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RE-EXAMINATION OF THE 1986 and 1988 TIME DOMAIN ELECTROMAGNETIC SOUNDINGS IN SEMINOLE COUNTY, FLORIDA

Performed For:

St. Johns River Water Management District
P.O. Box 1429
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Performed By:

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(BGI Project #92004)

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May 12, 1992

This is to certify that I, James Hild, have reviewed the figures, tables, and text of the following report, and have retained one copy for my files.

By: ______________________________

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SEAL

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EXECUTIVE SUMMARY

In 1986 and 1988, time domain electromagnetic (TDEM) measurements were made in Seminole County as part of formulating a 20 year water management plan for the County. Since then, some additional TDEM measurements were made for the St. Johns River Water Management District (SJRWMD) in Seminole County and other sites throughout the District. TDEM is a geophysical method that measures from the surface the resistivity layering (geoelectric section) of the subsurface. The objective of TDEM surveys is to infer from the geoelectric sections measured information about water quality in the Upper Floridan aquifer, such as the depth to the 250 mg/l and 5,000 mg/l isochlors.

In this report the TDEM measurements acquired in 1986 and 1988 were re-examined. The impetus for re-examining that data set was that (i) in the last five years improvements in data acquisition and processing have been made, particularly for stations located in urban (high noise) areas, and (ii) a better understanding has been developed for correlating the geoelectric sections derived from TDEM to water quality.

After re-examination of the 1986 and 1988 data, 80 of 142 stations were rejected because distortion of the data due to interference from metallic structures were suspected, or because data were not consistent with well information. The only reliable method to evaluate reliability of TDEM data is from multiple quality control measurements. Since this procedure was not developed in 1986 and 1988, rejection of some stations is subjective. New contour maps of the depth to the 250 mg/l and 5,000 mg/l isochlors were prepared. These new contour maps were subsequently compared to the contours prepared in 1988, prior water quality maps published, and to available well data. The contour maps prepared from the re-examination have trends very similar to the trends on the 1988 contour map, but isolated, one-point anomalies are now removed. Also, the depth to the 250 mg/l isochlor around the town of Longwood is deeper (over 1,000 ft versus less than 200 ft) than predicted in 1988, and is now consistent with water quality observed in pumping wells. This, however, is based on TDEM measurements adjacent to the Longwood area and no TDEM soundings were judged to be reliable within Longwood.

Finally, four areas are recommended in which additional soundings are needed to improve the resolution of the contour maps of depths to the 250 mg/l and 5,000 mg/l isochlor. These areas are

- northwest Seminole County (2 soundings),
- immediately west of the town of Sanford (1 to 2 soundings),
- the town of Longwood (1 to 2 soundings),
- between Casselberry and Oviedo (1 sounding).

1.0 INTRODUCTION

This report covers the results of a re-examination of time domain electromagnetic (TDEM) data collected by Blackhawk Geosciences, Inc. in 1986 and 1988 within Seminole County, Florida. Figure 1-1 shows the locations at which TDEM data were collected within Seminole County. TDEM is a geophysical method that determines from the surface the geoelectric section (resistivity layering) in the subsurface. From the geoelectric section information on geology and water quality can be inferred because the electrical resistivity of the Earth depends on lithology, porosity, and concentration of dissolved solids in the ground water.

The rationales for re-examining the 1986 and 1988 TDEM data collected within Seminole County are that improvements have been made in the last five years in data interpretation and processing. These improvements fall within two categories:

a) A better understanding of the interferences caused by cultural features, such as buried utilities, grounded power lines, metal fences and buildings on TDEM data quality; and

b) development of a more systematic approach for inferring water quality from the geoelectric section in the Floridan aquifer, particularly in the St. Johns River Water Management District (Blackhawk Geosciences, Inc. 1992).

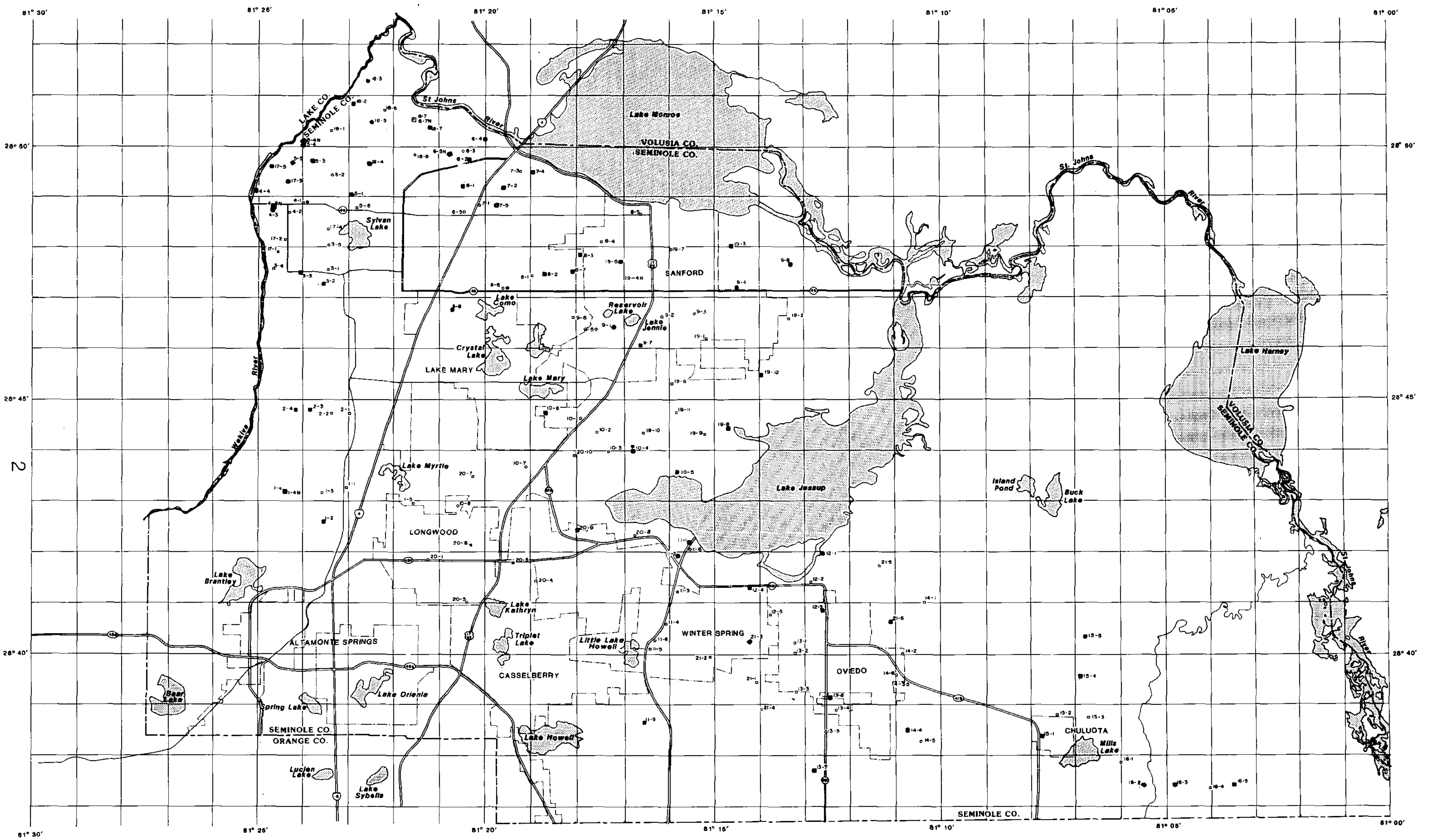
The scope of re-examination of the 1986 and 1988 TDEM surveys consisted of

- reinterpreting all 142 TDEM soundings and determining which soundings likely are affected by cultural interferences,

- utilizing the undistorted soundings to produce contour maps of the depths to the 250 mg/l and 5,000 mg/l isochlors within the Floridan aquifer,

- comparing the results of the present reinterpretations with the results of the interpretations of the 1986 and 1988 surveys,

- identifying areas where additional TDEM soundings are required.



— — County boundary

Surface water features

■ Undistorted Time Domain Electromagnetic (TDEM) soundings

□ Distorted Time Domain Electromagnetic (TDEM) soundings

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TDEM SURVEY LOCATION MAP

ST. JOHNS RIVER
WATER MANAGEMENT DISTRICT
SEMINOLE COUNTY FLORIDA

PROJECT NO: 82004 Figure 1

To determine the validity of the reinterpretation of the TDEM data and the inferences about water quality drawn from the geoelectric profiles, the publication by Tibbals (1977) and water quality information from various wells within the county were the main sources employed for ground truthing.

2.0 TECHNICAL APPROACH

General

The re-examination of the 1986 and 1988 data consisted of several tasks:

1) Task 1 - to distinguish between reliable soundings and soundings distorted by interferences by cultural features, and to reinterpret soundings expected to be undistorted.

2) Task 2 - to use the experiences gained in the last five years in correlating the geoelectric sections derived from TDEM soundings to water quality in the Floridan aquifer.

3) Task 3 - to construct contour maps of depths to 250 mg/l and 5,000 mg/l isochlors in the Floridan aquifer.

4) Task 4 - to perform comparisons between interpretation about water quality derived from the re-examination produced here, and the interpretations derived some four years ago.

5) Task 5 - to identify areas where additional soundings can improve the resolution of the isochlor contour maps.

This section of the report discusses the technical approach to accomplish these five tasks.

Definition of Apparent Resistivity, Inversion of Apparent Resistivity Curves into Geoelectric Profiles, Evaluation of Equivalence (Task 1)

The definition of apparent resistivity, the computation of apparent resistivity curves, and the inversion process in which a geoelectric section is modeled to the apparent resistivity data, are important steps in the interpretation of time domain electromagnetic (TDEM) data. Because of their importance, they are briefly reviewed here.

The field data from a TDEM geophysical survey consists of voltages (electromotive forces) which decay with time. These voltages are transformed into apparent resistivities to better visualize how the geoelectric profile, over which a measurement is made, differs from a geoelectric profile with a uniform resistivity.

Figure 2-1 shows three computed apparent resistivity curves for three different idealized geoelectric sections. In TDEM, effective exploration depth increases with time of measurement after turn-off. The principals of TDEM soundings are discussed in a technical note in Appendix A located at the back of this volume. In model 1 the resistivity is uniform with depth and the apparent resistivity is constant over the entire time interval. In model 2 true resistivities decrease with depth, and the apparent resistivity curves reflect that, i.e., the apparent resistivities can be seen to decrease with increasing time. In model 3 the resistivity increases with depth and at later time the apparent resistivity curve also shows an increase. Thus, qualitative information about the geoelectric section can be visualized from displaying the data as apparent resistivities.

The function of an apparent resistivity curve can be further explained by the example shown in Figure 2-2. The apparent resistivity values can be seen to continuously decrease with increasing time, and to asymptotically approach a value between 10 ohm-m and 20 ohm-m. Thus, from merely viewing the behavior of the apparent resistivity curve, the conclusions can be drawn that (i) the resistivities decrease with depth, and (ii) the resistivity of the lowest layer within the effective exploration depth of the measurement is between 10 ohm-m and 20 ohm-m.

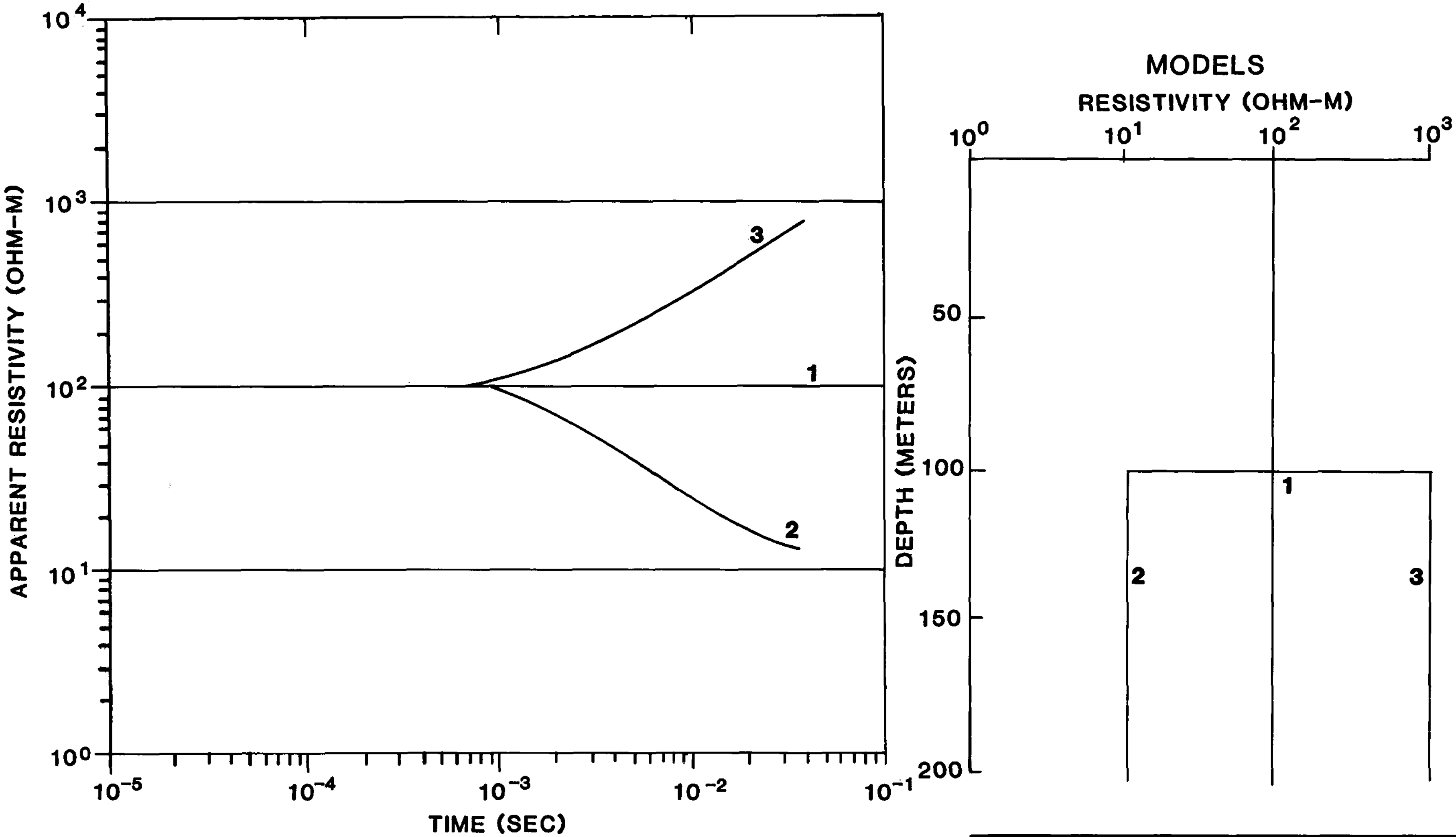
To derive more quantitative information the experimental data points are submitted to an automatic ridge regression transient inversion (ARRTI) program developed by Interpex Limited of Golden, Colorado. This inversion program finds the geoelectric section of the subsurface that best matches the observed data. The inversion program requires an initial model for the geoelectric section. A model consists of the number of layers within the effective exploration depth, and the resistivities and thicknesses for each layer. Such an initial model can be obtained in a number of ways, such as

- approximate matching of apparent resistivity curves with model curves from albums of model curves

- from knowledge of the geoelectric section based on resistivity logs run in drill holes

- from conceptual models formed on the basis of known geology and water quality.

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



1- Geoelectric section is uniform and equals 100 ohm-m.

2- Two layer Geoelectric section with layer 1 resistivity 100 ohm-m and thickness of 100 meters. Layer 2 with infinite thickness and resistivity of 10 ohm-m.

3- Two layer Geoelectric section with layer 1 resistivity 100 ohm-m and thickness 100 meters. Layer 2 has infinite thickness and resistivity of 1000 ohm-m.

