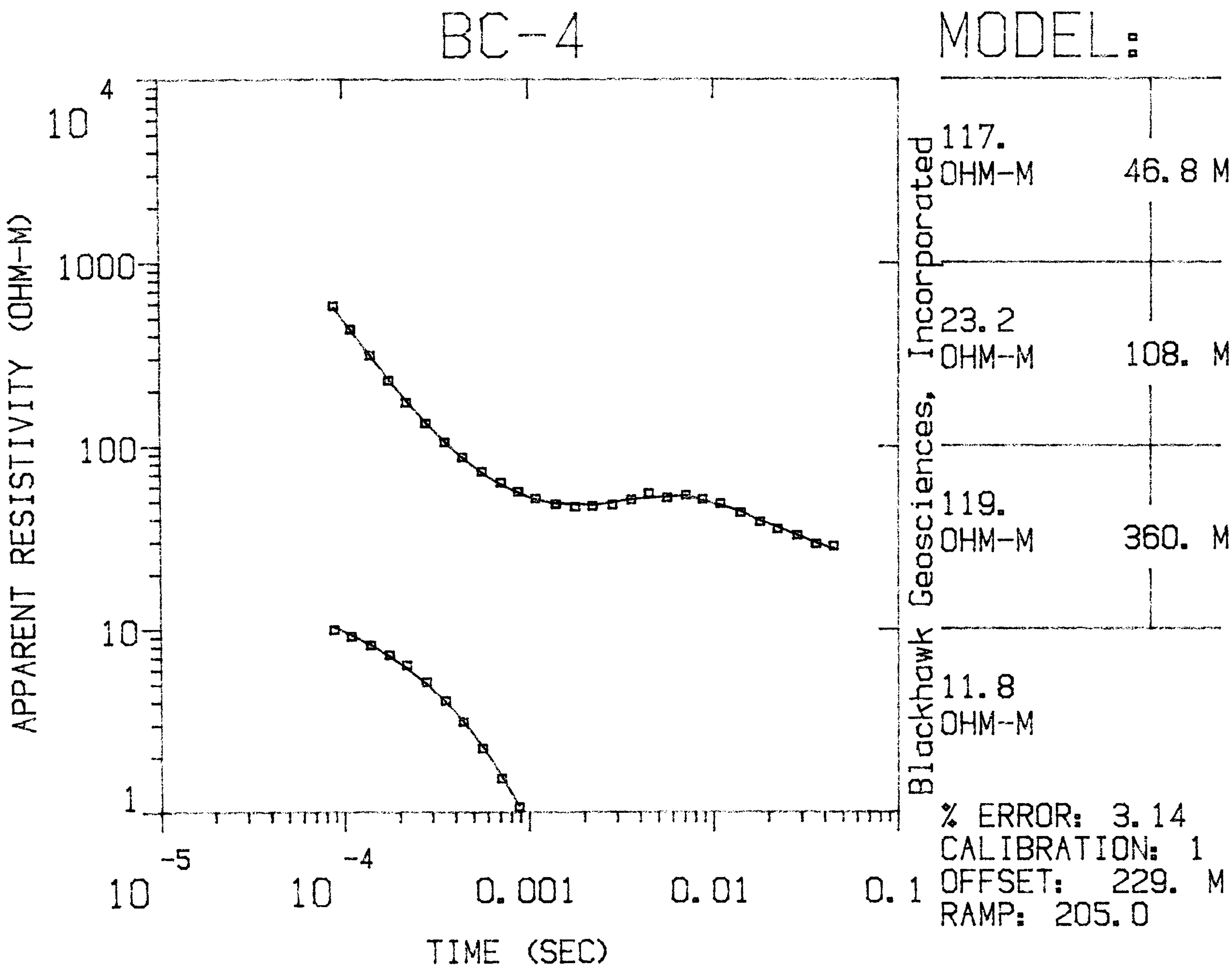
* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

