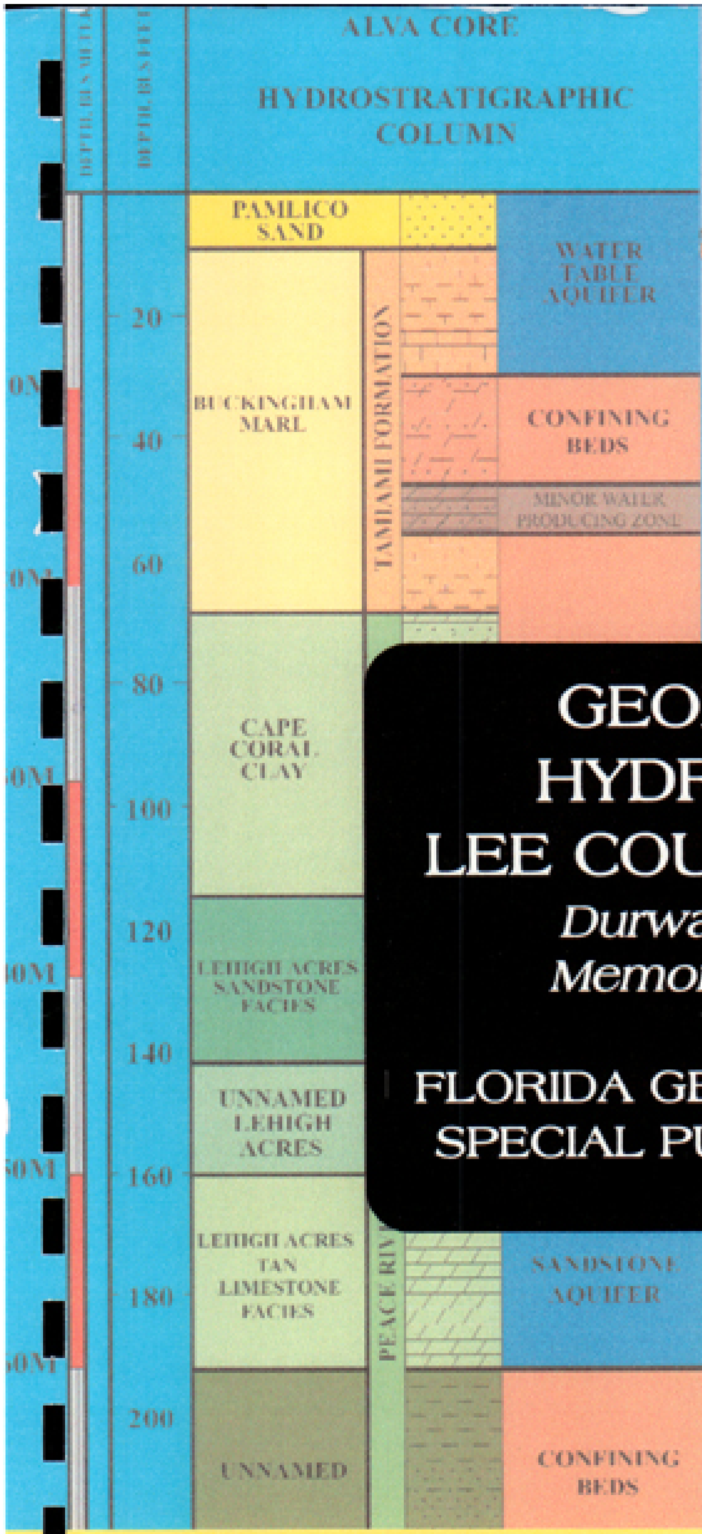

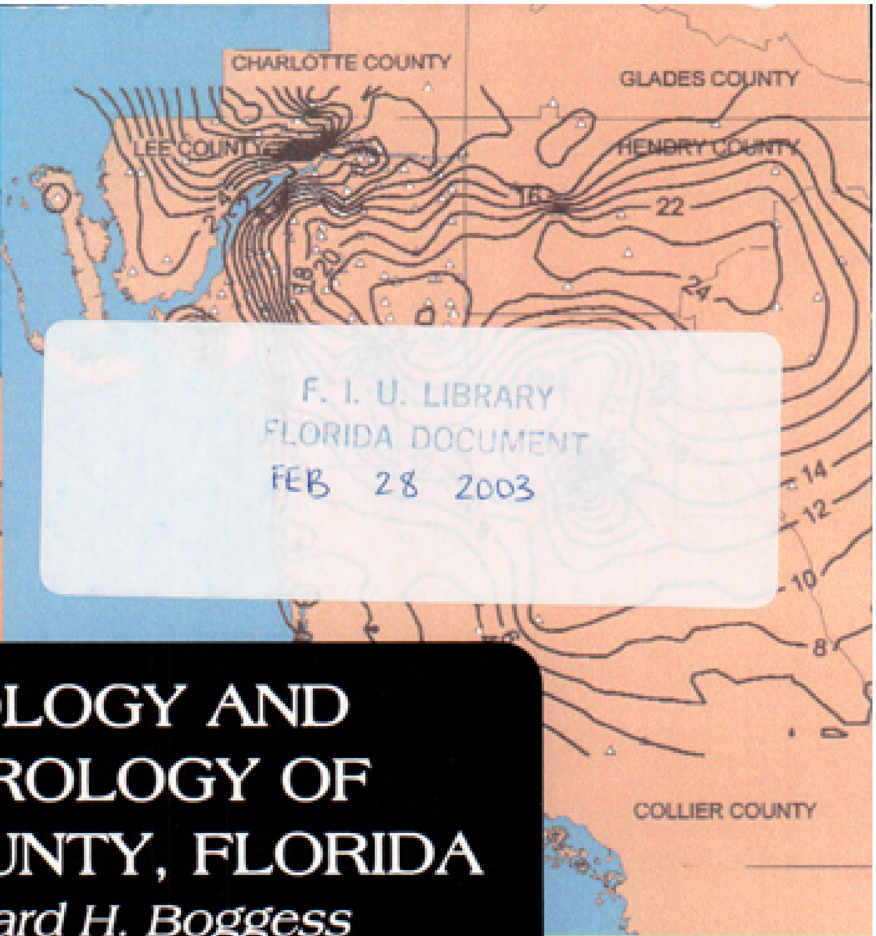

GEOLOGY AND HYDROLOGY OF LEE COUNTY, FLORIDA

Durward H. Boggess Memorial Symposium

FLORIDA GEOLOGICAL SURVEY
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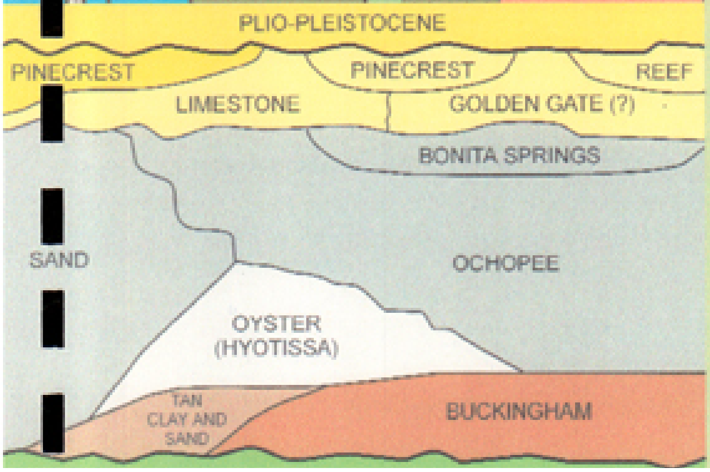

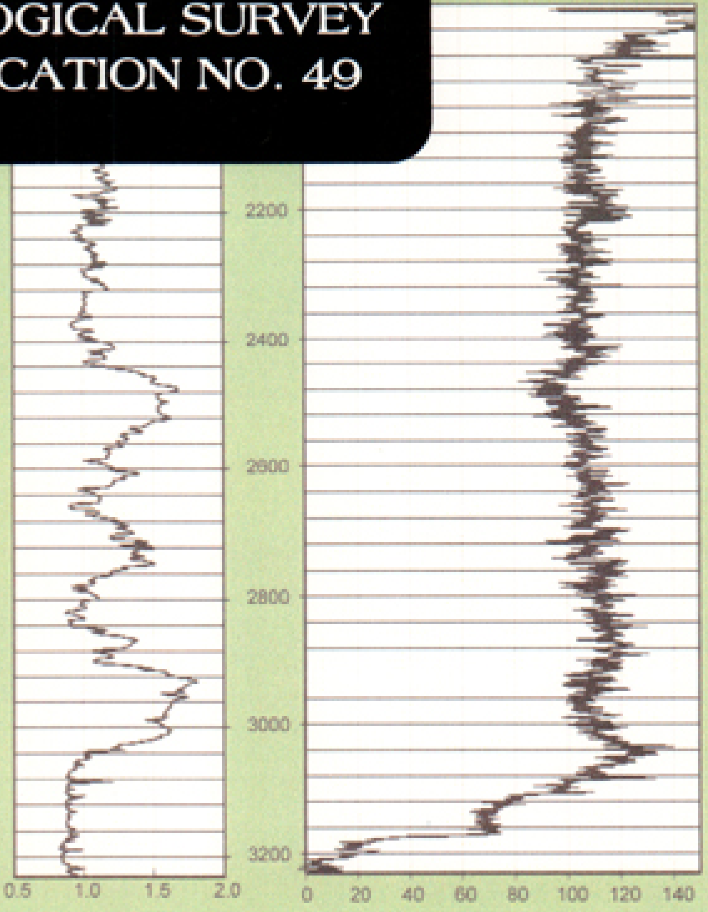

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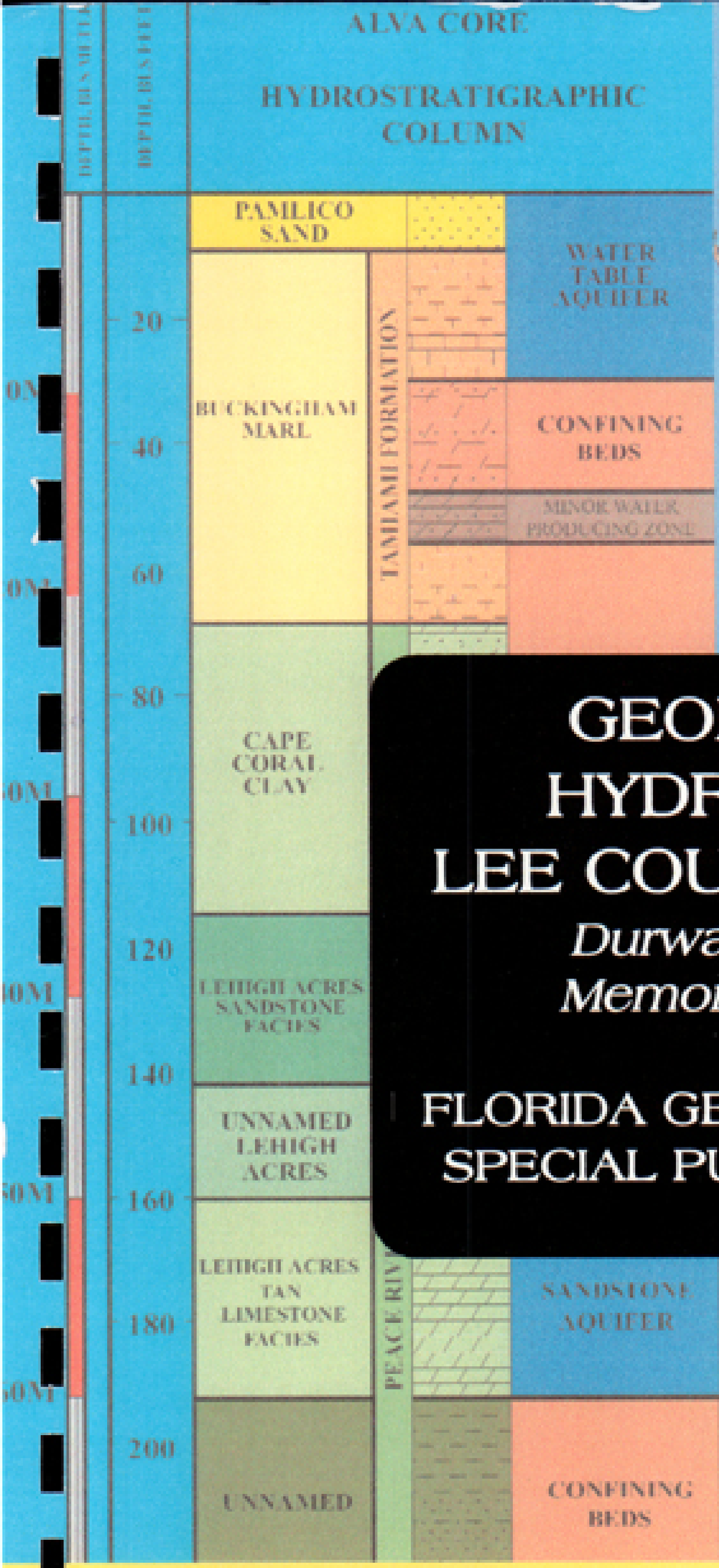

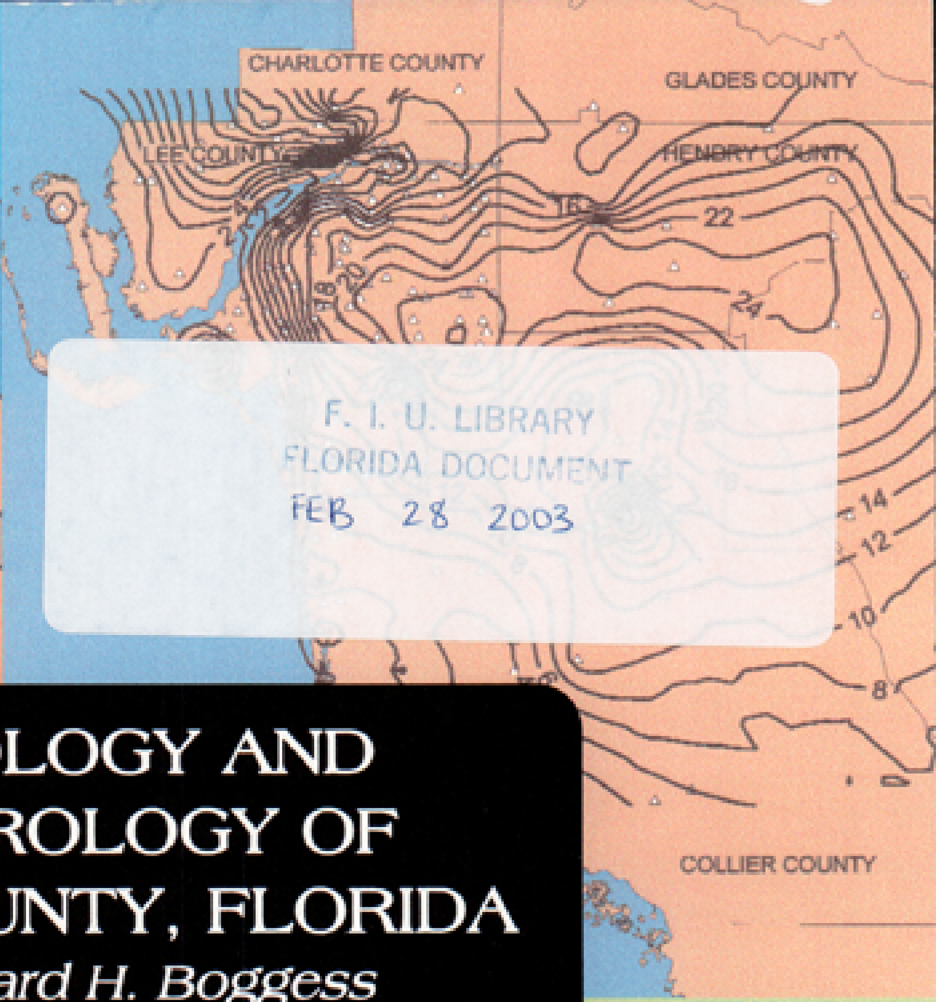

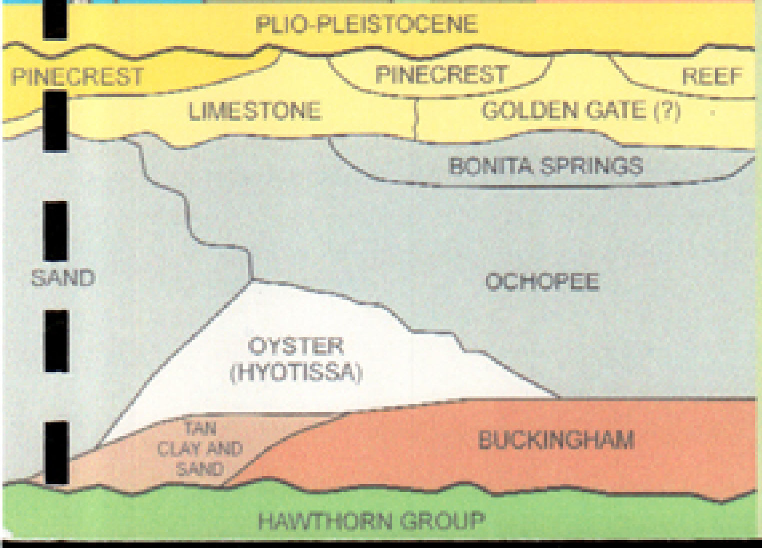

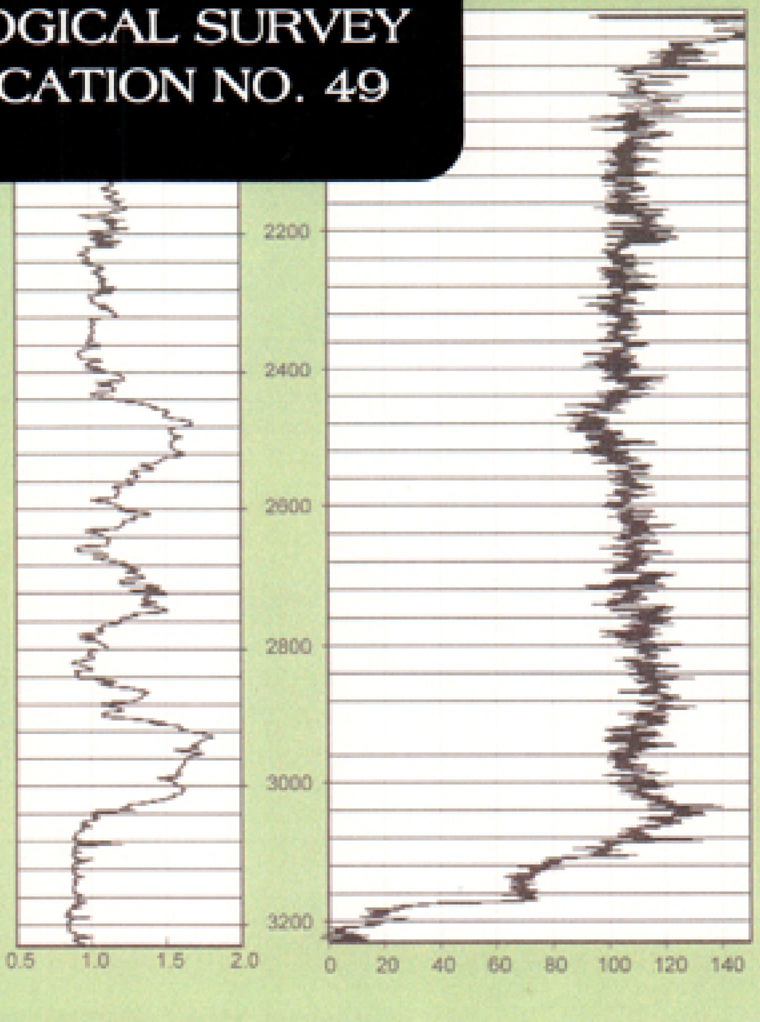

Durward H. Boggess

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SPECIAL PUBLICATION NO. 49

GEOLOGY AND HYDROLOGY OF LEE COUNTY, FLORIDA
DURWARD H. BOGGESS MEMORIAL SYMPOSIUM

EDITED BY
Thomas M. Missimer and Thomas M. Scott

Published for the
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Tallahassee
2001

LETTER OF TRANSMITTAL

FLORIDA GEOLOGICAL SURVEY
Tallahassee
2001

Governor Jeb Bush
Tallahassee, Florida

Dear Governor Bush:

The Florida Geological Survey, Division of Resource Assessment and Management, Department of Environmental Protection, is publishing as Special Publication No. 49, *Geology and Hydrology of Lee County, Florida, Durward H. Boggess Memorial Symposium*, edited by Thomas M. Missimer and Thomas M. Scott. The information presented herein is valuable in understanding the geology of the aquifers underlying this growing region. It will be useful to state planners and land managers who must make informed decisions concerning the valuable groundwater resources.

Respectfully,

Walter Schmidt

Walter Schmidt, Ph.D.
State Geologist and Chief
Florida Geological Survey

This collection of papers represents the authors' views and associated interpretations. The editors have reviewed the submitted manscripts for basic spelling errors and gross figure consistency and the FGS reformatted the text for final printing. Interpretive concepts, figures and other professional opinions and nomenclature are the responsibility of the authors and no endorsement by the Florida Geological Survey or the Department of Environmental Protection is intended.

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Tallahassee
2001

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DEDICATION AND EDITOR'S PREFACE

A special symposium on the geology and hydrology of Lee County, Florida was held in Fort Myers on November 18 and 19, 1999. This symposium was held as part of the 9th Southwest Florida Water Resources Conference. The conference was held in honor of Durward H. Boggess, who made significant contributions to the understanding of the geology and hydrology of Lee County.

Durward H. Boggess was a hydrologist with the U.S. Geological Survey in Fort Myers from 1966 to 1979. During this time period, Lee County was one of the most rapidly growing regions in the United States. Little was known about the geology and the aquifer system beneath the county, as evidenced by the small number of publications on this region by the Florida Geological Survey. Durward H. Boggess developed a geologic and hydrologic database that allowed the development of future water supplies to occur with a sound scientific basis.

Most of the papers published in this volume were presented at the conference and a few others were added to make the volume as complete as possible in terms of recent knowledge on the geology and hydrology of Lee County. The volume is organized with a discussion of the contributions of Durward Boggess, followed by a series of papers on the geology of the county. Based on the geologic framework, a series of papers follows on the hydrogeology of the county. Finally, some papers on the surface-water hydrology and water quality of the county complete the volume.

Lee County occurs in the geographic middle of the southern part of the Florida Platform. The geology of this region is rather unique, because there is a succession of carbonate sediments followed by a complex mix of carbonate and siliciclastic sediments (beginning in the Oligocene). The geographic location of the county and the mixing of the sediments caused the aquifer system beneath the county to be quite complex with numerous different aquifers present. Over 12 aquifers or major water-bearing zones occur beneath any given area of the county. It is critical to understand the geology and hydrology of this area, because many of the aquifers are or will be used for water supply. Also, the deep aquifer system is used for the disposal of liquid wastes, such as oil field brines, concentrates from desalination plants, and treated domestic wastewater.

It is extremely important that recent information on the geology and hydrology of this as well as other regions of Florida be made available to environmental managers and the general public in a timely manner.

Thomas M. Missimer, PG #144
Fort Myers

Thomas M. Scott, PG #99
Tallahassee

ACKNOWLEDGEMENTS

The editors wish to acknowledge a number of individuals whose efforts made this symposium and the resulting special publication possible. Perhaps the most difficult task, aside from finding the time to prepare a paper, was the meeting planning and organization. This task fell on the conference host committee, whose efforts are greatly appreciated: Ron Edenfield (Chair), Susan Brookman, John Capece, Clyde Dabbs, Win Everham, Samy Faried, Lynne Felknor, Jennifer Flaitz, Ron Hamel, Kurt Harclerode, Steve Kempton, Bonnie Kranzer, Jeff Krieger, Tom Missimer, John Musser, Dan VanNorman, and Sean Weeks.

The editors extend a special thanks to Mrs. Durward Boggess for providing the photo of her husband used inside the front cover of the publication. And we thank Frank Rupert for compiling the different text and graphics formats into QuarkXPress for publication.

CONTRIBUTIONS OF DURWARD H. BOGGESS TO THE HYDROLOGY AND GEOLOGY OF LEE COUNTY, FLORIDA

Thomas M. Missimer
CDM/Missimer International, Inc., 8140 College Parkway, Suite 202, Fort Myers, Florida 33919

ABSTRACT

Sparse investigation of the hydrology and geology of Lee County, Florida was conducted before Durward Boggess established the U.S. Geological Survey office in Fort Myers during 1966. Past work included a general description of the geology along the banks of the Caloosahatchee River (Heilprin, Dall, DuBar) and some paleontological studies of barrow pit spoils piles and some surface-water studies in a few streams. Durward Boggess quickly grasped the water-supply problems of Lee County and recognized the need for both surface-water and groundwater data.

The completion of the Okeechobee Waterway (construction of S-79) occurred only a short time before Mr. Boggess moved to Lee County. In 1966, the Caloosahatchee River was believed to be the most reliable source of water supply for the City of Fort Myers and the unincorporated areas of Lee County. Intakes were designed and constructed about 1 mile upstream of the W. P. Franklin Dam (S-79) on the river. These intakes fed the artificial recharge system for the City of Fort Myers Wellfield via a pipeline and the new Lee County Water Treatment Plant. Mr. Boggess was concerned about the proximity of the intake structures to the lock through S-79. Each time a boat passed through the lock in dry periods, a slug of saltwater moved upstream. So, his first work in Lee County was on how to control the upstream movement of saline water in the Caloosahatchee River.

Among the many contributions made by Durward Boggess to the study and management of water resources in Lee County were: 1) the establishment of permanent gaging stations on the Caloosahatchee River and other larger streams in Lee County, 2) the establishment of the crest-stage gages in Lee County to assess flooding and drainage problems, 3) the creation of an extensive data base on the geology and hydrology of Lee County, 4) the initial mapping of the shallow and intermediate aquifer systems, 5) the definition and naming of the principal aquifers used in Lee County, including the Lower Hawthorn Aquifer, the Upper Hawthorn Aquifer (now termed the Mid-Hawthorn Aquifer), the Sandstone Aquifer, and the water-table aquifer, 6) the recognition that brackish, saline-water in the Lower Hawthorn Aquifer was a resource to be conserved and would be a water supply for the future, 7) helped establish how saline water interacted with the shallow aquifer system of Sanibel Island and helped established development practices that would be fundamental to the writing of the City of Sanibel Comprehensive Land Use Plan, 8) recognized that cut and fill landfills, which were the state-of-the-art landfill type at that time, were causing groundwater contamination, 9) suggested that the shallow groundwater system in southern and eastern Lee County would be the source for future public water supplies in Lee County, 10) recognized that the Mid-Hawthorn Aquifer was being over-pumped in Cape Coral and Fort Myers, 11) recognized that improper well construction practices were causing contamination of the freshwater resources of the county with saline water, which led to the adoption of new well construction codes and the establishment of a well plugging program, 12) recognized that over-drainage of the Lehigh Acres area of Lee County was adversely affecting the water resources and wetlands, and 13) convinced the Lee County government that the planning process should include the management of the groundwater resources.

Without the scientific expertise and insight of Durward Boggess, Lee County would have had

severe water supply problems many years ago. Durward Boggess believed that it was very important for the public to understand how the hydrologic system functioned and he spent much time with the media and interested citizens to help educate them. He was one dedicated individual, who cared about Southwest Florida, that made a difference in molding the future management of water resources.

INTRODUCTION

Prior to the 1960's, geological and hydrological work on Lee County, Florida was very limited (Figure 1). Initial geological and paleontological investigation on this region began in the late 1880's. The first description of geological work in southwestern Florida was that of Heilprin (1887), who wrote "Prior to our visit, the only portion of the state that had been examined geologically, or on which a geological report had been prepared, was the region lying north of a line running almost due northeast from the Manatee River, just south of Tampa Bay, to the east coast. Below all this was conjectural, although the existence of certain limestones of undetermined age was hinted at, or even located, by a number of causal observers (Tuomey, Conrad) who chanced to navigate some of the outer waters. Such a limestone was reported by Tuomey to be found in Charlotte Harbor, but the exact locality of its occurrence is not noted." Heilprin (1887) described the geology and paleontology of the banks of the Caloosahatchee River from Fort Myers east to past Labelle in Hendry County. Rather extensive works on the paleontology of the exposed Pliocene and Pleistocene sediments along the Caloosahatchee River, Shell and Alligator creeks (Charlotte County) were made by William H. Dall of the Wagner Free Institute of Philadelphia. Dall (1890-1903) described many of the most common mollusk species of the Neogene sediments. Additional paleontological investigations were conducted in parts of Lee County by Wendall C. Mansfield (an original field assistant of Dall), Druid Wilson, Helen I. Tucker, and Axel Olsson. Some of the data collected are published in Tucker and Wilson (1932-33) and Olsson and Harbison (1953), but no stratigraphic descriptions were made. Petroleum exploration began in Southwest Florida in the 1930's with a number of "shallow" dry holes being drilled in Charlotte, Lee, and Collier counties. Few data were preserved from this early deep exploration work. Detailed investigations of the exposed Neogene paleontology and geology of the Caloosahatchee River from Lee County and Hendry County were published by DuBar (1958) with another study conducted in Charlotte County (DuBar, 1962). A surface geological map of the area was published by Parker and Cooke (1944), based on minimal data collected from exposures and barrow pits.

Some reconnaissance work on the hydrogeology of the Southwest Florida region was undertaken in the 1940's as a part of extensive studies directed by Gerald Parker of the U. S. Geological Survey. Some preliminary data on rainfall along with some logs of wells in Hendry County immediately to the east of Lee County were published in Parker et al. (1955). A study of surface water flows and surface-water quality in a few streams in Lee County was published by Kenner and Brown (1956). The U. S. Geological District office in Tallahassee was concerned about the lack of hydrogeologic data and aquifer definitions in the early 1960's and Nevin Hoy was assigned to make an assessment of the hydrology and geology of Lee County. A draft report by Hoy was submitted to the Florida Geological Survey but not published, because of insufficient data.

The U. S. Geological Survey decided to open a field office in Fort Myers under the direction of the Subdistrict office in Miami during 1965. A senior hydrologist with the U.S.G.S. in Maryland, Durward H. Boggess, was assigned to open the office. His assignment was to assess the water resource problems of Lee County, to develop a hydrogeologic data base, and to develop funding sources for conducting hydrologic investigations.

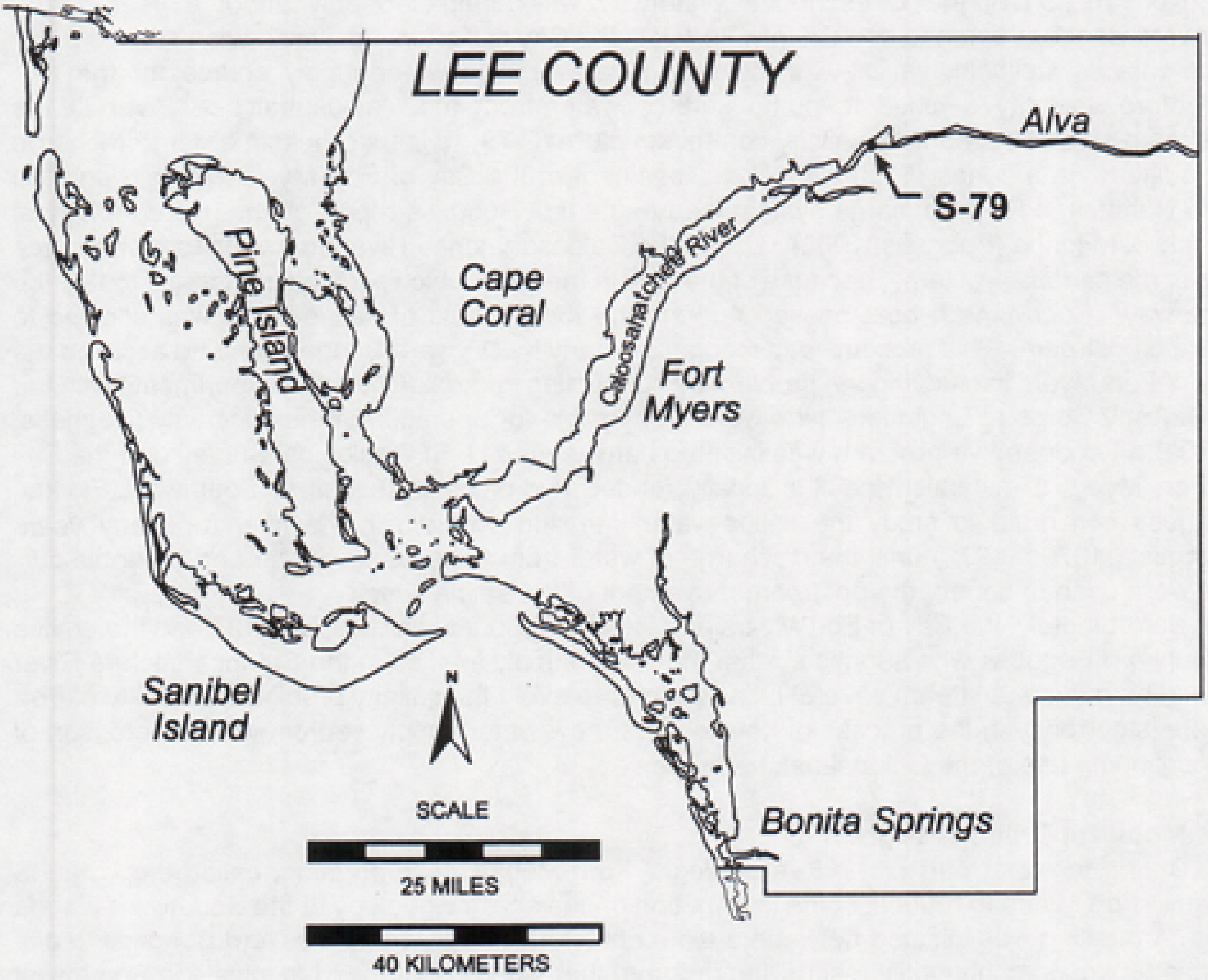

Figure 1. Map of Lee County showing locations mentioned in text.

In 1966, Lee County was a rural region, with a predominantly agricultural economy and a developing tourist industry. Population growth was beginning to accelerate and a number of water supply problems were becoming evident. Water supplies for the new residents of the county along with the expanding agricultural uses were beginning to become problematical. Durward Boggess arrived in Lee County in 1966 at a critical time in its development history. He made an immediate and long-term impact on the management of the water resources of Lee County. The problems he outlined in "Water-Supply Problems in Southwest Florida" (Boggess, 1968) set the beginning of his work on the geology and hydrology of Lee County. During the 13 years of service with the U. S. Geological Survey in Lee County, Durward Boggess made numerous contributions to the geologic and hydrologic knowledge of Southwest Florida. This paper outlines only a few of these contributions.