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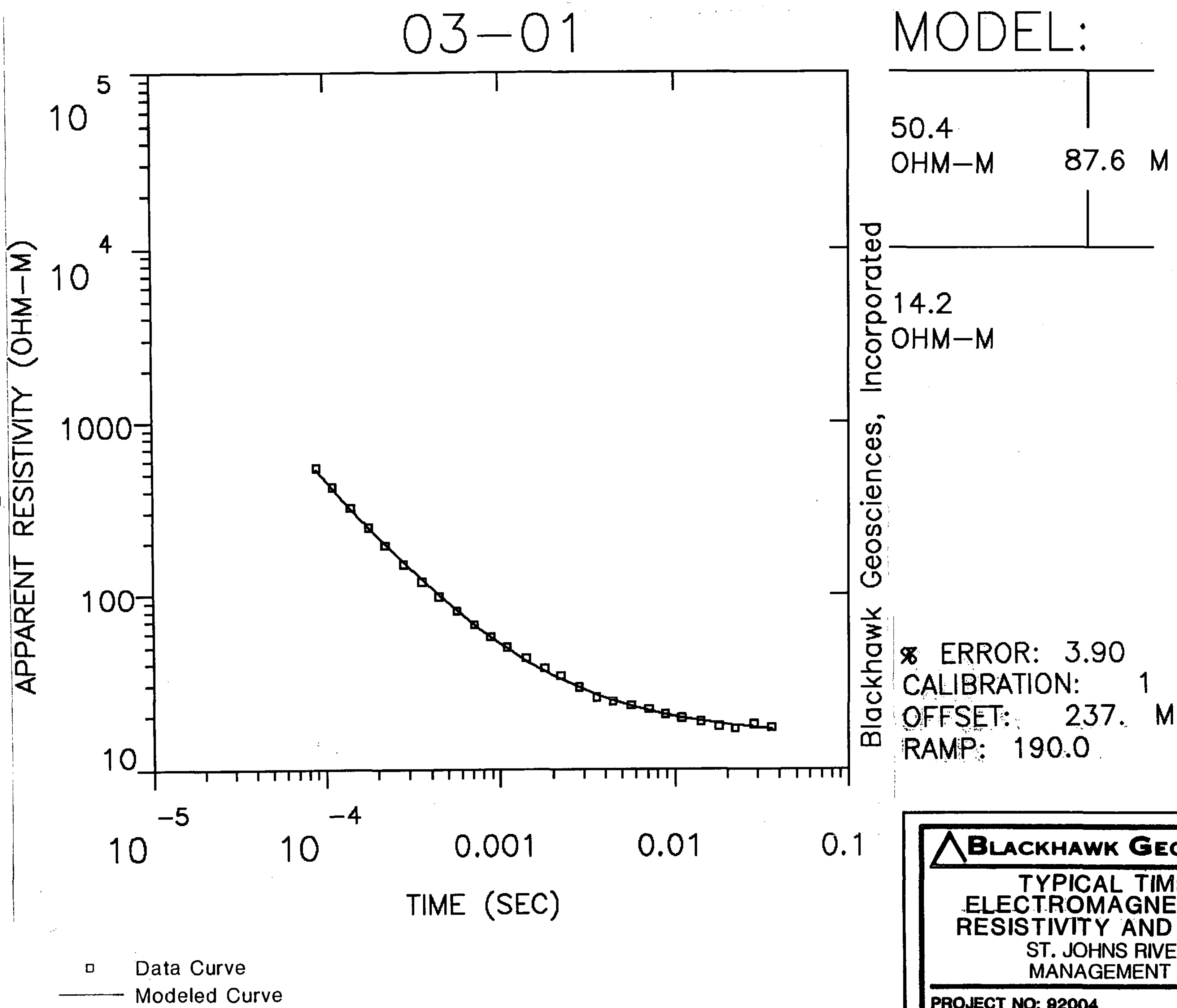
MODELED APPARENT RESISTIVITY CURVES

ST. JOHNS RIVER WATER MANAGEMENT DISTRICT

PROJECT NO: 92004 **Figure 2-1**



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TYPICAL TIME DOMAIN ELECTROMAGNETIC APPARENT RESISTIVITY AND 1-D INVERSION

ST. JOHNS RIVER WATER MANAGEMENT DISTRICT

PROJECT NO: 92004

Figure 2-2

the total number of layers submitted for the model, 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 may be run.

The geoelectric section obtained from the inversion routine that best matches the experimental data is shown on the right side of Figure 2-2. It consists of a two-layer geoelectric section consisting of an upper layer 87.6 m thick with a resistivity of 50.4 ohm-m. The second layer has a resistivity of 14.2 ohm-m and its thickness extends beyond the effective exploration depth of the measurement. The solid line on Figure 2-2 represents the computed behavior for the two-layer geoelectric section shown on the right, and the experimental data are superimposed on the solid line.

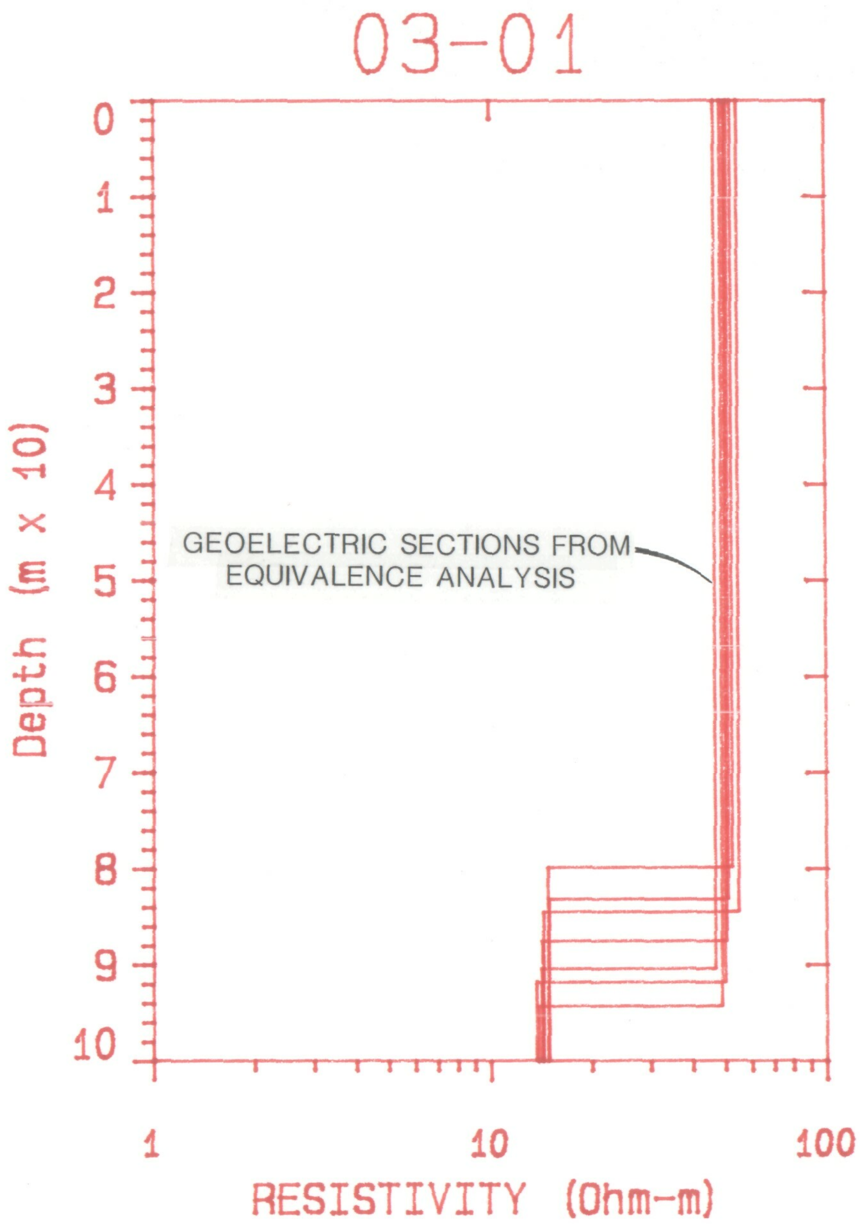
To evaluate the error between the geoelectric section derived from the inversion routine and the experimental data, a tabulation of the inversion and experimental data is also given for each site. The parameters listed on these tables are identified in Table 2-1 for the generalized sounding. Thus, this table lists the error (column 4) between experimental measurements (data, column 2) and calculated data (column 3) for each time gate of measurement (column 1). Also listed on the table is the root mean square (RMS) averaged over all time gates.

Analysis of Equivalence

The parameters derived for the geoelectric section by the ridge regression inversion are not unique, but generally a range of values will equally fit the observed data within the overall RMS error. This phenomena is called equivalence, and the range of equivalence differs for each parameter of a geoelectric section. It is a measure of how well each parameter is resolved, and for each sounding the equivalence was evaluated.

The equivalence analysis for the example sounding is shown on Figure 2-3, and the upper and lower bound for each parameter of the geoelectric section is also shown on Table 2-1. Thus, at this site the largest range of equivalence is in determining the depth to the second layer. It may vary from 80 m to 94 m and still result in the same RMS error. The ranges of equivalence for the resistivities of the first and second layer are relatively small.

Examination of the equivalence was performed for 10 representative sites within Seminole County. These soundings were chosen to be typical of the varying depths to the 250 mg/l and 5,000 mg/l isochlors within Seminole



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EQUIVALENCE IN 1-D INVERSION

ST. JOHNS RIVER WATER
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PROJECT NO: 92004

Figure 2-3

03-01

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		12.2	40.0		
50.36	87.6	-75.4	-247.3	1.7	1.7
14.19					

Solution Geoelectric Section

Inversion Table

	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	5.46E+02	5.36E+02	1.955	
2	1.10E-04	4.24E+02	4.14E+02	2.399	
3	1.40E-04	3.21E+02	3.15E+02	1.981	
4	1.77E-04	2.46E+02	2.46E+02	0.182	
5	2.20E-04	1.94E+02	1.97E+02	-1.253	
6	2.80E-04	1.51E+02	1.55E+02	-2.519	
7	3.55E-04	1.20E+02	1.23E+02	-3.069	
8	4.43E-04	9.80E+01	1.01E+02	-2.880	
9	5.64E-04	8.08E+01	8.16E+01	-0.902	
10	7.13E-04	6.75E+01	6.70E+01	0.826	
11	8.81E-04	5.75E+01	5.72E+01	0.541	
12	1.10E-03	4.99E+01	4.91E+01	1.570	
13	1.41E-03	4.32E+01	4.17E+01	3.603	
14	1.80E-03	3.78E+01	3.64E+01	4.045	
15	2.22E-03	3.42E+01	3.28E+01	4.404	
16	2.83E-03	2.94E+01	2.93E+01	0.574	
17	3.55E-03	2.56E+01	2.68E+01	-4.320	
18	4.43E-03	2.43E+01	2.49E+01	-2.452	
19	5.64E-03	2.32E+01	2.30E+01	0.983	
20	7.13E-03	2.20E+01	2.18E+01	1.075	
21	8.81E-03	2.06E+01	2.07E+01	-0.497	
22	1.10E-02	1.96E+01	1.97E+01	-0.497	
23	1.41E-02	1.86E+01	1.89E+01	-1.604	
24	1.80E-02	1.76E+01	1.82E+01	-3.485	
25	2.22E-02	1.70E+01	1.77E+01	-4.029	
26	2.85E-02	1.80E+01	1.72E+01	4.460	
27	3.60E-02	1.72E+01	1.68E+01	2.225	

R: 237. X: 0. Y: 237. DL: 475. REQ: 264. CF: 1.0000

TDHZ ARRAY, 27 DATA POINTS, RAMP: 190.0 MICROSEC, DATA: 03-01

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EXAMPLE INVERSION TABLE

ST. JOHNS RIVER WATER MANAGEMENT DISTRICT

PROJECT NO: 92004 Table 2-1

RMS Error

RMS LOG ERROR: 1.66E-02, ANTILOG YIELDS 3.8953 %

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

Result of Computation of Equivalence

LAYER		MINIMUM	BEST	MAXIMUM
RHO	1	46.620	50.357	54.730
	2	13.612	14.189	14.831
THICK	1	79.931	87.560	94.326
DEPTH	1	79.931	87.560	94.326

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EXAMPLE INVERSION TABLE (CONTINUED)

ST. JOHNS RIVER WATER MANAGEMENT DISTRICT

PROJECT NO: 92004 Table 2-1

County. The ranges of equivalence are dependent on the particular geoelectric section encountered. Also when the number of layers increases, the range of equivalence of some parameters in the section may be quite large.

Distinguishing Reliable Soundings From Soundings Distorted by Interference (Task 1)

Parts of Seminole County are heavily urbanized and TDEM station locations in such areas are subject to noise. In TDEM two types of noise must be considered:

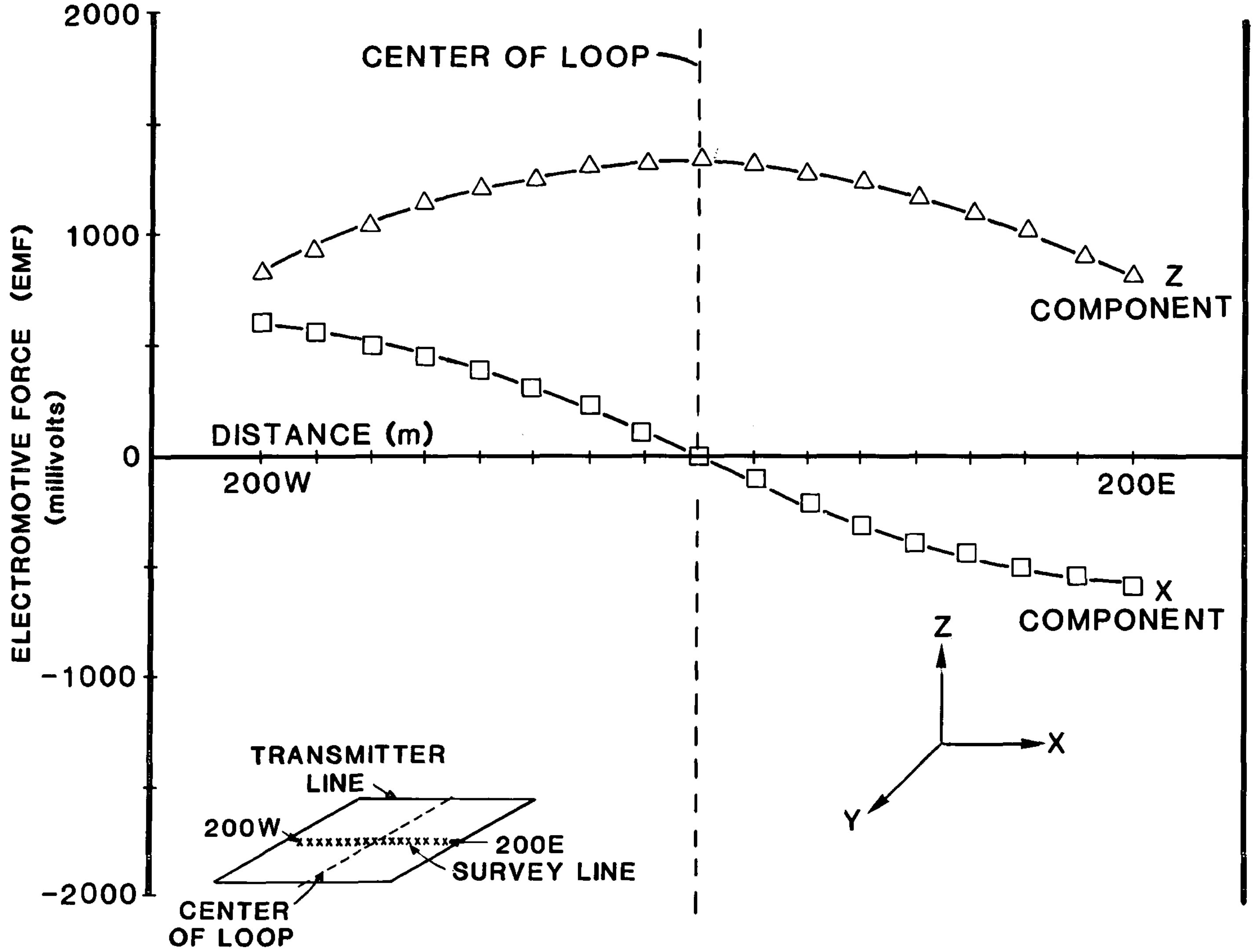
1) Ambient electrical noise due to power lines, radio stations and spherics. This noise can to a large extent be mitigated by stacking, which is the averaging of multiple sets of data taken at a sounding location. The duration of on-and-off pulses is a few milliseconds, and many pulses of positive and negative polarities are stacked in a short period of time and averaged to remove noise. That process can be very effective in dealing with ambient electrical noise, and successful surveys have been performed in athletic fields and parks in urban areas in the presence of strong ambient noise.

2) Inductive noise due to coupling in metallic structures, such as buried utilities, fences, grounded power lines and buildings. The primary magnetic field of the transmitter will not only induce eddy current flow in the subsurface, but also in metallic structures. These structures in turn will radiate a secondary magnetic field that is measured at the receiver together with the field caused by eddy currents in the ground. This source of noise cannot be removed by stacking, because it is coherent with the transmitter waveform. It can only be minimized by selecting locations away from the influence of inductive noise sources. The distance required between TDEM receiver stations and inductive noise sources depends on a number of factors, such as required exploration depth, transmitter loop dimension, geoelectric section, and the type of inductive noise source. It can range from 100 ft over conductive geoelectric sections and for small inductive noise sources (e.g., a building), to a thousand feet for resistive geoelectric sections for deep exploration depth requirements, and for elongated structures such as pipelines. Lack of availability of good measurement locations in urban and industrial areas is now recognized as a major limitation of TDEM surveys.