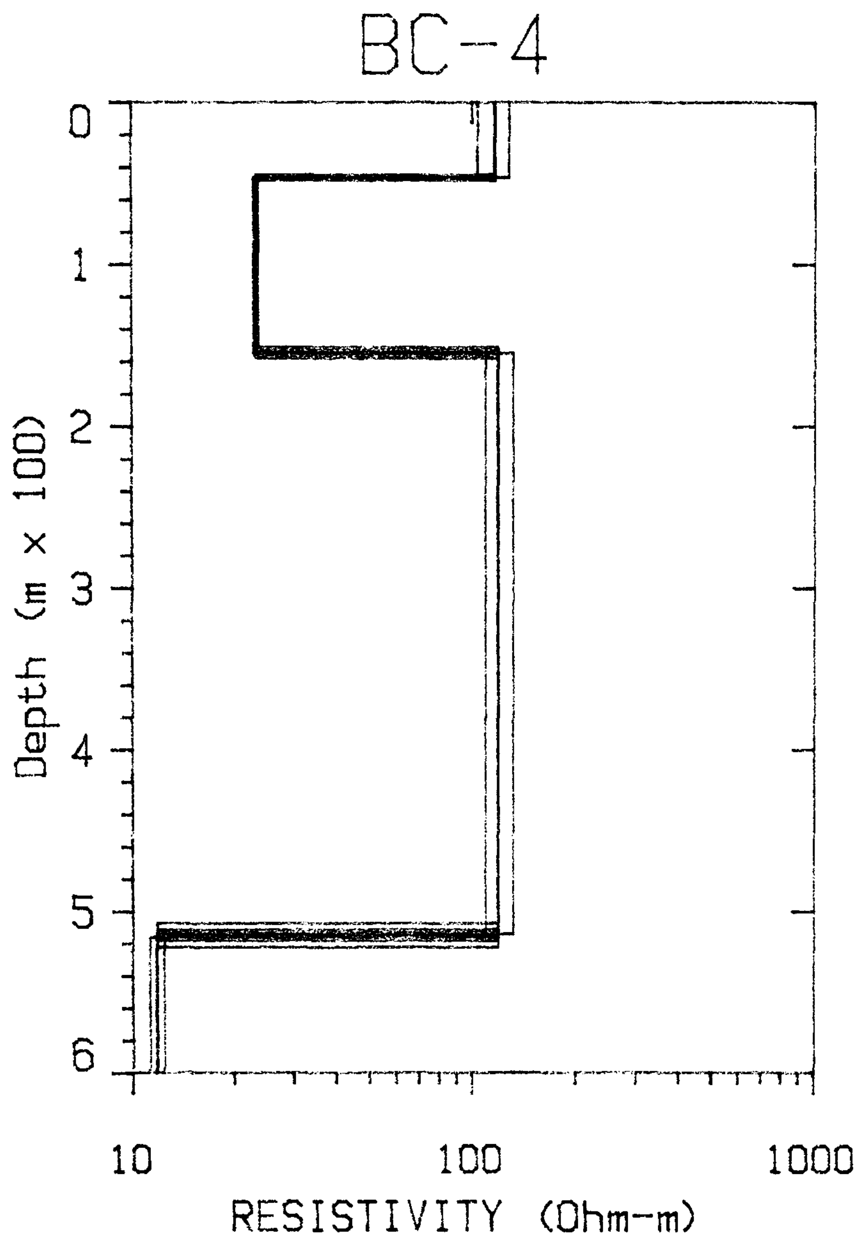
	P 1	P 2	P 3	P 4	T 1	T 2	T 3
P 1	0.93						
P 2	-0.01	0.98					
P 3	0.00	-0.05	0.39				
P 4	0.00	0.00	-0.05	0.95			
T 1	0.03	0.02	0.04	0.00	0.96		
T 2	-0.01	-0.05	-0.21	0.00	0.05	0.87	
T 3	0.00	0.01	0.14	0.03	-0.01	0.05	0.96

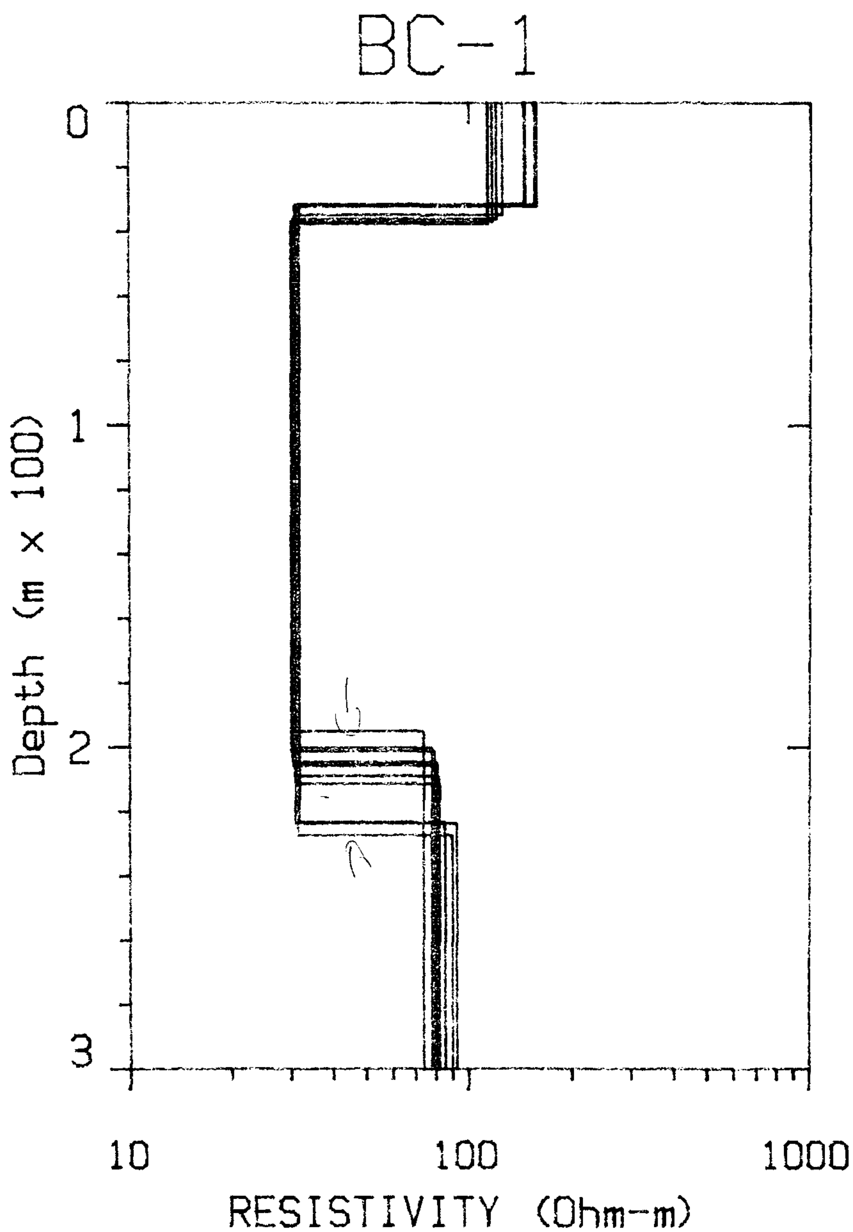
PARAMETER BOUNDS FROM EQUIVALENCE ANALYSIS

