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APPLICATION OF DC RESISTIVITY SURVEYS TO REGIONAL HYDROGEOLOGIC INVESTIGATIONS, COLLIER COUNTY, FLORIDA

FINAL PROJECT REPORT
USF-SFWMD COOPERATIVE PROGRAM,
PHASE 1 AND 2 COLLIER COUNTY
DC RESISTIVITY MAPPING PROJECT

Technical Publication 82-6

APPLICATION OF DC RESISTIVITY SURVEYS TO REGIONAL HYDROGEOLOGIC INVESTIGATIONS, COLLIER COUNTY, FLORIDA

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Final Project Report
USF-SFWMD Cooperative Program, Phase 1 and 2
Collier County DC Resistivity Mapping Project

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TABLE OF CONTENTS

PAGE

LIST OF TABLES

LIST OF FIGURES

PREFACE

This investigation was an element of the cooperative Collier County Resistivity Project between the Groundwater Division, Resource Planning Department, South Florida Water Management District (SFWMD) and the Geology Department of the University of South Florida, with primary project funding provided by the SFWMD.

This publication reports on the results of an investigation having two objectives. The first of these was to evaluate the use of DC restistivity techniques to define a fresh water-saltwater interface. The second objective was to determine the efficacy of DC resistivity continuous profiling in defining gross water quality trends on a regional basis and to assess how groundwater quality changes with depth.

ACKNOWLEDGEMENTS

This project, a cooperative effort of the University of South Florida and the South Florida Water Management District, was funded in large part by the South Florida WMD. Mr. Abe Kreitman and Dr. Leslie Wedderburn of the SFWMD carefully edited this report and their contributions are gratefully acknowledged. They also provided the lithologic and geologic data used for calibration of the geophysical data. A long list of USF undergraduate and graduate students participated in the field work. They provided essential field assistance and in turn received valuable field experience through their involvement in this project. A number of present and former SFWMD personnel, including Jon Shaw and Paul Jakob, contributed in some way to this project, and their assistance is greatly appreciated.

ABSTRACT

Direct current resistivity studies have been used to determine gross water quality and lithology in western Collier County, Florida. Studies were completed in two areas. A study of the salt-water interface was completed near Belle Meade, in southwestern Collier County. Also a reconnaissance-level survey was completed within an area extending from East Naples to Everglades Boulevard, and from U.S. 41 to the northern part of the county. The surveys used closely spaced vertical electrical soundings. Ninety-four soundings were completed in the Belle Meade area, and over two hundred soundings were completed along major roads in the reconnaissance study.

The vertical sounding field data were automatically interpreted using an automated computer routine. The interpreted electrical solutions give information on the thickness and resistivity of the units at the sounding site. Geologic information is inferred from the observed variations in bulk resistivity. The resistivity data were plotted and contoured using a computer graphics package (SYMAP) to produce resistivity cross-sections at a horizontal scale of 1:24,000.

In the Belle Meade area the DC method was able to locate the position of the salt-water interface. The interface as defined by bulk resistivity represents units saturated with waters with chloride ion concentrations in excess of approximately 350-450 mg/l. The interface is roughly parallel to the coastline, but exhibits deviations which extend up to one mile landward or seaward of the average position. The landward reentrants

are associated with Henderson Creek, a tidal creek, and areas of lower elevation associated with the absence of a hard, limestone caprock found under slightly higher areas.

The reconnaissance survey in western Collier County collected electrical sounding information along major roads. The sounding site spacing was 0.25 miles along most of the profiles. The resistivity cross-sections reveal that two features of hydrogeologic significance can be resolved with DC resistivity surveys. Units saturated with waters with high dissolved-solids content have distinctive, low bulk resistivities. By calibration with water samples from wells a bulk resistivity of 30 ohm-meters represents a conservative lower limit for units saturated with potable waters (less than 250 mg/l chlorides). Very dense, karstic, highly transmissive "reef" limestones of the upper Tamiami Formation have distinctive, high resistivities when saturated with fresh water. These high-resistivity units are excellent sites for ground water development as they have well-developed, secondary-solution porosity, and are saturated with good quality waters. These units are most extensive in north-central Collier County in the Golden Gates Highlands. West-central Collier County, near the intersection of U.S. 84 and SR 951, is a region of generally poor and highly variable water quality.

Direct current resistivity methods have been demonstrated to be a useful and cost-effective method for reconnaissance-level ground water surveys. Very high resistivity units (> 130 ohm-meters) in Collier County represent high-yield aquifers saturated with potable water. Bulk resistivities less than 20 to 30 ohm-meters represent units saturated with waters with chloride ion concentrations in excess of 250 mg/l.

INTRODUCTION

Western Collier County, encompassing over 600 square miles, is a region of limited water resources which is experiencing rapid population growth (Figure 1). To date, most of the information available on the shallow aquifer system, which is the principal groundwater supply source, is limited to the area near Naples. The other data which are available suggest that the hydrostratigraphy and water quality of the shallow aquifer both vary widely. The staff of the South Florida Water Management District feels that the water resource planning problems of Collier County require the development of a rapid and inexpensive method for assessing gross hydrogeologic conditions, including water quality and lithology, to aid in planning more detailed studies.

The principal objective of this project is to evaluate the feasibility of using direct current (DC) surface resistivity surveys for two applications:

1. Locating the position of the salt water/fresh water interface at the coastal margin of the shallow aquifer.
2. Mapping of gross water quality and lithology over large areas, particularly the approximate depth to waters of high conductivity (poor quality), in the shallow aquifer.

A second objective is to determine the most efficient methods of applying DC resistivity techniques to regional hydrogeologic surveys. These include field methods, instrumentation, data reduction, and data presentation. As the principal advantages of geophysical methods are low cost and the rapidity with which surveys can be completed, methods were developed to make maximum use of these advantages.

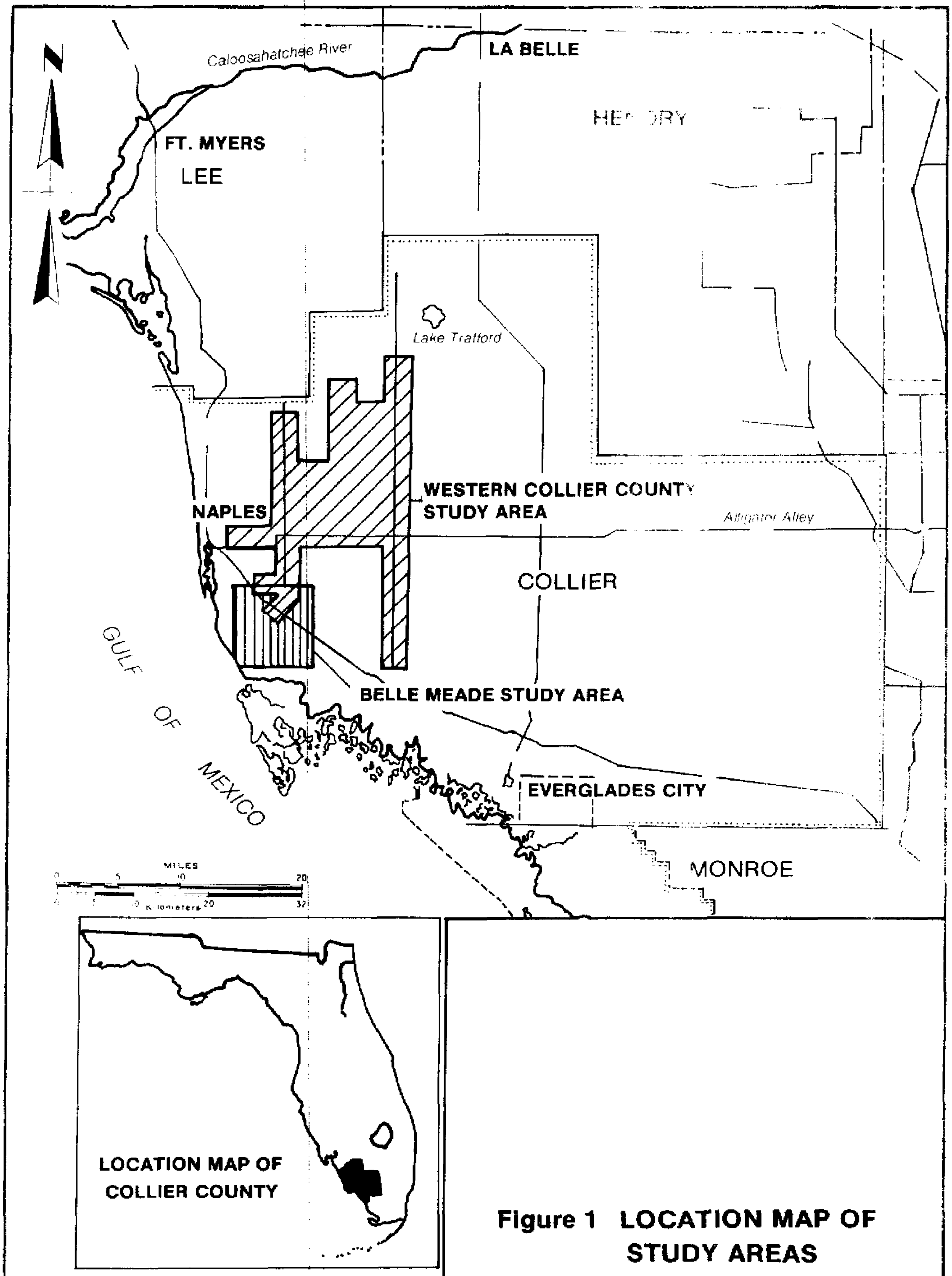


Figure 1 LOCATION MAP OF STUDY AREAS

REVIEW OF DC RESISTIVITY METHODS

Theory

Direct current (DC) resistivity methods involve the measurement of the resistivity of earth materials by introducing a direct current into the ground through electrodes driven into the earth. Resistivity is a measure of a material's resistance to the flow of electricity through it. It is an inherent physical property of a material. Figure 2 illustrates the definition and measurement of resistivity. Resistivity is the inverse of conductivity and is equal to a geometric factor times the measured resistance. While the resistance of the cylinder shown in Figure 2 varies with its length and diameter, its resistivity does not.

Figure 3 illustrates an electrode configuration for measurement of a homogeneous subsurface. If there is no variation in resistivity with depth, the measured resistivity will be equal to the true bulk resistivity of the formation. However, if there is a variation of resistivity with depth, the measured resistivity will be an integrated value, called the apparent resistivity. When the electrodes are very close together most of the introduced current will flow in the near-surface layers, and the apparent resistivity will reflect their bulk resistivity. As the electrode spacings are increased, more current flows through the lower layers, and the measured or apparent resistivity reflects their bulk resistivity. Thus, the change in apparent resistivity with increasing electrode spacings yields information about the variation of resistivity with depth.

Lithology and water quality can be inferred from the bulk resistivities determined from surface DC resistivity surveys. Typically, silicate and carbonate minerals have very high resistivities. The flow of electrical

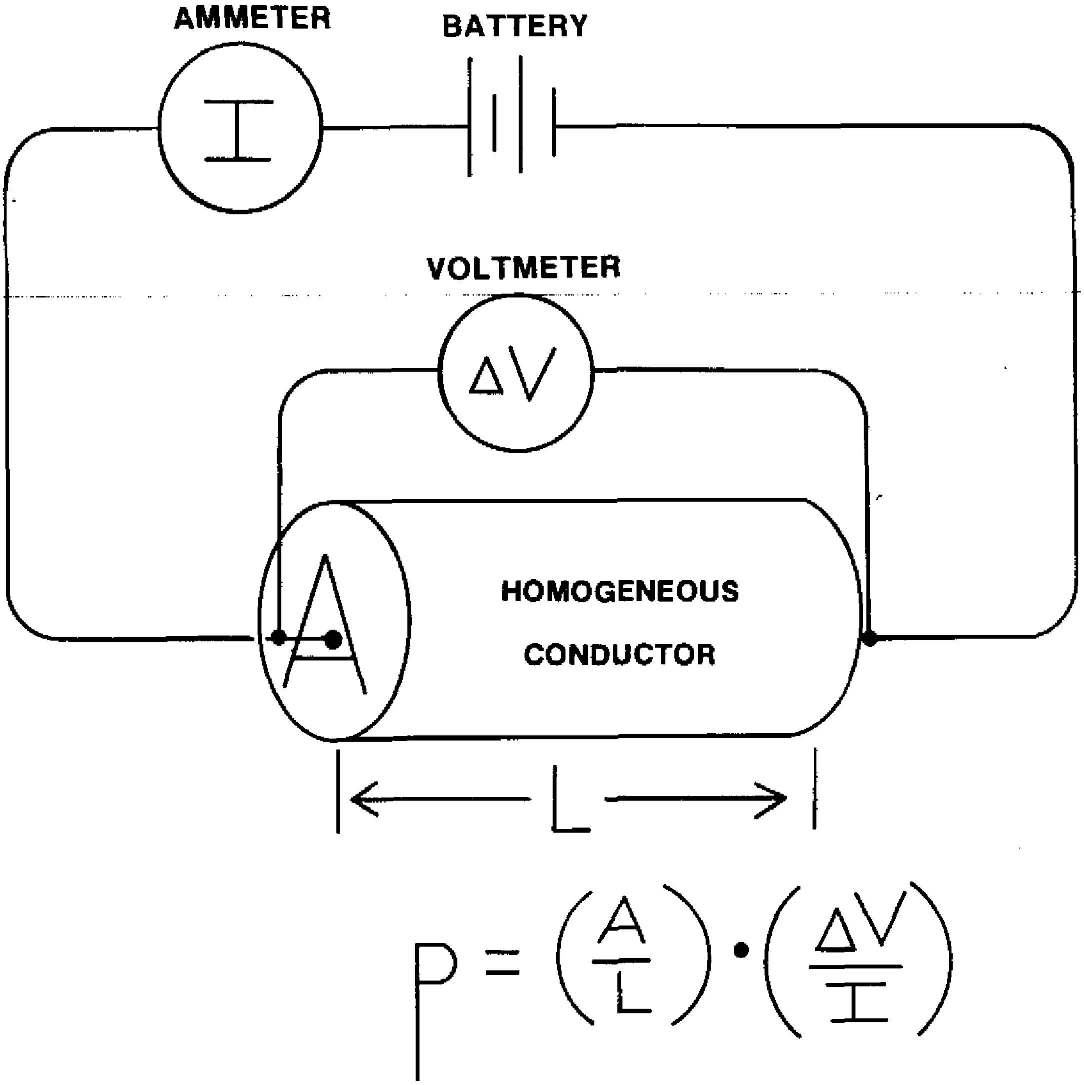


Figure 2 DEFINITION OF RESISTIVITY

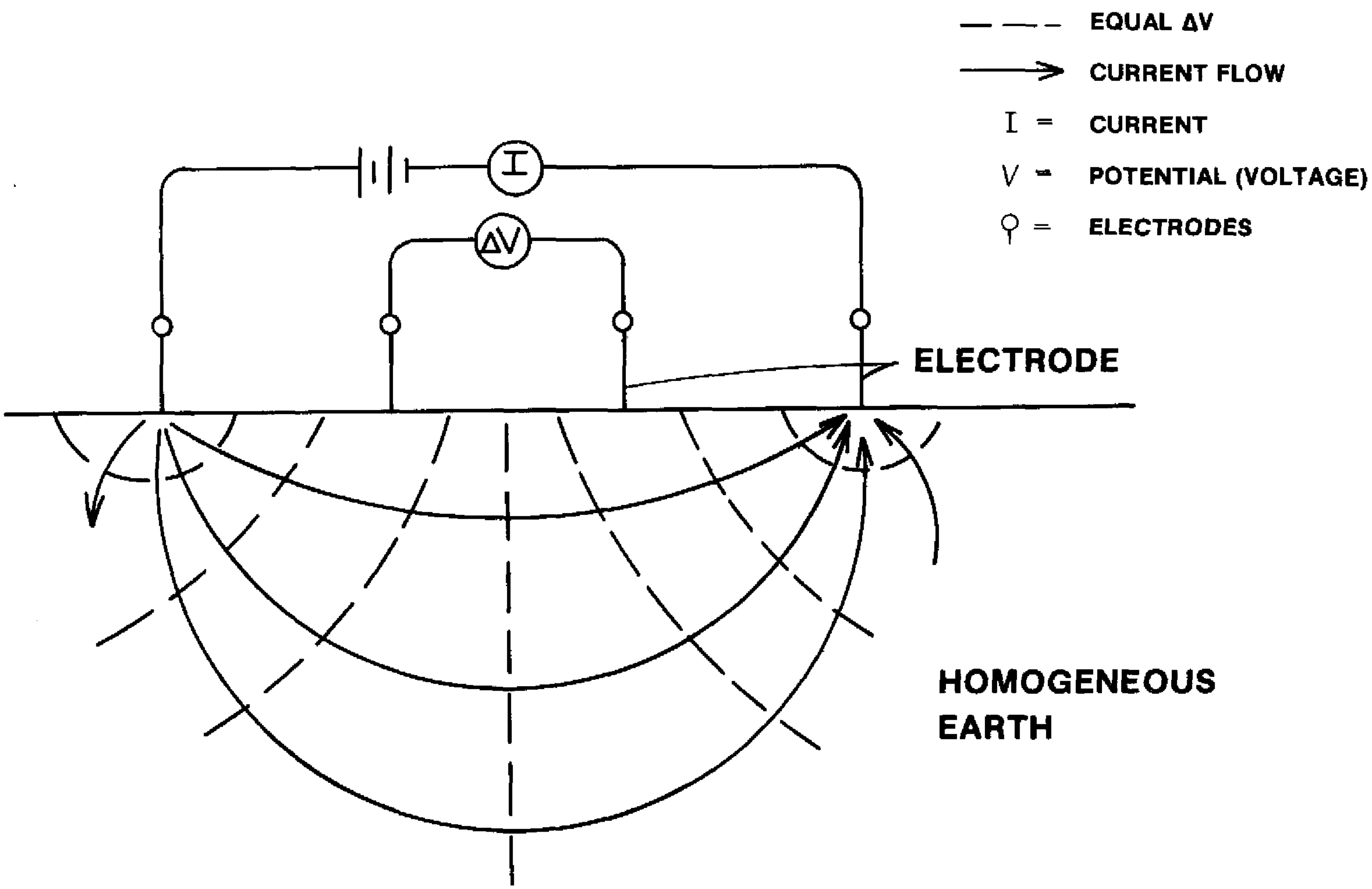


Figure 3 CURRENT FLOW IN A HOMOGENEOUS EARTH

currents in these materials is along the surface of pores or crystal faces and through any interstitial fluids; very little current flows through the minerals themselves. This means that porosity and the electrical properties of any interstitial fluids are the principal factors which influence resistivity. Some clay minerals, those with high cation exchange capacity, have unsatisfied electrical bonds on their surfaces which enhance the flow of electrons along the surfaces of pore spaces. This factor, coupled with the high porosity of most clay-rich geologic units, gives units with a high percentage of clay very low resistivities. In general, the higher the porosity the lower the resistivity.

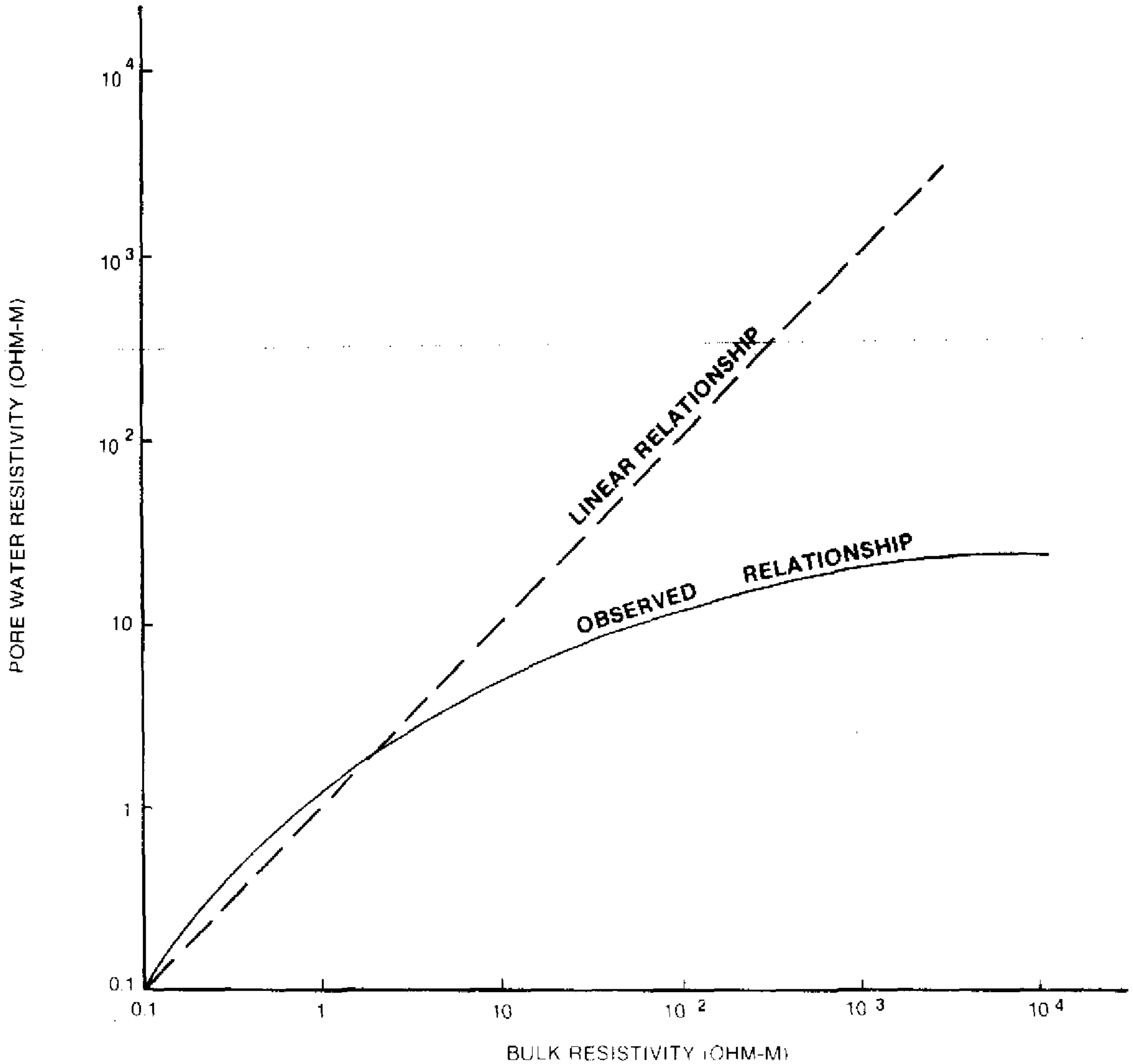
The quality of interstitial pore waters has a strong influence on the variation of resistivities of saturated geologic materials. When pore waters have a very low dissolved solids content most of the electrical current flows along the surfaces of pores and crystal faces. Porosity is the most important factor in determining bulk resistivity. As dissolved solids content and fluid conductivity increase, current flow through the interstitial fluid increases, lowering resistivity. Units saturated with brackish or saline waters typically exhibit very low resistivities (Table 1).

Figure 4 illustrates the relationship between bulk resistivity and fluid conductivity. When pore fluids are conductive there is approximately a one to one relationship between fluid resistivity and bulk resistivity. As bulk resistivities increase, however, fluid resistivity has a diminished effect on bulk resistivity. In geologic units saturated with fresh waters porosity is the dominant factor which influences resistivity. Very low porosity units exhibit very high resistivities. As fluid resistivity decreases it has an increasing effect on bulk resistivity. Geologic units

TABLE 1

Resistivities of Earth Materials
(Keller & Frischknecht, 1966)

LITHOLOGY	AGE	FORMATION	RESISTIVITY RANGE (ohm-m)
Sand/Gravel	Quaternary	Beaumont Clay	40-155
Limestone	Quaternary	Anastasia Fm.	106-193
Limestone, Marl, Clay	Eocene/ Oligocene	Wilcox/Midway	104-340
Limestone	Miocene	Tampa Limestone	119-357
Sandstone	Cretaceous	Dakota Sandstone	33-71
Chalk	Cretaceous	Selma Chalk	130-1300
Granite	Carboniferous	Appalachians	313-555
Sandstone/ Shale	Pennsylvanian	Pottsville Group	100-270
Dolomite	Silurian	Lockport Dolomite	63-114
Various	Pre-Cambrian	Huronian Rocks	900-1700
Oil Sands	Various	Various	4-800
Saline Sands	Various	Various	<1-10



(FROM KELLER & FRISCHKNECHT 1966)

Figure 4 PLOT OF BULK RESISTIVITY VERSUS PORE WATER RESISTIVITY saturated with brackish or saline waters will have very low resistivities unless porosity is very low. Units with intermediate resistivities can have many combinations of porosity and fluid resistivity, making lithologic or water quality interpretations of intermediate resistivities ambiguous. Units of high resistivity are saturated with fresh waters or are unsaturated. High resistivities can occur with poor quality fluids only if porosity is very low, such as in the case of evaporites.

Application of DC Methods - Electrode Configurations

The Wenner, Schlumberger, and bipole-dipole arrays are the usual electrode arrangements used for vertical electrical soundings (Figure 5). Each has certain advantages and disadvantages, and the choice of array depends on the target characteristics and the instrumentation available.

The Wenner array is often used in North America. It has the advantage of symmetry of electrode spacings, and for a given electrode spacing, less current is required to produce a measurable potential than with the Schlumberger or bipole-dipole arrays. The Wenner array, because of its widely separated potential electrodes, is more sensitive to lateral changes in resistivity. This is a disadvantage in vertical electrical soundings, but an advantage in horizontal profiling where lateral variations are the target. Distortions of Wenner sounding curves caused by lateral variation are more difficult to recognize than similiar distortions on Schlumberger curves. The principal advantage of the Wenner array for vertical electrical soundings is in increasing the depth of penetration possible with low-power equipment as compared to Schlumberger soundings.