The procedures adopted for recognizing the influence of inductive noise is based on the information conveyed by Figure 2-4. Figure 2-4 shows a typical measured behavior of the electromotive forces (emf's) due to the horizontal and vertical magnetic fields on a profile through the center of the loop over horizontally stratified ground at 2.2 millisec after current turn-off. At other times the behavior would be similar, but of different amplitude. The behavior of emf_z (vertical) is relatively flat about the center, so that measurements made at different locations inside the loop should be nearly identical. On the other hand, measurements in the presence of interference by metallic structures depend on distance of the receiver from such structures. Figure 2-5a shows four apparent resistivity data curves measured at different locations inside a transmitter loop. From the coincidence of the four curves of Figure 2-5a no inductive noise is expected. Figure 2-5b shows apparent resistivity curves from measurements at five stations inside a loop, and substantial deviation between the curves is observed, indicating the presence of inductive noise. This measurement would be rejected because at present no reliable procedures to accurately remove this inductive noise are available.

The procedures outlined above are now routinely performed for TDEM soundings in urban settings. However, they were only implemented about two years ago, and they were not in effect in the data acquisition of the 1986 and 1988 TDEM surveys. Distinguishing between distorted and undistorted soundings in the absence of such data becomes somewhat arbitrary. To avoid as much as possible subjective decision making, the following criteria were employed to reject soundings:

1) Noisy data. The apparent resistivity curve data points show a large amount of scatter along the entire curve and a large total RMS error. An example of this type of curve is shown in Figure 2-6. In addition, noisy data can be localized in some portion of the curve with only a limited amount of scatter along the rest of the curve. If this scatter occurs along the latter portion of the curve, these data points are deleted and an interpretation is made on the remaining data. The validity of this interpretation is checked based on other soundings in the vicinity or available ground truth.



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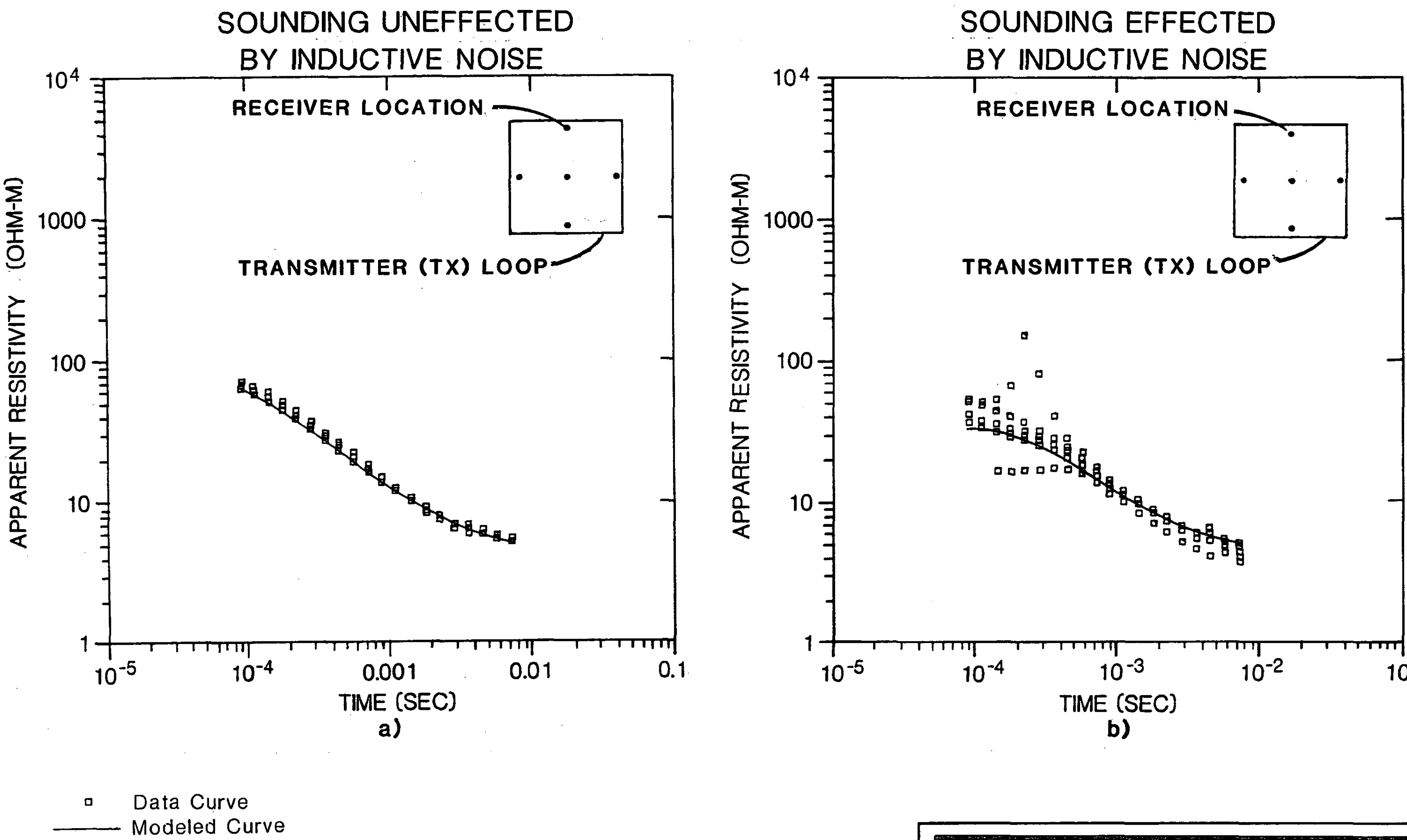
SPATIAL BEHAVIOR OF
EMF_Z AND EMF_X ON PROFILE
THROUGH CENTER OF LOOP
ST. JOHNS RIVER WATER
MANAGEMENT DISTRICT

PROJECT NO: 92004 | Figure 2-4



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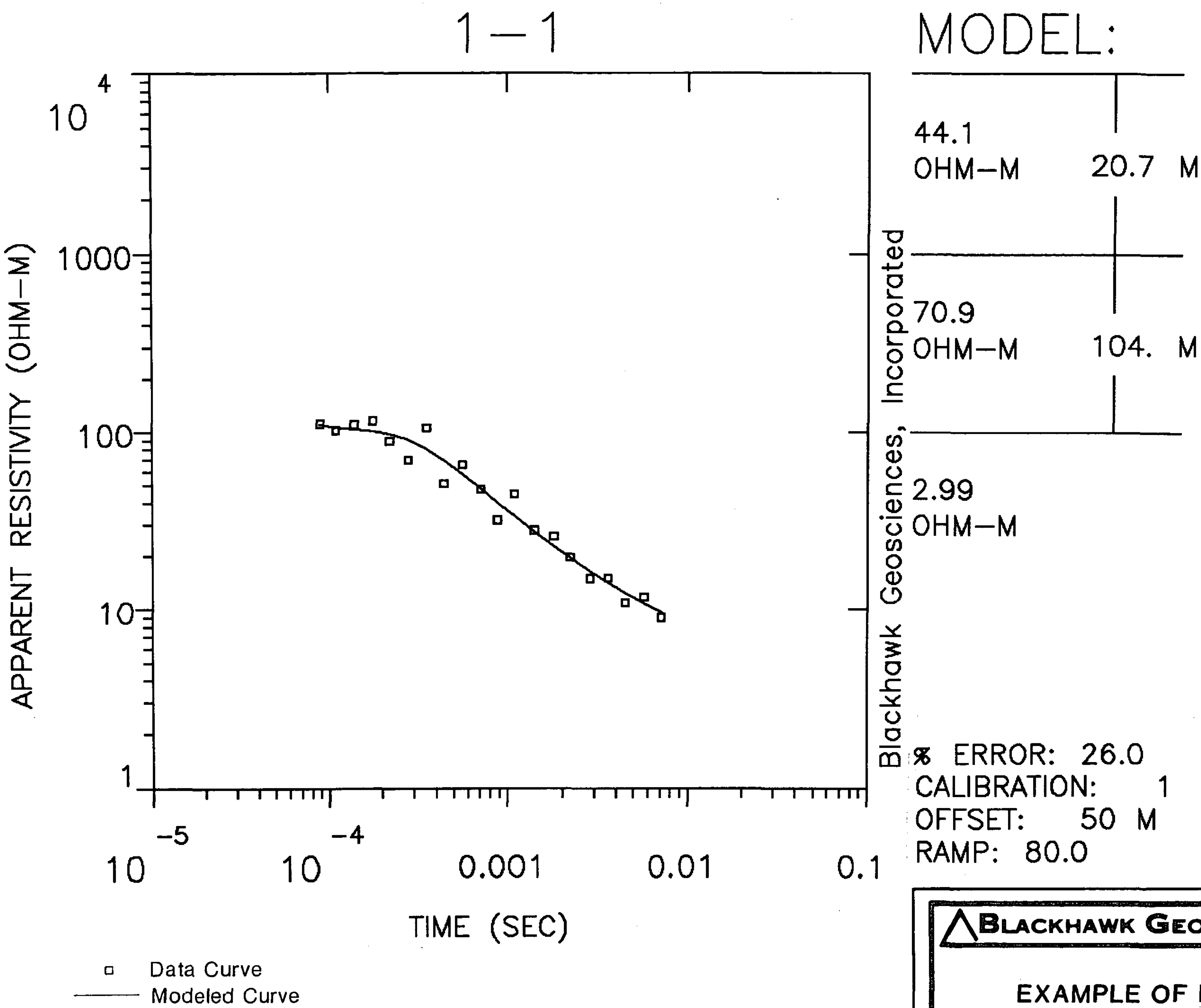
APPARENT RESISTIVITY CURVES AT POSITIONS INSIDE TX LOOP

ST. JOHNS RIVER WATER MANAGEMENT DISTRICT

PROJECT NO: 92004 **Figure 2-5**



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EXAMPLE OF NOISY DATA

ST. JOHNS RIVER WATER MANAGEMENT DISTRICT

PROJECT NO: 92004 **Figure 2-6**

2) Modeling of an unrealistic geoelectric section to the data. In certain soundings the data can be modeled only if very conductive (< 2 ohm-m) layers occur within the geoelectric section. It is unlikely that such low resistivity layers are present within the Floridan aquifer since they would require salinities greater than 30,000 mg/l Cl - assuming an average porosity of 25%. Figure 2-7 is an example of a sounding with unrealistic resistivities.

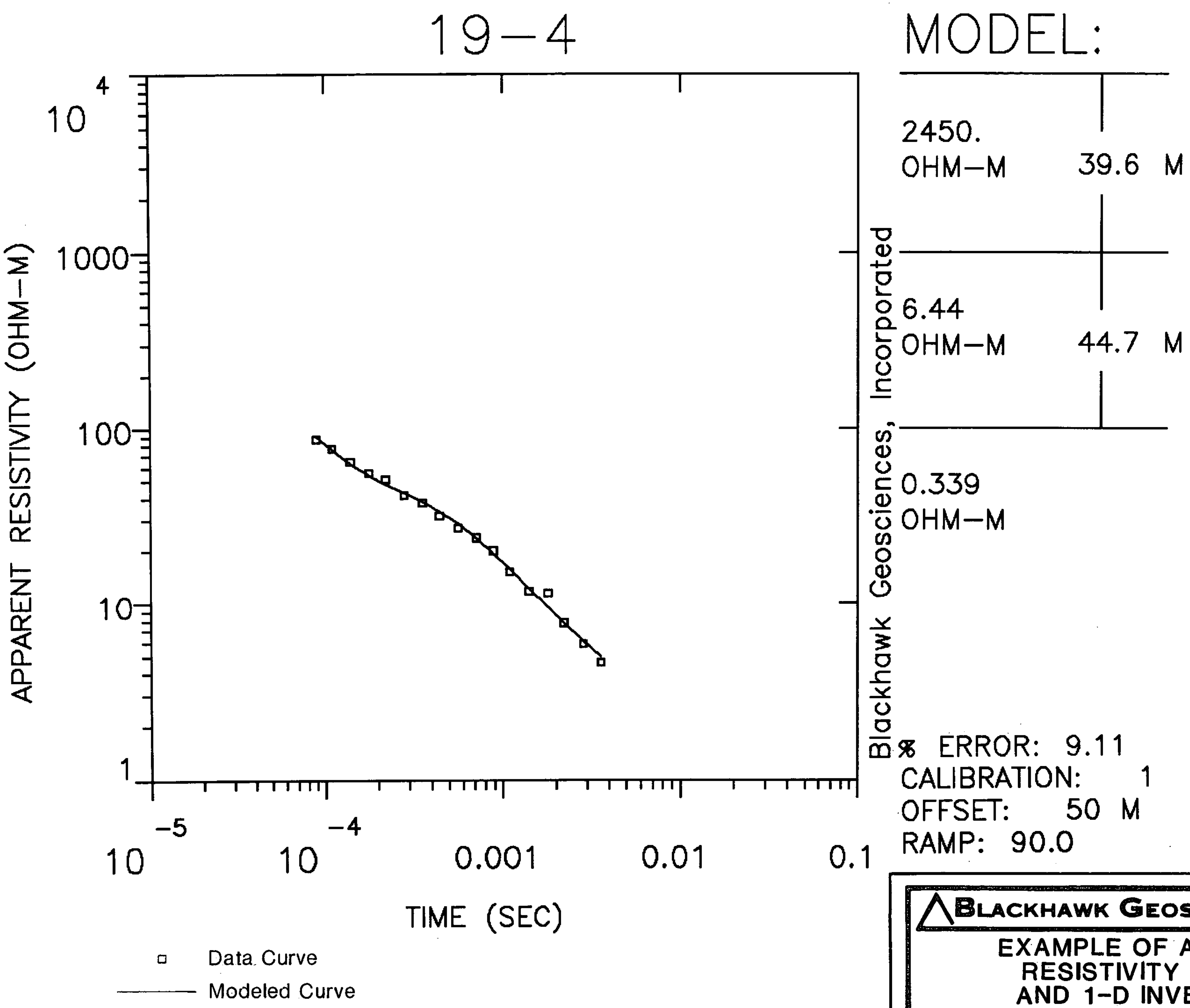
3) Modeled geoelectric section from a sounding is not consistent with other soundings or well data within the general area. This criteria is based on the assumption that large isolated fluctuations in the depth to either the 250 mg/l or 5,000 mg/l isochlor are unlikely. Rapid changes in the depths to the isochlors are assumed to occur only along regional trends. This criteria eliminates the "bullseye" type anomalies which are determined by one or two soundings. This clearly is the most subjective criteria, because it presupposes a certain behavior, albeit a reasonable one, on the isochlors. It may, however, result in the rejection of valid soundings in areas where isolated pockets of poor quality water (> 250 mg/l Cl) occur. Unfortunately, this subjectivity cannot be removed from analysis of the 1986 and 1988 surveys, because multiple quality control measurements were not taken at those times.

Correlation of Modeled Resistivities to Chloride Concentration (Task 2)

From the soundings determined to be reliable, geoelectric sections were derived by 1-D inversions. In this section the procedures used in correlating the geoelectric sections to water quality in the Floridan aquifer are discussed.

The hydrogeologic section is expected to be consistent across Seminole County. The Floridan aquifer system which is the primary focus of this report underlies the entire county. This system has been defined by Miller (1990) as being generally 10 times more permeable than its bounding upper and lower confining units. Within Seminole County it is divided into an Upper Floridan aquifer and a lower Floridan aquifer. These units are separated by a middle semi-confining unit which is from 400 to 800 ft thick and it occurs at a depth of 400 to 450 ft (Tibbals, 1990).

Figure 2-8 is a stratigraphic column from the Wekiva River area of West Seminole County and is generally typical of the county. The formations that comprise the Floridan aquifer system are all carbonate rocks, mostly of Eocene



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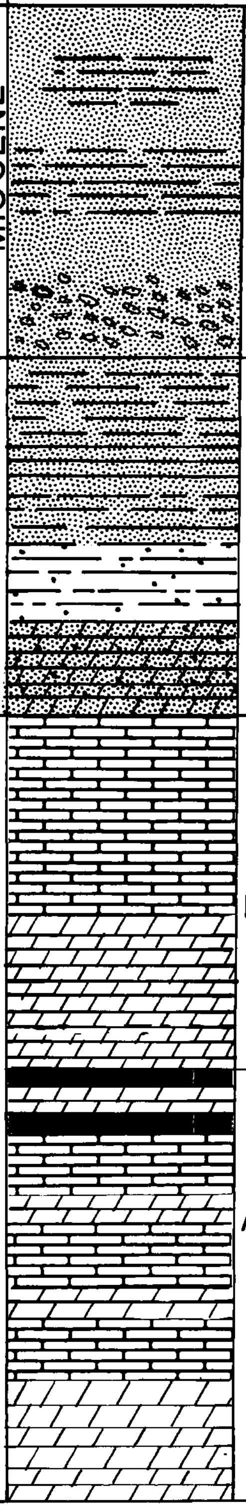
EXAMPLE OF APPARENT RESISTIVITY CURVE AND 1-D INVERSION

ST. JOHNS RIVER WATER MANAGEMENT DISTRICT

PROJECT NO: 92004 **Figure 2-7**

TYPICAL HYDROSTRATIGRAPHIC COLUMN IN WEKIVA RIVER AREA



AGE	FORMATION	AQUIFER	THICKNESS	DESCRIPTION
LATE AND POST MIOCENE	SURFICIAL MATERIAL	SURFICIAL AQUIFER	34 ft. to 139 ft.	Sand, Clay, and Coquina
MIOCENE	HAWTHORN GROUP	INTERMEDIATE AQUIFER AND CONFINING UNIT	25 ft. to 150 ft.	Sand, Clay, Limestone, and Dolostone, mostly phosphatic
			3 ft. to 32 ft.	Basal Hawthorn: Dolostone, sandy, phosphatic, hard
EOCENE	OCALA LIMESTONE	FLORIDAN AQUIFER	20 ft. to 112 ft.	Limestone, relatively pure Coquina, bio- and foraminiferal-
			9 ft. to 57 ft.	Lower Ocala: Limestone, dolomitic, coquinoid
	AVON PARK LIMESTONE		150 ft. to 330 ft.	Limestone and Dolostone with Peat (disseminated and as beds) or Clay beds
				Avon Park: Dolostone, very hard, low porosity zone

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TYPICAL HYDROSTRATIGRAPHIC COLUMN IN WEKIVA RIVER AREA

ST. JOHNS RIVER WATER MANAGEMENT DISTRICT

PROJECT NO: 92004 Figure 2-8

age. Overlying the Floridan are mainly the Hawthorn Group and younger primarily clastic material. The thickness and properties of these units are highly variable. The Hawthorn Group is not present in and around the town of Sanford.