LAYER		MINIMUM	BEST	MAXIMUM
RHO	1	92.559	115.003	128.191
	2	21.931	23.360	25.137
	3	109.957	144.642	176.547
	4	10.790	11.662	12.547
THICK	1	39.210	43.377	47.987
	2	98.636	113.425	131.371
	3	344.358	362.229	385.206
DEPTH	1	39.210	43.377	47.987
	2	144.360	156.802	171.654
	3	504.873	519.031	534.757



BC-4
MODEL:
APPARENT RESISTIVITY (OHM-M)
10^4
1000
100
10
1
10^-5
10^-4
0.001
0.01
0.1
TIME (SEC)
Blackhawk Geosciences, Incorporated
117. OHM-M 46.8 M
23.2 OHM-M 108. M
119. OHM-M 360. M
11.8 OHM-M
% ERROR: 3.14
CALIBRATION: 1
OFFSET: 229. M
RAMP: 205.0


BC-4
0
1
2
3
4
5
6
Depth (m x 100)
10
100
1000
RESISTIVITY (Ohm-m)


BC-1
0
1
2
3
Depth (m x 100)
10
100
1000
RESISTIVITY (Ohm-m)

MODEL: 4 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		0.0	0.0		
116.98	46.8	-46.8	-153.4	0.4	0.4
23.19	108.3	-155.0	-508.6	4.7	5.1
118.95	360.0	-515.0	-1689.7	3.0	8.1
11.81					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	5.83E+02	5.69E+02	2.412	
2	1.10E-04	4.33E+02	4.28E+02	1.261	
3	1.40E-04	3.12E+02	3.11E+02	0.119	
4	1.77E-04	2.28E+02	2.31E+02	-1.341	
5	2.20E-04	1.73E+02	1.78E+02	-2.720	
6	2.80E-04	1.33E+02	1.35E+02	-1.422	
7	3.55E-04	1.05E+02	1.06E+02	-0.750	
8	4.43E-04	8.67E+01	8.62E+01	0.487	
9	5.64E-04	7.24E+01	7.12E+01	1.703	
10	7.13E-04	6.31E+01	6.16E+01	2.485	
11	8.81E-04	5.63E+01	5.56E+01	1.348	
12	1.10E-03	5.17E+01	5.09E+01	1.515	
13	1.41E-03	4.81E+01	4.85E+01	-0.778	
14	1.80E-03	4.66E+01	4.79E+01	-2.806	
15	2.22E-03	4.70E+01	4.74E+01	-0.960	
16	2.85E-03	4.78E+01	4.93E+01	-3.070	
17	3.60E-03	5.10E+01	5.13E+01	-0.638	
18	4.49E-03	5.51E+01	5.23E+01	5.388	
19	5.64E-03	5.23E+01	5.32E+01	-1.737	
20	7.13E-03	5.40E+01	5.37E+01	0.522	
21	8.81E-03	5.13E+01	5.04E+01	1.851	
22	1.10E-02	4.85E+01	4.75E+01	2.059	
23	1.41E-02	4.33E+01	4.41E+01	-1.663	
24	1.80E-02	3.86E+01	3.91E+01	-1.358	
25	2.22E-02	3.52E+01	3.61E+01	-2.552	
26	2.85E-02	3.26E+01	3.26E+01	0.101	
27	3.60E-02	2.92E+01	2.97E+01	-1.623	
28	4.49E-02	2.84E+01	2.74E+01	3.808	

R: 229. X: 0. Y: 229. DL: 457. REQ: 254. CF: 1.0000
CLHZ ARRAY, 28 DATA POINTS, RAMP: 205.0 MICROSEC, DATA: BC-4

RMS LOG ERROR: 1.34E-02, ANTILOG YIELDS 3.1361 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