The Schlumberger array is preferred by most European geophysicists and is increasingly being used in North America. For field studies it has several advantages over the Wenner array. The potential electrodes are not

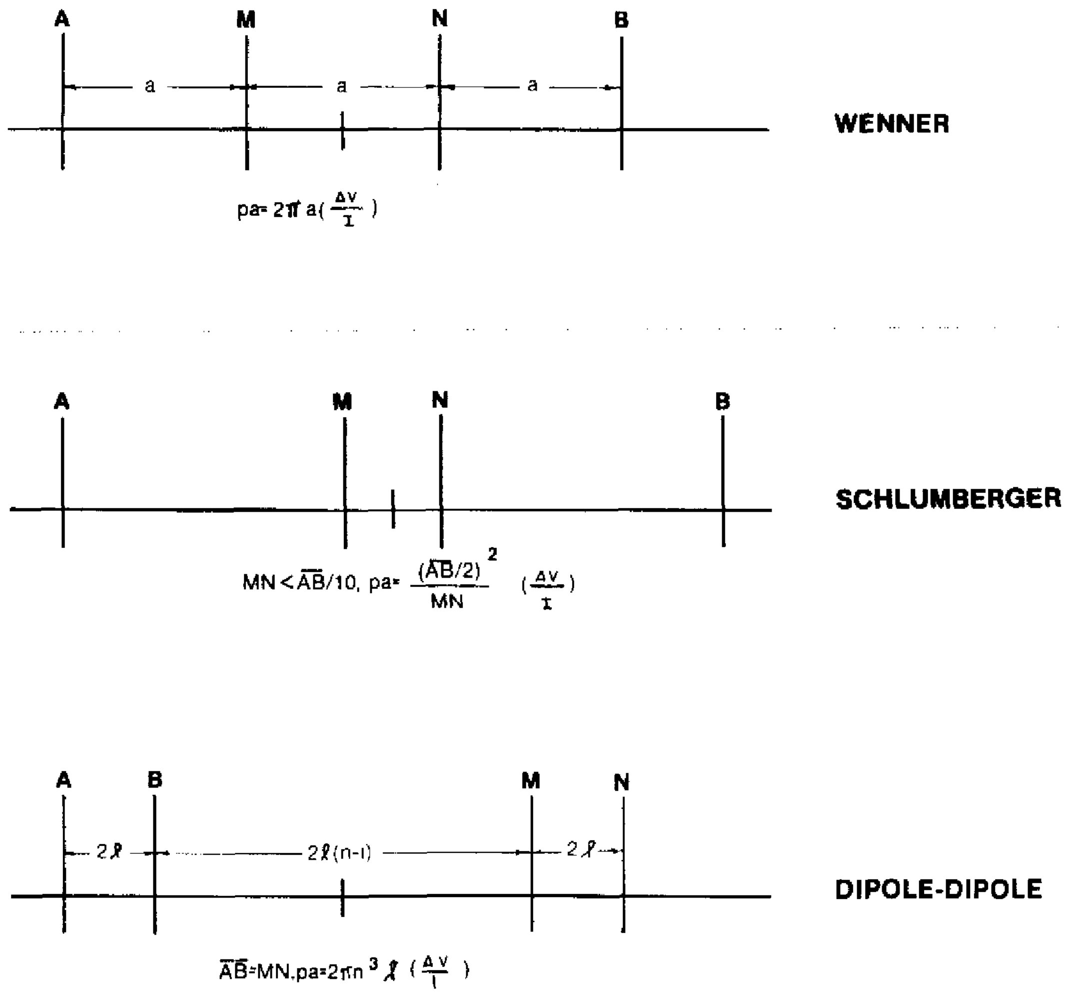


Figure 5 COMMON RESISTIVITY ELECTRODE CONFIGURATIONS

moved with each sounding, decreasing the background currents created by the interaction between the steel electrodes and soil moisture. Soundings can proceed more quickly as there are fewer electrode positions for the potential electrodes. Distortions of the sounding curves caused by lateral variations are more easily recognized and smoothed than is possible with data collected with the Wenner array. The principal disadvantage of the Schlumberger array is that more power is required to produce measurable potentials between the closely spaced potential electrodes. If the potential electrodes are moved often or their spacing is not small compared to the current electrode spacing, the advantages of the Schlumberger array over the Wenner array are diminished.

The bipole-dipole array is a variant of a dipole-dipole array. The current dipole has been lengthened to create a bipole. This allows a reduction in the power necessary to produce a measurable potential at the potential electrodes. This array has the highest power requirements of the three arrays. It has two advantages; first, apparent resistivities can be calculated for potential electrode positions at any radial position, although the equatorial or polar arrays are the most common; second, the current electrode spacing is small compared to the total spread length, and for very powerful transmitters this lessens the need for long cables charged with high voltages. Also, smaller crews can conduct soundings more quickly and safely as the current electrodes are relatively close to the transmitter and the potential electrodes are also close together. The principal disadvantage is the much higher power levels required than for the Schlumberger or Wenner arrays.

Instrumentation

Instrumentation for DC resistivity surveys may be very simple or somewhat complex. The basic requirement is a monitored current source and a millivoltmeter to measure potentials. The current source can simply be a number of 12-volt batteries wired in series, or can be a square-wave, low frequency AC current source. Amperage of current output has to be monitored with an accurate ammeter. Low-frequency AC (square-wave DC) transmitters pulse currents with 1 to 5 second cycles. Such pulsed signals can be "locked on" to by the receiver to increase the signal to noise ratio. Receivers are millivoltmeters with wide reading ranges. Scales typically range from 2 millivolts to 20,000 volts.

Depth of investigation is limited by transmitter power and receiver sensitivity. At very low potentials self-potential and telluric currents interfere with readings. This increases the signal to noise ratio and decreases errors due to background noise. Very high voltage levels also aid in overcoming high contact resistance of dry, sandy soils. Power outputs of under 250 watts are normally generated using rechargeable battery packs. Power outputs over 250 watts are achieved using motor driven generators. Receivers which lock on to square wave pulses generated by an appropriate transmitter can distinguish useful potentials at lower voltages because the coupling of transmitter and receiver allows filtering to increase the signal to noise ratio.

Increasing transmitter power has two disadvantages. The first is that engine driven generators are not very portable. Systems of 500-750 watts can be driven by small gasoline engines weighing 40 to 60 pounds, but more powerful systems require trailer-mounted generators. The second disadvantage is safety. The two common electrode arrangements, Schlumberger and Wenner, require the current electrodes to be placed at the extreme ends of the electrode spread. For depths of investigation of a few hundreds of feet, the current electrode spacing may be thousands of feet. These long current cables will be charged with high currents and voltages, requiring strict safety precautions. The danger in working with high power DC systems is equivalent to working with explosives, and such systems should be operated with respect for the hazards involved.

For hydrogeologic investigations, power requirements should be carefully evaluated. High power systems can penetrate more deeply, but such deep penetration may not be of enough value to a hydrogeologic investigation to justify the equipment and survey costs. The resoltuion of surface resistivity methods decreases exponentially with depth. A rough rule of thumb is that to be detected, the thickness of a layer must be a tenth of its depth. Also, deep surveys take considerably longer than shallower soundings and require long, straight open areas.

In summary, resistivity surveys to depths of 500-600 feet can be completed with lightweight portable, battery-powered transmitters. Deeper soundings generally require motor-driven generators. High sensitivity receivers which incorporate a method of enhancing the signal (filtering, stacking, pulsed signals, etc.) allow deeper surveys with low-power transmitters. For most ground water problems, systems of 250-500 watts with high quality receivers probably represent the most efficient compromise of cost, portability, accuracy, and depth of penetration.

Field Procedures

A vertical electrical sounding (VES) consists of a series of resistivity measurements made with increasing electrode spacings. The geometric center of the array is held constant while the electrodes are progressively moved outward. Variation in measured or apparent resistivity with electrode spacing contains the information on resistivity variation with depth.

Selection of a proper sounding site is relatively easy in the field, but difficult during planning stages using only topographic or planimetric maps. Recent aerial photographs can be very helpful in preliminary site selection. In Florida, rapid development quickly outdates maps and photos and recent or updated versions should be used. VES sites require open, straight survey lines four to six times as long as the desired depth of investigation. Longer spreads are required when conducting surveys in regions with low near-surface resistivities. In Collier County, Florida, current electrode spacings of 450 feet yield reliable resistivity data to depths of 90-100 feet. This is a region characterized by high surface resistivities underlain by very low resistivity units.

Straight sections of roads are the usual choice for VES sites. Hard-packed dirt roads with no shoulders are often poor choices as driving electrodes into the road surface can be very difficult. Open fields or woods are suitable sites if no roads are available. The only requirement is that a straight line and proper electode spacings be maintained. In wooded areas, electrodes, particularly potential electrodes, should not be placed near large trees. Tree roots are electrochemically active, and also, dense roots will produce a lateral resistivity inhomogeneity.

Soil conditions are also important in site selection. High electrode contact resistance prevents introducing usable current levels into the ground. Dry, sandy soils have very high contact resistivities and should be avoided. Occasionally moving a survey line to an area of slightly lower elevation and more moist soil helps. In Florida it is often very difficult to conduct resistivity surveys in November, April, and May because of dry soil conditions. County soil surveys can aid in avoiding sandy, excessively well-drained soils.

Data Interpretation and Presentation

DC resistivity data, like other potential field data, are normally interpreted by comparing field data to the calculated responses of proposed geologic models. This comparison can be done by hand, using theoretical master curves, or can be automated and accomplished in part or in total by digital computer programs. Hand matching is very time-consuming and requires some proficiency and training for three and four-layer solutions. Also the available albums of master curves are limited in the number of three-layer curves included.

The lowest level of computer-aided interpretation is to use a digital computer to calculate and plot master curves for comparison with field data (Zohdy and Bisdorf, 1975; Davis, 1979). After the smoothed field curve has been examined, the sounding curve for a possible geologic model is calculated (FORWARD, Zohdy & Bisdorf, 1975). The calculated and observed curves are compared and the geologic model is adjusted until a satisfactory match is obtained between the calculated and observed curves. With practice this procedure is reasonably quick, and requires little theoretical knowledge on the part of the interpreter.

Davis (1979) has written an automated curve-matching routine for digital computers. The interpreter inputs the field data and a suggested model. The program modifies the model until its calculated curve best fits the observed data. Statistics describing how good the match is are then provided to the interpreter. The interpreter can then decide to accept the model, or modify it and input it into the program again. This method is considerably faster than using manual curve-matching of computer-generated curves. However it works best using an interactive computer terminal, something which is both expensive and not always available.

Zohdy and Bisdorf (1975) has written a program which automatically inverts apparent resistivities and electrode spacings into layer resistivities and thicknesses (INVERSE, Zohdy & Bisdorf, 1975). Experience with this program (gained by the inversion of several hundred vertical electrical soundings) indicates that if the original data input into the program are good, then the solutions provided by the program compare well with available geologic and water quality data. The solutions, however, are quite sensitive to the quality of the field curve. A noisy field curve, or one which is distorted by lateral inhomogeneities, often yields solutions with unrealistic layer thicknesses or resistivities. Interpreter experience with the normal, undistorted appearance of VES curves allows noisy or distorted data to be smoothed or corrected before inversion. This greatly improves the quality of the solutions from this program.

The output from a typical INVERSE run yields a 6-10 layer solution. The program will generate a solution to depths of thousands of meters or feet, but any resistivity change below a depth equal to 1/2 - 1/3 the current electrode spacing should not be considered valid. Only boundaries above this depth should be used. In coastal areas the very low resistivities encountered in units saturated with salt water can lead to erroneous results due to rounding errors. In this case a field curve will show a steeply descending curve at longer electrode spacings, indicating the low resistivity saline zone. The INVERSE solution will match the field curve until the very low resistivities are reached. At this point it is not uncommon for the INVERSE solution to show increasing resistivities for the last one or two layers. If there is no clear increase in resistivity at longer electrode spacings on the field curve, such INVERSE solutions should be accepted only down to the last layer of decreasing resistivity, and the resistivity of that layer extended to an infinite depth.

Two options are available in the INVERSE program. IFORCE will force a solution even if a field curve is badly distorted. It should not be routinely used. Data sets rejected by the program when IFORCE = 0 should be smoothed or corrected, rather than forcing a solution by setting IFORCE = 1. MAXLYR will permit the program to continue its iterations in an attempt to produce the specified number of layers. The program will not produce a solution which contains fewer layers than the field curve. Also, the solution will often contain one or two layers more than the MAXLYR specification. For example, if a three-layer sounding is produced by program FORWARD and input into INVERSE, the solution may contain four or five layers which will yield a theoretical curve equivalent to a three-layer curve.

An interpreter unfamiliar with the FORWARD and INVERSE programs should use the FORWARD program to derive sounding curves for a number of geoelectric models. These sounding curves can then be input into INVERSE and the solutions compared to the original models. The theoretical sounding curves can also be deliberately distorted to simulate lateral inhomogeneities. This practice with the use of the INVERSE program is very useful in training the interpreter in the operation and limitations of the inverse method.

The output of the INVERSE program consists of a number of listings. The first listing is the data title and the field measurements. This is followed by a listing of the sum of the squares of the residuals. These describe how well the theoretical curve calculated from the INVERSE solution compares to the original field curve. The values should be significantly less than one. Larger values imply a noisy or distorted field curve. The sums are followed by the first resistivity solution. This solution will contain the same number of layers as data points plus six. The program then continues reducing the solution, printing the results as "REDUCED..." values. The listing "CALC. VES" is the theoretical sounding curve for the preceding geoelectric solution. The listing "SMOOTHED VES" represents the smoothed field curve used by the program to obtain a geoelectric solution. The first unreduced solution is often very useful, as the interpreter can often make more meaningful geologic interpretations from this listing than the reduced solutions.

The output from the INVERSE program is suitable for most resistivity applications; however, the solutions may not agree closely with geologic or geophysical logs from nearby drill holes. In such cases it may be useful to match hypothetical geoelectric solutions to the field data. The forward solution program FORWARD is used in this case. Geoelectric layers suggested by the borehole data and the INVERSE output are used as a starting point. The resulting theoretical sounding curve is compared to the original data, and the geoelectric layering adjusted until a satisfactory fit is obtained. The geoelectric layers then represent one possible solution to the field data. Because of the problem of equivalence, other geoelectric layers could also be fitted to the field curve, but if the original layers incorporated other geologic information, the resulting solution should be a reasonable model of the geoelectric layering.

At the University of South Florida (USF), several subroutines have been incorporated into program INVERSE which allow the output to be written on cards, tape, or disc, either as layer thicknesses and resistivities, depth to a specified resistivity, or resistivity at a specified depth. These values are written in a format compatible with the computer mapping program SYMAP (Dougenik and Sheehan, 1975). SYMAP will produce contoured maps or cross-sections of resistivity versus map position or depth, or maps of depth to a specified resistivity on the line printer. These maps and sections can be produced at any convenient scale. The output from INVERSE can also be input into plotting routines on a pen-plotter, such as the CALCOMP plotter at USF. SYMVU, a companion program to SYMAP, produces three-axis isometric plots of maps or sections on the pen-plotter.

GEOLOGY AND HYDROLOGY: WESTERN COLLIER COUNTY

The refief in southwest Florida is extremely low. The highest elevation in western Collier County included in this project are less than twenty feet, NGVD (Figure 6). There is a gentle rise in elevation inland, with local relief limited to a few feet or less. The water table is at or near the surface, and surface drainage is diffuse and poorly defined. Because of the low relief, water table gradients are extremely low, generally being less than 5×10^{-4} feet/foot.

Under natural conditions surface water flow was diffuse through broad, shallow sloughs trending generally southwest toward the Gulf. At present, an extensive system of canals intercepts much of the original surface drainage. Western Collier County is now subdivided into several surface

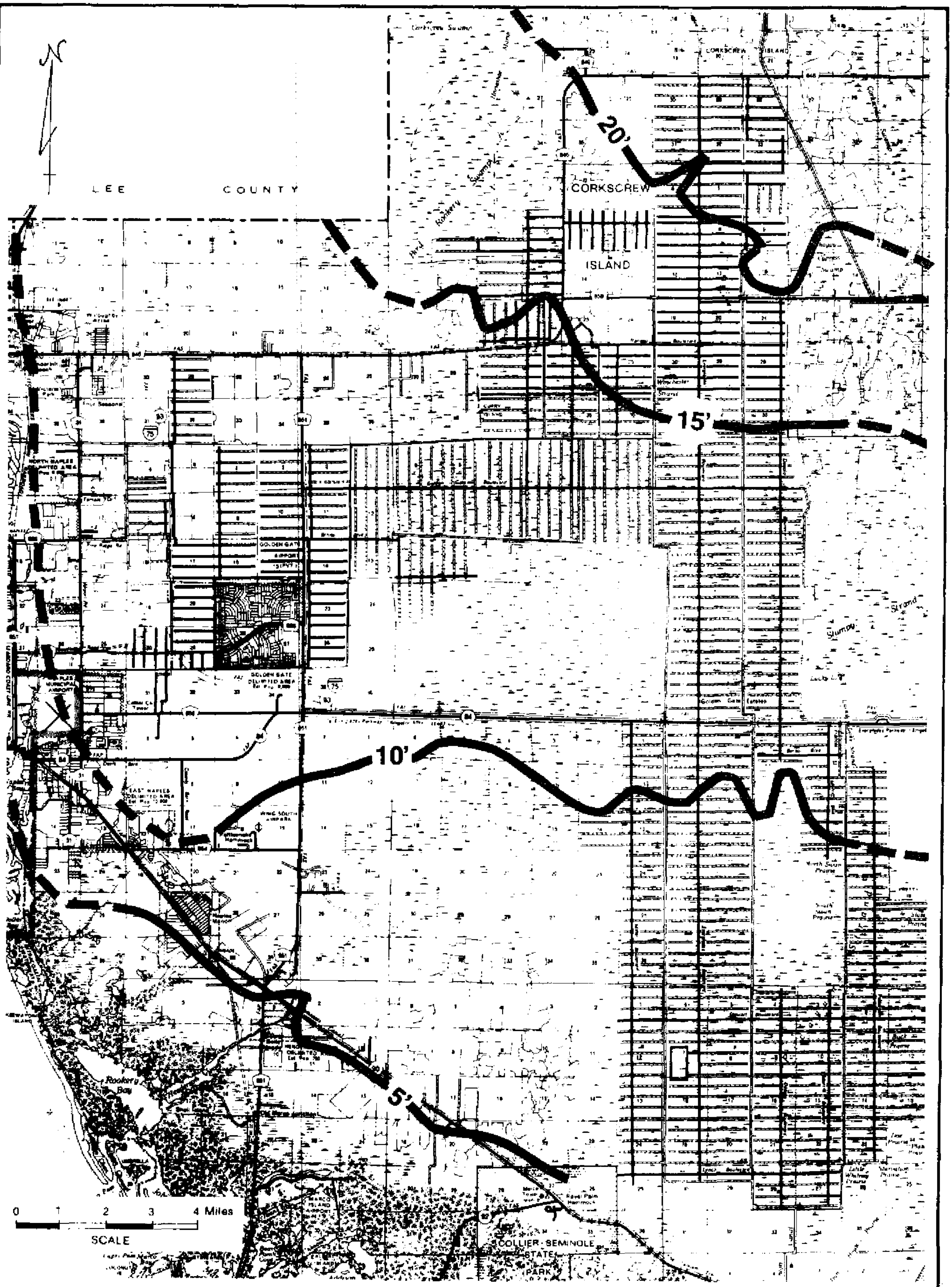


Figure 6 LAND SURFACE ELEVATIONS, WESTERN COLLIER COUNTY

water drainage basins by this canal system (McCoy, 1972). These canals have undoubtedly altered shallow groundwater flow patterns. The nature of this alteration, however, has not been determined.

The shallow aquifer system consists of four principal units (Figure 7). At the surface is the Pamlico Sand Formation, a silica sand 0-10 feet thick. The water table normally is located in the Pamlico Sand and the lower part of the unit is saturated. The next unit is the Fort Thompson-Caloosahatchee Marl Formations, possibly represented in this area primarily by a hard, shelly, sandy, limestone caprock (Jakob, 1980). Jakob reports extensive cavities in this unit, which is about 20 feet thick. The Ochopee Limestone member of the upper Tamiami Formation underlies the Ft. Thompson-Caloosahatchee, and is divided into two lithostratigraphic units in western Collier County. The upper unit, above 60-80 feet depth*, is a soft, very shelly, micritic limestone about 40-60 feet thick with extensive cavities up to two feet in height (Jakob, 1980). The lower unit, about 100 feet thick and extending to the bottom of the aquifer at 160-180 feet depth, is a soft, limey sandstone. The bottom of the aquifer is a carbonate mud (Jakob, 1980).

There are no laterally extensive, low permeability units present above the muds at the bottom of the aquifer. The entire system of four units is hydrologically inter-connected although transmissivities are significantly higher in the upper 60-80 feet of the aquifer. The limestones of the Ochopee Member and Ft. Thompson-Caloosahatchee Marl Formations have very high hydraulic conductivities in large part because of extensive secondary solution. Jakob (1980) reports a transmissivity of 40,000 square-feet/day for this unit from a pumping test at a well in southwest Collier County. The flowmeter log for this well indicates that 95% of the water was entering the well between the bottom of the casing and a depth of 60 feet. The

*Note: All depths are below land surface datum, unless otherwise specified.

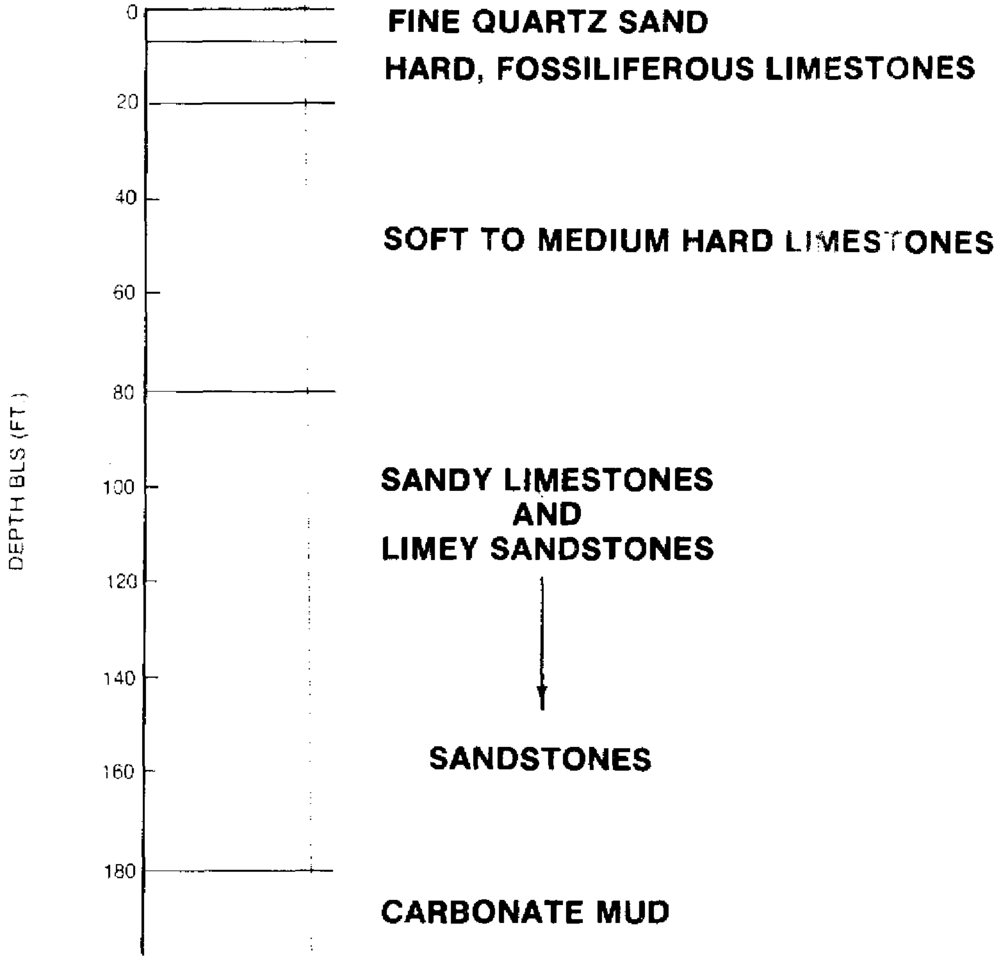


Figure 7 GENERAL GEOLOGIC SECTION, WESTERN COLLIER COUNTY

approximate hydraulic conductivity of the aquifer at this site is therefore 800 feet/day.

Water quality varies considerably within the shallow aquifer system, but in general, dissolved solids content increases with depth. In many places in western Collier County non-potable waters occur above the low permeability units at the bottom of the aquifer. Available chemical data show a wide variation of chloride/sulfate ratios. Close to the coast, groundwaters have a chemistry similar to sea water, but inland waters cannot be classified as sea water. Many samples seem similar to waters in the lower Tamiami and Floridan aquifers which underlie the surficial aquifer (Jakob, 1980). These systems have potentials higher than those in the shallow system. Thus upward leakance of higher TDS waters is a possible source for the poor quality waters found at depth in inland areas.

BELLE MEADE SALT WATER INTERFACE STUDY

Introduction

This study was completed in southwest Florida, southeast of the city of Naples (Figure 1). Southwest Florida is experiencing very rapid population growth, and is almost entirely dependent on groundwater for private and municipal supplies. Most of the growth is occurring on or near the coast, placing increasing stresses on the coastal sections of the aquifer system. The South Florida Water Management District and the University of South Florida initiated this cooperative project to determine the technical and economic feasibility of using DC resistivity soundings to delineate hydrogeologic conditions in the shallow aquifer system. The principal objectives were to determine gross water quality and lithology using inexpensive, rapid remote sensing methods. The geophysical surveys were intended to serve as a guide for conducting conventional drilling and water sampling investigations, with the expection that this would allow more efficient utilization of the available resources and personnel.