The resistivity of a water bearing rock is mainly a function of lithology, dissolved solids in ground water, and porosity. Most rock forming minerals are essentially insulators and nearly all electrical current is carried either by free ions in pore water or by exchangeable ions associated with clay particles. To separate the causes of vertical and lateral variation in a geoelectric section requires careful correlation with lithology, and often assumptions about the dominant cause of resistivity variation locally must be made. Within Seminole County variation in lithology is mainly expected in the Hawthorn Group and younger surficial units. The composition of these formations can vary from coarse-grained sands and gravels to clays. Thus, in the Hawthorn Group and younger sediments three factors potentially can influence resistivity, - lithology (clay content), porosity, and water quality. Without other independent information the causes of lateral and vertical resistivity variation cannot be separated, and no attempt has been made to infer information about water quality from resistivity measurements for the formations above the Floridan aquifer.

On the other hand, the lithology of the carbonate rocks comprising the Floridan aquifer system are expected to be uniform. The resistivity of the rocks of the Floridan aquifer will be mainly determined by porosity and dissolved solids concentrations of the pore fluids. Archie's Law is used to express the relationship between formation resistivity, Ro; fluid resistivity, Rw; and porosity, ϕ:

$$F = Ro/Rw = a\ \phi^{-m} \qquad [1]$$

where F = formation factor and a,m are empirically derived constants dependent on lithology and pore type distribution. Kwader (1982) found a value of m = 1.6 and a = 1 to best fit his many observations from wells completed in the Upper Floridan aquifer in Seminole County.

Fluid resistivity is a function of concentration of dissolved solids and ionic composition. The most common cations in water in the Upper Floridan aquifer are calcium, magnesium and sodium; the most common anions are bicarbonate, chloride and sulfate. Water quality is often expressed in terms of equivalent chloride concentrations. Kwader (1982) established on the basis of many measurements on water samples throughout Seminole County the relation between chloride concentration and fluid resistivity, Rw, given by

$$CL = 3500/Rw - 153 \qquad [2]$$

where CL is chloride concentration in mg/l, and Rw is fluid resistivity in ohm-meter.

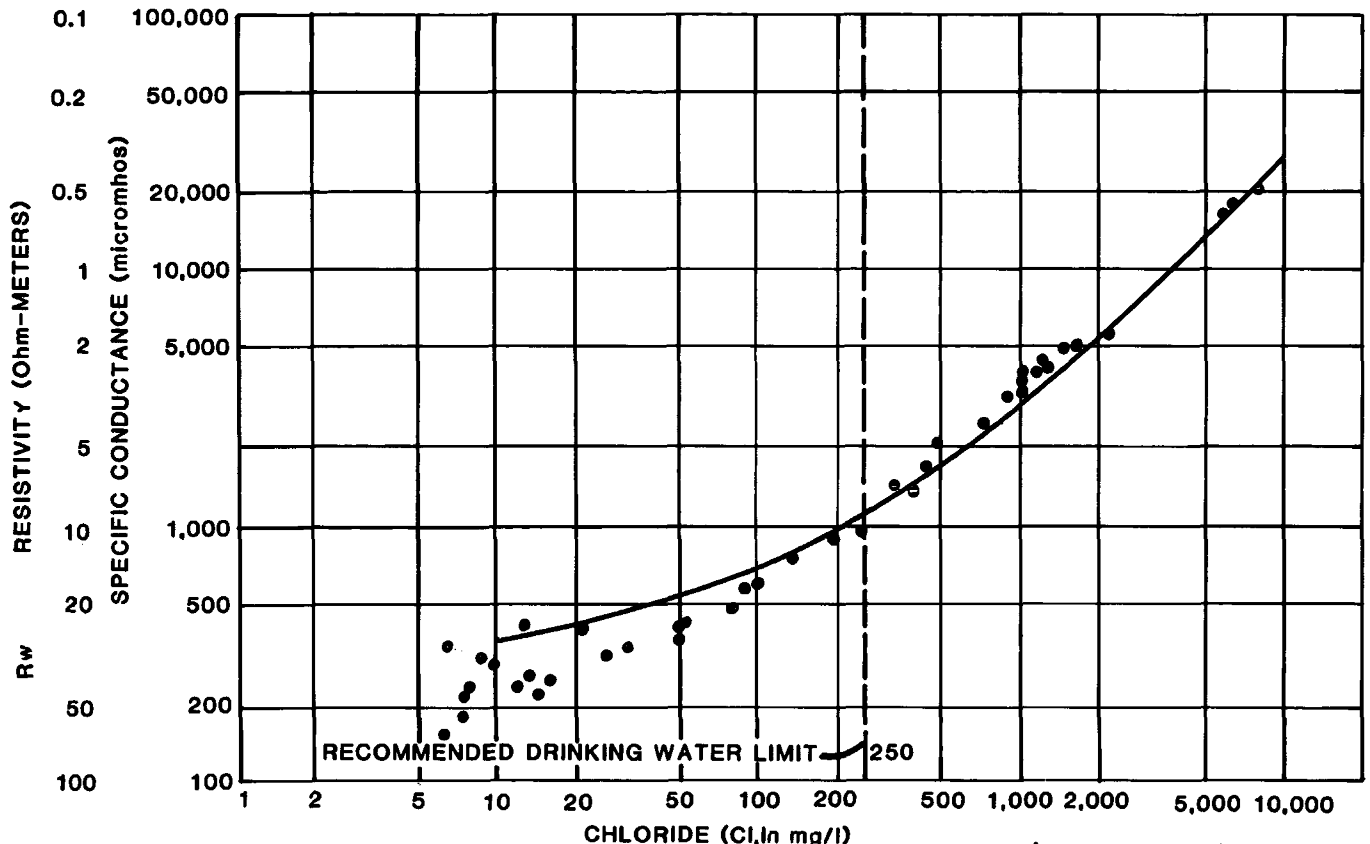
A graphic presentation of this relation is given in Figure 2-9, and it also shows the data points from which relation [2] was derived. The maximum chloride concentrations for which data points were available to Kwader (1982) was about 10,000 mg/l, and the relation is untested at higher chloride concentrations.

By combining equation [1] and [2] chloride concentration can be related to formation resistivity as a function of porosity, and this relation is displayed in Figure 2-10. Thus, for the Upper Floridan aquifer with an average porosity of 25%, chloride concentrations less than 250 mg/l are expected when its formation resistivity is greater than 80 ohm-m. Chloride concentrations greater than 5,000 mg/l would be indicated by formation resistivity values less than about 6.2 ohm-m.

It is evident from the above discussion that to derive chloride concentration from a measured value of formation resistivity certain assumptions must be made. The assumptions consistently made for all the TDEM soundings within Seminole County are:

a) The relation (Fig. 2-9) between fluid resistivity and chloride concentration established by Kwader (1982) for Seminole County is valid;

b) In deriving chloride content from formation resistivity an average porosity of 25% was used for all sites. Information about porosity of the Floridan aquifer is limited. In one published data set, porosities were computed from geophysical logs over the depth interval between 338 ft and 458 ft. Porosities over this depth range varied between 12% to 32% (NW Florida Water Management District, 1983). Since site specific information about porosities was not available, a porosity value of 25% has been used at all sites. In 1986 and 1988 data a porosity of 40% was used for salinity computations from TDEM derived geoelectric sections. The reference listed above is the only independent information about porosity available. Moreover, comparison between well information and TDEM derived geoelectric sections at several sites throughout the St. Johns River Water Management District indicate 25%



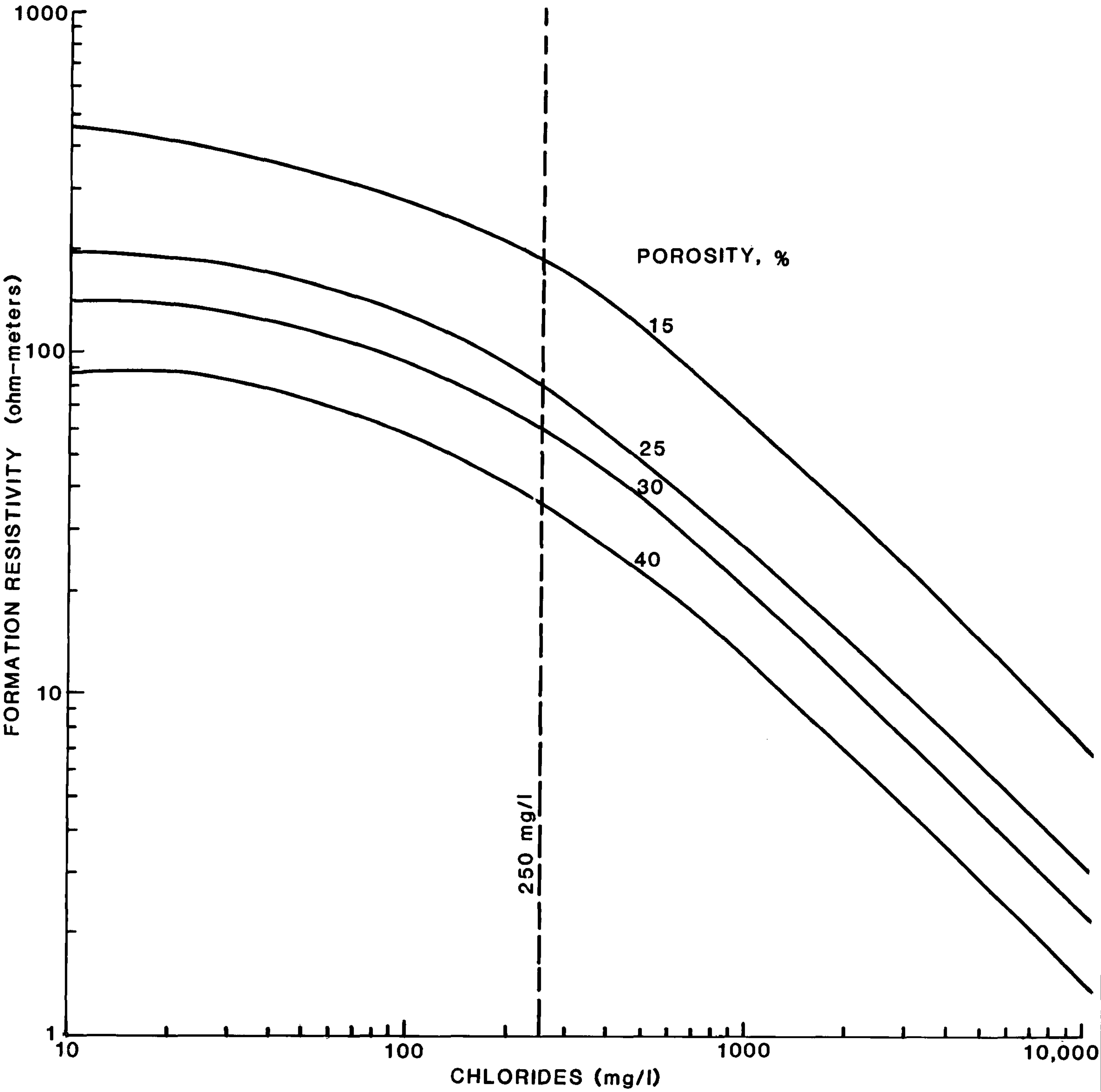
(After: Kwader, 1982

BLACKHAWK GEOSCIENCES, INC.

FLUID RESISTIVITY (Rw) VERSUS CHLORIDE CONCENTRATION

ST. JOHNS RIVER WATER MANAGEMENT DISTRICT

PROJECT NO: 92004 **Figure 2-9**



BLACKHAWK GEOSCIENCES, INC.

FORMATION RESISTIVITY VERSUS CHLORIDE CONCENTRATION

ST. JOHNS RIVER WATER MANAGEMENT DISTRICT

PROJECT NO: 92004

Figure 2-10

porosity to result in reasonable agreement (Blackhawk Geosciences, Inc., 1992).

c) In the Hawthorn Group and more recent formations, resistivity values are influenced by changes in lithology, porosity, and chloride concentration. This precluded inferring meaningful interpretations about chloride concentrations in the Hawthorn Group and the formations overlying it. Inferences about water quality are, therefore, ideally drawn only for the carbonate rocks below the Hawthorn Group, and for each site an evaluation must be made of the extent clay stringers in the Hawthorn Group may have influenced the average resistivity value measured. Therefore, the thickness of the first layer resolved in the undistorted geoelectric sections is fixed at a value in the inversion program model and not adjusted by the program. This layer likely represents surficial sediments and the Hawthorn Group. In several cases a thin (less than 25 ft) surficial conductor occurs within the geoelectric section. This layer is likely caused by surficial organics. For these soundings the Hawthorn Group and surficial sediments are represented by the first two layers in the geoelectric section. Soundings 6-4 and 7-4 are examples of this. No information about equivalent chloride concentration can be inferred for layers above the Floridan.

In Seminole County good information about the thickness of the surficial sediments and the Hawthorn Group is available from Tibbals (1977). This information was employed in the present re-examination of TDEM soundings by inserting a layer of a thickness, derived from the contour map of Tibbals (1977) in the inversion. The resistivity of layers below this first layer were assumed to correspond with strata within the Floridan aquifer.

Determination of Depth of Occurrence of 250 mg/l and 5,000 mg/l Isochlor (Task 3)

As discussed in the preceding section, a resistivity of 80 ohm-m within the Floridan aquifer corresponds to a chloride content of 250 mg/l, and a resistivity of 6.2 ohm-m corresponds to chloride content of 5,000 mg/l, assuming 25% porosity. In nearly all the inverted geoelectric sections these exact resistivities are not derived from 1-D inversions. Therefore, to determine the depth of occurrence of resistivities corresponding to chloride concentrations of 250 mg/l and 5,000 mg/l certain manipulations and assumptions need to be made.

The contact between saline water (> 250 mg/l Cl) and fresh water (< 250 mg/l Cl) in an aquifer is not abrupt. Normally, a transition zone exists, in which salinities gradually change from fresh water to saline water. Figure 2-11 shows a salinity profile encountered in a well drilled in northeast Seminole County (Fig. 3-3, Table 3-4). The transition zone from saline to fresh water in this example is approximately 100 ft thick. The TDEM method usually does not measure the transition zone as a separate layer unless its thickness is large, relative to its depth. The resistivity boundary determined by TDEM is normally positioned near the center of the transition zone. Thicknesses of transition zones are variable depending mainly on salinity contrasts and ground water mixing. Significant mixing is most prevalent in areas of high ground water flow. In the procedures adapted to compute depth to the 250 mg/l and 5,000 mg/l isochlor thicknesses of transition zones are varied based on probable assumptions derived from the geoelectric section. The geoelectric sections derived in Seminole County were placed in classes as shown in Figure 2-12. A summary of the criteria utilized in positioning the 250 mg/l isochlor is contained in Table 2-2.