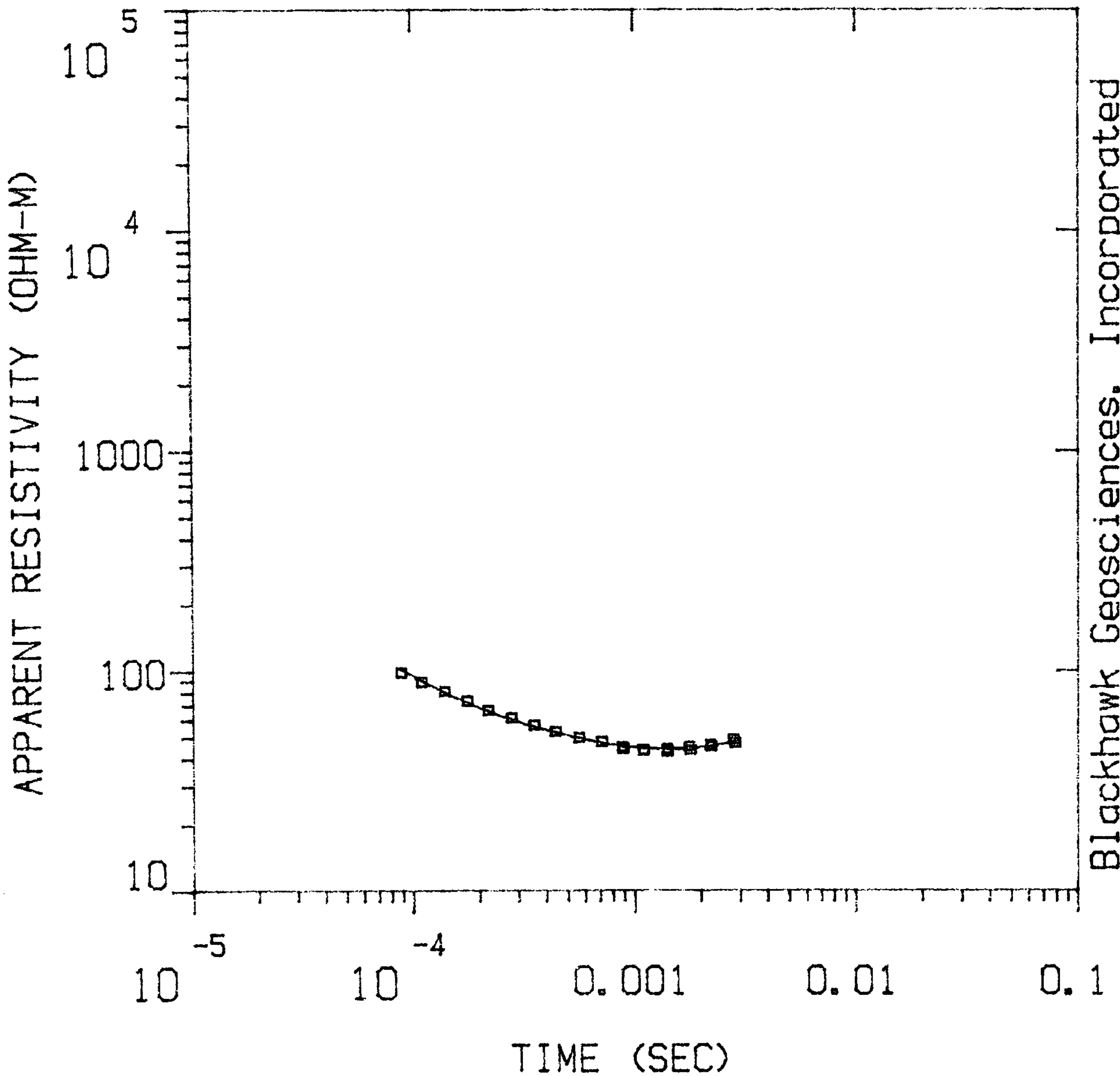
PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	0.01						
P 2	0.03	0.30					
P 3	0.00	0.04	0.01				
P 4	0.00	0.00	0.01	0.03			
T 1	0.02	0.06	0.00	0.01	0.06		
T 2	-0.01	-0.15	-0.02	0.01	0.00	0.10	
T 3	0.00	0.05	0.03	0.06	0.02	0.00	0.16
	P 1	P 2	P 3	P 4	T 1	T 2	T 3

PARAMETER BOUNDS FROM EQUIVALENCE ANALYSIS

LAYER		MINIMUM	BEST	MAXIMUM
RHO	1	104.047	116.978	127.814
	2	22.867	23.194	23.526
	3	109.265	118.949	131.741
	4	11.222	11.811	12.382
THICK	1	44.991	46.762	48.426
	2	105.012	108.264	111.548
	3	352.569	360.002	367.467
DEPTH	1	44.991	46.762	48.426
	2	151.768	155.026	158.317
	3	507.611	515.028	522.477