Data Acquisition and Reduction

The field data were collected over an eight-month period from November 1979 to July 1980. Ninety-five vertical electric soundings (VES) were obtained using the Wenner array (Figure 8). Where space and geoelectric conditions permitted, the electrode spacings were extended to an AB/3 distance of 600 feet. If a persistent apparent resistivity of less than 10 ohm-meter was obtained at shorter electrode spacings, the sounding was not carried out to 600 feet. The 10 ohm-meter value was chosen as the cutoff point, based on previous work by Jakob (1980) which indicated that

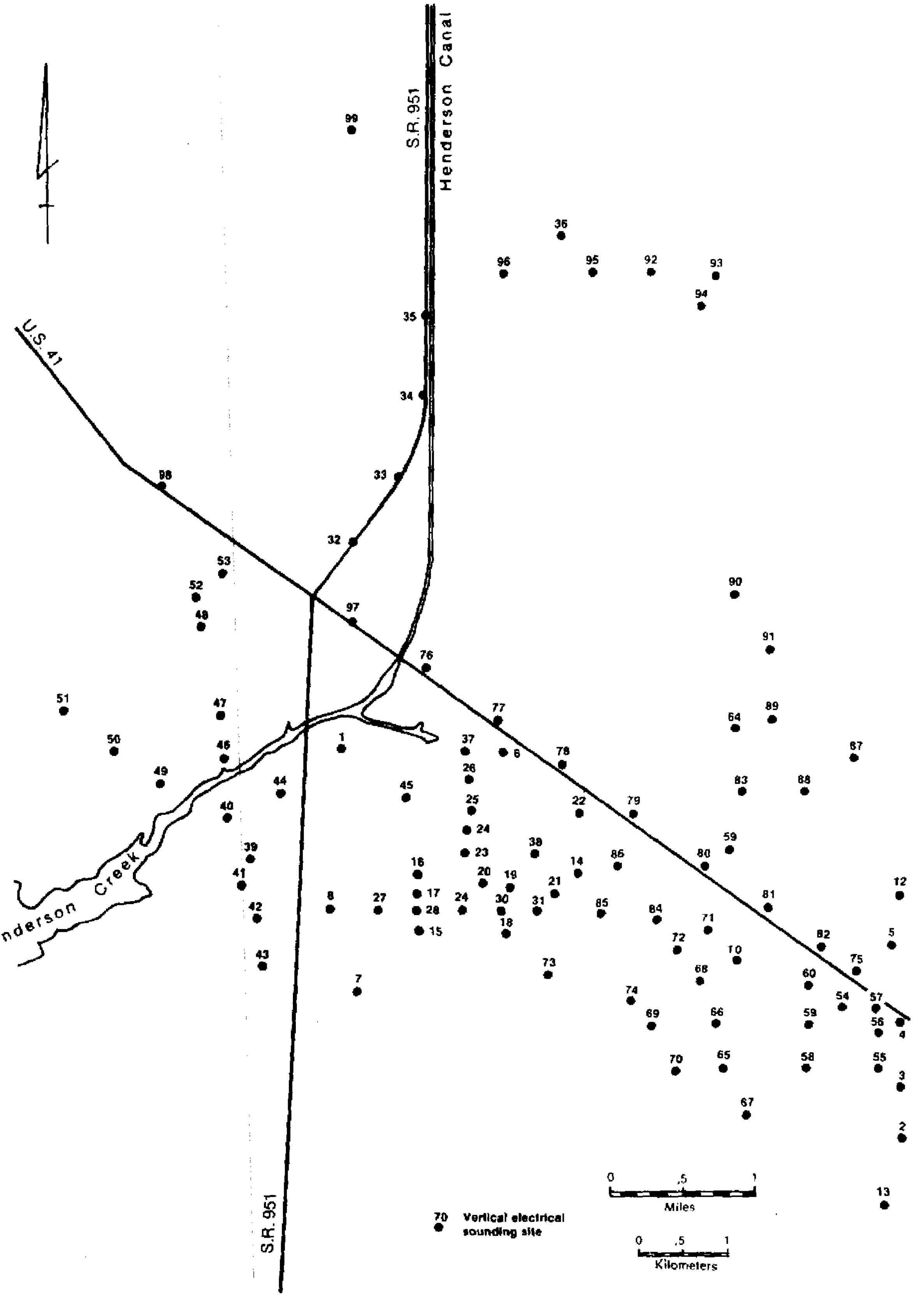


Figure 8 LOCATION OF VERTICAL ELECTRICAL SOUNDINGS, BELLE MEADE STUDY AREA

a 10 ohm-meter resistivity value was generally encountered well below the 250 mg/l salt water/fresh water interface.

All VES data were automatically reduced to geoelectric solutions of layer thicknesses and resistivities using program INVERSE (Zohdy and Bisdorf, 1975). Solutions which were geologically unreasonable (unrealistically complex solutions or thin layers) were reduced to solutions with fewer layers through an iterative process using program FORWARD. All field curves were smoothed before inversion, either by program INVERSE or manually.

Geoelectric solutions with a high resistivity for the lowest layer were considered to be geologically unreasonable, as it was assumed that low resistivity units saturated with poor quality water underlie all of the study area. In these cases a series of apparent resistivities were added to the field curve to represent the deeper low resistivity units, and the resulting field curve was automatically inverted. Such cases usually were caused by space or instrument limitations on sounding depth, preventing the sounding from reaching the low resistivity layers. These solutions indicate a final low resistivity at a depth comparable to nearby VES, but indicate higher resistivities at intermediate depths.

The final VES solutions were contoured using SYMAP, a computer graphics program (Dougenik and Sheehan, 1975). The program uses an inverse distance weighted average algorithm. The computer contouring was modified where edge effects or large resistivity variations caused distortions in the computer generated maps, or where resistivity trends could be inferred from geologic or water quality data.

VES Classification

Each VES was classified based upon the variation of resistivity with depth. Omitting the upper 6 feet (maximum water table depth) and small increases in resistivity of deeper layers, the VES solutions were placed in one of four classes: Type 1 - the entire geoelectric layer exhibits resistivities less than 10 ohm-meters; Type 2 - a continuous decrease in resistivity with depth; Type 3 - decreasing resistivities with depth, with the exception of a buried higher resistivity layer or layers less than 30 feet thick; Type 4 - decreasing resistivities with depth, with the exception of a buried higher resistivity layer or layers greater than 30 feet thick. Figure 9 shows the distribution of curve types.

Discussion

Defining the salt water interface from bulk resistivity values requires that an assumption be made as to which resistivities represent units saturated with salt water. In this area a resistivity of 10 ohm-meters appears to be good approximation of the interface. Soundings close to the coast in or near salt water marshes indicate shallow bulk resistivities of 1 to 10 ohm-meters. Water quality data from wells in this area exhibit a wide range in chloride ion concentrations, from 345 mg/l to 19,000 mg/l. The salt water interface can be assumed to be within those zones that contain waters with chloride values significantly above 345 mg/l and resistivity values less than 10 ohm-meters.

The 10 ohm-meter interface (Figure 10) reveals configurations which vary from the "classic" steep salt water/fresh water interface expected at the seaward margin to more complex, contorted patterns less obviously related to the seaward margin. The steep, straight section is southeast of and roughly parallel to US-41. The seaward edge of the interface has a slope of 2 to 3.5^{0}, descending from near the surface to a depth greater

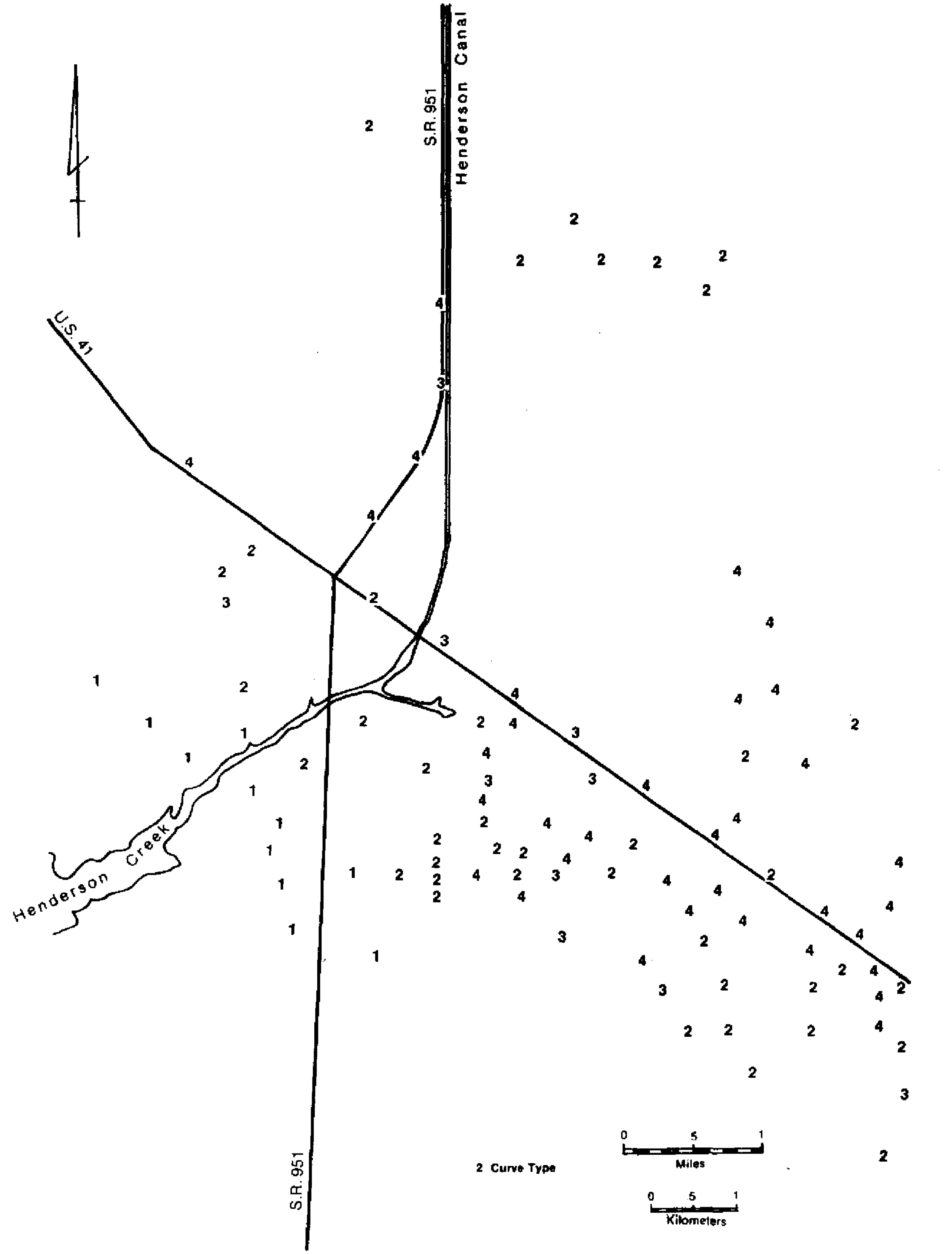


Figure 9 DISTRIBUTION OF VES CURVE TYPES 1, 2, 3, 4

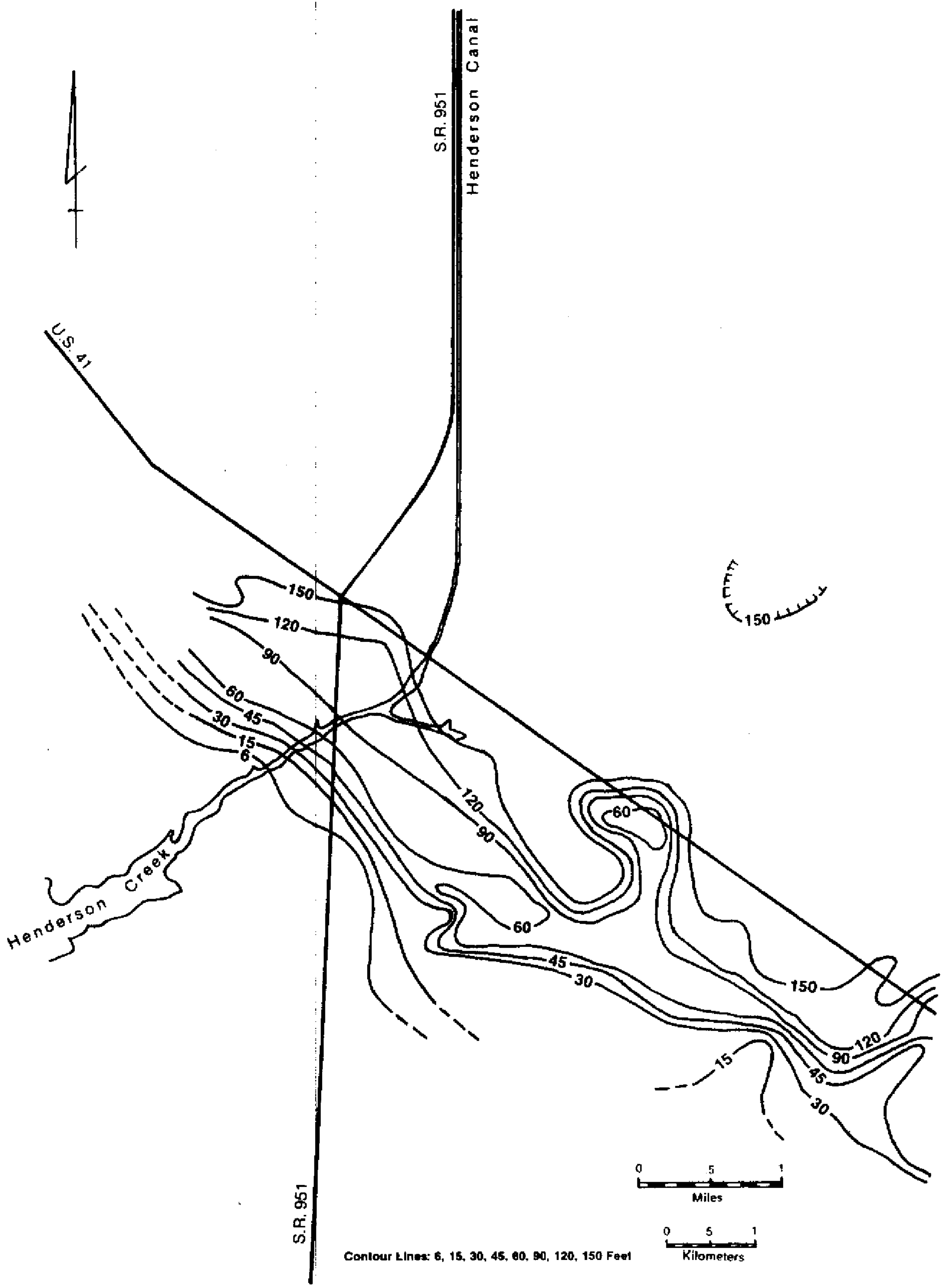


Figure 10 DEPTH TO A PERSISTENT RESISTIVITY EQUAL TO OR LESS THAN 10 OHM-M

than 150 feet within a distance of 0.5 to 0.7 mile. The general trend of the interface parallels the coastline.

The general coast-parallel configuration is modified by several landward reentrants of the interface. These reentrants seem to be controlled in part by the presence of absence of a hard shallow caprock. Elevations are slightly higher where the caprock is present, and lower where it is absent. Both of the reentrants shown in Figure 10 are associated with topographic depressions. VES data indicate that in both areas the caprock is absent or deeper than normal. Apparently the lower hydraulic heads and gradients associated with the depressions create a less dynamic flow system, leading to a shallow interface. These reentrants extend up to one mile inland from the average interface position.

It might be expected that Henderson Creek would exert a strong influence on the position of the interface, but this is not seen in the pattern of the 10 ohm-meter interface (Figure 10). This is probably the result of an insufficient number of soundings close to the creek. Part of the sampling problem is the shallow, very hard caprock near the junction of SR-951 and US-41. This caprock is so well indurated that it was not possible to drive steel electrodes into it.

Water Quality

As discussed earlier, bulk resistivity is dependent primarily on porosity and pore fluid resistivity. If porosity remains relatively constant, bulk resistivity decreases as fluid conductivity and dissolved solids content increases. For highly conductive fluids, bulk resistivities are low enough that units saturated with such fluids are easily recognized.

However, such fluids are often over 1000 mg/l chloride ion concentration, well above the 250 mg/l potable water standard. It would be useful if resistivity values could be used to distinguish potable from non-potable waters.

Jakob (1980) found that a six-foot lateral log resistivity of less than 30 ohm-meters is encountered in boreholes in the Belle Meade area when chloride concentrations of air-lift samples from that depth exceed 250 mg/l. Using this relationship Jakob mapped the depth to non-potable waters from lateral log resistivities (Figure 11).

Figure 12 is a map of the depth below which resistivity is 30 ohm-meters or less. Based on Jakob's findings, these depths may be assumed to approximate the thickness of potable waters overlying the brackish and saline waters. However, the measured resistivities are sensitive to porosity variations, since fluid conductivities in units with this bulk resistivity are low. In comparison with the 10 ohm-meter interface of Figure 10, the 30 ohm-meter interface is more complex inland than the 10 ohm-meter interface. A trough of greater depths to poor quality waters parallels US-41. Both seaward and landward of this trough low resistivities are found at depths of less than 150 feet. This suggests that inland, poor quality waters, which are not directly related to the interface at the seaward margin, are present at shallow depths in the aquifer.

It is not possible to determine the origin of the poor quality waters in the lower part of the aquifer from resistivity data alone. Jakob (1980) suggests several sources: upward leakance from the underlying artesian lower Tamiami, Hawthorn and Floridan aquifer/aquitard systems; inundation by hurricanes; and/or relict waters from periods of higher sea levels. Geochemical data from wells inland from the seaward aquifer margin indicate that these poor quality waters have $Cl^-/SO_4^=$ ratios less than that of sea

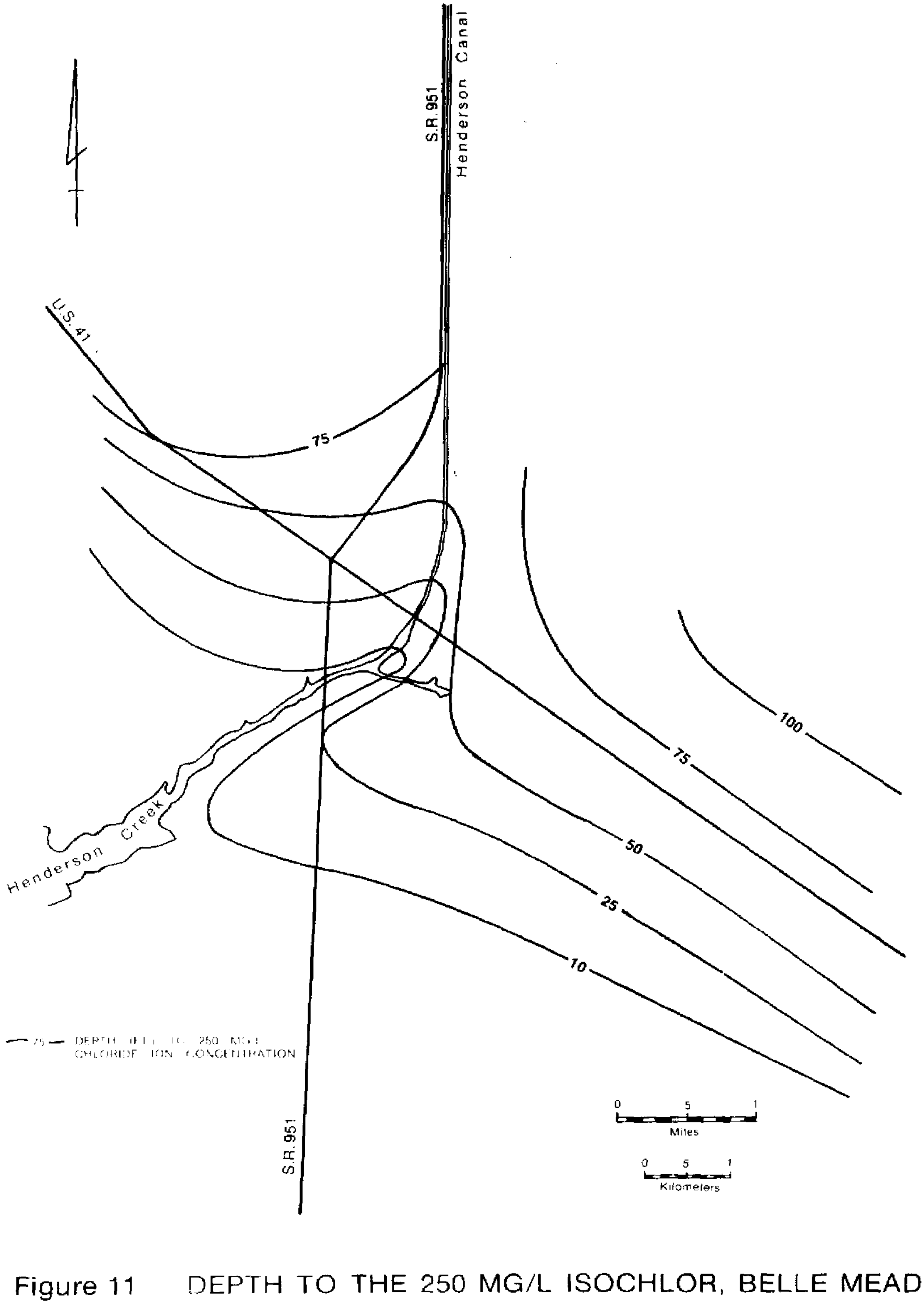


Figure 11 DEPTH TO THE 250 MG/L ISOCHLOR, BELLE MEADE STUDY AREA (FROM JAKOB, 1980)

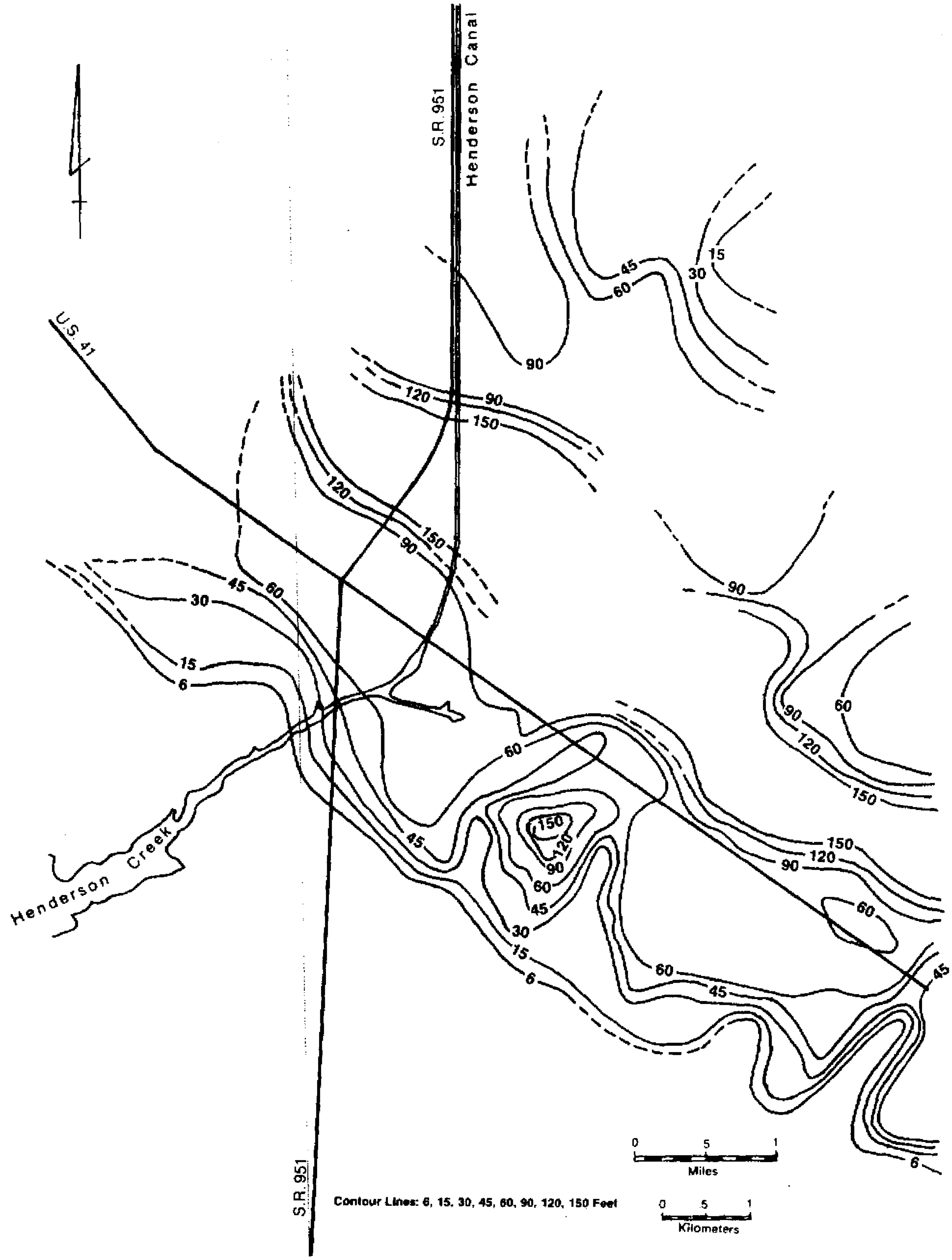


Figure 12 DEPTH TO A PERSISTENT RESISTIVITY EQUAL TO OR LESS THAN 30 OHM-M

water. As the lower Tamiami, Hawthorn, and Floridan aquifer/aquitard systems have potentials higher than water table elevations and $Cl^-/SO_4^=$ ratios less than sea water, upward leakance seems to be the most likely explanation. The uneven distribution of the depth to these waters, as revealed by resistivity data, implies a varying competence of the confining bed at the base of the surficial aquifer, allowing more upward leakance in areas with shallower depths to non-potable waters. Part of the variation may also be due to variable flushing rates. Where transmissivities or hydraulic gradients are low, upwelling waters are not flushed as quickly as in more dynamic parts of the surficial aquifer system. In general, bulk resistivities decline rapidly below the 12 to 60 foot depth high transmissivity zone defined by Jakob. This implies that groundwater movement is predominantly through the high transmissivity, karstic limestones, as suggested by Jakob (1980). Another source of isolated and areally limited zones of high conductivity pore fluids may be improperly abandoned oil and gas exploration wells. Such wells provide an upward conduit for poor quality waters from underlying artesian aquifers. Northern Collier and Southern Lee Counties are oil-producing areas, and exploration has been active for many years in south Florida.

