TECHNICAL PUBLICATION 82-5

July 1982

GEOPHYSICAL SIGNATURE OF PLIOCENE REEF LIMESTONES USING DIRECT CURRENT AND ELECTROMAGNETIC RESISTIVITY SURVEY METHODS COLLIER COUNTY, FLORIDA

FINAL PROJECT REPORT
USF-SFWMD COOPERATIVE
PROGRAM, PHASE III
COLLIER COUNTY REEF MAPPING
PROJECT

GEOPHYSICAL SIGNATURE OF PLIOCENE REEF LIMESTONES USING DIRECT CURRENT AND ELECTROMAGNETIC RESISTIVITY SURVEY METHODS, COLLIER COUNTY, FLORIDA

Michael C. Layton and Mark T. Stewart

Final Project Report
USF-SFWMD Cooperative Program, Phase III
Collier County Reef Mapping Project

Project Directors:

Mark T. Stewart, Associate Professor
Geology Department
University of South Florida
Tampa, Florida

Abe Kreitman, Director
Ground Water Section
South Florida Water Management District
West Palm Beach, Florida

July, 1982

Groundwater Division
Resource Planning Department
South Florida Water Management District
West Palm Beach, Florida

ACKNOWLEDGEMENTS

Dr. Richard A. Davis, Jr. and Dr. Alexander W. Ritchie deserve special appreciation for their efforts in reviewing the manuscript and suggesting improvements. Great appreciation is extended to the Ground Water Section of the South Florida Water Management District, especially Abe Kreitman, for providing financial support of this investigation.

Grateful acknowledgement is given to Mike Bradley, Gary D'Aluisio-Guerrieri, Ronnie Estep, George Foster, Bernard Kuhn, Chris Mraz, Mark Nuckels, Davie Osterlund, and David Smith all from the Geology Department of the University of South Florida, for their invaluable assistance with the extensive field work, without whom this project would not have been possible.

Special thanks to Mary Haney for the typing of the manuscript.

TABLE OF CONTENTS

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 major project funding provided by the SFWMD. This phase of the project involved the location and mapping of near-surface occurrences of a limestone reef facies in the shallow aquifer of northwestern Collier County, Florida, using geophysical techniques, specifically electromagnetic and direct current resistivity methods. The surface geophysical measurements were correlated with lithologic, water-quality, and bore-hole data available in the study area.

ABSTRACT

Direct current (DC) resistivity techniques have been applied to the surveying of areas with ground-water problems for some time, but electromagnetic (EM) methods, primarily employed for metallic ore exploration, have only recently been applied to ground-water exploration. Because of lesser time and manpower requirements for EM surveys, as opposed to DC surveys, a comparative analysis between the two methods was conducted to determine the applicability of EM techniques to ground-water surveys in southern Florida.

In northwestern Collier County, Florida, the shallow carbonate aquifer contains a discontinuous coralline reef facies of Pliocene age, which influences recharge of the shallow aquifer. Areas of relatively good quality water and low primary porosity, indicative of the reef facies, proved to have a distinctive high-resistivity signature, providing an excellent geophysical target. Several DC geoelectric cross sections were obtained to establish the locations of the geophysical targets. A subsequent EM survey conducted over 17 kilometers of a DC resistivity survey line provided a good relative correlation between the two methods. After a satisfactory correlation was established, the EM survey was extended over a 19.5 km^2 area to determine any possible trend of the reef facies. The EM measurements proved to be most sensitive to large resistivity contrasts at shallow depths, typified by the reef facies. No definite reef trend was established in the EM survey area. Both EM and DC resistivity data indicate recharge of the shallow aquifer through the highly permeable reef facies because of well developed solution porosity. Flushing of poorer quality (low resistivity) water beneath extensive occurrences of reef limestones is implied by the geophysical data.

INTRODUCTION

Background

In recent years, geophysical techniques have been increasingly applied to the solution of many shallow (less than 40 meters in depth) engineering, geologic, and hydrogeologic problems. The increased popularity of shallow surface geophysical methods is because of two factors: (1) economy; less time and manpower are involved in conducting geophysical surveys as compared with conventional surveys, and (2) quality of information; refinements in field and data reduction techniques within the past 10 years have increased the quality of information obtained by geophysical methods and have reduced interpretation effort. When examining the applicability of a geophysical method to a problem, both the economics and the quality of information obtained must be considered and a satisfactory balance between the two must be achieved. Unfortunately, the quality of information is often considered of secondary importance.

In the case of hydrogeologic investigations, direct current (DC) resistivity methods have been used with success for many years in defining the limits of salt-water intrusion in coastal areas (Davis and DeWiest, 1966, pp. 284-285; Lazreg, 1972; Fretwell and Stewart, 1981) and locating buried sand and gravel deposits (Davis and DeWiest, 1966, pp. 284-285; Zohdy and others, 1974, pp. 47-50; Heigold and others, 1979). Compared to a program of randomly placed chloridemonitor wells, as in the case of salt-water intrusion, or a closely spaced drilling program for locating buried sand and gravel deposits, DC resistivity satisfies both economic and quality-of-information factors, because definitive results can be obtained without a large capital expenditure.

Although DC resistivity works well in these cases, the method provides no direct information about ground-water flow or geohydrologic constants of permeability, transmissivity, and hydraulic conductivity (Van Dam, 1976). Under favorable conditions and proper supplementation with bore-hole data, porosity (and indirectly permeability) can be determined with surface DC resistivity in some instances (Griffith, 1976). Heigold and others (1979) claimed that hydraulic conductivity, and hence, transmissivity, of a glacial outwash aquifer in Illinois showed an inverse relationship to surface resistivity values. This conclusion was drawn after extensive supplementation of resistivity data with pumping-test and sediment-analysis data and could not be generalized to include other localities or geologic environments. The supplementation of geophysical data, such as DC resistivity data, with geologic information is a necessary part of the interpretive process in order to clarify inherent ambiguities which occur with all geophysical methods and handicap the formulation of valid data interpretations.

Another way of supplementing geophysical data is to conduct two surveys over the same area using two distinctively different geophysical methods. At first inspection, this may appear to be adding ambiguity to ambiguity, but by using two geophysical methods which respond differently to a given feature, better resolution of the feature may be possible with the combined surveys than either survey could provide separately. Lazreg (1972) used combined surface electrical surveys in the detection of salt-water intrusion, Roy and Elliot (1980) used surface electrical and induced polarization methods also for detection of salt-water intrusion, and Tripp and others (1977) used combined electrical and electromagnetic surveys to delineate geothermal areas. Although combined geophysical surveys can provide better resolution of a feature than single-method geophysical surveys, the necessity for supplementation by actual geologic information is not eliminated. Geologic information is still necessary in order to make valid data interpretations. Combined geophysical surveys only enhance the quality of information while keeping survey costs less than a conventional drilling operation.

Electromagnetic (EM) methods (sometimes called induction methods) have been used primarily in mineral exploration to locate buried conductive zones, especially base-metal deposits. In recent years, EM techniques have been applied to hydrogeologic investigations. Although airborne EM surveys are primarily used in mineral exploration for reconnaissance of large areas, Seigel and Pitcher (1978) used airborne EM surveys for delineation of gravel deposits in Canada and mentioned the application of this type of EM method to ground-water exploration. Surface EM surveys have also been applied to ground-water exploration (Koefoed and Biewinga, 1976) in north Africa. Surface EM techniques are particularly useful in areas where DC resistivity methods are impractical due to the difficulty of introducing current into highly resistive surface materials, such as crystalline rock or dry sand (Patra, 1976). EM methods depend upon current flow through the ground to detect resistivity variations, as does DC resistivity; however, because current flow is magnetically induced with EM methods, problems arising from improper ground contact with electrodes are not experienced as with DC methods.

The amount of electrical current which will flow through the ground is dependent upon three properties of earth materials: (1) mineralogy, (2) pore surface area and effective porosity, and (3) the amount and conductivity of interstitial fluids. Mineralogy is the least important property to be considered, and can largely be ignored because most earth materials behave as electrical resistors or at best semiconductors. However, if perceptible amounts of metallic or clay minerals are present, current flow through the matrix may be significant (Keller and Frischknecht, 1966). In the case of clay minerals, the current flow through the matrix is across grain surfaces and is greatly influenced by pore surface area. Actual current flow through matrix grains only occurs with certain metallic minerals and native metals. If no metallic or clay minerals are present in the matrix, current flow through an earth material is largely affected by pore surface area. Variations of pore surface area affects current flow in two ways: (1) by restricting the total cross-sectional area of pores filled with conducting fluids, such as saline water and (2) by reducing the amount of area along the outer portions of the interstices through which current will flow in the electrical double layer associated with the polarization of water molecules on pore surfaces. Current flow through interstitial fluids is a function of the amount and conductivity of the fluid. In the case of interstital water current flow is related to the amount of electrolytic ions in solution. If the concentration of electrolytic ions in solution is low, then the majority of current is conducted through the electrical double layer of polarized water molecules.

A quantitative value for the porosity of an earth material over a large area can be determined from surface resistivity measurements if the conductivity of interstital water and localized estimates of material porosity are known. Griffith (1976) used this method to determine the values of porosity for a Triassic sandstone aquifer in Great Britain. If core samples and water conductivity data are sparse or not available, quantitative determinations of porosity over large areas are not possible. However, qualitative delineation of high and low porosity areas may be possible if the general water conductivity and lithologic character of an area are known.

Statement of Problem

The population of southern Florida is expected to greatly increase in the 1980's. This population growth presents many problems with the allocation of potable ground water and location of waste disposal systems. Determination of ground-water characteristics in affected areas, including location of local recharge sites for the shallow aquifer, are necessary prior to effective management of the ground-water resource. Ground-water reconnaiassance surveys using surface geophysical measurements are more cost-efficient than random test-hole borings and can be used to determine areas for detailed investigation. In the present study, surface DC resistivity and EM surveys were conducted in an area of predominantly carbonate lithologies in northwestern Collier County, Florida. These data were compared to shallow-well data and drainage canal spoil in order to delineate lithologic variations (high and low porosities) of the shallow aquifer. These lithologic variations have been attributed to the occurrence of a coralline reef facies of Pliocene age (Meeder, 1979) in the Upper Tamiami Formation which influences the hydrology of the shallow aquifer. The use of electromagnetic terrain-conductivity measurements was evaluated as a geophysical survey method for ground-water investigations in southern Florida.

Study Area Location

The area of investigation is located in the northwestern portion of Collier County, Florida, near the Lee County border. Collier County is situated along the southwestern coast of the Florida peninsula (Figure 1). The study area is contained within three adjacent 7½' quadrangles just northwest of the main area of the Big Cypress Swamp. With the exception of a small portion of a west-to-east geoelectric cross section, the investigation was conducted within the Corkscrew SE and Belle Meade NE quadrangles bounded by 26°22'30" north latitude, and 81°37'30" and 81°30'00" west longitude (Figure 2).

Description of Study Area

Physiographically, much of Collier County is within the Big Cypress Swamp Basin, which extends from the Everglades westward to the coastal mangrove swamps of the Gulf of Mexico. The study area is along the north-western fringe of the Big Cypress Swamp. The terrain within the study area is very homogeneous with a maximum elevation of approximately 7.5 meters above sea level in the northern sections. Elevation decreases continuously to a minimum of approximately 3 meters above mean sea level in the southern sections, south of State Route 84. Maximum local relief in northwestern Collier County is approximately

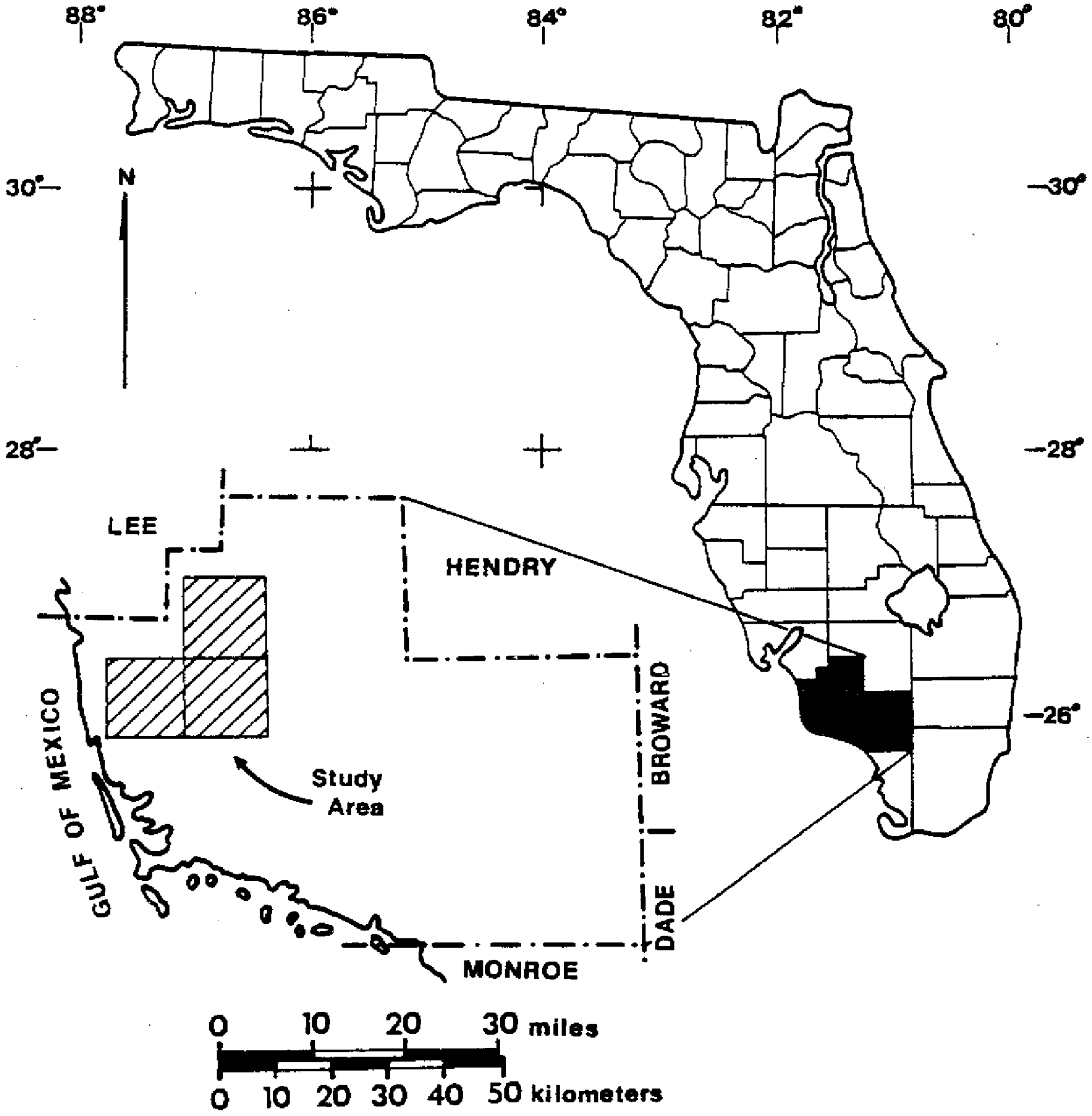


Figure 1. Location of study area within Collier County, Florida.

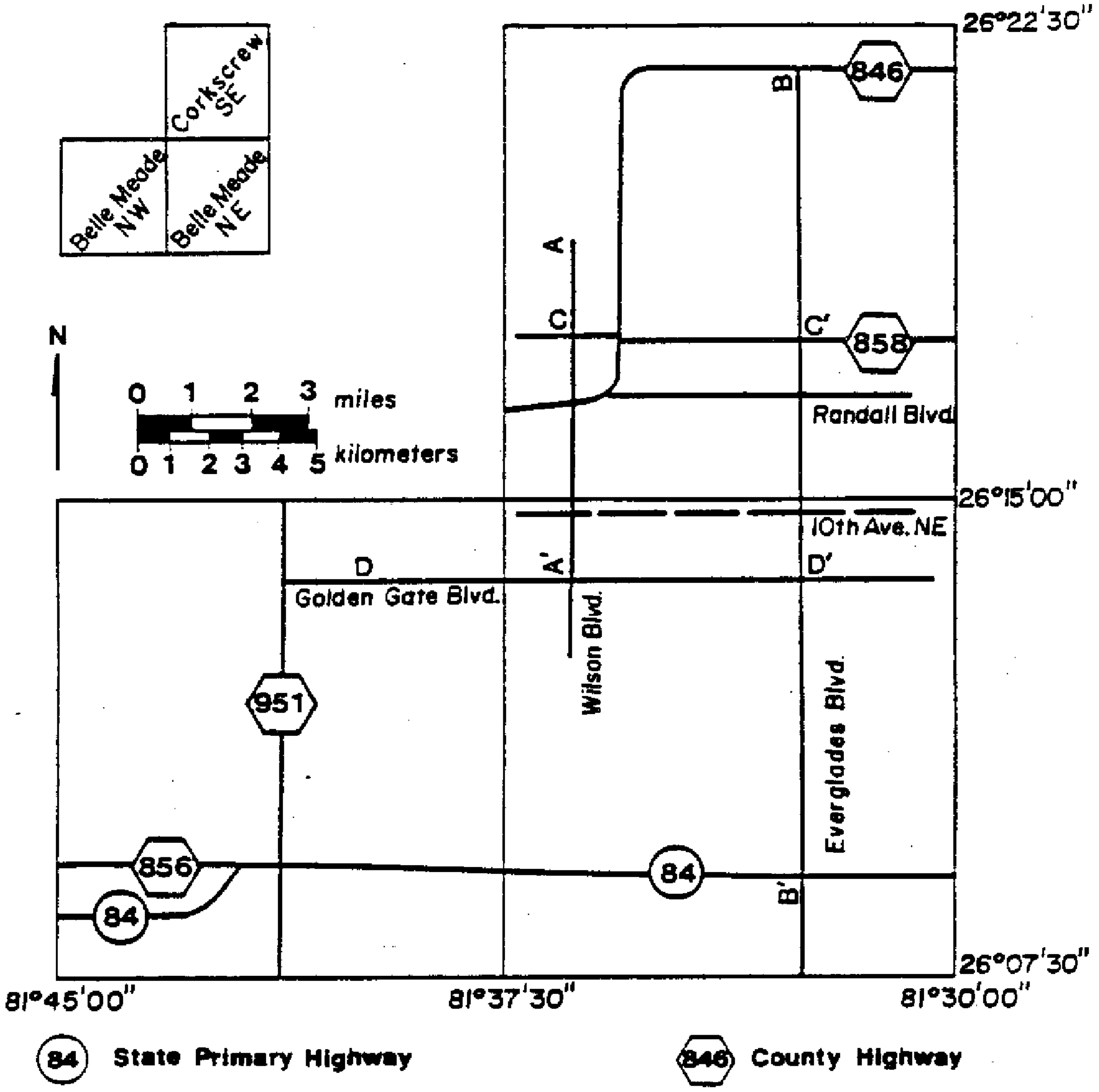


Figure 2. Major highways of study area quadrangles. Geoelectric cross section locations also given, A-A' Line 1, B-B' Line 2, C-C' Line 3, D-D' Line 4.

7.7 meters northeast of the investigation quadrangles. The 4.5 meters of elevation difference is distributed over a lateral distance of approximately 27 kilometers, producing an average grade of less than 0.02%. Throughout the area the water table remains within approximately 1 meter of the surface during most of the year. During the rainy season, standing water is not uncommon in many parts of northwestern Collier County.

Vegetation over much of the Big Cypress Swamp is stunted cypress, pine, and palmetto with the occurrence of pine and palmetto increasing to the north. This variation in vegetation can be seen within the study area quadrangles. Fresh-water marsh vegetation of the Everglades occurs to the east and southeast of the Big Cypress Swamp. The soil characteristics of the Big Cypress Swamp also differ significantly from those of surrounding localities. To the north of the Big Cypress Swamp, just north of the investigation site, soils are predominantly sandy and marly with no outcropping rock, while soils to the southeast are typically the mucky variety of the Everglades with no exposed rock. Large exposures of bedrock at or near the surface are common in the Big Cypress Swamp (Parker and Cooke, 1944), and occur throughout much of the study area. A general decrease in the amount of exposed rock can be seen as a function of distance north of the main extent of the swamp, as is exhibited in some of the north/south drainage canals within the investigation area.

The road network in the investigation locality is more extensive than the major highways shown in Figure 2. Much of the three-quadrangle area is covered by a network of streets which intersect most of the major highways at approximately 400 meter (¼ mile) intervals.