The Caloosahatchee River as a Water Supply Source

Construction of the Okeechobee Waterway was completed only about a year before Durward Boggess came to Lee County. In 1966, the City of Fort Myers was having serious problems with its wellfield, which was the only potable public water-supply source for the city. Therefore, the city decided to pump surface water from the Caloosahatchee River at the upstream side of the primary salinity control structure (S-79) to the wellfield in order to recharge the system via a series of canals. An assessment of the City of Fort Myers wellfield and the Caloosahatchee River recharge system lead to the first Boggess report on the hydrogeology of Southwest Florida (Boggess, 1968). Use of the Caloosahatchee River as a water supply source had some serious problems, because of the lock in the river, which allowed boat traffic to use the waterway. Each time a boat passed through the lock, a slug of saline-water was allowed to migrate upstream. This problem was recognized early by Durward Boggess and he assisted the City of Fort Myers in studying the problem by conducting controlled flushing experiments with the U. S. Army Corps of Engineers, who were responsible for operation of the waterway (Boggess, 1970a). A cooperative program was initiated between the U. S. Geological Survey and the City of Fort Myers to establish the first locally funded hydrological studies in Southwest Florida. Boggess continued to study the saline-water intrusion problem in the river for many years (Boggess, 1970b; 1972) until the discharge of water from Lake Okeechobee and a bubble curtain were used to control the upstream movement of the saline water.

Unfortunately, the City of Fort Myers and later, Lee County Utilities, did not heed the advice of Durward Boggess who suggested that the water supply intakes in the Caloosahatchee River should be moved upstream several miles in order to avoid the salinity problem. The City of Fort Myers is currently in the process of developing a new water supply source with the intention of discontinuing use of the Caloosahatchee River.

The Mobil Oil Drilling Program

During the later part of 1966, a geologist from Mobil Oil Corporation, called the U.S.G.S office in Fort Myers to request some information on the shallow geology of the Southwest Florida area. A meeting was initiated between a team of Mobil geologists and Durward Boggess to discuss a proposed confidential test drilling program that Mobil Oil intended to initiate in Southwest Florida. Mobil was actively involved in a petroleum exploration program in Southwest Florida at that time. There was some suggestion that the structure of the top of the middle Miocene and the top of the Eocene sediments in the region could give significant clues with regard to where to drill in the 12,000 foot zone of the late Cretaceous Sunniland Formation, which was the oil production horizon in the area. Durward Boggess and Mobil Oil struck a deal that proved to be the key factor in the development of an extensive hydrogeologic data base in Southwest Florida. Mobil decided to drill several hundred test holes to depths ranging from 200 to 1500 feet throughout Southwest Florida. Drill cuttings would be collected from each well, geologist logs would be made, and geophysical logs (electric and gamma ray) would be run on each test well. The deal was that if Durward Boggess agreed to help obtain permission to drill the test wells in road right-of-ways and assisted in the data collection, he would be given copies of all raw data and geophysical logs as long as he agreed not to make the information public for two years (shallow middle Miocene wells) or five years (upper Eocene wells). Despite being a one man office with significant responsibilities and some internal problems with U.S.G.S. policy, the agreement was made. For over a year, geological data were collected and even water quality information was obtained. This information formed the hydrogeological data base that allowed Durward Boggess to define and name the primary freshwater aquifers in Lee County and to suggest where future water supplies could be obtained (Sproul, Boggess, and Woodard, 1972; Boggess, Missimer, and O'Donnell, 1977).

The Cape Coral Canal System Salinity Barrier Issue

In the late 1960's and early 1970's, a new urban area in western Lee County, Cape Coral, was being developed. Gulf American Land Corporation was in the process of digging hundreds of lineal miles of canals at depths near or below sea level to both obtain fill material to increase the altitude of the land for flood control and septic tank function and to allow boat access.

In the northwestern part of the development area (north of S.R. 78), the state and local regulatory bodies were concerned about the potential for saltwater intrusion into the interior of the area (Figure 1). Durward Boggess was requested to assess the situation and assist both the regulatory agencies and the developer to decide where to control the potential landward movement of tidal surface-water (saltwater intrusion) through the canal system. After extensive discussion, Durward Boggess recommended that Burnt Store Road be designated as the salinity control line. A series of four control structures were constructed along this north-south oriented road. This was the first concerted effort in Lee County to control the intrusion of tidal saline-water into interior areas. The precedent set by this decision set the trend for future development throughout Southwest Florida.

Contamination of the Fresh Groundwater Resources with Artesian Saline-Water

When Durward Boggess arrived in Southwest Florida, all of the water wells in the region were constructed by the cable-tool method using as little casing as possible. Many of the wells tapped deep aquifers, under artesian pressure, that yielded saline water. These deep wells were used for irrigation of crops and for frost protection to some degree. Boggess recognized that these wells were problematical allowing the entry of saline water into the freshwater aquifers of Southwest Florida. An earlier study by Klein, Schroeder, and Lichtler (1962) in Hendry County had documented this problem, and Boggess (1968) first discussed the significance of the problem in Lee County.

The issue of improper well construction and the adverse effects on groundwater quality was studied by Boggess for his entire career in Southwest Florida. He demonstrated that if a deep well was properly plugged, the contamination caused by the discharge of saline-water into the water-table aquifer was rapidly attenuated by dilution with rainfall (Boggess, 1973). Saline-water intrusion into confined freshwater aquifers, such as the Sandstone Aquifer in eastern Lee County or the Mid-Hawthorn Aquifer in western Lee County proved to be a nearly permanent situation with very slow flushing and dilution (Sproul, Boggess, and Woodard, 1972; Boggess, Missimer, and O'Donnell, 1977). Boggess recognized that the deep aquifer intrusion of saline-water into the shallower fresh-water aquifers was not the only problem related to well construction (Figure 2). In Cape Coral, thousands of irrigation and single-family home supply wells were tapping the Mid-Hawthorn Aquifer. The potentiometric surface of the aquifer was drawn down far below sea level. Most of the small-diameter irrigation wells that were constructed into the Mid-Hawthorn Aquifer had steel casings driven by the cable-tool drilling method and contained no cement grout. Within a few years after construction, corrosion holes formed in the casing at near sea level (cathodic corrosion). The saline-water occurring within the water-table aquifer adjacent to tidal canals began to drain into the Mid-Hawthorn Aquifer via gravity feed. This problem virtually destroyed a large part of the Mid-Hawthorn Aquifer in Cape Coral (Boggess, Missimer and O'Donnell, 1977).

The research performed by Durward Boggess on the effects of improper well construction on the fresh groundwater resources lead to the development of new well construction permitting ordinances imposed by the Lee County government, the South Florida Water Management District, and years later by the City of Cape Coral. Boggess helped initiate a well plugging program to eliminate thousands of wells causing groundwater contamination.

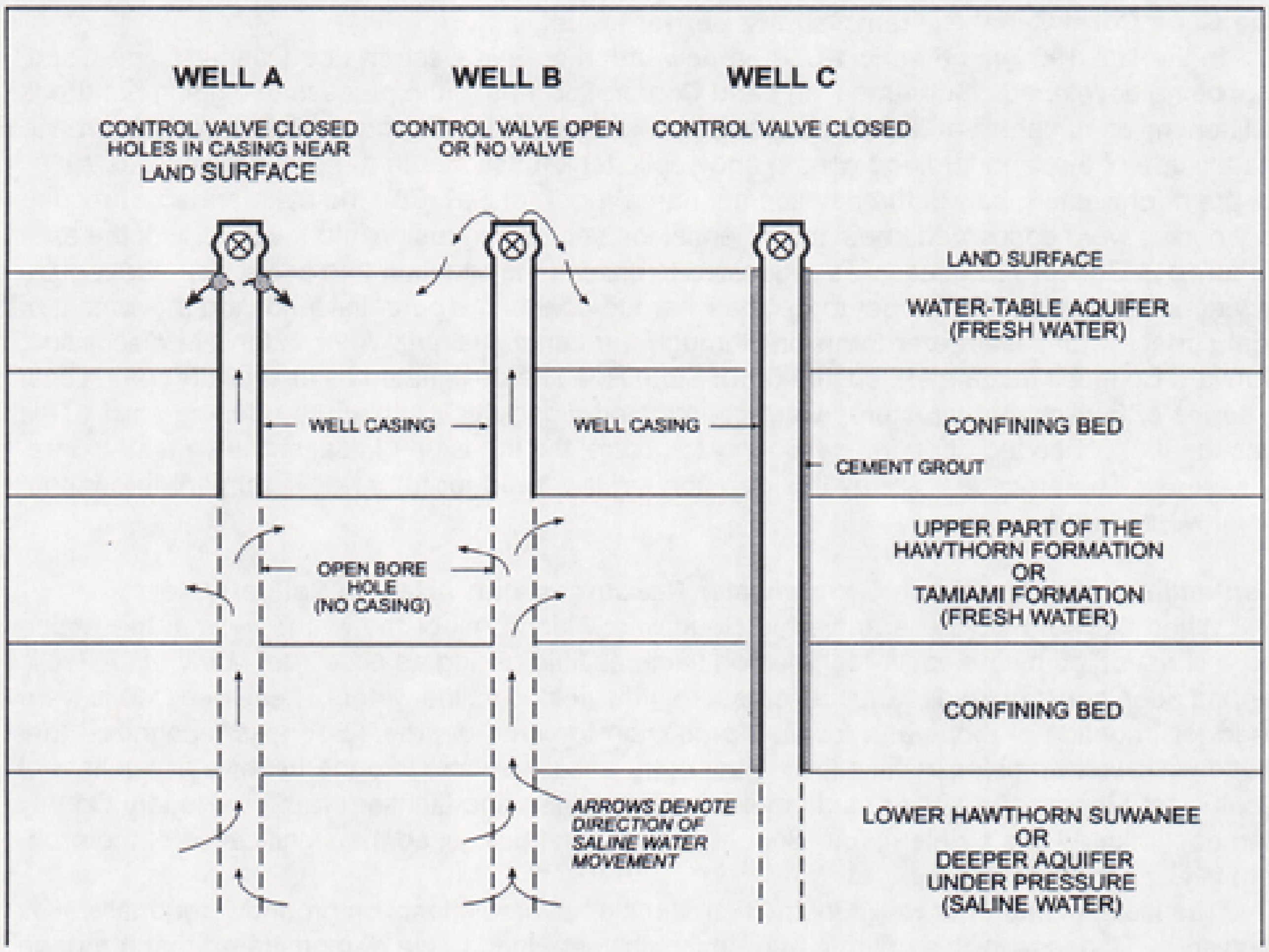

Figure 2. Diagram showing how saline-water contaminates freshwater aquifers by improper well construction or improper management. Well A has corrosion holes in the upper part of the casing and is not cased to the top of the aquifer containing pressurized saline water. Saline water migrates into both the confined and unconfined fresh-water aquifers. Well B also is not cased to the top of the pressurized saline-water aquifer and the wellhead value is either open or broken off. Saline-water enters all freshwater aquifers via the well or at land surface. Well C is a properly constructed well with the proper depth of casing and cement grout in the annulus. No saline water contamination occurs in this well.

Aquifers of Lee County Defined and Named

Little was known about the aquifer system beneath Lee County in 1966. On the Florida East Coast, the aquifer system was rather simple with the unconfined aquifer in the southeast area being termed the Biscayne Aquifer and the deep aquifer system being the Floridan Aquifer (Parker et al., 1955). Boggess recognized that the aquifer system in Lee County was much more complex than the Florida East Coast with a larger number of aquifers occurring with different pressures and water qualities. Boggess began to use formal names for the aquifers in order to communicate with the public in 1970. He was aware that the Floridan Aquifer beneath Lee County contained numerous individual flow zones. The uppermost two zones that were used for irrigation and contained slightly saline water, he named in ascending order, the Suwannee Aquifer and the Lower Hawthorn Aquifer (Figure 3). Two confined aquifers contained freshwater over large areas of the county. In western Lee County he named the confined freshwater aquifer the Upper Hawthorn Aquifer (now termed the Mid-Hawthorn Aquifer) and in eastern and southern Lee County he named the confined freshwater aquifer the Sandstone Aquifer. Boggess also recognized that another confined freshwater aquifer occurred in the southern part of Lee County in the Bonita Springs area, which was later termed the Lower Tamiami Aquifer (Figure 3).

There was considerable scientific importance in defining and naming these aquifers. Water level and quality information could be organized into a consistent scheme using the definitions. In subsequent years, the aquifer data were used to locate large public supply wellfields and to develop regional water supply plans.

The definition and naming of the aquifers in Lee County also served an even more important function. It allowed the public and press to understand the groundwater system to a greater degree, which lead to better planning and political decisions on protection and management of the groundwater resources.

Contamination Caused by Cut and Fill Municipal Landfills

In the 1960's and 1970's, the "state of the art" sanitary landfill design in Florida was the cut and fill type. In this type of landfill, a series of trenches were dug from land surface into the surficial aquifer to depths ranging from 8 to 20 feet below surface. A typical "cell" averaged about 15 feet in depth and was up to about 1000 feet in length. Water was removed from the trench during construction and filling via dewatering. No liners or other methods were used to separate the municipal waste buried in the cell from the surrounding groundwater. Upon completion of filling with waste, the trench was covered and another trench was constructed beside it.

The City of Fort Myers operated a cut and fill landfill east of town along Buckingham Road (Figure 1). The city established a groundwater quality monitoring program around the landfill to assess any impacts to the groundwater system and at the same time requested the U. S. Geological Survey to assist in the location of a new landfill site. In 1974, Durward Boggess informed the City of Fort Myers that the landfill was having an adverse impact on the shallow groundwater system adjacent to the landfill and on some surface-water bodies that drained into the headwaters of the Six-Mile Cypress. A report was delivered to the city in 1975 to document the findings (Boggess, 1975). Ultimately, the city consolidated its efforts to locate a new landfill site with the Lee County Government and a site was chosen south of State Road 82 (Gulf Coast Landfill). It should be noted that Durward Boggess advised the Lee County Government that the site chosen was not ideal for a landfill location, but the county had no other options at the time because of timing and public protests.

The study of the City of Fort Myers landfill as well as others in South Florida lead to major rule revisions by the Florida Department of Environmental Regulation (now Florida Department of Environmental Protection). Cut and fill landfills were outlawed and all landfills ultimately were required to be lined with impervious material to prevent groundwater contamination. Durward Boggess was one of the first hydrologists to point out the problem to the local and state government officials.

Saline-Water Intrusion into the Shallow Freshwater System of Sanibel Island, Florida

For many years Sanibel Island was a sparsely populated barrier island lying southwest of Fort Myers. It was connected to the mainland by a ferryboat that took residents and day-trippers to and from the island. In 1965, a bridge was completed to the island and activity greatly increased. A building boom began on the island in the early 1970's with a number of deep canals and artificial lakes being constructed. The shallow aquifer system on Sanibel Island contained a fragile freshwater lense that was critical to the maintenance of an internal freshwater marsh and the island vegetation. The construction activity was causing the intrusion of saltwater into

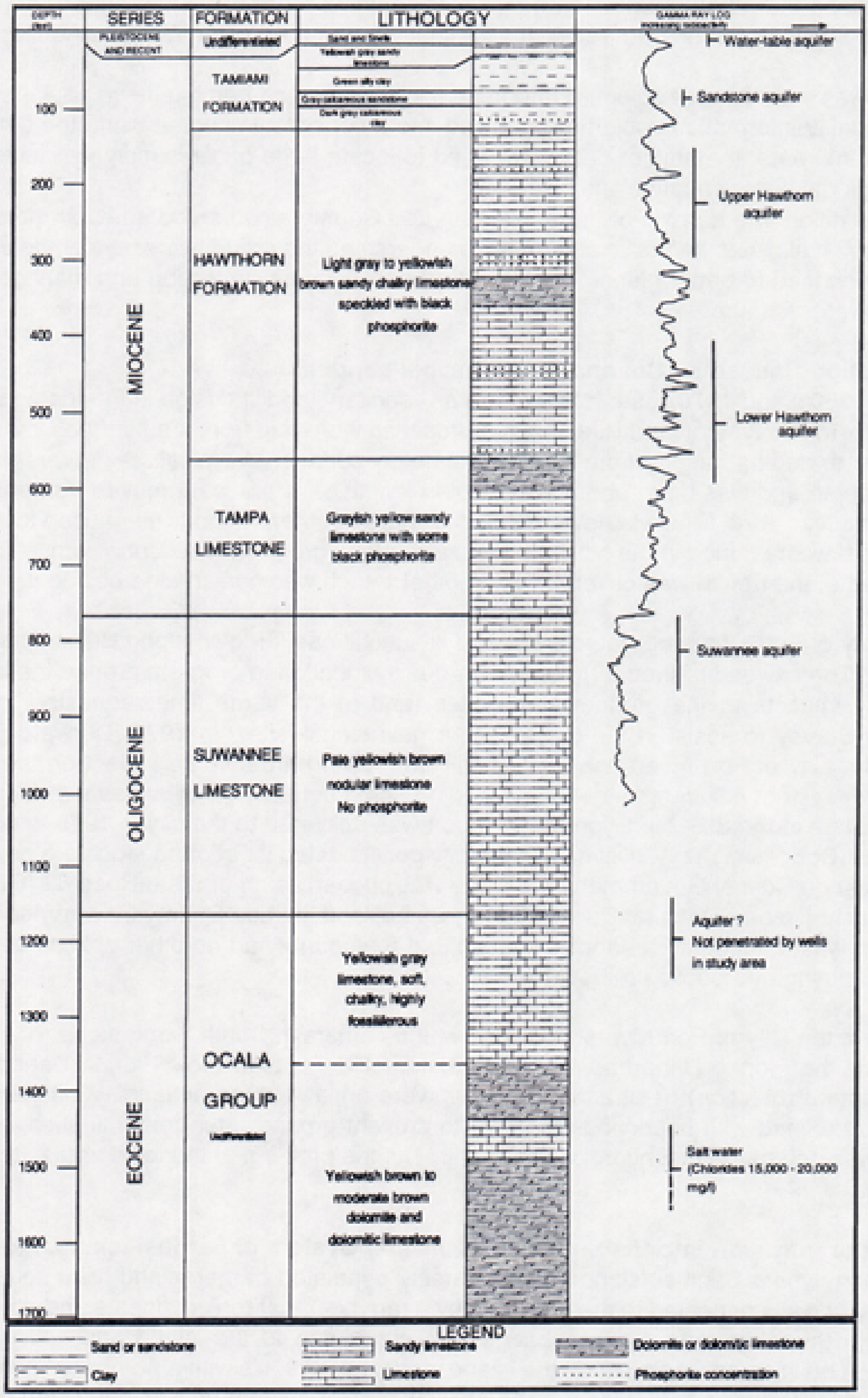

Figure 3. The original aquifer terminology for Lee County as named by Durward Boggess (modified from Sproul, Boggess & Woodard, 1972).

the shallow aquifer system and was destroying the freshwater lense.

Durward Boggess was asked to study the problem and conducted an investigation of the shallow water resources over a period of several years in the early 1970's (Boggess, 1974). The information obtained from this investigation was used to develop new construction standards for Sanibel Island and ultimately the information was used to help develop the comprehensive land use plan for the island (after the incorporation of the City of Sanibel).

Wetland Destruction in Lehigh Acres Caused by Over-Drainage

The development of a vast tract of land in eastern Lee County was very active in the late 1960's and early 1970's. Lehigh Acres was being carved out of pristine pine flatwoods and freshwater wetland areas. The area was flat and poorly drained, so a network of deep drainage canals was being constructed to drain the area to the north via the Orange River, Bedman Creek, and other streams to the Caloosahatchee River. Over a short period of time, a major wetland feature in the area, Halfway Pond, dried up and was lost. There was considerable public outrage over the destruction of this 400-acre pond and a number of state, federal, and local agencies took interest in the issue.

Durward Boggess was requested to make a rapid investigation of the area to provide a hydrogeologic assessment of the effects of drainage on the groundwater system (Boggess and Missimer, 1975). The report on the area was used by federal agencies to stop the over-drainage of the wetlands and the water management district required that water level control structures be placed in the drainage canals to retain groundwater.

Saline Water as a Future Water Supply for Lee County

Beginning in the late 1960's, Durward Boggess took a strong interest in the artesian, saline water resources of Lee County. First, he recognized that the deep, free-flowing wells were a source of contamination to the freshwater aquifers. However, as he studied the aquifers, he realized that these waters were also resources that could be treated using new water treatment technology. This realization was confirmed, when he was requested by the Island Water Association of Sanibel Island to help assist in the development of a public water supply system on the island. In the past, only shallow wells and cisterns were used for water supply on the island, but with rapid development, the shallow aquifer was not capable of yielding the necessary quantity of water required. The Island Water Association decided to use deep wells tapping the Lower Hawthorn Aquifer System to feed a new desalination system that used the electrodialysis process to desalt the water. Boggess provided considerable hydrogeologic data and expertise to develop the first saline-water wellfield in the Lee County (Boggess, 1974b; 1974b; Boggess and O'Donnell, 1982).

Over a period of several years, Boggess accumulated a large data base on the saline water resources of Lee County. In 1974, he published a critical document that provided the key hydrogeologic and water quality information to allow the successful development of those resources (Boggess, 1974). In the mid-1970's, Cape Coral and Pine Island developed wellfields to use the saline water resources, using the initial data base and forethought of Durward Boggess.

The Water-Table and Sandstone Aquifers of Eastern and Southeastern Lee County as Future Water Supplies

In his investigations of Lee County, Durward Boggess realized in the early 1970's that the county could be divided into the water poor western and northern area and the water rich eastern and southern area. From the geologic data base obtained from the Mobil Oil test drilling program and from extensive inventorying of existing wells, Boggess believed that the shallow and immediate aquifers in eastern and southern Lee County would be the only viable freshwater resources that could be developed in the future. During the later part of his career, he concentrated on compiling the hydrogeologic investigation in this area (Boggess, Missimer and O'Donnell, 1982; Boggess and Watkins, 1986). The information gathered by Boggess in eastern and southern Lee County was instrumental in the successful development of the Lehigh Acres Utilities Wellfield (Sandstone Aquifer), the Florida Cities Green Meadows Wellfield (water-table and Sandstone aquifers), the Lee County South Wellfield (water-table and Sandstone aquifers), the Gulf Utilities north and south wellfields (water-table aquifer), and the Bonita Springs Utilities west and east wellfields (Lower Tamiami Aquifer).

The Well Schedule and Well Log Data Base

Over his 13 years with the U. S. Geological Survey in Lee County, Durward Boggess was meticulous about the compilation of a well and geologic data base. He used topographic maps of the entire county to locate every well on which he could obtain data. The well was given a number and the data were recorded in a series of well schedules. When a geologic log existed, it was given a corresponding number and was recorded in a file. The same was true for water quality analyses. It was a time-consuming and tedious job to establish and maintain this record-keeping system, but it was critical in developing an accurate and detailed assessment of the groundwater resource. Data were collected on over 4000 wells in Lee County during the Boggess years. This is the most extensive hydrogeologic data base established for any county in the state of Florida and the credit for it goes to Durward Boggess.

Durward H. Boggess, The Man

Durward Boggess left a reputation as a man of impeccable integrity, who could always be relied upon to give fair and unbiased technical council. He never turned down any information request and talked to anyone who contacted the U. S. Geological Survey office. He established an excellent rapport with the press and helped educate numerous, young reporters. He talked with and provided information to elected officials, but he was never political, in the sense of pursuing some personal agenda. He was particularly skilled at finding solutions to the acquisition of technical data in the field, such as how to keep old, worn-out recording devices working, or how to collect flood stage data at minimal cost (crest-stage gages), or how to collect water samples at depths without expensive devices. He was also skilled at teaching water resources data collection methods to young geologists and to old engineers without ruffling sensitive egos. Durward Boggess never had said anything derogatory about any person, even when he was criticized. In his quiet, gentle way, he was able to obtain the funding he needed to perform scientific investigations of the highest quality without resorting to crisis creation via the media.

CONCLUSIONS

The contributions of Durward Boggess to the knowledge on the hydrology and geology of Lee County is a case study on how one man with integrity and spirit can make a profound contribution to science. The methods Mr. Boggess employed to glean the most information possible with minimal budgets is a case study for all practicing hydrologists and hydrogeologists. Without the development of the data base and the forethought given by Durward Boggess, the water resources of Lee County would have been severely damaged two decades ago. These contributions are still being used today as the population growth of Lee County causes further development of the water resources. Every citizen of Southwest Florida owes a debt of gratitude to Durward Boggess for his diligence and perseverance in working on the hydrology and geology of Lee County, Florida.

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THE SURFICIAL GEOLOGY OF LEE COUNTY AND THE CALOOSAHATCHEE BASIN

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ABSTRACT

Knowledge of the surficial geology is a processor to developing an understanding of the regional hydrogeology. Surficial geologic mapping in Florida is problematic because of the low relief and sand cover. The mapping effort in Lee County relied heavily on data from well cuttings and cores due to the sparse occurrence of pits, quarries and natural outcrops. The authors have spent many years visiting pits and quarries and working subsurface samples to develop an understanding of the regional geologic framework. The accumulated database was utilized to determine sand overburden thickness and the underlying stratigraphic units for creating the Lee County geological map.

The geologic units mapped were the Tertiary Tamiami Formation (Tt), Tertiary-Quaternary shell units (Tqsu - includes Caloosahatchee, Bermont, and Fort Thompson Formations of previous usage) and Quaternary (Holocene) coastal and estuarine sediments (Qh). Less than 20 feet of undifferentiated sands occurred within the map area.

INTRODUCTION

Geological maps provide an important tool for developing an understanding of geological history and natural resources. Knowledge of the regional surficial and near-surface geology is a necessary prerequisite to beginning to understand hydrogeology. The type and distribution of surficial and near-surface sediments has a direct bearing on the occurrence of surface water and the recharge of groundwater.

Vernon and Puri (1964) produced the last geological map by the Florida Geological Survey (FGS). Brooks (1982) published an independent version of the State geological map. Both maps required updating and revision. In the late 1980s, the FGS began an effort to create an updated and revised State geological map. In 1991, the mapping program focus changed toward the development of county geological maps for a statewide radon hazard analysis investigation. The maps created for this investigation formed the basis for the new State geological map.

Florida is the only state in the United States that lies entirely within a coastal plain province. With the highest elevation in the State of just 345 feet, relief is generally limited and few outcrops exist. The low relief of the southwestern Florida landscape yields little information to geologists from natural exposures making geological mapping problematic. As a result, the mapping effort in Lee County and the Caloosahatchee Basin utilized information gathered from well cuttings and cores (including a number of cores drilled by the FGS), quarries and pits, and limited natural outcrops. In developing a concept of the regional geologic framework, the authors have spent many years examining exposed sections and spoil piles in pits and quarries in addition to analyzing subsurface samples. The accumulated database was utilized in formulating the Lee County geologic map (Figure 1).

Much of the Florida landscape is covered by a sand blanket of varying thickness. Mapping the general surficial occurrence of the sands provides only limited information. As such, the convention was adopted of removing up to 20 feet of undifferentiated sands and mapping the underlying formations. In areas where the sand cover exceeded 20 feet in thickness, the occurrence of sand was mapped. Within Lee County, no areas of more than 20 feet of undifferentiated sand were identified. However, due to the nature of the database, sands thicker than 20 feet may occur locally within the county.

GEOLOGY

The geologic units mapped in Lee County were the Tertiary Tamiami Formation (Tt), Tertiary-Quaternary shell units (Qsu - includes Caloosahatchee, Bermont and Fort Thompson formations of previous usage) and Quaternary (Holocene) coastal and estuarine sediments (Qh).

The oldest formation shown on the Lee County geological map is the Pliocene Tamiami Formation (Tt). The Tamiami Formation is a poorly defined lithostratigraphic unit containing a wide range of mixed carbonate-siliciclastic lithologies and associated faunas (Missimer, 1992). The Peace River Formation, Hawthorn Group, underlies the Tamiami Formation throughout the county. The Tamiami Formation consists a mixture of variably sandy limestone, sands, and clays containing varying percentages of phosphate grains. Fossils, including mollusks, echinoids and corals, are commonly abundant in the Tamiami Formation. Fossil preservation varies from well preserved to molds and casts of the original fossils.

Overlying the Tamiami Formation throughout much of Lee County are sediments mapped as undifferentiated Tertiary/Quaternary (Plio-Pleistocene) shell-bearing units (Qsu). The Caloosahatchee, Bermont and Fort Thompson formations of previous references are included within the Qsu designation due to the primarily biostratigraphic nature of the units throughout their areal extent (see Scott, 1992). Within portions of the map area, the Caloosahatchee and Fort Thompson are lithologically separable. However, throughout much of the rest of southern Florida, the units are lithologically indistinct. This unit consists of sand with subordinate limestone and clay. Fossils, including mollusks and corals, are common, often abundant and preservation is often excellent.

A quartz sand blanket (less than 20 feet thick) overlies Tt and Qsu throughout the county. The sand is generally a fine to medium well sorted sand with no fossils. Along the coast, below an altitude of approximately 5 feet msl, are sediments mapped as Holocene age sediments. These sediments consist of quartz sand with a variable organic component and occasional peat to muck deposits. The Holocene sediments include the beach ridge and dune sands.

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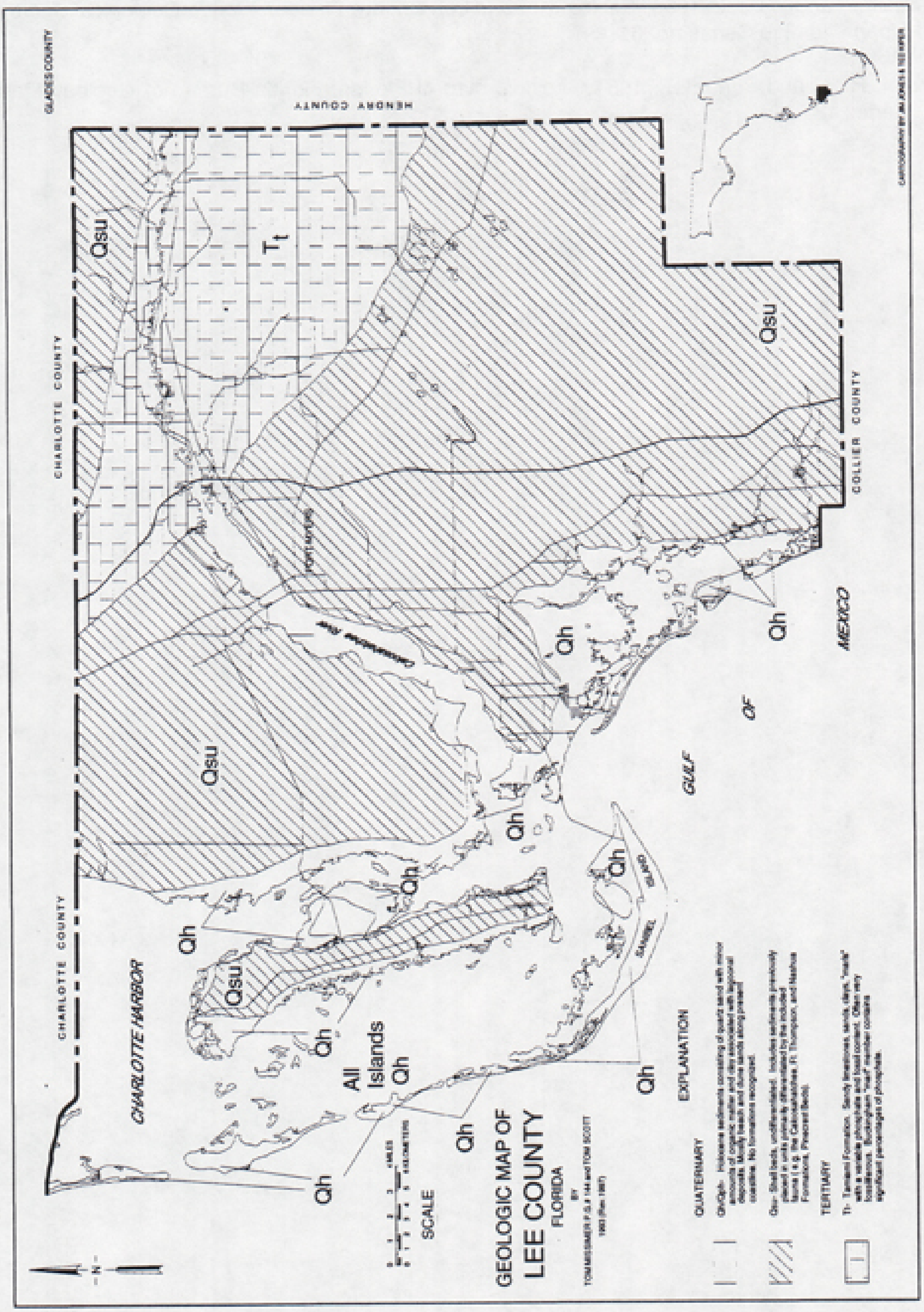

Figure 1. Geologic Map of Lee County, Florida.

T. Missimer and T. Scott, 1993, Geologic map of Lee County, Florida: Florida Geological Survey Open File Map Series no. 61.

Vernon, R.O., and Puri, H.S., 1964 Geologic map of Florida, Florida Bureau of Geology Map Series 18.

LATE NEOGENE GEOLOGY OF NORTHWESTERN LEE COUNTY, FLORIDA

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ABSTRACT

During the past 24 years, the Neogene geology of northwestern Lee County has been studied in numerous dewatered, shell pits. The thickness of the stratigraphic section studied is about 30 feet and contains three formations; the Tamiami, the Caloosahatchee, and the Fort Thompson. The Tamiami Formation is a predominantly siliciclastic unit, equivalent to the Sand Facies of Missimer (1992) with one occurrence of the Pinecrest Member (predominantly aragonitic mollusk shell) at Acline (Charlotte County). The Caloosahatchee Formation is a mixed carbonate and siliciclastic unit that is divided into three separate units by two intraformational unconformities. The Fort Thompson Formation is a shell and quartz sand unit that contains two or three stratigraphic units. From the base to the top of the formation, the relative percentage of quartz sand increases from about 20 to 100% by volume.

The lithostratigraphy of the shallow Neogene sediments adjacent to Charlotte Harbor shows that numerous transgressive and regressive sea level events produced a series of depositional environment changes over the last 4 million years. The region was blanketed with a sheet of quartz sand similar to the West Florida Shelf of today during the Pliocene as the Tamiami Formation was deposited. During deposition of the Caloosahatchee Formation, the region was subtropical with predominantly carbonate deposition and a coastal influx of quartz sand. Tropical and subtropical mollusks and corals were abundant in the region producing an environment similar to the present area between Cape Sable and Florida Bay. Deposition of the Fort Thompson Formation brought a substantial change to the environment with an evolution to barrier island and shallow nearshore deposition patterns similar to those observed today.