Lithology

It is difficult to make definitive correlations between rock type and bulk resistivity values when there is a wide range of pore water conductivity. In particular, pore waters with a high total dissolved solids content tend to mask differences in porosity associated with lithologic variation. As pore waters become fresher, porosity (i.e.,lithologic) variations became more pronounced.

In the Belle Meade area the decline in water quality with depth makes lithologic correlations with bulk resistivity values difficult to make below 30 to 50 feet. However, one of the lithologic units of hydrologic significance, the dense, karstic limestones of the upper Tamiami and Ft. Thompson-Caloosahatchee Marl Formations, has a distinctive resistivity signature (Figure 13). These limestones have low primary porosities, yielding high (>100 ohm-m) bulk resistivities when saturated with fresh water. The contours shown on Figure 13 are therefore primarily indicative of depths of this unit, and under these conditions, a resistivity greater than 100 ohm-meters may be considered as a distinctive resistivity signature for these limestones. However, because of their karstic character, they exhibit very high transmissivities. When saturated with poor quality waters even these dense limestones lose their resistivity signature. Dense limestones encountered in a borehole approximately one mile north of US-41 on SR 951 have resistivities of less than 100 ohm-meters when saturated with waters with chloride ion concentrations greater than 250 mg/l (Jakob, personal communication).

Figure 14 shows the location of VES solutions which exhibit shallow bulk resistivities less than 25 ohm-meters. All of these sites are underlain by higher resistivity units and available water quality data show that these near-surface low resistivity units are saturated with fresh water. About 3 miles southeast of the US-41 and SR-951 intersection an outcrop of red clay occurs. This type of material is generally characterized by low resistivities and it is therefore assumed that the near-surface low resistivity units consist of similar silicate clays. These sites are located at or near the periphery of the shallow, high resistivity caprock, (Figure 15) and the units may represent a weathering residuum. The resistivity pattern at eleven of the other sites can be

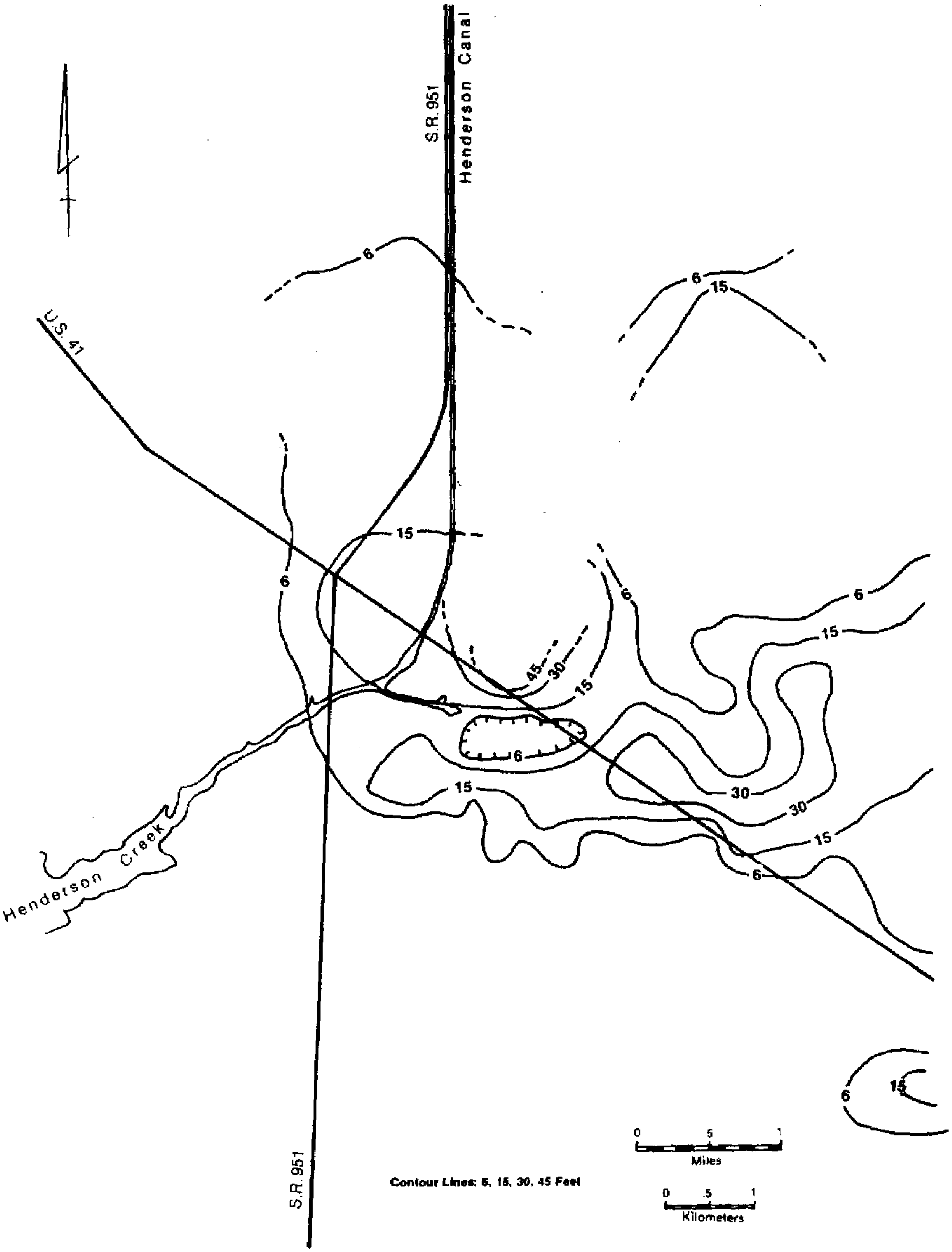


Figure 13 DEPTH TO A PERSISTENT RESISTIVITY EQUAL TO OR GREATER THAN 100 OHM-M

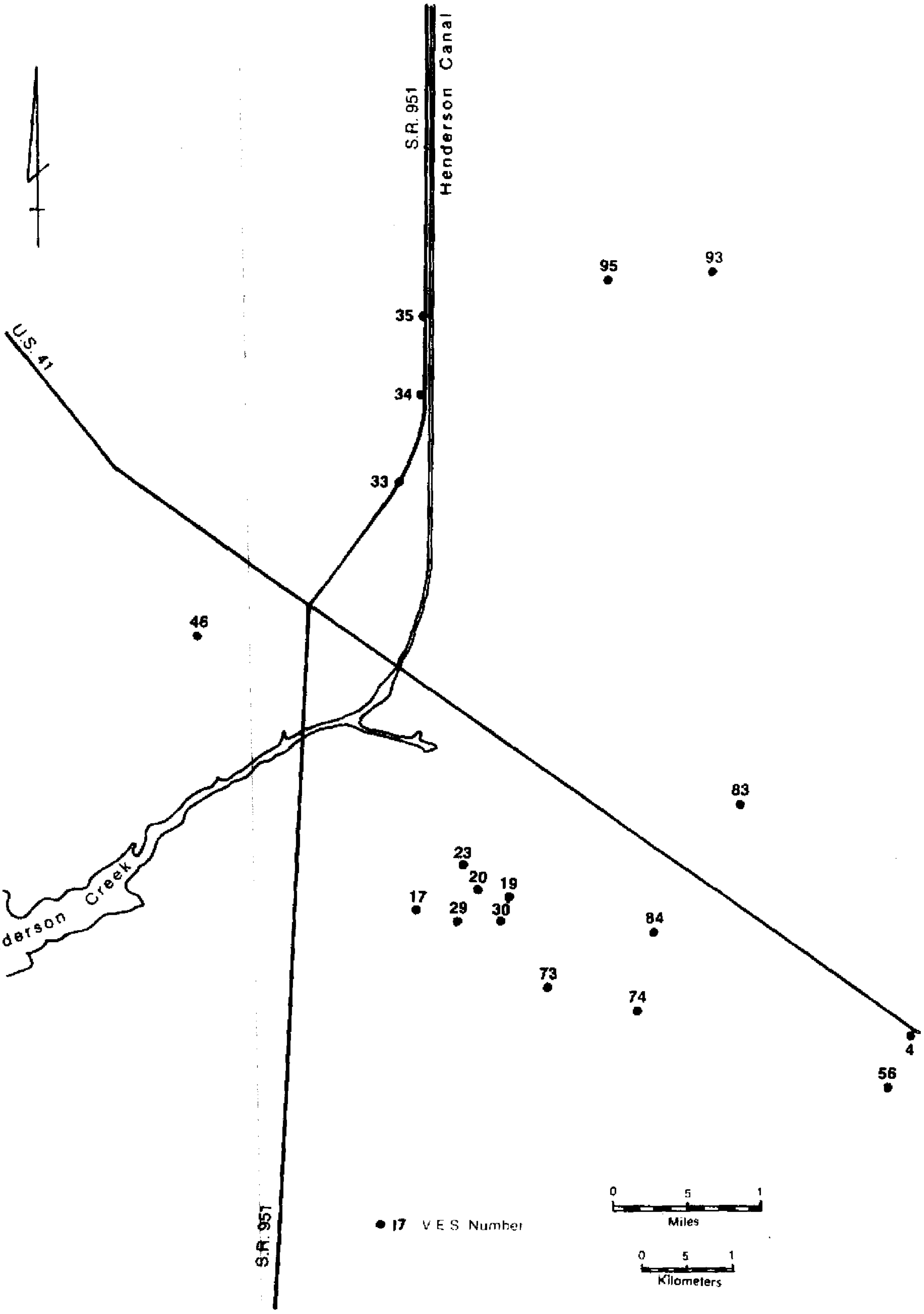


Figure 14 VES SITES WITH SHALLOW RESISTIVITIES LESS THAN 25 OHM-M

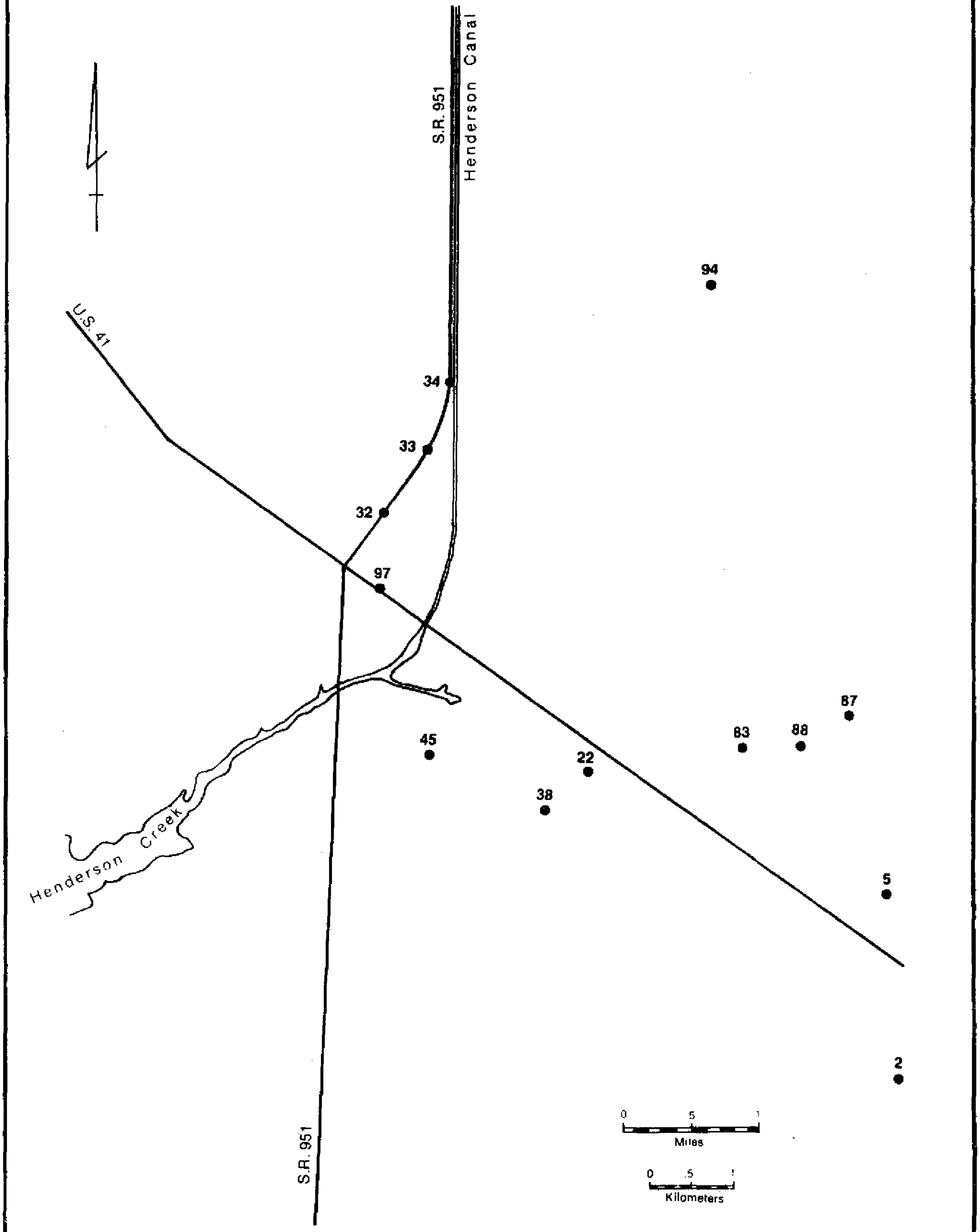


Figure 15 VES SITES WITH SHALLOW (LESS THAN 10′) RESISTIVITIES GREATER THAN 100 OHM-M, INDICATING LIMESTONE CAPROCK

correlated with an absence of shallow caprock and the presence of organic materials in the surficial sands. The absence of a dense caprock leads to a surface depression or low. The more moist soils in these depressions accumulate organic matter.

In summary, differences in porosity which are related to lithologic variations can be used to distinguish the dense, karstic, highly transmissive hydrostratigraphic unit, but only when pore fluid conductivities are low and relatively constant. Increasing fluid conductivities with depth mask resistivity changes due to lithologic variation. For example, resolution of the bottom of the surficial aquifer was not possible because the high fluid conductivities masked the lithologic change from loose sandstones to silts and marls at depths of 160-200 feet.

Conclusions

Automatic interpretation of VES data (Zohdy and Bisdorf, 1975) greatly enhances the utility of DC resistivity methods for preliminary hydrogeologic investigations. The rapidity of digital processing and presentation of data saves considerable time and effort over traditional curve matching techniques. This time and effort saved in interpretation can be applied to obtaining more field data. When large amounts of resistivity data are available, confidence in the results increases, correlations between soundings are easier, and anomalous areas or erroneous data are more easily identified.

The salt water interface, approximated by the 10 ohm-meter interface, is dominated by a classic, coast-parallel, steep seaward face geometry. However, on a smaller scale it is influenced by lithology and elevation. Where a shallow, indurated caprock is absent lower elevations produce landward reentrants in the interface. These reentrants are probably due to lower water table elevations and less dynamic flow systems in the areas of lower elevation. These reentrants extend up to one mile inland from the average interface position.

Determination of water quality from bulk resistivity values is somewhat ambiguous if porosity also varies. However, correlation of lateral-log borehole resistivities and water quality data suggests that bulk resistivities less than 30 ohm-meters represent units saturated with waters with chloride ion concentrations above potable water limits. In general, resistivities and water quality both decline sharply with depth. The source of these low quality waters inland from the coast cannot be determined from resistivity measurements, but geochemical data and head relationships suggest upward leakance is the most probable source (Figure 16).

Because of the increase in fluid conductivities with depth, it is difficult to correlate bulk resistivity values with particular lithologies below depths of 30-50 feet. However, a singificant hydrostratigraphic unit, the dense, karstic limestones found the upper 50-60 feet of the section, can be distinguished using bulk resistivities. Where this unit is saturated with potable waters, it generlly exhibits resistivities of over 100 ohm-meters and as high as 400 ohm-meters. This is in contrast to the 30-100 ohm-meter resistivities of the softer limestones and sands.

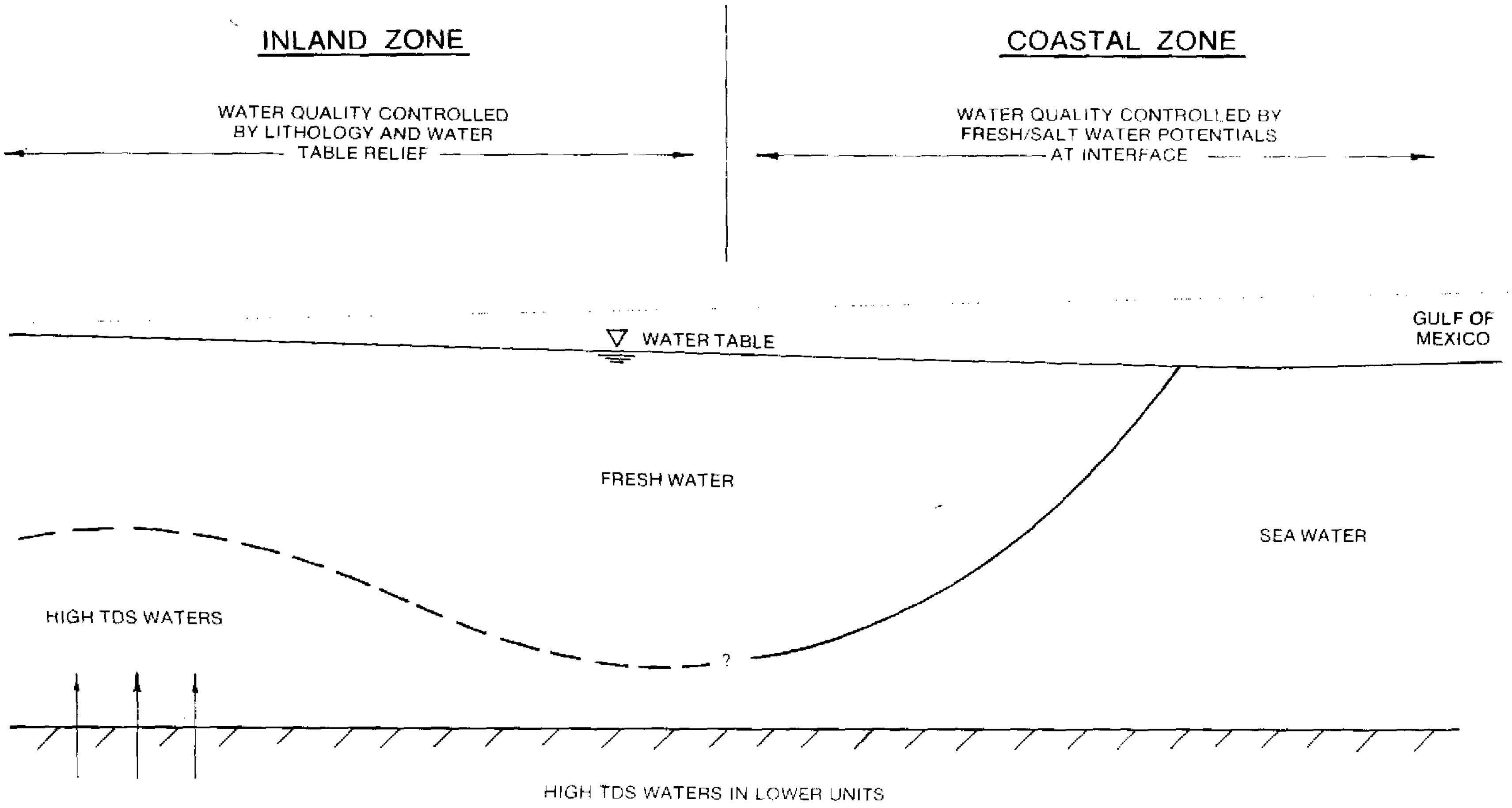


Figure 16 CONDITIONS INFLUENCING GROUND WATER QUALITY IN BELLE MEADE AREA

WESTERN COLLIER COUNTY DC RESISTIVITY GROUNDWATER RECONNAISSANCE SURVEYS

Introduction

The Belle Meade DC resistivity study in coastal Collier County, Florida suggests that two features of importance to the hydrogeology of the region can be mapped using surface DC resistivity surveys. The two features are the presence of pore waters with low resistivities (high fluid conductivities) which have been shown from well surveys (Jakob, 1980) to correspond to waters with chloride concentrations in excess of the 250 mg/l potable water limit, and shallow, well-indurated, "reef" limestones which characteristically exhibit high bulk resistivities (>100 ohm-meters). The correlation of high bulk resistivity to indurated limestone "reefs" or "caprock" has also been substantiated by geologic logs compiled by the South Florida Water Management District (Jakob, 1980, and personal communication).

The objectives of this study were to determine if the conclusions of the earlier study could be extended inland in Collier County, and to evaluate surface DC resistivity soundings as a basin or county-wide reconnaissance survey method for locating zones with potential groundwater resources ("reef" tracts) or areas with water qualities which exceed potable water limits (low resistivity areas). It was felt that if the conclusions reached in the coastal study (Belle Meade study) applied inland, DC resistivity surveys would provide an economic and rapid method of pinpointing areas which warrant closer investigation by conventional methods.

Because the resistivity signatures which indicate either "reef" limestones or poor quality waters can be recognized at relatively shallow depths (less than 75 feet), and because deep vertical electrical soundings take considerably longer to complete than shallow soundings, it was decided to limit the electrode spacings used to a maximum of 154 feet (50 meters). The time saved by limiting the depth of investigation was used to complete more soundings providing a greater data density.

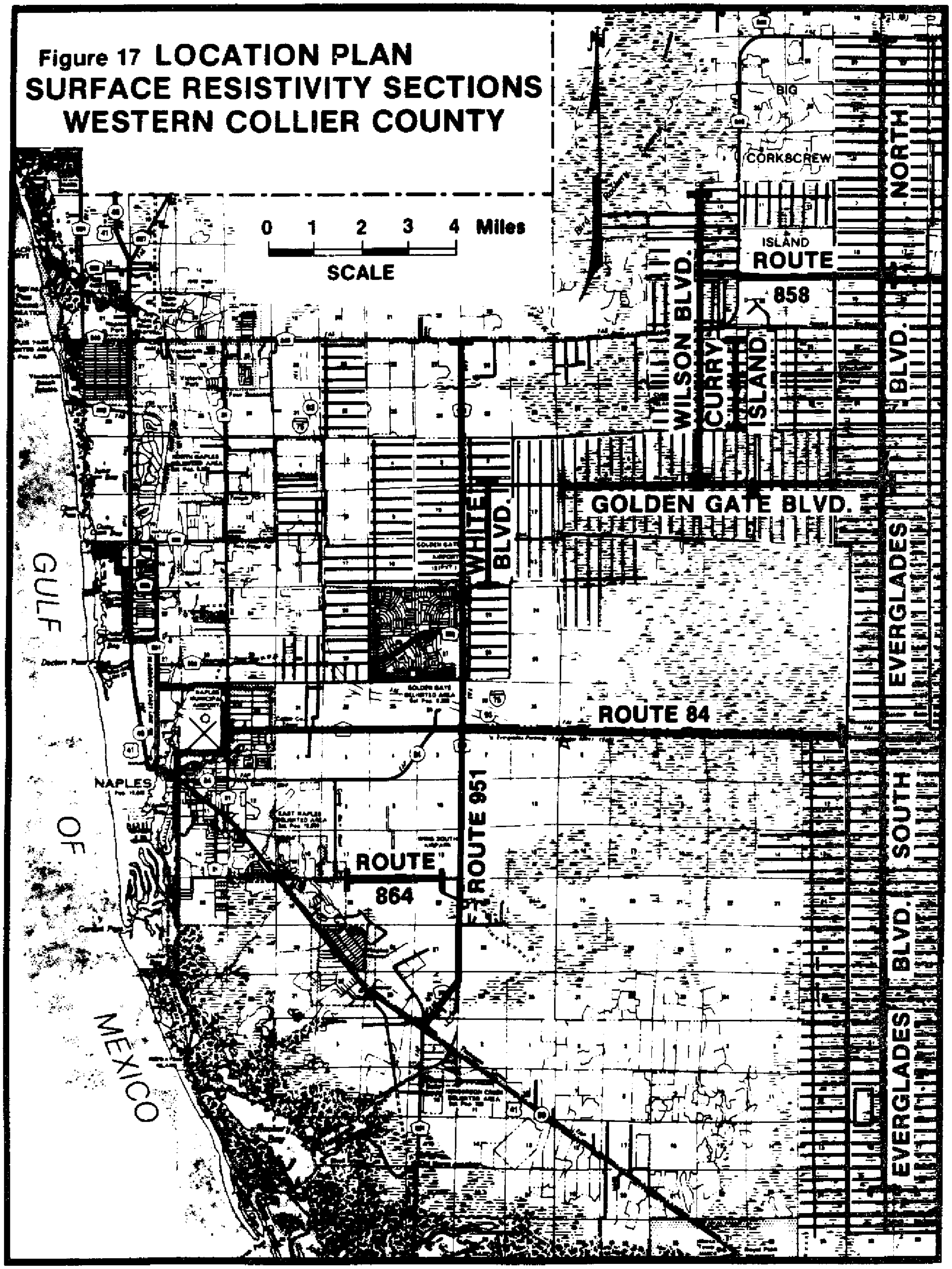
The field data were interpreted and mapped using several computer programs, greatly shortening the time required for data reduction. These programs were adapted from existing programs (Zohdy and Disdorf, 1975; Dougenik and Sheehan, 1975). The principal objective in data acquisition and reduction was to use rapid, inexpensive methods which require little special training to apply.