Prior to the construction of the street network, an interconnected system of drainage canals was dredged in the northwestern sections of the county. Although the drainage canal and street networks have been in existence since the late 1960's to early 1970's, little urbanization has occurred to date. With the exception of single-family housing units along the major county roads, the area is largely undeveloped.

General Geologic Setting

As is true for all of southern Florida, Collier County is underlain by thick sequences of predominantly carbonate rock. Exploratory well data in the central part of the county show a sedimentary rock thickness in excess of 3600 meters (Parker and Cooke, 1944, p. 18). Above a depth of 200 meters, the predominant rock materials in the county are quartz sand, limestone, and clay, while limestone and dolostone are the predominant materials below 200 meters (McCoy, 1962, p. 10). The oldest exposed bedrock in Collier County is of the Tamiami Formation (Figure 3). Many authors have placed the Tamiami Formation entirely within the Miocene Series; however, recent stratigraphic revisions and nanofossil examination by Akers (1974) indicate that some of the upper portions of the Tamiami Formation are of Mid-Pliocene age. Stratigraphically below the Tamiami Formation are the Mid-Miocene Hawthorn and Lower Miocene Tampa Formations, the Suwannee Limestone (Oligocene), and the Ocala and Avon Park Limestones (Eocene). These six units comprise most of the Tertiary System in southern Florida.

Above the Tamiami Formation are the Caloosahatchee Marl, Anatasia and Fort Thompson Formations, Miami Oolite, Talbot Formation and Pamlico Sands (Figure 3). Because of the lack of continuous exposures,

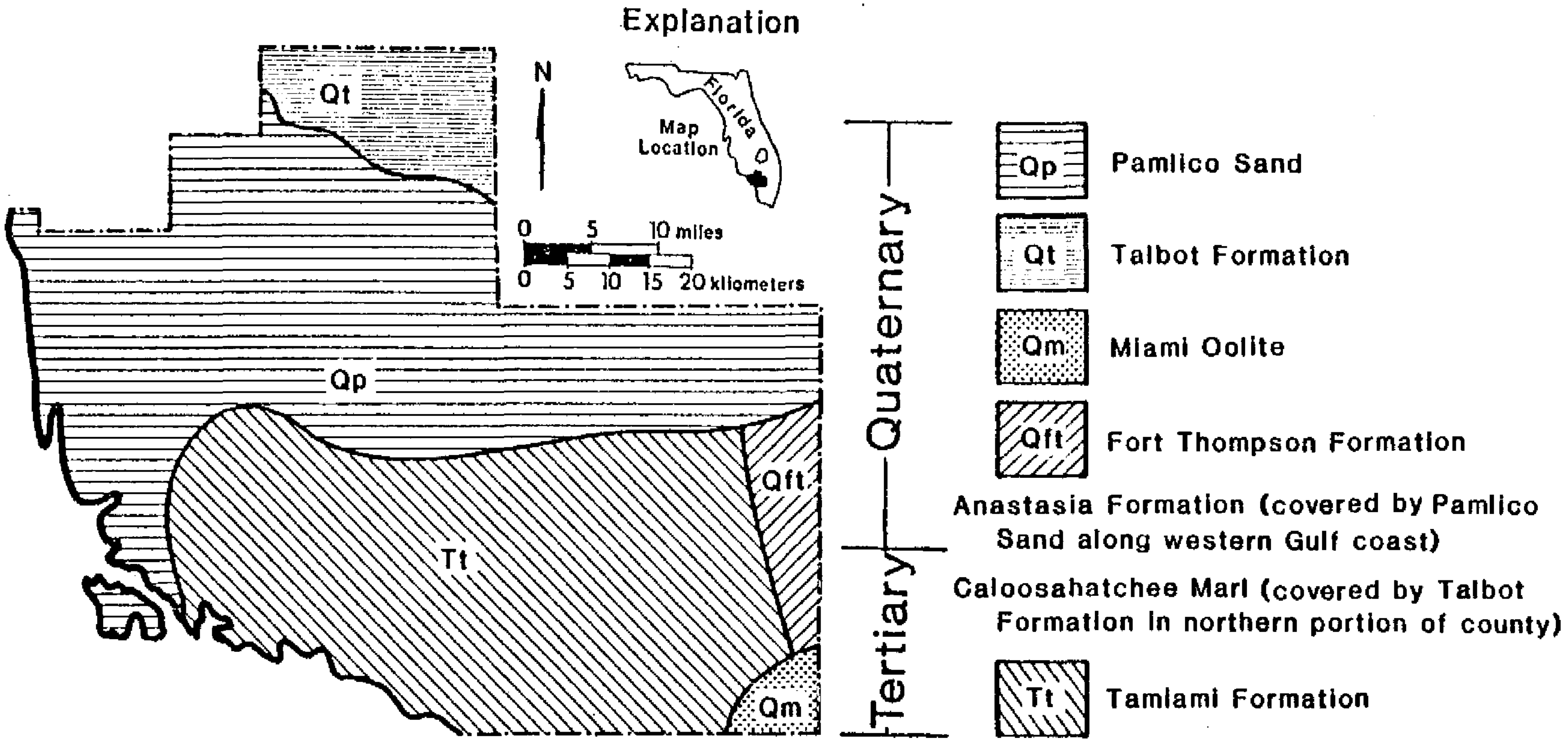


Figure 3. Geology of Collier County, Florida, exclusive of organic soils (after McCoy, 1962).

gradational contacts, and in some localities absence of fossil control, stratigraphic relationships and age determinations of these younger deposits are difficult to decipher. The general stratigraphic and age relationships of these younger deposits are shown in Figure 3. Nomenclature and stratigraphic problems of the Late Tertiary and Quaternary strata of southern Florida have been addressed by Hunter (1978).

Hunter (1978) also proposed several revisions of terminology to settle some of the controversy surrounding the stratigraphy of southern Florida. With regard to the Tamiami Formation, Hunter suggests a division of the formation into upper and lower parts based on the occurrence of two major unconformities in the stratigraphic section. In the Caloosahatchee River area, these divisions are as follows (after Hunter, 1978):

---------unconformity---------
Tamiami Formation (upper part)
Pinecrest Sand Member
Buckingham Limestone Member > Equivalent and Interfingering

---------unconformity---------
Tamiami Formation (lower part)
LaBelle Clay Member
Ortona Sand Member

Hunter also states that other members of the Tamiami Formation are known from other areas, but only the above four have been recognized along the Caloosahatchee River area. The older of the two unconformities occurs between the upper and lower parts of the Tamiami Formation and appears to represent a hiatus of as much as 3.5 to 4 million years. The younger unconformity, at the top of the Tamiami Formation, may represent a time span of as much as 2 to 2.5 million years (Hunter, 1978, p. 65). Based on surface mapping and quarry spoil examination, Meeder (1979) agrees with Hunter's suggestion that the Pinecrest Sand and Buckingham Limestone Members are contemporaneous and further suggests the addition of a coralline reef limestone and a bioturbated mud facies to the Upper Tamiami Formation.

Meeder (1979) describes the reef as occurring as a continuous tract from central Collier County northwestward into Lee County. The reef limestone facies is described as ranging from "white aragonitic coral heads to totally recrystallized corals in coarser carbonate matrix to total dissolution of coral in a carbonate mud matrix" (Meeder, 1979, p. 2). Meeder noted a highly-diverse coral assemblage within the reef facies. Forty-nine coral species, of which twenty-two are extinct, have been identified from the reef facies. Comparison of extinct coral species of the Collier and Lee Counties reef facies with those of the Bowden beds of Jamaica suggest a Mid-Pliocene age (Meeder, 1979). Subsequent evidence from surface and subsurface geology (Meeder, 1980) suggests that the reef limestone and bioturbated mud facies be expanded to at least three biofacies (coral reef, coral rubble, and oyster bioherm). For the purpose of identifying biofacies in the Upper Tamiami Formation, Meeder (1980) noted that the surface (cap) rock, which is as much as 2 meters thick, is essentially useless because of repeated episodes of dissolution and recrystallization of the limestone. Final descriptions of the reef limestones and associated facies in Collier and Lee Counties are pending completion of the coring program (Meeder, 1980).

General Hydrogeologic Setting

The Florida peninsula is underlain by an extensive carbonate aquifer from which most of the potable ground water for central and northern Florida is derived. This aquifer has been named the "Floridan Aquifer" by Parker and others (1955, p. 189) and includes all of the Mid- and Upper Eocene Series (Avon Park and Ocala Limestones), the Oligocene Series (Suwannee Limestone), the Lower Miocene Tampa Formation, and the permeable portions of the Mid-Miocene Hawthorn Formation. The depth to the top of the aquifer varies from at or near the surface in north-central Florida to greater than 270 meters in southern Florida (Vernon, 1973). Thickness of the Floridan Aquifer ranges from less than 360 meters to more than 760 meters (Klein, 1971). The Floridan Aquifer extends well into southern Florida and underlies all of Collier County (McCoy, 1962). Artesian conditions exist in the aquifer in southern Florida, south of the latitude of Lake Okeechobee, with a potentiometric surface approximately 15 meters above mean sea level in the northeastern portion of Collier County, decreasing to approximately 9 meters above mean sea level along the Gulf coast (Healy, 1975). Unfortunately, with sulfate concentrations in excess of 250 ppm (Shampine, 1965a) and chloride concentrations from 251 to greater than 1000 ppm (Shampine, 1965b), the Floridan Aquifer is not a potable water source for southern Florida (Klein, 1971).

A shallow, nonartesian aquifer is also present over most of Florida, but it is not an important ground-water source in most areas because of better supply availability from other aquifers, such as the Floridan. In southern Florida, the shallow aquifer is the principal source of potable ground water (Hyde, 1975). The shallow aquifer of southern

Florida varies in lithology, thickness, and hydrologic characteristics from location to location, but generally it is composed of permeable Miocene limestones of the Upper Hawthorn and Tamiami Formations, quartz sand and shell beds of the Pleistocene Anastasia Formation, and Pleistocene marine-terrace quartz sand deposits (Hyde, 1975).

Missimer (1978) describes the shallow aquifer in central and southern Lee and western Collier Counties as consisting of two principal water-bearing zones contained mostly within the Tamiami Formation. Zone I occurs in the upper portions of the Tamiami Formation and is confined to a variable degree in southern Lee and western Collier Counties by limemuds of the Fort Thompson Formation and Caloosahatchee Marl. Zone I occurs from approximately 4.5 to 30 meters below the surface and is terminated by low-permeability sediments at 30 to 45 meters of depth. Zone II occurs at depths of 45 to 60 meters and is confined by the low-permeability sediments beneath Zone I. The thickness of zone II ranges from approximately 3 to 12 meters. Zone II extends laterally throughout most of southern Lee and western Collier Counties (Missimer, 1978).

Water quality through most of the shallow aquifer in Lee and Collier Counties is relatively good. Recharge of the shallow aquifer results largely from percolation of local rainfall. During periods of high surface-water levels in the rainy season, drainage canals would also provide some recharge. Recharge is restricted in areas with impermeable layers near the surface and much potential recharge in these areas is lost to sheet flow (McCoy, 1962). Chloride concentrations in shallow aquifer waters are usually low, except where contaminated by adjacent salt-water bodies; however, color and iron content are commonly high (Hyde, 1975). Nuzman (1971) describes a shallow aquifer system in northwestern Collier County similar to that described by Missimer (1978) in central and southern Lee and western Collier Counties. Nuzman (1971, p. 2) describes the water quality of the upper water-bearing horizon as generally satisfactory with regard to mineral content (Cl^-, SO_4^{--}, and hardness), but containing excess amounts of organic acids and iron. Nuzman also found that the clay layer separating the upper and lower horizons provided an effective barrier from direct infiltration of waters from the upper horizon into the lower horizon. Water color and appearance generally improve in the lower water-bearing horizons; however, in the southern portions of Collier County, water in the deeper horizons becomes brackish (Nuzman, 1971). Inferior water quality in the shallow aquifer also occurs to the southeast of the study area, approximately 16 kilometers inland from the Gulf (McCoy, 1972).

The occurrence of brackish water within the lower portions of the shallow aquifer may be attributed to at least three possible sources (Jakob, 1980). Near the coast the brackish water is most likely the result of contact with Gulf waters. Inland, brackish water in the shallow aquifer may be due to residual sea water from past inundations or upward leakance of mineralized water from the deeper artesian aquifer (McCoy, 1962; Jakob, 1980). Based on ground-water chemistry, McCoy (1962) indicates that the brackish water occurring inland is probably the result of connate salt water from previous sea water inundations rather than upward leakance from the deeper aquifer. Retention of this inland poor quality water is probably the result of inadequate flushing of ground water in the shallow aquifer caused by relatively impermeable limestones at shallow depths which retard surface-water infiltration (McCoy, 1962).

FIELD AND LABORATORY TECHNIQUES

The acquisition of field data involved the use of a Soiltest Model R-50 Stratameter direct current resistivity unit and a Geonics, Ltd. EM 34-3 electromagnetic terrain conductivity unit. All field data were collected from November, 1980 through July, 1981, with the collection of DC resistivity data completed before June, 1981. A total of 316 survey stations over an approximately 224 km^2 area was obtained during the field season. Of the 316 survey stations, DC resistivity was used at 125 stations, and EM was used at 191 stations. Fifty-one of the EM stations are coincident with stations surveyed with DC resistivity, which were used for comparison of the two methods. The location and distribution of the DC resistivity survey lines and the EM survey area are shown in Figure 4.

The DC resistivity data were obtained using the Wenner electrode array in which four electrodes are driven into the ground in a line at equidistant spacings ("a" spacing). The Wenner array has produced good results in ground-water investigations in Florida in the coastal aquifer of Citrus County (Fretwell and Stewart, 1981), and in the coastal and inland aquifer of Collier County (Stewart, Lizanec, and Kreitman, in press). With the Wenner array, current is introduced into the ground through the electrodes and the potential (voltage) difference at a known current (amperage) is measured. The equidistant "a" spacing is then expanded logarithmically after each potential-difference reading

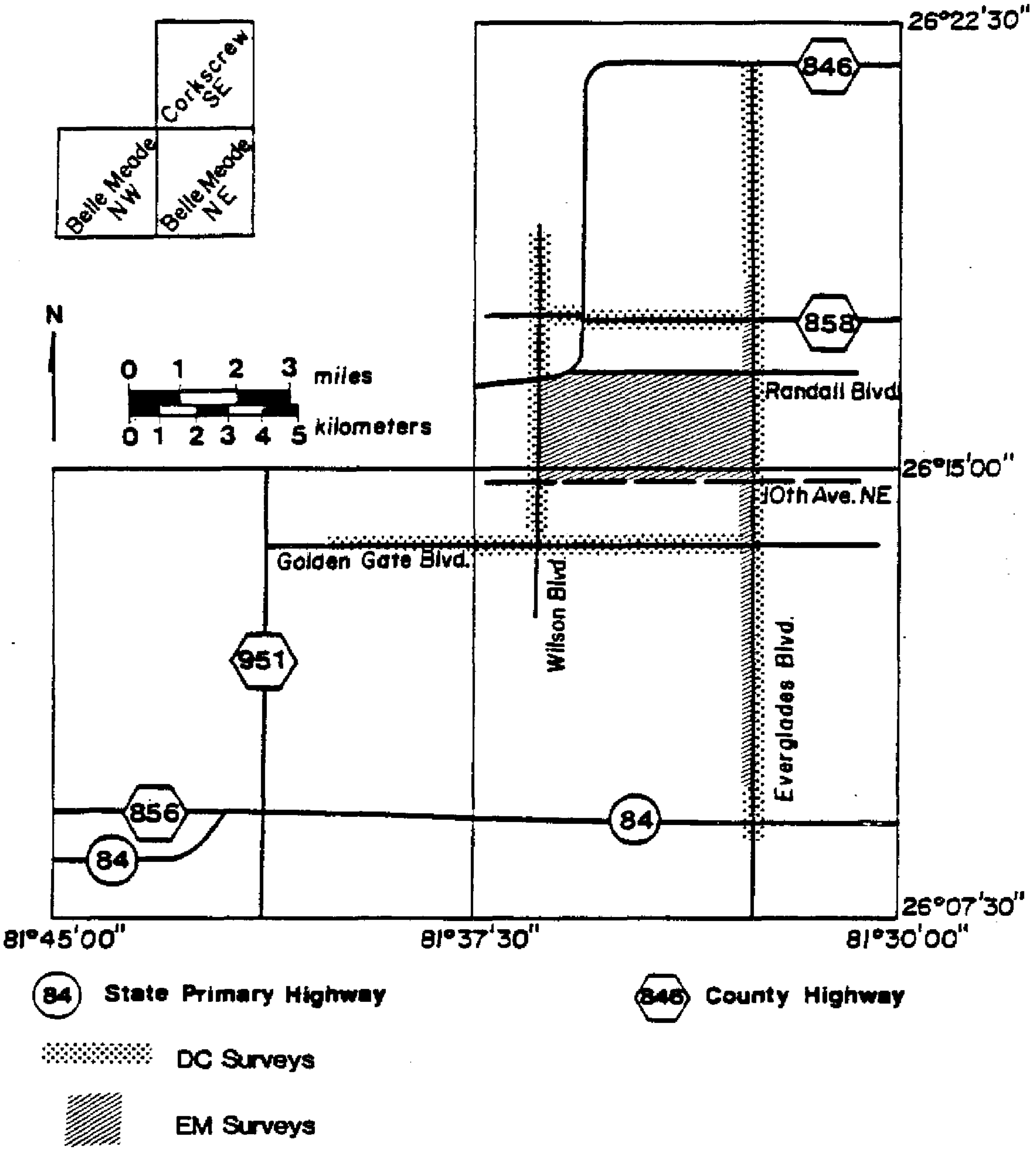


Figure 4. Location and distribution of DC resistivity and EM surveys within study area.

in order to increase the depth of penetration of the current through the geoelectric section. The maximum "a" spacing used at each of the 125 DC resistivity stations was 50 meters. The survey stations were placed at approximately 400 meter centers along the DC resistivity lines shown in Figure 4.

All DC resistivity field data were reduced using an automatic inversion computer program devised by Zohdy and Bisdorf (1975), which provided depth, thickness, and bulk resistivity values for layers in the geoelectric section. The reduced data from the automatic inversion program were contoured using the SYMAP program from the Laboratory for Computer Graphics and Spatial Analysis at Harvard University (Dougenik and Sheehan, 1975).

The collection of the EM data involved the use of a variable-coil-separation, terrain-conductivity unit. With electromagnetic methods, an alternating current is passed through a transmitter coil which produces a time-varying, primary magnetic field. The primary magnetic field from the transmitter coil induces small currents within the earth which in turn produce a weaker secondary magnetic field which can be sensed, along with the primary field, by a receiver coil at some known distance of separation. The circuitry of the instrument allows direct reading of the ground conductivity which is a function of the secondary magnetic field strength, intercoil separation, and operating frequency. The instrument provides conductivity readings at predetermined coil separation distances of 10, 20, and 40 meters. The resulting conductivity readings represent an integrated conductivity value of the measured geoelectric section. As with DC resistivity, the depth of penetration or exploration is a function of intercoil separation; however, by changing the coil orientation, and hence, the dipole arrangement, the depth of exploration can also be varied as is shown in Table 1.

Table 1. Exploration depths for the EM 34-3 terrain conductivity meter at various intercoil spacings (after McNeill, 1980a).

Intercoil Spacing (meters)	Exploration Depth (meters)	
	Horizontal Dipole (Vertical Orientation)	Vertical Dipole (Horizontal Orientation)
10	7.5	15
20	15	30
40	30	60

Although the conductivity value provided by the instrument represents an integrated conductivity of the measured geoelectric section, the contribution to the secondary magnetic field at various depths in the section is not equal. In the case of the vertical dipole, McNeill (1980a) demonstrates that near-surface material makes a very small contribution to the secondary magnetic field, with the maximum contribution occurring at approximately 0.4 of the intercoil spacing. This means that the vertical dipole arrangement is relatively insensitive to conductivity variations near the surface. For the horizontal dipole, McNeill (1980a) demonstrates that the maximum contribution to the secondary magnetic field occurs at the surface and the response decreases exponentially with depth.

All EM survey stations were spaced approximately 320 meters apart, with the exception of the fifty-one stations coincident with the DC resistivity survey which were spaced at 400 meters. All conductivity values measured with the instrument were converted to values of resistivity in ohm-meters and hand contoured using a calculator to determine the contour location between the four adjacent data points at each mode.