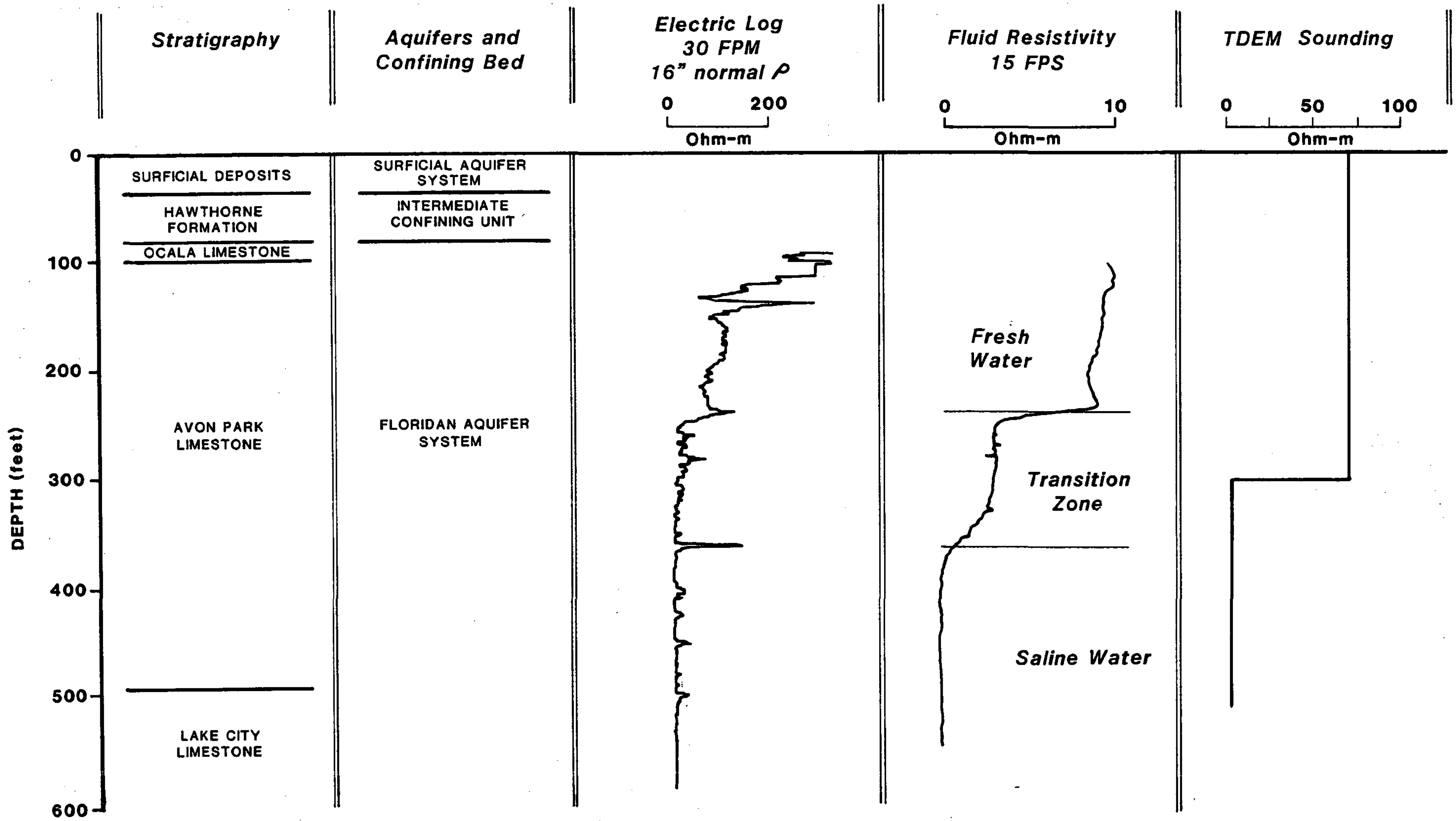
Table 2-2. **Summary of Criteria for Positioning the 250 mg/l Isochlor**

Class	Lowest Resistivity Encountered in Geoelectric Section	Chloride Values Corresponding to Lowest Resistivity in Geoelectric Section	Position of Isochlor Relative to Modeled Geoelectric Boundary
A	< 20 ohm-m	> 1450 mg/l	50 ft higher
B	> 20 ohm-m, < 40 ohm-m	> 650 mg/l, < 1450 mg/l	25 ft higher
C	> 40 ohm-m, < 80 ohm-m	> 250 mg/l, < 650 mg/l	Same position
D	> 80 ohm-m	< 250 mg/l	Requires modeling

Class A

In the geoelectric section (Fig. 2-12a) layers with resistivities greater than 80 ohm-m overlay layers with resistivities less than 20 ohm-m. The corresponding model for equivalent chloride concentrations used is also shown in Figure 2-12a. An example of a sounding over a geoelectric section in this class is Sounding 10-6. The assumptions made in relating the geoelectric sections to equivalent chloride concentration profiles are:

1) The transition zone is assumed to be 100 ft thick. The 250 mg/l isochlor occurs at the top of the interface, and 50 ft above the

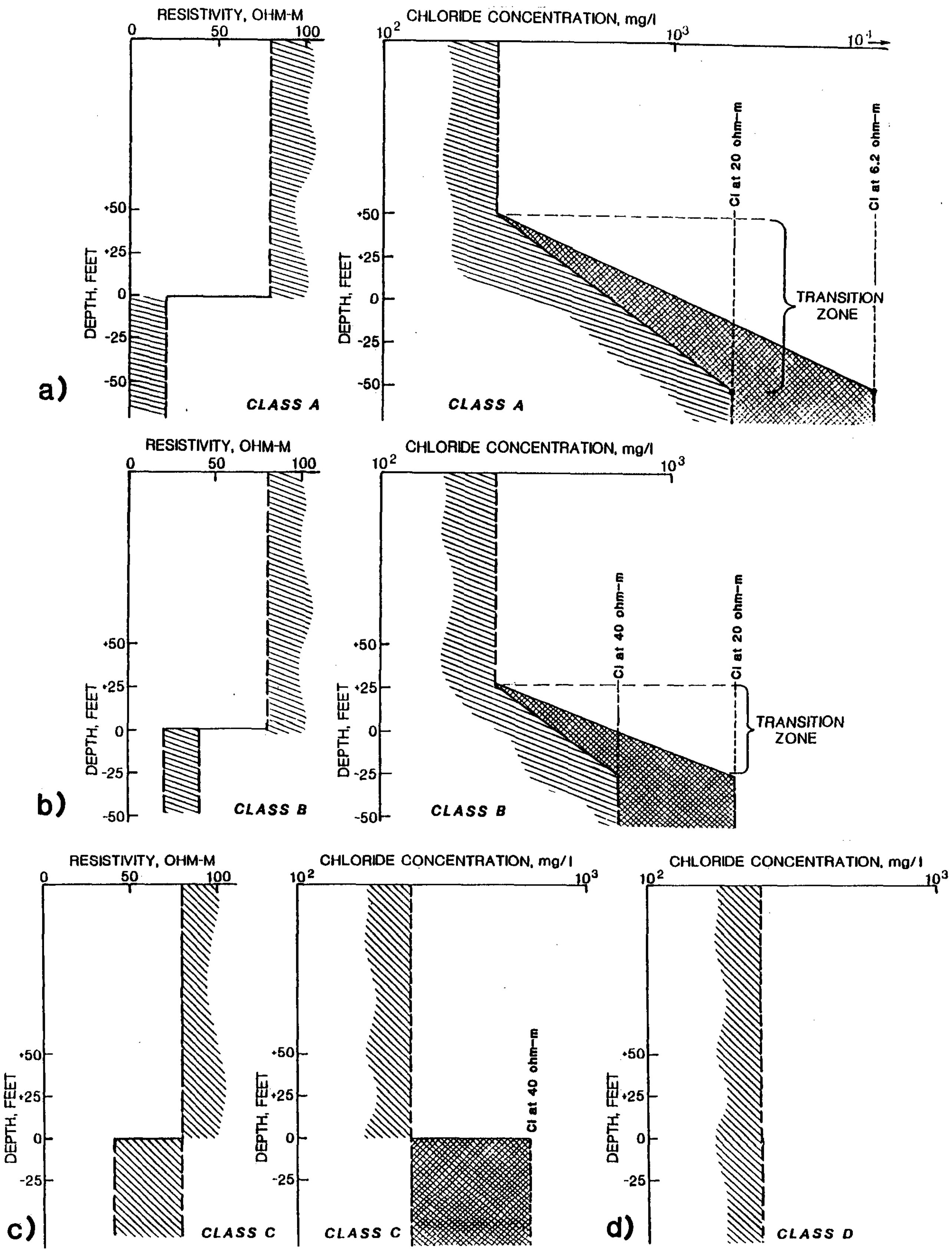


BLACKHAWK GEOSCIENCES, INC.

SALINITY PROFILE OF WELL IN SEMINOLE COUNTY
ST. JOHNS RIVER WATER MANAGEMENT DISTRICT

PROJECT NO: 92004

Figure 2-11



BLACKHAWK GEOSCIENCES, INC.

CLASSIFICATION OF TYPICAL GEOELECTRIC PROFILES AND ASSUMED SALINITY PROFILES
ST. JOHNS RIVER WATER MANAGEMENT DISTRICT

PROJECT NO: 92004 Figure 2-12

resistivity boundary measured with TDEM. In the transition zone chloride concentration varies exponentially with depth. Hence, Cl (mg/l) = A exp $(\text{depth})^B$, where A and B are constants.

2) The chloride concentration at the bottom of the transition zone depends on the resistivity determined in the geoelectric section immediately below the layer with a resistivity greater than 80 ohm-m.

Class B

In the geoelectric section layers with resistivities greater than 80 ohm-m overlay layers with resistivities greater than 20 ohm-m and less than 40 ohm-m. The corresponding model for equivalent chloride concentrations used is also shown on Figure 2-12b. An example of a sounding over a geoelectric section in this class is Sounding 8-2. The assumptions made in relating the geoelectric section to equivalent chloride concentration profiles are:

1) The transition zone is assumed to be 50 ft thick. The 250 mg/l isochlor occurs at the top of the interface and 25 ft above the resistivity boundary measured with TDEM. Again, in the transition zone chloride concentrations are assumed to increase exponentially with depth.

2) The chloride concentration at the bottom of the transition zone depends on the resistivity of the geoelectric section immediately below the layer with a resistivity greater than 80 ohm-m.

Class C

In the geoelectric section (Fig. 2-12c) layers with resistivities greater than 80 ohm-m overlay layers with resistivities greater than 40 ohm-m and less than 80 ohm-m. The corresponding model for equivalent chloride concentrations used is also shown on Figure 2-12c. An example of a sounding over a geoelectric section in this class is Sounding 1-2. The assumptions made in relating the geoelectric section to equivalent chloride concentration profiles are:

1) The transition zone is assumed to be thin and the top of the 250 mg/l isochlor is assumed to be at the same depth as the resistivity boundary.

2) The chloride concentration at the bottom of the transition zone depends on the resistivity of the geoelectric section immediately below the layer with a resistivity greater than 80 ohm-m.

Class D

In the geoelectric section (Fig. 2-12d) no layers with a resistivity less than 80 ohm-m are encountered within the effective exploration depth of the measurement, and the 250 mg/l isochlor also is assumed to occur at a depth greater than the effective exploration depth of the measurement. An example of a sounding over a geoelectric section in this class is sounding #1-4. The minimum depth of occurrence is computed by placing a layer with a resistivity of 80 ohm-m below the geoelectric section measured and computing by iterations the minimum depth at which errors greater than 5% are observed between the model and measured data in the last three time gates. This approach gives only an approximation of minimum depth. The error in the modeled minimum depth depends on a number of factors, such as geoelectric section, data quality, depth to 250 mg/l interface. Because of these uncertainties reported depths are rounded off to the nearest 50 ft in Table 3-2 and Figures 3-1 and 3-2.

The grouping of the geoelectric sections in four classes yielded an approach for calculating the depth to the 250 mg/l isochlor. Next, an approach for determining the depth to the 5,000 mg/l isochlor is discussed.

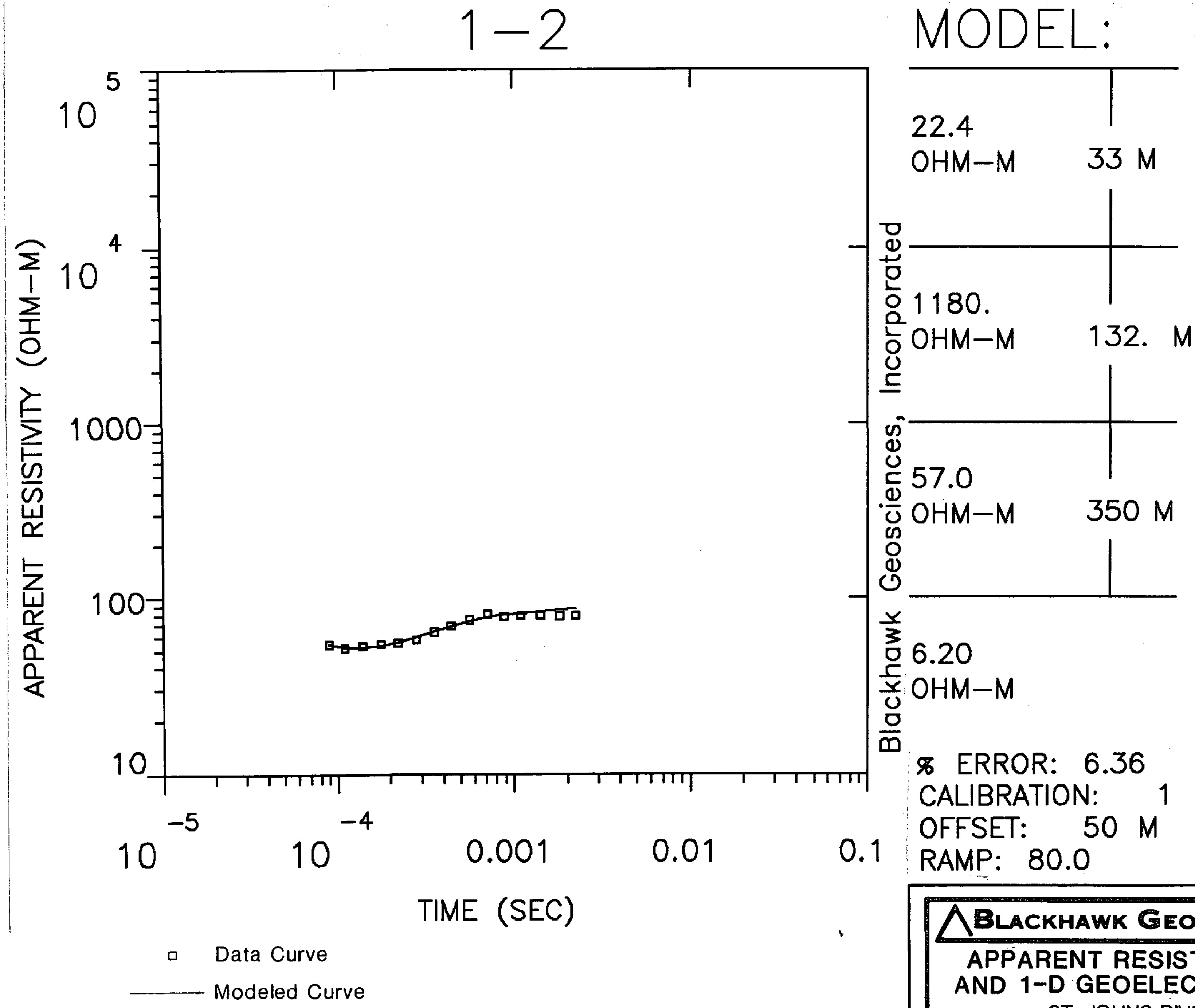
Using a porosity of 25% for the Upper Floridan aquifer and the relation shown in Figure 2-10, a resistivity of 6.2 ohm-m corresponds to an equivalent chloride concentration of 5,000 mg/l. The criteria utilized in determining the depth of the 5,000 mg/l isochlor is dependent on the type of geoelectric section encountered and is explained below:

1) When the contrast in resistivities in the modeled geoelectric section is between a layer with a resistivity greater than 80 ohm-m (corresponding to chlorides less than 250 mg/l) and a layer with a resistivity of less than 10 ohm-m (corresponding to chlorides greater than 3,000 mg/l) the transition zone between these waters is assumed to be approximately 100 ft thick, as shown in Figure 2-11 and as previously explained for Class A. The position of the 5,000 mg/l isochlor is assumed to be 50 ft below the position of the mapped resistivity contrast which normally occurs near the center of the transition zone (Fig. 2-11). It is likely that chloride concentrations rapidly increase with depth at

high salinities and the 5,000 mg/l isochlor occurs only a small distance below the 3,000 mg/l isochlor.

2) When the contrast in resistivities in the modeled geoelectric section is between a layer with resistivities from 10 ohm-m to 80 ohm-m (corresponding to chlorides of between 3,000 and 250 mg/l) and a layer with a resistivity of less than 10 ohm-m (corresponding to chlorides greater than 3,000 mg/l) it is assumed that the transition zone between the two ground waters is thin since the chloride concentration gradient is expected to be steep at higher salinities. For this type of geoelectric section, the position of the 5,000 mg/l isochlor is placed at the the top of the layer with a resistivity of less than 10 ohm-m.

3) When resistivities less than 10 ohm-m are not encountered within the effective exploration depth of the measurement, the minimum depth of occurrence of the 5,000 mg/l isochlor is computed by placing a layer with a resistivity of 6.2 ohm-m below the geoelectric section measured, and computing by iterations the minimum depth at which errors greater than 5% are observed between model and measured data in the last three time gates. This procedure is illustrated for Sounding 1-2 of the 1986 survey in Figure 2-13 and Table 2-3. For this sounding the minimum depth of occurrence of the 5,000 mg/l isochlor is estimated to be 1,700 ft below surface. As explained for Class D, this approach gives an approximate minimum depth of occurrence. Accuracy of this determination again depends on a number of factors, such as geoelectric section and depth to the interface.



BLACKHAWK GEOSCIENCES, INC.