Data Collection and Reduction

Vertical electrical soundings (VES) were completed along nine cross-sections in Collier County (Figure 17). The VES sites were spaced 0.25 mile apart where site conditions permitted for the sections along Highway 84 and SR-951, Wilson Boulevard, SR-858, Everglades Boulevard North, and the eastern half of Golden Gate Boulevard. The other cross-sections used longer spacings between soundings. The electrode configuration used was the Wenner four-electrode array with equal spacings between electrodes. Soundings were completed using maximum electrode spacing of 154 feet (50 meters) and logarithmic spacings of six data points per decade.

The SR-951, US-84 and Everglades Boulevard profiles were chosen to provide long north-south and east-west resistivity cross-sections of western Collier County. The SR-951 profile is approximately fourteen miles long and is defined by 59 vertical electrical soundings. It begins at US-41 at its southern end, and ends at SR-846 in the north. The

Figure 17 LOCATION PLAN SURFACE RESISTIVITY SECTIONS WESTERN COLLIER COUNTY



US-83 profile is approximately thirteen miles long and is defined by 55 vertical electrical soundings. The Everglades Boulevard profiles combined are 24 miles long, defined by 55 soundings. The shorter profiles were selected to investigate specific lithologic or geochemical anomalies described in other reports such as reef trends (Meeder, 1980), zones of poor quality waters at shallow depths (Nuzman, 1970) or to connect longer profiles.

The field data of apparent resistivity versus electrode spacing were automatically inverted into geoelectric layers using the Wenner inverse solution programmed by Zohdy and Bisdorf (1975). The output from this program is a series of geoelectric layers representing a theoretical electrical section which matches the observed field data. Previous experience with the program has shown that it provides reasonable solutions for reconnaissance surveys provided that care is taken to input undistorted field curves.

A computer subroutine developed by T. Lizanec picks resistivity values from the Zohdy-Bisdorf solution at depths of 3 feet (1 meter), 10 feet (3 meters), 15 feet (5 meters), 21 feet (7 meters), 30 feet (10 meters), 45 feet (15 meters), 60 feet (20 meters), and 90 feet (30 meters). These resistivity values are then printed on cards, magnetic tape, or disc-storage units in a format suitable for submission to the SYMAP computer mapping program (Dougenik and Sheehan, 1975). SYMAP produces a contoured cross-section of electrical resistivities along each profile. Sections were produced at scales of 1 inch = 1000 feet and 1 inch = 2000 feet (1:24,000) and a vertical exaggeration of 100.

Discussion

The SR-951 cross-section (Figure 18) can be divided into five sections based on the depth to resistivities less than or equal to 30 ohm-meters. From 0.0 to 25,000 feet south of SR-846 the 30 ohm-meter contour is generally below a depth of 70 feet. Between 25,000 and 29,000 feet south there is an undulatory pattern to the 30 ohm-meter contour, with a "wave length" of 2,000 to 3,000 feet. The depth to resistivities of 30 ohm-meters of less varies from depths of 70 to 80 feet to as shallow as 5 to 15 feet. From 49,000 to 54,000 feet south there is a very distinctive zone with higher resistivities extending to depths greater than 100 feet. In contrast, from 54,000 to 63,000 feet the 30 ohm-meter contour rises to depths of 20 to 25 feet. At 63,000 feet the 30 ohm-meter descends to 60 to 80 feet, ending in a zone of high resistivities at depth at the extreme south end of the profile.

There are three prominent zones of higher resistivities extending to depths of 40 to 60 feet. These are at 1,000 to 3,000 feet south, 49,000 to 54,000 feet south, and at the south end of the profile at US-41. A well penetrating the southernmost zone encountered coralline "reef" facies within the zone delineated by the 70 ohm-meter contour (Jakob, personal communication). Quarries operating just north and east of the SR-951 and SR-846 intersection are mining "reef" facies limestones, suggesting that the high resistivities at depth at the 951/846 intersection are associated with the coralline "reef" facies reported by Meeder (1980). The correlation of "reef" facies with high resistivities at the north and south ends of the profile suggests that the zone from 39,000 to 54,000 feet south also represents similar lithologies.

The higher resistivities (130 ohm-meters) between depths of 3 to 20 feet are probably associated with dense, well-indurated, limestone "caprock" which is encountered in many wells in this region (Jakob, 1980, personal communication). This association of resistivity, depth and lithology has been documented for the southern end of the profile near the US-41 and SR-951 intersection (Belle Meade study). The caprock is often associated with slightly higher elevations, apparently resulting in more active flow systems and greater depths to low resistivities. In seven places along the SR-951 profile where shallow resistivities exceed 210 ohm-meters, the depth to resistivities less than 30 ohm-meters is greater than 70 feet at five of the seven. In three out of five places where very low resistivities are within 30 feet of the surface, shallow resistivities are less than 130 ohm-meters, suggesting a caprock may not be present. This relationship between shallow, high resistivities and depth to low resistivities suggests that the presence or absence of a caprock can strongly influence local flow systems. However, it should be noted that this relationship does not hold true everywhere in the profile, suggesting some other factor (or factors) also influences the depth to low resistivities. Areas of high resistivities sometimes are associated with small isolated zones of low resistivities, as at 42,000; 47,000 and 68,500 feet south.

The US-84 profile (Figure 19) can be divided into two sections on the basis of the depth to resistivities of less than 30 ohm-meters. The western third, from 0 to 27,000 feet east is characterized by depths of 60 feet to greater than 100 feet to the 30 ohm-meter contour. However, from 2,000 to 10,000 feet east there are several areas of resistivities less than 30 ohm-meters surrounded by higher resistivities. Also between

27,000 and 20,500 feet east there is a tongue or wedge of low resistivities 5 to 20 feet thick which rises from 70 feet below land surface at 27,000 feet east, to within 10 to 15 feet of the surface at 20,500 feet east. This wedge is well-defined by five vertical electrical soundings. Its cause cannot be determined from resistivity data alone, although it does flank a zone of very high resistivities on its eastern side. The relationship between the low resistivity wedge and the high resistivity zone is not clear.

The eastern two-thirds of the profile is a zone of variable depths to the 30 ohm-meter contour, with depths averaging less than 30 feet except in two zones. From 31,000 to 39,000 feet east there is a large and well-defined zone of high resistivities. This zone is divided roughly in half by a low resistivity wedge at 36,000 feet east. Under both parts of this zone the 30 ohm-meter contour is at depths of 80 to 90 feet. At the eastern end of the profile from 60,500 to 68,000 feet east, the 30 ohm-meter contour descends from 30 feet to 60 feet or 70 feet below land surface. Both of these zones of greater depths to low resistivities are associated with zones of high (greater than 100 ohm-meters) resistivities to depths of 60 feet.

There are two likely areas of "reef" facies on this profile, between 31,000 and 39,000 feet east and between 60,500 and 68,000 feet east. Both zones exhibit resistivities higher than 110 ohm-meters, with areas of resistivities greater than 210 ohm-mters, similar to the resistivities of areas where the corraline "reefs" are known to occur. There does not appear to be an obvious relationship on this profile between shallow resistivity values (5 to 15 feet) and depths to resistivities less than 30 ohm-meters.

Several wells drilled by Gee and Jenson (Gee and Jenson, 1980) for the South Florida Water Management District and three District wells provide geologic, lithologic, and geophysical data for comparison with the resistivity data for sections SR-951 and US-84. Figure 20 illustrates the locations and identification numbers of the wells used for comparison. A complete suite of geophysical logs and water quality data were not available for each well; however, detailed lithologic logs were available for all.

Figures 21-30 compare surface DC resistivity data to borehole data collected in wells on or close to SR-951 or US-84. Figure 21 is a plot of lithology and bulk resistivity versus depth below land surface for well GJ 5-1. The effect of the hard, limestone caprock is obvious. As no water quality or borehole information is available above the 60 foot casing depth, the effects of fluid conductivity and lithology on bulk resistivity at shallow depths are hard to separate. Below 60 feet depth, both fluid conductivities (from water samples) and fluid resistivities (from borehole logs) show moderately high but constant pore fluid conductivity to below 120 feet depth. Bulk resistivity decreases at the contact between the sandy porous limestone and the soft, silty limestone at about 50 feet, as well as at the top of the very porous limestone at 90 feet depth. The decrease at 90 feet is probably due to an increase in porosity, and therefore indicates that decreases in resistivity can be caused by increases in primary porosity. High primary porosity units often are silty, chalky limestones with lower transmissivities than dense, karstic units. The cause of the change at 50 feet depth cannot be determined without water quality data.

Figure 22 is a plot of bulk resistivity, fluid resistivity, conductivity, and lithologic versus depth for well GJ-4. Again the caprock

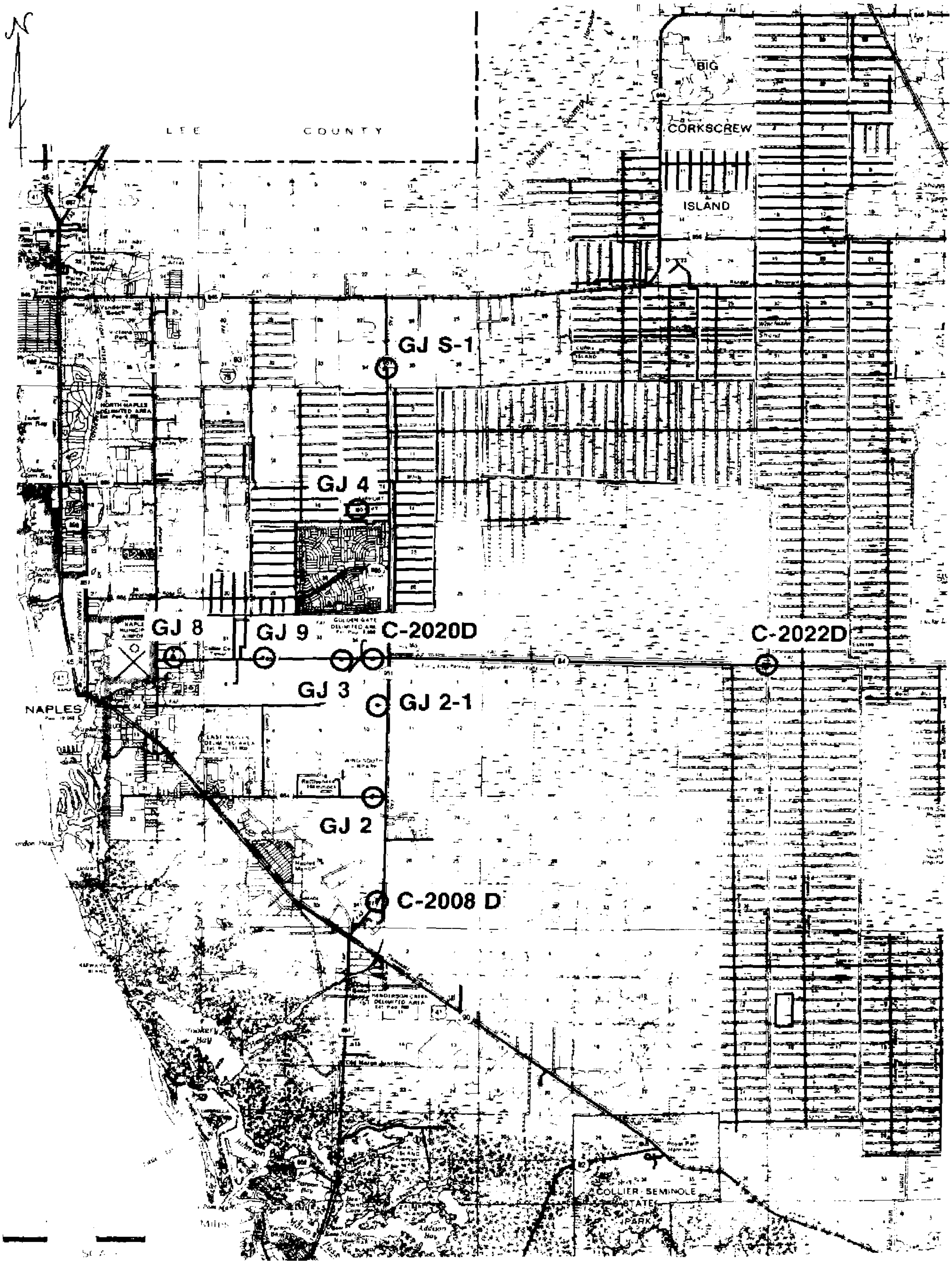


Figure 20 LOCATION OF REFERENCE WELLS

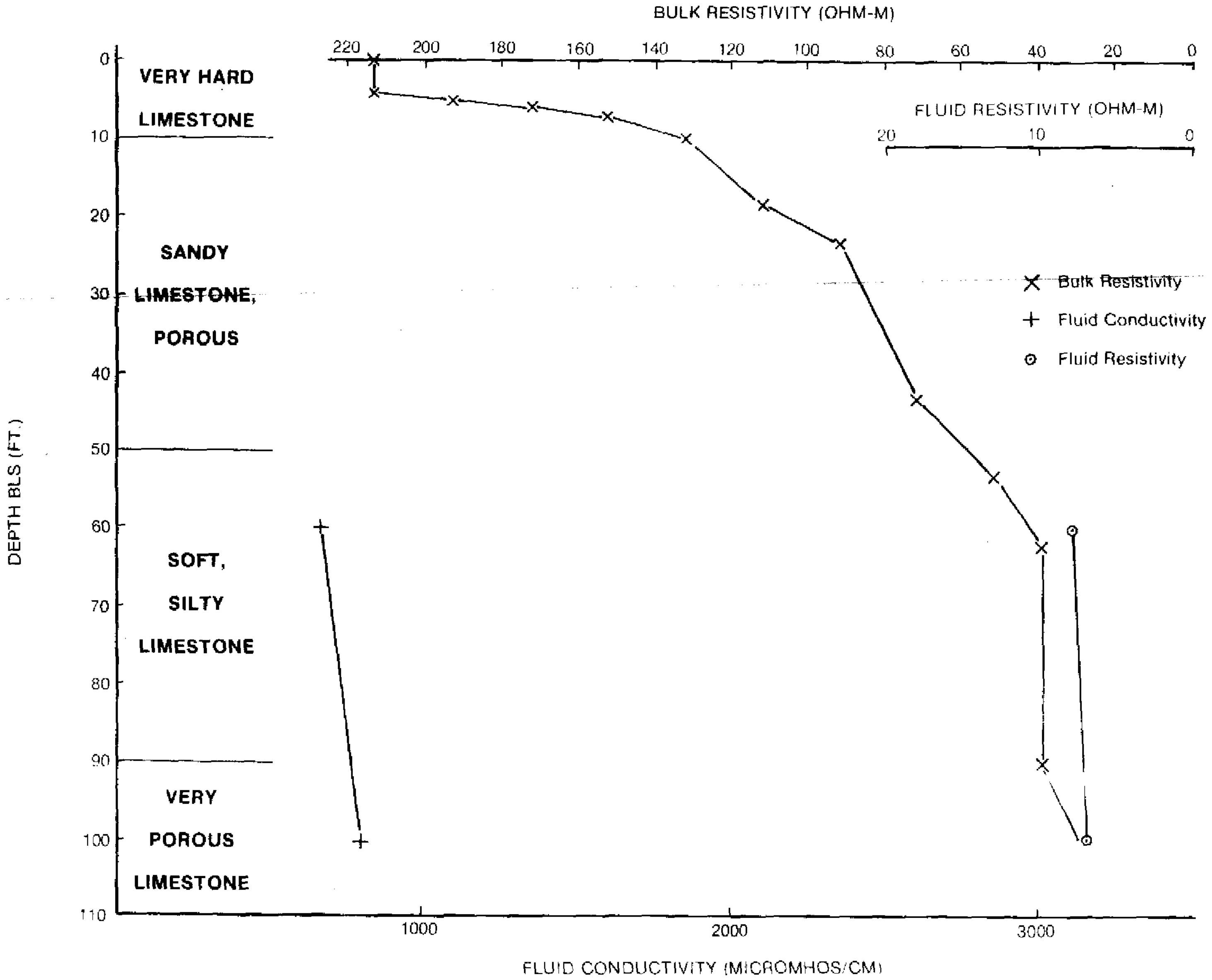


Figure 21 BULK RESISTIVITY VERSUS GEOLOGIC, GEOCHEMICAL, AND GEOPHYSICAL DATA FROM WELL GJ 5-1

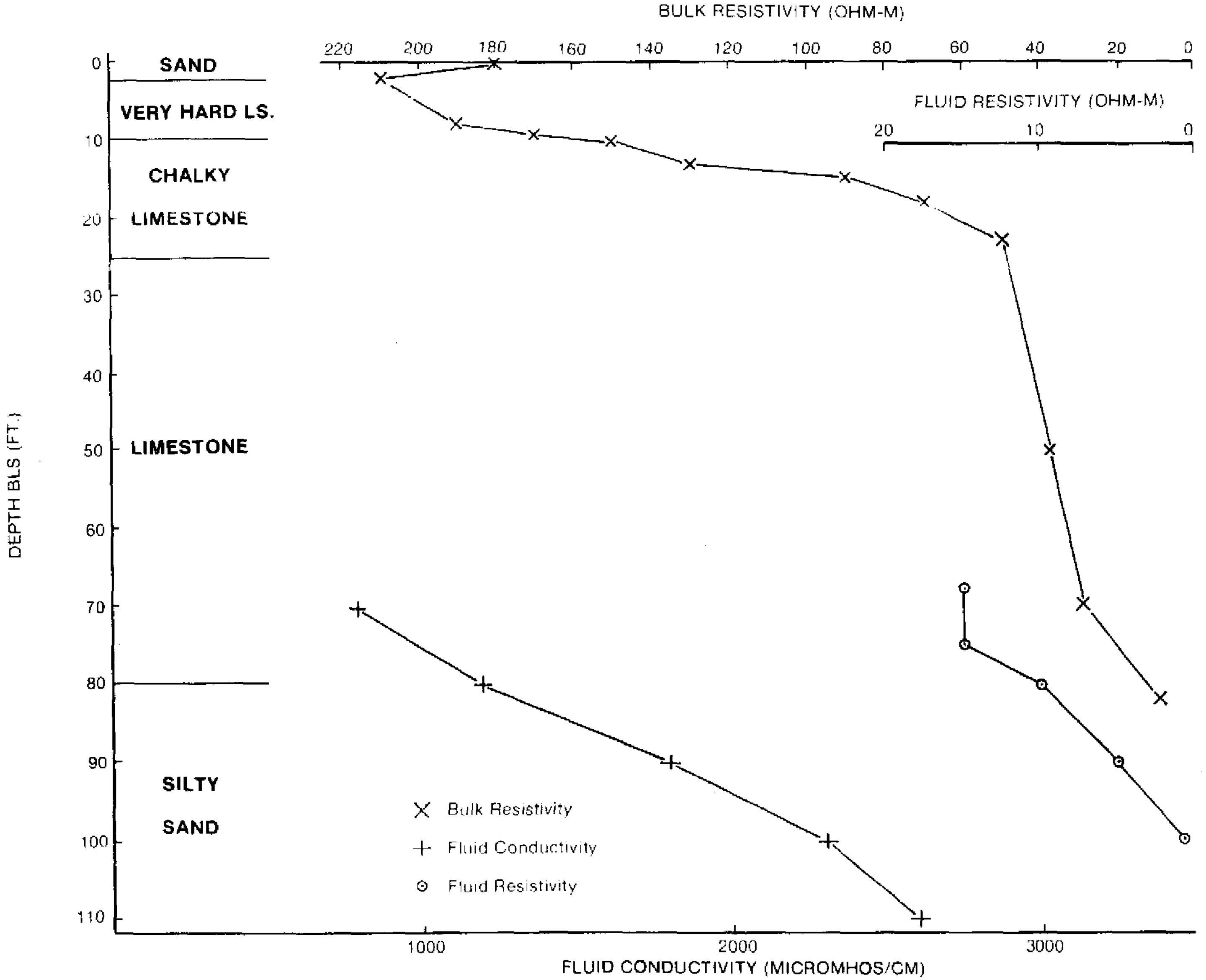


Figure 22 BULK RESISTIVITY VERSUS GEOLOGIC, GEOCHEMICAL, AND GEOPHYSICAL DATA FROM WELL GJ 4

strongly influences near-surface resistivities. Below the [illegible] foot casing depth the bulk resistivity, conductivity, and fluid resistivity curves are roughly parallel, showing decreasing resistivities with depth. Water quality appears to be the predominant control on bulk resistivity values below 68 feet depth. Figure 23 is a similar plot for well GJ 2-1. Bulk resistivity and fluid conductivity are roughly parallel, but the fluid resistivity log shows gradually decreasing values to a depth of 120 feet. Figure 24 is a plot of data for well GJ-2. Bulk resistivity, fluid conductivity, and fluid resistivity all show similar changes with depth. In particular there is a sharp decline in bulk resistivity and fluid resistivity and an increase in fluid conductivity between 80 to 100 feet depth.

Figure 25 is a plot of fluid conductivity, bulk resistivity for well C-2008D, and 64 inch normal borehole resistivity. All three curves are closely parallel. The bulk resistivity values clearly indicate the influence of the hard limestone above 20 feet depth. Both the bulk resistivity and 64 inch normal resistivity show a "kick" or zone of higher resistivity between 40 to 50 feet depth. This is a lithologic effect as fluid conductivity decreases through this zone. This "kick" probably represents a more lithified zone in the softer limestones below 20 feet depth.