Several references are available which explain the theory and application of DC resistivity and EM methods. Keller and Frischknecht (1966), Dobrin (1976), and Telford and others (1976) provide detailed information about DC, EM, and other geophysical methods. NcNeill (1980a, 1980b) provides an explanation of survey and interpretative techniques for the EM 34-3 terrain-conductivity unit used in this investigation.

RESULTS

Four geoelectric cross sections were compiled from DC resistivity data collected along some of the major roads in the study area. Two of the cross sections were north-to-south traverses and two were west-to-east traverses. The extent and location of the north-to-south traverses along Wilson Boulevard (A-A') and Everglades Boulevard (B-B'), and the west-to-east traverses along County Route 858 (C-C') and Golden Gate Boulevard (D-D') are shown in Figure 4. The total length of cross-section coverage within the study area is approximately 80 kilometers. All four of the geoelectric cross sections (Figures 5, 6, 7, and 8) are shown with a vertical exaggeration of 100x. The resistivity data of the cross sections are divided into six classes of values ranging from less than 10 ohm-meters to greater than 210 ohm-meters.

In all of the cross sections, three sets of distinctive features appear. The first set of features is the occurrence of sites of high-resistivity response near the surface, approximately delineated by the 130-210 ohm-meter and >210 ohm-meter classes. In Figure 5, these sites of high-resistivity response are discontinuous patches at approximately 2, 5, 7, 8.5, and 9 kilometers and occur to depths of nearly 10 meters. Near-surface, high-resistivity sites also occur as discontinuous patches between kilometers 11 and 19 in Figure 6; however, the high-resistivity response is more continuous and generally thicker in the northern portion of Figure 6 between kilometers 0 and 9. In the

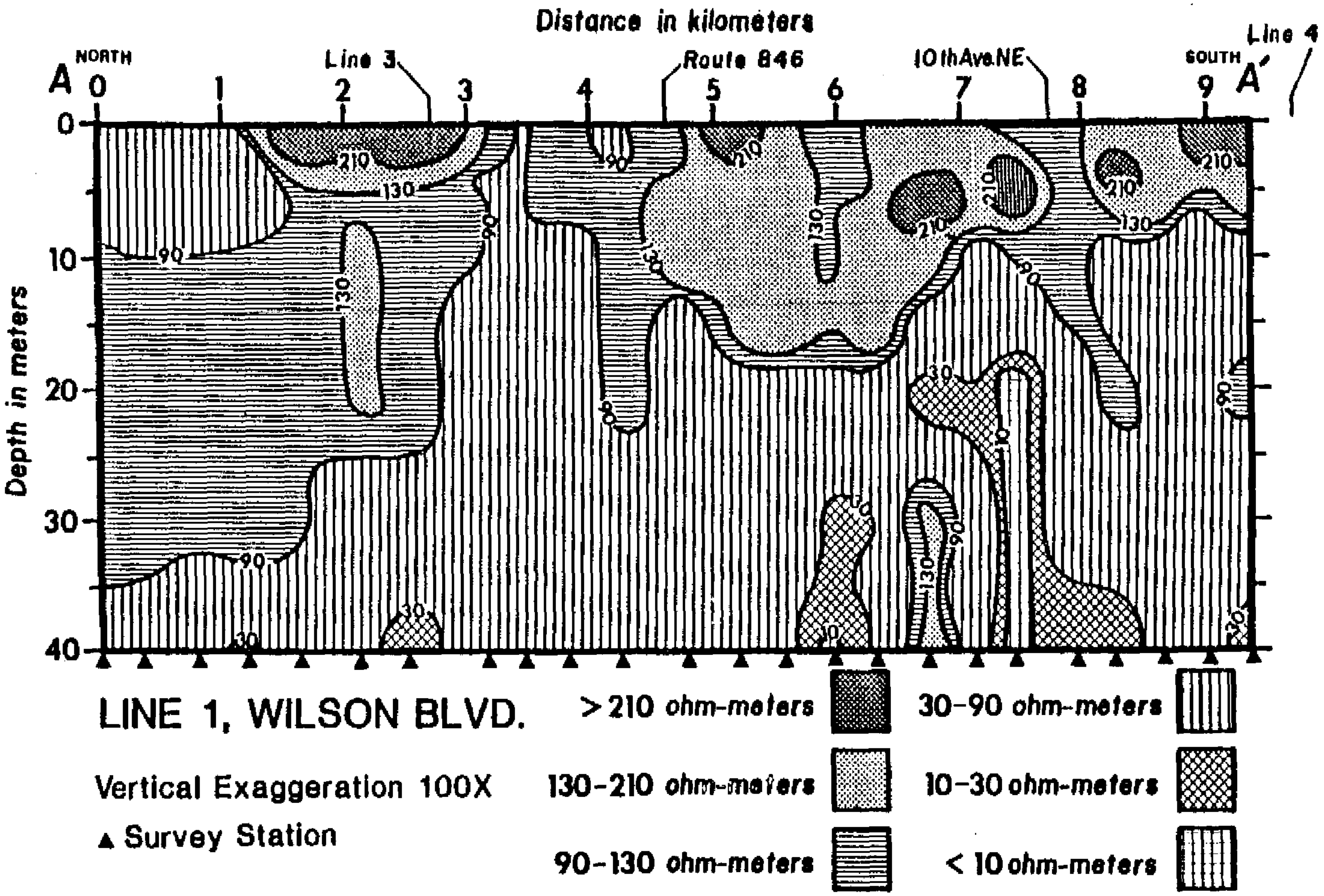


Figure 5. DC resistivity geoelectric cross section, Line 1, Wilson Boulevard. Cross section location shown in Figure 2.

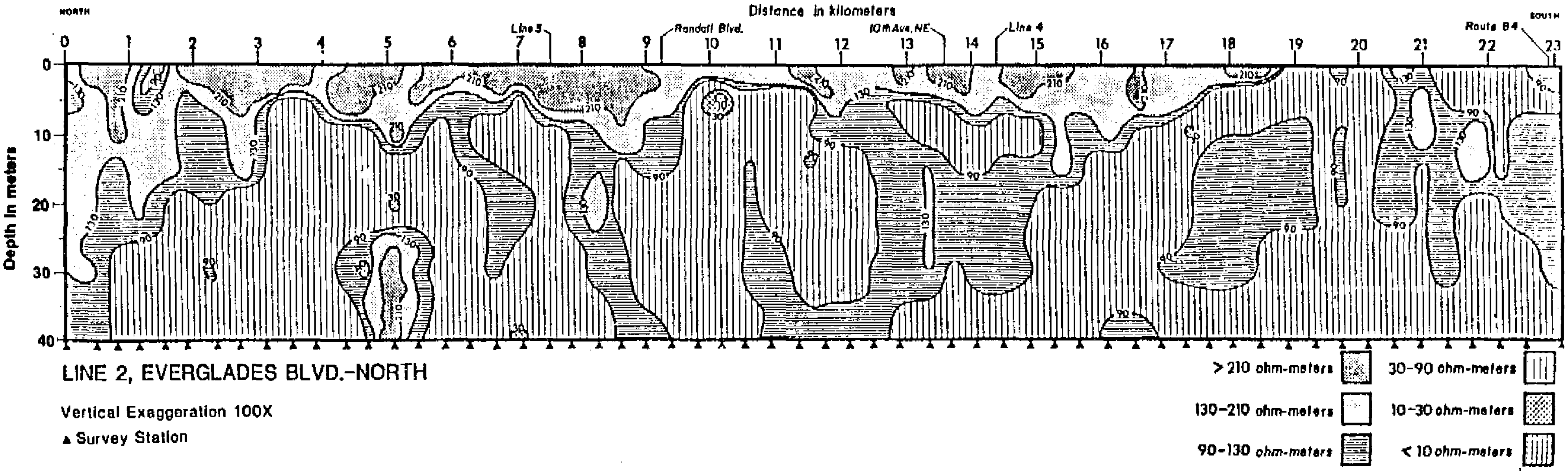


Figure 6. DC resistivity geoelectric cross section, Line 2, Everglades Blvd. - North. Cross section location shown in Figure 2.

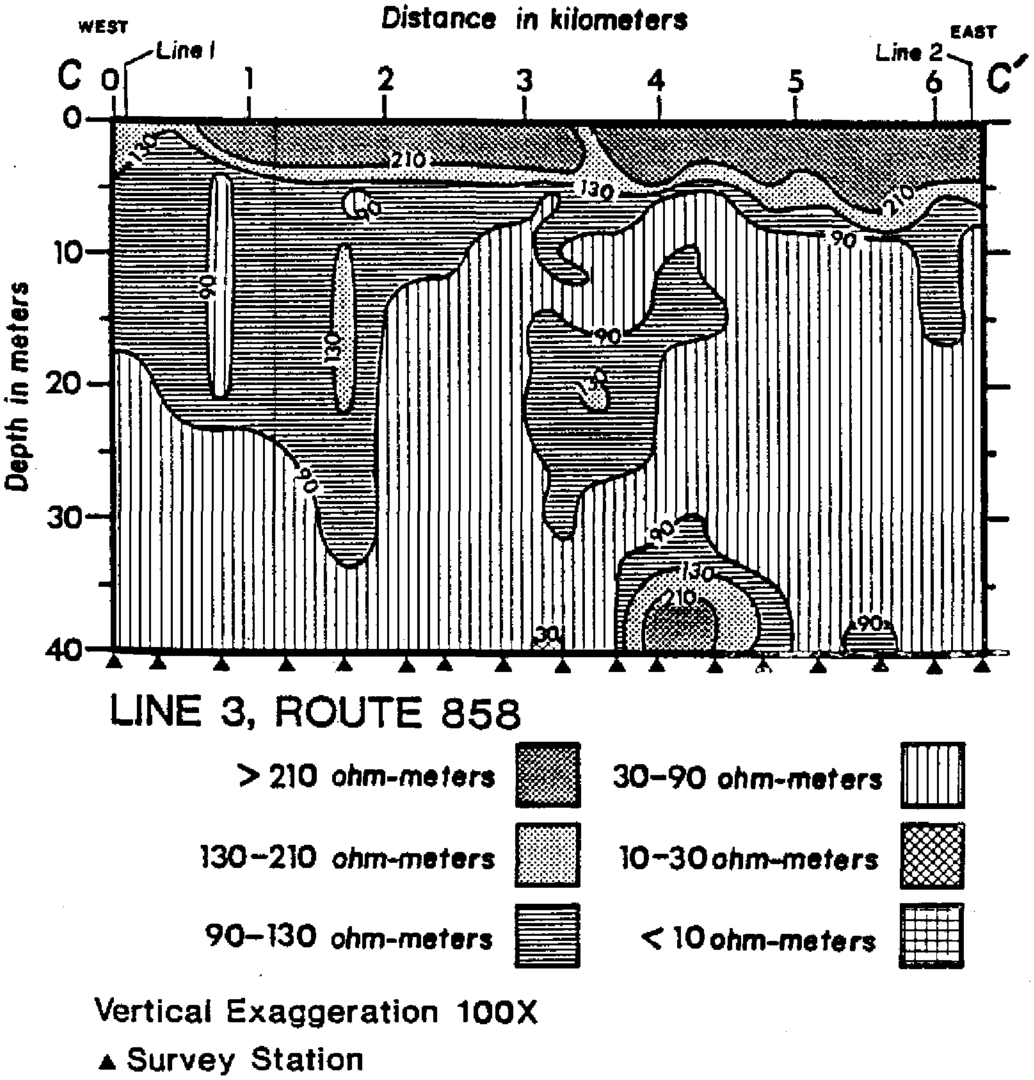


Figure 7. DC resistivity geoelectric cross section, Line 3, County Route 858. Cross section location shown in Figure 2.

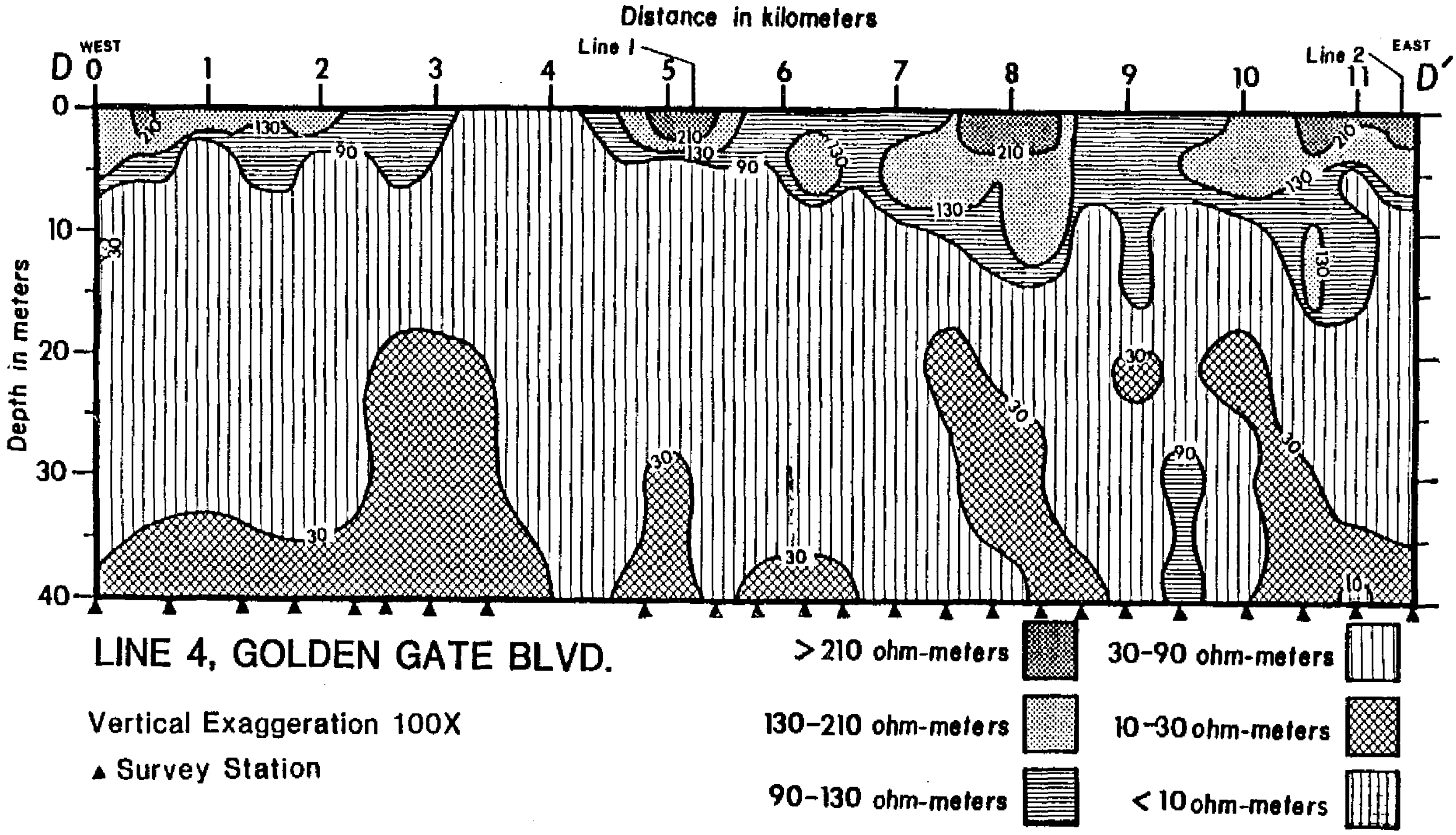


Figure 8. DC resistivity geoelectric cross section, Line 4, Golden Gate Boulevard. Location shown in Figure 2.

southern portion of Figure 6 (19 to 23 kilometers), the only high-resistivity responses near the surface are three isolated patches with resistivities of slightly greater than 130 ohm-meters. Figure 7 shows a continuous occurrence of near-surface, high-resistivity along the entire length of the cross section. The high-resistivity features occurring near the surface in Figure 8 appear again as discontinuous patches; however, there is a general increase in the size and thickness of these features in the eastern portion of the cross section.

The second set of features in the cross sections are sites of low-resistivity response (less than 30 ohm-meters) occurring between 20 and 40 meters of depth. In Figure 5 these sites of low resistivity are located at 1, 2, 6, 7.5, and 9.5 kilometers. In Figures 6 and 7 low-resistivity sites below a depth of 20 meters are inconsequential. Figure 8 shows a common occurrence of low-resistivity response below 20 meters. In the cross sections which contain a continuous or nearly continuous occurrence of high resistivity between 0 and 10 meters of depth (Figures 6 and 7), the occurrence of sites of low-resistivity response below a depth of 20 meters is minor in comparison to the cross sections with discontinuous near-surface, high-resistivity patches (Figures 5 and 8).

The third distinctive feature seen in the cross sections is the occurrence of a high-resistivity response below a depth of 20 meters in each of the sections. In Figures 6 and 7 these features occur at kilometers 5 and 4 respectively, and are characterized by maximum resistivities in excess of 210 ohm-meters and a limited horizontal extent. At kilometers 6.5 and 9.5 in Figures 5 and 8, respectively, high-resistivity responses occur below 20 meters; however, the maximum resistivity values are lower than those of Figures 6 and 7. The high-resistivity features at depth in Figures 5 and 8 also occur with the low-resistivity responses below 20 meters. The location within each cross section of these high-resistivity features at depth is also significant. The map location of each of these high-resistivity features is shown in Figure 9. The high-resistivity features in Figures 5, 6, and 7 are nearly linear with an alignment of approximately N 44°E. The high-resistivity feature at depth in Figure 8 lies approximately 6.3 kilometers southeast along the perpendicular to the trend of the other three high resistors.