APPARENT RESISTIVITY CURVE AND 1-D GEOELECTRIC SECTION

ST. JOHNS RIVER WATER MANAGEMENT DISTRICT

PROJECT NO: 92004 **Figure 2-13**

MODEL: 4 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		0.0	0.0		
22.42	33.0	-33.0	-108.3	1.5	1.5
1179.72	131.6	-164.6	-540.0	0.1	1.6
57.04	350.0	-514.6	-1688.3	6.1	7.7
6.20					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	5.43E+01	5.41E+01	0.323	
2	1.10E-04	5.18E+01	5.26E+01	-1.516	
3	1.40E-04	5.34E+01	5.24E+01	1.871	
4	1.77E-04	5.46E+01	5.37E+01	1.803	
5	2.20E-04	5.54E+01	5.60E+01	-0.955	
6	2.80E-04	5.76E+01	5.97E+01	-3.471	
7	3.55E-04	6.36E+01	6.42E+01	-0.999	
8	4.43E-04	6.91E+01	6.89E+01	0.295	
9	5.64E-04	7.49E+01	7.37E+01	1.623	
10	7.13E-04	8.05E+01	7.75E+01	3.885	
11	8.81E-04	7.79E+01	8.00E+01	-2.715	
12	1.10E-03	7.91E+01	8.19E+01	-3.434	
13	1.41E-03	7.90E+01	8.37E+01	-5.644	
14	1.80E-03	7.86E+01	8.54E+01	-7.931	
15	2.22E-03	7.89E+01	8.68E+01	-9.094	

R: 50. X: 0. Y: 50. DL: 100. REQ: 56. CF: 1.0000
CLHZ ARRAY, 15 DATA POINTS, RAMP: 80.0 MICROSEC, DATA: 1-2
2805 0010 0020 Z OPR XTL H 6 8+100
Ch.21 = 0.08 Ch.22 = 0.089 Ch.23 = 23 Ch.24 = 1
RMS LOG ERROR: 2.68E-02, ANTILOG YIELDS 6.3593 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *
CURRENT RESOLUTION MATRICES NOT AVAILABLE

BLACKHAWK GEOSCIENCES, INC.

INVERSION TABLE
APPARENT RESISTIVITY CURVE

ST. JOHNS RIVER WATER
MANAGEMENT DISTRICT

PROJECT NO: 92004 **Table 2-3**

3.0 RESULTS AND DISCUSSION

Task 1 - Distinguish between reliable soundings and soundings distorted by interferences, and reinterpret undistorted soundings

Of the 142 soundings made in Seminole County, 80 soundings were rejected because of probable distortion of the data (Table 3-1) while 62 were determined not to be affected by cultural interferences (Table 3-2). The majority of these soundings (48) were rejected because they were not consistent with other soundings or well data in the same general area. Although this criteria is subjective, it appeared necessary because of the difficulty in identifying TDEM data influenced by inductive noise when data are acquired only in the center of the transmitter loop. In the urban setting, in which most of these soundings were made, the likelihood of sources of inductive noise occurring near the sounding location was judged to be high.

The apparent resistivity curves and inversion tables of all rejected soundings (Table 3-1) are contained in Attachment A, and those soundings which are expected to be undistorted (Table 3-2) are contained in Attachment B. These attachments are separate volumes to the main report. All soundings in Attachment B were reinterpreted using the most recent inversion algorithms.

An analysis of the range of equivalence was performed on ten representative soundings. These soundings were chosen to be representative of the varying depths to ground water with chloride concentration greater than 250 mg/l and 5,000 mg/l, and are distributed throughout the county. The equivalence plots and tables for the soundings are contained in Attachment B and their locations are shown in Figure 1-1. The results of the equivalence are furthermore summarized in Table 3-3. For each parameter of the geoelectric section (resistivities and thicknesses) the range of equivalences are given in terms of the minimum and maximum value this parameter can assume, and the "best" value.

Equivalence analysis of the 10 representative soundings (Table 3-3) show that for each sounding the depth to the lower modeled conductor, which corresponds to higher salinity ground water, is determined to an accuracy better than $\pm$ 10% of total depth. This is the most important parameter for the investigation and the equivalence analysis indicates that these depths are well resolved. In most of the soundings the depth to the top of the second layer, which corresponds to the top of the Floridan aquifer, is not well resolved. This is caused by the low contrast in resistivities between the Upper Floridan aquifer and the overlying sediments in many of the soundings.

When this contrast is larger, such as sounding 2-4, this interface is better resolved.

The resolution of the resistivities of the various layers depends on the resistivity value and the thickness of the layer. Generally, resistivities less than 100 ohm-m are determined to ± 15%, while resistivities significantly greater than 100 ohm-m are poorly resolved. Fortunately, these ranges of equivalence do not significantly affect the conclusions about depth of isochlors, because layers with resistivities greater than 100 ohm-m are inferred to have chloride concentrations less than 250 mg/l. At low resistivity values the small ranges of equivalence do not significantly affect inferred chloride concentrations.

Task 2 and Task 3 - Use the experience gained in the last five years to better correlate the geoelectric section derived from TDEM soundings to water quality in the Floridan aquifer, and to construct contour maps of depths to 250 mg/l and 5,000 mg/l isochlors

The 62 TDEM soundings in which no cultural interference of the data is anticipated were used to produce contour maps of depths to the 250 mg/l and 5,000 mg/l isochlors. The depths are listed on Table 3-2. These maps are shown in Figures 3-1 and 3-2 (in map pocket). The 250 mg/l isochlor generally cuts across the county from the NW to the SE, and its depth increases towards the SW. Along the Wekiva River, which forms the western boundary of the County, the 250 mg/l isochlor parallels the river in a north-south direction. In this area the depth to the isochlor increases to the east. The contours are based only on TDEM data. Nearly all the well data available did not give information on the depth to waters with a specific chloride concentration. The data available from wells normally reported the average chloride concentrations for the upper Floridan aquifer that was intersected by the well. This information was compared to nearby TDEM soundings to evaluate if the sounding was consistent with the well data. Figure 3-3 (in map pocket) shows the position of the boundary separating the areas with ground water exceeding 250 mg/l chloride concentration at the top of the Floridan aquifer, from areas with some thickness of ground water with a chloride concentration less than 250 mg/l. Three such boundaries are shown on the map. One boundary is from Tibbals (1977), another boundary was constructed from wells provided by SJRWMD, and the third boundary was derived from the TDEM data. Table 3-4 lists some of the wells available in Seminole County, and their location is also plotted on Figure 3-3 (in map pocket). All three boundaries, which map the extent of fresh water (less than 250 mg/l) in the Upper Floridan aquifer, generally parallel each other. The Tibbals boundary and the boundary from well data nearly coincide because they are based on the same well data, with perhaps some additional wells added since 1977. The boundary from the TDEM data generally is displaced some distance towards the southwest from the other boundaries. There are several possible reasons for this displacement. They include:

1) Ground water chloride concentrations are normally not obtained from a specific depth within the well, and the measured chloride concentrations may be influenced by ground water from zones above the Upper Floridan aquifer.

2) Many of the well data were obtained in the 1950's and over time the chloride concentrations of the Upper Floridan aquifer may have increased due to pumping.

3) The data density across the steepest part of the gradient of the depth of the 250 mg/l isochlor is different for the TDEM survey than for the well data. A higher station density improves the resolution of the contours.

4) The TDEM data was derived assuming a 25% porosity. If the Upper Floridan aquifer average porosities are substantially different, it would affect the position of this boundary as determined by TDEM soundings.

The trend of the contours are similar to those of the 250 mg/l isochlor. The shallowest depths to the 5,000 mg/l isochlor occur in the eastern portion of the county, along the St. Johns River to the north, and along the Wekiva River to the west. This is consistent with data from Tibbals (1977) who also identifies these areas as ground water discharge zones in which saline water from depths flows towards the surface.

<u>Task 4 - Compare interpretations about water quality derived from the present re-examination of the TDEM data, with the interpretation produced some five years ago</u>

The geoelectric sections derived from the undistorted TDEM soundings generally are similar to those previously derived. The main differences between the 1986/88 analysis and the present study are due to the rejection of 80 TDEM soundings. This rejection of soundings resulted in some differences between the contour maps of the depth to the 250 mg/l isochlor. The map of the 250 mg/l isochlor from this study shows

- smoother contours of the data,

- no isolated "bullseye" type anomalies where rapid changes in depths to isochlors occur over aerially isolated areas,

- a depth to the 250 mg/l isochlor significantly deeper (over 1,000 ft versus less than 200 ft) in the area of the town of Longwood.

The most significant difference in the two studies between the results of the interpretations of the TDEM data made in 1988 and at present is in the town of Longwood. The original study showed shallower depths in this area based on seven TDEM soundings located in and around the town of Longwood. These soundings were relatively consistent in their modeled geoelectric sections, and the data showed no obvious cultural influence. Information made available for this study shows the Longwood water supply wells (Fig. 3-3, Table 3-4) to be located near the center of the area in which the depth to 250 mg/l isochlor was interpreted to be less than 200 ft in the 1986/1988 analysis. These wells are approximately 400 ft deep and are pumping water from the Floridan aquifer with chloride concentrations less than 50 mg/l (Toth, personal communication). Because this area is highly urbanized and sounding locations were restricted to small parks and vacant lots, these soundings may be distorted. Without quality control measurements, this is a subjective conclusion. The soundings in the Longwood area were not utilized in mapping depths to the 250 mg/l isochlors. Consequently, the depth to the 250 mg/l isochlor in the Longwood area increased based on undistorted soundings located immediately adjacent to the Longwood area. By not including TDEM soundings within Longwood, the conclusion is reached that there are no anomalous pockets of shallow high salinity water in the Longwood area. This conclusion is not based on any TDEM measurement within Longwood.

<u>Task 5 - Identify areas where additional soundings can improve the isochlor contour maps</u>.

There are several areas in which additional soundings are required to fill in data gaps, particularly for depths to the 5,000 mg/l isochlor. These areas are shown in Figure 3-4 (in map pocket). The number of the locations required in each area is dependent on the specific objectives of SJRWMD.

The areas where additional soundings are recommended are as follows:

1) <u>Area 1</u>. This area, located in northwest Seminole County, requires at least two TDEM soundings. The rapid change in the

depth to the 5,000 mg/l isochlor east of the Wekiva River warrants one sounding about two thousand feet east of the river. In addition, a sounding should be made near the center of the area, since none of the soundings from the 1986/1988 surveys directly detected the 5,000 mg/l isochlor. It is recommended that the dimension of the transmitter loop here should be at least 700 ft by 700 ft in this area.

2) Area 2. This area is located west of Sanford. One to two soundings, utilizing a minimum transmitter loop size of 1,000 ft by 1,000 ft, to detect the 5,000 mg/l Cl isochlor is recommended. Soundings from the 1986/1988 surveys did not directly detect the 5,000 mg/l isochlor in this area.

3) Area 3. This area is located around the town of Longwood. The rejection of 1986 and 1988 TDEM soundings around Longwood necessitates at least one to two soundings. Transmitter loops should be 1,000 ft by 1,000 ft to detect the 5,000 mg/l isochlor. Locating areas where reliable soundings can be made in this area may be difficult.

4) Area 4. This area is located between Casselberry and Oviedo in southern Seminole County. At least one sounding utilizing a transmitter loop with dimensions of 1,000 ft by 1,000 ft to map the depth to the 5,000 mg/l isochlor is required. It is expected that the depth to this isochlor is greater than 1,000 ft and it was not directly detected in the 1986/1988 soundings.

In all TDEM soundings it is important to choose sounding locations which are as far removed from known cultural sources in order to minimize the potential of data distortion from these features. Data should be recorded for several positions within the transmitter loop to determine if the data are influenced by cultural features.

Table 3-1. Time Domain Electromagnetic Soundings from 1986 and 1988 Surveys Rejected Due to Cultural Interferences

Sounding	Latitude	Longitude	Reason for Rejection
1-1	28°43'16"	81°23'03"	1
1-3	28°43'10"	81°23'35"	3
1-4N	28°43'10"	81°24'23"	3
1-5	28°42'58"	81°21'34"	3
2-1	28°44'44"	81°22'59"	2
2-2	28°44'43"	81°23'23"	3
3-1	28°47'34"	81°23'26"	1
3-4	28°47'34"	81°24'42"	3
3-5	28°48'02"	81°23'25"	2
4-1	28°48'53"	81°23'59"	1
4-2	28°48'42"	81°24'18"	3
5-2	28°49'16"	81°23'22"	3
5-6	28°48'46"	81°22'48"	1
6-3	28°49'54"	81°20'30"	1
6-5	28°48'41"	81°20'29"	1
6-7	28°50'33"	81°21'33"	3
6-7N	28°50'31"	81°21'32"	3
7-1	28°48'49"	81°20'08"	3
7-3	28°49'30"	81°19'12"	2

1 = Noisy Data
2 = Unrealistic Inversion
3 = Inconsistent with nearby data

Table 3-1. (Continued)

Sounding	Latitude	Longitude	Reason for Rejection
8-1	$28^0 47'19"$	$81^0 18'57"$	2
8-4	$28^0 48'07"$	$81^0 17'29"$	2
8-5	$28^0 48'42"$	$81^0 16'38"$	3
8-6	$28^0 47'12"$	$81^0 19'36"$	3
9-2	$28^0 46'38"$	$81^0 16'10"$	3
9-3 ('86)	$28^0 46'41"$	$81^0 15'26"$	3
9-3 ('88)	$28^0 46'41"$	$81^0 15'26"$	3
9-5	$28^0 46'23"$	$81^0 17'34"$	2
9-6	$28^0 46'37"$	$81^0 18'03"$	1
10-1	$28^0 44'39"$	$81^0 17'55"$	2
10-2	$28^0 44'22"$	$81^0 17'34"$	3
10-3	$28^0 43'59"$	$81^0 17'20"$	1
10-7	$28^0 43'40"$	$81^0 19'06"$	3
10-8	$28^0 42'55"$	$81^0 20'37"$	3
11-3	$28^0 41'13"$	$81^0 15'50"$	3
11-4	$28^0 40'36"$	$81^0 16'08"$	2
11-5	$28^0 40'06"$	$81^0 16'26"$	2
11-6	$28^0 42'04"$	$81^0 15'32"$	3
11-8	$28^0 40'18"$	$81^0 16'20"$	2
12-2	$28^0 41'57"$	$81^0 12'34"$	3
12-5	$28^0 40'47"$	$81^0 13'46"$	3

1 = Noisy Data
2 = Unrealistic Inversion
3 = Inconsistent with nearby data

Table 3-1. (Continued)

Sounding	Latitude	Longitude	Reason for Rejection
13-1	28°40'14"	81°13'13"	3
13-2	28°40'01"	81°13'14"	3
13-3	28°39'14"	81°13'12"	1
13-4	28°38'53"	81°12'18"	3
13-5	28°38'28"	81°12'32"	2
14-1 ('86)	28°41'00"	81°10'22"	3
14-1 ('88)	28°41'00"	81°10'22"	3
14-2	28°40'02"	81°10'51"	3
14-3	28°39'23"	81°10'44"	1
14-5	28°38'16"	81°10'26"	1
15-2	28°38'47"	81°07'24"	3
15-3	28°38'44"	81°06'44"	3
16-1	28°37'51"	81°06'00"	3
16-4	28°37'21"	81°04'04"	3
17-1	28°47'54"	81°24'35"	3
17-2	28°48'09"	81°24'23"	3
17-4	28°48'19"	81°23'27"	3
18-1	28°50'19"	81°23'23"	3
18-6	28°50'42"	81°22'12"	3
18-8	28°49'50"	81°21'32"	3

1 = Noisy Data
2 = Unrealistic Inversion
3 = Inconsistent with nearby data

Table 3-1. (Continued)

Sounding	Latitude	Longitude	Reason for Rejection
19-1	$28^0$46'10"	$81^0$15'10"	2
19-2	$28^0$46'34"	$81^0$13'20"	3
19-4	$28^0$47'14"	$81^0$16'37"	2
19-6	$28^0$45'18"	$81^0$15'57"	2
19-7	$28^0$47'58"	$81^0$16'58"	2
19-9	$28^0$44'19"	$81^0$15'12"	3
19-10	$28^0$44'20"	$81^0$16'35"	3
19-11	$28^0$44'44"	$81^0$15'50"	3
20-1	$28^0$41'50"	$81^0$21'15"	2
20-3	$28^0$41'01"	$81^0$21'24"	2
20-4	$28^0$41'14"	$81^0$18'53"	3
20-5	$28^0$41'47"	$81^0$19'23"	3
20-6	$28^0$42'52"	$81^0$20'18"	2
20-7	$28^0$43'28"	$81^0$20'16"	3
20-8	$28^0$42'19"	$81^0$16'46"	3
20-10	$28^0$43'53"	$81^0$18'01"	1
21-1	$28^0$39'25"	$81^0$14'05"	1
21-2	$28^0$39'56"	$81^0$15'06"	1
21-4	$28^0$38'54"	$81^0$13'59"	3
21-5	$28^0$41'43"	$81^0$11'21"	3