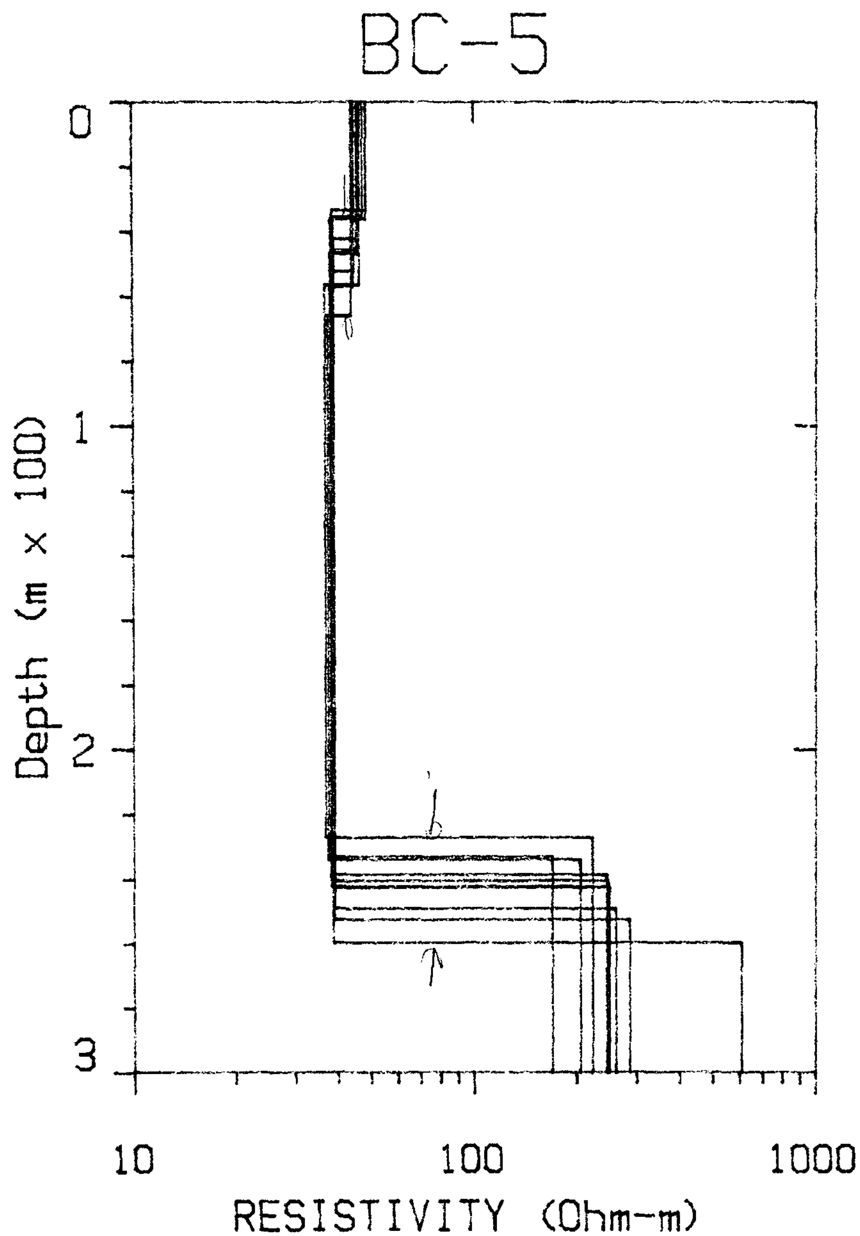
BC-5



MODEL:

45.8 OHM-M	46.7 M
38.4 OHM-M	194. M
247. OHM-M	

% ERROR: 2.70
CALIBRATION: 1
OFFSET: 76.2 M
RAMP: 100.0


BC-5
0
1
2
3
Depth (m x 100)
10
100
1000
RESISTIVITY (Ohm-m)

MODEL: 3 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		0.0	0.0		
45.78	46.7	-46.7	-153.3	1.0	1.0
38.39	194.1	-240.9	-790.2	5.1	6.1
247.43					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	9.78E+01	1.01E+02	-3.588	
2	1.10E-04	8.87E+01	8.97E+01	-1.146	
3	1.40E-04	8.05E+01	7.92E+01	1.622	
4	1.77E-04	7.28E+01	7.12E+01	2.334	
5	2.20E-04	6.61E+01	6.52E+01	1.376	
6	2.80E-04	6.11E+01	5.98E+01	2.219	
7	3.55E-04	5.64E+01	5.55E+01	1.765	
8	4.43E-04	5.28E+01	5.22E+01	1.282	
9	5.64E-04	4.96E+01	4.91E+01	1.056	
10	7.13E-04	4.75E+01	4.68E+01	1.479	
11	8.81E-04	4.48E+01	4.52E+01	-0.902	
12	8.90E-04	4.42E+01	4.52E+01	-2.093	
13	1.10E-03	4.36E+01	4.42E+01	-1.392	
14	1.10E-03	4.35E+01	4.42E+01	-1.581	
15	1.40E-03	4.40E+01	4.40E+01	0.160	
16	1.41E-03	4.30E+01	4.40E+01	-2.117	
17	1.77E-03	4.50E+01	4.43E+01	1.620	
18	1.80E-03	4.35E+01	4.43E+01	-1.750	
19	2.20E-03	4.60E+01	4.52E+01	1.728	
20	2.22E-03	4.53E+01	4.53E+01	0.046	
21	2.80E-03	4.87E+01	4.74E+01	2.734	
22	2.85E-03	4.70E+01	4.76E+01	-1.386	