In addition to the four DC resistivity geoelectric cross sections, electromagnetic terrain conductivity measurements were taken along the southern 18 kilometers of the Everglades Boulevard - North geoelectric cross section (Figure 6), utilizing the same survey stations as the DC resistivity survey. This first set of EM measurements was taken in order to directly compare the DC resistivity and EM responses. Figure 10 shows the results of this comparison. The southern portion of the EM traverse in Figure 10 (between kilometers 19 and 22), shows little lateral change in resistivity except for a small peak in the 20 meter coil separation plot at kilometer 21. This peak at kilometer 21 corresponds to the location of three isolated high-resistivity (slightly greater than 130 ohm-meters) sites in the geoelectric cross section. A larger increase in the EM response is seen between kilometers 15 and 18, which corresponds with near-surface, high-resistivity patches in the cross section. The gap in the 40 meter coil separation plot of the EM data between kilometers 14 and 18 is the result of the instrument interference from an outside electromagnetic field produced by a pumping

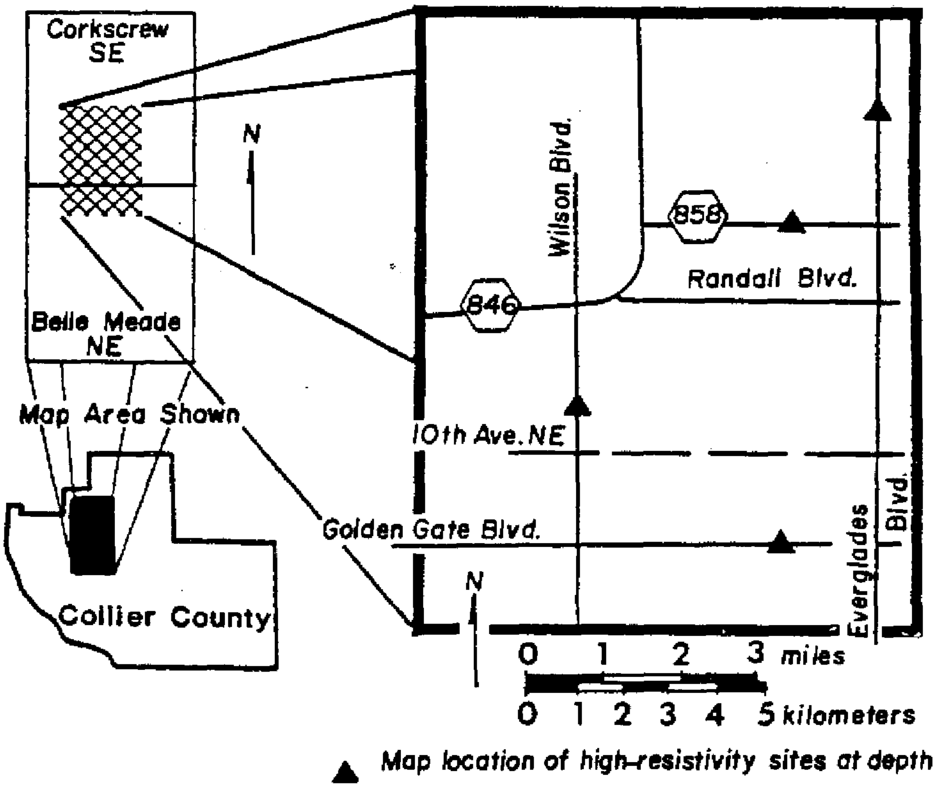
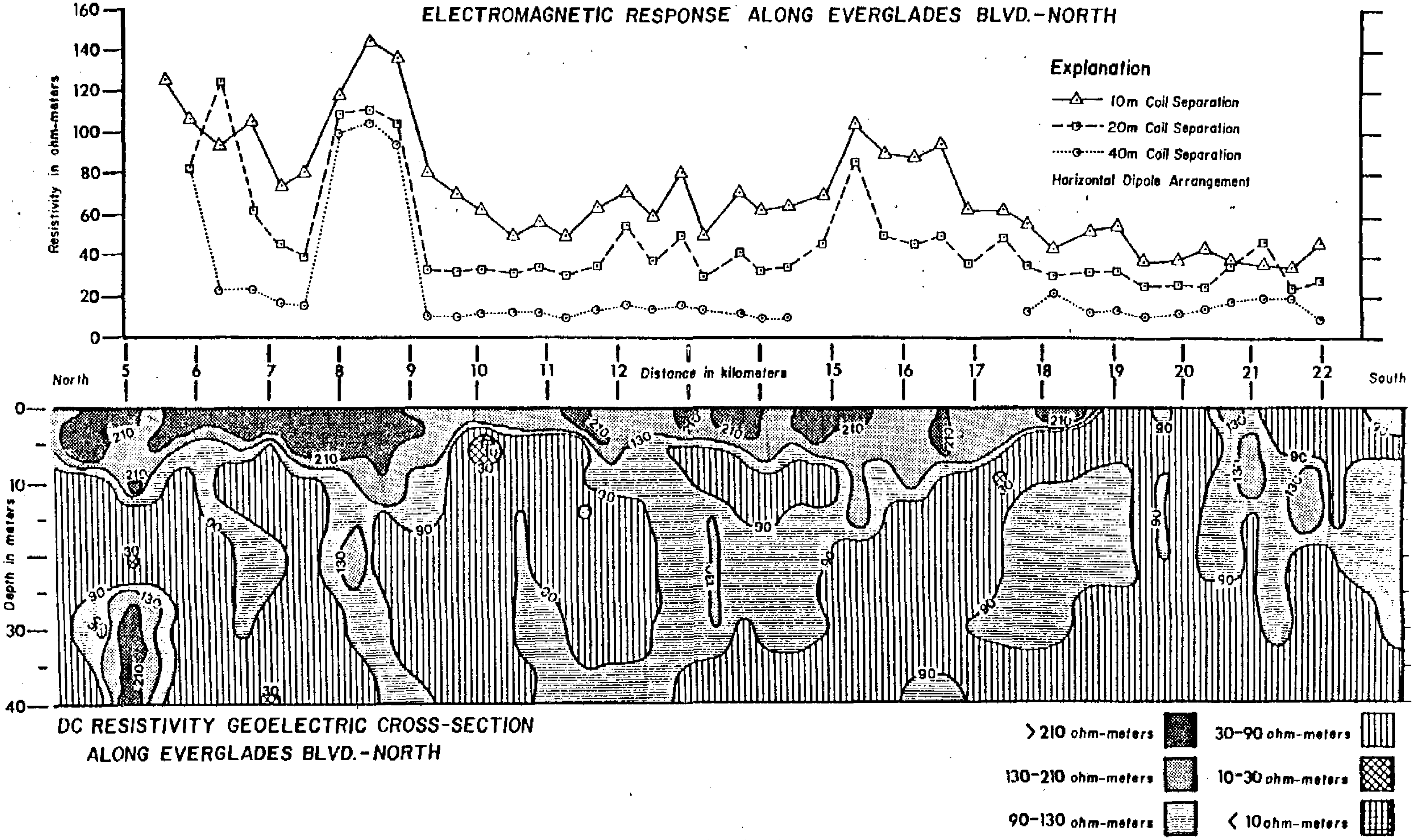


Figure 9. Location of high-resistivity sites at depth, based on DC resistivity geoelectric cross sections.



ELECTROMAGNETIC RESPONSE ALONG EVERGLADES BLVD.-NORTH

DC RESISTIVITY GEOELECTRIC CROSS-SECTION ALONG EVERGLADES BLVD.-NORTH

Figure 10. EM and DC resistivity response along portion of Line 2, Everglades Blvd. - North.

well-field located to the east of the survey traverse. The EM response generally decreases between 10.5 and 15 kilometers where the geoelectric cross section shows a thinning of the higher resistivities near the surface. The large increase in the EM response between kilometers 8 and 9 correlates with the occurrence of large, thick, high-resistivity sites near the surface, and high resistivities continuing to a depth of nearly 30 meters. The variable EM response at the northern end of the EM plot (kilometers 5 to 6) reflects a more complicated portion of the geoelectric cross section in which the resistivities are very high near the surface, low at a moderate depth, and very high in the deeper part of the section.

With a good relative correlation established between the electromagnetic and DC resistivity data, the EM survey was continued with a greater station density (approximately 320 meter centers) within the area enclosed by the four geoelectric cross sections (Figure 11). This EM survey consisted of both horizontal and vertical dipole arrangements of the 10 and 20 meter coil separations. The contoured resistivity data of these coil separations and dipole arrangements are shown as resistivity maps in Figures 12, 13, 14, and 15.

Figure 12 shows the EM response within the survey area using the 10 meter/horizontal dipole arrangement. The effective depth of exploration of this coil separation and dipole arrangement is approximately 7.5 meters (Table 1), with approximately 70% of the response resulting from material shallower than the 7.5 meter exploration depth. A more detailed explanation of the relationships between coil separation, dipole arrangement, depth of exploration, and contribution to total response is given in Appendix I. In Figure 12, several high-resistivity

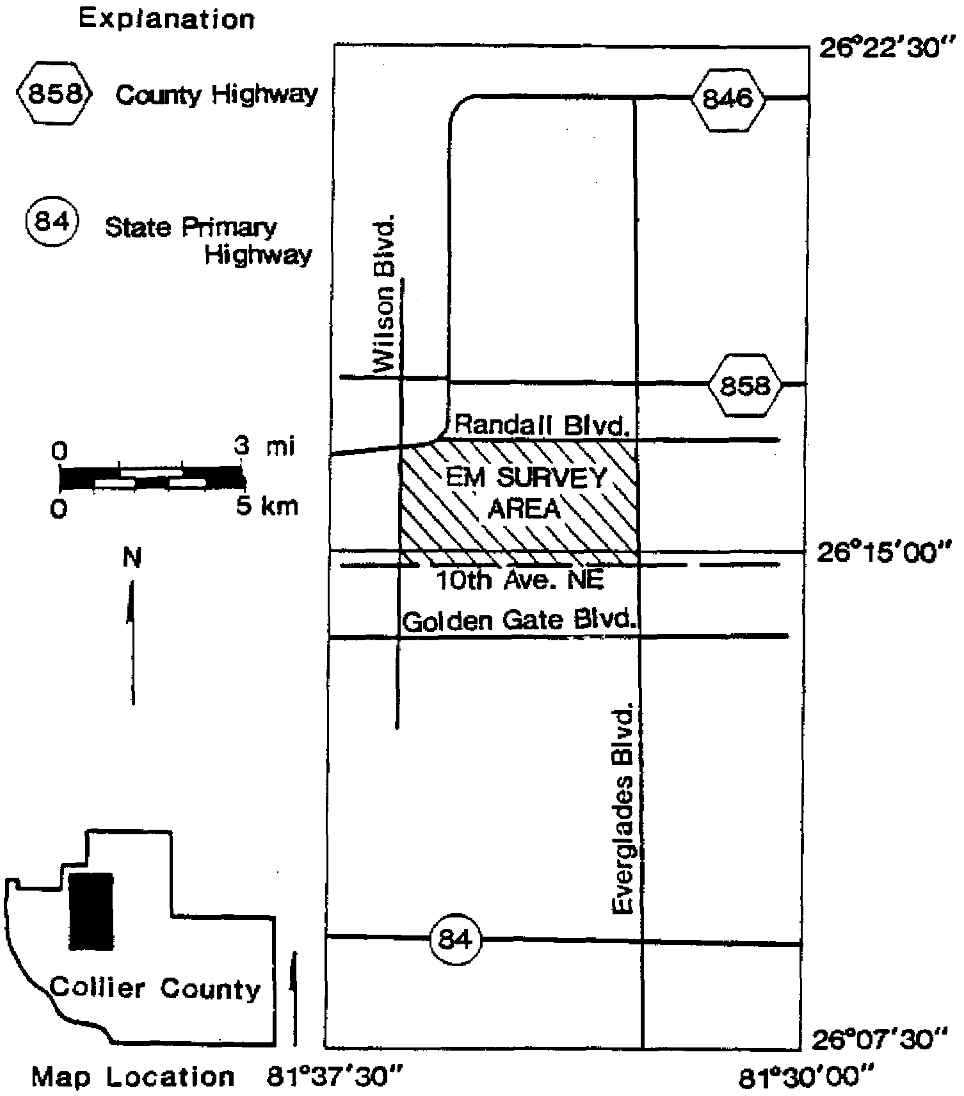


Figure 11. Location of EM survey area within Corkscrew SE and Belle Meade NE 7½' quadrangles, Collier County.

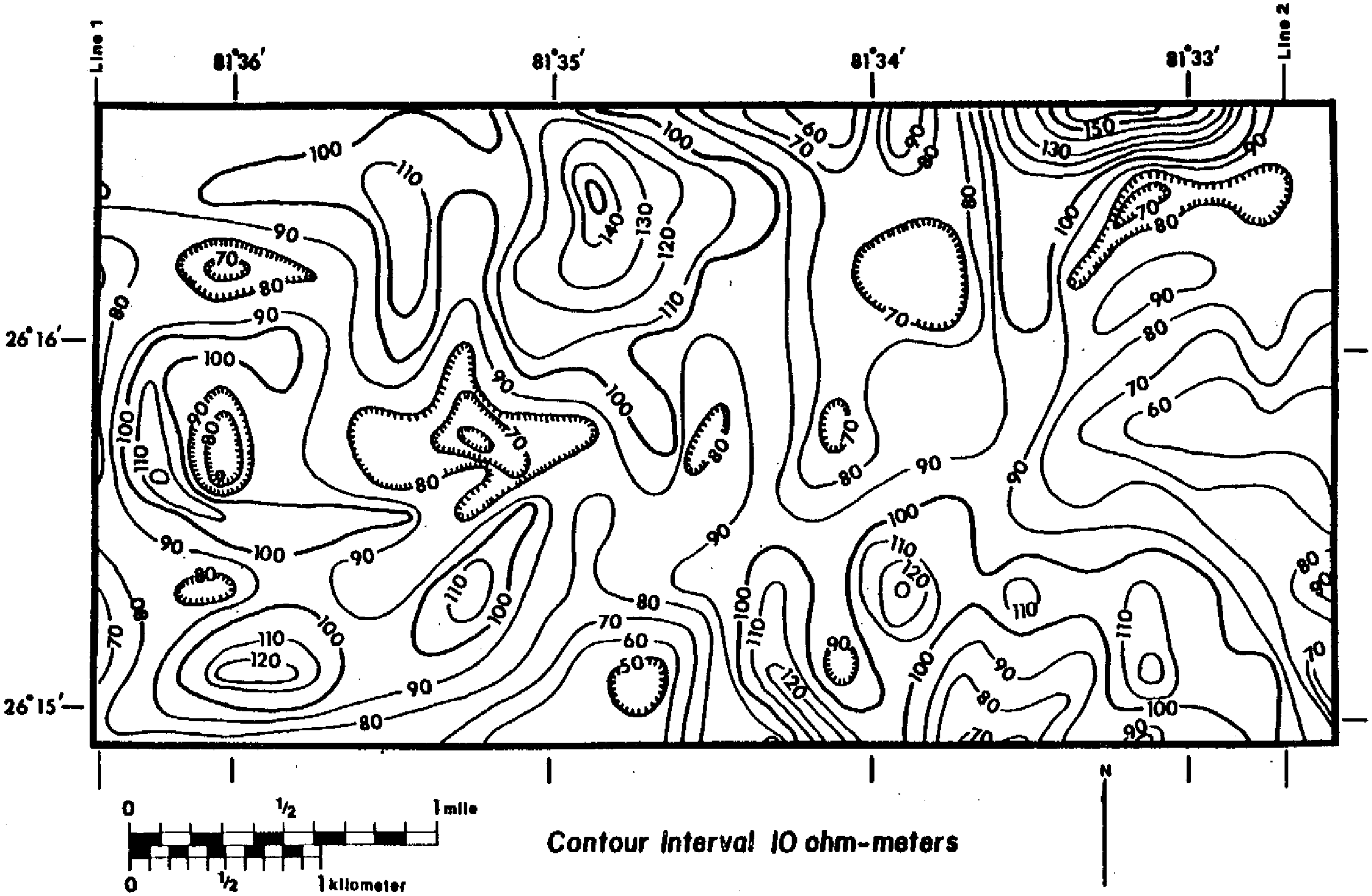


Figure 12. EM response for 10 meter coil spacing, horizontal dipole arrangement. Map location shown in Figure 11.

sites (greater than 110 ohm-meters) occur throughout the survey area. Two sites with higher resistivities than other portions of the map occur in the north-central and northeast portions of the survey area, with resistivities >150 and >160 ohm-meters, respectively. A site of low resistivity (<50 ohm-meters) occurs in the south-central portion of the area.

The 10 meter/vertical response, shown in Figure 13, also exhibits several sites with resistivities >110 ohm-meters; however, only one location in the northeastern portion of the area has resistivities in excess of 150 ohm-meters. The lowest resistivity sites in this map occurs at the east-central margin of the survey area and is slightly greater than 50 ohm-meters. The depth of exploration of this coil separation and dipole arrangement is 15 meters, with 70% of the response resulting from material 6 to 15 meters in depth.

The 20 meter/horizontal response (Figure 14) shows a marked change in the resistivity response from the previous map. The resistivity values range from 36 to 133 ohm-meters with the high low-resistivity sites occurring in the northeast and east-central portions of the survey area, respectively. Although the depth of exploration of this coil separation and dipole arrangement is also 15 meters, the 20 meter/horizontal response is more strongly influenced by the deeper portion of the measured 15 meter section than the 10 meter/vertical response (see Appendix I). For this reason, Figure 14 shows generally lower resistivities as compared to the 10 meter/vertical map (Figure 13).

Figure 15 shows the 20 meter/vertical response with an effective depth of exploration of 30 meters. For these measurements, 70% of the resistivity response results from material between 12 and 30 meters in

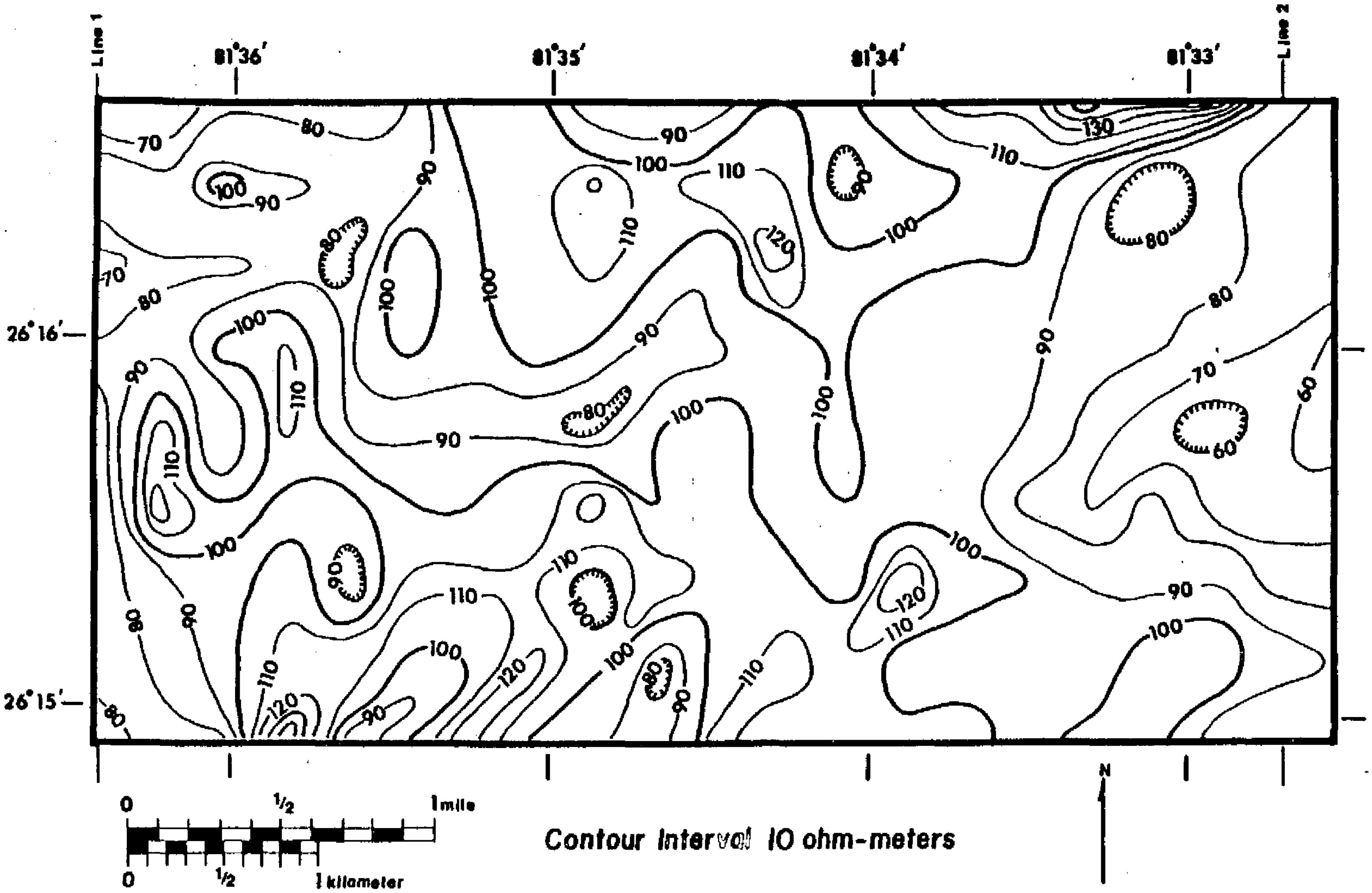


Figure 13. EM response for 10 meter coil spacing , vertical dipole arrangement. Map location shown in Figure 11.