Figure 26 is a bulk resistivity, fluid conductivity, fluid resistivity plot fo well GJ-8. Bulk resistivity is moderately high between 5 to 20 feet depth due to the hard, limestone caprock. Below the 20 foot depth all three curves are paralllel, indicating water quality is influencing changes in bulk resistivity. Figure 27 is a similar plot for well GJ-9. Here again, all three curves show that lithologic effects predominate at shallow depths (down to 50 feet depth), and a rapid increase in fluid

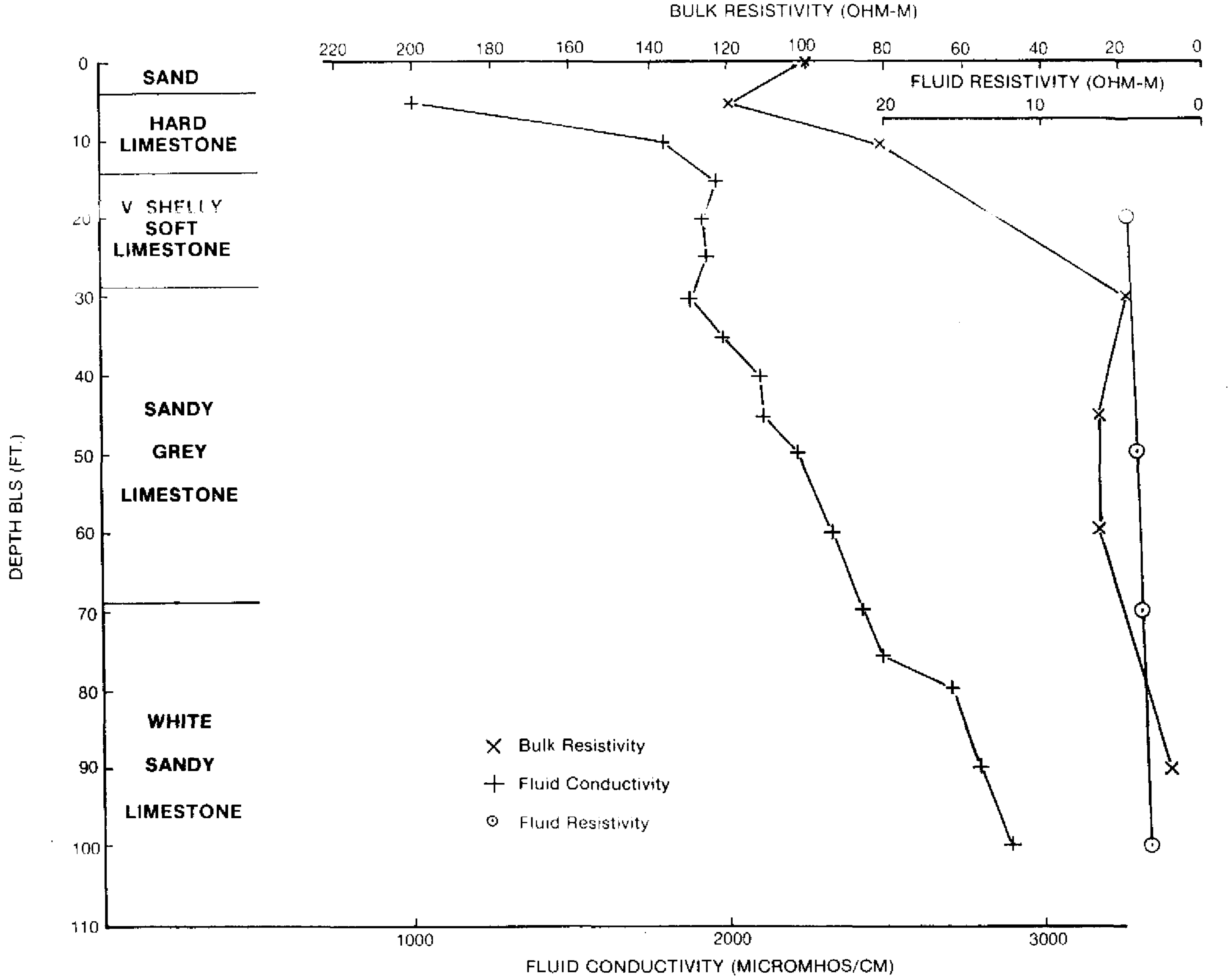


Figure 23 BULK RESISTIVITY VERSUS GEOLOGIC, GEOCHEMICAL, AND GEOPHYSICAL DATA FROM WELL GJ 2-1

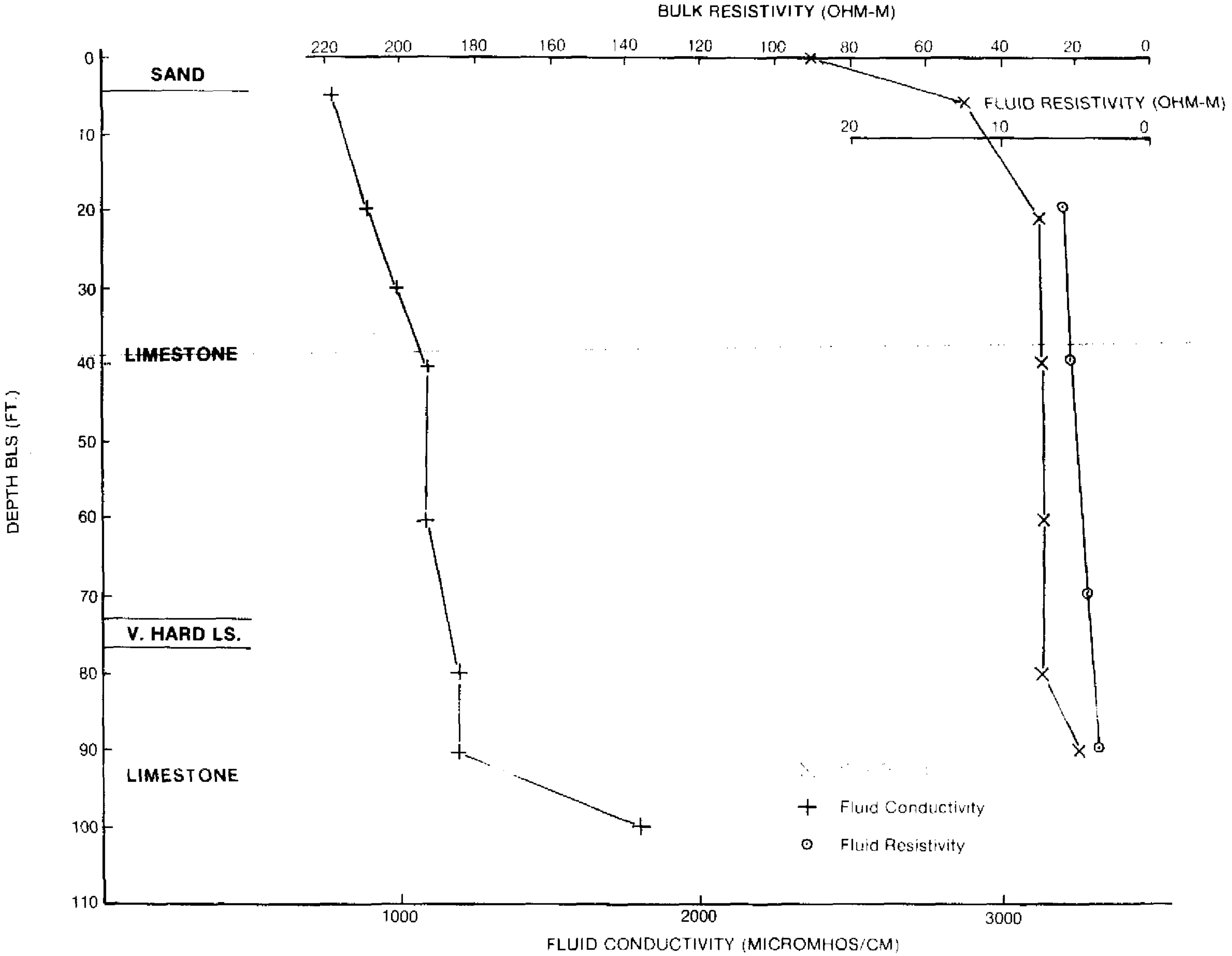


Figure 24 BULK RESISTIVITY VERSUS GEOLOGIC, GEOCHEMICAL, AND GEOPHYSICAL DATA FROM WELL GJ 2

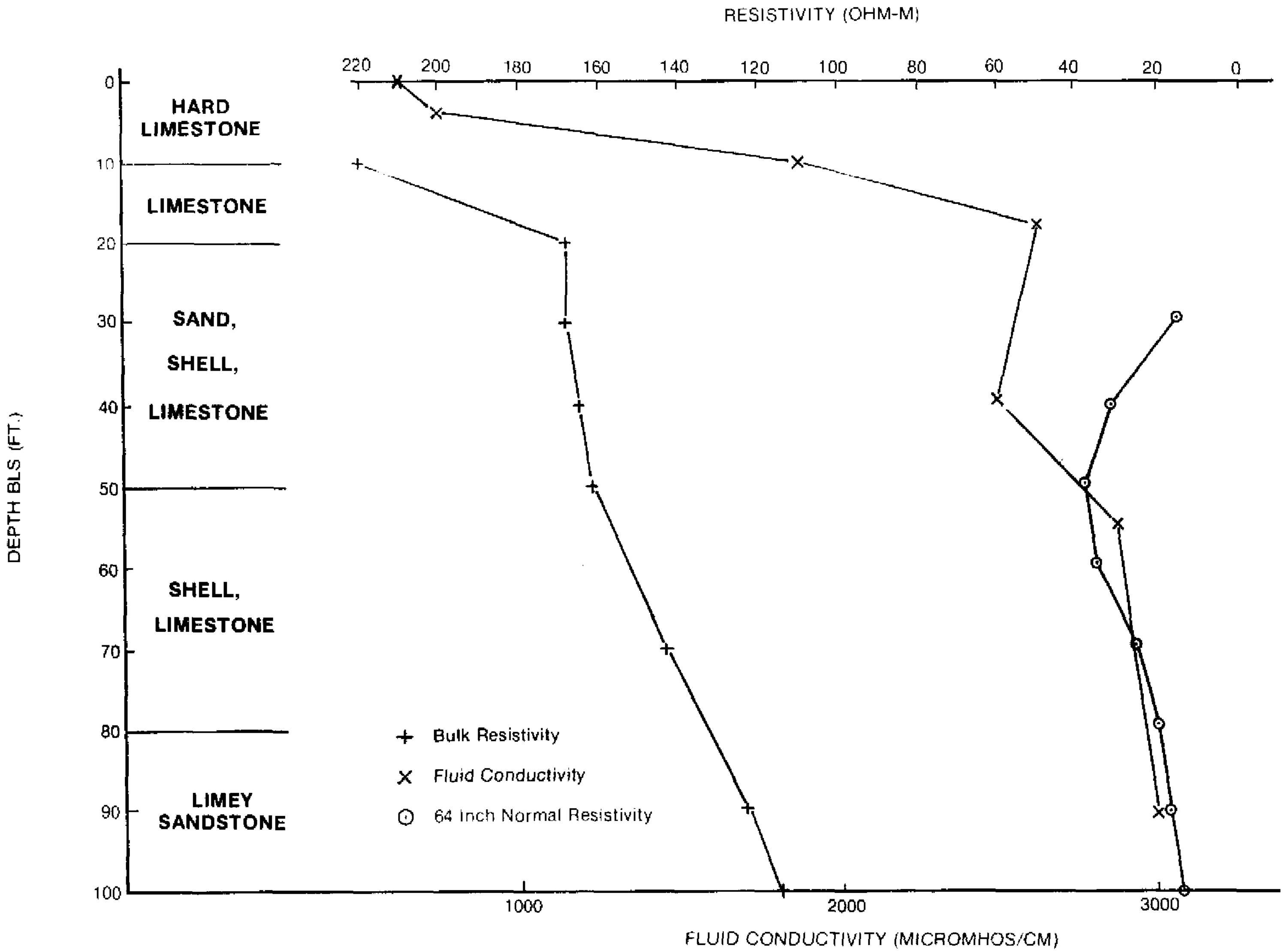


Figure 25 BULK RESISTIVITY VERSUS GEOLOGIC, GEOCHEMICAL, AND GEOPHYSICAL DATA FROM WELL C-2008D

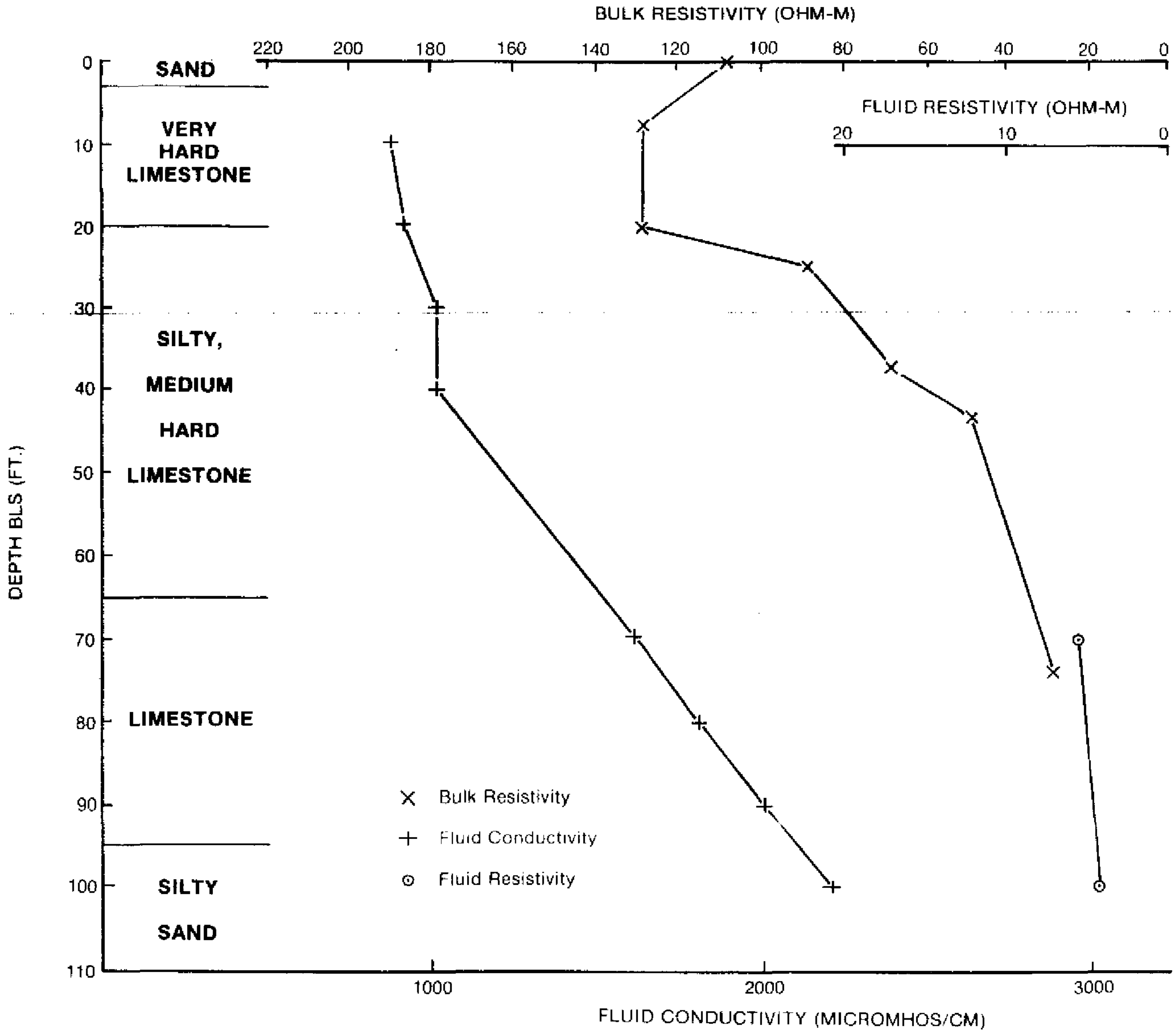


Figure 26 BULK RESISTIVITY VERSUS GEOLOGIC, GEOCHEMICAL, AND GEOPHYSICAL DATA FROM WELL GJ 8

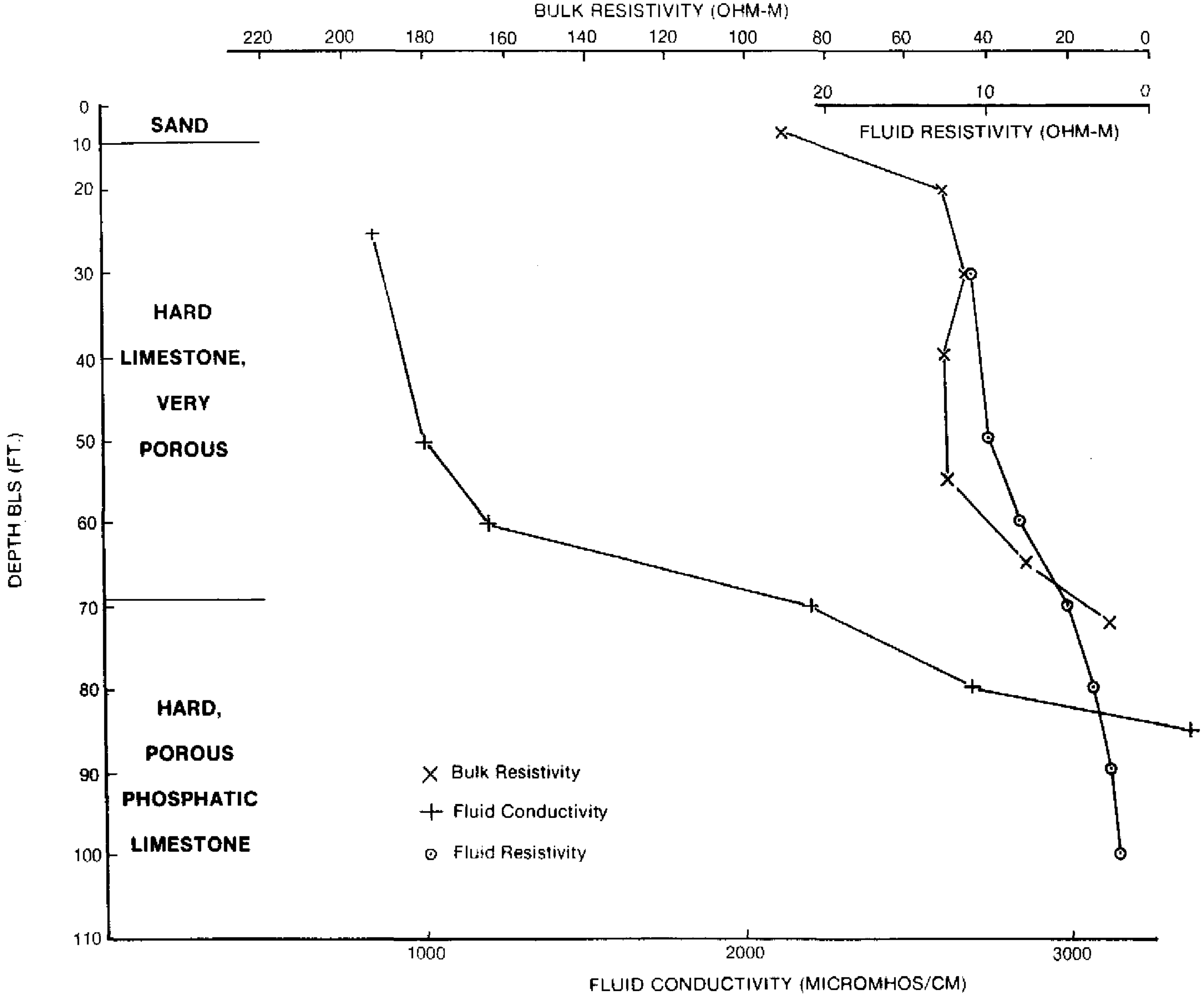


Figure 27 BULK RESISTIVITY VERSUS GEOLOGIC, GEOCHEMICAL, AND GEOPHYSICAL DATA FROM WELL GJ 9

conductivity below 50 feet depth leads to a sharp decline in bulk resistivity. Lithologic effects are more obvious on the plot of bulk resistivity and fluid conductivity for well GJ-3 (Figure 28). A hard, cherty limestone at the surface has moderate to high resistivities. A sharp decline in bulk resistivity between 20 to 50 feet depth is not accompanied by a similar increase in fluid conductivity, suggesting a lithologic change, probably a highly porous zone. Below 60 feet fluid conductivity increases sharply and bulk resistivity decreases sharply.

Water quality data and electric logs were not available for wells C-2020D (Figure 29) and C-2022 (Figure 30). Plots of bulk resistivity versus lithology and depth show the strong influence of the shallow, hard limestones. The rapid decline of bulk resistivity below a depth of 30 to 50 feet on both plots is probably a result of declining water quality. For well C-2020D this 30 to 50 foot low resistivity zone corresponds to the low-resistivity wedge between 20,500 and 27,000 feet east on the US-84 section (Figure 19). Figure 29 does show a strong "kick" in bulk resistivity between 40 to 70 feet depth associated with hard limestones.

Jakob (1980) derived an impirical relationship between chloride ion content and fluid conductivity for water samples from wells in southwestern Collier County. The approximate chloride ion concentration values for Figure 21-30 can be derived using this relationship:

> Chloride ion concentration (mg/l) = 0.31 (fluid conductivity
> in micromhos/cm) - 215

Correlation of fluid conductivity and bulk resistivity values leads to the relationships shown in Table 2.

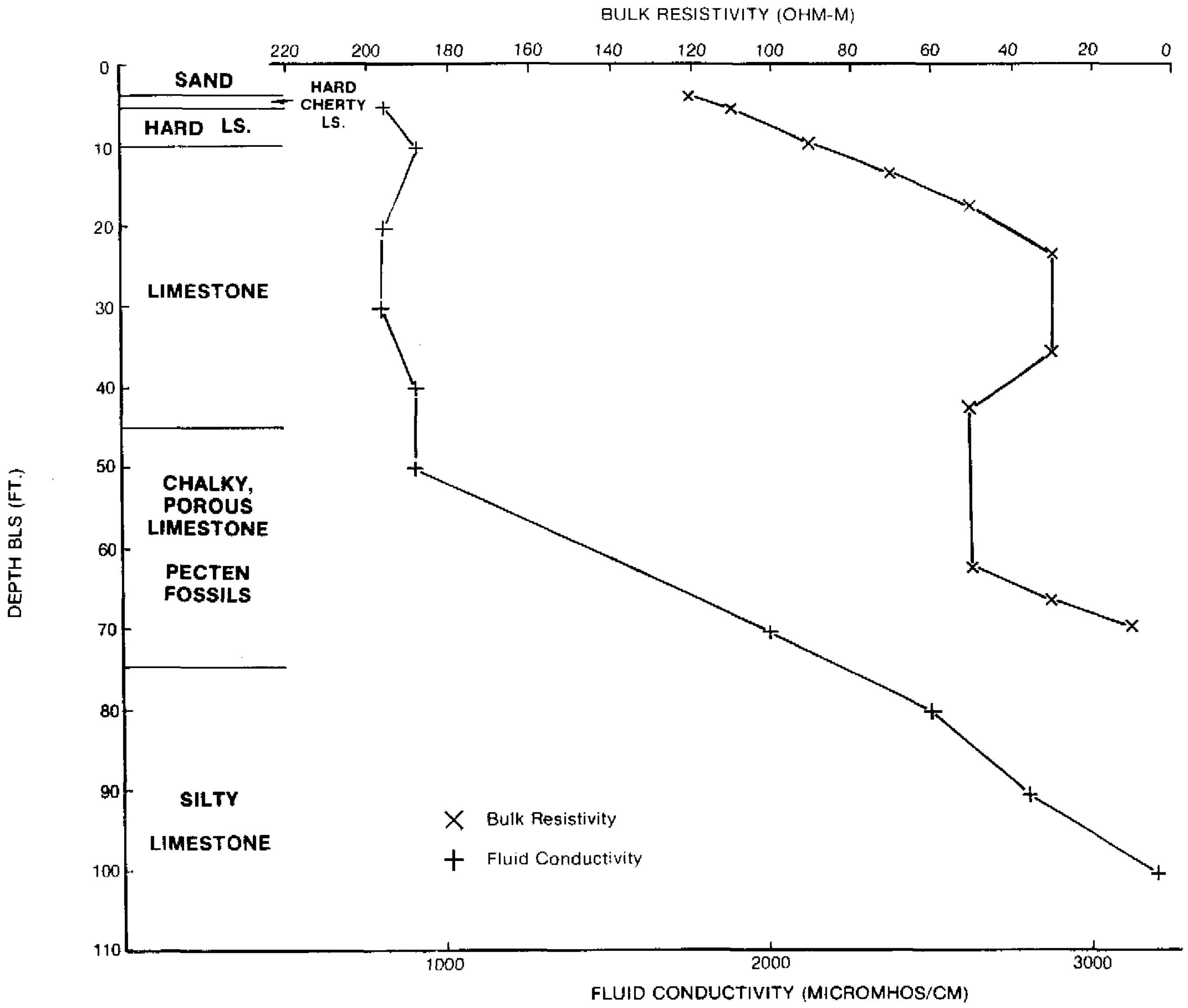


Figure 28 BULK RESISTIVITY VERSUS GEOLOGIC, GEOCHEMICAL, AND GEOPHYSICAL DATA FROM WELL GJ 3

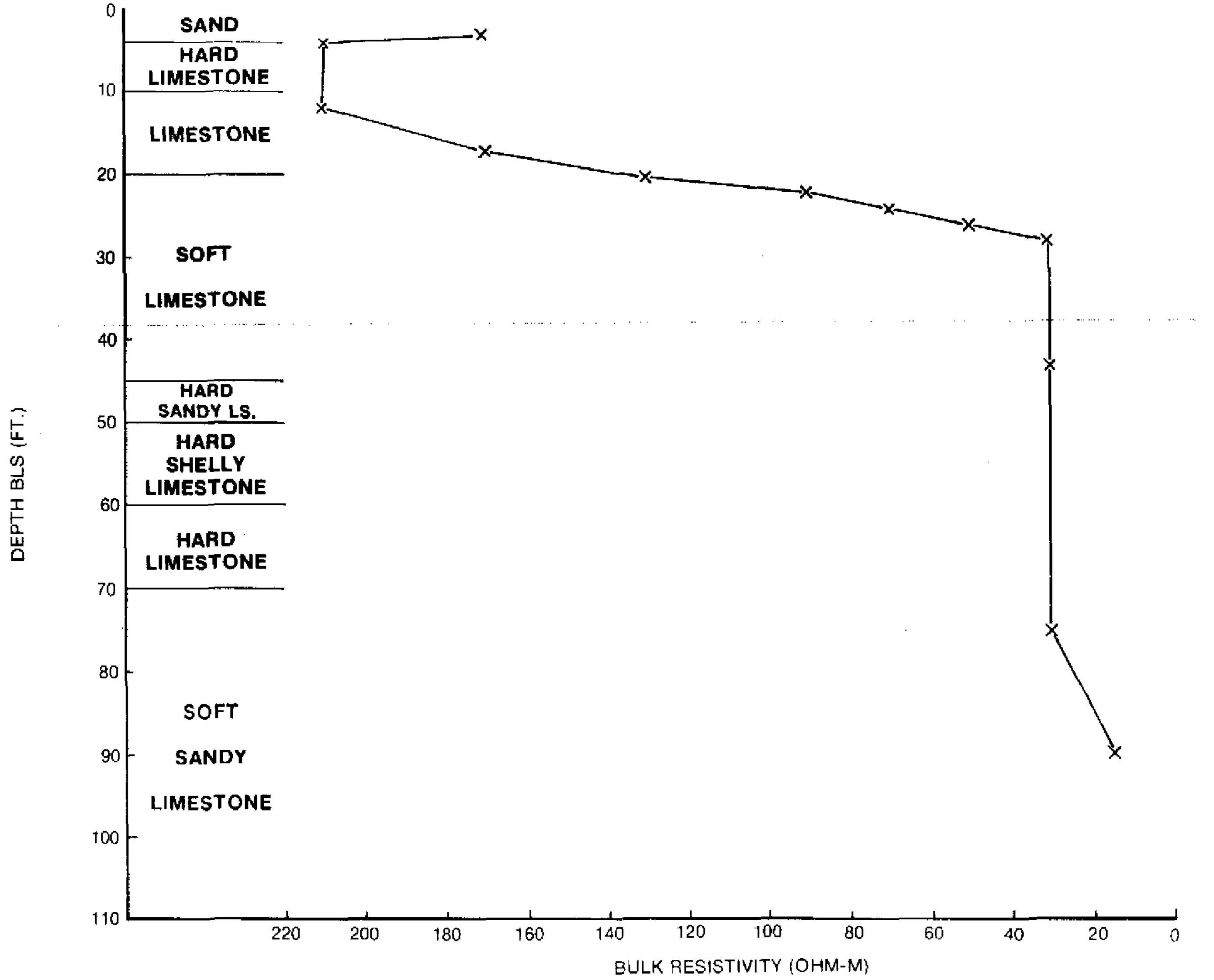


Figure 29 BULK RESISTIVITY VERSUS GEOLOGIC DATA FROM WELL C-2020D

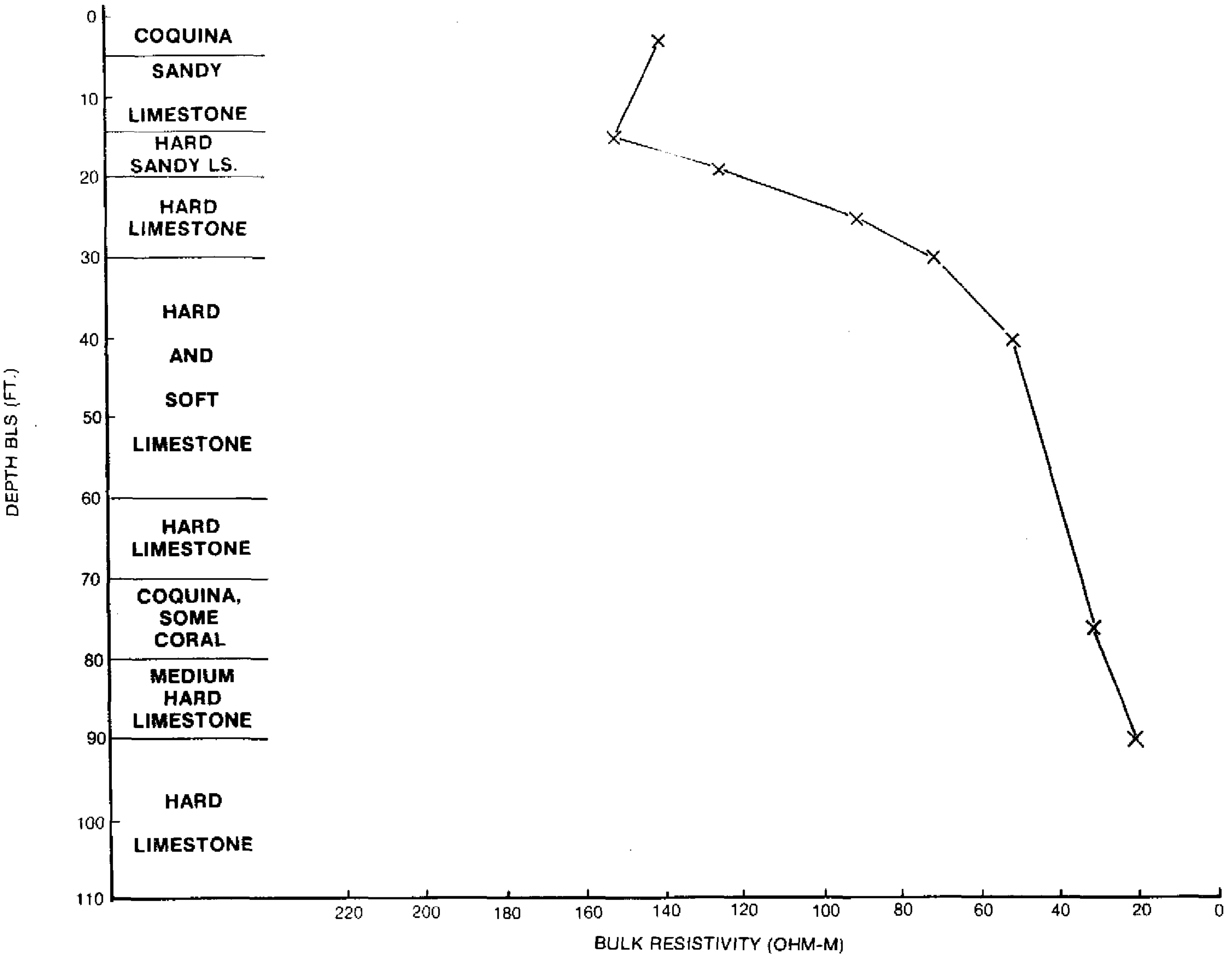


Figure 30 BULK RESISTIVITY VERSUS GEOLOGIC DATA FROM WELL C-2022D

TABLE 2. Relationship of Fluid Conductivity, Chloride Ion Content, and Bulk Resistivity