INTRODUCTION

Geological work in the northwestern area of Lee County and southern area of Charlotte County began during the 1880's with a few early descriptive works. In his classic work on the geology of the lower Florida West Coast, Heilprin (1887) wrote "Prior to our visit, the only portion of the state that had been examined geologically, or on which a geological report had been prepared, was the region lying north of a line running almost due northeast from the Manatee River, just south of Tampa Bay, to the east coast. Below this all was conjectural, although the existence of certain limestones of undetermined age was hinted at, or even located, by a number or causal observers (Tuomey, Conrad) who chanced to navigate some of the outer waters. Such a limestone was reported by Tuomey to be found in Charlotte Harbor, but the exact locality of its occurrence is not noted." Another scientist from the Wagner Free Institute of Philadelphia, William H. Dall, was the first geologist to visit some of the late Neogene exposures in the Charlotte Harbor area, immediately north of Lee County. Dall (1890-1903) described many of the fossils found in the Pliocene and Pleistocene sediments of the region. During the 1930's, several geologists examined exposures of the Caloosahatchee and Fort Thompson formations at locations near Shell Creek, Alligator Creek, and in spoil piles adjacent to excavations. Wendall C. Mansfield, Druid Wilson, Helen I. Tucker, and Axel A. Olsson visited several sites and collected fossil mollusks. The paleontology of the fossil mollusks was described in a few publications (Tucker and Wilson, 1932a; Olsson and Harbison, 1953). In 1958, a shell pit located near Acline (Figure 1) was drained to make bed collections of the fossils and to describe the geology. Druid Wilson of the U.S. Geological Survey and Stanley Olsen of the Florida Geological Survey made these collections, but no work other than a fauna list (Tucker and Wilson, 1932b; also in DuBar, 1962) was ever published. A detailed investigation of the Neogene geology of the Charlotte Harbor area was published by DuBar (1962). DuBar described the geology at 13 sites located adjacent to Charlotte Harbor and the geology adjacent to Shell Creek.

The geologic descriptions presented in this paper are considered to be preliminary and were compiled at numerous locations in Lee and Charlotte counties over a period of 24 years by the author and a number of associates. The author was first introduced to the geology of the Charlotte Harbor area by F. Sternes McNeill, who was one of W. C. Mansfield's field assistants in the 1930's. McNeill accompanied Durward Boggess and the author to several locations in the area between 1972 and 1975.

NEOGENE STRATIGRAPHY

Introduction

A number of shell and sand pits have been excavated adjacent to the southeastern margin of Charlotte Harbor in Charlotte and Lee counties and in the Cape Coral area of Lee County over the past 40 years. Many of these excavations were dewatered to facilitate sediment removal, which allowed detailed descriptions of the sediments to be made. Three Neogene stratigraphic units were penetrated in most of the excavations, which include the Tamiami, Caloosahatchee, and the Fort Thompson formations. Neogene time includes the Miocene to the end of the Pleistocene or 23.8 to 0.01 Ma or a million years before present (Berggren et al. 1995). A general stratigraphic column is shown in Figure 2 using the stratigraphic terminology of Missimer (1992) for the Tamiami Formation and the terminology of DuBar (1962) for the Caloosahatchee and Fort Thompson formations. Although geologic information was collected at each of the locations (sections measured and described) shown in Figure 1, detailed descriptions of the geology are presented for only the Burnt Store Road North Pit (4), the Nelson Road Pit (5), and the Chiquita Sand Pit (6).

Tamiami Formation

The Tamiami Formation is a Pliocene unit that contains a wide variety of members or facies dependant upon the specific location studied. Missimer (1992) presented a stratigraphic correlation of the various lithologic units found within the Tamiami Formation in Southwest Florida (Figure 3). In the northern part of the study area, the exposures of the Tamiami Formation in Alligator Creek are a sandy, calcareous clay with some phosphate and a few calcitic fossil fragments (DuBar, 1958). The calcareous clay facies correlates to the tan clay and sand facies, which occurs near the base of the formation (Figure 3). At all other locations, with the exception of the Acline Pit, the section of the Tamiami Formation penetrated was either a sand and partially indurated sandstone (Burnt Store Road North Pit), an unlithified quartz sand with solely calcitic fossils interbedded with some limestone (Nelson Road Pit), or a partially indurated sand and barnacle hash (Chiquita Sand Pit). All of these predominantly quartz sand units correlate lithostratigraphically with the sand facies of Missimer (1992) shown in Figure 3.

The only exposure of the classical Pinecrest Member containing a wide diversity of molluscan species with preserved aragonitic shell is at the Acline Pit site. The Pinecrest Member of the Tamiami Formation is the youngest member of the formation and does not occur as a continuous stratigraphic unit in the area of Charlotte Harbor.

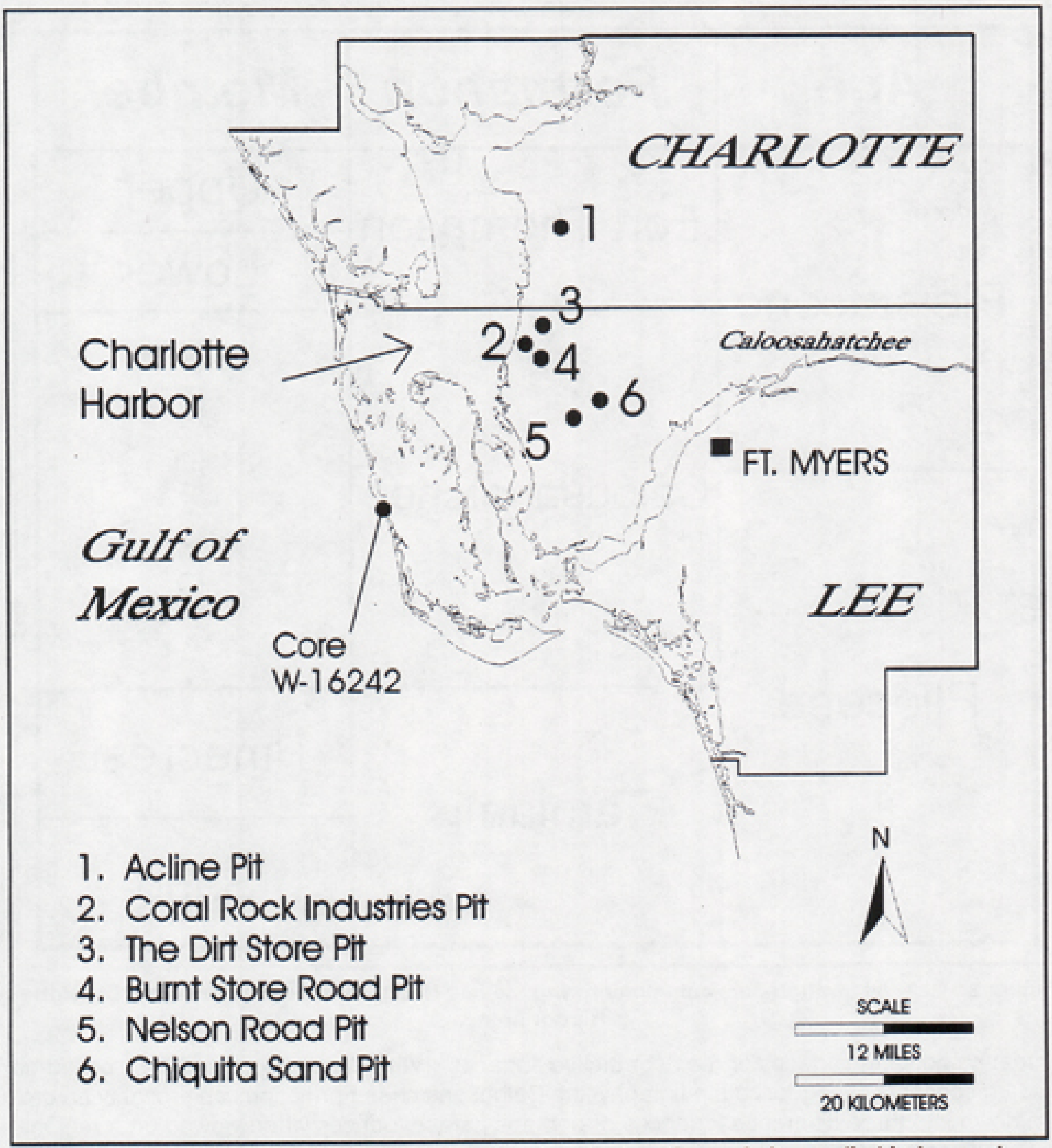

Figure 1. Map of Charlotte Harbor area showing the locations of pits studied in Lee and Charlotte counties.

Caloosahatchee Formation

DuBar (1962) recognized five stratigraphic subdivisions of the Caloosahatchee Formation in the Charlotte Harbor area (Figure 4). Although these subdivisions of the formation do occur, they are rarely if ever all present at a single location or in the same stratigraphic position Stratigraphic sections are commonly described in terms of sequence stratigraphy, in which a sequence is defined as an unconformity-bounded stratal unit (Van Wagoner et al. 1990). A sequence is subdivided into parasequences, which are the building blocks of the sequence. A parasequence is defined as "relatively conformable successions of genetically related beds or bedsets bounded

Age	Formation	Member
Pleistocene	Fort Thompson	Upper
		Lower
	Caloosahatchee	F E D C B A
Pliocene		
	Tamiami	Pinecrest
		Sand

Figure 2. General stratigraphic column showing the late Neogene units studied in the Charlotte Harbor area.

by marine-flooding surfaces or their correlative surfaces" (Van Wagoner et al. 1990). Based on modern concepts of sequence stratigraphy, the Caloosahatchee Formation can probably be broken down into three different sequences or perhaps parasequences when viewed on a regional basis. There are at least two distinctive breaks in the Caloosahatchee stratigraphic section, marked by the occurrence of either a laminated crust and disconformity or the occurrence of a freshwater limestone. These breaks correspond to either marine-flooding surfaces or to terrestrial discontinuities as in the case of freshwater limestones. In the general stratigraphic column show in Figure 4, the unconformities dividing the section occur at the top of Units C and E. It is not possible to correlate regionally individual lithologic units within the formation, because of spatial variability caused by depositional environment changes. However, the correlation of the unconformities in stratigraphic order does allow correlation of time lines, which was the method used by Perkins (1977) for correlating these stratigraphic units along the Florida East Coast.

The Caloosahatchee Formation at the Burnt Store Road North Pit contained four different

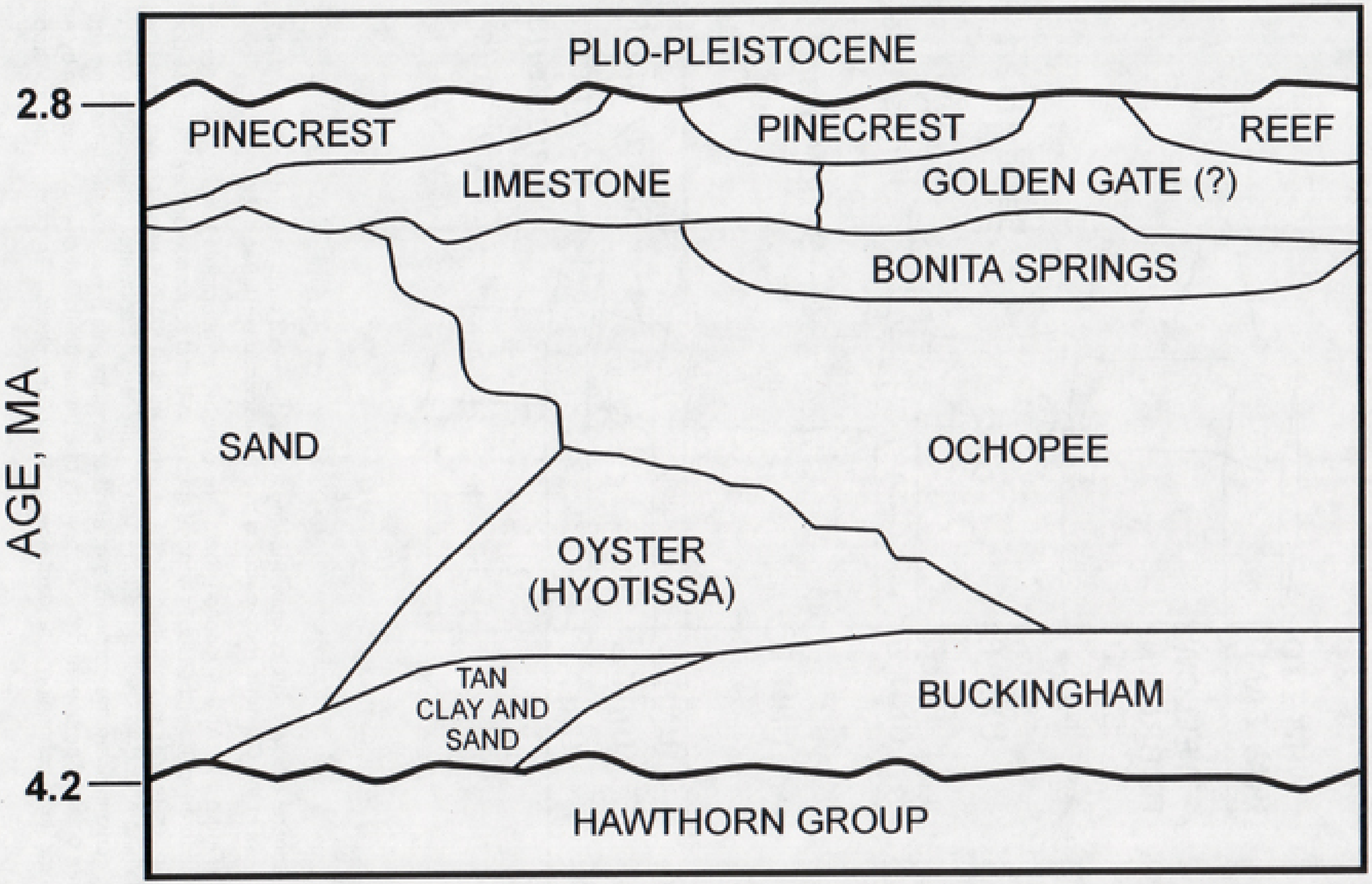

Figure 3. Diagram showing the correlation of lithostratigraphic unit, defined facies, and formal members of the Tamiami Formation (from Missimer, 1992).

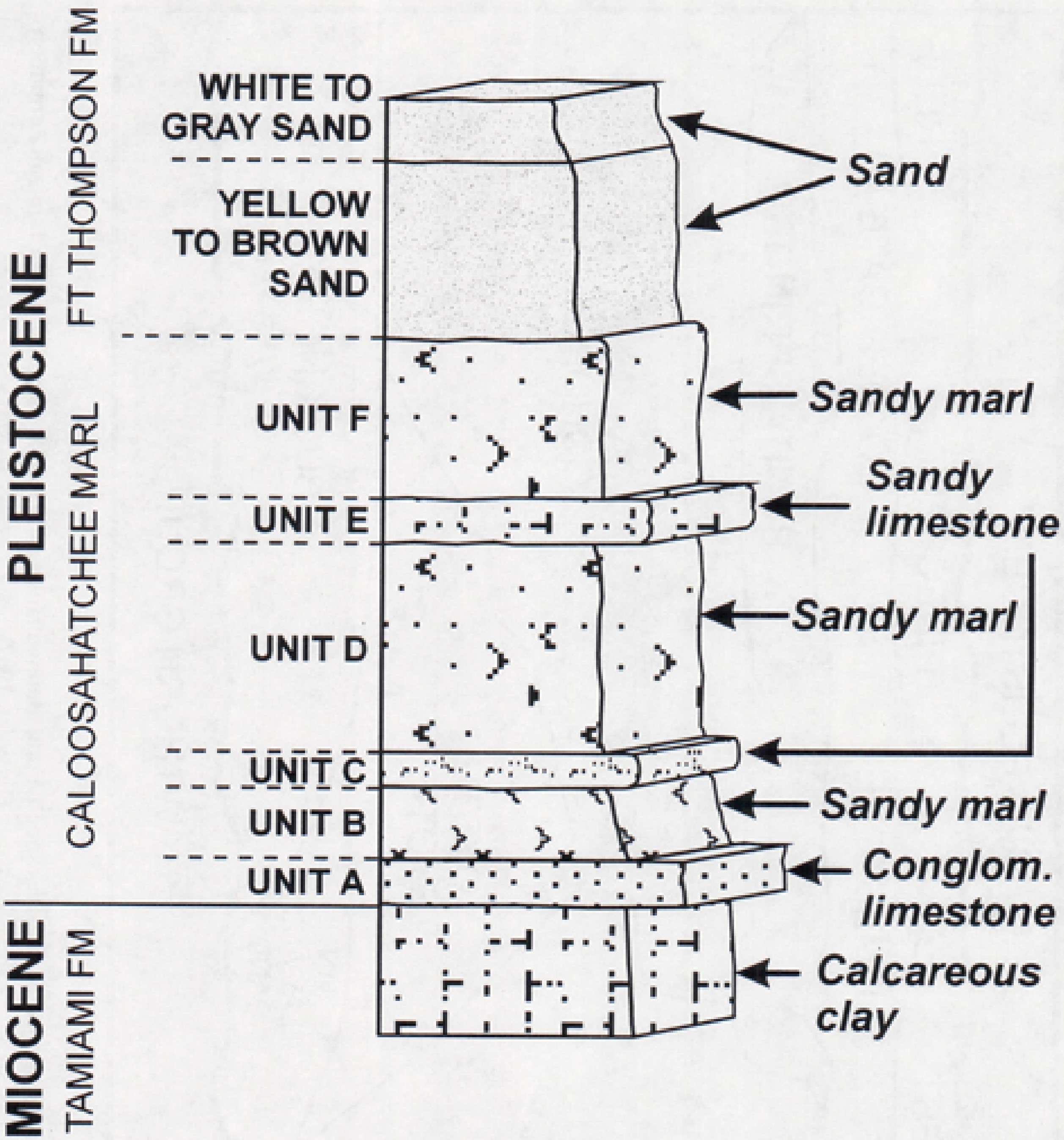

Figure 4. General stratigraphic column showing the stratigraphic units studied by DuBar (1962) in the Charlotte Harbor area with unit descriptions (DuBar, 1962).

lithic units (Figure 5). At this location there are only two stratigraphic breaks in the section instead of the three found in the DuBar general section. A basal sequence or parasequence contains two lithic units with an unlithified shell and sandy mud at the base and an indurated limestone containing abundant shell at the top. The occurrence of freshwater fossils at the base of the section could indicate the occurrence of another stratigraphic break, but the remaining section does not occur. The uppermost unit consists of a basal, unlithified shell unit overlain by an indurated limestone containing abundant aragonitic mollusk shells. The top of the limestone

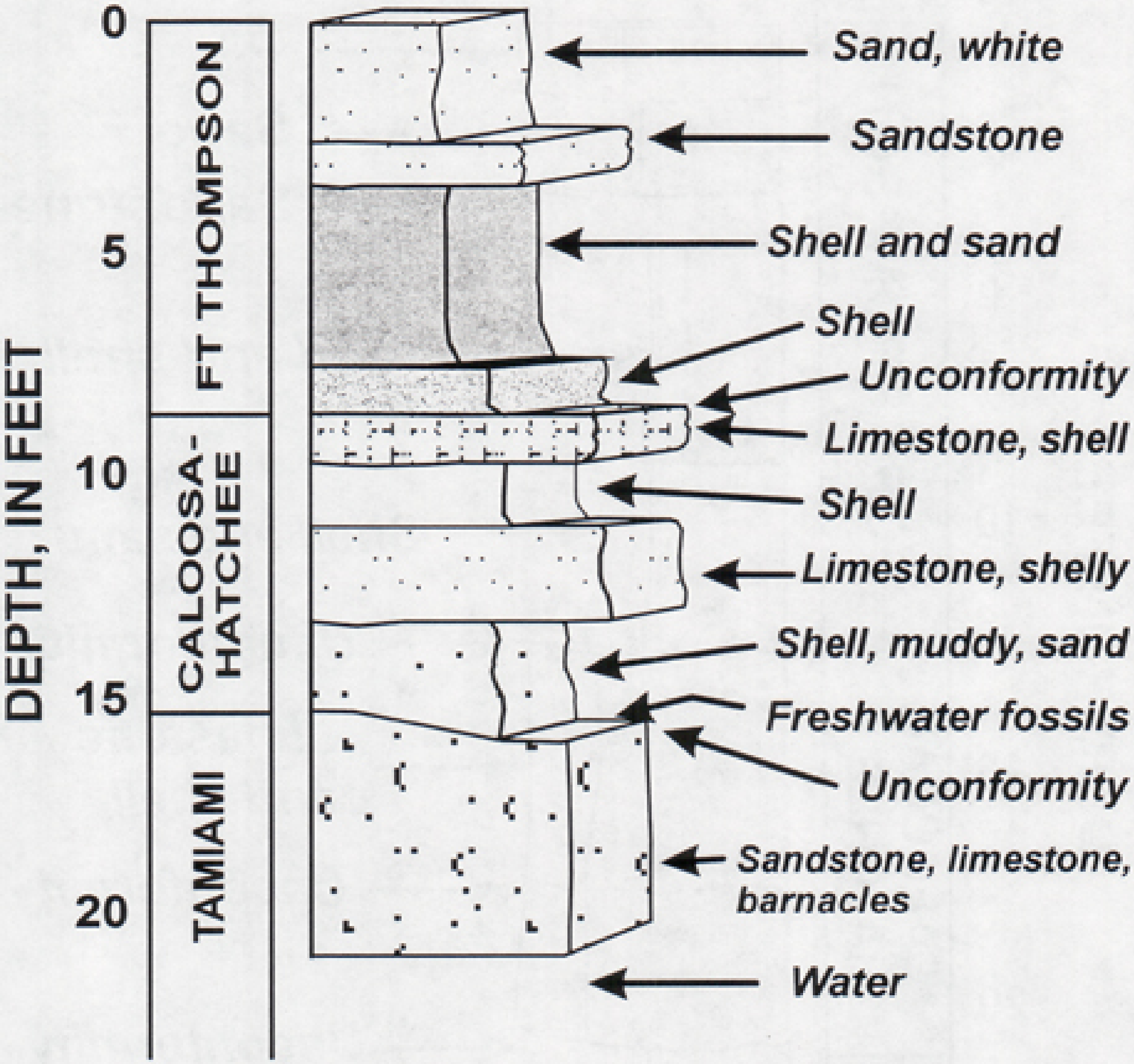

Figure 5. Neogene stratigraphy of the Burnt Store Road North Pit in Lee County.

contains a laminated crust at some locations in the pit. Without some absolute time control, it is not possible to correlate this section with the general DuBar typical section.

To the southeast of Charlotte Harbor, the occurrence of the Caloosahatchee Formation is limited to only a few locations, because the formation has been removed by erosion or was not deposited. The southernmost known occurrence of the formation on the Florida West Coast is at the Nelson Road Pit, but only in the northeast corner of the pit (Figures 6 and 7). Despite the relatively thin section of the formation at about 8 feet, nine different lithologies were found in three sequences or parasequences. The basal unit is bounded with a disconformity at the base and a freshwater limestone at the top. The lowest lithologic unit is an unlithified quartz sand and shell. An indurated sandy limestone with shell lies conformably above the lowest unit and the sequence is capped by a freshwater limestone. The middle sequence contains three different lithologic units beginning at the base with a partially indurated limestone containing well-pre-

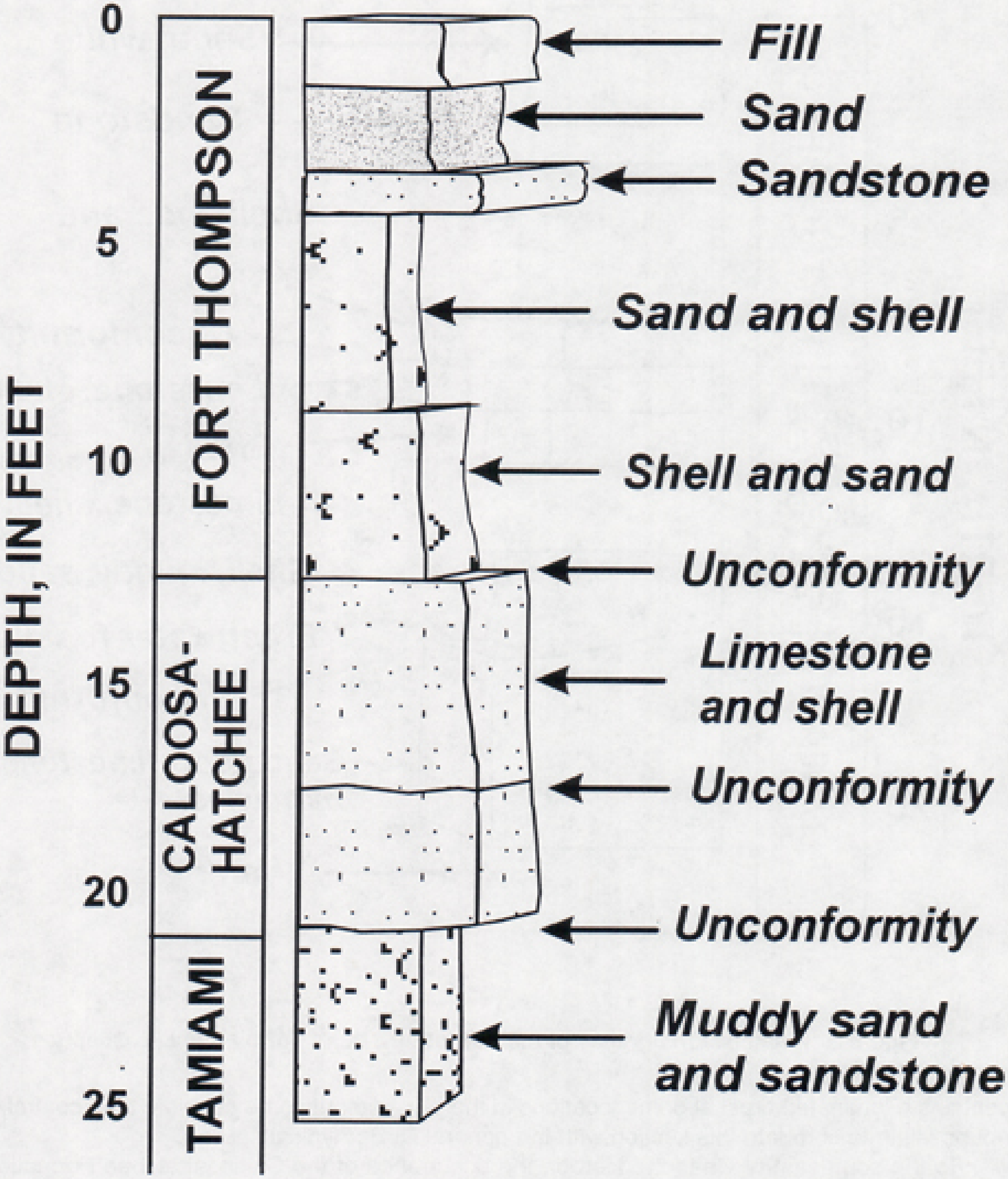

Figure 6. Neogene stratigraphy of the Nelson Road Pit located in Lee County.

served aragonitic mollusk shells. This lithic unit is underlain by a coralline boundstone, containing about ten different species of corals. The sequence is capped by a highly altered limestone containing predominantly sparite and no preserved aragonitic fossils. The top of the limestone contains some solution depressions partially infilled with indurated laminated muds. The uppermost sequence also contains three different lithologies. The base is an unlithified quartz sand

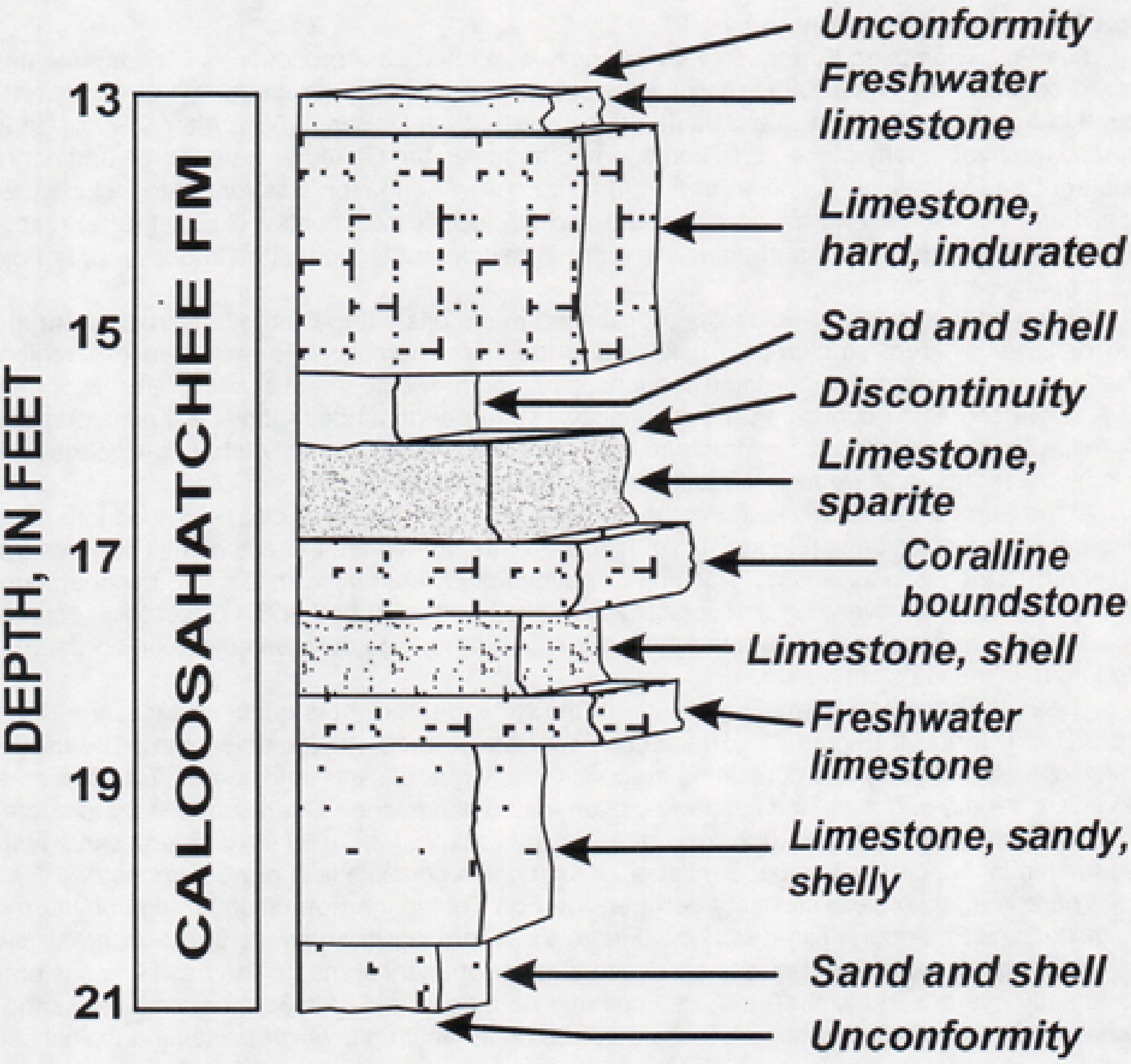

Figure 7. Detailed stratigraphy of the Caloosahatchee Formation at the Nelson Road Pit in Lee County.

and shell. It is topped by a hard, indurated limestone containing preserved aragonitic shell. The sequence is capped with a freshwater limestone with some preserved laminations at the surface. The Nelson Road Pit is the only known location in the region that contains all three sequences described by DuBar (compare Figure 7 to 4).

No Caloosahatchee Formation sediments were found in the Chiquita Sand Pit located east of the Nelson Road Pit. Specifically defined Caloosahatchee Formation sediments have not been identified at any other location to the south in Lee or Collier counties.

Fort Thompson Formation

The Fort Thompson Formation was originally described as a predominantly carbonate unit based on outcrops located along the Caloosahatchee River and the carbonate shell deposits found in a number of pits in South Florida (Dall, 1890-1903; DuBar, 1958). After DuBar (1962) studied the stratigraphy of the Fort Thompson Formation in the Charlotte Harbor area and northwestern Lee County, the definition of the Fort Thompson Formation was forced to include predominantly siliciclastic and mixed carbonate and siliciclastic sediments. DuBar (1962) recognized two separate quartz sand units within the formation in the Charlotte Harbor area, but did not formally separate them.

Based on the stratigraphic sections described in the pits along Charlotte Harbor, there are two or three different stratigraphic units within the Fort Thompson Formation in this region. These units may represent individual sequences related to two separate sea level events or may be a single sequence containing a discontinuity. The uppermost unit, above a laminated crust representing an unconformity is problematical and may represent a very late sea-level deposit or may be an erosional deposit related to soil development.

At the Burnt Store Road North Pit, the Fort Thompson Formation is clearly divided into three different stratigraphic units (Figure 5). At the base of the formation, there is a shell bed averaging about 12 inches in thickness. This unit is predominantly aragonitic shell with a minor amount of quartz sand. The overlying unit consists of a shell and sand bed about 5 feet thick capped by a laminated sandstone. The uppermost unit is a quartz sand containing little on no carbonate and is sometimes laminated.

The Fort Thompson Formation section at the Nelson Road Pit is quite similar to the Burnt Store Road North Pit (Figure 6). The section consists of three stratigraphic units. The lowest unit is a shell and sand bed containing aragonitic shell, quartz sand, and some mud. The middle unit is a sand and shell bed capped by a laminated sandstone. Quartz sand is the predominant component of the middle unit with up to 70% by volume. About 60 cm of quartz sand overlies the laminated crust. The uppermost quartz sand unit contains little or no carbonate.

There is again a clear similarity between the Fort Thompson Formation stratigraphy at the Chiquita Sand Pit and the pits described (Figure 8). There are three stratigraphic units with the lowest unit being a shell and quartz sand with a minor quantity of mud. The middle unit is predominantly quartz sand with 10 to 20% shell and no mud and is capped by a laminated sandstone crust. About 2.5 feet of sand occurs as the uppermost unit, which contains a typical soil profile.