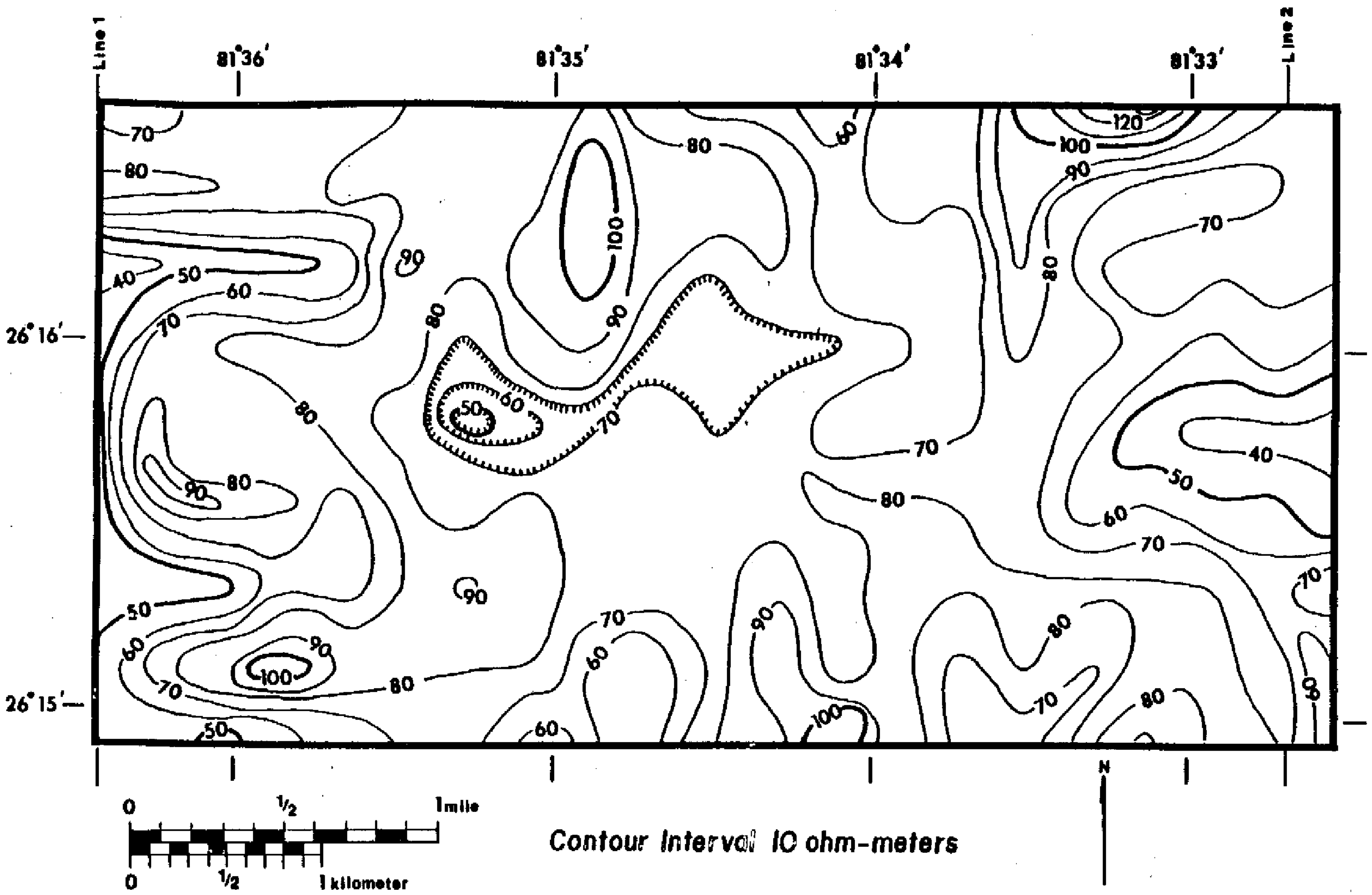


Figure 14. EM response for 20 meter coil spacing, horizontal dipole arrangement. Map location shown in Figure 11.

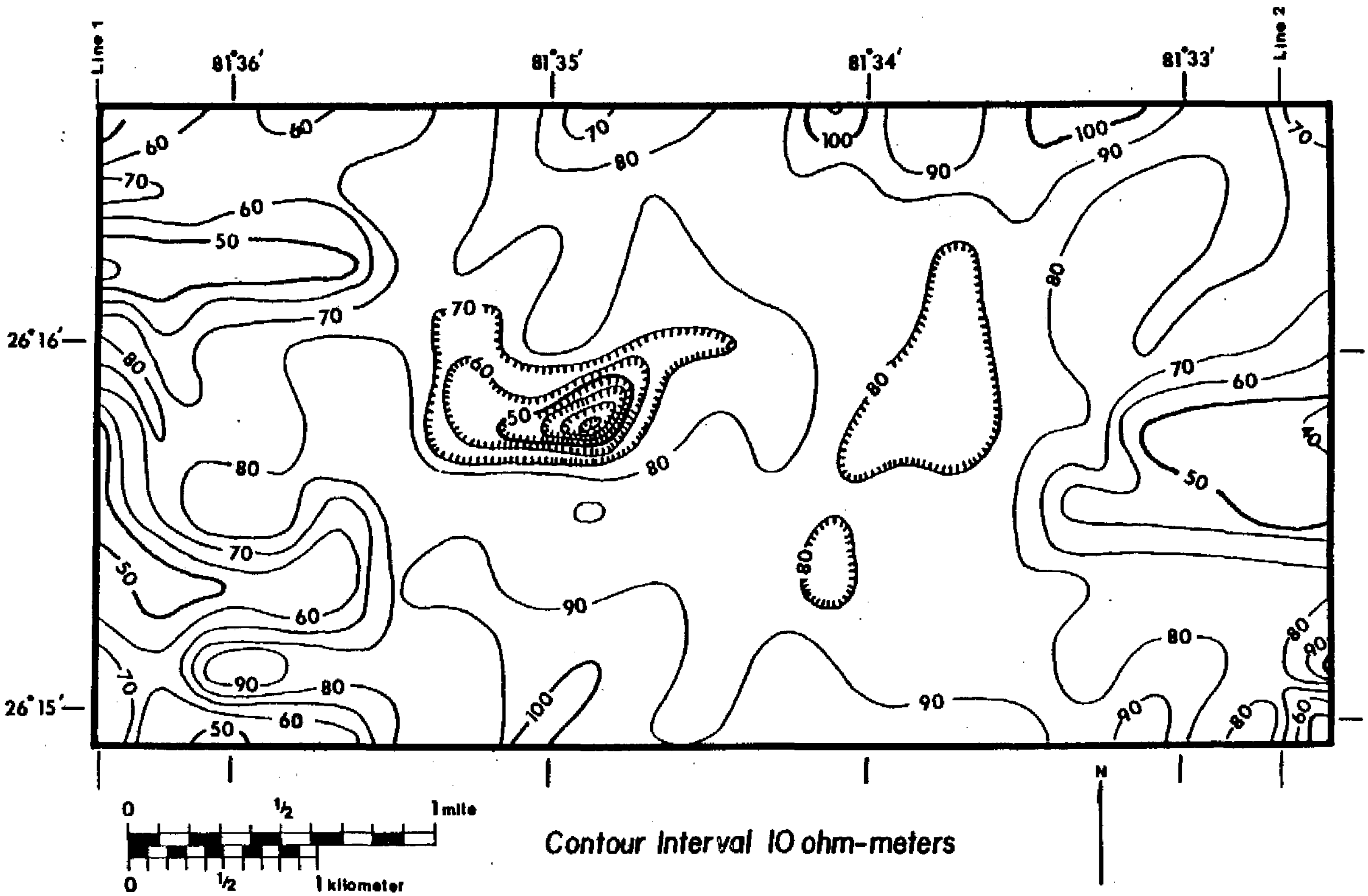


Figure 15. EM response for 20 meter coil spacing, vertical dipole arrangement. Map location shown in Figure 11.

depth. It is interesting to note that the high-resistivity responses are restricted to the central portions of the 10 meter horizontal and vertical maps, while the low-resistivity responses predominate in the eastern and western portions of the 20 meter horizontal and vertical maps.

DISCUSSION

As previously described, the amount of electrical current - measured as conductivity - that will flow through an earth material is a function of the matrix mineralogy, porosity, and the amount and conductivity of interstitial fluids. Where metallic or clay minerals in the measured section are not common, the resistivity of an earth material may be expressed in terms of porosity and conductivity of interstitial water. In southern Florida, and particularly in the area of investigation, the earth materials present are carbonates (limestones), terrigenous clastics (quartz sands), and marls (carbonate silts). These materials do not conduct current electronically; therefore, the resistivities of earth materials in southern Florida may be expressed in terms of their porosities and quality of interstitial water. The relationship between porosity and water quality as related to the resistivity of nonconducting materials is diagrammatically represented in Figure 16.

In Figure 16, the influence of poor quality water (high electrolyte concentration) in the section is represented by moderately-low or low values of measured resistivity. Porosity will affect resistivity to some degree when water quality is poor, however, not to the extent of producing moderately-high or high resistivity values. By making a comparison between chemical analyses and geophysical well-log data (lateral resistivity logs) from water wells drilled in southwestern Collier County, Jakob (1980) found that the potable water limit of 250 ppm Cl^-

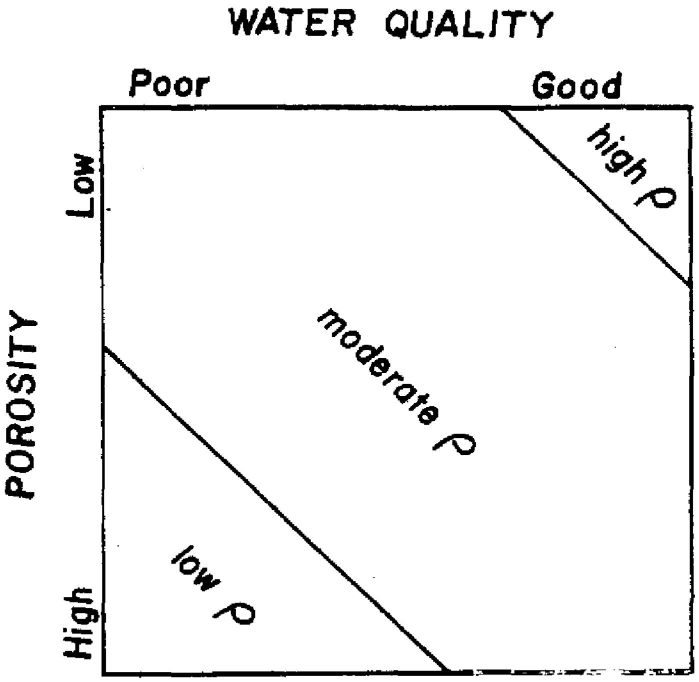


Figure 16. Diagrammatic relationship of resistivity (ρ) to porosity and water quality.

corresponds approximately to a resistivity of 30 ohm-meters. Comparison of electrical sounding, well-water conductivities, and chemical analyses data (Stewart and others, in press) of similar areas in Collier County suggests a resistivity value of 20 ohm-meters for the potable water limit. The vertical sounding and lateral resistivity well-log data indicate a wide range for the resistivity value of the potable water limit; however, the 30 ohm-meter value appears to be a safe, conservative estimate of the potable water limit in southern Florida.

Resistivity values generally increase as water quality becomes better because of lessened electrolytic conduction of current in fresher water. Unfortunately, moderate resistivities (30 to 100 ohm-meters) are not as diagnostic of water quality as low resistivity values (< 30 ohm-meters). The reason for the ambiguity with moderate resistivities is because of the nonuniqueness of the moderate resistivity response to varying combinations of porosity and water quality. Moderately good quality water may produce moderate resistivity responses regardless of porosity, but conditions of poor quality water and low porosity (Figure 16) may also produce the same moderate resistivity response. Porosity begins to affect the resistivity response to a greater degree as water quality becomes better. In Figure 16, as water quality becomes relatively good and porosity decreases, the resistivity response approaches higher values (>100 ohm-meters). This high resistivity response is unique to either (1) the combination of low primary porosity and good water quality, or (2) very dry, nonconducting material, but because of the high water-table conditions of the study area, the latter explanation is discounted.

In the geoelectric cross sections (Figures 5, 6, 7, and 8) the only large occurrences of resistivities in excess of 100 ohm-meters are within the upper 10 meters of the section. Water analyses from wells drilled in the northwestern portion of the county (Nuzman, 1971) indidate that the water quality within most of the upper 20 meters of the section is relatively good. Accordingly, localities in this portion of the county with near-surface resistivity responses in excess of 100 ohm-meters, as measured by surface DC and EM resistivity methods, must be indicative of sites of materials with low primary porosity. Canal-spoil and well control throughout the northwestern portion of the county show the upper 10 meters of the stratigraphic section to be largely limestone (see Appendix II). Based on the resistivity data, in light of the water quality and lithologic information, the near-surface limestones appear to have lower primary porosities than materials immediately beneath them. Therefore, variability in the porosity and permeability of the near-surface limestones will greatly influence the interaction between surface water and ground water in the shallow aquifer.

The description of porosity in limestones and other carbonates can be very difficult and complicated. Choquette and Pray (1970) devised a scheme for porosity classification in carbonate rocks based on the interaction of many related and unrelated factors. They describe porosity development as being fabric and non-fabric selective. Fabric-selective porosity develops with regard to existing pore spaces, whether they are interstices between grains or voids in the framework of organisms. Non-fabric-selective porosity (such as localized solution cavities) develop independently of existing pore spaces. Choquette and Pray (1970) also mention that mineral assemblage, as well as porosity, changes as carbonates diagenetically mature from sediment to rock. Carbonate porosity decreases as sediment matures and the mineral assemblage changes from one of unstable forms of calcium carbonate, such as aragonite and high-magnesium calcite, to one of stable $CaCO_3$ forms of low-magnesium calcite. Choquette and Pray (1970) summarize this concept by saying, "In essence, very porous, heterogeneous mixtures of stable and unstable carbonate minerals become non-porous rocks composed of calcite or dolomite." (Choquette and Pray, 1970, p. 213).

The development of limestone porosity can also be facies-selective by virtue of the structural framework and mineral composition of various fossil organisms within the limestone. Because aragonite and high-magnesium calcite are the more unstable forms of $CaCO_3$ and will dissolve more readily than the stable forms, carbonate facies which contain large percentages of fossil organisms composed of unstable $CaCO_3$ should develop porosity by solution more rapidly than facies composed of stable $CaCO_3$, given the same conditions. The more rapid solution of aragonitic fossil material coupled with the open structural framework of some organisms, such as corals, should produce a limestone with very high solution porosity. Although this process may begin as fabric-selective, it can rapidly become non-fabric selective. Choquette and Pray (1970) discussed the localization of solution porosity which is not fabric-selective and concluded that the solution seems to be related chiefly to the presence and flow of permeating waters which produce solution along the walls of major flow passageways. The open framework of corals in a reef limestone facies would provide the initial permeability necessary to begin the development of solution cavity porosity in the limestone.

With the solution of aragonite in the limestone-forming cavities, the increased contribution of dissolved $CaCO_3$ in the pore water will have an effect on the precipitation of $CaCO_3$ as calcite cement on the remaining carbonate grains in the rock. When dissolved $CaCO_3$ in the pore water becomes saturated with respect to calcite, some calcite will precipitate on grain boundaries, cementing the grains together and reducing the size of interstices among grains. If the amount of aragonite to be dissolved within the limestone is great, large solution cavities may be opened and a great deal of cementation of the remaining rock will occur, producing a very low primary porosity limestone with large solution cavities. The overall limestone porosity would be very low, while the permeability would be high because of the localized solution.

Porosity development in the reef limestone facies of the Upper Tamiami Formation as described by Meeder (1979), and as examined in the field for this investigation, illustrates the diagenetic scheme outlined above. The large aragonitic coral heads of the reef facies have been removed by solution and in some instances replaced by calcite and the remaining carbonate grains have been very well cemented. Associated facies with fewer aragonitic fossils and more quartz sand are not as well cemented as the reef facies and generally have a higher porosity. The very low-porosity, high-permeability reef limestones should have a higher resistivity response than the associated facies with slightly greater porosity and presumably less permeability. The areas outlined in Figure 17 which shows the distribution of highly-cemented/high solution porosity limestones, low quartz sand content, and extent of coralline facies, all correspond with one another which supports the

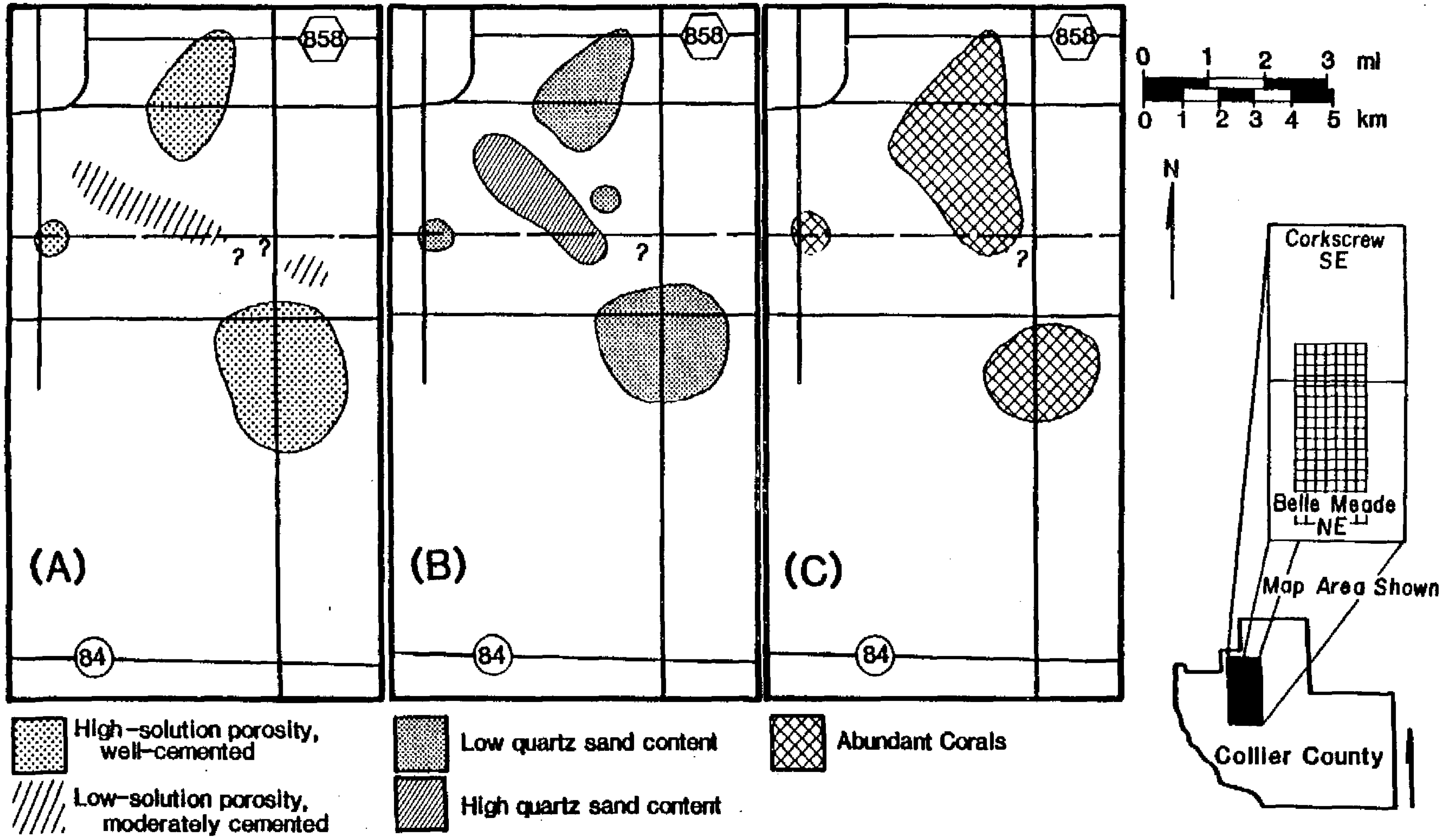


Figure 17. Extent of (a) well-cemented and high solution porosity, (b) high and low quartz sand content, and (c) coralline facies limestones based on examination of canal spoil within study area.

porosity development scheme. These areas also generally correspond to the highest resistivity responses in the geoelectric cross sections and the shallower EM profiles. The criteria used to describe the limestone blocks in canal spoil are explained in Appendix III.

The greater permeability of the low-porosity reef limestones is also implied by the DC and EM data. As described in the results section of this report, sites of low-resistivity response occurring below a depth of 20 meters - interpreted as poor quality (nonpotable) water based on the findings of Jakob (1980), Stewart and others (in press), and the absence of clay in the measured section (Appendix II) - are sparse beneath the highly resistive surface limestones (reef facies) and becomes more prevalent beneath less resistive limestones. The more permeable reef limestones allow open communication between fresh surface water and ground water of the shallow aquifer, providing a flushing of poorer-quality, nonpotable water from the shallower portions of the aquifer. Where flushing does not occur, as beneath the less permeable, lower solution porosity limestones, poor quality water remains in the shallower portions of the aquifer.