Bulk Resistivity (ohm-m)	Fluid Conductivity (micromhos/cm) Average	Range	Cl^- (mg/l)*	No. of Wells
30	1,200	800-1900	160	8
20	1,500	900-2100	250	7
10	2,100	1400-2800	450	4

*(After Jakob, 1980)

The potable water limit for chloride ion is 250 mg/l. The data in this Table suggest that a DC bulk resistivity value of 20 ohm-meters corresponds roughly to a chloride ion concentration near the potable water limit. Because of the effect of porosity on bulk resistivity, it is probably safer to assume that chloride ion concentrations go above the potable water limit within the resistivity range of 10-30 ohm-meters. For planning purposes 30 ohm-meters is a conservative bulk resistivity value for units saturated with waters at or near the potable water limit for chloride ion. It should be emphasized that these relationships between bulk resistivity, fluid conductivity, and chloride ion content are approximate, empirically derived, and valid only for western Collier County. However, a similar empirical correlation of fluid conductivity and bulk resistivity could be made wherever bulk resistivity and fluid conductivity variation with depth is known. Figure 31 graphically illustrates the data in Table 2.

In the Belle Meade study a value of 30 ohm-meters was used as the bulk resistivity which correlates with units saturated with waters at or near the 250 mg/l potable water chloride ion limit. This was based on Jakob's observation that chloride ion concentrations exceeded 250 mg/l when six-foot lateral log resistivities were less than 30 ohm-meters (Jakob, 1980). Figure 31, based on wells both in and out of Jakob's

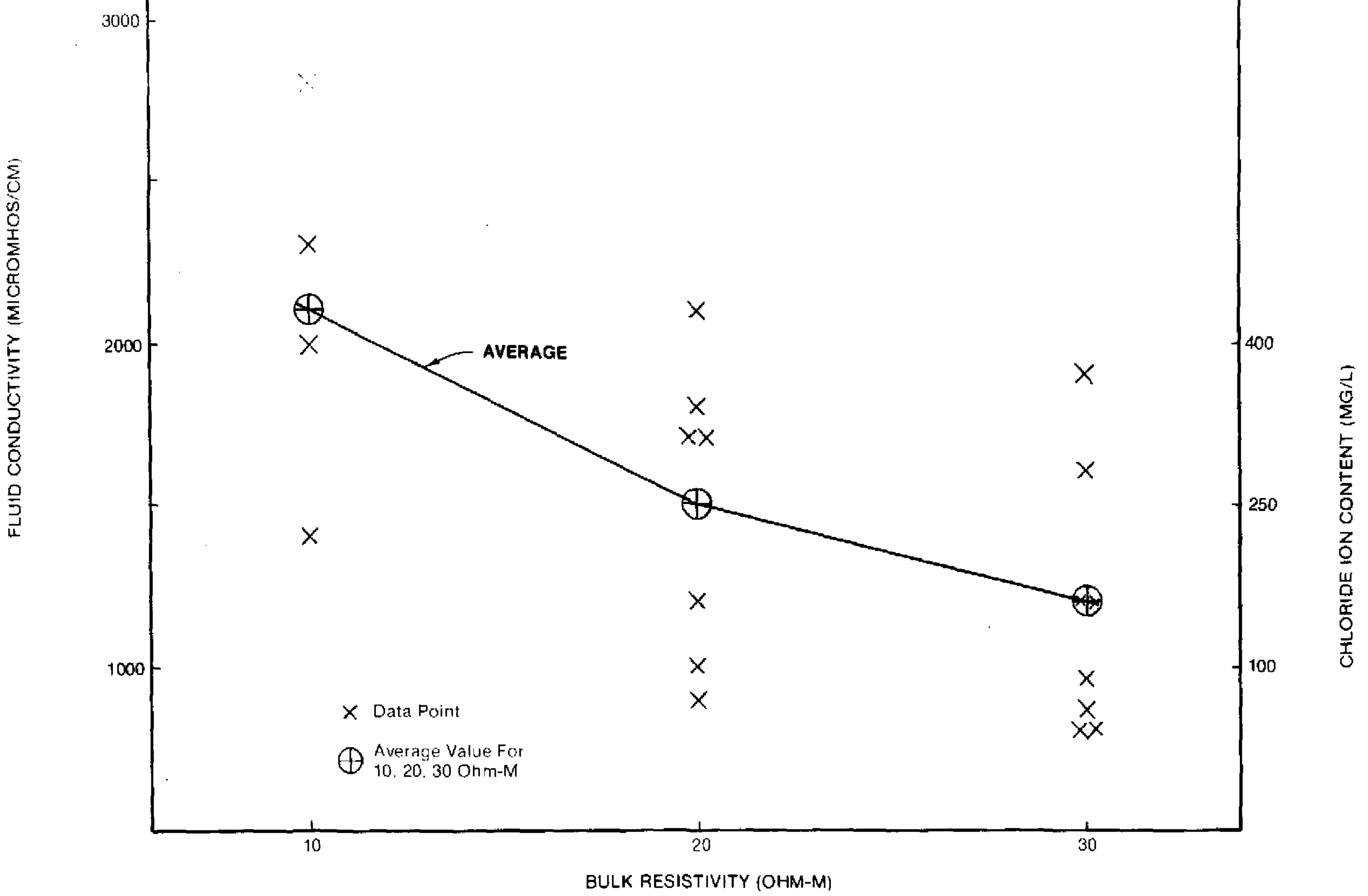


Figure 31 BULK RESISTIVITY VERSUS FLUID CONDUCTIVITY AND CHLORIDE ION CONTENT FOR SAMPLES FROM 8 REFERENCE WELLS

study area suggests that in some very porous units, the 250 mg/l chloride limit may not be exceeded until bulk resistivities are less than 20 ohm-meters. It is important to point out that Figure 31 indicates a bulk resistivity of 30 ohm-meters correlates with fluid conductivities of 800-1900 micromhos/cm in eight wells, or an approximate chloride ion concentration range of 30-370 mg/l. Obviously, bulk resistivity values are useful only for approximating water quality on a reconnaissance level. However, Figure 31 does illustrate that in western Collier County bulk resistivities less than 10 ohm-meters indicate waters with conductivities greater than 1400 micromhos/centimeter.

The SR-864 profile (Figure 32) was chosen to investigate a low resistivitiy zone at shallow depths. The profile reveals a wedge of low resistivities rising from depths of 70 to 80 feet near SR-951 to within 15 feet of the surface 8,000 feet west of the 864/951 intersection. This low resistivity zone appears to be associated with a topographic low, and may be related to the discharge zone of a local flow system.

The Curry Island and White Boulevard profiles are located on or near outcrops of "reef" facies reported by Meeder (1980), and noted in spoil banks along canals. The Curry Island section (Figure 33) starts on a coral boundstone outcrop at its north end, and rocks exposed at the south end appear to be "reef" facies associated with the coral boundstones, shelly limestones with abundant oyster-pecten fossils. The main "reef" trend may be indicated by the thick sequence of high resistivities extending to depths of 70 to 80 feet. The very high resistivities associated with the coral boundstones at the north end of the section do not extend to depths greater than 50 feet and an isolated zone of low resistivity is indicated at 60 feet.

The White Boulevard section (Figure 34) parallels the SR-951 profile (Figure 18). It illustrates the high resistivity zone noted between 20,000 and 25,000 feet south on the 951 section. Resistivities of less than 30 ohm-meters are within 40 feet of the surface on Figure 34, with the shallowest depths lying directly under the zone of highest near-surface resistivities. The very high resistivities may represent a very "tight" reef unit which limits recharge, causing low resistivity pore waters to occur at shallow depths.

The Everglades Boulevard South section (Figure 35) was completed to investigate a zone of high total dissolved solids content in shallow wells noted in another study (Nuzman, 1972) in southeast Collier County. Soundings are one mile apart on this profile. The northern half exhibits a zone of generally lower resistivities between depths of 15 and 100 feet, as compared to the southern half of the profile and the extreme northern end. Water quality data indicate that shallow groundwaters in this zone are high in chloride and sulfate content, apparently causing the low bulk resistivities. Wells near 15,000 feet south encounter high sulfate/chloride waters at relatively shallow depths. This isolated zone may represent upward leakance through an improperly abandoned well.

The remaining four sections were chosen to help define and investigate the occurrence of coralline "reefs" reported in north central Collier County by Meeder (1980). Meeder's two cores were taken along an east-west line between the Everglades Boulevard North section and the Wilson Boulevard profile (Figure 17; Meeder, 1980). The SR-858 and Golden Gate Boulevard sections parallel Meeder's proposed line of cores and connect the north-south sections (Figure 17). The sections form a box around the reported "reef" tract, with the intention that any significant linear trends can be defined.

In contrast to the resistivity profiles further to the southwest and closer to the Gulf, the profiles in the northeast corner of the study area (Everglades Boulevard North, Figure 36; Wilson Boulevard, Figure 37; SR-848, Figure 38; Golden Gate Boulevard, Figure 39) do not have extensive areas of bulk resistivities less than 30 ohm-meters, and bulk resistivities less than 10 ohm-meters are limited.

Only the Golden Gate Boulevard section (Figure 39) has a significant number of areas where bulk resistivities are less than 30 ohm-meters. This profile also has lower near-surface resistivities than the other three profiles. As suggested earlier, the low resistivities at depth may be associated with less vigorous flow systems, as possibly indicated by the lower near-surface resistivities. Also the higher bulk resistivities occur in the eastern half of the section, where the relief is greater than 1 to 1.5 feet, as compared to the western half, where relief is less than 0.5 foot. Curry Island is represented by the higher resistivities between 5,000 and 9,000 feet east.

All four sections have zones of very high near-surface resistivities (>210 ohm-meters). These high resistivities zones correlate with hard, well-lithified "reef" facies limestones exposed in canal spoil banks. The two principal facies are coral boundstones and well-cemented, molluscan grainstones, packstones, and wackestones. These shallow, high resistivity units are particularly evident along the SR-858 section. As indicated by the Everglades Boulevard North section (Figure 36) the extent of these units decreases to the south and southwest, suggesting a roughly northwest southeast trend for the occurrence of these facies. It should be noted, however, that is is difficult if not impossible to trace individual "reef" units any great distance along this trend, suggesting a patchy or irregular distribution of high resistivity units.

The "reef" facies are most prevalent in the "Golden Gate Highlands", an area of slightly higher relief extending northwest from Big Corkscrew Island near the Golden Gate Boulevard and Everglades Parkway intersection to Fourth Island and Bird Rookery Swamp. This higher relief is probably the result of the more extensive, well-lithified, "reef" facies caprock present in this area. It would be expected that because of the relief, higher elevation karstic limestones, and thin soils, that this is an area of higher groundwater recharge. Analysis of water quality data from the Golden Gate Highlands suggests that this area is one of rapid recharge, as waters are high in turbidity, phosphate, iron, and silica, suggesting a strong influence of rapidly recharged surface waters (Nuzman, 1972). The Golden Gate Highlands region should be recognized as an area of significant recharge for purposes of planning and protection.

A very interesting feature noted on all four sections is a narrow, moderately high to very high resistivity zone below a depth of 60 to 80 feet. On the Everglades Boulevard North (Figure 36) and SR 858 (Figure 38) sections, resistivities exceed 210 ohm-mters. On all except the Everglades Boulevard section, this narrow zone of high resistivity is flanked on one or both sides by low resistivities (as low as 10 ohm-meters). The high resistivity zone appears to be quite narrow, less than 0.5 miles wide. The associated low resistivity zones are somewhat wider and less well defined. Three of the high resistivity zones define a linear trend along a southwest strike for six miles (Figure 40).

A well drilled in the NE 1/2, NE 1/4, Sec. 24, Twp. 48S, Rge. 27E by Layne-Western (Nuzman, A. C., 1972) is within 1000 feet of the deep high resistivity zone indicated on the SR 858 section (Figures 36, 40). The lithologic log (Table 3) indicates that a sand and sand shell unit extending

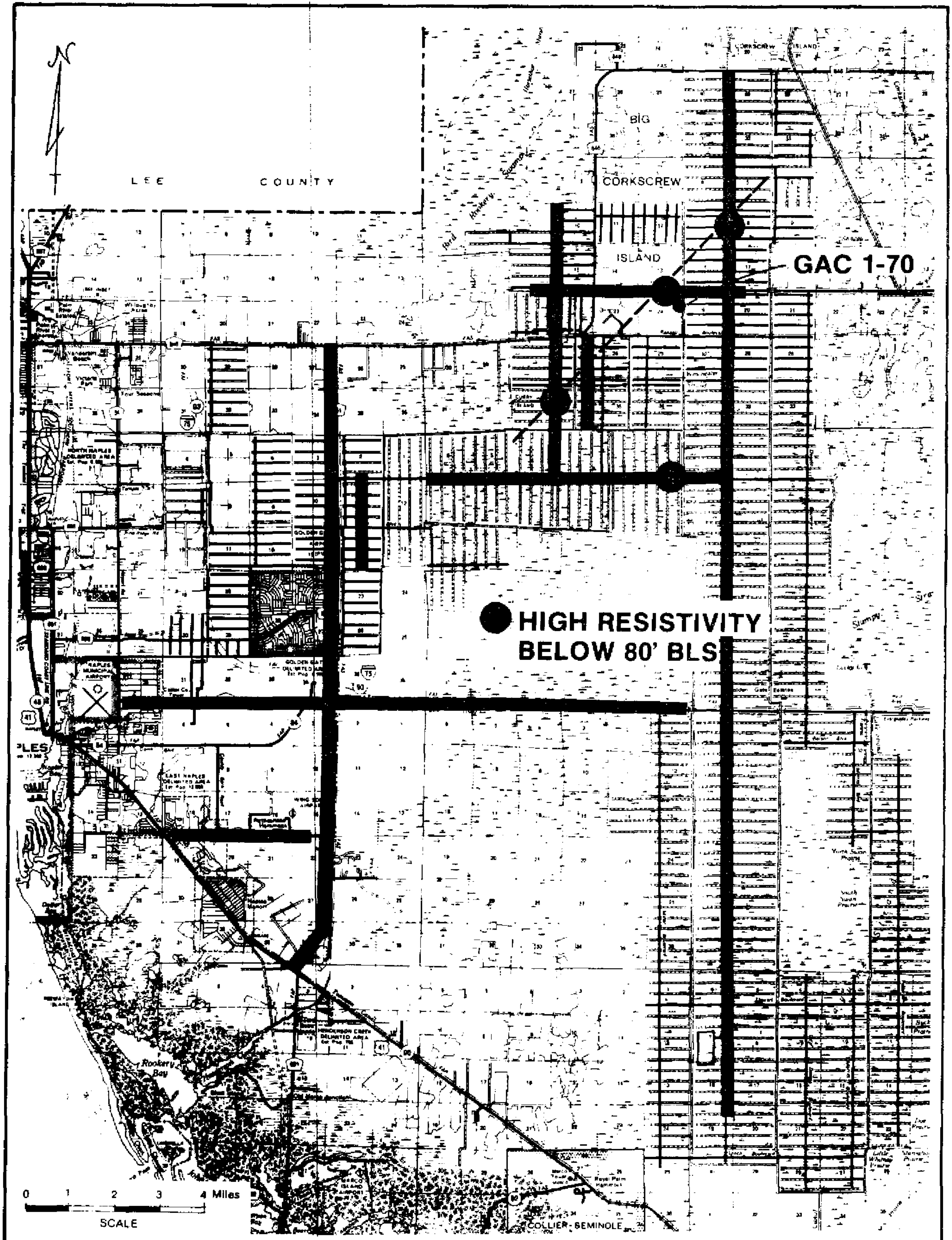


Figure 40 LOCATION OF DEEP HIGH RESISTIVITY ZONES

to a depth from 81 to 152 feet corresponds to the high resistivity zone. At 200 to 268 feet depth there is another sand unit. A water sample from a depth of 200 feet indicates a chloride ion content of 30 mg/l, sulfate ion concentration of 3 mg/l and a total dissolved solids content of 375 mg/l. The top of the high resistivity zone correlates with the top of the upper sand. The high resistivities are the result of a clean sand saturated with very fresh water. The narrowness of the zone and its linear trend suggests that it represents a restricted environment of deposition, such as a channel or beach sand. In oil-field terminology this unit would be called a "shoestring" sand. A pumping test indicates transmissivities close to 13,000 ft^2/day for the section to 230 feet. This high transmissivity, coupled with the excellent water quality, makes this unit a potential high-yield aquifer. The extent of the unit and the significance of the flanking low resistivity zones should be investigated before large scale exploitation of this aquifer is undertaken. Closely spaced vertical electrical soundings carried out to Wenner "a" spacings of 500 feet would allow for closer definition of the extent of both the high and low resistivity zones.

Conclusions

Correlation of the resistivity profiles with available geologic, geophysical and water quality data suggests that two targets of hydrogeologic significance can be identified in western Collier County using surface DC methods. The two targets are well-lithified limestone "reef" facies described by Meeder (1980), and pore waters of high fluid conductivity. The very high and very low resistivities, respectively, associated with these targets allow them to be easily distinguished on a resistivity cross-section.

Resistivities greater than 170-190 ohm-meters are considered to represent well lithified limestone "reef" facies. In southwestern Collier County the occurrence of these high resistivity zones is irregular. However, in the north-central part of the county, in the region called the Golden Gate Highlands, large areas of shallow, high resistivity units, occur which are assumed to represent a roughly northwest to southeast trending zone of coral boundstone "reefs" and associated molluscan packstone, grainstone, and wackestone facies. Water quality data, relief and shallow stratigraphy suggest that this is an area of rapid recharge. The well-lithified units are karstic in nature, and the flow systems may not extend below 80 to 100 feet.

A distinctive deep, linear, high resistivity unit is shown on four of the resistivity cross-sections (Figure 40). Lithologic and water quality data from a well drilled close to this high resistivity zone suggest that it is a shelly sand saturated with very fresh water (Table 3). Three of the sections delineate a six mile linear trend. The relationship of the fourth occurrence to the other three is uncertain. These sands may form a high hydraulic conductivity pathway for high quality groundwater moving generally southwest. These high resistivity zones are flanked by low resistivity zones. The geometry of the sands suggests a restricted depositional environment, such as a channel or strandline. Because of the excellent quality of the waters saturating these sands, they may represent a valuable source of fresh water for Collier and southern Lee Counties.

Except for the low resistivities flanking the deep sand aquifers in the northcentral part of the county, low resistivity units do not occur with a readily predictable pattern. The Golden Gate Boulevard section (Figure 39) and parts of the SR 951 and US 84 sections suggest that where shallow

TABLE 3

Lithologic log for well GAC 1-70
(Nuzman, 1972)

Depth BLS (Ft.)		Lithology
From	To	
0	3	Sand
3	7	Brown, hard limestone
7	12	Soft limestone
12	15	Limestone
15	17	Sand
17	23	Soft, yellow limestone
23	25	Hard limestone
25	31	Soft, yellow limestone
31	59	Sand, shell, and gravel
59	80	Porous limestone
80	96	White sand
96	152	White sand and shell
152	200	Clay
200*	231	Coarse to fine sand
231	268	Fine sand
268	300	Clay

*Water sample at 200':

Chloride	30 ppm
Sulfate	5 ppm
TDS	375 ppm

resistivities are low or moderate, suggesting an absence of a caprock, resistivities of less than 30 ohm-meters occur at relatively shallow depths. However, some very high resistivity units have isolated adjacent or subjacent areas of low resistivities. The distribution of low resistivity zones is very irregular, although the depth to resistivities less than 30 ohm-meters decreases to the southwest.

Correlation of borehole geophysics water quality data, and bulk resistivities from DC soundings allows an approximate relationship between bulk resistivity and water quality to be made (Table 2, Figure 31). On an average, bulk resistivities of 30 ohm-meters indicate pore waters with chloride ion concentrations below, but near, the 250 mg/l limit for potable water. Resistivities of 20 ohm-meters represent pore waters at or near the potable water limit for chloride, and resistivities of 10 ohm-meters or less represent pore waters of greater than 300-400 mg/l chloride.

SIGNIFICANCE OF RESULTS

Evaluation of DC Resistivity Method

Data acquisition using DC surveys is relatively rapid compared to drilling. In this study 4-6 vertical electrical soundings could be completed in one hour, yielding information to a depth of approximately 100 to 120 feet. This rate requires a field party of three people, or 1-2 soundings/man-hour. Interpretation and presentation of the field data can be handled entirely by computer processing, which allow large amounts of field data to be quickly interpreted. Table 4 summarizes the principal direct costs incurred in the acquisition of DC resistivity data in Collier County.

TABLE 4

DC Resistivity Survey Costs*

Personnel:	
3 Technicians	\$300/day
Instrument Rental	\$ 40/day
Computer Costs	\$ 10/sounding
- assuming 20 soundings/day	\$540/day
- assuming 0.25 mile spacing of soundings	\$135/mile

Notes: 1) These costs do not include interpretation of final survey results (computer output).

2) No indirect costs, transportation, or other field costs are included.

*All costs are in 1981 dollars and reflect direct costs only.

The geophysical data agree well with available well data. The high to very high resistivity units correlate with the very hard, highly transmissive, coralline and molluscan limestones reported in well logs. Low resistivity units correlate with either poor quality groundwater or high primary porosity, low yield hydrostratigraphic units. An empirical relationship has been established between bulk resistivity and groundwater quality, as summarized in Table 5. This relationship allows bulk resistivity values to be used to make rough estimates of water quality.

TABLE 5

Cl^- Concentration Range vs. Bulk Resistivity Values, Western Collier County

Bulk Resistivity (ohm-m)	Cl^- Concentration Range (mg/l)
30	35-375
20	65-435
10	220-650

The resistivity data can be used to map two features of hydrogeologic significance in western Collier County. Jakob (1980) found the very hard, well-lithified, high resistivity units to be very productive aquifers. This relationship between resistivity and productive hydrostratigraphic units suggests that searches for high-yield units should start with detailed resistivity surveys. Resistivities less than 30 ohm-meters indicate either poor quality water or high primary porosity. These units are poor choices for sources of potable water as either water quality is poor or yields are low.