1 = Noisy Data
2 = Unrealistic Inversion
3 = Inconsistent with nearby data

Table 3-2. Time Domain Electromagnetic Soundings from 1986 and 1988 Surveys Used in Construction of Depth Isochlor Contour Maps

			Depth to Isochlor (ft)	
Sounding	Latitude	Longitude	250 ppm	5000 ppm
1-2	$28^0 43'16''$	$81^0 23'03''$	540	1700 (M)
1-4	$28^0 43'12''$	$81^0 24'24''$	650 (M)	1050 (M)
2-3	$28^0 44'48''$	$81^0 23'50''$	1025	1850 (M)
2-4	$28^0 44'49''$	$81^0 24'10''$	1011 (G)	1111 (G)
3-2	$28^0 47'16''$	$81^0 23'34''$	750 (M)	1450 (M)
3-3	$28^0 47'29''$	$81^0 24'05''$	322	1450 (M)
4-3	$28^0 48'46''$	$81^0 24'40''$	NP	307
4-3N	$28^0 48'42''$	$81^0 24'39''$	NP	302
4-4	$28^0 49'06''$	$81^0 25'02''$	NP	150
5-1	$28^0 49'04''$	$81^0 22'48''$	342 (G)	850 (M)
5-3	$28^0 49'43''$	$81^0 23'46''$	304 (G)	1150 (M)
5-4	$28^0 50'03''$	$81^0 24'00''$	NP	750 (M)
5-4N	$28^0 50'05''$	$81^0 24'00''$	NP	800 (M)
5-5	$28^0 49'40''$	$81^0 24'00''$	332	1150 (M)
6-1	$28^0 49'12''$	$81^0 20'30''$	346	1000 (M)
6-2	$28^0 49'44''$	$81^0 20'21''$	342 (G)	442 (G)
6-4	$28^0 50'09''$	$81^0 20'02''$	NP	403
6-5N	$28^0 49'19''$	$81^0 20'46''$	NP	600 (M)

(M) = Minimum Modeled Depth
(G) = Depth Estimated From Gradient
NP = 250 ppm Isochlor Not Present

Table 3-2. (Continued)

Sounding	Latitude	Longitude	Depth to Isochlor (ft) 250 ppm	5000 ppm
7-2	28°49'12"	81°19'34"	NP	270
7-4	28°49'29"	81°18'56"	NP	292
7-5	28°48'49"	81°19'44"	219 (G)	319 (G)
8-2	28°47'22"	81°18'40"	678 (G)	1000 (M)
8-3	28°47'48"	81°17'29"	NP	264
8-7	28°47'32"	81°18'05"	NP	373
8-8	28°46'46"	81°20'44"	1050 (M)	1400 (M)
9-1	28°46'25"	81°17'14"	NP	1050 (M)
9-4	28°47'13"	81°14'30"	NP	500 (M)
9-7	28°46'30"	81°16'39"	360 (G)	900 (M)
9-8	28°47'40"	81°13'18"	NP	210
10-4	28°43'59"	81°16'47"	NP	282
10-5	28°43'35"	81°15'50"	NP	400 (M)
10-6	28°44'45"	81°18'40"	813 (G)	1350 (M)
11-1	28°42'12"	81°15'35"	165 (G)	265 (G)
11-2	28°41'13"	81°15'48"	554 (G)	654 (G)
11-9	28°38'38"	81°16'34"	300 (M)	1450 (M)
12-1	28°41'57"	81°12'34"	NP	239
12-3	28°40'52"	81°12'35"	NP	337
12-4	28°40'17"	81°14'12"	NP	527

(M) = Minimum Modeled Depth
(G) = Depth Estimated From Gradient
NP = 250 ppm Isochlor Not Present

Table 3-2. (Continued)

Sounding	Latitude	Longitude	Depth to Isochlor (ft) 250 ppm	5000 ppm
13-6	28°39'08"	81°12'15"	436 (G)	800 (M)
13-7	28°37'42"	81°12'47"	1300 (M)	1650 (M)
14-4	28°38'28"	81°10'44"	1044 (G)	1550 (M)
14-6	28°39'34"	81°10'59"	NP	1100 (M)
15-1	28°38'23"	81°07'42"	NP	341
15-4	28°39'31"	81°06'54"	NP	355
15-5	28°40'20"	81°06'46"	NP	267
16-2	28°37'25"	81°05'32"	NP	386
16-3	28°37'25"	81°04'50"	NP	384
16-5	28°37'24"	81°03'30"	NP	305
17-3	28°49'17"	81°24'28"	441	1600 (M)
17-5	28°49'34"	81°24'40"	NP	650 (M)
18-2	28°50'51"	81°22'51"	NP	700 (M)
18-3	28°51'17"	81°22'33"	NP	250
18-4	28°49'39"	81°22'31"	NP	550 (M)
18-5	28°50'30"	81°22'31"	NP	700 (M)
18-7	28°50'22"	81°21'14"	NP	450 (M)
19-3	28°48'00"	81°14'37"	NP	254
19-5	28°47'33"	81°17'05"	NP	316

(M) = Minimum Modeled Depth
(G) = Depth Estimated From Gradient
NP = 250 ppm Isochlor Not Present

Table 3-2. (Continued)

Sounding	Latitude	Longitude	Depth to Isochlor (ft) 250 ppm	5000 ppm
19-8	28°44'26"	81°14'40"	NP	500 (M)
19-12	28°45'29"	81°13'57"	NP	329
20-9	28°42'24"	81°17'59"	910 (G)	1450 (M)
21-3	28°40'15"	81°14'14"	567 (G)	667 (G)
21-6	28°40'38"	81°11'06"	NP	338

(M) = Minimum Modeled Depth
(G) = Depth Estimated From Gradient
NP = 250 ppm Isochlor Not Present

Table 3-3. Results of Equivalence Analysis for 10 Typical Soundings from 1986 and 1988 Surveys

Sounding Number	Number of Modeled Layers in Geoelectric Section	Layer 1						Layer 2						Layer 3					
		Resistivity P_1 (ohm-m)			Thickness h_1 (meters)			Resistivity P_2 (ohm-m)			Thickness h_2 (meters)			Resistivity P_3 (ohm-m)			Total Depth to Top (meters)		
		Min	Best	Max	Min	Best	Max	Min	Best	Max	Min	Best	Max	Min	Best	Max	Min	Best	Max
2-4	3	29	32	36	28	33	39	380	540	910	280	290	300	9	10	12	308	323	339
4-3	3	32	37	46	25	25	25	37	48	59	62	69	76	9	10	12	87	94	101
6-2	3	14	18	22	19	32	45	67	110	220	77	88	100	4.0	4.9	5.9	96	120	145
9-1	2	14	20	23	10	20	28	47	49	52									
10-6	3	25	26	34	14	15	22	195	210	260	230	250	255	14	17	23	244	265	277
14-4	3	22	31	39	16	27	38	160	185	205	290	300	310	18	22	24	306	327	348
15-4	3	27	31	36	27	27	27	40	53	63	78	81	87	5.0	5.7	6.3	105	108	114
16-3	3	19	21	23	22	33	51	31	38	49	69	84	100	3.7	4.6	5.4	91	117	151
18-5	2	9.3	10	11	7.3	8.3	9.0	58	59	61									
21-3	3	50	59	74	24	24	24	94	110	130	156	164	172	5.8	7.8	10	180	188	196

Table 3-4. Wells Used in Ground Truthing Time Domain Electromagnetic Data in Seminole County

(Map #) Well	Latitude	Longitude	Cl (mg/l)	Sample Date
(1) 837101	$28^{0}37'02''$	$81^{0}01'18''$	930	1953
(2) 839109	$28^{0}39'12''$	$81^{0}09'56''$	170	1974
(3) S-0547	$28^{0}39'18''$	$81^{0}12'53''$	50	1989
(4) 839113	$28^{0}39'20''$	$81^{0}12'59''$	142	1954
(5) 839104	$28^{0}39'56''$	$81^{0}04'02''$	679	1973
(6) 840107	$28^{0}39'56''$	$81^{0}07'20''$	243	1954
(7) 840107	$28^{0}40'05''$	$81^{0}07'24''$	1214	1956
(8) 840108	$28^{0}40'07''$	$81^{0}08'19''$	85	1956
(9) 840113	$28^{0}40'13''$	$81^{0}13'32''$	71	1974
(10) S-0106	$28^{0}40'25''$	$81^{0}10'03''$	320	1955
(11) 840105	$28^{0}40'43''$	$81^{0}05'44''$	2500	1982
(12) 841110	$28^{0}41'00''$	$81^{0}10'48''$	950	1944
(13) 840112	$28^{0}41'04''$	$81^{0}12'55''$	130	1973
(14) 841106	$28^{0}41'11''$	$81^{0}06'34''$	21	1982
(15) 841112	$28^{0}41'21''$	$81^{0}12'31''$	236	1954
(16) 841110	$28^{0}41'22''$	$81^{0}10'34''$	1090	1955
(17) 841113	$28^{0}41'25''$	$81^{0}13'17''$	110	1973
(18) 841114	$28^{0}41'25''$	$81^{0}14'52''$	94	1974
(19) S-0744	$28^{0}41'31''$	$81^{0}11'31''$	152	1990
(20) McNair	$28^{0}41'33''$	$81^{0}08'55''$	2000	1982
(21) S-0762	$28^{0}41'50''$	$81^{0}12'19''$	419	1990
(22) S-0070	$28^{0}41'51''$	$81^{0}26'08''$	354	1990
(23) Colema	$28^{0}41'50''$	$81^{0}08'46''$	2100	1982

Table 3-4. (Continued)

(Map #) Well	Latitude	Longitude	Cl (mg/l)	Sample Date
(24) S-0064	28°41'53"	81°10'18"	1010	1991
(25) 842111	28°41'58"	81°11'21"	1300	1956
(26) 846113	28°46'46"	81°13'22"	725	1955
(27) 846115	28°46'46"	81°15'44"	131	1954
(28) 847116	28°47'10"	81°16'08"	148	1955
(29) 847117	28°47'10"	81°17'36"	10	1952
(30) 847114	28°47'16"	81°14'37"	380	1973
(31) 847115	28°47'34"	81°15'21"	163	1954
(32) 847116	28°47'37"	81°16'52"	47	1955
(33) S-0023	28°47'39"	81°24'42"	180	1973
(34) S-0581	28°47'45"	81°13'36"	936	1989
(35) 847118	28°47'51"	81°18'54"	8	1954
(36) 847114	28°47'52"	81°15'01"	260	1956
(37) 847117	28°47'54"	81°17'52"	370	1955
(38) 847116	28°47'58"	81°16'17"	310	1992
(39) S-0206	28°48'02"	81°21'11"	10	1973
(40) S-0848	28°48'08"	81°17'38"	720	1991
(41) 848118	28°48'23"	81°18'34"	71	1954
(42) S-0232	28°48'27"	81°20'47"	8	1954
(43) S-0599	28°48'39"	81°18'25"	97	1989
(44) 848119	28°48'42"	81°19'42"	10	1954
(45) S-0230	28°48'44"	81°22'14"	6.5	1954
(46) S-0530	28°48'51"	81°17'25"	857	1989

Table 3-4. (Continued)

(Map #) Well	Latitude	Longitude	Cl (mg/l)	Sample Date
(47) S-0542	28°48'59"	81°18'14"	385	1989
(48) S-0759	28°48'56"	81°18'54"	532	1990
(49) S-0240	28°49'04"	81°24'07"	12	1973
(50) S-0095	28°49'06"	81°25'05"	420	1986
(51) S-0789	28°49'17"	81°19'37"	24	1991
(52) S-0261	28°49'31"	81°21'16"	222	1991
(53) S-0242	28°49'40"	81°20'28"	170	
(54) 842123	28°42'39"	81°23'38"	100	1954
(55) S-0058	28°43'00"	81°23'56"	97	1986
(56) S-0113	28°43'05"	81°19'20"	6	1991
(57) S-0868	28°43'08"	81°26'13"	106	1991
(58) 843119	28°43'19"	81°19'12"	9	1982
(59) 843116	28°43'22"	81°16'20"	544	1973
(60) 843121	28°43'23"	81°21'37"	6	1973
(61) S-0772	28°43'59"	81°16'27"	361	1990
(62) S-0013	28°44'03"	81°16'51"	500	1973
(63) 844115	28°44'04"	81°15'53"	692	1954
(64) 844114	28°44'17"	81°14'59"	1300	1974
(65) 844120	28°44'25"	81°20'05"	7	1954
(66) S-0004	28°43'35"	81°22'58"	4	1973
(67) 844117	28°44'46"	81°17'44"	13	1954
(68) S-0535	28°44'48"	81°15'52"	618	1989
(69) S-0227	28°45'14"	81°22'34"	11	1954

Table 3-4. (Continued)

(Map #) Well	Latitude	Longitude	Cl (mg/l)	Sample Date
(70) 845115	28°45'19"	81°15'51"	118	1954
(71) S-0010	28°45'21"	81°13'05"	1300	1973
(72) 845117	28°45'29"	81°17'11"	50	1956
(73) 845119	28°45'29"	81°19'21"	7	1953
(74) 845111	28°45'43"	81°17'40"	70	1955
(75) S-0823	28°46'01"	81°12'41"	944	1991
(76) 846116	28°46'15"	81°16'56"	334	1955
(77) 846116	28°46'25"	81°16'41"	430	1954
(78) 846115	28°46'45"	81°15'24"	31	1955
(79) 846118	28°46'45"	81°18'37"	10	1955
(80) 849119	28°49'46"	81°19'43"	200	1956
(81) S-0550	28°49'54"	81°21'34"	74	1989
(82) S-0551	28°50'00"	81°21'47"	88	1989
(83) S-0097	28°50'01"	81°24'23"	1910	1991
(84) S-0020	28°50'02"	81°21'51"	110	1973
(85) Test Well 1	28°47'04"	81°19'30"	241 mg/l @ 1300'*	
(86) Test Well 2	28°44'52"	81°16'48"	486 mg/l @ 160'*	
(87) Test Well 3	28°48'48"	81°24'56"	178 mg/l @ 640'* 532 mg/l @ 650'*	

*Chloride content at specific depth.

Table 3-4. (Continued)

(Map #) Well	Latitude	Longitude	Cl (mg/l)		Sample Date
Longwood Public Supply Wells			Depth of Well	Cl (mg/l)	
(88)	28°41'59"	81°20'44"	372'	12	2/11/91
(89)	28°42'01"	81°20'36"	390'	12	2/11/91
(90)	28°42'16"	81°21'43"	427'	12	2/11/91
(91)	28°47'18"	81°5'24"	Well utilized in Fig. 2-11		

4.0 SUMMARY AND CONCLUSIONS

In 1986 and 1988, 142 TDEM soundings were made in Seminole County to assist in determining water quality in the Upper Floridan aquifer. The rationale for re-examining these soundings are the improvements made since then in procedures of data acquisition and processing in urban environments. In these environments the potential for interference by metallic structures such as buried utilities, power lines, fences and buildings is high, and only recently have methods become available to properly recognize their influence on data quality. Unfortunately, these procedures dominantly rely on recognizing cultural interferences in data acquisition by measuring electromotive forces at various distances from the center. Since such procedures were not yet implemented in the 1986 and 1988 surveys, recognizing inductive noise in the 1986 and 1988 data set is somewhat subjective. Using a conservative approach in separating soundings anticipated to be influenced by cultural interferences from those free of such interferences, 80 of the 142 soundings were rejected. Reinterpretation of the 62 soundings judged to be undistorted yielded modeled geoelectric profiles near identical to those derived in the 1986 and 1988 surveys.

Next, an approach was developed to infer from the geoelectric section water quality in the Upper Floridan aquifer. The approach employed makes extensive use of correlations established by Kwader (1982) on a large number of samples from wells. This approach was identical to that employed on several surveys at sites throughout the St. Johns River Water Management District. Contour maps of the depth to the 250 mg/l and 5,000 mg/l isochlor were subsequently prepared. The contour maps prepared from this re-examination were subsequently compared to (i) maps of chloride concentrations within the Upper Floridan aquifer prepared for Seminole County by Tibbals (1977), (ii) a map at the lateral position of the 250 mg/l isochlor in the Upper Floridan aquifer derived from available well information, and (iii) contour maps prepared from the 1986 and 1988 surveys.

The conclusions derived from those comparisons are:

1) The contours derived from re-examination of the data in Seminole County have similar trends compared to those derived from the 1986 and 1988 interpretation. Some differences are

   - isolated (one-point) anomalies present in the 1986 and 1988 surveys are not present in the 1992 contour maps,

- an anomaly in the depth to the 250 mg/l isochlor around the town of Longwood present in the 1986 and 1988 survey is not present in the 1992 contour maps.

2) The position of the lateral 250 mg/l isochlor from the 1992 study is generally displaced towards the southwest compared to the map derived by Tibbals (1977).

3) The 1992 contour maps are consistent with all available well data.

5.0 REFERENCES

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Appendix A

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.