Another feature described in the geoelectric cross sections is a nearly linear, high-resistivity trend occurring below a depth of 20 meters (Figure 9). EM measurements, using the 40 meter horizontal and vertical dipoles, were taken within a narrow survey area in line with the trend, in order to determine the vertical continuity and electromagnetic response of the trend. Figure 18 shows the contoured data from this EM survey. The same survey stations were used for the narrow survey area as were used in all other coil separation and dipole arrangements in the larger EM survey area. Parts (a) and (b) of Figure 18

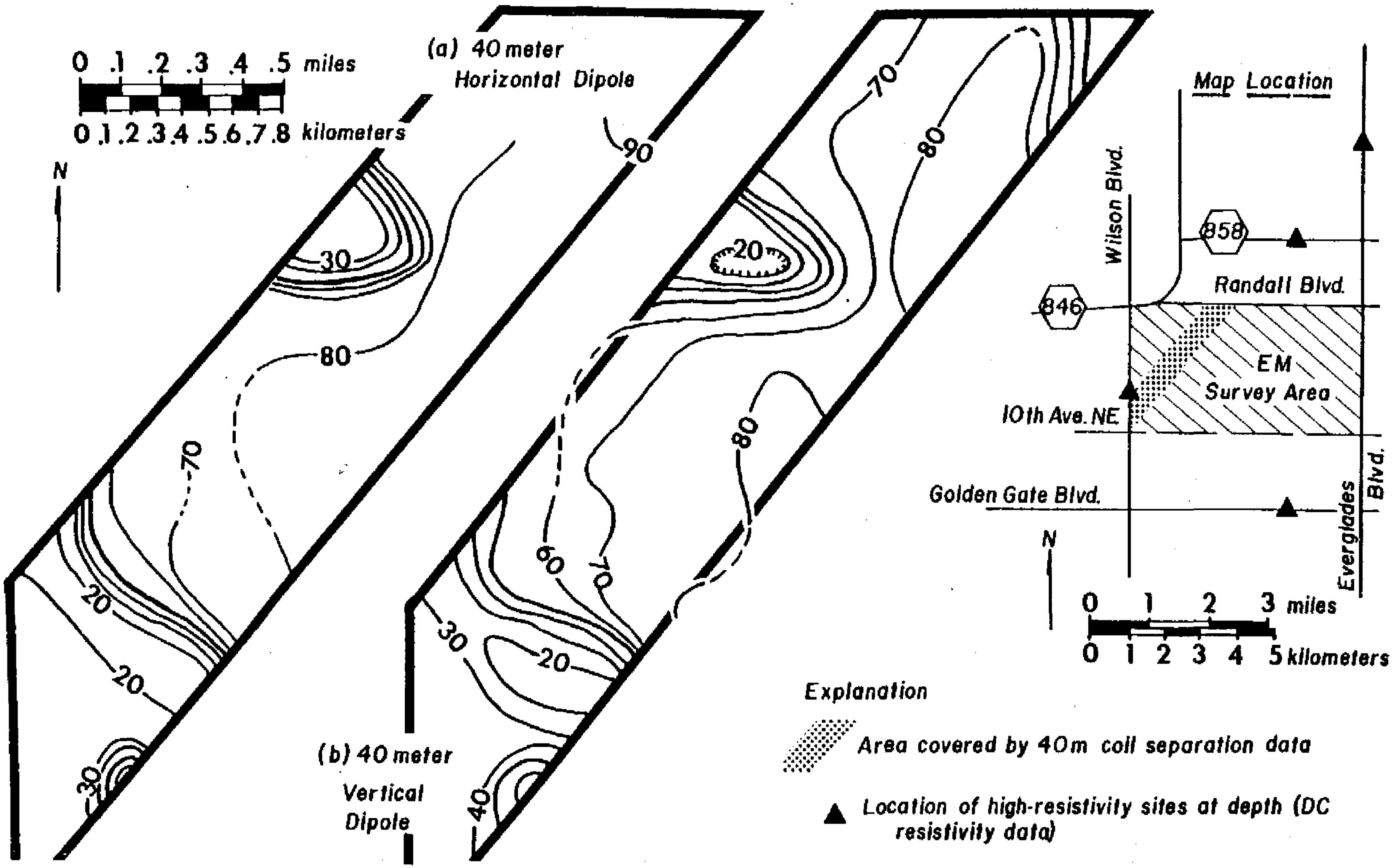


Figure 18. Electromagnetic response along high-resistivity trend as depth, as defined by DC resistivity data; (a) 40 meter horizontal dipole, (b) 40 meter vertical dipole.

show low resistivities occurring in the western and southern portions of the narrow survey area, while higher resistivities occur in the eastern portion. The occurrence of both low and high resistivities at these locations in the narrow survey area are in agreement with the locations of high and low resistivities from the 20 meter horizontal and vertical dipoles of the larger EM survey area (Figures 14 and 15, respectively). Although there is good agreement of location between the EM maps, the higher resistivities of the 40 meter surveys do not show the same general decrease in resistivity values as is seen with the other maps as depth of exploration is increased. This implies a continuation of higher-resistivity material to depths greater than the 60 meter exploration depth of the 40 meter/vertical survey. If low-resistivity material occurred beneath the higher-resistivity material, then the 30% of the EM response which is sensitive to material deeper than the 1.5 intercoil spacing would influence the resistivities of the measured section such that resistivities of the deeper exploration depths would be lower than those observed. This is not conclusive evidence of the vertical continuity of the high-resistivity trend, but it is one indication that higher-resistivity material occurs deeper in the section.

One explanation for the high-resistivity response below a depth of 20 meters is shown in Figure 19. In this figure, DC resistivity data from the geoelectric cross section along Route 858 are compared to bore-hole and water-bearing capacity information from a water well drilled approximately 200 meters south of the survey line. The very-high-resistivity response near the surface corresponds to hard limestones occurring to a depth of 10 meters. The deeper high-resistivity response

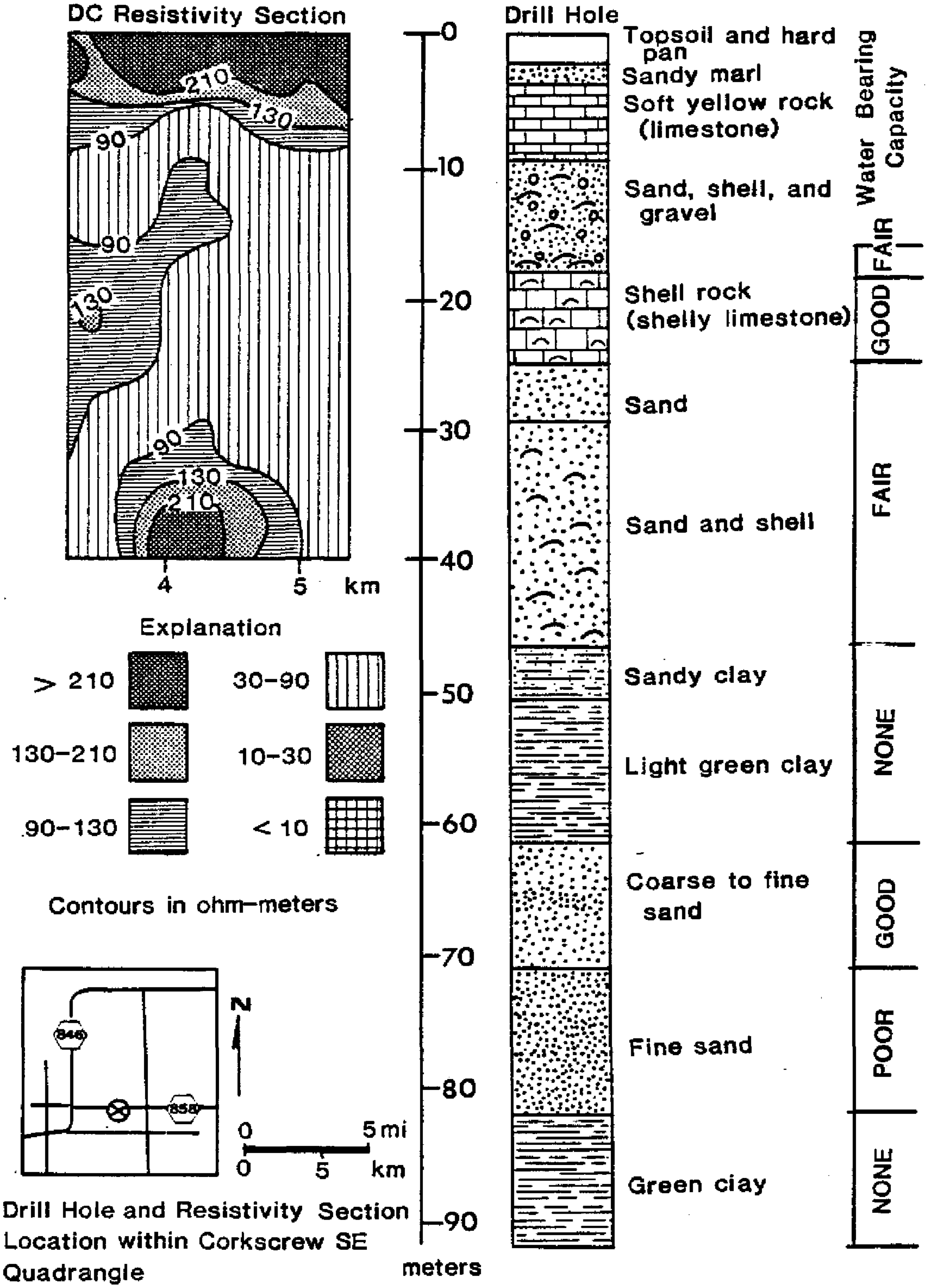


Figure 19. Comparison of DC resistivity, drill hole, and water-bearing capacity data of a portion of Line 3, County Route 858 (Nuzman, 1981, p. 83).

corresponds to a shelly sand with a fair water-bearing capacity and good water quality (Nuzman, 1971). Although extrapolations based on one drill hole are risky at best, the linearity and limited width of the deeper high-resistivity response, the indication of a continuation of higher-resistivity material at depth from EM data, and the correspondence of resistivity data to a shelly-sand facies with good water quality may indicate the presence of more permeable sand channel deposits in the stratigraphic section, possibly being recharged from the higher topographic areas to the northeast of the study area. The occurrence of a sand channel would also accomodate the location of the deeper high-resistivity response along Golden Gate Boulevard as another channel possibly connecting to the linear trend defined by the other geoelectric sections. The generally lower resistivities of the deeper high-resistivity responses of the Wilson and Golden Gate Boulevard sections may be explained simply as a greater influence of poorer-quality water as the recharged waters travel farther from the recharge area southwestward into areas of poorer quality water in the southwestern portions of the study area. This explanation of the high-resistivity trend below 20 meters of depth is very speculative because of limited data. Confirmation or rejection will result only after further resistivity surveys and more bore-hole and pumping data.

SUMMARY AND CONCLUSIONS

Several surface electrical surveys using DC resistivity, conducted in northwestern Collier County, Florida, reveal the occurrence of a distinct high-resistivity response near the surface of the measured geoelectric section. The high-resistivity response is characterized by resistivities in excess of 130 ohm-meters occurring as patchy features at depths generally less than 10 meters. The relatively good ground-water quality, and absence of significant amounts of clay in the shallow section in this portion of the county indicate that the high-resistivity response is the result of lithologic variations near the surface. These lithologic variations are related to primary porosity changes of the materials present.

Examination of limestone blocks in spoil banks of drainage canals throughout the survey area revealed marked variability of cementation, solution-cavity development, and quartz sand content of limestones present. The high-resistivity response correlates closely with the location of very well-cemented, low-quartz-sand limestones with well-developed-solution porosity. This lithologically-distinctive limestone is also distinguished by a distinctive coralline/molluscan biofacies which is described by Meeder (1979) as a reef facies of Mid-Pliocene age within the Upper Tamiami Formation.

The limestone reef material within the study area appears to have favored solution-porosity development to a much greater degree than associated facies because of the greater quantity of aragonite-utilizing organisms in the reef facies. The aragonitic material of the limestone was more easily removed by solution than the more stable forms of calcium carbonate. Not only did the abundance of aragonite in the reef facies influence solution-porosity development, but also must have influenced the cementation history of the carbonate. The excess calcium carbonate in the pore water, provided by the dissolution of aragonite, produced a very well-cemented limestone with well-developed solution cavities. The high-resistivity signature of these limestones is the result of low primary-porosity of the material and good quality, low conductivity, interstital waters.

Because the development of solution porosity appears to be facies selective, the locations of the limestone reef facies and their influence on the rechange of the shallow aquifer are significant. The high-resistivity response of the reef limestones provides the opportunity to map the areal extent of the facies with surface geophysical methods. DC resistivity proved to be an excellent method for delineating the reef facies; however, because of the manpower and time required to conduct DC soundings, the number of soundings necessary to sufficiently define the extent of the reef facies may not be feasible on a large scale.

Electromagnetic terrain conductivity measurements were taken, utilizing the same station locations as the DC resistivity survey, along a 17 kilometer portion of Everglades Boulevard. The EM measurements were obtained in order to directly compare the EM and DC resistivity response to the same features. A good relative response was established between the two methods and the EM survey was continued at a greater survey station density to determine the areal extent of the reef facies over approximately a 19.5 km^2 area. Sites of high resistivity (in excess of 110 ohm-meters) coincided with locations of the distinctive reef facies as defined from examination of canal spoil banks. Data obtained with the EM surveys also indicate that the high-resistivity response is largely limited to the near-surface portions of the geoelectric section.

Both EM and DC resistivity data obtained in the survey area indicate that the near-surface, high-resistivity limestone reef facies influences the interaction between surface waters and the shallow aquifer. In general, portions of the study area in which the reef facies are more common and continuous exhibit only isolated low-resistivity responses below 20 meters of depth. The low-resistivity responses are interpreted as representing poorer-quality ground water in the measured geoelectric section. Portions of the study area in which the reef facies are discontinuous or absent show a much greater occurrence of low-resistivity responses below 20 meters. The segregation of high- and low-resistivity responses in the geoelectric section is indirect evidence of the reef facies acting as sites of surface water recharge for the shallow aquifer, by virtue of high permeability provided by well-developed solution porosity. Beneath extensive occurrences of reef limestones, the poor quality water, which may be from various sources, is flushed from the shallow aquifer by recharging surface waters. Areas which do not contain much of the reef limestones have lower permeabilities, which are related to the primary porosity of the material. Recharge through the associated limestones is small or nonexistant. Pumping tests and chemical analyses of the shallow aquifer waters will provide better information about surface water and ground water interactions in the study area.

An unexpected feature was detected within the study area with the DC resistivity survey. Each geoelectric gross section contained an anomalous zone of high resistivity below 20 meters of depth. Three of these deeper high-resistivity responses are linear with an alignment of approximately N 44° E. The fourth deep, high resistor lies to the southeast of the trend of the other three. The two southernmost high resistors exhibit lower resistivities than the other two. A drill hole in the proximity of one of the high resistors showed a shelly, quartz sand with good water-bearing capacity and good water quality at the same depth as the high-resistivity response (Nuzman, 1971). The restricted width, linearity, and information from the drill hole can be interpreted as indicating a sand channel with possibly slightly coarser material than the surrounding sediments. The lower resistivities of the trend toward the southwest may indicate an increased influence of poor-quality water in the shallow aquifer. The channel sand may be recharged from higher topographic areas to the northeast of the study area.

Significance of Results to Hydrogeology of Northwestern Collier County

Because of extremely low land-surface and even lower water-table gradients in northwestern Collier County, much concern must be given to the ease of contamination and available water supply of the shallow aquifer. With the population of southern Florida expected to increase greatly in the 1980's, great care must be taken in managing ground-water consumption and location of waste disposal systems to keep the shallow aquifer a viable potable water resource. Prior to effective management, determination of aquifer characteristics, including location of local rechange areas will be necessary.

From the electromagnetic and direct current resistivity surveys conducted for this investigation, some of the limestone "cap" rock which underlies the northwestern sections of the county is seen to provide open communication between surface waters and the shallow aquifer because of well developed, facies-selective, solution porosity. Areas with these highly-permeable limestones may prove to be very productive portions of the shallow aquifer. Jakob (1980) and Nuzman (1971) suggest that hard (well-cemented) limestones in the shallow parts of the aquifer are very productive in some portions of the county. Delineation of these highly permeable limestones is very useful not only for defining possible recharge areas, but also for locating potential high-yield portions of the aquifer.

Both EM and DC resistivity surveys of the area were able to delineate the well-cemented, permeable limestone facies. EM measurements proved to be more rapid to conduct than DC measurements. Because EM surveys are faster, they can provide the necessary data point density required to define the patchy occurrence of the limestone over large areas. The same survey station density used with a DC resistivity survey would require a much greater expense of manpower and time to survey the same area. Although EM measurements are more rapid, DC resistivity provides more detailed information than the EM method. However, from the standpoint of reconnaissance of the general earth conductivity of an area, the EM method is more than adequate and probably superior to DC resistivity because of the reduced time and greater data density acquired. EM measurements are more sensitive to interference from cultural and natural sources than DC resistivity, but in undeveloped areas such as northwestern Collier County, most electromagnetic interference sources can be avoided.

Based on the EM and DC resistivity data, supplemented by lithologic information, locations of permeable reef limestones are shown in Figure 20. These areas hold the greatest potential for high yields of good quality water from the shallow aquifer. Currently the City of Naples operates a well field along the Fahka Union Canal, east of Everglades Boulevard, which is within one of the reef limestone locations. High-resistivity responses similar to those attributed to the well-cemented, reef limestones occur to the north of the known localities shown in Figure 20 and are believed to be extensions of the same lithologies; however, because of the lack of outcrop and spoil bank exposures, shallow coring will be required to confirm this hypothesis.

Further investigation of areas to the north and east of the study area using surface geophysical methods, especially electromagnetic terrain conductivity measurements, is warranted in order to determine the location and extent of the permeable reef limestones and provide a good basis for future detailed ground-water surveys of the area. Further study will also be needed to determine the presence or absence of channel sand deposits in the lower part of the shallow aquifer, which may prove to be an excellent source of potable ground water.

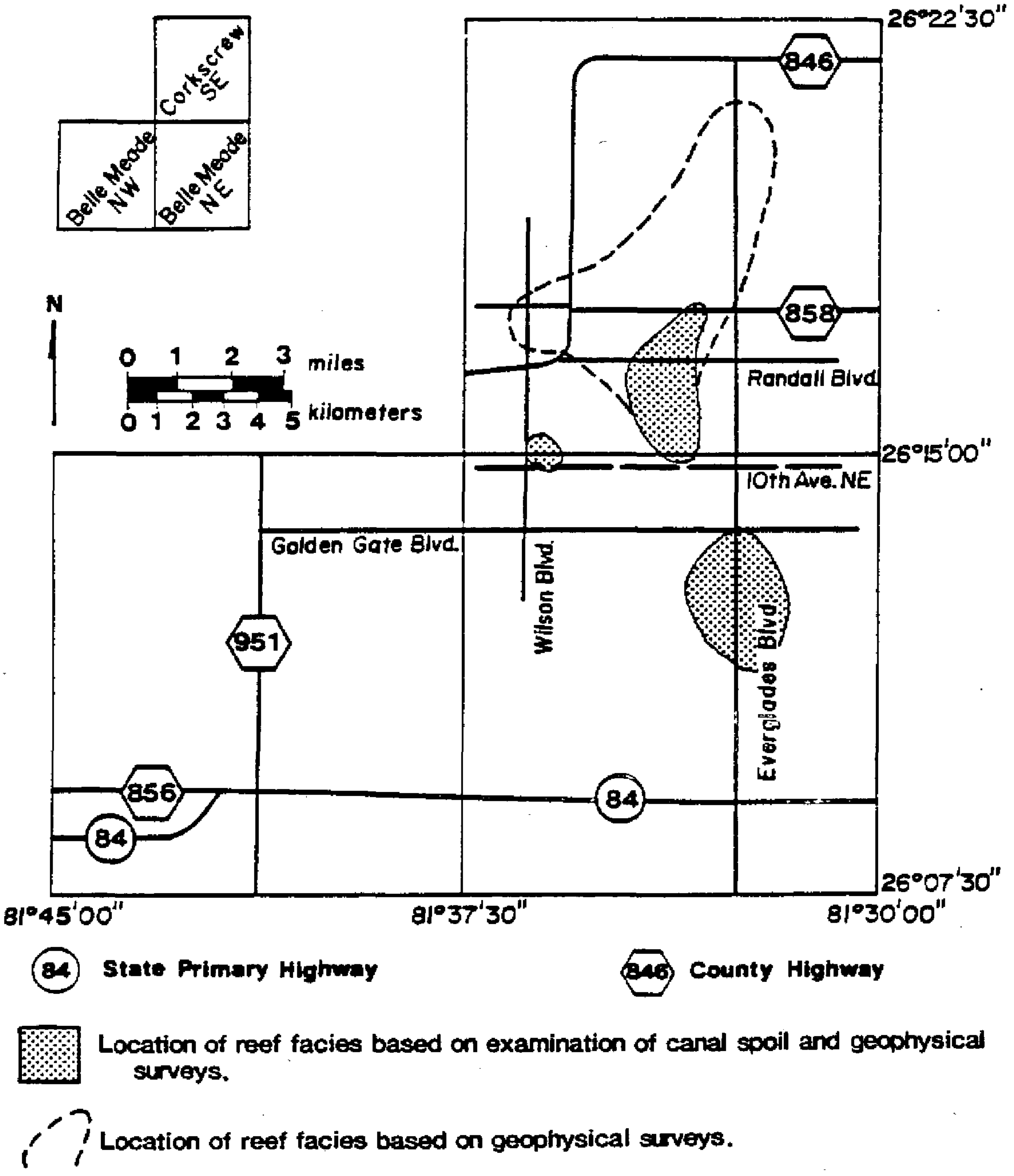


Figure 20. Locations of limestone reef facies based on EM and DC resistivity surveys and lithologic information.