Hydrogeologic Implications of Resistivity Data

Examination of Figures 41, 42, and 43 reveals that in general, water quality becomes poorer and the occurrence of "reef" limestones decreases southwest from the Golden Gates Highlands in north-central Collier County (Figure 44). There are relatively few extensive areas of good quality

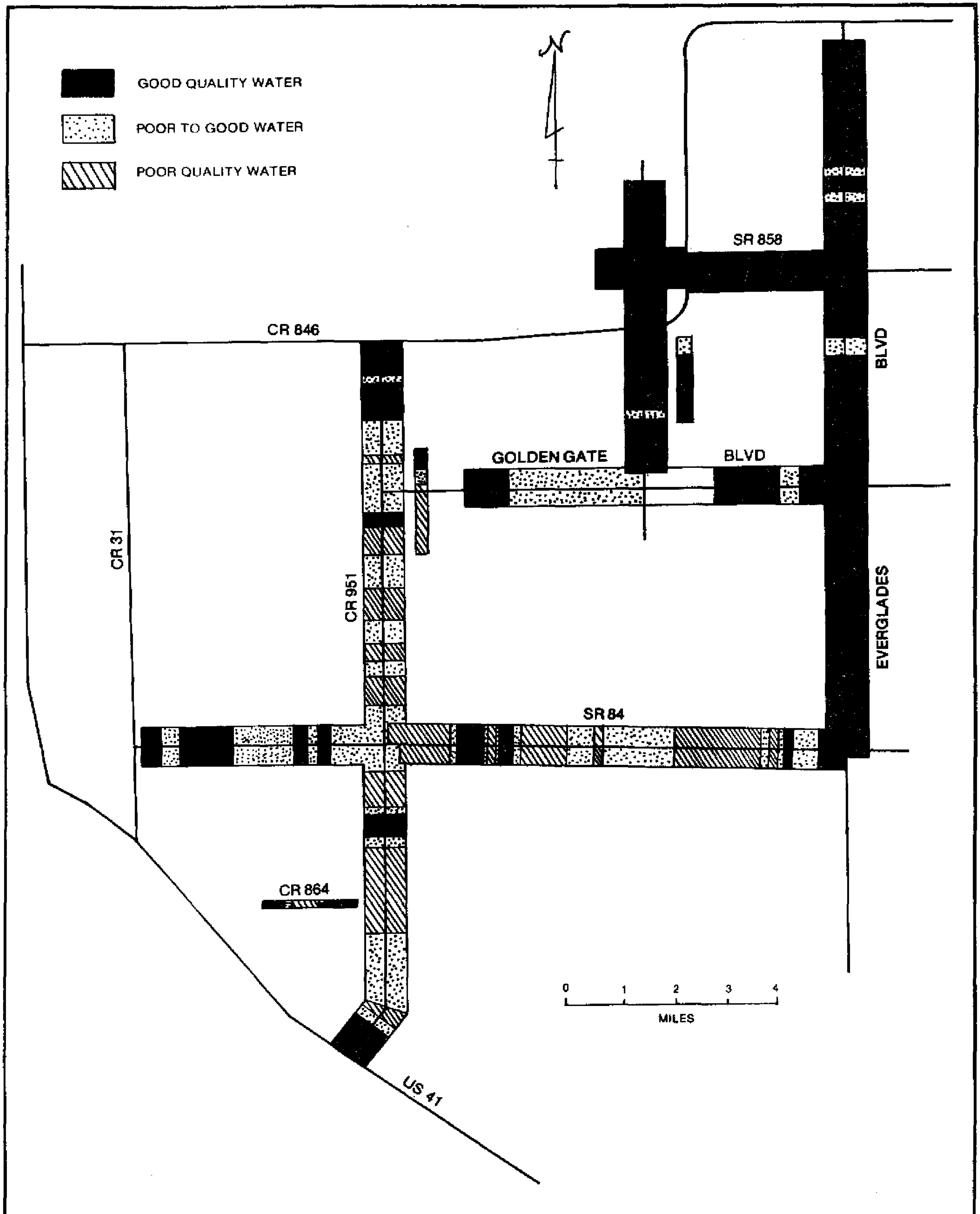


Figure 41 WATER QUALITY AT A DEPTH OF 50', WESTERN COLLIER COUNTY, AS INTERPRETED FROM DC RESISTIVITY SURVEYS.

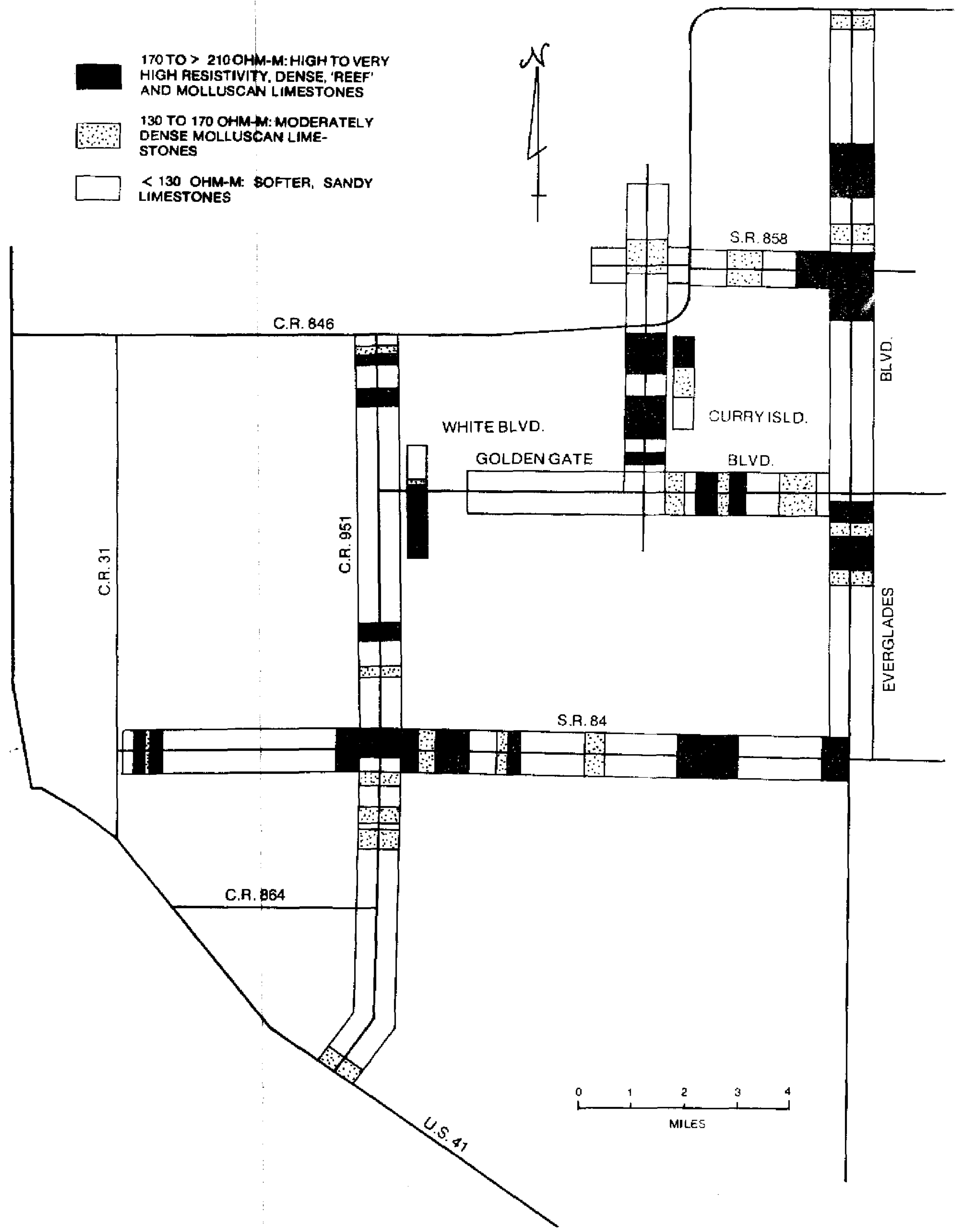


Figure 42 OCCURRENCE OF HIGH-RESISTIVITY "REEF" LIMESTONES, WESTERN COLLIER COUNTY, INTERPRETED FROM DC RESISTIVITY SURVEYS.

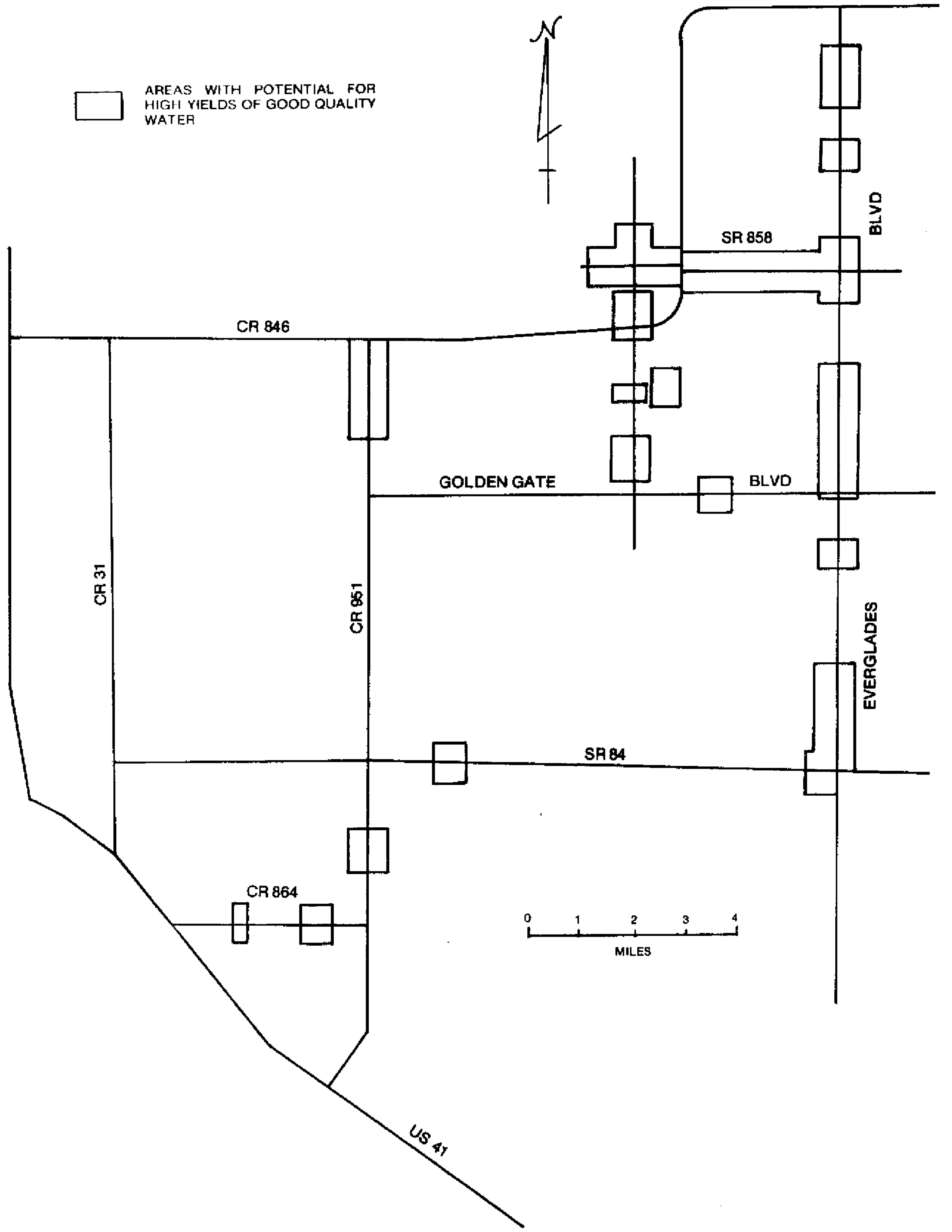


Figure 43 ASSESSMENT OF GROUND-WATER QUALITY AND PRODUCTIVITY TO A DEPTH OF 50′, WESTERN COLLIER COUNTY, AS INTERPRETED FROM DC RESISTIVITY SURVEYS.

groundwater and high yield aquifers along SR 84. One exception is just east of the toll gate at SR 951. The problem with this site is that it is close to the county landfill (Figure 19). SR 951 has several promising sites for groundwater development, particularly north of US 84 (Figure 18). Golden Gates Boulevard has extensive areas of poor quality water or low yield units and limited areas of high resistivity, high yields units (Figure 39). The Golden Gates Highlands (Figure 44) is an area of extensive, well-lithified, shallow "reefs", and is probably an important recharge area. This probability should be recognized in land use and water resource management plans.

The occurrence of poor quality groundwater at shallow depths in Collier County is irregular and difficult to predict at this point. Further geologic, geophysical, and hydrogeologic studies are necessary to determine the processes that determine the distribution of poor quality waters. For permitting or planning purposes it should be realized that the occurrence of good quality water in closely-spaced wells does not insure an adequate or extensive water supply. The resistivity data suggest that abrupt changes in water quality occur over horizontal distances of a few thousand feet or less, and a few tens of feet (often less) vertically. Water quality varies dramatically and sharply within short distances. Prospective users of large quantities of groundwater should assess water quality in the vicinity of the wellfield out to a distance at least as far as the maximum possible radius of influence of the wellfield over its operating life.

The deep, high-resistivity unit in north-central Collier County detected by resistivity (Figure 40) may represent a significant groundwater resource (Figure 45). The water quality at a depth of 201 feet reported by Nuzman (1972) is better than water quality at shallower depths in other

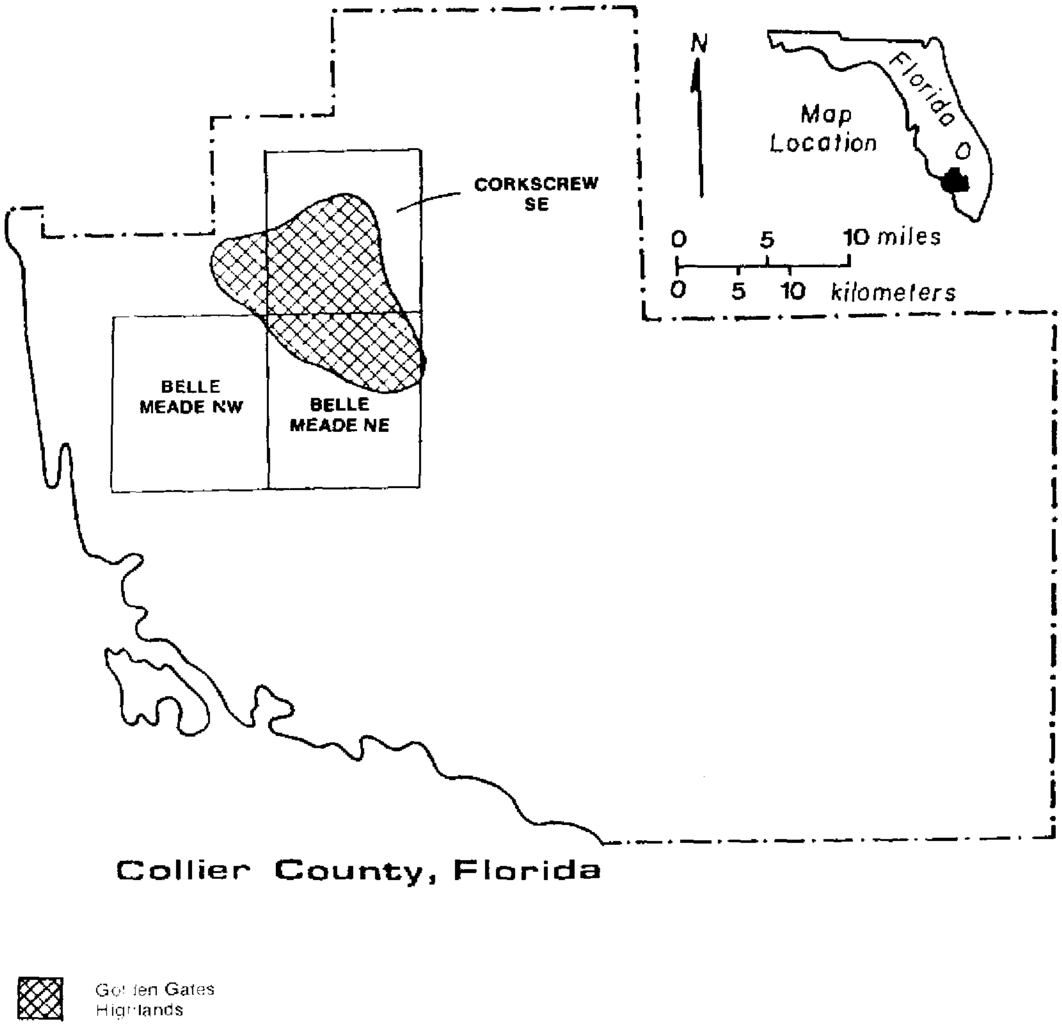


Figure 44 LOCATION OF GOLDEN GATES HIGHLANDS, COLLIER COUNTY.

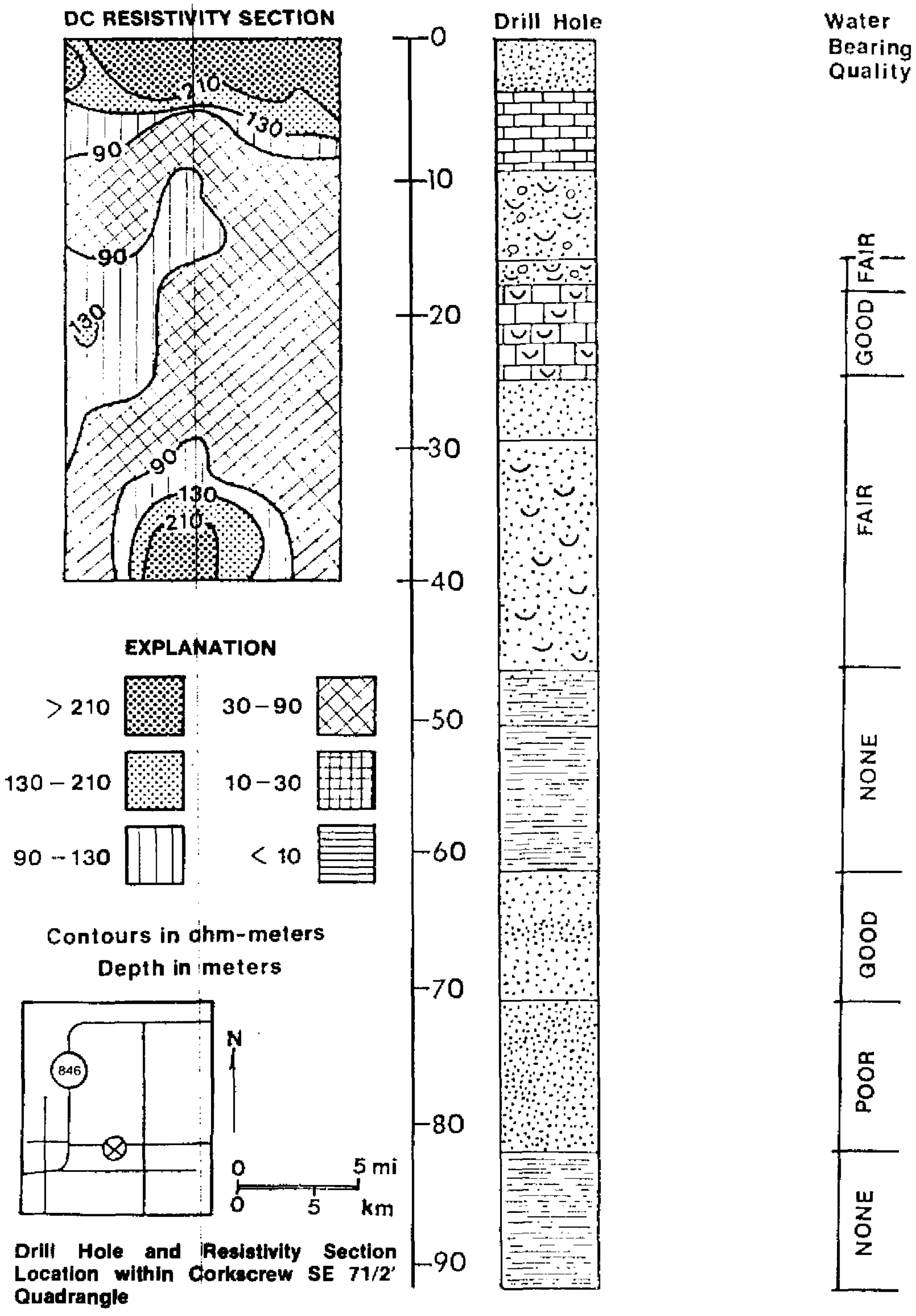


Figure 45 COMPARISON OF RESISTIVITY SIGNATURE OF DEEP, HIGH-RESISTIVITY UNITS IN NORTHCENTRAL COLLIER COUNTY WITH BOREHOLE DATA FROM NUZMAN (1972).

parts of Collier County. The geometry of the occurrences of this unit suggests that it is a channel sand. Any exploratory drilling program in this unit should recognize that it may be narrow and meandering. The lower sand, below 201 feet (Nuzman, 1972), may act as a high transmissivity conduit for high quality waters recharging somewhere to the northeast and moving southwest and upward into the overlying units.

Recommendations for Further Work

1) The South Florida Water Management District Resource Planning Department, Groundwater Division, should determine the hydrologic characteristics of the major hydrostratigraphic units through drilling, borehole geophysical logging, aquifer evaluation tests, and reevaluation of aquifer tests performed by private consultants. Selection of test sites should be based on the data presented in this report and other data available to the District.

2) The Big Cypress Basin Board, in cooperation with the South Florida Water Management District's Resource Planning Department, should determine from this report and the results of the aquifer evaluation study, which areas in western Collier County are potential sites for extensive potable water supplies and which are in areas planned for development or wellfield expansion. This information can then be included in planning decisions.

3) Areas which have water resource potential and are being considered for groundwater development should be investigated with closely-spaced (500 foot - 250 foot centers) vertical electrical soundings to determine the geometry and location of the probably potable water zones. Such

surveys should attempt to map these zones in three dimensions, i.e. surveys should be extended some reasonable distance on either side of the principal survey lines.

4) Final, site-specific, hydrogeologic investigations of potable water supplies should use the results of this report, the SFWMD's drilling program, and the detailed resistivity surveys to guide exploratory drilling. Because of the highly variable quality of groundwater in western Collier County, all major water resource exploration programs should incorporate surface geophysical surveys to reduce exploration costs. The City of Naples and Collier County governments should encourage their consultants to extend the results of exploratory drilling programs with electrical surface geophysical methods.

5) This study has demonstrated that resistivity maps are useful in Collier County for delineating hydrogeologic conditions. Should the agencies responsible for groundwater resource planning and/or exploitation in the county decide that an overall assessment of the total groundwater resource available in the western part of the county is crucial to their planning objectives, methods exist that can assess the resource on a regional scale using geophysical techniques. Such a regional survey could be completed by either ground-based or airborne surveys. A survey of western Collier County (500 square miles) would cost $75,000 to $150,000 (1981 dollars). The cost varies with the spacing of the survey lines and the method. The results of this extensive survey covering all of western Collier County would be similar to the results obtained along major highways as described in this report, except that the data would be three-dimensional, rather than along profiles.

SUMMARY

Direct current resistivity soundings, coupled with supporting geologic and geochemical data, allow rapid reconnaissance surveys of groundwater resources in areas such as Collier County, where the principal aquifer is within a few hundred feet of the surface. Two important characteristics of the hydrogeologic system - shallow, high resistivity karstic limestones and areas of very poor quality groundwater - can be delineated with DC surveys.

Automatic inversion of field data allows rapid processing of vertical electrical soundings without extensive training required of the operator. The only stringent requirement on the part of the interpreter is that he become familiar with the theoretical limits on the shapes of sounding curves so that distorted field data can be recognized and corrected. Digital processing greatly speeds up the interpretation and presentation of VES data, allowing more time and money to be devoted to the collection of field data.

It should be noted that resistivity data require correlation with other geologic, geophysical, and/or geochemical data to avoid errors in interpretation. Bulk resistivity values are not unique, even for similar lithologies, and bulk resistivities must be calibrated against other data, preferably subsurface data. The most efficient use of resistivity surveys is to extend or augment existing knowledge of a groundwater system, and to locate areas worthy of detailed study.

REFERENCES CITED

Davis, P. A., 1979. Interpretation of resistivity sounding data: computer programs for solutions to the forward and inverse problems. Information Circ. 17, Minn. Geol. Survey, St. Paul, MN.

Dougenik, J. A., and D. E. Sheehan, 1975. WYMAP User's Reference Manual. Laboratory for Computer Graphics and Spatial Analysis, Harvard University, Cambridge, Mass.

Gee and Jenson, Inc., 1980. Hydrogeology of East Naples area. Unpublished report submitted to South Florida Water Management District.

Jakob, P., 1980. Some aspects of the hydrogeology of coastal Collier County; Florida. IN Water, Oil, and the Geology of Collier, Lee, and Hendry Counties, P. J. Gleason, ed., Miami Geological Society, 1980 Field Experience guidebook, pp. 21-26.

Keller and Frischknecht, F. C., 1966. Electrical methods in geophysical prospecting, Pergamon Press, London.

McCoy, J., 1972. Hydrology of western Collier County, Florida. Report of Investigation No. 63, Florida Bureau of Geology, 32 p.

Meeder, J., 1980. New information on Pliocene reef limestones and associated facies in Collier and Lee Counties, Florida. IN Water, Oil, and the Geology of Collier, Lee, and Hendry Counties, P. J. Gleason, ed., Miami Geological Society, 1980 Field Experience guidebook, pp. 27-30.

Nuzman, C., 1972. Golden Gate Estates investigation for water supply and soil depth for septic tanks. Layne-Western Co., Inc., Kansas City, Mo., unpublished report.

Zohdy, A. A. R., and R. Bisdorf, 1975. Computer programs for the forward calculation and automatic inversion of Wenner sounding curves. National Tech. Infor. Service, PB-247 265/AS, Springfield, VA.