Age of the Neogene Stratigraphic Units

The most recent data available on the age of the Neogene formations discussed in this paper was collected from Florida Geological Survey core W-16242, located at South Seas Plantation on Captiva Island east of pit sites (Missimer, 1997). Based on this work, the estimated age ranges using the time scale of Berggren et al. (1995) for the formations discussed are: Tamiami Formation, 4.29 to 2.15 Ma; Caloosahatchee Formation, 2.14 or 1.77 to 0.6 Ma; and Fort Thompson Formation, 0.6 to 0.12 Ma. The Pinecrest Member of the Tamiami Formation has an age range of 3.22 to 2.15 Ma in this core. These estimated age ranges for the formations are likely to be similar for the sections discussed based on the close proximity of the Captive Island core to the pit locations.

DISCUSSION

Study of the Neogene geology of the Charlotte Harbor area indicates that there is considerable spatial variability in the lithologic units constituting the Tamiami, Caloosahatchee and Fort

Thompson formations. Conventional lithostratigraphic correlation is not possible, but mapping of regional disconformities does allow correlation of time-equivalent units because of the relatively flat relief of the South Florida Platform (Perkins 1977).

At nearly every location studied, the Tamiami Formation is predominantly a siliciclastic unit consisting of quartz sand with calcitic shell or slightly cemented quartz sand. The described lithologic unit is equivalent to the Sand Facies of Missimer (1992). The only location containing any section of the Pinecrest Member is the Acline Pit, which is further evidence that the Pinecrest Member is not a regionally mappable stratigraphic unit.

There are two disconformities within the Caloosahatchee Formation that divide it into three sequences or parasequences. It is likely that each of the three units found represent a single sea-level event based on the generally shoaling-upward nature of the sediments (note the depth

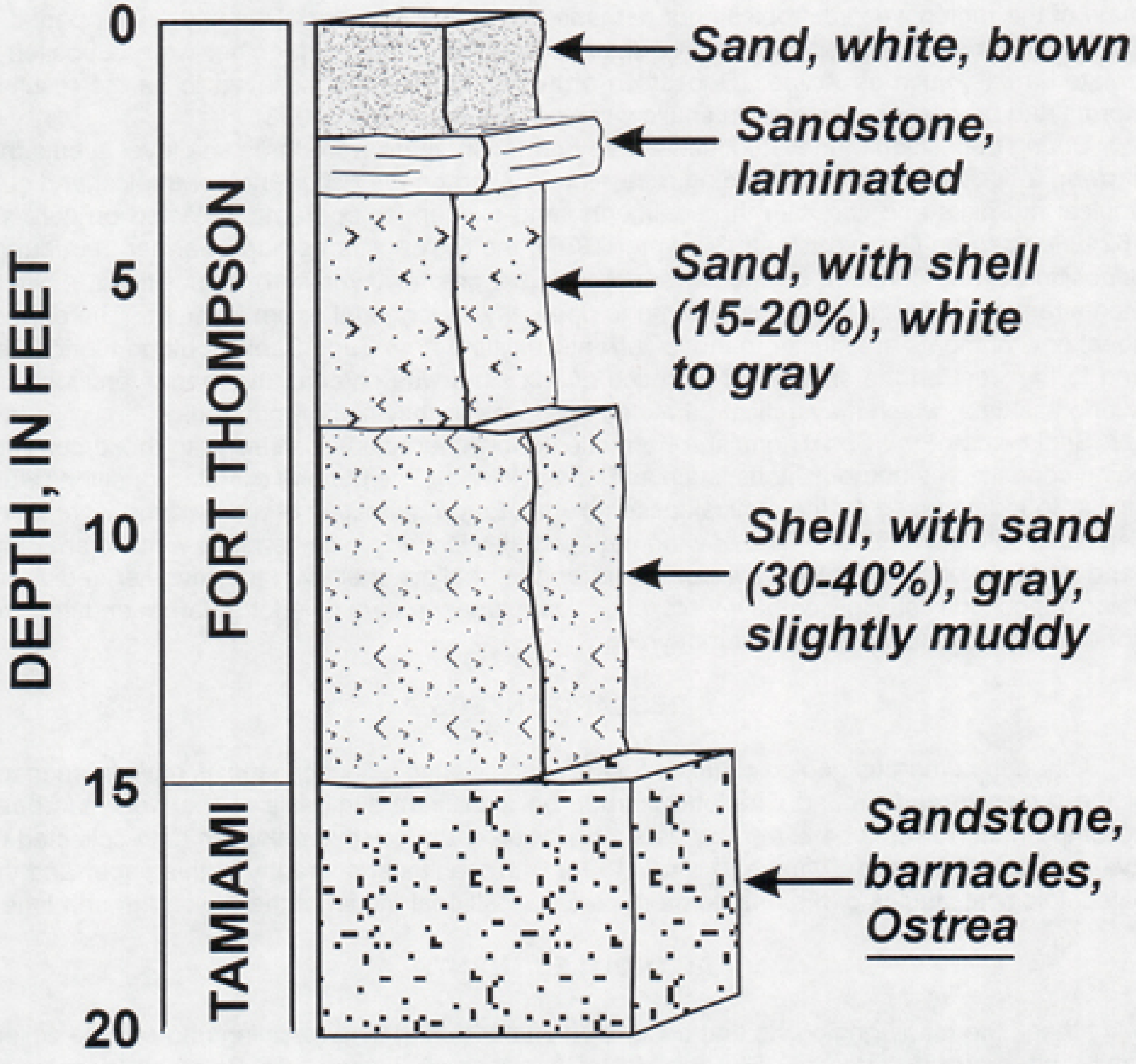

Figure 8. Neogene stratigraphy of the Chiquita Sand Pit in Lee County.

of water in which the sediments were deposited becomes progressively shallower). Based on recent age-dating work by Missimer (1997), the uppermost sequence is likely a Pleistocene sea-level event while the lower two sequences are Pliocene events. Similar ages for these sediments was determined by Jones et al. (1991) in Sarasota County.

Three different lithologic units were found within the Fort Thompson Formation. These units show remarkable uniformity in composition. The units become progressively more siliciclastic from bottom to top of the formation.

CONCLUSIONS

Over the last 4 million years, the geological character of the Charlotte Harbor region has changed considerably. When the Tamiami Formation was being deposited, the area was predominantly a sandy, shallow marine environment, similar to the current conditions on the West Florida shelf with deeper water (Meeder 1987). Based on the work of Meeder (1987), the climate of the region was subtropical, but perhaps cooler than present. During the later period of Tamiami Formation deposition, massive shell beds of the Pinecrest Member were deposited in isolated areas, such as Acline. Deposition of these shell beds is believed to be the result of storms and processes occurring in shallow coastal waters (Allmon 1993).

During deposition of the Caloosahatchee Formation, there were three sea level events that showed a rise and then a succeeding recession. Based on the occurrence of tropical and subtropical mollusks and corals in the sediments, and oxygen isotope data collected on core W-16242 located on Captiva Island (Missimer 1997), the region was perhaps warmer than during deposition of the Tamiami Formation and showed a greater diversity of depositional environments ranging from shallow shelf or ramp to open bay, to lagoonal or embayment. The depositional environments are similar to those currently existing from Cape Sable south to Florida Bay and to the west on the shelf. Not as much quartz sand was entering the marine environment during this time, which may indicate that sea level was slightly higher than today.

Sediments of the Fort Thompson Formation show characteristics similar to those currently being deposited as barrier islands, such as Sanibel Island. The general climatic conditions were similar to today based on the mollusk assemblage. Large quantities of quartz sand were being deposited with the mollusks. The environment probably looked similar to today with the shell and sand deposits occurring along the coast and on the shallow shelf with the muddier sediments being deposited in shallow embayments, such as the upper part of Charlotte Harbor and the interior of the Caloosahatchee River embayment.

RESEARCH NEEDS

Although numerous geologic, paleontologic, and seismic reflection studies have been made of the region in and around Charlotte Harbor, no significant synthesis of the work has been accomplished. It would be extremely useful to correlate the seismic reflection data collected by Evans et al. (1989) and Evans and Hine (1991) with the lithostratigraphy in this paper and the paleontological studies of the past to produce a depositional model of the region through time.

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SEQUENCE STRATIGRAPHY OF A SOUTH FLORIDA CARBONATE RAMP AND BOUNDING SILICICLASTICS (LATE MIOCENE-PLIOCENE)

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ABSTRACT

In southern peninsular Florida, a late-early to early-late Pliocene carbonate ramp (Ochopee Limestone Member of the Tamiami Formation) is sandwiched between underlying marine siliciclastics of the late Miocene to early Pliocene Peace River Formation and an overlying late Pliocene unnamed sand. At least three depositional sequences (DS1, DS2, and DS3), of which two contain condensed sections, are recognized in the Peace River Formation; an additional depositional sequence (DS4) is proposed to include the Ochopee Limestone.

Established chronologies and new biostratigraphic results indicate that the Tortonian and Zanclean ages bracket the Peace River Formation. Depositional sequence 1 (DS1) prograded across the present-day peninsular portion of the Florida Platform during the Tortonian age and laps out near the southern margin of the peninsula. During the latest Tortonian and Messinian ages, progradation of DS2 overstepped the southern lap out of DS1 and extended at least as far as the Florida Keys. Deposition of DS2 ended, at the latest, near the Miocene-Pliocene boundary. Siliciclastic supply was reduced during early Pliocene deposition of DS3, which is absent in southernmost peninsular Florida. This reduction in supply of siliciclastics was followed by aggradational accumulation of heterozoan temperate carbonate sediments on a widespread carbonate ramp that includes the Ochopee Limestone. The Ochopee Limestone was deposited during eustatic cycle TB3.6 and ended in the late Pliocene with basinward lap out near the southern margin of the Florida peninsula. The Ochopee Limestone ramp was buried with a late Pliocene resumption of southward influx of siliciclastics (unnamed sand and Long Key Formation) that extended south beyond the middle and upper Florida Keys.

INTRODUCTION

Until the early 1990's, stratigraphic investigations of Miocene-Pliocene siliciclastics and carbonates beneath southern Florida focused on lithostratigraphy (Peck et al., 1979; Wedderburn et al., 1982; Peacock, 1983; Missimer, 1984; Knapp et al., 1986; Scott, 1988; Smith and Adams, 1988; Missimer, 1992). Recently, sequence stratigraphy has contributed to conceptualizing a more accurate spatial and temporal framework of the Miocene-Pliocene stratigraphic framework of southern Florida (Evans and Hine, 1991; Warzeski et al., 1996; Missimer, 1997; Cunningham et al., 1998; Guertin et al., 1999; Missimer, 1999; Guertin et al., 2000). This developing sequence-stratigraphic framework for southern Florida is the result of integrating lithostratigraphy, micropaleontology, magnetostratigraphy, strontium-isotope chemostratigraphy, and seismic stratigraphy along with delineating unconformities that bound depositional sequences (Missimer, 1997; Weedman et al., 1997; Cunningham et al., 1998; Edwards et al., 1998; Guertin, 1998; Missimer, 1999; Weedman et al., 1999). The purpose of this study is to integrate new lithologic and paleontologic data with established subsurface data to more accurately describe the regional lithostratigraphic and sequence-stratigraphic framework of the Miocene-Pliocene siliciclastics and carbonates of southern Florida. Correlating these data will improve understanding of the regional stratigraphic framework and constrain time boundaries for depositional sequences.

METHODS

A total of 89 coreholes and cuttings from 18 test wells were used to map lithostratigraphic boundaries and to develop facies associations and sequence stratigraphy (Fig. 1). The cuttings were described using a binocular microscope. Descriptions of the cores are from Causaras (1985), Causaras (1987), Fish (1988), Fish and Stewart (1991), McNeill et al. (1996), Missimer (1997), Weedman et al. (1997), Cunningham et al., (1998), Edwards et al., (1998), Guertin (1998), Weedman et al. (1999), Reese and Cunningham (2000, in press), and from the data archives of the Florida Geological Survey and U.S. Geological Survey.

Co-authors David Bukry and Tokiyuki Sato identified coccolith taxonomy, and John Barron determined diatom taxonomy. Bukry and Barron conducted identifications by standard U.S. Geological Survey methods. Sato identified coccoliths for each sample by counting 200 nannofossil specimens for quantitative analysis. The terms abundant (greater than 32 percent of specimens in total assemblage), common (32 to 8 percent of specimens in total assemblage), rare (less than 8 percent of specimens in total assem-blage) and present (found but not counted) were used to describe quantitatively coccolith populations defined by Sato. Coccolith taxomony has been assigned to the biostratigraphic zones of Okada and Bukry (1980) as calibrated to the coccolith datums of ODP Leg 171B from the Blake Nose east of northern Florida (Shipboard Scientific Party, 1998) with normalized modifications from Bukry (1991).

Co-author Laura Guertin identified benthic foraminifera at the genus level using data from Bock et al. (1971), Poag (1981), and Jones (1994). Paleoenvironmental interpretations are based on grouping of individual benthic foraminiferal associations and species into the broad depth categories of inner and outer shelf, defined as mean sea level to an approximate water depth of about 305 feet and from about 305 to 610 feet, respectively (Murray, 1991). Ages are reported in accordance with the integrated magnetobiochronologic Cenozoic time scale of Berggren et al. (1995).

CARBONATE RAMP AND BOUNDING SILICICLASTICS TEMPORAL AND SPATIAL BOUNDARIES

Lithologic units of primary interest in this study, from oldest to youngest, are the Peace River Formation of the Hawthorn Group, Ochopee Limestone Member of the Tamiami Formation, and an unnamed sand member (Fig. 2). Facies associations pre-sented for the Peace River Formation, Ochopee Limestone, and unnamed sand are based on examination of cores and on existing descriptions within the study areas outlined in Figure 1.

Peace River Formation

Lithostratigraphy

Three depositional sequences (DS1, DS2, and DS3) are newly defined on a regional scale within the Peace River Formation (Fig. 2). Although interpreted to be depositional sequences, DS3 actually may be a parasequence. Much of the lithofacies analysis completed by Reese and Cunningham (2000, in press) for southeastern Florida was limited mostly to DS2 and DS3. Depositional sequence 1 (DS1) was characterized primarily by Weedman et al. (1997) and Edwards et al. (1998). Five lithofacies have been identified by Reese and Cunningham (2000, in press) for the upper part of the Peace River Formation in an area shown in Figure 1: (1) diatoma-

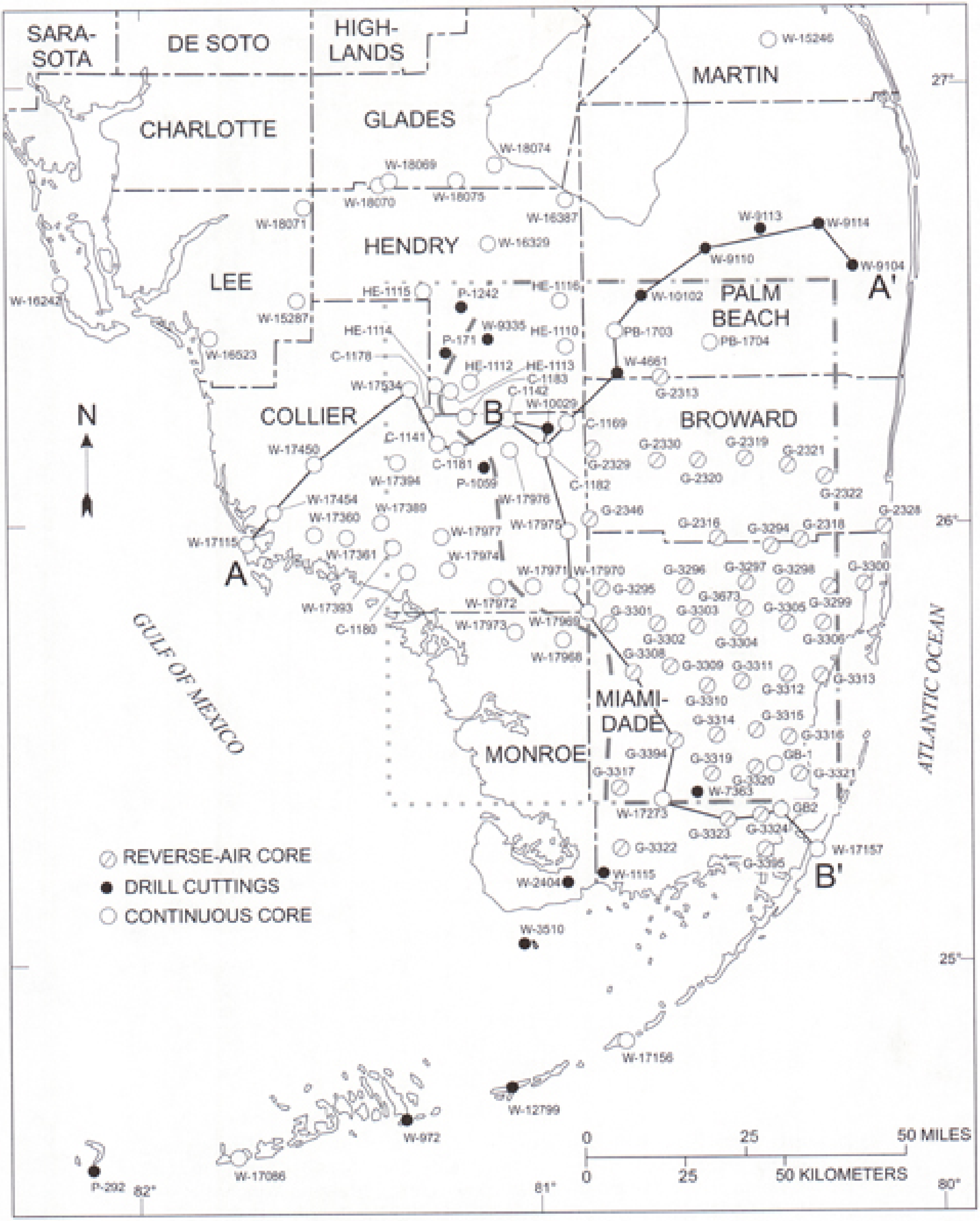
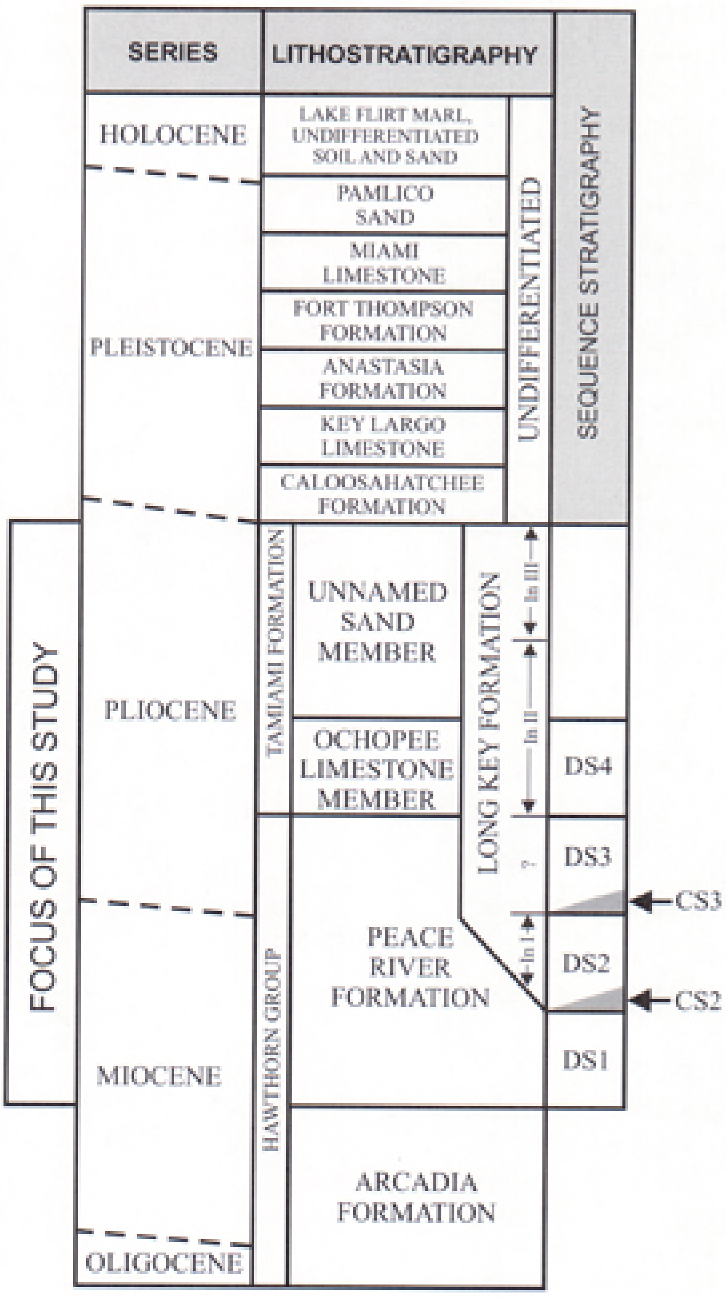


Figure 1. Location map of test wells used in this study. Data from this study, Florida Geological Survey lithologic data base, Causaras (1985, Causaras (1987), Fish (1988), Fish and Stewart (1991), McNeill et al. (1996), Missimer (1997), Weedman et al. (1997), Edwards et al. (1998), Guertin (1998), Weedman et al. (1999), and Reese and Cunningham (2000, in press). The dashed polygon shows the area used to develop facies associations for the upper part of the Peace River Formation (Table 1), and the stippled box indicates the area used for development of the facies associations of the Ochopee Limestone Member of the Tamiami Formation and an unnamed sand (Tables 6 and 7). Locations of cross-sections A-A' (Fig. 5) and B-B' (Fig. 6) are shown.



In I = Interval I
In II = Interval II
In III = Interval III

Figure 2. Correlation of chronostratigraphy, lithostratigraphy, and sequence stratigraphy recognized in much of the study area. Modified from Olsson (1964), Hunter (1968), Miller (1990), Missimer (1992), Brewster-Wingard et al. (1997), Missimer (1997), Cunningham et al. (1998), Guertin et al. (1999), Missimer (1999), Weedman et al (1999), and Reese and Cunningham (2000, in press). The Long Key Formation occurs in southernmost peninsular Florida and the Florida Keys (Cunningham et al., 1998). DS1, DS2, DS3, and DS4 are depositional sequences, and CS2 and CS3 are condensed sections. Intervals I, II, and III of Guertin et al. (1999) are integrated into the correlation scheme.

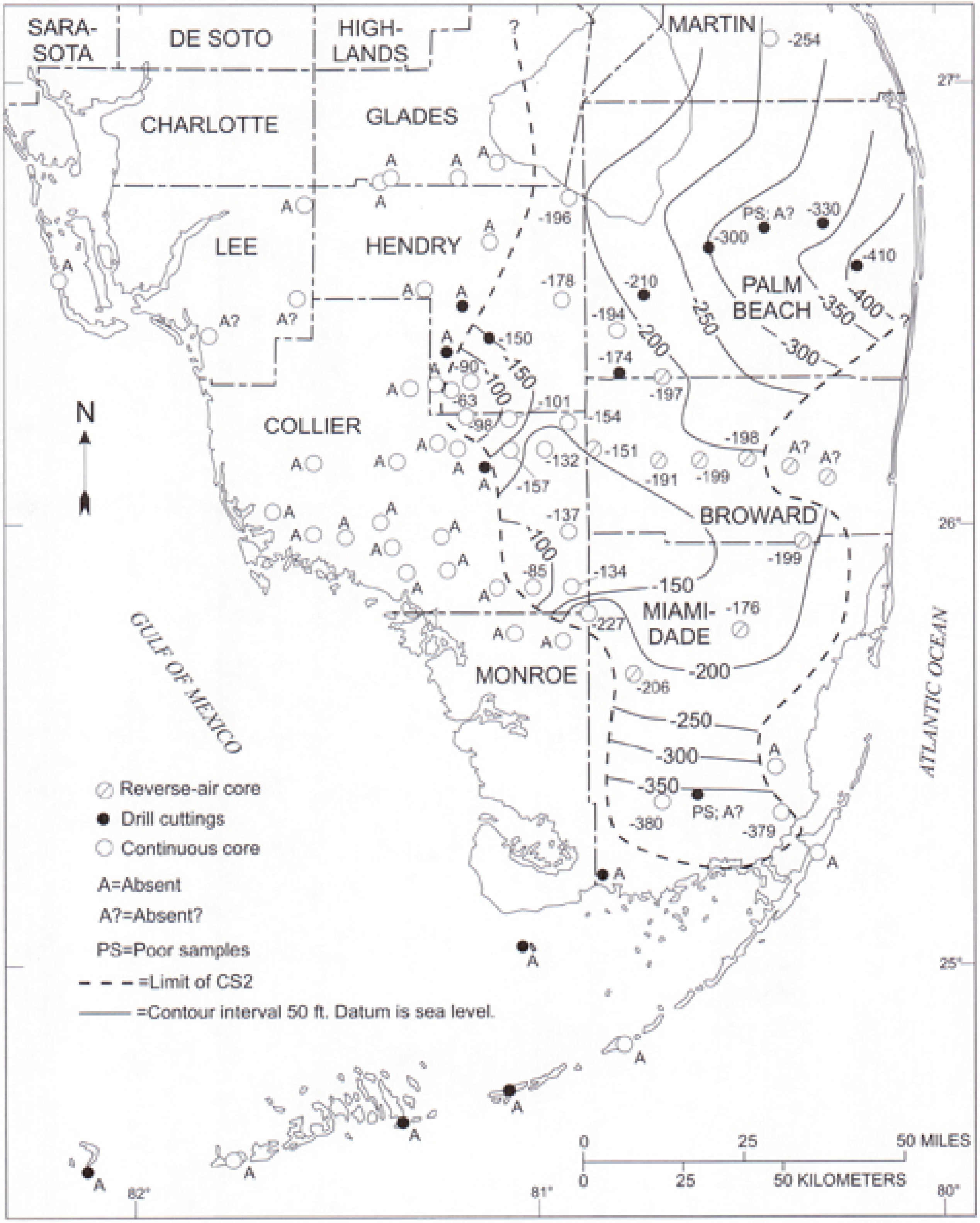


Figure 3. Structure contour map of the top of the mudstone contained in condensed section 2 (CS2) within depositional sequence 2 (DS2) of the Peace River Formation in southern Florida. The dashed line shows the mapped limit of CS2. Structure contours show altitude in feet below sea level of top of the mudstone.

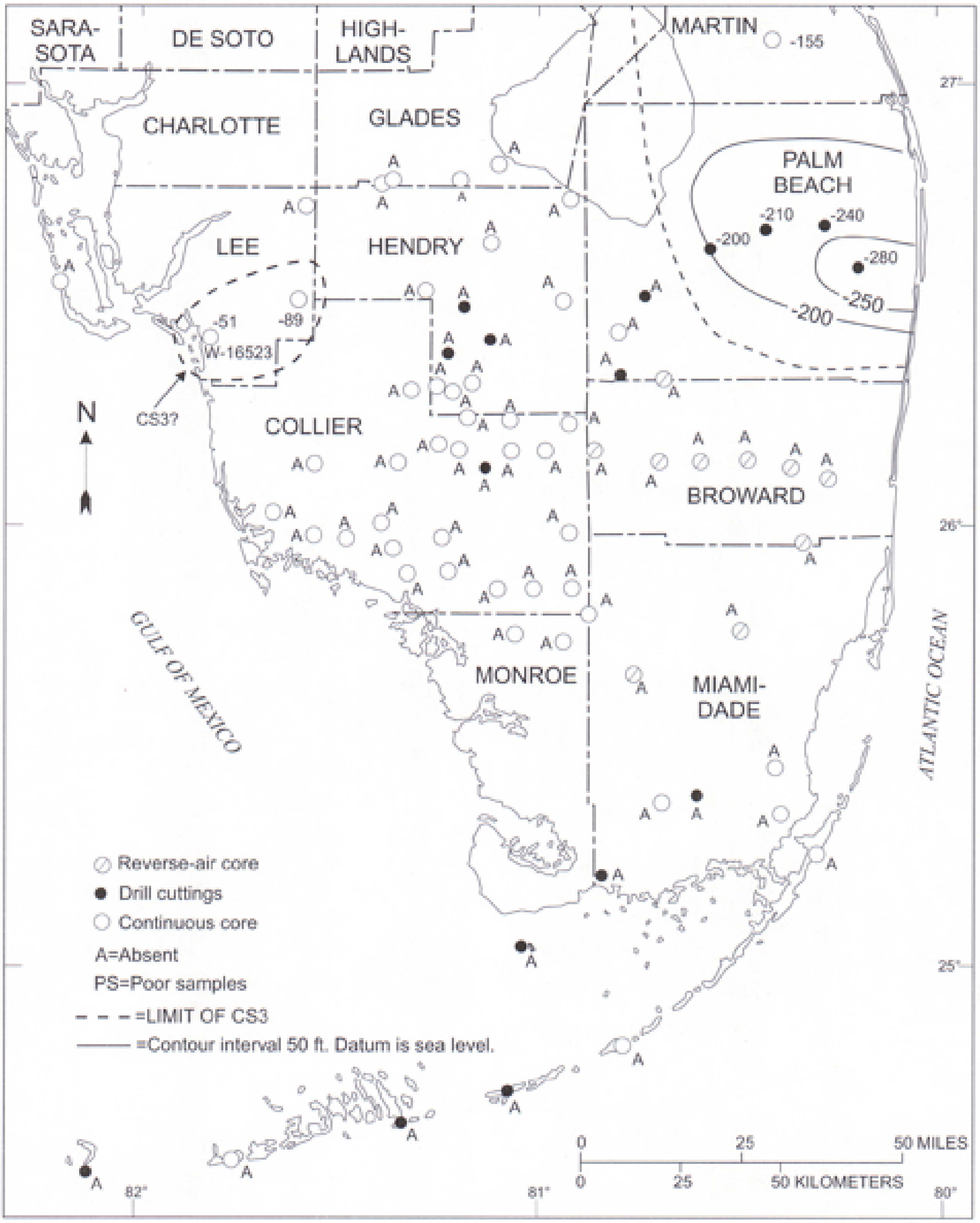


Figure 4. Structure contour map of the top of the mudstone contained in condensed section 3 (CS3) within depositional sequence 3 (DS3) of the Peace River Formation in southern Florida. Both mudstones mapped on the southwestern and southeastern parts of Florida were deposited during the early Pliocene, possibly synchronously, as suggested by dating from Missimer (1997) for the W-16523 corehole in Lee County and the biochronology of the mudstones in Palm Beach and Martin Counties. Structure contours show altitude in feet below sea level of top of the mudstone.

ceous mudstone, (2) terrigenous mudstone, (3) clay-rich quartz sand, (4) quartz sand, and (5) pelecypod-rich quartz sand or sandstone (Table 1).

The diatomaceous mudstone and terrigenous mudstone typically occur as a couplet with the diatomaceous mudstone underlying the terrigenous mudstone. Two mudstone couplets were identified as CS2 and CS3 (Fig. 2). Structure contour maps of the two condensed sections show that the lower condensed section (CS2) extends over about 6,000 square miles of southeastern Florida (Fig. 3); the upper condensed section (CS3) is considerably more limited in areal extent (Fig. 4). The lower condensed section (CS2) thins and pinches out in a paleo-landward or western direction (Figs. 5 and 6). The paleo-seaward lap out of CS2 is near the southern margin and probably near the southeastern margin of the Florida peninsula (Figs. 3 and 6). The updip lap out of CS3 is in a paleo-seaward direction from the updip lap out of CS2, suggesting eastward offlapping progradation of Peace River siliciclastics (Fig. 6).

Above the lower mudstone in much of the study area, the Peace River Formation is composed, from bottom to top, of clay-rich quartz sand, quartz sand, and pelecypod-rich quartz sand and sandstone (Table 1). Some of the clay-bearing facies of the Peace River Formation may grade laterally into mainly quartz sand facies in the western part of the study area.

Sequence Stratigraphy

In developing a regional sequence stratigraphy, it is common practice to initially identify the more easily recognized condensed sections of unconformity-bound depositional sequences (Posamentier and James, 1993). In prior studies of the Peace River Formation and equivalent sediments in southern Florida, only bounding unconformities have been proposed (Missimer, 1997; Guertin, 1998; Guertin et al., 1999; Missimer, 1999).

In the proposed southern Florida sequence stratigraphy for this study, downdip portions of some sequence boundaries are equivalent to the parasequence concept of shoaling-upward cycles bounded by flooding surfaces (Van Wagoner et al., 1988) instead of unconformities. The framework herein provides guidance for further investigation into recognition of unconformities and a more precise definition of sequence boundaries. Additionally, two newly identified condensed sections of the Peace River Formation are placed into the established framework of unconformities. A condensed section is a relatively thin marine stratigraphic unit composed of pelagic to hemipelagic sediments that accumulated at very low sedimentation rates (Loutit et al., 1988). Condensed sections are important for biostratigraphic dating, defining and correlating depositional sequences, and reconstructing depositional environments (Loutit et al., 1988; Posamentier and James, 1993). In much of the study area, the distinct lithology of the condensed sections facilitates their recognition in the context of the proposed developing sequence stratigraphy.

The diatomaceous mudstone that forms the two condensed sections of the Peace River Formation (Figs. 5 and 6) contains a greater concentration of planktic fossils than overlying terrigenous mudstone, suggesting the upper surface of the diatomaceous mudstone defines the surface of maximum flooding within each couplet. The maximum flooding surface represents a time of maximum flooding within a depositional sequence, and marks the change from a transgressive systems tract to a highstand systems tract (Van Wagoner et al., 1988; Posamentier and James, 1993).