R: 76. X: 0. Y: 76. DL: 152. REQ: 84. CF: 1.0000
CLHZ ARRAY, 22 DATA POINTS, RAMP: 100.0 MICROSEC, DATA: BC-5

RMS LOG ERROR: 1.16E-02, ANTILOG YIELDS 2.7016 %
LATE TIME PARAMETERS

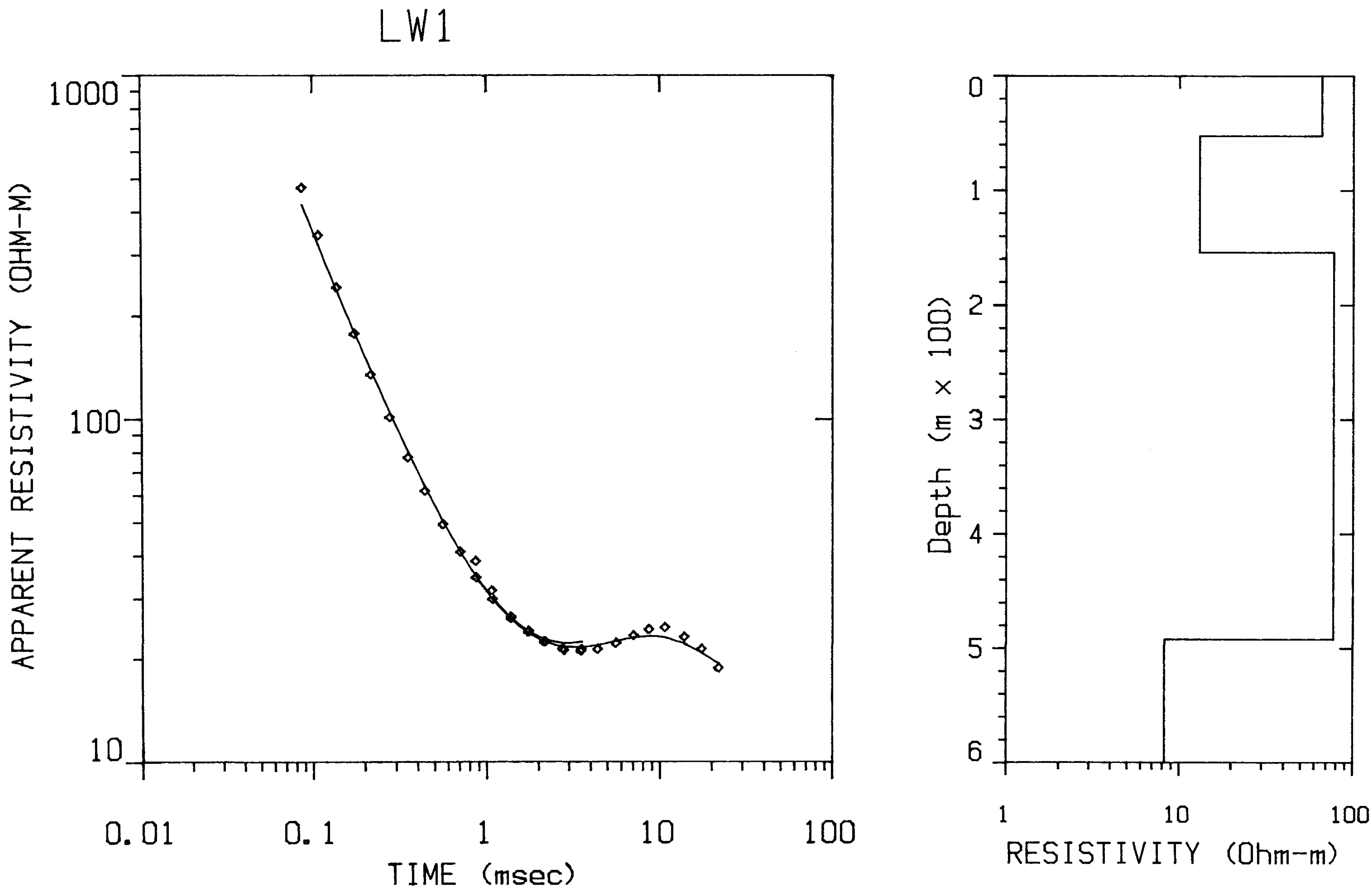
* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	0.97				
P 2	0.00	1.00			
P 3	0.00	-0.01	0.05		
T 1	0.14	0.02	0.02	0.16	
T 2	-0.02	-0.01	-0.10	0.19	0.92
	P 1	P 2	P 3	T 1	T 2

PARAMETER BOUNDS FROM EQUIVALENCE ANALYSIS

	LAYER	MINIMUM	BEST	MAXIMUM
RHO	1	43.880	45.783	48.420
	2	36.888	38.395	39.165
	3	169.649	247.427	607.359
THICK	1	33.576	46.713	66.265
	2	168.015	194.144	217.117
DEPTH	1	33.576	46.713	66.265
	2	227.433	240.857	260.011


LW1
APPARENT RESISTIVITY (OHM-M)
1000
100
10
0.01
0.1
1
10
100
TIME (msec)
Depth (m x 100)
0
1
2
3
4
5
6
1
10
100
RESISTIVITY (Ohm-m)

DATA SET: LW1

CLIENT: ST. JOHNS RWMD
LOCATION: 0011 0000
COUNTY: BREVARD
PROJECT: SJRWMD
LOOP SIZE: 304.000 m by 731.000 m
COIL LOC: 0.000 m (X), 0.000 m (Y)
SOUNDING COORDINATES: X: 0.0000 Y: 0.0000

DATE: 2105
SOUNDING: 00000
ELEVATION: 0.00 m
EQUIPMENT: Geonics PROTEM

FITTING ERROR: 5.937 PERCENT

L #	RESISTIVITY (ohm-m)	THICKNESS (meters)	ELEVATION (meters)	CONDUCTANCE (Siemens)
			0.0	
1	65.49	53.01	-53.01	0.809
2	13.04	101.6	-154.7	7.79
3	76.88	337.8	-492.5	4.39
4	8.26			

ALL PARAMETERS ARE FREE

PARAMETER BOUNDS FROM EQUIVALENCE ANALYSIS

	LAYER	MINIMUM	BEST	MAXIMUM
RHO	1	61.171	65.493	129.503
	2	11.418	13.046	14.101
	3	55.139	76.888	132.801
	4	3.040	8.260	10.364
THICK	1	41.435	53.019	58.544
	2	83.593	101.683	118.256
	3	311.311	337.809	382.946
DEPTH	1	41.435	53.019	58.544
	2	140.587	154.702	168.401
	3	471.398	492.511	542.244