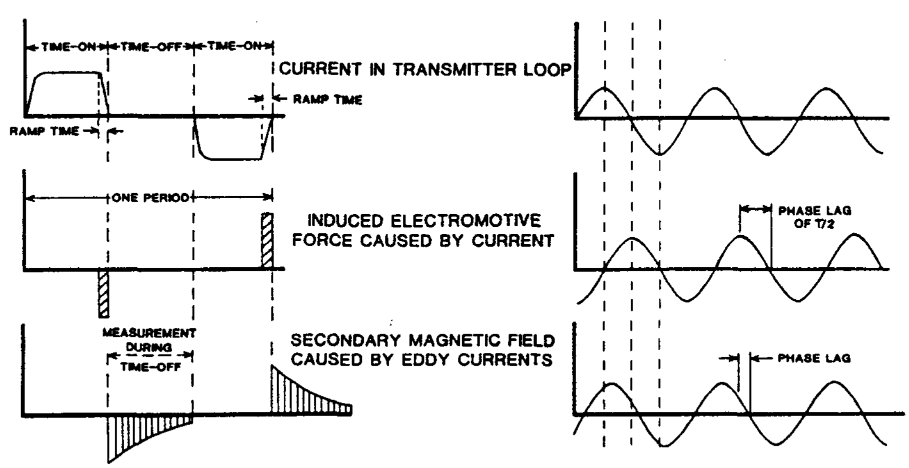

Fig. 1. System waveforms in time domain EM (TDEM) and frequency domain EM (FDEM).

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.

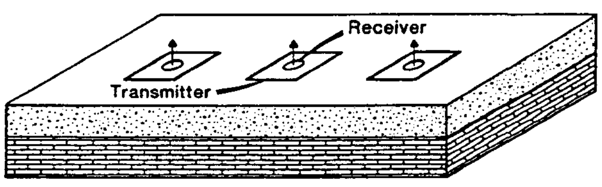

Fig. 2. Transmitter-receiver array in TDEM.

The current waveform driven through the 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 instrumentation 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 there will be an electromagnetic induction during this time (Figure 1b). This electromagnetic induction in turn results in eddy current flow in the subsurface. The intensity of these currents at a certain time and depth depends on ground conductivity.

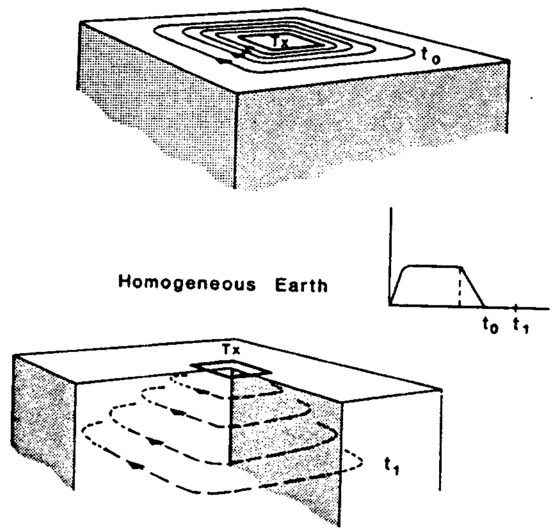

Fig. 3. Current distribution in FDEM at two times after current turn-off.

In near horizontally layered ground, the eddy currents are horizontal closed rings concentric about the center of the transmitter loop. A schematic 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 are mainly concentrated near the surface, the emf measured will mainly reflect the electrical resistivity of near surface layers. With increasing time, as currents are induced at greater depth, the emf measured will progressively be more influenced by properties of deeper layers. Thus, in TDEM exploration, depth is mainly a function of time of measurement after turn-off.

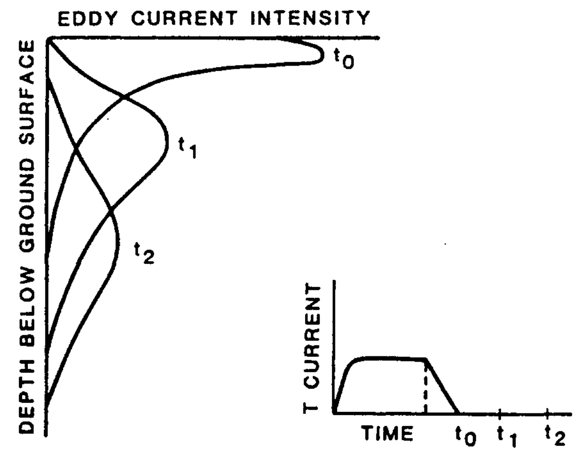

Fig. 4. Schematic illustration of eddy current distribution at different times after turn-off.

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.

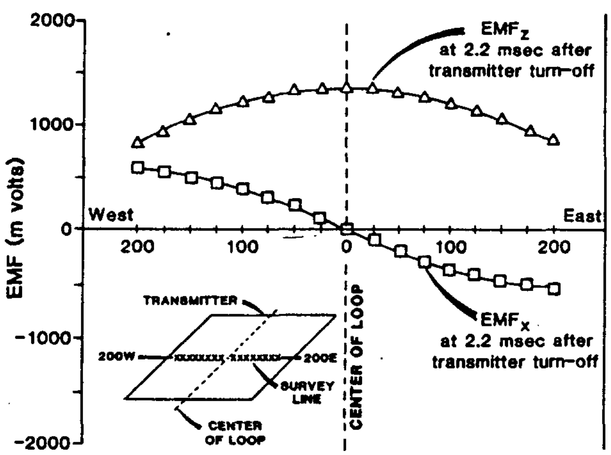

Fig. 5. Spatial behavior of emfs due to vertical (emf_z) and horizontal (emf_x) magnetic field on a profile through the center of square transmitter loop at one time (2.2 millisec) after turn-off.

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 value because it (1, reduces the cost of land surveys and measurement errors, and (2) allows for some flexibility in the field in positioning the measurement stations.

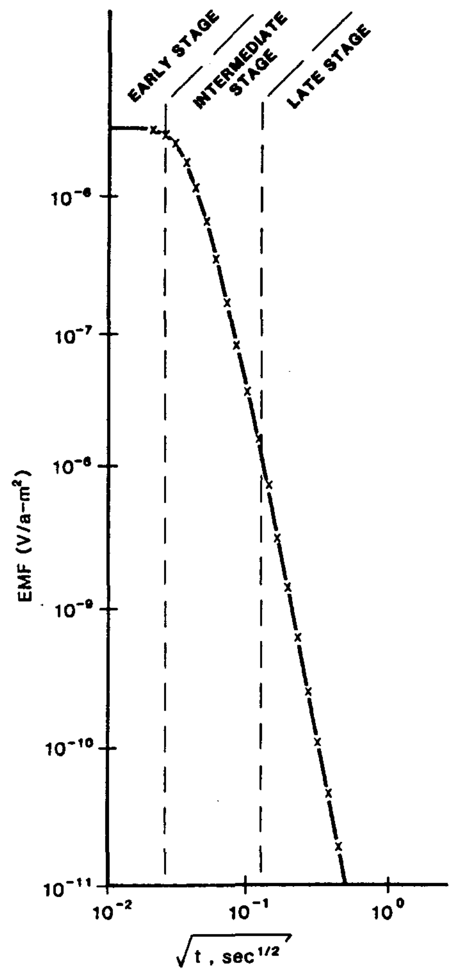

Fig. 6. Typical transient behavior of emf_z in center of square transmitter loop.

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

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

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	7.39E+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.

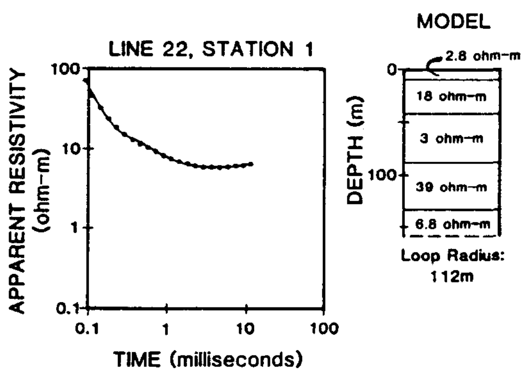

Fig. 7. Example of TDEM apparent resistivity curve and inverted geoelectric section.

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 in electrical geophyics, why has it not been extensively used in ground water and environmental applications?

Answer.-- TDEM has been in common use in the search for base and precious metals, and for deep electrical soundings in support of hydrocarbon and geothermal exploration for about 15 years. The reason 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.

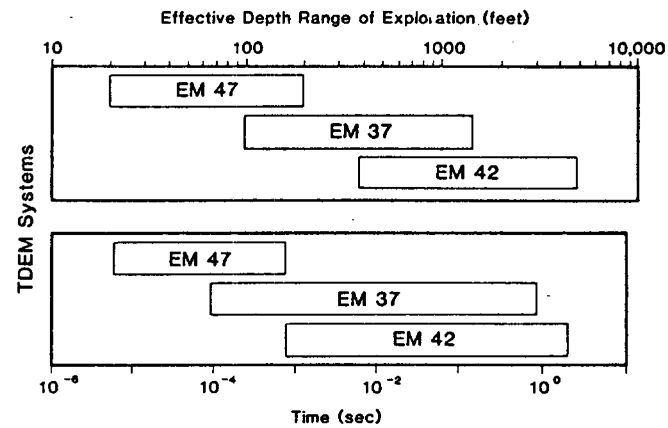

Fig. 8. Effective depth range of exploration and time range of measurement of various TDEM systems.

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.

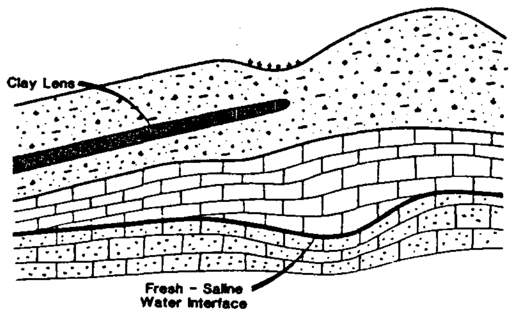

Fig. 9. Schematic geologic section of Floridan aquifer.

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.

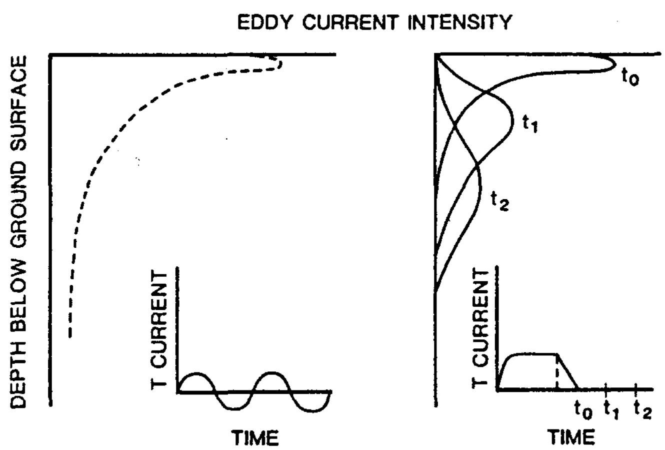

Fig. 10. Eddy current intensity in FDEM and TDEM.

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.

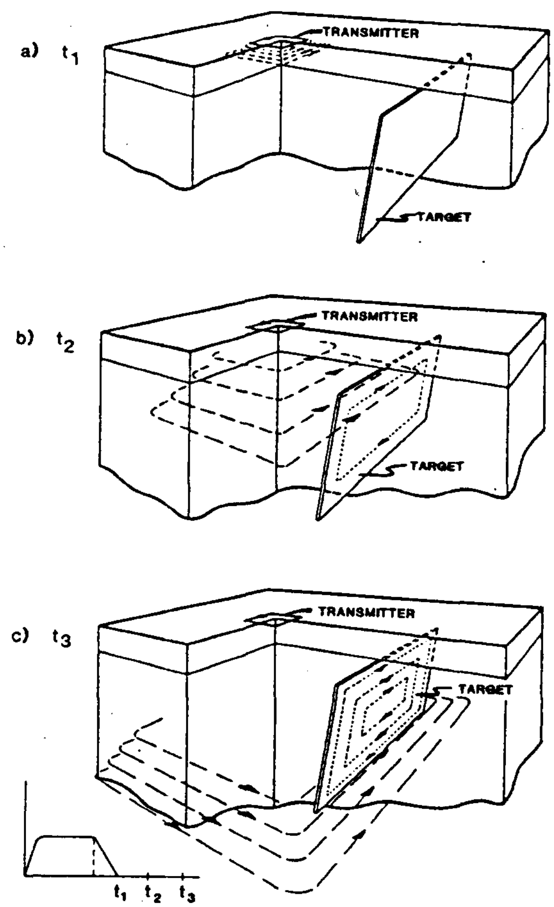

Fig. 11. Illustration of eddy current flow induced in overburden, host rock, and fracture or shear zones at different times.

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.

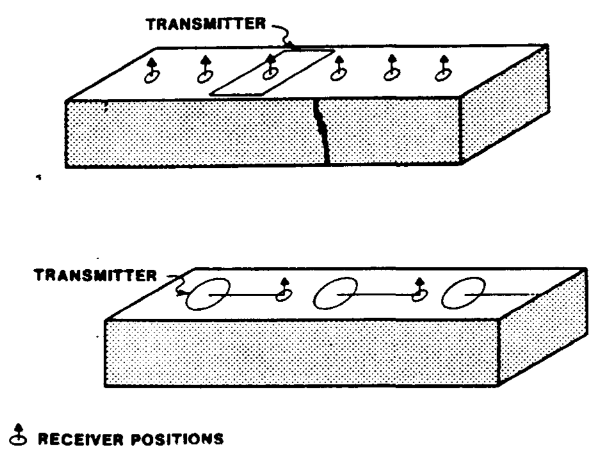

Fig. 12. Transmitter-receiver arrays useful in fracture mapping.

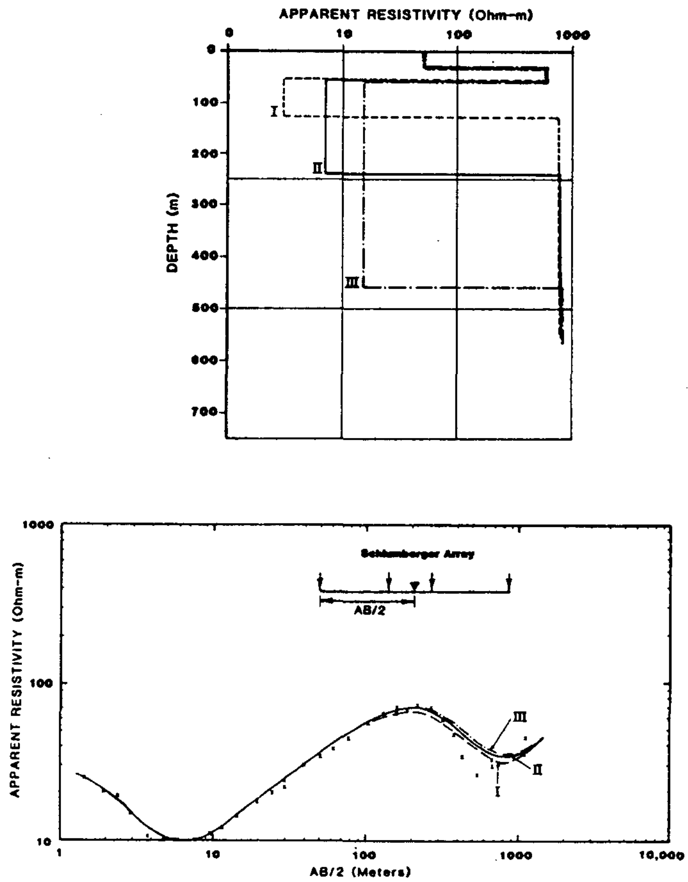

Fig. 13. Schlumberger measured apparent resistivities (a) superimposed on three one-dimensional geoelectric sections (b).

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.

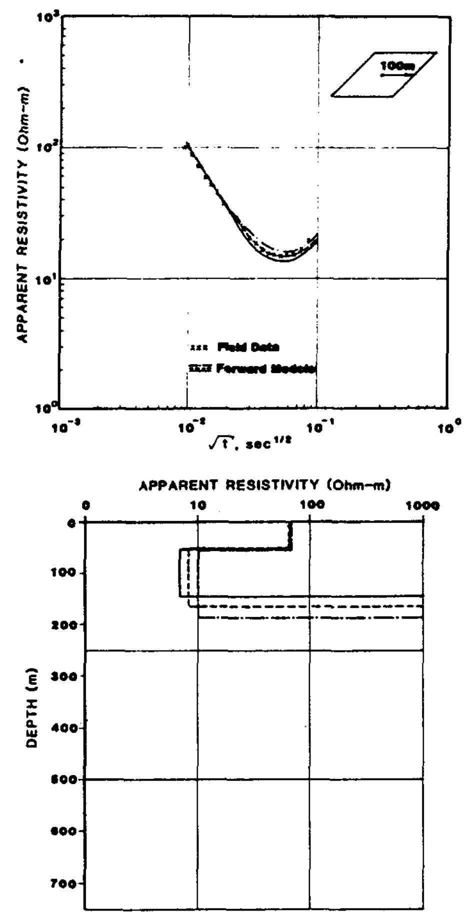

Fig. 14. TDEM measured apparent resistivities (a) superimposed on three one-dimensional geoelectric sections.