Depositional sequence 1 (DS1) is a wedge-shaped deposit of quartz sand, sandstone, and minor carbonate that thins toward the southern and eastern edges of the Florida peninsula. This depositional sequence laps out north of the W-17273 corehole in Miami-Dade County toward the southern edge of the Florida peninsula (Fig. 6). Downlap of internal strata onto the top of the Arcadia Formation is suggested by correlations shown in Figure 5. The southern lap out thinning toward the east and probable downlap to the east suggest progradation of a siliciclastic shelf

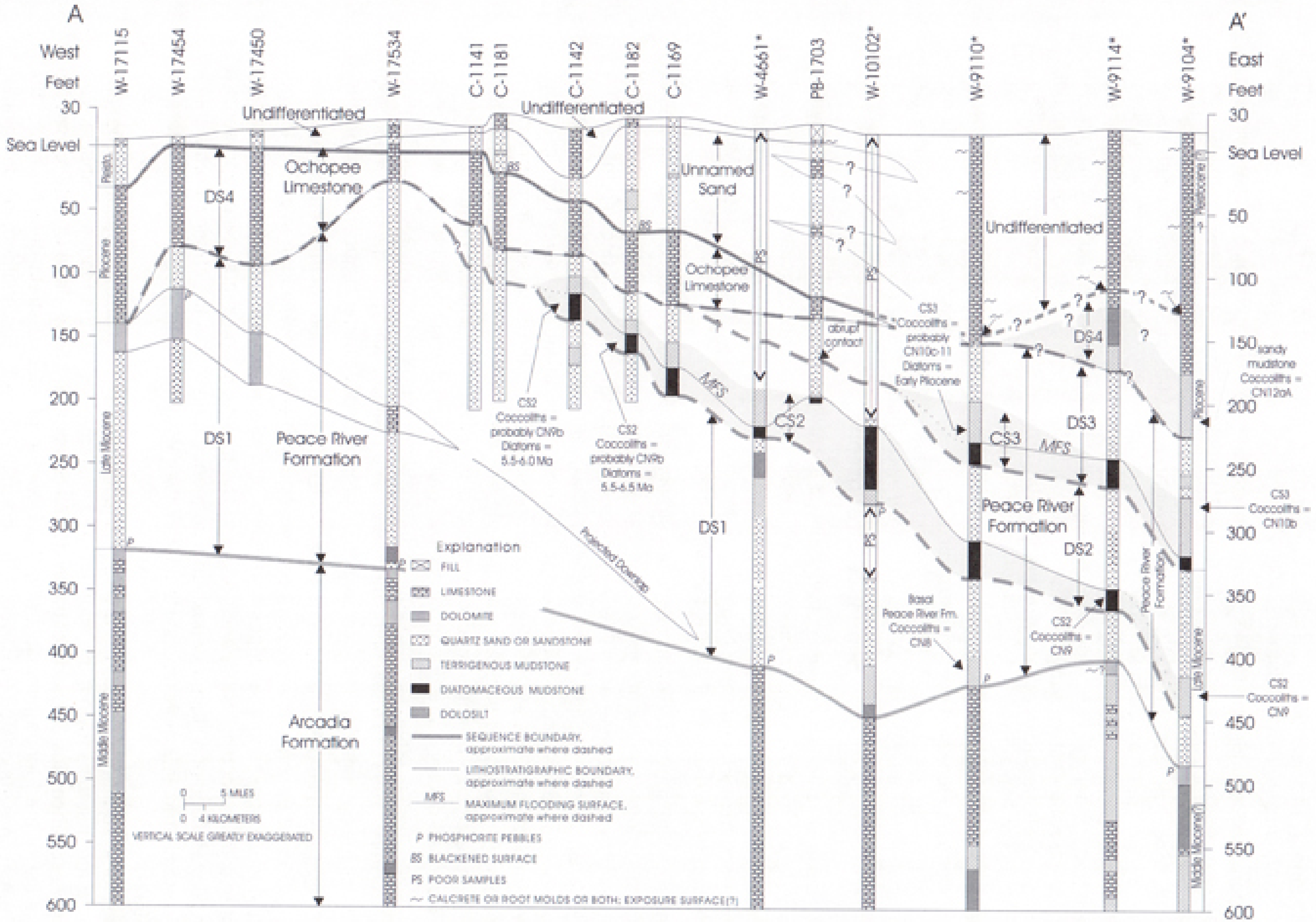


Figure 5. Geologic cross-section A-A' showing lithostratigraphy, sequence stratigraphy, and biostratigraphy of the upper Tertiary of southern Florida. An additional condensed section and possible depositional sequence may occur between DS3 and DS4 in wells W-9114 and W-9104. The location of the lower boundary of DS4 in wells W-9114 and W-9104 above the lower lithostratigraphic boundary of the Ochopee Limestone Member of the Tamiami Formation may be due to poor samples. Portions of some sequence boundaries are equivalent to the parasequence concepts of shoaling-upward cycles bounded by flooding surfaces (Van Wagoner et al., 1988). All lithologic descriptions were taken from continuous cores, except for wells marked by an asterisk which were taken from well cuttings. Location of cross section shown in Figure 1.

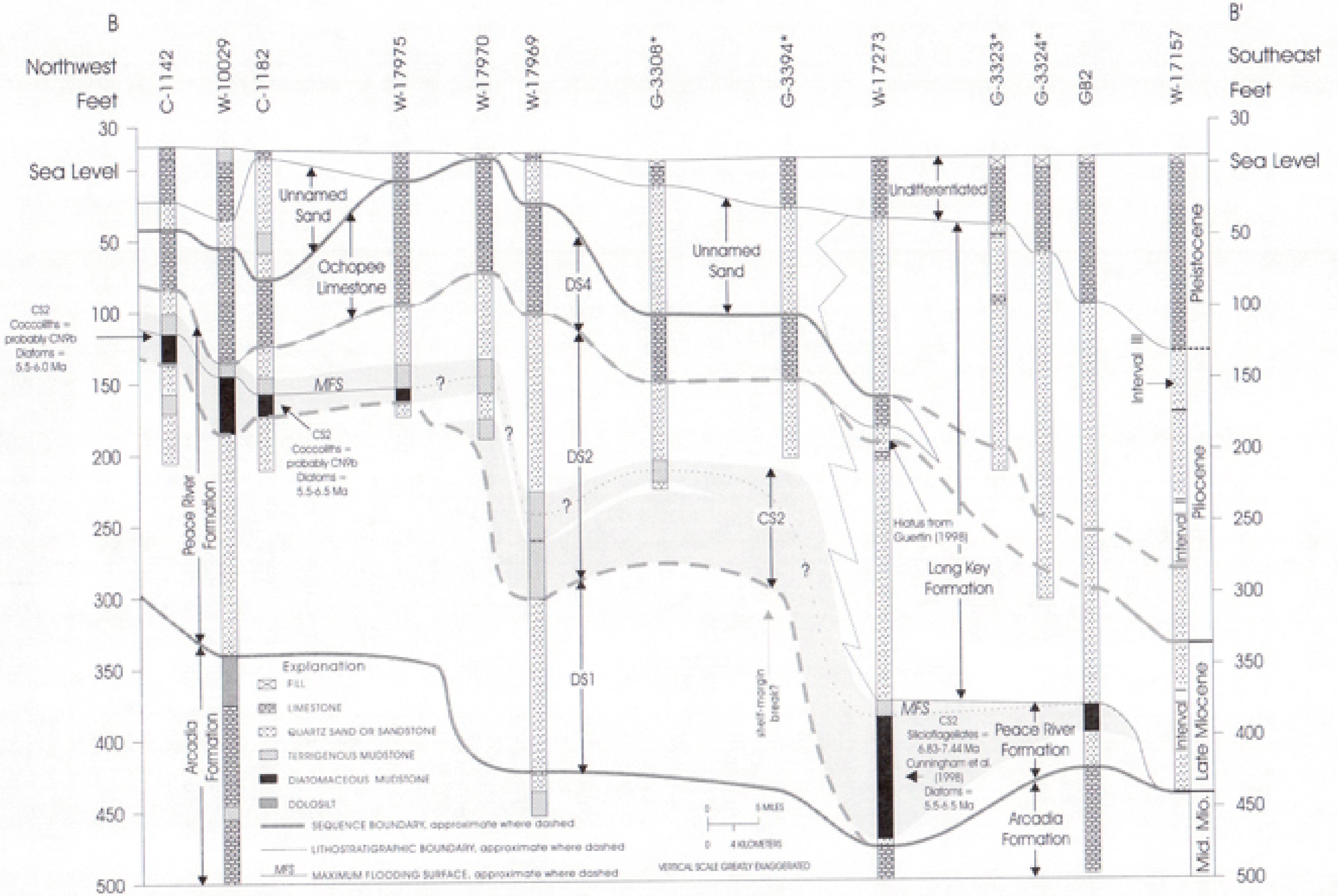


Figure 6. Geologic cross-section B-B' showing lithostratigraphy, sequence stratigraphy, and biostratigraphy of the upper Tertiary of southern Florida. Southern lap out of depositional sequence DS1 and condensed section CS2 within the Peace River Formation and southern lap out of the Ochopee Limestone Member of the Tamiami Formation are shown. Depositional Intervals I, II, and III from Guertin et al. (1999). Portions of some sequence boundaries are equivalent to the parasequence concepts of shoaling upward cycles bounded by flooding surfaces (Van Wagoner et al., 1988). All lithologic descriptions were taken from continuous coreholes, for wells marked by an asterisk which were taken from reverse-air core samples. Location of cross section shown in Figure 1.

Table 1. Lithofacies characteristics of the upper part of the Peace River Formation for the area outlined in Figure 1

[Visual estimation was made for porosity. Hydraulic conductivity was estimated by comparison of corehole from Fish and Stewart (1991, table 6)]

Characteristic	Lithologic description
	Diatomaceous Mudstone Facies
Depositional textures	Diatomaceous mudstone
Color	Mainly yellowish-gray 5Y 7/2 and light-olive-gray 5Y 5/2
Grain size	Mainly terrigenous clay and fine sand-size diatoms; minor silt-size quartz; local very fine sand-size quartz and phosphate grains, and fish scales
Carbonate grains	Local benthic foraminifers
Accessory grains	Common quartz grains and local phosphate grains
Porosity	Minor microporosity
Hydraulic conductivity	Very low (less than 0.1 foot per day)
	Terrigenous Mudstone Facies
Depositional textures	Terrigenous mudstone and claystone
Color	Mainly light-olive-gray 5Y 5/2, yellowish-gray 5Y 7/2, and olive-gray 5Y 4/1, 5Y 3/2
Grain size	Mainly terrigenous clay; minor silt-size quartz; local very fine sand- to granule-size quartz grains and very fine sand- to pebble-size phosphate grains
Carbonate grains	Local benthic foraminifers and pelecypod fragments
Accessory grains	Common quartz grains; local diatoms, phosphate grains, mica, fish scales, shark's teeth
Porosity	Minor microporosity
Hydraulic conductivity	Very low (less than or equal to 0.1 foot per day)
	Clay-Rich Quartz Sand Facies
Depositional textures	Terrigenous clay-rich sand
Color	Mainly yellowish-gray 5Y 7/2 and 5Y 8/1, and light-gray-olive 5Y 6/1
Grain size	Mainly very fine quartz grains; minor silt-size quartz grains and terrigenous mud; local micrite, fine sand-size to small pebble-size quartz grains and very fine sand-size to pebble-size phosphate grains
Carbonate grains	Local thin-shelled pelecypods, oysters, *Turritella* and benthic foraminifers
Accessory grains	Common phosphate grains (trace to 40 percent); minor heavy minerals; trace mica
Porosity	Mainly intergrain; local moldic; ranges from 5 to 20 percent
Hydraulic conductivity	Mainly very low (less than 0.1 foot per day) to low (0.1 to 10 feet per day); ranges from very low (less than 0.1 foot per day) to moderate (10 to 100 feet per day)
	Quartz Sand Facies
Depositional textures	Quartz sand with less than 10 percent skeletal grain
Color	Mainly yellowish-gray 5Y 8/1 and yellowish-gray 5Y 7/2; locally medium-dark-gray N4 to very light gray N8, light- olive-gray 5Y 5/2, grayish-yellow-green 5GY 7/2, pale-olive 10Y 6/2, very pale orange 10YR 8/2, and pale-yellowish-brown 10YR 6/2
Grain size	Mainly very fine to medium quartz sand; ranges from silt to granule size; carbonate grains range from silt to pebble size; terrigenous clay
Carbonate grains	Pelecypods (local *Pecten* and *Chione*), benthic foraminifers, echinoids, and undifferentiated skeletal grains
Accessory grains	Trace to 30 percent phosphate and heavy mineral grains; local minor terrigenous clay; local trace mica; trace to 1 percent plagioclase; trace microcline
Porosity	Intergrain; ranges from 5 to 20 percent
Hydraulic conductivity	Mainly low (0.1 to 10 feet per day) to moderate (10 to 100 feet per day); ranges from very low (less than 0.1 foot per day) to moderate (10 to 100 feet per day)
	Pelecypod-Rich Quartz Sand or Sandstone Facies
Depositional textures	Quartz sand matrix with pelecypod rudstone framework, or quartz sand supporting skeletal floatstone
Color	Mainly yellowish-gray 5Y 8/1 and 5Y 7/2; locally light-gray N7 to white N9, light-olive-gray 5Y 5/2, light-olive- gray 5Y 6/1, and very pale orange 10YR 8/2
Grain size	Mainly very fine to fine quartz sand; ranges from silt to very coarse quartz sand; carbonate grains range from silt to cobble size; local terrigenous clay and lime mudstone
Carbonate grains	Pelecypods (including *Pecten* and oysters), undifferentiated skeletal grains, gastropods (including *Turritella*), bryo zoans, serpulids, and echinoids
Accessory grains	Trace to 40 percent phosphate and heavy mineral grains; local minor terrigenous clay and lime mudstone; local trace mica
Porosity	Intergrain and moldic; ranges from 5 to 25 percent; local abundant pelecypod molds contribute to high porosity
Hydraulic conductivity	Mainly low (0.1 to 10 feet per day) to moderate (10 to 100 feet per day); ranges from very low (less than 0.1 foot per day) to high (100 to 1,000 feet per day)

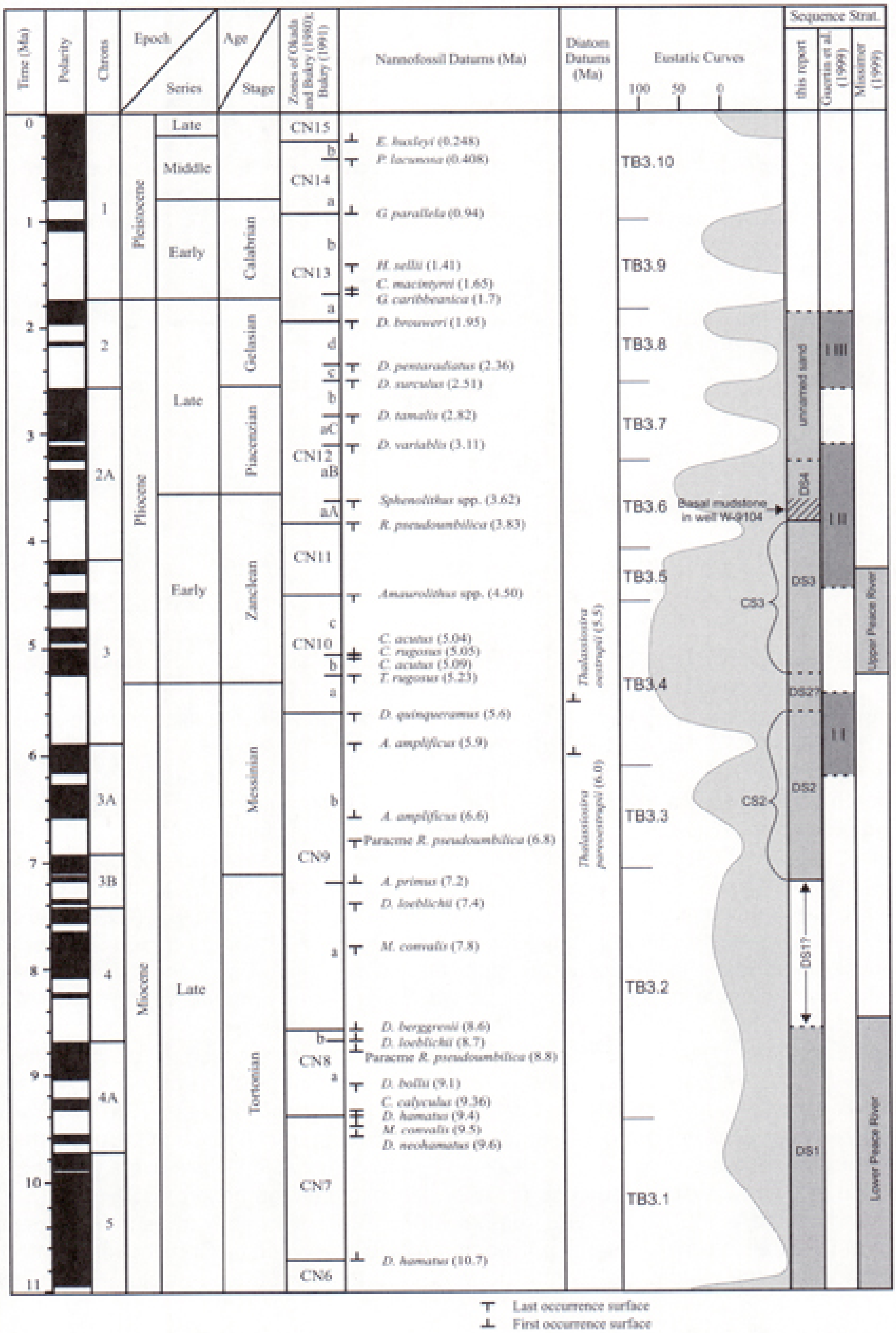


Figure 7. Correlation of the chronostratigraphy of a portion of the late Tertiary geomagnetic polarity time scale (Berggren et al., 1995) and coccolith zonation. From ODP Leg 171B at the Blake Nose east of northern Florida (Shipboard Scientific Party, 1998) with normalized additions of Subzones CN12aA, aB, and aC from Bukry (1991), the eustatic curves of Haq et al. (1988), diatom datums from offshore California, and southern Florida sequence stratigraphy.

Table 2. Occurrence of stratigraphically important diatom taxa and the silicoflagellate *D. frugalis* in wells W-9110, C-1142, C-1182 and W-17273

[CS2, condensed section 2 of the Peace River Formation; CS3, condensed section 3 of the Peace River Formation; <, less than the value. Genus: DF, *Distephanus frugalis*; HO, *Hemidiscus ovalis*; KA, *Koizumia adaroi*; KT, *K. tatsunokuchiensis*; RF, *Rhaphoneis fatula*; TE, *Thalassiosira eccentrica*; TO, *T. oestrupii*; TP, *T. praeoestrupii*]

Well No.	Sample depth (feet below sea level)	Sample type	Strati-graphic unit	Subepoch	Esti-mated age (million years ago)	Genus present							
						DF	HO	KA	KT	RF	TE	TO	TP
W-9110	208-218	Cuttings	CS-3	Early Pliocene	<5.5				X	X	X	X	
	238-248	Cuttings	CS-3	Early Pliocene	<5.5		X		X	X	X	X	
C-1142	123.2	Core	CS-2	Late Miocene	6.0 - 5.5			X			X		X
C-1182	147.5	Core	CS-2	Late Miocene	6.0 - 5.5			X	X		X		
W-17273	410.0	Core	CS-2	Late Miocene	6.5 - 5.5			X	X		X		
	430.0	Core	CS-2	Late Miocene	6.5 - 5.5	X		X	X		X		
	445.0	Core	CS-2	Late Miocene	6.5 - 5.5			X	X		X		
	455.0	Core	CS-2	Late Miocene	6.5 - 5.5			X	X		X		

toward the east and south (Figs. 5 and 6). A shelf-margin break is postulated to occur between the W-17969 and W-17273 cores (Fig. 6).

The bottom of DS1 is delimited by a regional unconformity that separates the Peace River Formation from the Arcadia Formation. This unconformity in southern Florida represents a hiatus of about 1.6 to 11.5 million years based mostly on strontium-isotope chemostratigraphy (Guertin et al., 2000). An unconformity, with local evidence of subaerial exposure (discussed later) defines the top of DS1 in the western part of the study area (Fig. 5). In the east and southeast, the base of a condensed section (CS2) delineates the top of DS1 (Figs. 5 and 6). A sequence stratigraphy produced by Missimer (1999) at the W-17115 corehole in Collier County (Fig. 5) was linked to the sequence stratigraphy developed here, suggesting that DS1 is equivalent to a supersequence defined within the lower Peace River Formation (Fig. 7) by Missimer (1999).

Depositional sequences 2 and 3 (DS2 and DS3) contain coarsening upward siliciclastic deposits defined by mudstone (CS2 and CS3) at the base that grades upward into mostly very fine to fine quartz sand and sandstone (Figs. 5 and 6). Depositional sequence 2 (DS2) has a profile in Figure 6 that thins landward, thickens as fill along the marginal slope of DS1 and thins seaward in cross-section B-B' (Fig. 6). The profile in Figure 5 shows landward thinning of this unit in a sheet like geometry. Most of the base of DS2 is delimited as the base of CS2 (Figs. 5 and 6). Quartz sands in the W-17273 and GB2 coreholes (Fig. 6) form an early transgressive deposit at the base of DS2 that is consistent with palynomorph data presented by Cunningham et al. (1998). These sands and the diatomaceous mudstone of CS2 form the transgressive systems tract of DS2.

Depositional sequence 2 (DS2) is probably equivalent to Interval I of the Long Key Formation (Guertin et al., 1999) in the Florida Keys. This depositional sequence is bounded at the top by an unconformity identified in southernmost Florida by Guertin et al. (1999) at the top of Interval I of the Long Key Formation (Fig. 6). This unconformity is probably regional in extent and may merge to form an amalgamated unconformity with the top of DS1 (Fig. 5). The limits of CS2 in Figure 3 and the cross sections shown in Figures 5 and 6 suggest that southward transport of quartz sand to the Florida Keys during deposition of DS2 was mostly along the southeastern coast of Florida.

Depositional sequence 3 (DS3) is the youngest depositional sequence defined within the Peace River Formation in the study area. The condensed section (CS3) of DS3 seems to be restricted to an area in Martin and Palm Beach Counties and possibly an area mostly contained in Lee County (Fig. 4). Depositional sequence 3 (DS3) contains CS3 as the basal unit in most of the area, and is partly overlain by the Tamiami Formation (Fig. 5). The PB-1703 corehole (Fig. 1) contains an abrupt contact that may be an erosion/truncation surface and may define an unconformity at the base of DS3 (Fig. 5). This potential unconformity may become conformable down dip at the base of CS3 (Fig. 5). An unconformity has not been identified at the top of DS3 in Martin and Palm Beach Counties. An unconformity that bounds the upper Peace River Formation of early Pliocene age in southwestern Florida (Missimer, 1997; 1999) is a depositional sequence possibly equivalent to DS3 based on similar age (Fig. 7).

Micropaleontology

Taxonomic identification of diatoms, silicoflagellates and coccoliths from the Peace River Formation are limited to the condensed sections contained in DS2 and DS3 (Figs. 5 and 6). Micropaleontologic analyses focused on CS2 and CS3 because these mudstone units contain microfossils that are useful for constructing a chronostratigraphy. Examination of samples for benthic foraminifera was conducted on both mudstones and quartz sands of the Peace River Formation. Both the benthic foraminifera and diatom populations were helpful in defining depositional environments.

Diatoms and silicoflagellates

Biostratigraphic analysis of diatoms was conducted on samples from the W-9110, C-1142, C-1182, and W-17273 cores (Table 2). Diatoms from one sample of CS2 in the C-1142 corehole suggest an age of 6.0 to 5.5 Ma (million years ago). Four diatomaceous mudstones samples of CS2 in the W-17273 corehole and one sample from the C-1182 corehole contain very similar diatom assemblages. A latest Miocene age older than 5.5 Ma is suggested for CS2 in both of these cores based on the absence of *Thalassiosira oestrupii*, which first occurs at 5.5 Ma (Fig. 7). Other diatoms present in the assemblage *(Paralia sulcata, Stephanopyxis sp., Delphineis sp., Actinoptychus sp., Actinocyclus octonarius, Thalassionema nitzschioides, Thalassiosira. eccentrica, Thalassiosira leptopus, Koizumia adaroi,* and early forms of *Koizumia tatsunokuchienis)* are consistent with an age younger than 6.5 Ma (Yanagisawa and Akiba, 1998; J.A. Barron, U.S. Geological Survey, written commun., 2000).

The diatom analyses herein suggest that the age of CS2 can be constrained to 6.5 to 5.5 Ma. The presence of the silicoflagette *Distephanus frugalis* in the W-17273 corehole supports an age younger than 6.5 Ma (Barron, 1976). Alternatively, prior work by Cunningham et al. (1998) reported the age of the diatomaceous mudstones (CS2) of the Peace River Formation in the W-17273 corehole to range from 7.44 to 6.83 Ma (Fig. 6). This time frame brackets the Tortonian-Messinian boundary based on the presence of two cosmopolitan silicoflagellate species *Distephanus pseudofibula* and *Bachmannocena triodon* (Cunningham et al., 1998). The 7.44 to 6.83 Ma range in age is consistent with the broader age range for biostratigraphic assignment of coccoliths from CS2 (Zone CN9, perhaps only Zone CN9b) as shown in Figure 7.

The assemblages from the C-1142, C-1182, and W-17273 cores are composed predominantly of shelf-dwelling taxa. The diatomaceous mudstones in the C-1142 and C-1182 cores record a transgressive event, upwelling of nutrients, or possibly both across a siliciclastic shelf

Plate 1. Photographs of coccoliths from well W-9104. Photographs 1 to 16 are from a sample interval of 318 to 328 feet below sea level. Photographs 17 to 20 are from a sample interval of 428 to 438 feet below sea level.

1a,b. *Coccolithus pelagicus* (Wallich) Schiller: (1a) cross-polarized light, and (1b) plane light.

2a,b. *Calcidiscus leptoporus* (Murray and Blackman) Loeblich and Tappan: (2a) cross-polarized light, and (2b) plane light.

3a,b. *Calcidiscus macintyrei* (Bukry and Bramlette) Loeblich and Tappan: (3a) cross-polarized light, and (3b) plane light.

4a,b. *Reticulofenestra pseudoumbilica* (Gartner) Gartner: (4a) cross-polarized light, and (4b) plane light.

5a,b. *Reticulofenestra pseudoumbilica* (Gartner) Gartner: (5a) cross-polarized light, and (5b) plane light.

6a,b. *Sphenolithus abies* Deflandre: (6a) cross-polarized light, and (6b) plane light.

7a,b. *Ceratolithus armatus* Muller: (7a) cross-polarized light, and (7b) plane light.

8a,b. *Ceratolithus armatus* Muller: (8a) cross-polarized light, and (8b) plane light.

9a,b. *Ceratolithus armatus* Muller: (9a) cross-polarized light, and (9b) plane light.

10a,b. *Amaurolithus primus* (Bukry and Percival) Gartner and bukry: (10a) cross-polarized light, and (10b) plane light.

11. *Discoaster brouweri* Tan. Plane light.

12. *Discoaster brouweri* Tan. Plane light.

13. *Discoaster pentaradiatus* Tan. Plane light.

14. *Discoaster pentaradiatus* Tan. Plane light.

15. *Discoaster surculus* Martini and Bramlette. Plane light.

16. *Discoaster surculus* Martini and Bramlette. Plane light.

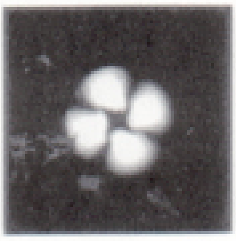
17. *Discoaster quinqueramus* Gartner. Plane light.

18. *Discoaster quinqueramus* Gartner. Plane light.

19. *Discoaster berggrenii* Bukry. Plane light.

20. *Discoaster berggrenii* Bukry. Plane light.


1a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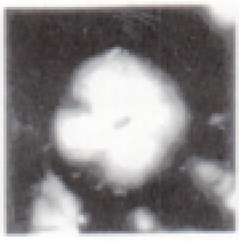
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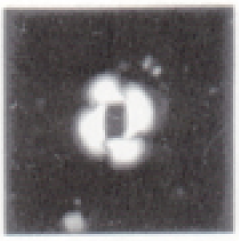
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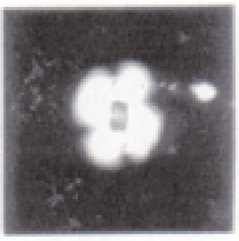
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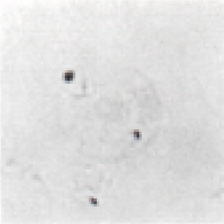
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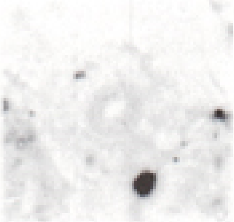
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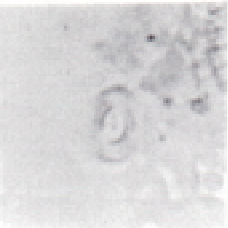
4b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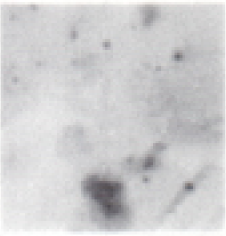
6a


7a


8a


9a


10a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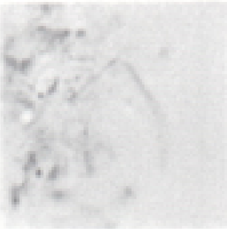
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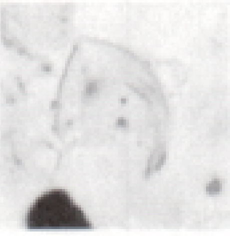
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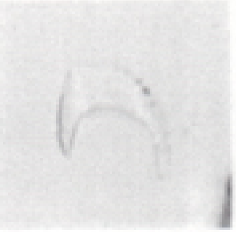
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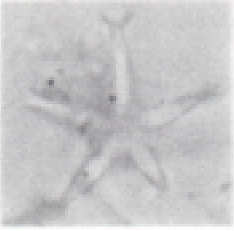
10b


11


12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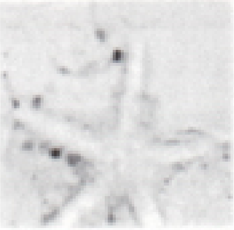
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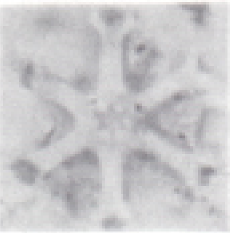
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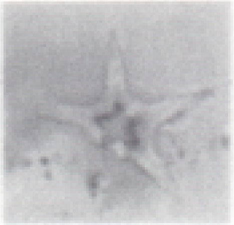
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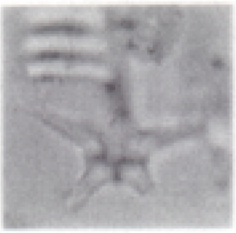
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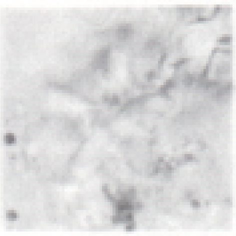
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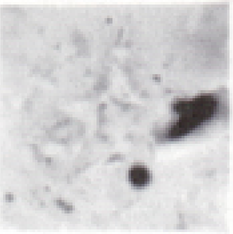
20

10 μm

Table 3. Occurrence of coccolith taxa in cuttings from wells W-9104 and W-9114

[Stratigraphic position: CS2, condensed section 2 of the Peace River Formation; CS3, condensed section 3 of the Peace River Formation; DS4, depositional sequence 4; BPR, base of Peace River Formation. Genus: C, *Ceratolithus rugosus*; CP, *Coccolithus pelagicus*, D, *Dictyococcites* sp. (small); DB, *Discoaster bellus*; DBE, *Discoaster berggrenii*; DBR, *Discoaster brouweri*; DP, *Discoaster pentaradiatus*; DQ, *Discoaster quinqueramus*; DS, *Discoaster surculus*; DSP, *Discoaster* sp; DV, *Discoaster variabilis*; HN, *Helicosphaera neogranulata*; RP, *Reticulofenestra pseudoumbilica*; RS, *Reticulofenestra* sp. (small); SA, *Sphenolithus abies*. Other abbreviations: A, abundant (greater than 32 percent of specimens in total assemblage); C, common (32 to 8 percent of specimens in total assemblage); R, rare (less than 8 percent of specimens in total assemblage; P, present (found but not counted); S, sparse or poorly preserved; ?, not determined]

Well No.	Sample depth (feet below sea level)	Strati-graphic position	Nanno-fossil abun-dance	Nanno fossil zone	Genus present														
					C	CP	D	DB	DBE	DBR	DP	DQ	DS	DSP	DV	HN	RP	RS	SA
C-1142	132	CS2	Barren	--															
W-9104*	205 - 215	DS4	?	CN12aA						P	P		P	P	P				
	315 - 325	CS3	Abundant	CN10b		C	A			P	P		P	C		P	P	A	P
	325 - 335	CS2	Abundant	CN9		P			P			P	P	P			C	A	R
W-9110	208-218	CS3	?	CN9-12									S						
	238-248	CS3	?	CN10c-11	S												S		
	308-318	CS2	Barren	--															
	328-338	CS2	Barren	--															
	408-418	BPR	?	CN8				S		S	S								
W-9114	253 - 263	CS3	Barren	--															
	353 - 363	CS2	Rare	CN9					P			P	P	P			P	P	P
W-17273	415	CS2	Barren	--															
	425	CS2	Barren	--															
	450	CS2	Barren	--															
	460	CS2	Barren	--															

*The following genera also are present (found but not counted) in well W-9104 at a depth interval of 315 to 325 feet: *Acanthoica* sp., *Amaurolithus primus*, *Calcidiscus leptoporus*, *Calcidiscus macintyrei*, *Ceratolithus acutus*, and *Ceratolithus armatus*.

as indicated by the dominance of the shelf-dwelling taxa. The diatomaceous mudstones of the W-17273 corehole (Fig. 6) also contain an abundance of shelf-dwelling taxa, but the stratigraphic position of the taxa (Fig. 6) suggests deposition in a shelf-slope or toe-of-slope environment. Environmental conditions such as currents, wave sweeping, or both could explain the transport of shelf-dwelling taxa into this off-shelf environment.

Two samples of well cuttings from upper and lower parts of CS3 were collected for analysis from well W-9110 (Fig. 5 and Table 2). The upper sample (Table 2, 208-218 feet below sea level) is from the terrigenous mudstone facies (Table 1), and the lower sample (Table 2, 238-248 feet below sea level) is from the diatomaceous mudstone facies (Table 1). A maximum flooding surface separates the two samples (Fig. 5).