CURRENT: 1.00 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 30.00 Hz GAIN: 0 RAMP TIME: 210.00 muSEC

No.	TIME (ms)	Apparent Res (ohm-m) DATA	SYNTHETIC	DIFFERENCE (percent)

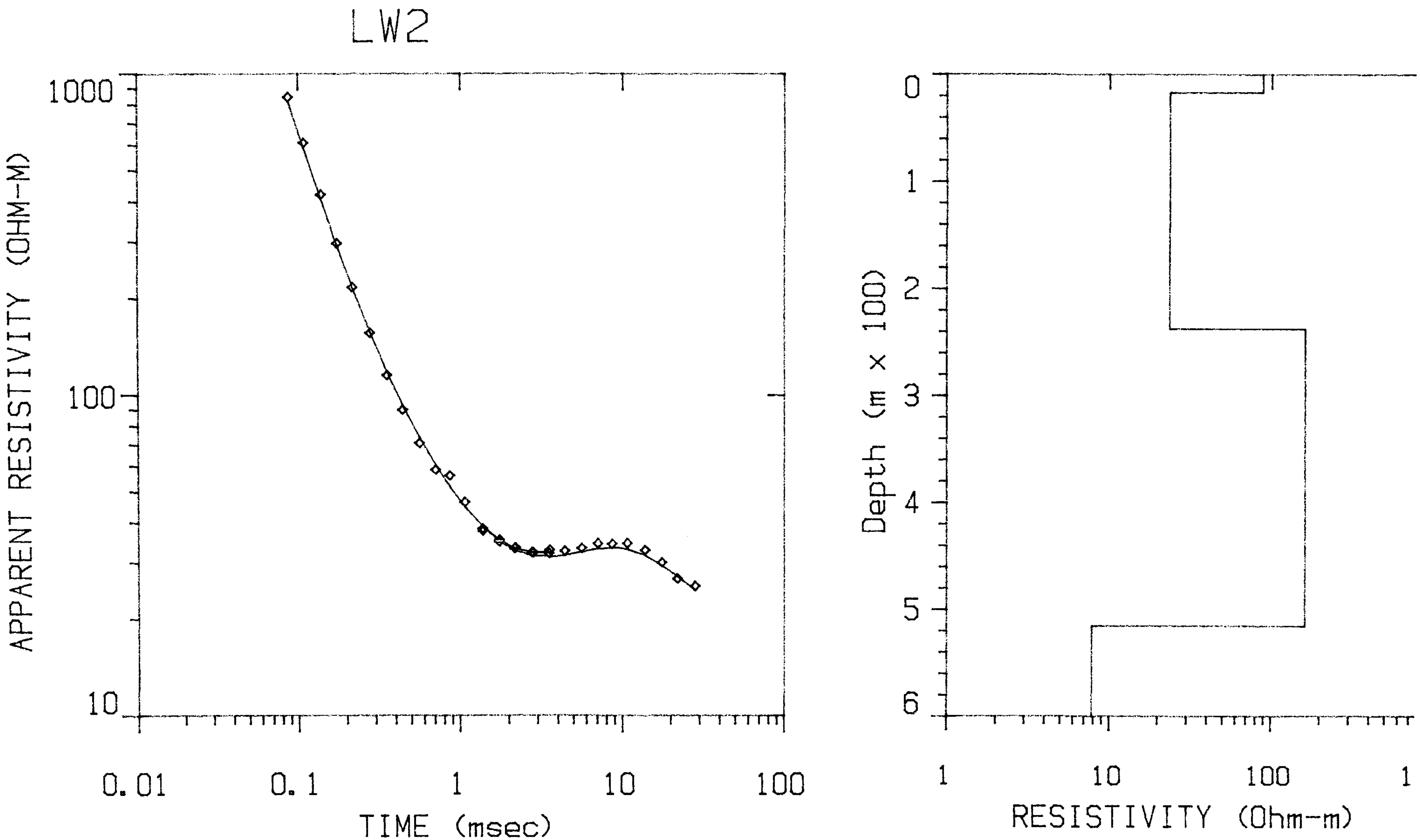
1	0.0870	-472.2	421.4	189.2
2	0.108	-342.7	321.1	193.6
3	0.138	-241.6	237.2	198.1
4	0.174	-177.4	179.3	201.0
5	0.216	-134.7	139.2	203.3
6	0.277	-101.2	104.9	203.6
7	0.353	-77.33	80.51	204.1
8	0.441	-61.69	63.80	203.4
9	0.561	-49.34	50.40	202.1
10	0.706	-40.99	41.06	200.1
11	0.865	-38.55	34.94	190.6
12	1.07	-31.62	30.22	195.5
13	1.38	-26.52	26.30	199.1
14	1.75	-24.12	23.96	199.3
15	2.19	-22.44	22.67	201.0
16	2.82	-21.17	22.14	204.5
17	3.56	-21.30	22.39	205.1

CURRENT: 1.00 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 3.00 Hz GAIN: 0 RAMP TIME: 210.00 muSEC