REFERENCES CITED

Akers, W.H., 1974, Age of Pinecrest Beds, South Florida, Tulane Studies in Geol. and Paleo., 11:119-120.

Choquette, Phillip and L. Pray, 1970, Geologic Nomenclature and Classification of Porosity in Sedimentary Carbonates, AAPG Bull.,54(2): 207-250.

Davis, S.N. and R. DeWiest, 1966, Hydrogeology, Wiley and Sons, New York. 463p.

Dobrin, M.B., 1976, Introduction to Geophysical Prospecting, 3rd ed., McGraw-Hill, New York. 622p.

Dougenik, J.A. and D. Sheehan, 1975, SYMAP User's Reference Manual, 5th ed., Laboratory for Computer Graphics and Spatial Analysis, Harvard Univ., Cambridge, MA.

Fretwell, Judy and M.T. Stewart, 1981, Resistivity Study of a Coastal Karst Terrain, Florida, Ground Water, 19(2):156-162.

Griffith, D.H., 1976, Application of Electrical Resistivity Measurements for Determination of Porosity and Permeability in Sandstone, Geoexploration, 14:207-213.

Healy, H.G., 1975, Potentiometric Surface and Areas of Artesian Flow of the Floridan Aquifer in Florida, May, 1974, Florida Bureau of Geol. Map Series No. 73.

Heigold, P.C., R.H. Gilkeson, K. Cartwright, and P.C. Reed, 1979, Aquifer Transmissivity from Surficial Electrical Methods, Ground Water, 17(4):338-345.

Hunter, M.E., 1978, What is the Caloosahatchee Marl?, in Southeastern Geol. Soc. West Palm Beach, Florida, Pub. 20:61-88.

Hyde, L.W., 1975, Principal Aquifers in Florida, Florida Bureau of Geol. Map Series No. 16.

Jakob, Paul, 1980, Some Aspects of the Hydrogeology of Coastal Collier County, Florida, in Water, Oil, and the Geology of Collier, Lee, and Hendry Counties, P. Gleason (ed.), Miami Geol. Soc., Miami, FL.,21-26.

Keller, George and F.C. Frischknecht, 1966, Electrical Methods in Geophysical Prospecting, Pergamon Press, New York, 519p.

Klein, Howard, 1971, Depth to Base of Potable Water in the Floridan Aquifer, Florida Bureau of Geol. Map Series No. 42.

Koefoed, O. and B.T. Biewinga, 1976, The Application of Electromagnetic Frequency Sounding to Groundwater Problems, Geoexploration, 14:229-241.

Lazreg, H., 1972, Application of Surface Resistivity Methods to the Detection of Salt-Water Intrusion in Shippegan, New Brunswick, CIM Transactions, 75:32-41.

McCoy, H.J., 1962, Ground-Water Resources of Collier County, Florida, Florida Geol. Survey, Report of Invest. No. 31, 36p.

McCoy, Jack, 1972, Hydrology of Western Collier County, Florida, Florida Bureau of Geol., Report of Invest. No. 63, 32p.

McNeill, J.D., 1980a, Electromagnetic Terrain Conductivity Measurements at Low Induction Numbers, Technical Note TN-6, Geonics, Ltd., Mississauga, Ontario.

____________ 1980b, EM 34-3 Survey Interpretation Techniques, Technical Note TN-8, Geonics, Ltd., Mississauga, Ontario.

Meeder, J.F., 1979, A Field Guide with Road Log to the Pliocene Fossil Reef of Southwest Florida, 1979 Field Trip Guidebook, Miami Geol. Soc., Miami, FL. 19p.

____________ 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. Gleason (ed.), Miami Geol. Soc., Miami, FL., 27-30.

Missimer, T.A., 1978, The Tamiami Aquifer System in Southwest Florida, in Southeastern Geol. Soc., West Palm Beach, Florida, Pub. 20: 89-102.

Nuzman, C.E., 1971, Golden Gate Estates Investigation for Water Supply and Soil Depth for Septic Tanks, unpublished consultant's report, Layne-Western Co., In.c, Kansas City, MO, 86p.

Parker, C.G. and W.C. Cooke, 1944, Late Cenozoic Geology of Southern Florida with a Discussion of the Ground Water, Florida Geol. Survey Bull. No. 27, 119p.

____________, G.E. Ferguson, S.K. Love, and others, 1955, Water Resources of Southeastern Florida, with Special Reference to the Geology and Ground Water of the Miami Area, U.S. Geological Survey, Water Supply Paper 1255, 936p.

Patra, H.P., 1976, Electromagnetic Depth Sounding for Ground Water with Particular Reference to Central Frequency Sounding: Principles, Interpretation, and Application, Geoexploration, 14:254-258.

Roy, K.K. and H.M. Elliott, 1980, Resistivity and IP Survey for Delineating Saline Water and Fresh Water Zones, Geoexploration, 18:145-162.

Seigel, H.O. and D.H. Pitcher, 1978, Mapping Earth Conductivities Using a Multifrequency Airborne Electromagnetic System, Geophysics, 43 (3):563-575.

Shampine, W.J., 1965a, Sulfate Concentration of Water from the Upper Part of the Floridan Aquifer in Florida, Florida Division of Geol. Map Series No. 15.

_______________ 1965b, Chloride Concentration of Water from the Upper Part of the Floridan Aquifer in Florida, Florida Division of Geol. Map Series No. 12.

Stewart, M.T., T. Lizanec, M. Layton, in press, Application of DC Resistivity Surveys to Regional Hydrogeologic Investigations, Collier County, Florida, SFWMD Technical Report, W. Palm Beach, FL.

_____________, T. Lizanec, A. Kreitman, in press, Hydrogeologic Reconnaissance of a Coastal Aquifer Using DC Resistivity Methods, SFWMD Technical Report, W. Palm Beach, FL.

Telford, W.M., L.P. Geldart, R.E. Sheriff, and D.A. Keys, 1976, Applied Geophysics, Cambridge Univ. Press, London. 841p.

Tripp, A.C., S.H. Ward, W.R. Sill, C.M. Swift, and W.R. Petrick, 1978, EM and Schlumberger Resistivity Soundings in the Roosevelt Hot Springs KGRA, Geophysics, 43(7):1450-1469.

Van Dam, J.C., 1976, Possibilities and Limitations of the Resistivity Method of Geoelectrical Prospecting in the Solution of Geohydrologic Problems, Geoexploration, 14:179-193

Vernon, R.O., 1973, Top of the Floridan Artesian Aquifer, Florida Bureau of Geol. Map Series No. 56

Zohdy, A.A.R., G.P. Eaton, and D.R. Mabey, 1974, Application of Surface Geophysics to Ground-Water Investigations: Techniques of Water-Resources Invest. of the USFS, U.S. Gov't Print. Off., 116p.

_____________ and R.J. Bisdorf, 1975, Computer Programs for the Forward Calculation and Automatic Inversion of Wenner Sounding Curves, National Technical Information Service, PB-247-265/AS, Springfield, VA.

APPENDICES

Appendix I: Relationship of coil spacing and dipole arrangement to depth of exploration for the EM34-3 electromagnetic terrain conductivity meter, based on McNeill (1980a).

The Geonics, Ltd. model EM34-3 electromagnetic terrain conductivity unit consists of a transmitter and receiver coil with accompanying instrumentation and is operated at set intercoil spacings of 10, 20, and 40 meters with either horizontal or vertical dipole arrangements. The transmitter coil is energized with an alternating current at an audio frequency, which produces a time-varying primary magnetic field. The primary magnetic field induces small currents within the earth which generate a secondary magnetic field that can be sensed by the receiver coil along with the primary magnetic field. McNeill (1980a) describes the secondary magnetic field as being a complicated function of the intercoil spacing, operating frequency, and ground conductivity. With operation at low values of induction numbers (McNeill, 1980a, p.14), the ground conductivity may be expressed as a ratio of the secondary magnetic field to the primary magnetic field, frequency, and intercoil spacing. The EM34-3 is a direct-reading instrument which displays values of terrain conductivity by measuring the relationship of the secondary to primary magnetic field ratio at a given operating frequency and intercoil spacing.

The depth of exploration may be changed by varying either the coil separation distance or the magnetic dipole arrangement of the coils from horizontal or vertical dipoles. Horizontal dipole arrangement may be accomplished by operating the instrument with the coils aligned in a vertical coplanar orientation. Dipole arrangement is switched from horizontal to vertical by simply realigning the coil orientation from vertical to horizontal coplanar. Combinations of coil separation distances and dipole arrangements produce three depths of exploration for each dipole arrangement as shown below.

Table 1. Exploration depths for the EM 34-3 terrain conductivity meter at various intercoil spacings (after McNeill, 1980a).

Intercoil Spacing (meters)	Exploration Depth (meters)	
	Horizontal Dipole (Vertical Orientation)	Vertical Dipole (Horizontal Orientation)
10	7.5	15
20	15	30
40	30	60

McNeill (1980a) describes exploration depth as being "source" or "geometry" limited rather than "skin depth" limited because induced current flow is horizontal in homogeneous or horizontally stratified earth, and current flow at any particular point in the ground is independent of current flow at any other point because magnetic coupling between induced current loops is negligible. For these reasons the depth of exploration is controlled by the increase of the dipole transmitter field with distance. The relative response of the two dipole arrangements to material at various depths is defined as the relative contribution to the secondary magnetic field from all material below a certain depth and is given in the following equations (after McNeill, 1980a):

$$\phi_V(z) = \frac{4z}{(4z^2+1)^{3/2}} \tag{1}$$

$$\phi_{H(z)} = 2 - \frac{4z}{(4z^2+1)^{\frac{1}{2}}} \tag{2}$$

where: $\phi_{v(z)}$ = relative response of vertical dipole at depth z.

$\phi_{H(z)}$ = relative response of horizontal dipole at depth z.

z = normalized depth, d/s.

d = depth of exploration.

s = intercoil spacing distance.

Plots of the relative contribution versus normalized depth based on equations (1) and (2) are shown in Figure 21. The general shape of the response curves does not change as intercoil spacing is changed so that a normalized depth can be used and the plots shown in Figure 21 hold true for any coil spacing using either dipole arrangement. The relative response of the horizontal dipole ($\phi_{H(z)}$) is most sensitive to material near the surface. The response for $\phi_{H(z)}$ decreases exponentially with depth. The vertical dipole ($\phi_{v(z)}$) response is relatively insensitive to near-surface material and reaches a maximum at approximately 0.4 z, then decreases at greater depth.

The plot of the cumulative response versus normalized depth (Figure 22) shows that approximately 70% of the response is sensed at 0.75 intercoil spacings (s) for the horizontal dipole and 1.5 s for the vertical dipole arrangement. These are the ratios used to calculate values for exploration depth in Table 1. Although the majority of the response is contributed by material less than the assigned exploration depth, significant contribution results from material to depths of 2 s.

As shown in Table 1, an exploration depth of 15 meters can be

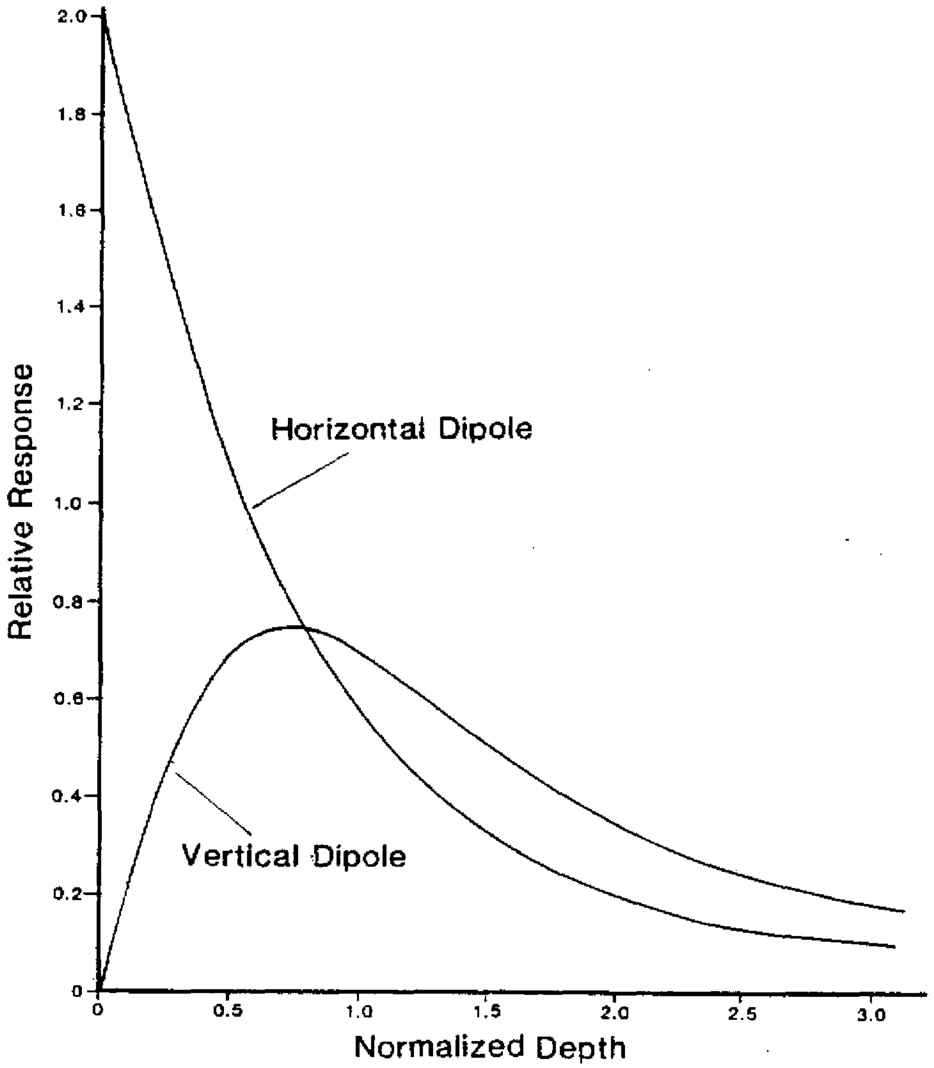


Figure 21. Comparison of relative response for vertical and horizontal dipole arrangements (after McNeill, 1980a).

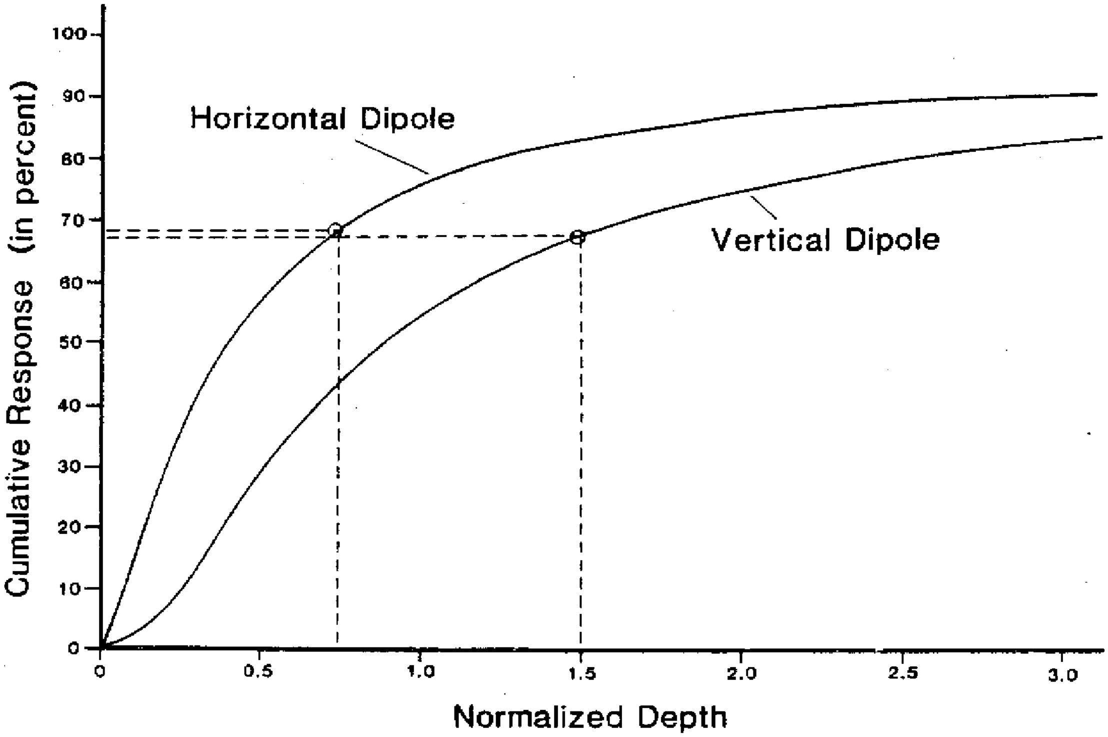


Figure 22. Cumulative response versus normalized depth for vertical and horizontal dipole arrangements (after McNeill, 1980a).

achieved by using either the 10 meter vertical or 20 meter horizontal dipole arrangement. A similar situation exists with the 30 meter exploration depth. Although both dipole arrangements produce the same depth of exploration with appropriate coil spacings, resulting measurements taken with each dipole arrangement over the same section of stratified earth may show marked variation for the same exploration depth. Recall that the vertical dipole measurements are less sensitive to near-surface material than horizontal dipole measurements as shown in Figure 21. This comparison of sensitivity between dipole arrangements is true if the comparison is made at the same coil separation distance. In order for a comparison of relative response to be made between different coil spacings and dipole arrangements for the same exploration depth, the relative response curves for each dipole arrangement must be plotted against a value of exploration depth without being normalized to coil spacing. The resulting plot is shown in Figure 23.

The curves of both dipole arrangements for the 10, 20, and 40 meter coil spacings in Figure 23 maintain the same general shapes when plotted as relative response versus non-normalized exploration depth. In Figure 23 the relative response of the vertical dipole for each coil spacing is larger than the relative response of the horizontal dipole for deeper exploration depths. This comparison is also seen in Figure 21 with the relative response curves plotted against normalized depth. The comparison of relative response for dipole arrangements using different coil spacings (Figure 23) shows why variation of observed measurements can exist for the same exploration depth. Notice that the 20 meter horizontal dipole curve of Figure 23 maintains a higher relative response than does the 10 meter vertical dipole curve

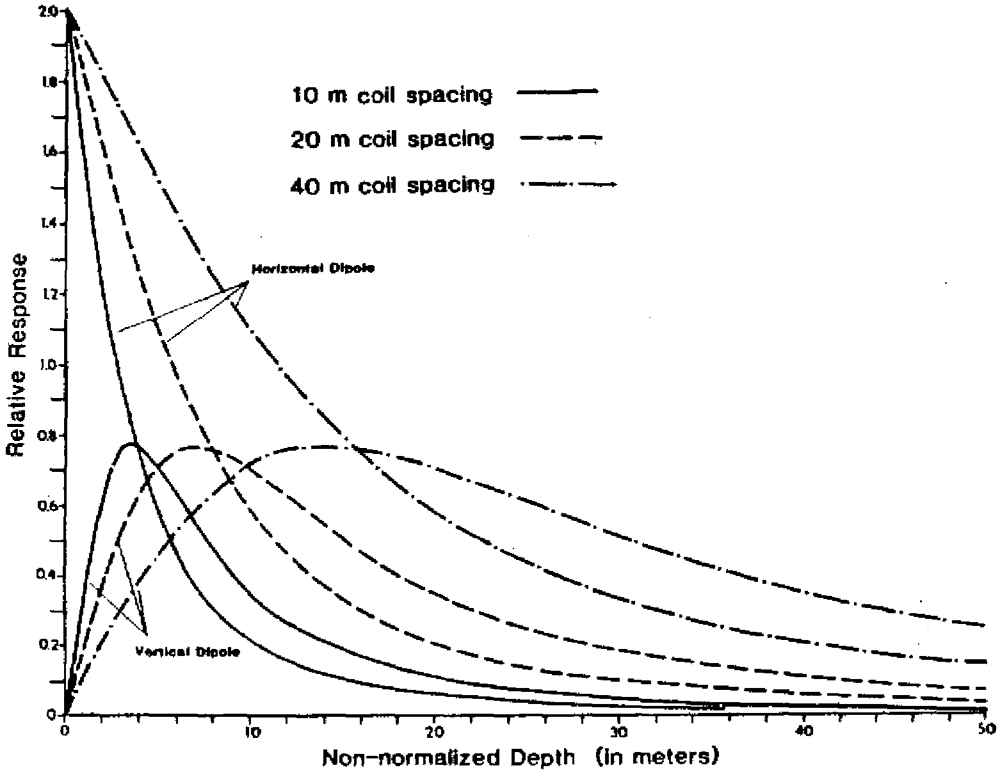


Figure 23. Comparison of relative response for vertical and horizontal dipoles at various coil spacings for non-normalized exploration depth.

although both arrangements are used to measure the 15 meter exploration depth (Table 1). The higher relative response for the 20 meter horizontal dipole means that it is more sensitive to material deeper in the measured section than the 10 meter vertical dipole arrangement even though the vertical dipole is more sensitive to deeper material than the horizontal dipole when compared with the same coil spacing. The same situation exists with the 40 meter horizontal and 20 meter vertical dipoles with an exploration depth of 30 meters.