The sample from the upper part of CS3 in well W-9110 contains *Paralia sulcata*, *Actinocyclus octonarius*, *Actinoptychus senarius*, *Stephanopyxis sp.*, *Koizumia tatasunokuchienis*, *Thalassionema nitzschioides*, *Thalassiosira eccentrica*, *Thalassiosira leptopus*, *Thalassiosira oestrupii*, and *Rhaphoneis fatula*. An occurrence of *T. oestrupii* suggests an age

Table 4. Benthic foraminiferal genera and their distribution with depth in wells W-9104, W-9114, C-1169, PB-1703 and C-1142

[Seven samples are not included in this table due to barren results. Stratigraphic position: DS2, depositional sequence 2 of the Peace River Formation; DS3, depositional sequence 3 of the Peace River Formation, US, unnamed sand. Genus: A, *Archaias*; BO, *Bolivina*; BU, *Bulimnella*; C, *Cancris*; CA, *Cassidulina*; CI, *Cibicides*; CR, *Cribroel- phidium*; E, *Eponides*; F, *Fursenkoina*; H, *Henzawaia*; N, *Nonion*; NO, *Nonionella*; R, *Rosalina*]

Well No.	Sample depth (feet below sea level)	Sample type	Strati-graphic position	Genus present												
				A	BO	BU	C	CA	CI	CR	E	F	H	N	NO	R
W-9104	315 - 325	Cuttings	DS3									X			X	
W-9114	253 - 263	Cuttings	DS3	X												
C-1169	163.0	Core	DS2			X							X	X		
	179.0	Core	DS2			X	X				X	X		X	X	X
P-1703	55.9	Core	US			X			X		X		X	X		X
	181.0	Core	DS2											X		
C-1142	131.5	Core	DS2			X					X		X	X		
	134.0	Core	DS2			X					X	X	X	X		
	139.0	Core	DS2			X							X	X		
	144.0	Core	DS2			X		X		X		X	X	X	X	
	149.0	Core	DS2		X	X	X			X	X	X	X	X	X	
	154.0	Core	DS2		X	X	X			X	X	X	X	X	X	

Table 5. Ecological data for benthic foraminiferal genera identified in the W-17614, PB-1703 and C-1142 coreholes

[Depth and environment information according to Murray (1991). Environment information for *Criboelphidium* according to Bock et al. (1971). >, greater than the value]

Genus	Approximate depth (feet)	Environment
Archaias	0 - 66	Inner shelf
Bulimnella		Lagoon, shelf, upper bathyal
Cancris	164 - 492	Shelf
Cassidulina		Shelf
Cibicides	0 - >6,562	Lagoon, shelf-bathyal
Cribroelphidium		Florida; away from reef
Eponides		Shelf-abyssal
Fursenkoina	0 - 3,937	Lagoon, shelf, upper bathyal
Hanzawaia		Inner shelf
Nonion	0 - 591	Shelf
Nonionella	33 - 3,281	Shelf
Rosalina	0 - 328	Lagoon, inner shelf

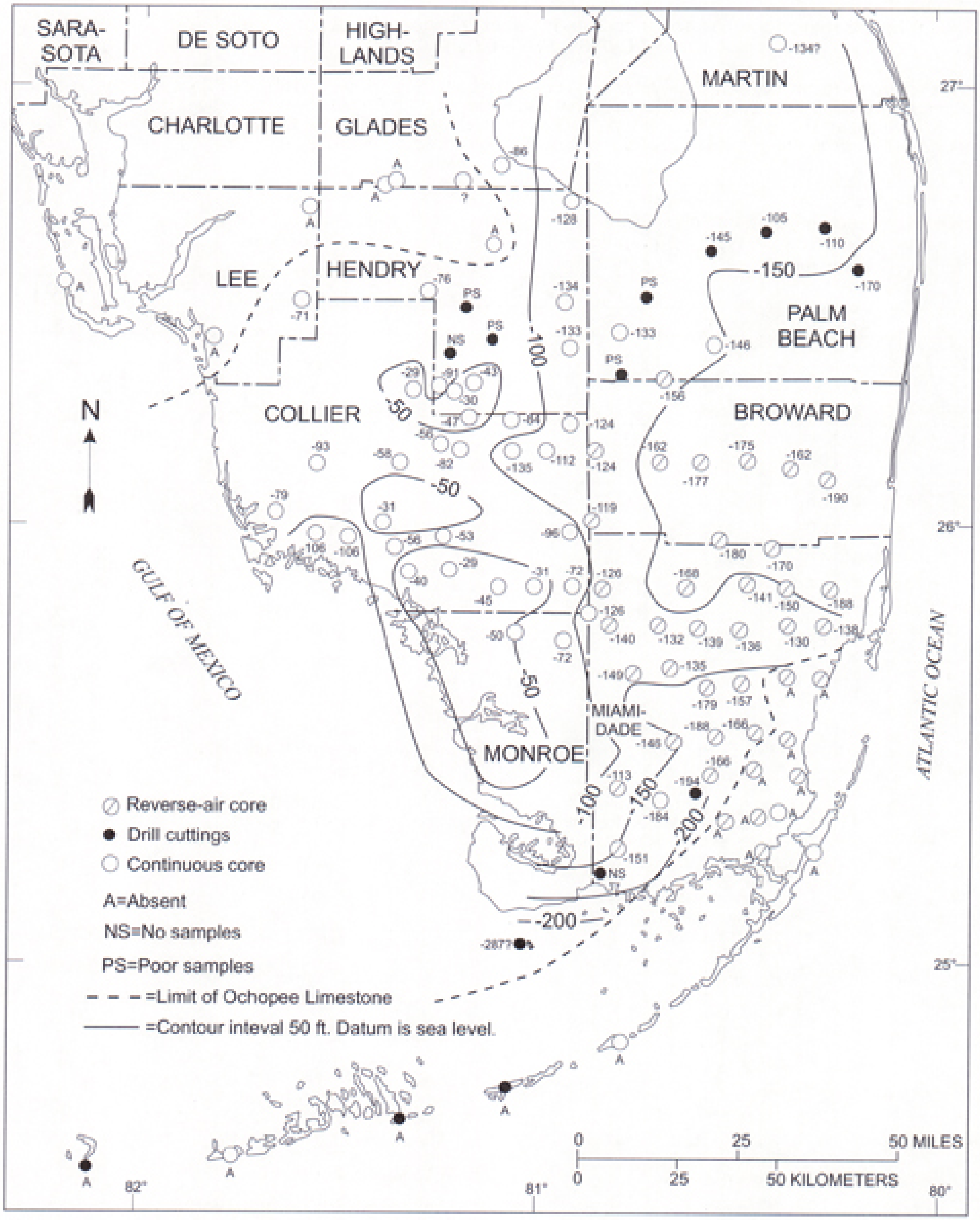

Figure 8. Structure contour map of the base of the Ochopee Limestone Member of the Tamiami Formation. Structure contours show altitude in feet below sea level of base of the Ochopee Limestone.

younger than 5.5 Ma (Fig. 7). A rare presence of R. fatula suggests an early Pliocene age based on comparison with occurrences in California (Dumont and Barron, 1995). An abundant presence of *P. sulcata* possibly indicates that this is an outer shelf assemblage (Sancetta, 1981).

The lower sample from CS3 in well W-9110 contains an assemblage similar to the sample from the upper portion but yields few *Paralia sulcata*. In addition to the taxa identified in the upper sample, the lower sample includes the occurrence of *Hemidiscus ovalis*. The presence of *Thalassiosira oestrupii* (Fig. 7) and *H. ovalis* indicates an early Pliocene age (Dumont and Barron, 1995). Planktic diatoms are more common in the sample from the lower part (diatomaceous mudstone facies) of CS3 relative to the upper part of the sequence (terrigenous mudstone facies). Relatively more planktic diatoms in the sample from the lower portion of CS3 is consistent with greater interpreted water depth during deposition of the diatomaceous mudstone relative to the terrigenous mudstone above the maximum flooding surface. This surface is defined by the boundary between the diatomaceous mudstone and terrigenous mudstone (Fig. 5).

Coccoliths

Samples were collected for analysis of coccoliths from wells C-1142, C-1182,W-9104, W-9110, W-9114, and W-17273. These samples were taken from a terrigenous mudstone near the base of the Peace River Formation and the two condensed sections (CS2 and CS3) of the Peace River Formation (Figs. 5 and 6). A single sample from the terrigenous mudstone near the base of the Peace River in well W-9110 (Fig. 5) contains abundant coccoliths that include *Discoaster bellus, Discoaster brouweri, Discoaster prepentaradiatus, and a questionable Discoaster bollii.* The assemblage of coccoliths probably belongs to Zone CN8 (Fig. 7), suggesting a Tortonian age (Perch-Nielsen, 1985).

Coccolith and diatom occurrences suggest assignment of CS2 to Subzone CN9b, but could be as old as Zone CN9 and as young as Subzone CN10a (Fig. 7). Coccoliths contained in eight samples from CS2 in the C-1182 corehole suggest assignment of CS2 to Subzone CN9b (7.2-5.6 Ma) based on the presence of *Discoaster berggrenii, Discoaster quinqueramus, Discoaster surculus,* and *Amaurolithus primus* (Fig. 7). Reworking of coccoliths in samples from the C-1182 corehole was investigated, but is unlikely since no uniquely older or younger taxa were identified. Two samples from CS2 in the C-1142 corehole contain D. surculus and thus are no older than Zone CN9. The upper biostratigraphic range of the C-1142 corehole sample is indefinite and assigned to Zone CN9 or Subzone CN10a, but associated diatoms are late Miocene; therefore, samples of CS2 from both the C-1182 and C-1142 cores suggest a late Miocene age no older than Zone CN9 or probably Subzone CN9b (Figs. 5 and 6). The occurrence of the coccoliths *D. quinqueramus and D. berggrenii* in one sample of CS2 collected from well W-9104 and another of CS2 from well W-9114 suggests that CS2 in these wells belongs to Zone CN9 (Fig. 5 and Table 3)

Combined diatom and coccolith data suggest assignment of CS3 to Subzone CN10b through Zone CN11 or early Pliocene (Fig. 7). Coccoliths from CS3 in well W-9104 are characterized by the presence of *Ceratolithus acutus, Ceratolithus armatus,* and *Amaurolithus primus* (Plate 1 and Table 3). These taxa and especially the presence of *C. acutus* indicate assignment of CS3 to Subzone CN10b (5.23-5.05 Ma) and an early Pliocene age (Fig. 7; Table 3). Two samples from CS3 in well W-9110 contain a trace to sparse presence of coccoliths including *Discoaster surculus, Ceratolithus rugosus, and Reticulofenestra pseudoumbilica.* These coccoliths are consistent with assigning CS3 in well W-9110 to Subzones CN10c through Zone CN11 (5.05-3.83) and an early Pliocene age (Fig. 7).

Table 6. Lithofacies characteristics of the Ochopee Limestone Member of the Tamiami Formation for the area outlined in Figure 1

[Visual estimation was made for porosity. Hydraulic conductivity was estimated by comparison of corehole from Fish and Stewart (1991, table 6)]

Characteristic	Lithologic description
	Pelecypod Lime Rudstone or Floatstone Facies
Depositional textures	Pelecypod lime rudstone or floatstone with quartz sand-rich lime packstone or grainstone matrix
Color	Mainly medium-light-gray N6 to very light gray N8 and yellowish-gray 5Y 8/1; locally yellowish-gray 5Y 7/2, black to medium-gray N5, white N9, and very pale orange 10YR 8/2
Grain size	Carbonate grains range from silt to cobble size; quartz sand mainly very fine to fine, ranges from silt to very coarse
Carbonate grains	Pelecypods (local oysters, *Pecten*, *Chione*, and *Ostrea*), undifferentiated skeletal fragments, bryozoans, gastropods (local *Turritella* and *Vermicularia*), benthic foraminifers, echinoids, serpulids, barnacles, planktic foraminifers, ostracods, encrusting foraminifers, corals (hermatypic)
Accessory grains	Common quartz sand and phosphate grains
Porosity	Mainly intergrain and moldic; local intrafossil and boring; ranges from 5 to 25 percent
Hydraulic conductivity	Mainly moderate (10 to 100 feet per day); ranges from low (0.1 to 10 feet per day) to high (100 to 1,000 feet per day)
	Pelecypod-Rich Quartz Sand or Sandstone Facies
Depositional textures	Pelecypod-rich quartz sand and quartz-rich sandstone
Color	Mainly yellowish-gray 5Y 8/1 and light-gray N7 to very light gray N6; locally medium-dark-gray N4 to medium-light-gray N6, very pale orange 10YR 8/2, light-olive-gray 5Y 6/1, yellowish-gray 5Y 7/2, and pale-yellowish-brown 10YR 6/2
Grain size	Mainly very fine to fine quartz sand; ranges from silt to coarse quartz sand; carbonate grains range from silt to cobble size
Carbonate grains	Pelecypods (local oysters), undifferentiated skeletal fragments, gastropods, echinoids, barnacles, serpulids, intraclasts, bryozoans, and encrusting fora minifers
Accessory grains	Absent to 5 percent phosphate and heavy mineral grains; local minor terrige nous clay or lime mudstone matrix
Porosity	Mainly intergrain with local moldic and intragrain; ranges from 10 to 20 per cent
Hydraulic conductivity	Mainly low (0.1 to 10 feet per day) to moderate (10 to 100 feet per day); ranges from low (0.1 to 10 feet per day) to moderate (10 to 100 feet per day)

Benthic foraminifera

Nine samples from CS2 were examined for benthic foraminifera. The benthic foraminifera of CS2 belong to a marine shelf assemblage. Two samples from CS3 were examined. The assemblage present in CS3 is consistent with deposition on a marine shelf (Tables 4 and 5).

Ochopee Limestone Member of the Tamiami Formation

Lithostratigraphy and Depositional Environments

The Ochopee Limestone Member of the Tamiami Formation (Hunter, 1968; Meeder, 1987; Missimer, 1992; Edwards et al., 1998; Weedman et al., 1999) includes a regionally extensive limestone facies that can be mapped throughout much of the study area (Fig. 8). The Ochopee Limestone has a sheet-like geometry that drapes over an unconformity at the top of the Peace River Formation (Figs. 5 and 6). The Ochopee Limestone represents a shift in sedimentation on the Florida Platform from the retrogradation of DS3 within the Peace River Formation to aggradation of the Ochopee Limestone. The Ochopee Limestone laps out near the southern margin of the Florida peninsula. The lapout is probably coincident with the edge of the siliciclastic shelf containing DS2 of the Peace River Formation (Fig. 6).

Two lithofacies characterize the Ochopee Limestone in an area shown in Figure 1: (1) pelecypod lime rudstone or floatstone, and (2) pelecypod-rich quartz sand or sandstone (Table 6). The rudstone or floatstone facies is the most common lithofacies, whereas the sand or sandstone facies occurs only locally as thin to thick beds. The quartz sand is typically very fine to fine grained, but locally may range from silt to very coarse sand. Skeletal carbonate grains of the pelecypod lime rudstone or floatstone include fossils listed in Table 6.

The Ochopee Limestone was deposited in a carbonate ramp depositional system (Burchette and Wright, 1992) during a reduction in siliciclastic supply to much of southern Florida. Criteria to support the environmental interpretation include: (1) a low basinward depositional gradient of less than 1 degree without a break in slope, as suggested by the upper and lower lithostratigraphic boundaries (Fig. 6); (2) widespread continuity of facies patterns; and (3) an almost complete absence of internal exposure surfaces. In the study area, most of the Ochopee Limestone was deposited in a mid-ramp depositional environment (Burchette and Wright, 1992). Evidence for this depositional environment is indicated by the common occurrence of coarse-grained lime rudstone that has a well washed, grain-dominated matrix (Lucia, 1995) and limemud-rich floatstone (Table 6). The mixture of these grain-dominated and mud-dominated carbonates and the lack of shallow-water faunal indicators suggest deposition below fair-weather wave base (FWWB) but above storm wave base (SWB). The zone between FWWB and SWB defines the mid-ramp depositional environment of Burchette and Wright (1992). Planktic foraminifera-rich sandstone--similar to lithofacies of the Stock Island Formation of Cunningham et al. (1998)--between depths of 275 and 336 feet below sea level in the W-17157 corehole may represent a distal portion of the Ochopee ramp that accumulated in relatively deep sea water (Fig. 6). Although the Ochopee Limestone contains quartz sand, the overwhelming abundance of carbonate grains represents a period of reduced quartz sand, silt, and mud to the southern Florida Platform.

The benthic carbonate grains of the Ochopee Limestone represent a heterozoan particle association, which James (1997) defined as a group of carbonate particles produced by light-independent, benthic organisms that may or may not contain red calcareous algae. Red algae were not observed in the Ochopee Limestone within the study area. The predominately heterozoan assemblage of carbonate particles and an absence of shallow-marine particles, such as ooids and green algae, is consistent with deposition in a mid-ramp depositional environment with temperate bottom-water conditions. An almost complete absence of exposure surfaces within the Ochopee Limestone is also consistent with mid-ramp deposition at water depths sufficient to minimize changes in water-bottom conditions during low-amplitude changes in relative sea level.

Sequence Stratigraphy

Depositional sequence 4 (DS4) is bounded at the base and top by regional subaerial unconformities and is composed of the Ochopee Limestone (Figs. 5 and 6). The regional-scale sequence boundary at the base of the Ochopee Limestone is evidenced by several established unconformities reported between the top of the Peace River Formation and the base of the Tamiami Formation in southwestern Florida (Edwards et al., 1998; Missimer, 1999). An unconformity and sequence boundary reported by Missimer (1999) separating the Peace River Formation and the Tamiami Formation in southwestern Florida is probably equivalent to the unconformity separating Intervals I and II of the Long Key Formation (Fig. 6) in the Florida Keys (Guertin et al., 1999). This unconformity may also be present as a hiatus identified by Guertin (1998) in the W-17273 corehole of Miami-Dade County (Fig. 6). A subaerial exposure surface occurs in the W-17394 corehole (Fig. 1) between the top of an unnamed quartz sand that is equivalent to the top of the Peace River Formation (this study) and the Ochopee Limestone in

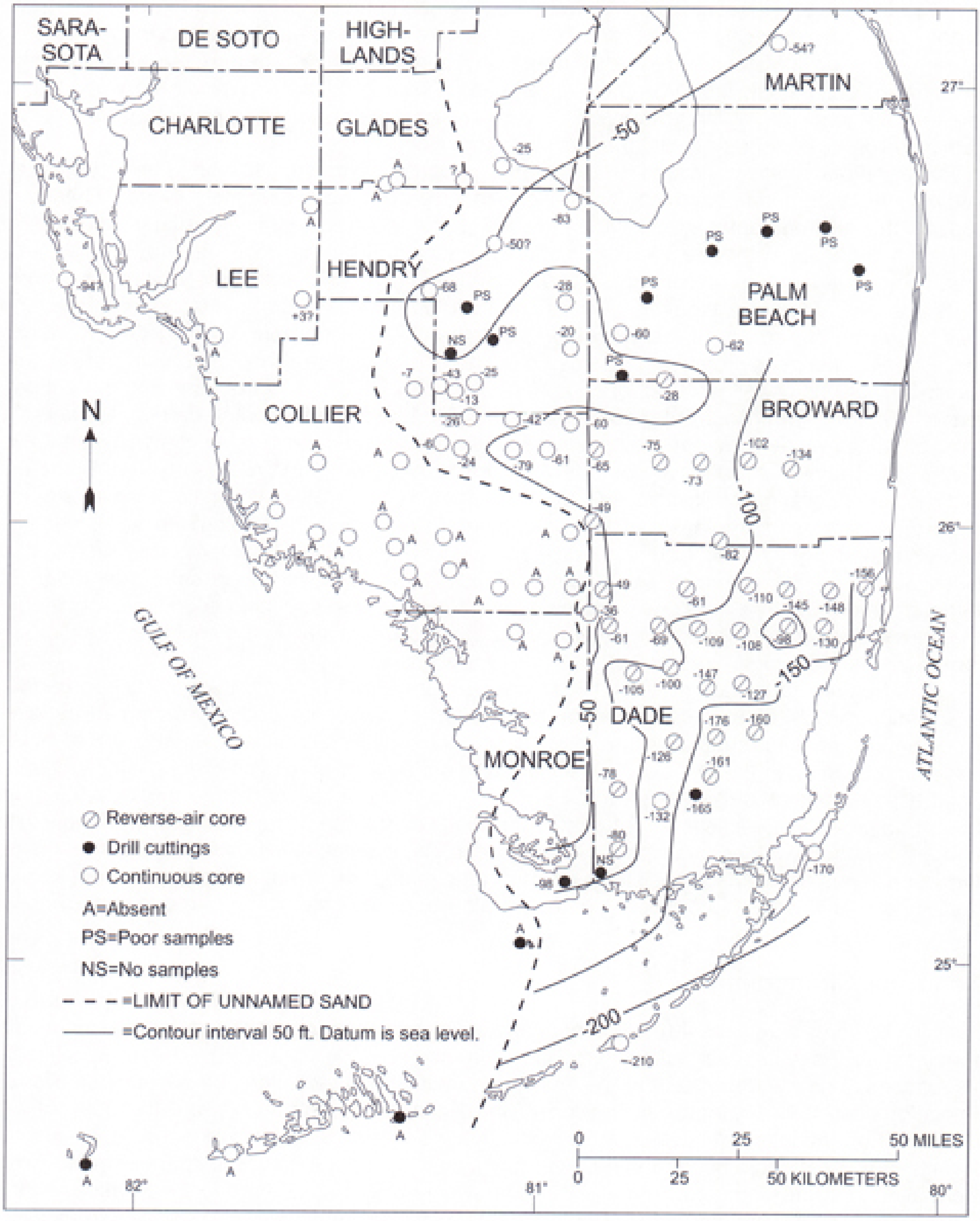

Figure 9. Structure contour map of an unnamed sand that overlies the Ochopee Limestone Member of the Tamiami Formation. Structure contours show altitude in feet below sea level of base of the Pinecrest Sand.

Table 7. Lithofacies characteristics of the unnamed sand for the area outlined in Figure 1
[Visual estimation was made for porosity. Hydraulic conductivity was estimated by comparison of corehole from Fish and Stewart (1991, table 6)]

Characteristic	Lithologic description
	Quartz Sand Facies
Depositional textures	Quartz sand with locally abundant fossils
Color	Mainly yellowish-gray 5Y 8/1 and yellowish-gray 5Y 7/2; locally medium- gray N5 to very light gray N8, very pale orange 10YR 8/2, light-olive-gray 5Y 6/1, light-olive-gray 5Y 5/2, grayish-yellow 5Y 8/4, grayish-orange 10YR 7/4, and dark-yellowish-orange 10 YR 6/6
Grain size	Mainly very fine to fine quartz sand; ranges from silt to very coarse quartz sand; carbonate grains range from silt to pebble size
Carbonate grains	Pelecypods (local oysters), undifferentiated skeletal fragments, echinoids, ser pulids, bryozoans, and benthic and planktic foraminifers
Accessory grains	Trace to 3 percent phosphate and heavy mineral grains; local trace mica; local minor terrigenous clay
Porosity	Mainly intergrain and local intragrain, ranges from 5 to 25 percent
Hydraulic conductivity	Mainly low (0.1 to 10 feet per day); ranges from very low (less than 0.1 foot per day) to moderate (10 to 100 feet per day)
	Pelecypod Lime Rudstone and Floatstone Facies
Depositional textures	Pelecypod lime rudstone or floatstone with quartz sand-rich lime packstone and grainstone matrix
Color	Yellowish-gray 5Y 8/1, medium-gray N5 to light-gray N7, very pale orange 10YR 8/2, pale-yellowish-brown 10YR 6/2
Grain size	Carbonate grains up to pebble size; quartz sand mainly very fine to fine and ranges from silt to coarse size
Carbonate grains	Pelecypods, undifferentiated skeletal fragments, gastropods, oysters, ser pulids bryozoans, cerithiids, and echinoids
Accessory grains	Trace to 3 percent phosphate and heavy mineral grains
Porosity	Mainly intergrain and moldic; local intragrain and shelter; ranges from 5 to 15 percent
Hydraulic conductivity	Mainly low (0.1 to 10 feet per day); ranges from very low (less than 0.1 foot per day) to moderate (10 to 100 feet per day)
	Terrigenous Mudstone Facies
Depositional textures	Silty terrigenous mudstone to quartz sand-rich terrigenous mudstone; locally grades into terrigenous clay-rich lime mudstone
Color	Light-olive-gray 5Y 5/2, light-olive-gray 5Y 6/1 and yellowish-gray 5Y 8/1; locally pale-olive 10Y 6/2, light-olive-gray 5Y 6/1, dusky-yellow-green 5GY 5/2, and yellowish-gray 5Y 7/2
Grain size	Mainly terrigenous clay; quartz grains range from silt to fine sand size; local medium to coarse quartz sand
Carbonate grains	Pelecypods (local oysters), benthic and planktic foraminifers, undifferentiated skeletal fragments, and fish scales
Accessory grains	Locally common quartz grains; trace to 1 percent phosphate grains; trace to 3 percent heavy mineral grains; local trace mica; trace plagioclase and micro cline
Porosity	Intergrain; less than or equal to 5 percent
Hydraulic conductivity	Very low (less than 0.1 foot per day)

Collier County (Edwards et al., 1998). The unconformity recognized in southwestern Florida (Missimer, 1999), in the W-17157 corehole (Guertin et al., 1999), in the W-17273 corehole (Guertin, 1998), and in the W-17394 corehole (Edwards et al., 1998) all occur near the Miocene-Pliocene boundary, suggesting that these unconformities may form a correlative sequence bound-ary of regional scale (Fig. 6).

The top of the Ochopee Limestone is interpreted to represent a depositional sequence boundary. Typically, the contact between the top of the Ochopee Limestone and the unnamed sand is abrupt. Several coreholes (Fig. 1; C-1181, C-1182, and G-3673) contain an abrupt contact with core-scale microtopography, small dissolution cavities filled with quartz sand of the unnamed sand, and local blackened crust. Blackened surfaces are reported to characterize the tops of late Neogene unconformities bounding depositional sequences in southwestern Florida (Evans and Hine, 1991). Analyses by x-ray diffraction indicate the blackened surfaces at the top of the Ochopee Limestone do not contain a measurable amount of phosphorite. The absence of phosphorite possibly suggests that the surface is not a submarine hardground and condensed section (Loutit et al., 1988). The blackening could be due to fire above the surface during subaerial exposure (Shinn and Lidz, 1988) or to darkened organic matter in soilstone crusts as noted by Ward et al. (1970).

At the C-1178 corehole in Collier County (Fig. 1), the upper bounding surface of the Ochopee Limestone contains strong evidence for subaerial exposure (Reese and Cunningham, 2000, in press). Reese and Cunningham (2000, in press) describe an exposure zone (30 feet thick) bounding the top of the Ochopee Limestone that contains root molds lined with calcrete. This unconformity is postulated to be equivalent to a lithofacies boundary in the Long Key Formation at the W-17157 corehole in the Florida Keys. Along this boundary, there is an upward shift from foraminifera-rich quartz sandstones--similar to lithofacies of the Stock Island Formation of Cunningham et al. (1998)--to overlying quartz sandstone at a depth of 280 feet below sea level (Guertin, 1998) as shown in Figure 6.

Micropaleontology

One sample of well cuttings was collected for analysis of coccoliths from well W-9104. This sample was taken from a sandy mudstone at the base of the Tamiami Formation and possible basal Ochopee Limestone at a depth interval of 205 to 215 feet below sea level (Fig. 5). Coccoliths from the interval are assigned to the early Pliocene Subzone CN12aA (Fig. 7) identified by Bukry (1991). Coccoliths present in this interval include *Discoaster brouweri*, *D. surculus*, *D. variabilis*, and *Sphenolithus abies*. *Reticulofenestra pseudoumbilica* is absent. This assemblage along with the absence of *R. pseudoumbilica* is characteristic of Subzone CN12aA (Bukry, 1991).

Unnamed Sand

Lithostratigraphy

An unnamed sand that overlies the Ochopee Limestone has been mapped in the study area (Fig. 9). The stratigraphic relation to existing Pliocene-Pleistocene units, such as the Pinecrest Member of the Tamiami Formation, has not been resolved. Future analysis of mollusks could help to clarify relations, but Scott and Wingard (1995) have discussed the problems associated with biostratigraphy and lithostratigraphy of the Plio-Pleistocene in southern Florida.

Three lithofacies have been identified within the unnamed sand for an area shown in Figure 1: (1) a quartz sand facies, (2) a pelecypod lime rudstone and floatstone facies, and (3) a terrigenous mudstone facies (Table 7). The quartz sand facies is characteristic of most of the unnamed sand. The terrigenous mudstone facies occurs mainly in the north-central part of the study area outlined in Figure 1 where the facies typically occurs as one or two units within the lower part of the unnamed sand. The pelecypod lime rud-stone is found only locally as discrete beds within or near the top of the unnamed sand. Figure 6 shows that the unnamed sand is probably equivalent to much of Interval II and all of Interval III defined by Guertin et al. (1999) within the Long Key Formation.

The unnamed sand ranges from 20 to 60 feet in thickness in most of the study area. The unnamed sand is thickest (about 120 feet) in central and south-central Miami-Dade County. A structure contour map of the base of the unnamed sand (Fig. 9) shows that the unit pinches out in the western portion of the Florida peninsula. In southern Miami-Dade County, the unnamed sand merges with siliciclastics of the Long Key Formation as defined by Cunningham et al. (1998) in the Florida Keys. The structure contour map at the base of the unnamed sand and the cross sections shown in Figures 5 and 6 indicate that quartz sands of the unnamed sand were transported southward mostly along the southeastern coast of Florida to the Long Key Formation in the Florida Keys.

Sequence Stratigraphy

The sequence stratigraphy of the unnamed sand is more poorly defined than that of the Ochopee Limestone and Peace River Formation. The unconformity and sequence boundary at the top of the Ochopee Formation defines the base of the unnamed sand. Possibly a subaerial unconformity at the base of the Pleistocene defined by Perkins (1977) bounds the top of the unnamed sand. The unnamed sand is correlated to the middle and upper parts of Intervals II and all of Interval III defined by Guertin et al. (1999) within the Long Key Formation (Fig. 6), suggesting assignment to the early and late Pliocene. For the present study, however, assignment of the Ochopee Limestone to Sub-zone CN12aA, at least in part, suggests that the unnamed sand has a late Pliocene age (Fig. 7).

Micropaleontology

One sample from the terrigenous mudstone lithofacies of the unnamed sand from the PB-1703 corehole in Palm Beach County was examined (Fig. 1 and Table 4). The assemblage present is consistent with deposition on a marine shelf (Tables 4 and 5).

SUMMARY OF DEPOSITIONAL TIMING

Peace River Formation

Established chronologic data (Cunningham et al., 1998; Edwards et al., 1998; Guertin et al., 1999; Missimer, 1999; Weedman et al., 1999) and the new biochronology of this study indicate that the Tortonian and Zanclean ages bracket deposition of the Peace River Formation. These chronologic data allow constraints to be placed on the ages of DS1, DS2, and DS3. In southwestern Florida, Missimer (1999) divided the Peace River Formation into one supersequence (lower Peace River Formation) and one depositional sequence (upper Peace River Formation). Deposition of the lower Peace River Formation of Missimer (1999) occurred between the intervals of 11 and 8.5 Ma (Tortonian age) and deposition of the upper Peace River Formation of Missimer (1999) was between 5.2 and 4.3 Ma (Zanclean age).

Biostratigraphic results presented herein indicate that terrigenous mudstones from the base of DS1 of the Peace River Formation in Palm Beach County probably can be assigned to Zone CN8 (Tortonian age). The boundaries of Zone CN8 are 9.4 and 8.6 Ma (Fig. 7). Micropaleontologic results show that deposition of CS2 of the Peace River Formation occurred from late Tortonian and Messinian age. Micropaleontologic results also suggest that CS2 is, at most, 7.2 Ma and likely no younger than 5.6 Ma; however, results from Cunningham et al. (1999) suggest an age ranging between 7.44 and 6.83 Ma.

Missimer (1999) reports a hiatus in deposition of the Peace River Formation between 8.5 and about 5.2 Ma in southwestern Florida--an interval in time that brackets deposition of CS2 in southeastern Florida. Edwards et al. (1998) indicate that the unnamed formation in western Collier County, which is equivalent to the Peace River Formation for the present study, ranges in age from 9.5 to 5.7 Ma based on strontium-isotope chemostratigraphy, but biostratigraphic data suggest it may be as young as Pliocene. Weedman et al. (1999) produced similar results for the

Peace River Formation and unnamed formation in eastern Collier and northern Monroe Counties, which are equivalent to the Peace River Formation for the study herein. Weedman et al. (1999) report a late Miocene age for the Peace River Formation based on dinocysts and strontium-isotope chemostratigraphy, and an age for the unnamed formation ranging between 6.9 and 4.6 Ma (late Miocene to Pliocene) based on strontium-isotope chemostratigraphy. Coccolith data from the condensed section of DS3 and the age of overlying mudstones in well W-9104 con-strain the age of DS3 to range from 5.23 to 3.83 Ma.

Depositional sequence 1 (DS1) correlates to the lower Peace River Formation of Missimer (1997; 1999) where the data from the present study are linked to data from Missimer at the W-17115 corehole (Figs. 5 and 7). Data presented by Edwards et al. (1998) and Weedman et al. (1999) are consistent with deposition of DS1 during the Tor-tonian and Messinian ages (11.2-5.32 Ma). Results herein suggest that the age of DS1 is probably at most 11 Ma and no younger than 7.2 Ma, the probable maximum age of CS2. Biostratigraphic data from CS2 and CS3 are consistent with deposition of DS2 during the latest Tortonian and Messinian ages (Fig. 7). Interval I of the Long Key Formation in the Florida Keys (Guertin et al., 1999) is probably equivalent to DS2 (Fig. 7). Guertin et al. (1999) assign Interval I to the Messinian age, suggesting that Interval I may be equivalent to the upper portion of DS2 that occurs beneath the Florida peninsula (Fig. 7). Deposition of the upper Peace River Formation of Missimer (1999) in southwestern Florida may be coincident with DS3 in southeastern Florida as suggested by an early Pliocene age for the upper Peace River Formation (Fig. 7).

Ochopee Limestone Member of the Tamiami Formation

Results presented herein suggest that the Ochopee Limestone or DS3 was deposited during a time spanning the early-late Pliocene boundary and during the eustatic cycle TB3.6 of Haq et al. (1988) as shown in Figure 6. Coccolith data from the base of DS4 in well W-9104 are consistent with assignment to Subzone CN12aA (3.83-3.62 Ma) as shown in Figures 5 and 6. Cunningham et al. (2000, in press) used silicoflagellate and coccolith data to determine the age of the lower boundary of the Tamiami Formation to be near the early-late Pliocene boundary in the W-18074 and W-18075 coreholes in Glades County (Fig. 1). Cunningham et al. (2000, in press) also show a regional-scale seismic sequence boundary at the contact between the Peace River Formation and the Tamiami Formation. The Tamiami ages at well W-9104 and the two coreholes (W-18074 and W-18075) in Glades County are consistent with determination by Missimer (1999) that deposition of the Tamiami Formation began about 0.2 million years after the Peace River Formation at 4.3 Ma or Tamiami deposition began at about 4.1 Ma. Edwards et al. (1998) and Weedman et al. (1999) determined the Ochopee Limestone was most likely deposited during the early Pliocene, but the margin of error spans the late Miocene to late Pliocene age. A distinctive molluscan assemblage in several coreholes indicates an age for the Ochopee Limestone near the early-late Pliocene boundary (Edwards et al., 1988).

Age determinations of Edwards et al. (1998), Weedman et al. (1999), and Missimer (1999), and correlations for the present study suggest that deposition of the Ochopee Limestone was coincident with deposition of the lower portion of Interval II of the Long Key Formation (Fig. 6). Foraminiferal sandstone beds occurring at the base of Interval II are composed of a lithofacies characteristic of the Stock Island Formation (Cunningham et al., 1998), and may represent a distal portion of the Ochopee Limestone ramp (Fig. 6).