No.	TIME (ms)	Apparent Res (ohm-m) DATA	SYNTHETIC	DIFFERENCE (percent)
18	0.870	-34.60	34.65	200.1
19	1.08	-29.88	29.89	200.0
20	1.38	-26.28	26.10	199.3
21	1.74	-23.97	23.75	199.0
22	2.16	-22.46	22.38	199.6
23	2.77	-21.42	21.62	200.9
24	3.53	-21.06	21.54	202.2
25	4.41	-21.35	21.89	202.5
26	5.61	-22.25	22.52	201.1
27	7.06	-23.40	23.07	198.6
28	8.65	-24.37	23.31	195.6
29	10.70	-24.70	23.07	193.4
30	13.80	-23.17	22.15	195.6
31	17.50	-21.37	20.78	197.2
32	21.90	-18.79	19.33	202.8

PARAMETER RESOLUTION MATRIX:
"F" INDICATES FIXED PARAMETER
P 1 0.33
P 2 -0.02 0.81

P 3	0.02	0.03	0.07				
P 4	-0.01	0.00	0.00	0.05			
T 1	0.24	0.14	-0.03	0.01	0.67		
T 2	-0.10	-0.26	-0.12	0.04	0.18	0.50	
T 3	0.00	0.01	0.14	0.12	0.00	0.00	0.69
	P 1	P 2	P 3	P 4	T 1	T 2	T 3



LW2
APPARENT RESISTIVITY (OHM-M)
1000
100
10
0.01
0.1
1
10
100
TIME (msec)
Depth (m x 100)
0
1
2
3
4
5
6
1
10
100
1
RESISTIVITY (Ohm-m)

DATA SET: LW2

CLIENT: ST. JOHNS RWMD
LOCATION: 0012 0000
COUNTY: ------------------
PROJECT: ST. JOHNS
LOOP SIZE: 498.167 m by 609.000 m
COIL LOC: 0.000 m (X), 0.000 m (Y)
SOUNDING COORDINATES: X: 0.0000 Y: 0.0000

DATE: 2205
SOUNDING: 00000
ELEVATION: 0.00 m
EQUIPMENT: Geonics PROTEM

FITTING ERROR: 3.774 PERCENT

L #	RESISTIVITY (ohm-m)	THICKNESS (meters)	ELEVATION (meters)	CONDUCTANCE (Siemens)
			0.0	
1	88.22	17.05	-17.05	0.193
2	23.59	220.7	-237.8	9.35
3	162.4	277.7	-515.6	1.70
4	7.84			

ALL PARAMETERS ARE FREE

PARAMETER BOUNDS FROM EQUIVALENCE ANALYSIS

LAYER		MINIMUM	BEST	MAXIMUM
RHO	1	46.250	88.229	275.335
	2	22.776	23.597	24.603
	3	62.965	162.465	454.340
	4	6.143	7.844	10.141
THICK	1	9.577	17.056	23.665
	2	189.433	220.782	264.538
	3	235.153	277.782	325.532
DEPTH	1	9.577	17.056	23.665
	2	211.364	237.837	277.213
	3	487.372	515.619	550.534

CURRENT: 1.00 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 3.00 Hz GAIN: 0 RAMP TIME: 210.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)

1	1.38	-265.5	256.8	196.7
2	1.74	-167.3	166.8	199.6
3	2.16	-104.6	106.9	202.2
4	2.77	-58.73	60.98	203.8
5	3.53	-32.36	33.72	204.1
6	4.41	-18.05	18.96	205.0
7	5.61	-9.60	9.99	204.0
8	7.06	-5.13	5.43	205.8
9	8.65	-3.10	3.22	203.9
10	10.70	-1.81	1.93	206.7
11	13.80	-1.03	1.09	205.9
12	17.50	-0.651	0.673	203.3
13	21.90	-0.442	0.432	197.6
14	28.20	-0.254	0.267	204.8

CURRENT: 1.00 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 30.00 Hz GAIN: 0 RAMP TIME: 210.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
15	0.0870	-2503.9	2630.9	205.0
16	0.108	-2391.1	2516.9	205.2
17	0.138	-2261.3	2361.2	204.4
18	0.174	-2137.3	2182.6	202.1
19	0.216	-1995.1	1985.7	199.5
20	0.277	-1748.7	1725.4	198.6
21	0.353	-1503.0	1448.1	196.3
22	0.441	-1252.3	1189.5	194.9
23	0.561	-981.9	924.7	194.1
24	0.706	-736.9	701.1	195.1
25	0.865	-472.5	533.2	212.8
26	1.07	-369.2	388.2	205.1
27	1.38	-260.2	254.0	197.5
28	1.75	-161.9	162.3	200.2
29	2.19	-100.3	101.5	201.2
30	2.82	-56.34	56.44	200.1
31	3.56	-30.54	31.29	202.4

PARAMETER RESOLUTION MATRIX:
"F" INDICATES FIXED PARAMETER

P 1	0.93		
P 2	0.00	1.00	
P 3	-0.03	0.00	0.26

P 4	0.00	0.00	-0.05	0.99			
T 1	0.03	0.00	0.02	0.00	0.99		
T 2	-0.01	0.00	-0.07	0.00	0.00	0.99	
T 3	0.00	0.00	0.10	0.01	0.00	0.01	0.99
	P 1	P 2	P 3	P 4	T 1	T 2	T 3