Appendix II. Lithologic and water chemistry information from shallow wells in northwestern Collier County, Florida.

The following is a list of lithologic and water chemistry data within the investigation area from drill-hole records published by McCoy (1962) and reported by Nuzman (1971). Water chemistry information from McCoy (1962) only consisted of chloride concentration with no sample depth recorded. Nuzman (1971) reported results for 29 chemical analyses for each sample taken. Only four results of the chemical analyses from Nuzman (1971) which demonstrate the general water quality of this portion of the county are listed in this appendix. Figure 29 shows the location of all drill holes listed in this appendix.

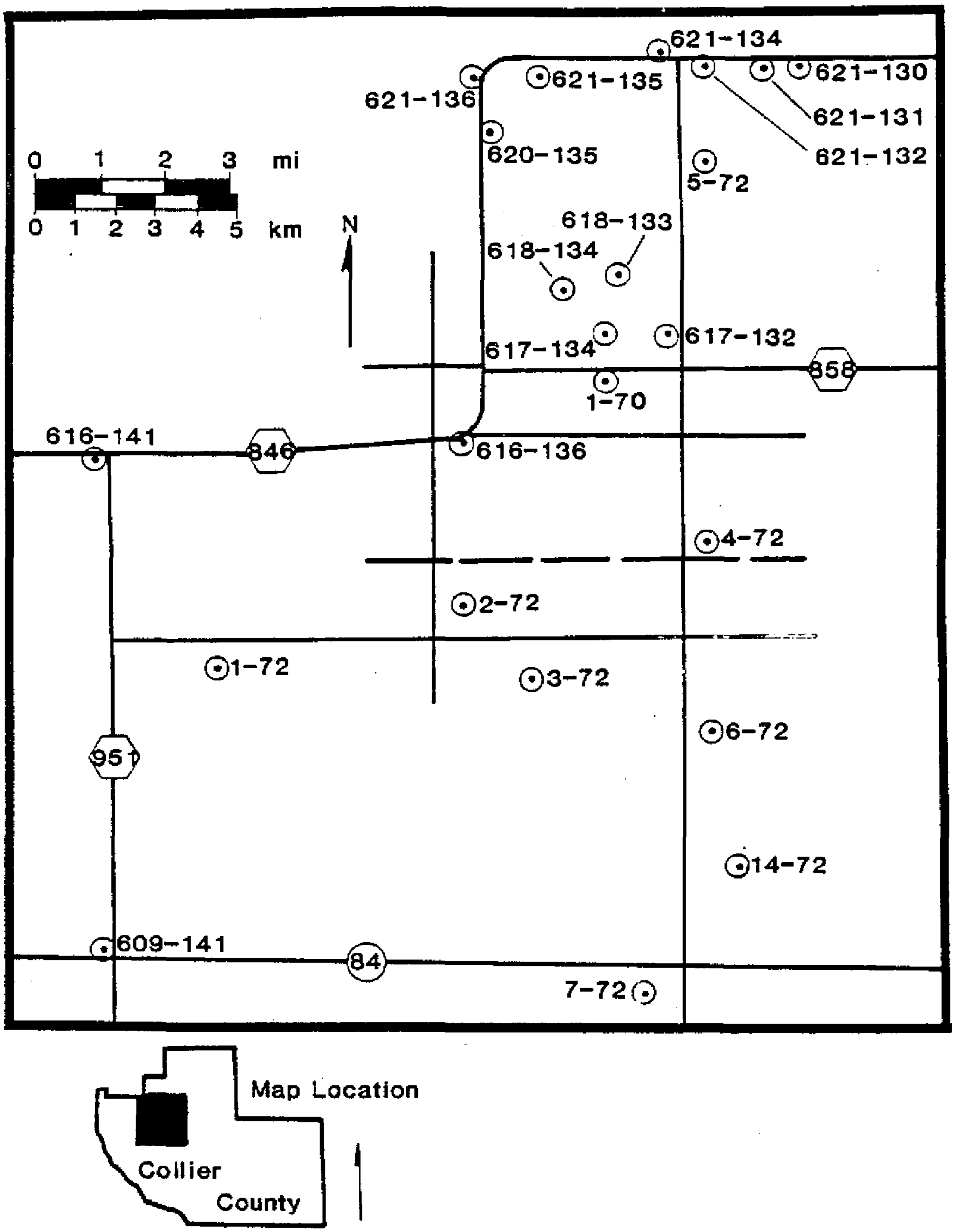


Figure 24. Location of drill-hole data in northwestern Collier County.

Lithologic information from Nuzman, 1971 (see Figure 24 for locations).

Drill Hole 5-72

Depth in feet		Description
from	to	
0.0	18.0	Sandy soil
18.0	36.0	Conglomerate (med. hard sand and shell)
36.0	40.0	Hard material (very hard, dense sand - cemented lime and sandstone)

Drill Hole 1-70

Depth in feet		Description
from	to	
0	0.8	Top soil
0.8	3	White sand
3	7	Brown hard pan
7	12	Sandy marl
12	15	Rock
15	17	Sand
17	23	Soft yellow rock
23	25	Hard rock
25	31	Soft yellow rock
31	53	Green sand, shell and gravel
53	59	Sand, shell and gravel
59	81	Shell rock (water bearing)
81	96	Sand
96	152	Sand and shell
152	165	Sandy clay
165	200	Light green clay
200	201	Coarse white sand and rock
201	231	Coarse to fine sand
231	268	Fine sand
268	300	Green clay

Drill Hole 4-72

Depth in feet		Description
from	to	
0	5.5	Dark brown sand
5.5	12.5	Hard pan material (light brown)
12.5	13.5	Rock
13.5	14.5	Soft material (limey clay)
14.5	17.5	Rock
17.5	25	Soft conglomerate (limey, sandy clay)
25	30	Moderately hard rock
30	55	Soft material (limey clay)
55	63	Lime rock of moderate to high density

Drill Hole 2-72

Depth in feet from	 to	Description
0.0	6.5	Dark brown sand
6.5	10.5	Rock
10.5	11.0	Soft material (limey clay)
11.0	16.0	Rock
16.0	18.0	Soft material (limey clay)
18.0	19.5	Rock
19.5	42.0	Soft rock material (soft lime rock
42.0	47.0	Hard material

Drill Hole 1-72

Depth in feet from	 to	Description
0	7.5	Light brown sand
7.5	9	Soft rock (boulder?)
9	10	Soft soil layer
10	13.5	Rock
13.5	13.75	Soft material (limey clay)
13.75	17	Rock
17	17.25	Soft material (limey clay)
17.25	19	Rock
19	28	Soft material (limey clay)
28	28.5	Rock
28.5	73	Soft material (limey, sandy clay)
73	76	Lime rock

Drill Hole 3-72

Depth in feet from	 to	Description
0	7	Light brown sand
7	13	Rock
13	13.5	Soft material (limey clay)
13.5	14	Rock
14	18	Soft material (limey clay)
18	18.5	Rock
18.5	76	Soft material (limey, sandy clay)
76	82	Lime rock

Drill Hole 6-72

Depth in feet from	 to	Description
0.0	4.0	Light brown sand
4.0	8.5	Rock
8.5	38.0	Soft material (limey clay)
38.0	38.5	Hard material (seems to be dense sand)
38.5	40.0	Soft material (limey clay)

Drill Hole 14-72

Depth in feet from	 to	Description
0	2	Brown sand
2	4	Rock
4	6.5	Soft material (limey clay)
6.5	7	Rock
7	40	Conglomerate (limey, sandy clay)
40	-	Lime rock

Drill Hole 7-72

Depth in feet from	 to	Description
0	4	Brown sand
4	6	Gray sandy clay
6	9.5	Rock
9.5	31	Gray sandy silt
31	40	Lime rock

Lithologic information from McCoy, 1972 (see Figure 24 for locations).

Drill Hole 621-136-5

Depth in feet from	to	Description
0	10	Sand, quartz, fill material, organic material
10	20	Shell, tan, hash, fill material
20	30	Limestone, light gray and shell hash
30	55	Limestone, light gray, sandy, marly, becoming harder and darker gray at bottom; permeable
55	118	Limestone, gray to white, with greenish gray clay, sand and phosphatic material in lower part; permeable
118	120	Sand, quartz, very fine; white and gray limestone fragments
120	130	Sand, quartz, fine, white

Drill Hole 621-135-2

Depth in feet from	to	Description
0	10	Fill material
10	40	Sand, quartz, medium, tan; gray limestone; shell in lower part
40	60	Clay, marly, shelly, greenish tan
60	90	Limestone, dark gray, shelly, becoming sandy in lower part
90	95	Sand, quartz, very fine, limey, clayey, phosphatic
95	123	Limestone, buff colored, phosphatic, sandy, becoming shelly in last 7 feet; permeable

Drill Hole 616-141-2

Depth in feet from	to	Description
0	10	Limestone fill rock and sand
10	35	Shell, hash, cream colored; limestone, marly
35	46	Limestone, light cream, shelly phosphatic
46	90	Limestone, white to dark gray; light green clay in varying amounts
90	150	Limestone, gray, sandy, sand-filled cavity at 105 feet
150	160	Clay, gray-green, soft, sandy, phosphatic
160	170	Limestone, light cream, sandy, phosphatic
170	220	Limestone, very shelly, clayey, and phosphatic; clay increasing
220	240	Limestone, white and gray, clayey, phosphatic
240	270	Clay, green, sandy, phosphatic; gray limestone
270	300	Clay, green, sandy, hard

Water Chemistry Information from Nuzman, 1971.

Drill hole	Sample depth in feet below land surface	Chloride as Cl in ppm	Sulfate as SO_4 in ppm
5-72	40	20	2
1-70	200	40	not taken
"	200	30	not taken
4-72	12.5	9	130
"	63	30	2
2-72	12	7	51
"	42	13	46
1-72	10.5	7	72
"	75	76	2
3-72	82	30	1
6-72	8	5	93
"	36	36	1
14-72	10	17	4
"	40	27	0
7-72	9	19	43
"	40	44	1

TDS at 105° in ppm	TH as $CaCO_3$ in ppm
370	265
330	266
325	264
600	432
430	282
580	398
610	392
497	354
725	395
480	336
485	396
615	410
450	291
300	210
596	360
560	342

Water Chemistry Information from McCoy, 1962.

Drill Hole	Chloride in ppm	Total depth in feet
621-134-1	49	84
621-132-1	85	115
621-130-1	48	82
621-131-1	51	92
621-131-2	111	112
621-131-3	57	105
621-131-5	44	130
620-135-1	55	63
618-134-1	47	18
618-134-2	34	31
618-134-3	56	100
618-133-1	59	52
618-133-2	37	25
617-134-1	785	875
617-134-2	61	60
617-134-3	71	38
617-132-1	43	30
616-141-1	87	51
616-141-2*	1100	300
616-136-1	39	130
609-141-1	885	144

*Water sample taken between 230 and 240 feet below land surface.

Appendix III. Criteria used to describe outcrop and canal spoil exposures in northwestern Collier County, Florida.

All descriptions of outcrop and canal spoil exposures of near-surface limestones in northwestern Collier County are based on hand sample examination in the field. Five general categories were used to classify all exposures described. The categories and criteria are shown below:

A. Degree of Cementation

(1) Well cemented, - difficult to fracture with hammer, very little open pore space observed with hand lens.

(2) Moderately cemented, - easily fractured with hammer, open pore spaces common.

(3) Poorly cemented, - easily fractured with hammer, grains can be disaggragated by hand.

B. Quartz Sand Content

(1) High, - approximately 50% to 75% quartz sand by visual estimate.

(2) Medium, - approximately 25% to 50% quartz sand by visual estimate.

(3) Low - less than 25% quartz sand by visual estimate.

(4) None - no visible quartz sand.

C. Degree of Solution

(1) High - cavities greater than 2 cm in diameter over approximately 15% of rock by visual inspection.

(2) Medium - cavities less than 2 cm in diameter over less than 10% of rock by visual inspection.

   (3) Low - cavities less than 1 cm in diameter over less than 5% of rock by visual inspection.

D. Fossil Abundance (>2 mm in size)

   (1) High - greater than 40% by visual examination.
   (2) Moderate - approximately 10% to 40% by visual examination.
   (3) Low - less than 10% by visual examination.

E. General Fossil Type Present

   (1) Bivalves other than oysters.
   (2) Oysters.
   (3) Gastropods.
   (4) Corals.

Figure 25 shows the location of exposures in the study area. Table 2 is a tabulation of data based on the categories of classification for each sample location.

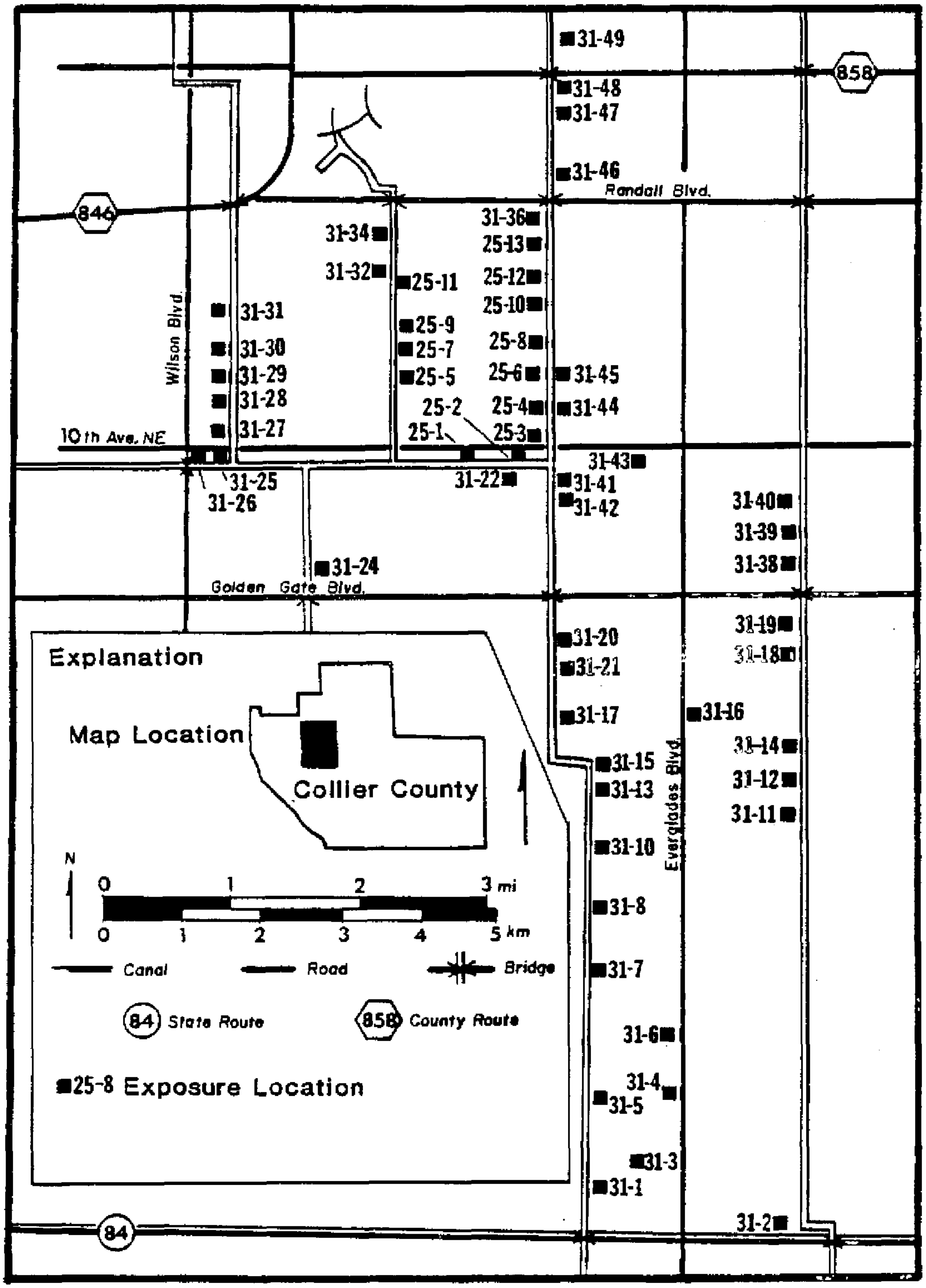


Figure 25. Location of outcrop and canal spoil exposures within study area.

Table 2. Tabulation of data for each exposure location within study area (see Figure 24 for locations).

Location Number	Cementation	Quartz Sand Content	Solution	Fossil Abundance	Fossil Type
31-49	H	N	H	M-H	B,C,G
31-48	H	N	H	M-H	B,C,G
31-47	H	N	H	M-H	B,C,G
31-46	H	N	H	M-H	B,C,G
31-34	H	N	H	M	C,B
31-36	H	L-M	H	L	-
31-32	H	N	H	M	C,B
25-13	H	L	M	H	C
31-31	L	H	L	H	B
25-12	H	L	M	H	C,B
25-11	H	L	M	H	C
31-30	L-M	H	L	M	B
25-9	M	L-M	L	H	B,C
25-10	H	L	M-H	H	C
31-45	H	L-M	L	H	B,C
25-8	M	M	L	L	C
25-7	H	L-M-H	M-H	H	B,C
31-44	H	M	H	M	B
31-28	H	M	M	M	B
25-5	L	H	L	M-L	B
25-6	H	L-M-H	M-H	H	B,C
31-27	H	L	H	H	B
25-4	H	L	M	L	B,C
31-25	H	N	H	H	C
31-26	H	N	H	H	C
25-3	H	L	M	L	B,C
25-1	L	H	L	M	B
31-43	M-H	M	H	M	B
31-22	M	H	L	M	B
31-41	H	M	L	L	-
31-42	M	M	H	M	B

Table 2 cont.

Location Number	Cementation	Quartz Sand Content	Solution	Fossil Abundance	Fossil Type
31-40	M	M	L	H	B
31-39	M	M	L-M	H	B
31-38	M	M	L-M	H	B
31-24	H	L	L-M	H	B,G
31-20	H	L	H	L	B
31-19	H	N	M-H	L-M	C,G
31-21	H	L	H	H	C
31-18	H	L	H	M	C,B,G
31-17	H	N	H	M	B,C
31-16	M-H	L-M	H	M	B
31-15	H	N	H	H	C
31-14	H	L	H	H	O,G,B,C
31-13	H	N	H	H	C
31-12	H	N	H	H	G,B,C
31-11	H	N	H	H	G,B
31-10	H	L-M	M	L	B
31-8	M-H	M-H	L-M	M-H	B
31-7	M	H	L-M	M	B
31-6	M	H	L	H	B
31-5	M	M	L	M	B
31-4	M-H	M	L-M	M	O
31-3	M	L-M	L	M	B
31-1	M	L	M	M	B
31-2	M	L	M	M	B
31-37	H	N	H	H	B,C,G
25-2	M-H	M	L	M	B

H = high or well

M = medium or moderate

L = low or poor

N = none