Unnamed Sand

The unnamed sand was probably deposited during the late Pliocene based on age determinations for DS4 (Fig. 6). Correlations shown in Figure 6 suggest that the unnamed sand is coincident with deposition of the middle and upper parts of Interval II and all of Interval III

(Guertin et al., 1999) within the Long Key Formation.

CONCLUSIONS

In southern Florida, a late-early to early-late Pliocene carbonate ramp (Ochopee Limestone Member of the Tamiami Formation) is sandwiched between underlying marine siliciclastics of the late Miocene-to-early Pliocene Peace River Formation and an overlying late Pliocene unnamed sand. The Peace River Formation contains at least three depositional sequences (DS1, DS2, and DS3), and the Ochopee Limestone forms a fourth depositional sequence (DS4). The two youngest depositional sequences of the Peace River Formation, DS2 and DS3, contain condensed sections composed of terrigenous mudstone typically overlying diatomaceous mudstone. A maximum flooding surface is interpreted to coincide with the contact between diatomaceous mudstone and terrigenous mudstone. The maximum flooding surface bounds the transgressive and highstand systems tracts of DS2 and DS3. The condensed sections have yielded abundant microfossils, which contribute to their importance for biochronology, defining and correlating the sequences, and reconstructing depositional environments.

Established chronologies and new micropaleontologic results indicate that the Tortonian and Zanclean ages bracket deposition of the Peace River Formation and provide constraints on the timing of the deposition of the three Peace River depositional sequences. Depositional sequence (DS1) prograded across the present-day southern peninsular portion of the Florida Platform during the Tortonian age and laps out near the southern margin of the peninsula. The age of DS1 is probably at most 11 Ma and no younger than 7.2 Ma. During the latest Tortonian and Messinian ages (probably between 7.2 and 5.6 Ma), progradation of DS2 overstepped the southern lap out of DS1 and extended at least as far as the Florida Keys. Deposition of DS2 siliciclastics ended, at the latest, near the Miocene-Pliocene boundary.

Presence of DS3 in southeastern Florida and possibly southwestern Florida and absence in southernmost Florida suggest a reduction in the southward supply of quartz sand during deposition of the sequence (between 5.23 and 3.83 Ma). This reduction in supply of siliciclastics to southernmost Florida was followed by aggradational accumulation of heterozoan temperate carbonate sediments of the Ochopee Limestone. Deposition of the Ochopee Limestone ended with basinward lap out near the southern margin of the present-day Florida peninsula. The lap out is probably coincident with the edge of the siliciclastic shelf containing DS2 of the Peace River Formation. Deposition of the Ochopee Limestone probably occurred during a late-early to early-late Pliocene trans-gressive to high-stand sea-level conditions during eustatic cycle TB3.6 of Haq et al. (1988). Increased supply of siliciclastics to southern Florida resumed in late Pliocene, burying the Ochopee Limestone ramp. These siliciclastics extend as far south as the middle and northern Florida Keys. The unnamed sand includes these siliciclastics, which probably are coincident with middle to upper quartz sands of the Long Key Formation beneath the Florida Keys. Southward transport of quartz sands of the unnamed sand was mostly along the eastern coast of Florida.

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LATE PALEOGENE AND NEOGENE CHRONOSTRATIGRAPHY OF LEE COUNTY, FLORIDA

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ABSTRACT

Ages of the geologic formations underlying Lee County, Florida have been in dispute for the last century. A new, unified chronostratigraphy (age analysis) was developed for the upper Paleogene and Neogene sediments of the Southwest Florida region. The age constraints were determined from analysis of samples collected from continuous cores and from compilation of existing age-data collected by a number of investigators. The ages of the sediments were determined by the combined use of calcareous nannofossils, planktonic foraminifera, diatoms, strontium isotope stratigraphy, and magnetostratigraphy. Based on these integrated dating techniques, the following age constraints using the Berggren et al. (1995) time scale were placed on the formations underlying Lee County: the Suwannee Limestone ranges from 33.7 (?) to 28.5 Ma, the Arcadia Formation of the Hawthorn Group from about 26.5 to 12.4 Ma., the Peace River Formation of the Hawthorn Group from 11(?) To 4.3 Ma, the Tamiami Formation from 4.3 to 2.1 Ma, and the Caloosahatchee Formation from 1.8 to 0.6 Ma. Based on these ages, the Suwannee Limestone was deposited in the early Oligocene, the Hawthorn Group was deposited from the late Oligocene to the early Pliocene, the Tamiami Formation was deposited from the early to the late Pliocene, and the Caloosahatchee Formation was deposited within the late Pliocene and early Pleistocene.

INTRODUCTION

Ages of the upper Paleogene and Neogene sediments in Lee County have been subject to debate for many years. Previous stratigraphic investigations have assigned ages to many of the formations based on paleontological data correlated to areas outside of the Florida Platform (Cooke, 1939; Mansfield, 1937, 1939; MacNeil, 1944; Parker and Cooke, 1944; Cooke, 1945; Parker et al., 1955; Akers, 1972; Riggs, 1979; Miller, 1986; COSUNA, 1988; Scott, 1988). The currently accepted ages of many reference sections used for correlation to the Florida Platform have changed, but little effort has been given to revising the chronostratigraphy of the Florida Platform until relatively recently. Beginning in 1972, a series of stratigraphic investigations were conducted that yielded a large quantity of new age data based on planktonic foraminifera (Akers, 1972; Peck, 1976; Peck et al., 1976; Slater, 1978; Peck et al., 1979a; Peck et al., 1979b; Armstrong, 1980; Peacock, 1981; Peacock and Wise, 1981, 1982; Jones et al., 1991), calcareous nannoplankton (Peck, 1976; Covington, 1992), diatoms (Klinzing, 1980, 1987), helium-uranium dating (Bender, 1973), vertebrate fossil stratigraphy (Jones et al., 1991), strontium isotope stratigraphy (Jones et al., 1991; Hammes, 1992; Compton et al., 1993; Mallinson and Compton, 1993; Weedman et al., 1993; Edwards et al., 1998; Weedman et al., 1999), and magneto-stratigraphy (Jones et al., 1991).

It is the purpose of this paper to present new data refining the age ranges in the central part of the South Florida Platform of the Suwannee Limestone, the Arcadia and Peace River Formations of the Hawthorn Group, the Tamiami Formation, and the Caloosahatchee Formation (Figure 1). A series of three continuous core borings were used in this investigation (Nos. W-16242, W-16523, and W-17115 in Figure 2). The new data were obtained using strontium-isotope age dating and magnetostratigraphic analyses with a comparison to and correlation with

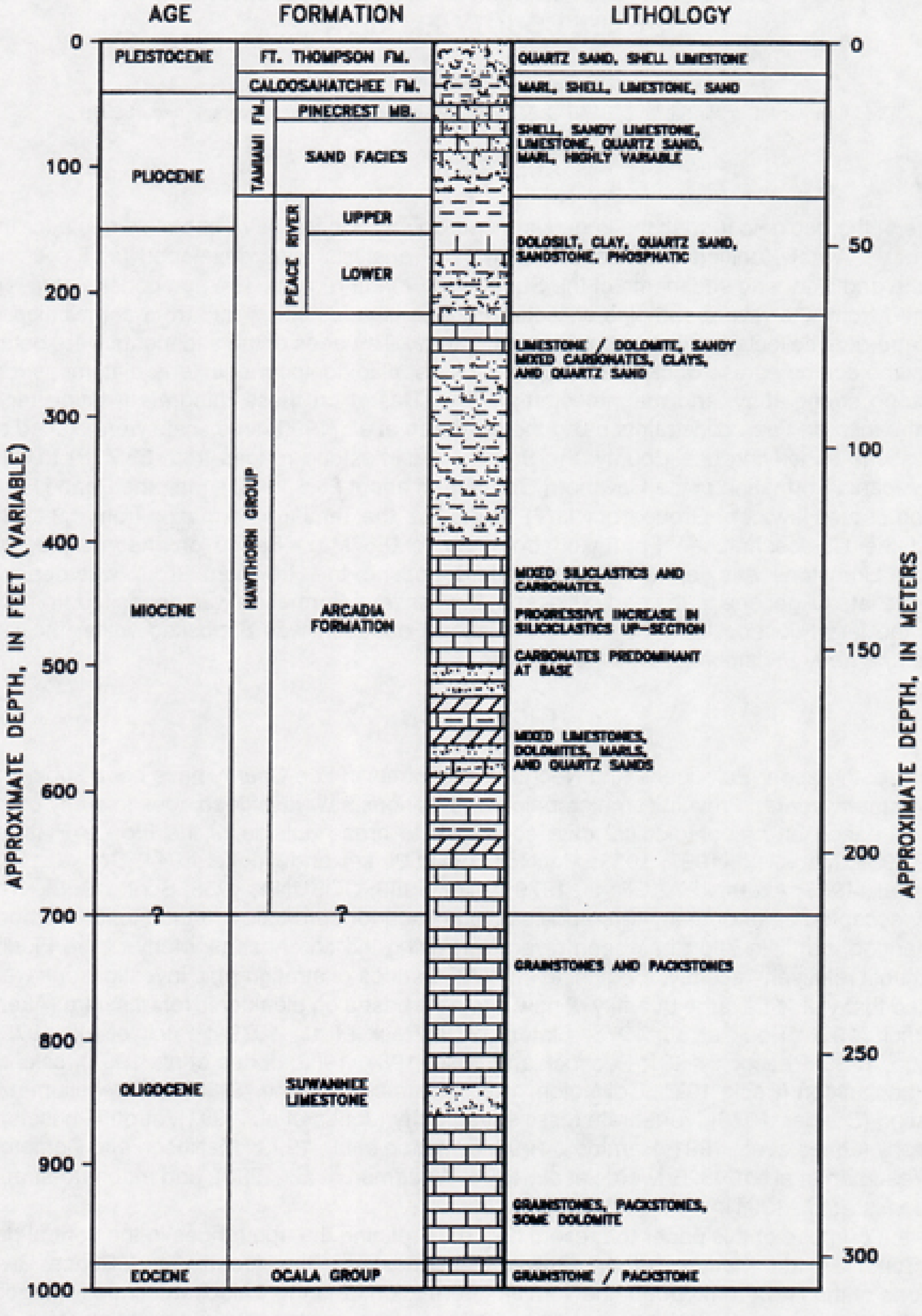

Figure 1. Generalized stratigraphic column of Lee County showing the accepted ages of the formations before this paper.

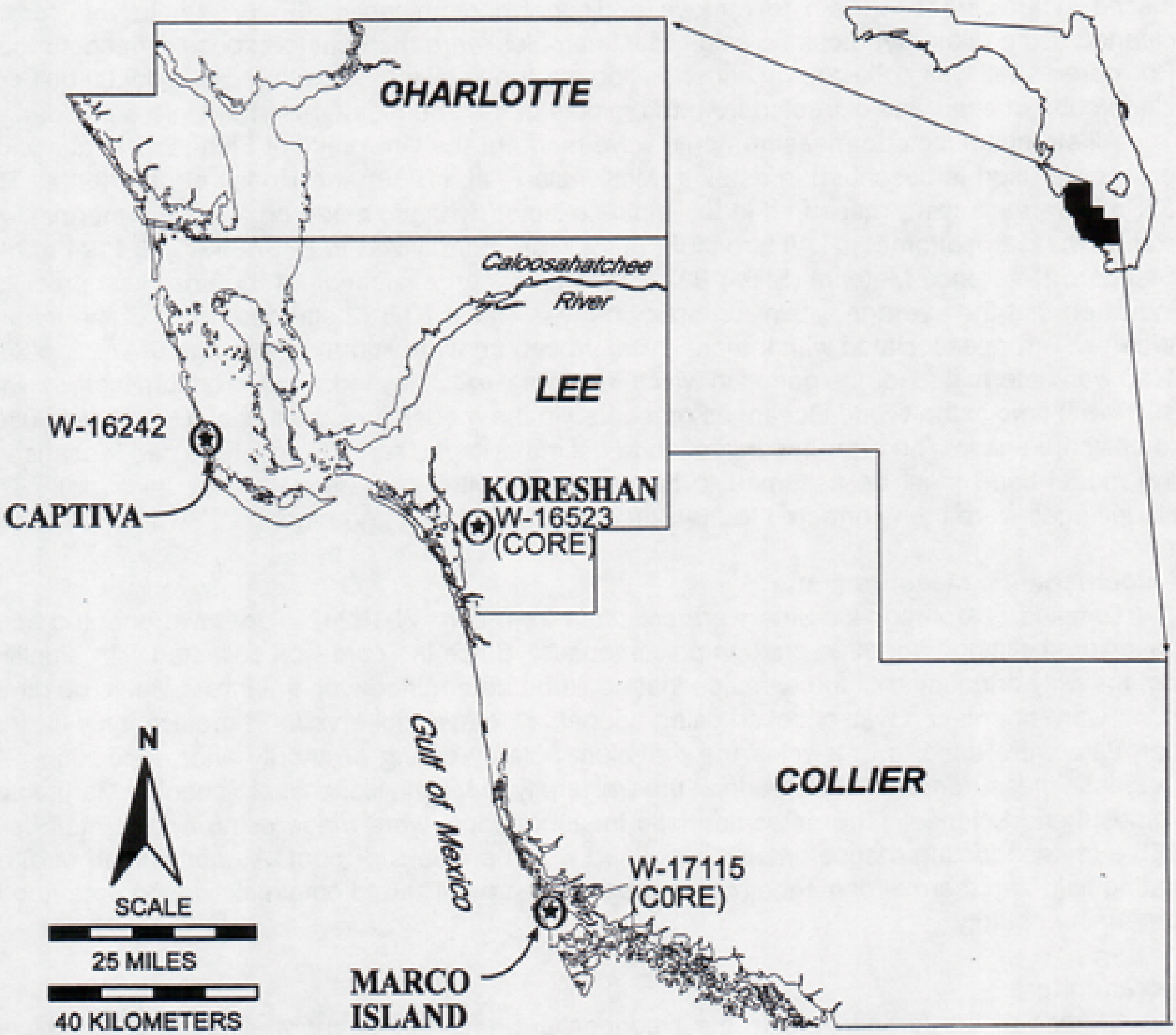

Figure 2. Map of southern Florida showing the locations of the primary cores used in this investigation.

existing planktonic foraminifera, calcareous nannoplankton, and other paleontological data. All age determinations made in this paper utilize the geologic time scale of Berggren et al. (1995).

METHODS

Strontium and Stable Isotope Sample Preparation

Samples of unaltered calcitic mollusk shell and a few phosphorite nodules were collected from cores W-16242, W-16523 in Lee County, and W-17115 from Collier County for the purpose of measuring the strontium-isotope ratios to make age determinations. A total of 62 samples were chosen for analysis from all samples collected based on the location of the samples within the stratigraphic section and the quality of the shell material. A large percentage of the samples were collected and analyzed from core W-16242 (34 samples), because of the abundant quantity of unaltered shell, the high percentage of core recovery, and the designation of this core for magnetostratigraphic analysis. All samples were carefully washed in distilled water, then placed in an ultrasonic bath to remove additional contaminants. Each sample was further cleaned using dilute hydrochloric acid. Most samples were then cut to expose a fresh surface. Powdered shell was collected by either drilling out the shell interior with a clean dental drill or a clean cube of shell was extracted from the middle of the sample and crushed into a powder.

All strontium isotope measurements were made at the University of Florida. The analytical procedure used is described in detail in McKenzie et al. (1988) and Hodell et al. (1990). The 87Sr/86Sr ratios were measured in the triple-collector dynamic mode on a VG354 thermal ionization mass spectrometer. All strontium ratios were normalized to 86Sr/88Sr = 0.1194 and to Standard Reference Material (SRM) 987 = 0.710235. An evaluation of the analytical precision indicated that the average within-run precision was +/-1 x 10-5 (2 standard error of the mean). When all errors associated with the analytical procedure were summed, a range of +/-22 to 24 x 10-6 was determined for the period in which the data were collected. The strontium isotope variation with time in the World Ocean, as presented in the model of Hoddell et al. (1991), was used to estimate ages. The error in conversion to estimated ages cannot be determined, because the model used must be assumed to be correct (P. Mueller, personal communication). The Hodell ages were then corrected to the Berggren et al. (1995) age model.

Paleomagnetic Measurements

Detailed paleomagnetic data were collected from core W-16242. Up-down oriented samples were collected from 291 stratigraphic intervals. Since the core was collected with a drilling rig, the only orientation of the samples that could be determined was the stratigraphic up direction. Core orientation was checked using geopels wherever observed. Therefore, only inclination data were used to determine the prevalent polarity during or shortly after deposition. All magnetic measurements were made at the University of Miami, Rosenstiel School of Marine and Atmospheric Science. The paleomagnetic measurements were made using a 2G Enterprises 755 superconducting magnetometer contained within a shielded room. A combination of alternating field and thermal demagnetization methods were utilized to obtain inclination data and to determine polarity.

Foraminifera

Studies of the foraminifera in the Neogene and late Paleogene sediments in Southwest Florida were presented in a series of theses and resultant publications (Peck, 1976; Peck et al., 1976; Peck et al., 1977; Peck et al., 1979a; Peck et al., 1979b; Slater, 1978; Peacock, 1981; Peacock and Wise, 1981; Peacock and Wise, 1982). Since detailed analyses of foraminifera were previously performed on nearby wells having very direct and reliable lithostratigraphic correlation to the cores in this study, projected planktonic foraminifera ages are used. The stratigraphic correlation between the cores studied and the planktonic information collected from nearby wells was accomplished by tracing continuous seismic reflection lines between the wells and core W-16242 on the north (20 km) and by direct correlation of the stratigraphic units into core W-16523 on the south (8 km).

The entire Neogene and late Paleogene stratigraphic section was not studied in the foraminifera research, but the work was concentrated on the "Tamiami Formation," which was defined at that time as all sediments lying between the disconformity marking the top of the Arcadia Formation and the disconformity marking the base of the Caloosahatchee Formation. Since the definitions of the stratigraphic units have been changed to produce a more consistent framework (Scott, 1988), the foraminiferal investigations were performed on both the Tamiami and Peace River Formations. The only age diagnostic data, however, were obtained from the Peace River Formation. The work performed by Peacock (1981) was mostly limited to the foraminiferal occurrences in the lower part of the Arcadia Formation.

Calcareous Nannofossils

Introduction

Samples were collected throughout cores W-16242 and W-16523 for calcareous nannofossil analysis. This work was conducted as a research project at the Florida Geological Survey by J. Mitchner Covington. The results of the calcareous nannofossil analyses of these cores was reported by Covington (1992).

Calcareous Nannofossil Stratigraphy of Core W-16242

Calcareous nannofossils were found in core W-16242 only above the contact with the Arcadia Formation or in the Peace River Formation and younger Neogene units. Also, the samples for calcareous nannofossils were not collected from the lowermost part of the Peace River Formation. Heavy alteration of the carbonate sediments probably caused the destruction of any calcareous nannofossils that may have occurred in the Arcadia Formation.

The investigation conducted by Covington (1992; unpublished Florida Geological Survey data) showed that samples from core W-16242 contain varying abundance and diversity of calcareous nannofossils. The age ranges of the calcareous nannofossils are plotted with the other age data on the unified chronostratigraphy of core W-16242 (Figure 3).

The observed assemblage included common to abundant *Sphenolithus abies* and *Reticulofenestra pseudoumbilica*, which collectively yield an early Pliocene age estimate. Discoasters were also present in this interval for the first time, suggesting that the paleoenvironment was more favorable for the deposition of these forms at that time. No calcareous nannofossils were found in the core below a depth of 88.4 m, or just above the contact between the upper and lower part of the Peace River Formation.

Abundant calcareous nannofossils occurred between 73.2 and 88.4 m. Nannofossil abundance began to decrease at a depth of 67.1 m and samples collected from the interval between 48.4 and 64.6 m contained no preserved calcareous nannofossils.

The rare species, *Sphenolithus abies*, was observed at the 27.4 m depth. The extinction of *S. abies* occurs in the NN15/CN11b interval and approximates the boundary between the early and late Pliocene. This depth interval occurs within the Pinecrest Member of the Tamiami Formation. A barren interval between 21.2 and 22 m was observed.

In the uppermost samples collected from 3 to 12.2 m, a few *Gephyrocapsa caribbeanica* were found and no *Pseudoemiliania lacunosa* were observed. This interval is probably within nannofossil zone NN20/CN14b of Martini (1971) and Okada and Burky (1980). Diversity is quite low in this interval and the absence of *P. lacunosa* may be a function of paleoenvironment rather than age. Therefore, the inferred age may be older than indicated. The general age of these sediments is interpreted to be late Pliocene or Pleistocene.

Calcareous Nannofossil Stratigraphy of Core W-16523

Calcareous nannofossils were found in core W-16523 from the mid-section of the Arcadia Formation to the top of the core. They were not found in every stratigraphic interval, but the general state of fossil preservation was better in core W-16523 compared to core W-16242.

The occurrence of *Cyclicargolithus floridanus* was noted at 177.4 m. This species may be indicative of the uppermost Oligocene. A noteworthy occurrence includes that of *Helicosphaera ampliaperta* at 153.6 m below surface. This species indicates an age between CN3/NN4 and CN1/NN2 or early Miocene.

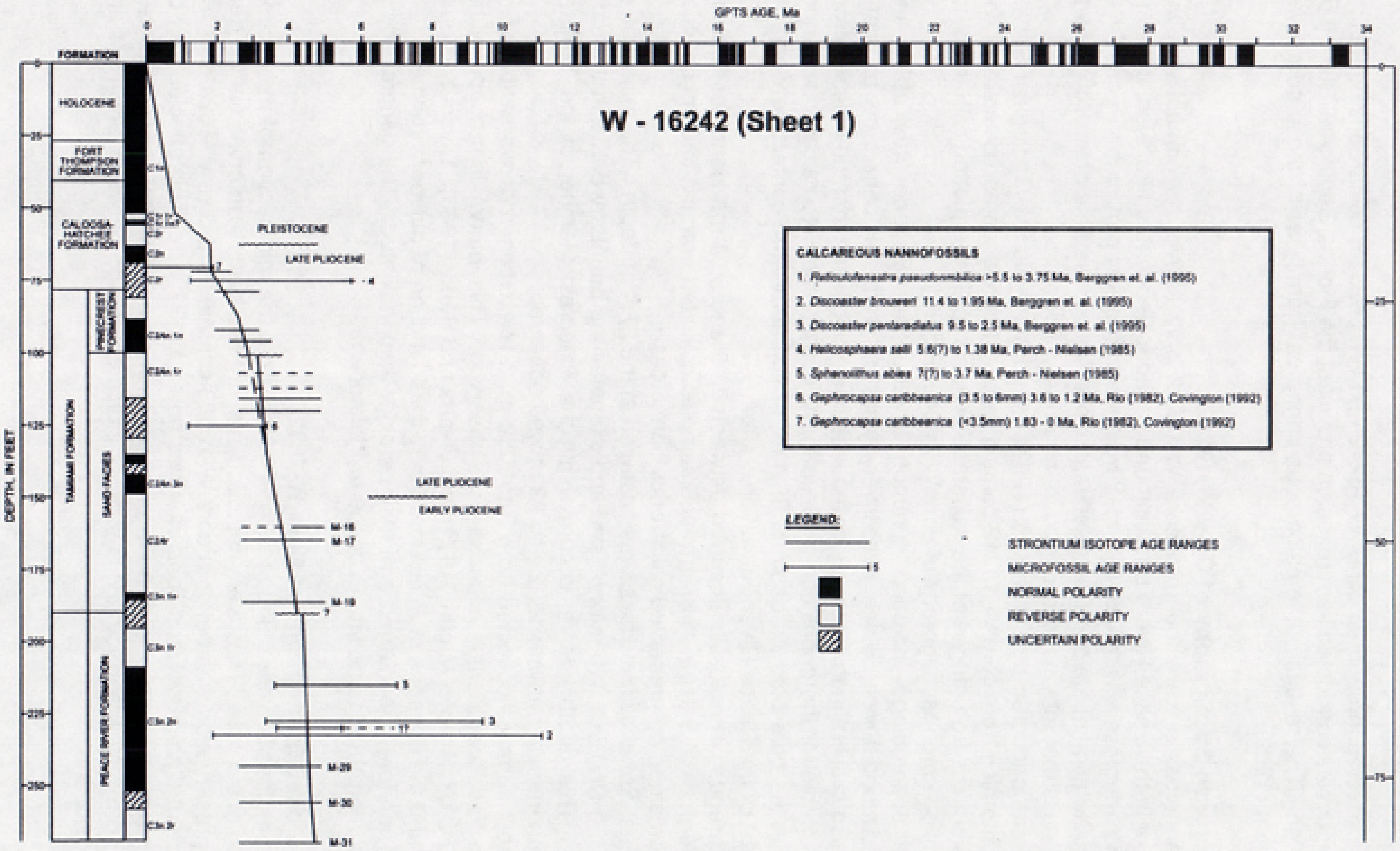

Figure 3. Unified chronostratigraphy of core W-16242 (Captiva Island). The ages of the Global Polarity Time Scale conform to Berggren et al. (1995).

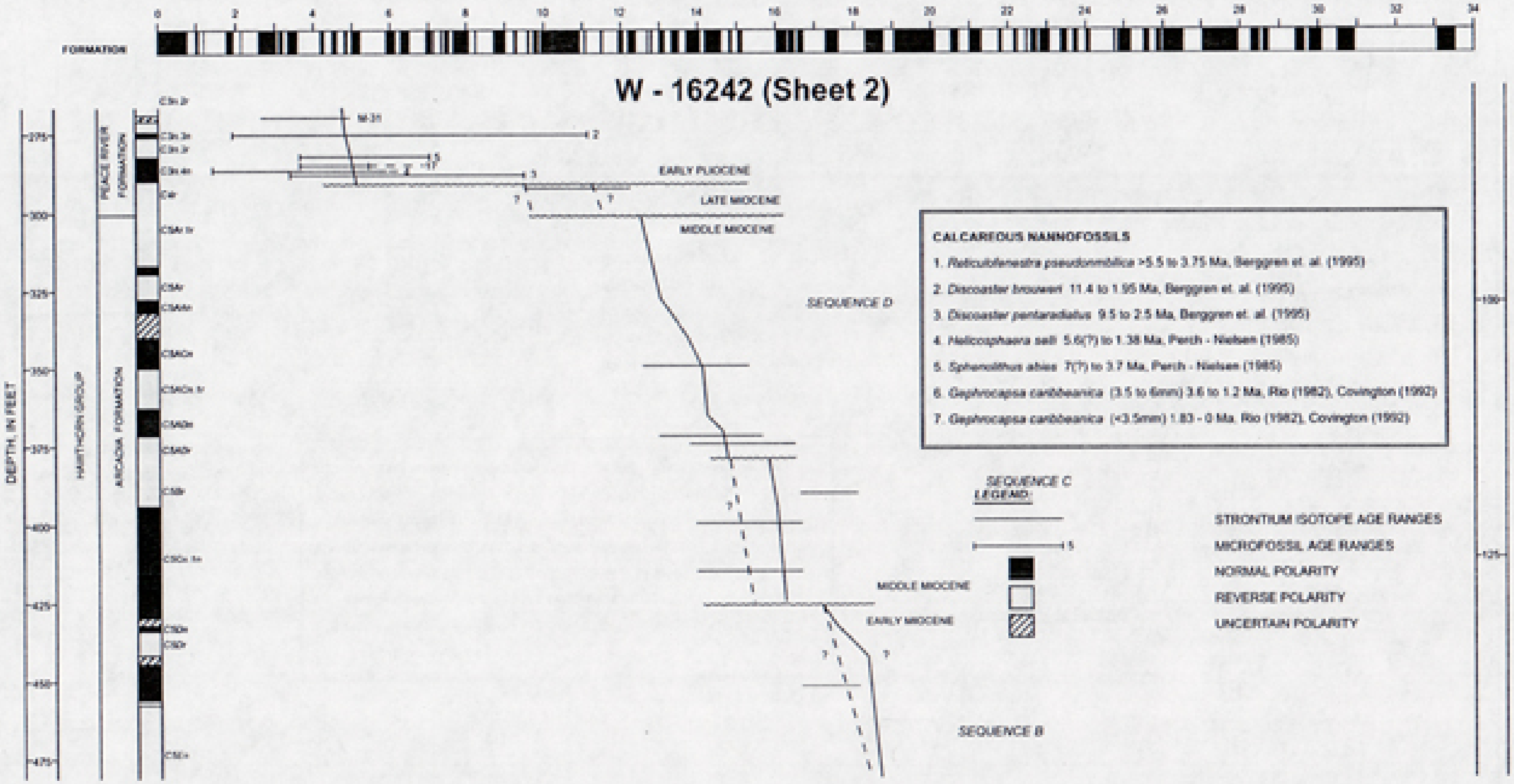

Figure 3. continued.

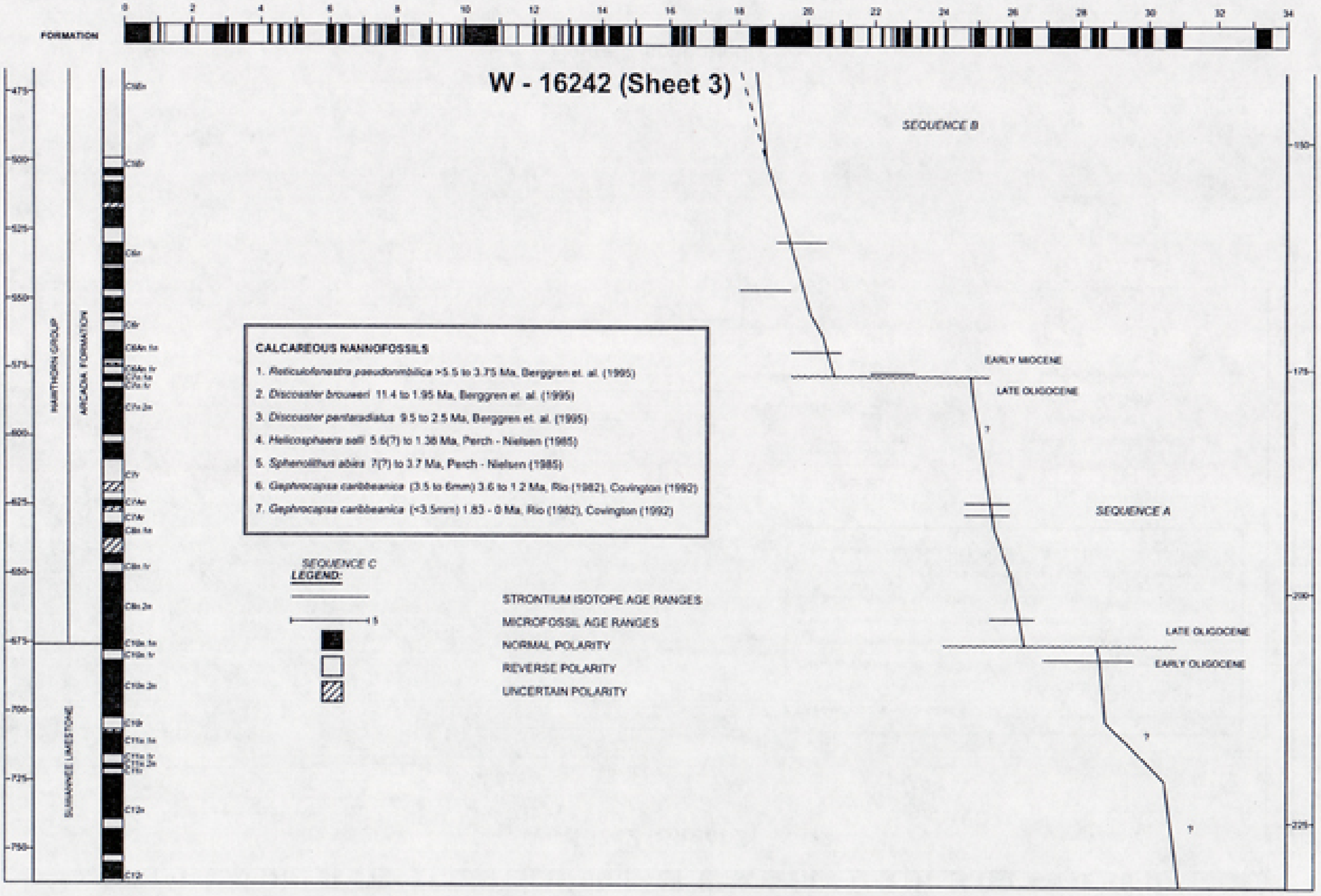

Figure 3, continued.

Diatoms

Diatoms were found in various zones within the Peace River Formation. The diatom stratigraphy of this section was studied by Klinzing (1987) and the diatom occurrences were noted in the Peck et al. (1979). Klinzing (1987) described an assemblage of diatoms in core W-14072, which is located about 7 km to the east of core W-16523. Peck et al. (1979) noted the occurrence of the diatoms in unit 2B and stated that only two of the diatoms were age diagnostic. The species *Actinoptycus bismarkii* and *Diploneis exemta* were reported to occur exclusively in the late Miocene. Klinzing (1987) concluded that the Peace River Formation was Pliocene in age based on the occurrence of two species, *Thalassiosira oestrupii* and *Cussia tatsunokuchiensis*, which were believed to occur exclusively in the Pliocene. The work of Klinzing (1987) may indicate that the primary diatom bed, which occurs near the base of the upper Peace River Formation is Pliocene in age. However, the absence of detailed range data for each diatom species raises questions with regard to the actual stratigraphic occurrence of the marker species. Based on the diatom data obtained on the Peace River Formation, it is concluded that no diagnostic age designation can be made.

Strontium-Isotope Stratigraphy

Introduction

The ratio of $^{87}Sr/^{86}Sr$ in seawater has varied significantly during Phanerozoic time (Wickman, 1948; Brass, 1976; Burke et al., 1982; Koepnick et al., 1985; Hess et al., 1986; Miller et al., 1988; Smalley et al., 1994). In the Tertiary, the ratio has increased, but at a variable rate (Hodell et al., 1989; Hodell et al., 1990; Hodell et al., 1991). The origin of the strontium isotope variation is not fully understood, but the long-term changes are related to tectonic processes, which caused changes in the exposure of the earth's crust and rock types exposed at surface to weathering. Short time-scale climatic changes influencing continental weathering, such as glaciation, may be responsible for exposing old shield rocks, leading to accelerated erosion rates of rocks with higher $^{87}Sr/^{86}Sr$ ratios (Armstrong, 1971).

If equilibrium between the isotopic ratios of strontium in seawater and living, shell-producing organisms is assumed, the time dependant change of the strontium-isotope ratios in seawater is reflected in unaltered shell tests and can be used to date the material (Hoddell et al., 1991). Therefore, the $^{87}Sr/^{86}Sr$ ratio in unaltered calcareous marine fossils has been used successfully to determine the age of marine sediments (McKenzie et al., 1988). Both marine microfossils (benthic foraminifera) and mollusk shells have been dated using the $^{87}Sr/^{86}Sr$ technique (Hodell et al., 1991, Jones et al., 1991; Bryant et al., 1992; Compton et al., 1993). Compton et al. (1993) also demonstrated that phosphorite nodule strontium-isotope dates can be used to estimate the age of marine sediments when reworking is not significant.

Results

Strontium-isotope ratios were measured on 62 samples collected from cores W-16242, W-16523, and W-17115 (Table 1). Age determinations were made using the regression curves developed by Hodell et al. (1991) with an extrapolation to the late Oligocene and comparison to the curve developed by Oslick et al. (1994). The measured $^{87}Sr/^{86}Sr$ ratios were normalized to the appropriate NBS-987 value before age determinations were made. A total of 34 samples were analyzed from core W-16242, 17 from core W-16523, and 11 from core W-17115. In core W-16242, the material used for strontium-isotope analysis was mostly unaltered calcitic mollusk shell with the exception of samples M-5, M-6, and M-7 (aragonitic mollusks), sample M-36 (phosphorite nodule), sample M-37 (phosphorite crust), sample M-40 (recrystallized coral), and sample M-42 (foraminifera extracted from whole rock). In cores W-16523 and W-17115, all material analyzed for strontium isotopes were unaltered calcitic mollusk shell.

The reduction in the $^{87}Sr/^{86}Sr$ ratio with depth was relatively consistent in core W-16242 (Figure 3) with the exception of three samples within the Tamiami Formation section, numbers M-13, M-14, and M-15 and one sample in the lower part of the Peace River section, number M-20. The four samples with lower than expected strontium-isotope ratios were shell samples, from the genus *Hyotissa*. Petrographic examination of thin sections containing *Hyotissa* showed that in some cases very fine sand-sized phosphorite grains were trapped within the shell structure of the mollusk. Since phosphorite is reworked throughout the younger part of the stratigraphic section above the Arcadia Formation, it is likely that any phosphorite incorporated in younger mollusk shells would be much older and would be a significant factor in causing a lower $^{87}Sr/^{86}Sr$ ratio. It is also possible, although less likely, that these samples were reworked. There is consistency in the $^{87}Sr/^{86}Sr$ ratio above and below the suspect samples, which strengthens the case to dismiss the validity of these samples. A similar case can be made for sample M-20, which yielded a $^{87}Sr/^{86}Sr$ ratio much lower than anticipated. In this case, it is likely that this shell material was reworked, because of its stratigraphic position near a major disconformity. Based on the variation in the data within the stratigraphic framework, it can be concluded that this set of data appears to yield a relatively consistent pattern and that it is necessary to have a fairly large number of analyses in order to rely strictly on strontium-isotope data for age determination.

Strontium-isotope data collected from core W-16523 showed considerable scatter, but the overall trend for the stratigraphic units was similar to core W-16242. Sample K105.5 showed a very low $^{87}Sr/^{86}Sr$ ratio, which is the probable result of phosphorite contamination as previously described or the shell may be reworked. Sample K585.3 showed a very high 87Sr/86Sr ratio, which cannot be explained, but may be the result of sample contamination.

The strontium-isotope data from core W-17115 also show a relatively consistent stratigraphic pattern similar to the other cores. There is some scatter in the data in the lower part of the core with sample MI571 showing a higher than expected $^{87}Sr/^{86}Sr$ ratio. The lower stratigraphic section of core W-17115 was not extensively sampled because of a lack of acceptable material for strontium-isotope analysis.

Magnetostratigraphy

Introduction

Determination of magnetic polarity changes within sediment sequences is an accepted method of approximating the age of the sediments (Cande and Kent, 1992; Berggren et al., 1995a). However, the use of the magnetostratigraphy is not an independent method to determine age, especially when a stratigraphic section is divided by one or more disconformities. In this study, a number of biostratigraphic and chronostratigraphic methods were applied to assist magnetostratigraphic correlation to the Global Polarity Time Scale (GPTS) of Berggren et al. (1995).

Measurement of depositional remanent magnetization or early post-depositional remanent magnetization in carbonate sediments has been recently utilized to determine polarity changes (McNeill et al., 1988; McNeill, 1989). The Neogene sediments of the South Florida Platform present some interesting problems, because they contain both weakly magnetized carbonate sediments and detrital siliciclastic sediments containing a significantly stronger magnetic carrier.

TABLE 1.

$^{87}Sr/^{86}Sr$ MEASUREMENTS AND CALCULATED AGES OF SAMPLES
FROM CORES W-16242, W-16523, AND W-17115

Sample No.	Description	Depth (m)	$^{87}Sr/^{86}Sr$ Raw	Regression $^{87}Sr/^{86}Sr$	Age[1] (Ma)	Age[2] (Ma)	Age Range[3] (Ma)
Core W-16242							
M-5	Chione cancellata (bivalve)	21.03	0.709086	0.709077	1.81		2.37-1.25
M-6	Turritella sp.	23.77	0.709048	0.709039	2.45		3.01-1.89
M-7	Pecten	28.04	0.709041	0.709032	2.45		3.01-1.89
M-8	Chlamys eboreous	29.95	0.709022	0.709013	2.91		3.47-2.35
M-9	Chlamys eboreous	31.70	0.709049	0.70904	...**		4.92-2.61
M-10	Belanus sp.	33.04	0.709015	0.709006	...**		4.92-2.61
M-11	Pecten	35.36	0.709064	0.709055	...**		4.92-2.61
M-12	Pecten	36.91	0.709025	0.709016	...**		4.92-2.61
M-13	Hyotissa	43.98	0.708874	0.708865	10.49*		11.85-9.13
M-14	Hyotissa	44.58	0.708907	0.708898	9.23*		10.59-7.87
M-15	Hyotissa	47.24	0.708905	0.708894	9.38*		10.74-8.02
M-16	Pecten	49.12	0.709032	0.709023	...**		4.92-2.61
M-17	Pecten	50.29	0.709065	0.709056	...**		4.92-2.61
M-19	Oyster	57.04	0.709031	0.709022	...**		4.92-2.61
M-29	Pecten	74.07	0.70905	0.709041	...**		4.92-2.61
M-30	Pecten	78.09	0.70901	0.709001	...**		4.92-2.61
M-31	Pecten	88	0.70903	0.709021	...**		4.92-2.61
M-20	Oyster	88.7	0.708626	0.708617	17.5*	17.98	18.24-16.76
M-32	Oyster	89.21	0.70886	0.708851	10.9		12.26-9.54

TABLE 1.

$^{87}Sr/^{86}Sr$ MEASUREMENTS AND CALCULATED AGES OF SAMPLES FROM CORES W-16242, W-16523, AND W-17115

Sample No.	Description	Depth (m)	$^{87}Sr/^{86}Sr$ Raw	Regression $^{87}Sr/^{86}Sr$	Age^1(Ma)	Age^2(Ma)	Age Range^3 (Ma)
M-33	Oyster	106.22	0.70878	0.708771	13.8	15.7	15.16-12.44
M-21	Oyster	113.33	0.708768	0.708759	14.3	17.5	15.66-12.94
M-22	Oyster	113.69	0.708746	0.708737	15.1	17.2	16.46-13.74
M-25	Oyster	118.57	0.708643	0.708634	17.3	21.7	18.04-16.56
M-27	Oyster	121.46	0.708752	0.708743	15.3	16.9	16.66-13.94
M-28	Oyster	126.49	0.708742	0.708733	15.3	16.9	16.66-13.94
M-34	Oyster	137.89	0.70864	0.708631	17.3	17.79	18.04-16.56
M-35	Pecten	162.92	0.70849	0.708481	19.8	19.95	20.54-19.06
M-36	Phosphorite nodule	166.42	0.70855	0.708541	18.8	19.12	19.54-18.06
M-37	Phosphorite crust	173.13	0.70846	0.708451	20.3	20.3	21.04-19.56
M-38	Mollusk	176.48	0.70834	0.708331	22.5	22.2	23.24-21.76
M-39	Pecten	190.23	0.70813	0.708121	25.2	25.7	25.94-24.46
M-40	Coral (altered)	192.02	0.70813	0.708121	25.2	25.7	25.94-24.46
M-41	Bivalve	202.69	0.70807	0.708061	26	26.7	26.74-25.26
M-42	Whole rock (forams)	207.87	0.70801	0.708001		28.3	29.61-26.99
W-16523							
K18	Oyster	5.49	0.70908	0.709071	1.89		2.45-1.33
K55	Oyster (thin walled)	16.76	0.70893	0.708921	...**		4.92-2.61

TABLE 1.

$^{87}Sr/^{86}Sr$ MEASUREMENTS AND CALCULATED AGES OF SAMPLES FROM CORES W-16242, W-16523, AND W-17115

Sample No.	Description	Depth (m)	$^{87}Sr/^{86}Sr$ Raw	Regression $^{87}Sr/^{86}Sr$	Age[1] (Ma)	Age[2] (Ma)	Age Range[3] (Ma)
K71.6	*Anomia* (bivalve)	21.82	0.70900	0.708991	---**		4.92-2.61
K105.5	Oyster	32.16	0.70868	0.708671	16.6	17.2	17.34-15.86
K148.5	Pecten	45.26	0.70884	0.708831	11.7	13.3	13.06-10.34
K193	Oyster	58.83	0.70885	0.708841	11.3	13.0	12.66-9.94
K206	Oyster	62.79	0.70852	0.708511	19.4	19.6	20.14-18.66
K252.1	Oyster	76.84	0.70857	0.708561	18.5	18.4	19.24-17.76
K301.9	Oyster	92.01	0.7085	0.708491	19.6	19.8	20.34-18.86
K397	Oyster	121.01	0.70856	0.708551	18.6	18.9	19.34-17.86
K443.2	Pecten	135.09	0.70859	0.708581	18.9	18.5	19.64-18.16
K492.1	*Plicula* (bivalve)	149.99	0.70844	0.708431	20.5	20.5	21.24-19.76
K553	Pecten	168.55	0.70828	0.708271	23.7	23.9	24.44-22.96
K585.3	Pecten	178.4	0.70873	0.708721	15.9	17.9	16.64-15.16
K623.6	*Hyotissa*	190.07	0.70813	0.708121	25.2	25.7	25.94-24.46
K664.5	Pecten	202.54	0.70812	0.708111	25.4	25.8	26.14-24.66
K708.2	Pecten	215.86	0.70805	0.708041	26.2	27.0	26.94-25.46
W-17115							
MI47.5	*Hyotissa*	14.48	0.70903	0.709021	---**		4.92-2.61
MI75.5	Oyster-thin wall	23.01	0.70903	0.709021	---**		4.92-2.61

TABLE 1.

^{87}Sr/^{86}Sr MEASUREMENTS AND CALCULATED AGES OF SAMPLES FROM CORES W-16242, W-16523, AND W-17115

Sample No.	Description	Depth (m)	^{87}Sr/^{86}Sr Raw	Regression ^{87}Sr/^{86}Sr	Age[1] (Ma)	Age[2] (Ma)	Age Range[2] (Ma)
MI111.1	Oyster thin-wall	33.86	0.70904	0.709031	...**		4.92-2.61
MI144.5	Pecten	43.89	0.70902	0.709011	...**		4.92-2.61
MI192	Bivalve	58.52	0.70889	0.708881	9.94		11.30-8.58
MI340	Oyster	103.63	0.70873	0.708721	15.7	16.5	17.06-14.34
MI389.3	Oyster	118.66	0.70871	0.708701	16.3	16.8	17.04-15.56
MI447	Bivalve	136.25	0.70872	0.708711	16.1	16.7	16.84-15.36
MI474.4	Oyster-thin wall	144.6	0.70857	0.708561	18.5	18.8	19.24-17.76
MI571	Pecten	174.04	0.70863	0.708621	17.5	17.9	18.24-16.76
MI623.3	Hyotissa	189.98	0.70852	0.708511	19.4	19.5	20.14-18.66

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[1] Age from Hodell, et al. (1991)
Corrected to time scale of Berggren, et al. (1995)

[2] Age from Oslick, et al. (1994)
Corrected to time scale of Berggren, et al. (1995b)

* Not plotted, obvious stratigraphic error

** On flat part of Hoddell curve

Laboratory Methods

Analytical procedures utilized in this investigation closely follow those described by McNeill et al. (1993). Detailed descriptions of the paleomagnetic measurement methods are given in Missimer (1997; 2000).

Magnetostratigraphy and Age Implications

Paleomagnetic polarity data are useful to refine and constrain the age of sediments when they can be correlated to the GPTS using other age-dating techniques, including strontium isotopes and microfossil assemblages. The magnetic polarities for core W-16242 in relationship to the core lithologic properties and other isotopic data are presented in Figure 3. In order to correlate the magnetic polarity data to the GPTS, the magnetic polarity data, strontium-isotope ages, and ranges of calcareous nannofossils for core W-16242 are presented in a graphic plot (Figure 3). Analyses of the magnetic polarity changes in the core are discussed for stratigraphic units, which include: 1) the Suwannee Limestone, 2) the Arcadia Formation, 3) the Peace River Formation, 4) the Tamiami Formation, 5) the Caloosahatchee Formation, and 6) the combined Fort Thompson Formation and Holocene.

DISCUSSION

Ages of Late Paleogene and Neogene Stratigraphic Units

Introduction

A unified chronostratigraphic analysis was performed on core W-16242 on sediments from the Suwannee Limestone to land surface (Figure 3). Then, other data on the same stratigraphic section were compiled from this and other geologic investigations on the South Florida Platform to synthesize the most current age constraints on the late Paleogene and Neogene sediments in Lee County. The age ranges of each of the formations investigated, including the Suwannee Limestone, the Hawthorn Group, the Tamiami Formation, and the Caloosahatchee Formation are given in Table 2. These new age ranges for each of the stratigraphic units are compared to past

TABLE 2. POSSIBLE AGES OF SELECTED NEOGENE AND LATE PALEOGENE FORMATIONS ON THE SOUTH FLORIDA PLATFORM

Formation	Estimated Age Range (Ma)
Suwannee Limestone	33.7(?) to 28.5
Arcadia Formation	26.6 to 12.4
Lower Peace River Formation	11(?) to 8.5
Upper Peace River Formation	5.23 to 4.29
Hawthorn Group	26.6 to 4.29
Pinecrest Member	3.22 to 2.15
Tamiami Formation	4.29 to 2.15
Caloosahatchee Formation	2.14 or 1.77 to 0.6

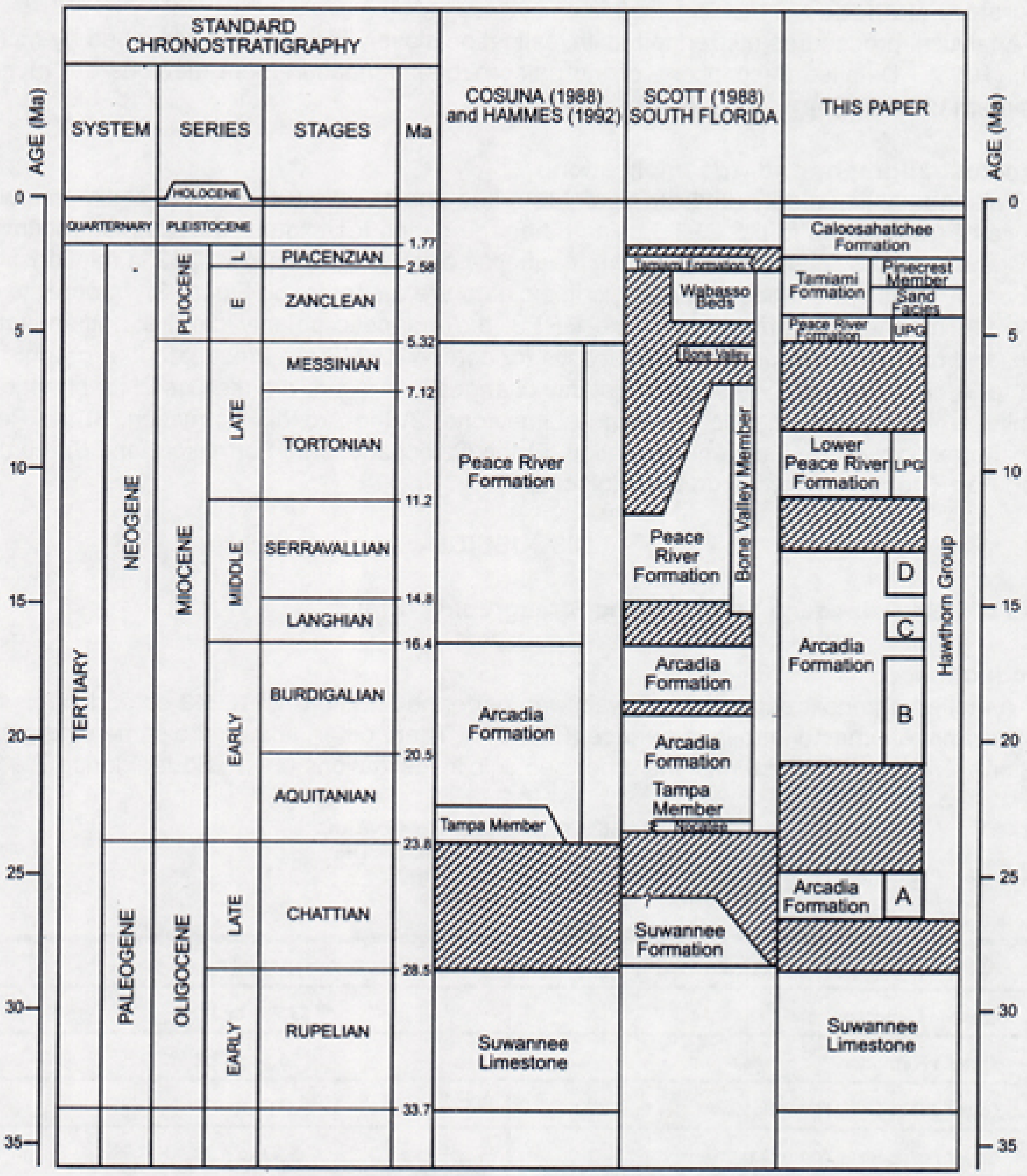

Figure 4. Unified chronostratigraphy of core W-16242 (Captiva Island). The ages of the Global Polarity Time Scale conform to Berggren et al. (1995).

age estimates and to the current geologic and paleontological time scales in Figure 4.

Suwannee Limestone

Only one strontium-isotope age determination was made on the Suwannee Limestone in core W-16242, but a large number of additional isotope age determinations were made on the Suwannee Limestone in several other cores located to the north of the this investigation (Hammes, 1992; Brewster-Wingard et al. 1997). Hammes (1992) concluded that the age of the

Suwannee Limestone ranged from 33.7 to 29.2 Ma (corrected to time scale of Berggren et al., 1995) and was confined strictly to the Rupelian Age of the early Oligocene. The strontium-isotope data point in core W-16242 was from a sample collected from near the top of the core. It produced an age of 29.5 to 26.8 Ma. The magnetostratigraphic analysis of core W-16242 showed a good correlation between the magnetic polarities and the GPTS. The top of the Suwannee Limestone has a normal polarity that is correlated to Chron C10n.1n, which has an age range from about 28.5 to 28.3 Ma. Since the full thickness of the Suwannee Limestone was not penetrated in core W-16242, it is not possible to constrain the basal age of the unit. Based on the data collected from core W-16242 and the large amount of data collected on the formation to the north, it is concluded that the Suwannee Limestone at this location has an estimated age range from 33.7 to 28.5 Ma and is restricted to the early Oligocene. The disconformity on top of the unit is believed to be the mid-Oligocene sea-level event, which constrains the upper age limit to 28.5 Ma. This analysis is in agreement with Hammes (1992), but differs from Brewster-Wingard et al. (1997), who believes the upper age range extends into the early Miocene.

Hawthorn Group-Arcadia Formation

A large number (31) of strontium-isotope age determinations were made on Arcadia Formation sediments in cores W-16242, W-16523, and W-17115. Also, many additional strontium-isotope age determinations were made on the Arcadia Formation in core W-10761 by Compton et al. (1993) and in other cores to the north by Brewster-Wingard et al. (1997). Most of the age determinations range from 26.8 to 13.1 Ma for the Arcadia Formation (all ages corrected to the time scale of Berggren et al. 1995). In the very middle of the platform, which occurs near the site of the Koreshan core (W-16523), some younger carbonate sediments were preserved in the section. At this location a single sequence, A1 in the core, was deposited on top of the middle Miocene disconformity as suggested by a carbon isotope shift at this location. The magnetostratigraphy of the Arcadia Formation is quite complex and subject to several interpretations within the constraints of the strontium-isotope ages. The base of the Arcadia Formation has a strontium-isotope age of about 26.6 to 25.3 Ma based on the data from core W-16242. The magneto-stratigraphic correlation to the GPTS indicates that the normal polarity unit at the base of the formation correlates to Chron C8n.2n, which has an age range of 26.6 to 26.0 Ma. The top of the formation correlates to Chron C5Ar, which has an age range of 12.8 to 12.4 Ma. Based on the strontium isotope data and the magnetostratigraphic data, the top of the Arcadia Formation at most locations has an age of about 12.4 Ma. It must be stated, however, that this surface is a major disconformity and is subject to rather extreme variation in erosional relief that could lead to a variable age at any location as shown in Guertin et al. (2000). Based on all of the data analyzed, the Arcadia Formation deposition began in the late Oligocene and terminated in the middle Miocene.

Hawthorn Group-Peace River Formation

The Peace River Formation is divided into two distinctively different stratigraphic units by a regional disconformity. The lower part of the formation is a relatively flat-bedded, predominantly siliciclastic unit with some carbonate sediment. The upper part of the formation is a mixed siliciclastic/carbonate, deltaic unit containing graded beds with topset, foreset geometries. Because of the differences in sediment facies, the presence of the disconformity, and inferred significant difference in age between the two units, they are discussed individually.

The age data on the lower Peace River Formation has been determined in a number of wells in Lee and Hendry counties by analysis of the calcareous nannofossil and planktonic foraminifera assemblage (Peck et al., 1979a; Peck et al., 1979b; Covington, 1992). A late

Miocene age was determined for the lower part of the Peace River Formation with the general age restricted to foraminiferal zones N18 and N17 or the solely N17 based on the age of the Discoaster quinqueramus Zone of Gartner (1969). The strontium-isotope data of core W-16242 yielded a single age determination of 11.8 to 9.3 Ma. Single strontium-isotope age determinations were made on the lower Peace River Formation in cores W-16523 and W-17115, which yielded ages of 13.1 to 10.3 Ma and 11.3 to 8.6 Ma, respectively. Compton et al. (1993) also obtained several age determinations in the 13.1 to 10.0 Ma range, particularly on phosphorite nodules in the lower part of the Peace River Formation. The lower Peace River section in core W-16242 is only about 3.5 m thick and is therefore either a condensed section or a small part of the full section. Paleomagnetic analysis of the lower Peace River Formation in core W-16242 showed that all samples yielded a reversed polarity. A quite tentative correlation of this section was made to the GPTS. It correlates to Chron C5r, which has an age range from about 11.9 to 10.9 Ma. Based on the data collected in this investigation and in previous investigations, the Peace River Formation has a probable age range from about 11 to 8.5 Ma, which is late Miocene. The older phosphorite nodules dated by Compton et al. (1993) are believed to be reworked from the erosion of the underlying Arcadia Formation or from erosion of the Peace River Formation to the north where it is older.

Past investigations of the foraminifera and calcareous nannofossils within the Upper Peace River Formation (defined at one time to be part of the Tamiami Formation) suggested that the formation ranges from late Miocene to early Pliocene in age (Peck et al., 1979a; Peck et al., 1979b; Covington, 1992). Strontium-isotope age determinations from core W-16242 all occurred on the flat part of the curve, yielding an age range of 4.9 to 2.6 Ma. Ages determined by Compton et al. (1993) for the Peace River Formation in core W-10761 are in the 5.7 to 4.9 Ma range. Because of the flattening in the seawater strontium-isotope curve, virtually all sediments having an age range of 4.9 to 2.6 Ma date about the same. The magnetostratigraphy of core W-16242 correlated to the GPTS produced some reasonably diagnostic age data for the Peace River Formation (Figure 3). The base of the core has a reversed polarity that corresponds to Chron C3n.4n, which has an age range of 5.2 to 5.0 Ma. The base of the Peace River Formation is constrained to this age range, but there is a very high probability that the age of the formation base is a maximum of 5.23 Ma. This conclusion is reached based on the assumption that the late Miocene (Messinian) global sea level event should create a hiatus at this age. The reversed polarity section at the top of the Peace River Formation corresponds to the Chron C3n.lr, which has an age range from 4.5 to 4.3 Ma. Therefore, the top of the formation is constrained to this age range, but it is believed that the actual age is probably about 4.4 Ma based on the probable rapid deposition of the deltaic facies and the age constraint provided by the overlying formation. The polarity changes measured in core W-16242 correlate well with the GPTS in this stratigraphic interval. It is concluded that the upper part of the Peace River Formation is early Pliocene in age with the absolute age ranging from about 5.23 to 4.29 Ma. The Miocene-Pliocene contact lies between the deltaic sediment sequence and the underlying flat-bedded mixed siliciclastic/carbonate sequence. The occurrence of coarse siliciclastic and phosphatic lag deposits commonly marks this boundary. A similar age was determined for this unit in Collier County by Edwards et al. (1998) and Weedman et al. (1999).

Tamiami Formation.

Age determinations on the Tamiami Formation in core W-16242 were made primarily by strontium-isotope analysis and magnetostratigraphic analysis. The formation is divided by a disconformity, which separates the Sand Facies from the overlying Pinecrest Member, using the terminology of Missimer (1992). Each of these units has a different age range and they are discussed separately.

All of the strontium-isotope samples collected from the lower part of the upper Peace River

Formation and the overlying Tamiami Formation yield approximately the same age, because of the flatting of the strontium-isotope curve and less stratigraphic resolution. The magnetic polarity of the Lower Tamiami Formation is predominantly reversed with the exception of a very thin interval in the middle of the section and another thin interval, about 1 m, in the lower part of the section. A significant part of the section was unlithified sand and friable sediment from which no good quality samples could be obtained. Based on all data obtained, the base of the Sand facies of the Tamiami Formation correlates to Chron C3n.ln and the top of the unit with Chron C2Ar. This correlation gives the Sand Facies Member of the Tamiami Formation an age range of about 4.3 to 3.0 Ma. In consideration of the disconformity at the top of the Sand Facies, the upper boundary is more likely at about 3.2 Ma and the lower boundary of the Pinecrest Member at about 3.0 Ma. This interpretation is not unique because of the uncertainty in the measurements within core W-16242. It is possible that less time is missing across the disconformity between the Pinecrest Member and Sand Facies Member. However, there is a significant change in faunal assemblage and mineralogy of the sediment at this point in the core from the occurrence of multiple species of abundant aragonitic shell above the disconformity to a much lower diversity of molds and casts with no aragonitic shell below it. This suggests a significant time lapse, which would be at least 0.3 m.y. based on this interpretation or as small as 70 k.y. based on correlation of each magnetic polarity change to the GPTS.

Three strontium-isotope analyses were made in the Pinecrest section. The age ranges for these analyses are from 3.4 to 2.0 Ma with the ages being in stratigraphic order. The two younger age determinations have a higher probability of being more accurate than the older age, because of a general flattening of the strontium-isotope curve from 4.9 to 2.6 Ma (Hoddell et al., 1990). Correlation of the magnetic polarity changes in core W-16242 to the GPTS using the strontium-isotope ages as guides was made. The lower part of the Pinecrest Member in core W-16242 has a normal polarity correlating to Chron C2An.ln. This corresponds to the upper part of the Gauss chron with an age range of 3.2 to 3.1 Ma. This normal polarity interval in the core could represent all of the C2An.ln chron or more likely represents only part of it. However, the age constraint on the base of the Pinecrest must be placed on the maximum age of 3.2 Ma. The age constraint on the upper boundary is more problematical, because there is a small gap in the polarity data with reversed polarity underlying it. The reversed polarity interval correlates to anomaly Chron C2r.2r, which has a time range of 2.581 to 2.15 Ma. This time increment is equivalent to the lower Matuyama Chron. If the interpreted correlation to the GPTS is assumed to be correct, the constraint on the upper boundary is about 2.15 Ma. Therefore, based on the available data from core W-16242, the Pinecrest Member of the Tamiami Formation in core W-16242 has an age range of 3.2 to 2.2 Ma (with consideration of the disconformities bounding the Pinecrest) the most probable range is 3 to 2 Ma. This age range correlates quite well to the ages determinations made for the Pinecrest Member in the Sarasota site to the north of the study area by Jones et al. (1991). Bender (1973) used the uranium/helium technique to determine the age of two corals from the Pinecrest Member. These corals produced ages of 4.24 and 3.69 Ma (corrected to time scale of Berggren et al., 1995). Akers (1974) determined that the age of the Pinecrest Member was Mid-Pliocene based on the concurrent occurrence of *Gephyrocapsa caribbeannica*, *Reticulofenestra pseudoumbilica*, and *Sphenolithus abies*, which have age ranges of younger than 3.6 Ma, 11.9 to 3.7 Ma, and 7(?) to 3.66 Ma, respectively. It has also been noted by Olsson (1964; 1968) that there is a distinctive relationship between the fauna of the Caloosahatchee Formation and the Pinecrest Member, which may be indicative of a relatively small time gap between deposition of the two units. Based on the proposed chronologic framework suggested, the time interval is less than 0.2 m.y., which is consistent with the faunal assemblage similarity. In conclusion, the age of the Pinecrest Member of the Tamiami Formation in core W-16242 correlates with the upper portions of the Tamiami Formation to the north. The older ages for the member as determined by Jones et al. (1991) would then correlate to the age of the underlying Sand Facies of the Tamiami Formation. Edwards et al. (1998) found that the Tamiami Formation in Collier County was early to late Pliocene in age.

Caloosahatchee Formation

Information was collected from core W-16242 on the age of the Caloosahatchee Formation. The strontium-isotope and magnetostratigraphic data show that the age is approximately from 2.14 or 1.77 to 0.6 Ma. This age range is considered to be uncertain because only one strontium-isotope age determination was made and the magnetostratigraphic data are not continuous to the base of the Caloosahatchee Formation in core W-16242. Further work will be required to better resolve the age of the Caloosahatchee Formation in core W-16242. Continued study of this core is merited, because the Caloosahatchee Formation is 11.3 m thick at this location. This thickness may represent one of the more complete stratigraphic sections for this unit in southern Florida.

The age of the Caloosahatchee Formation in southern Florida has been open to dispute for many years. Dall (1892) considered the formation to be Pliocene in age based on the ratio of extinct verses living species of mollusks. DuBar (1958; 1974) suggested the entire Caloosahatchee Formation was Pleistocene in age based on the presence of a fossil horse skull, Equus leidyi (Hay), which was found in the uppermost shell bed. Brooks (1968) and Conklin (1968) placed the Pliocene-Pleistocene boundary in the middle of the formation based on the reassignment of some specific lithologic members into the overlying Fort Thompson Formation and others into the Caloosahatchee Formation. Perkins (1969; 1977) used the mapping of discontinuity surfaces to separate the Pleistocene sediments of South Florida and his lowermost Pleistocene (Q1) surface occurred in the top of the Caloosahatchee Formation. Bender (1973) used the uranium/helium dating method to determine the age of some corals collected from the Caloosahatchee Formation. These ages were 1.97 and 1.88 Ma (corrected to time scale of Berggren et al., 1995). Unfortunately, the corals were not specifically located within the overall stratigraphic section of the formation, making it quite difficult to interpret the significance of the ages.

Based on the historic data collected on the formation, the recent data collected by Jones et al. (1991) from the Sarasota shell pits to the north of the study area, and the data from core W-16242, the Caloosahatchee Formation is late Pliocene to early Pleistocene in age. The formation is separated into several depositional sequences by regional disconformities, one of which is the Pliocene-Pleistocene boundary. This boundary lies at the base of Chron C2r in core W-16242 at a depth of 19.2 m below surface.

CONCLUSIONS

Strontium-isotope stratigraphy, magnetostratigraphy, carbon and oxygen isotope stratigraphy, foraminifera, calcareous nannofossils, and diatoms were collectively used to constrain the ages of the major lithostratigraphic formations lying from the Suwannee Limestone to land surface in Lee County, Florida. Although this investigation concerning the age of these units may be the most comprehensive to date, the detailed age ranges of the units cannot be uniformly applied over the entire platform or even all of the southern part of it. The geometry of the sediments within each formation and the spacing of time lines was affected by a number of factors, such as topography of the shelf at the beginning of each depositional episode, the rate of sedimentation as each depositional environment responded to changes in sea level, and the pattern of erosion during sea level low stands. All of these factors and others cause spatial variations in the chronostratigraphy of the stratigraphic sequences, as even locally observed in the variation between the three cores studied in detail. However, because the Florida Platform has a relatively flat, rather narrow geometry, major sea level events have caused platform-wide disconformities to develop that help constrain the ages of the formations to general ranges in time. Therefore, the deposition of units, such as the Arcadia Formation, on the southern part of the platform began at a given point in time and deposition of the same unit in the north-central part of the platform may not have occurred until later in time or may not have occurred at all. But the major lithostratigraghic units that can be correlated will have common age constraints within the framework of the global sea level cycles. The Suwannee Limestone was believed to have been deposited during the entire Oligocene. Through the work of Hammes (1992), and this work, it is now clear that deposition of the Suwannee Limestone is restricted to the early Oligocene.

Hawthorn Group deposition was restricted to the middle Miocene in the past. Based on the new chronostratigraphic data, it is concluded that deposition of the phosphatic sediments of the Hawthorn Group began in the late Oligocene and continued into the early Pliocene.

For many years, researchers on Florida geology believed that virtually no deposition occurred during Pliocene time. It is now verified that deposition of the upper Peace River Formation, all of the Tamiami Formation, and the lower part of the Caloosahatchee Formation, were deposited during Pliocene time.

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THE HYDROGEOLOGY OF LEE COUNTY, FLORIDA

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ABSTRACT

All three regional aquifer systems defined in Florida, the Floridan, Intermediate, and Surficial aquifer systems, occur beneath Lee County. There are more individual aquifers within these systems in the County than any other region of Florida. The Floridan Aquifer System is subdivided from the bottom to the top into the following aquifers: the Boulder Zone, the Avon Park Aquifer, the Ocala Aquifer, the Lower Suwannee Aquifer, the Upper Suwannee Aquifer, and the Lower Hawthorn Aquifer. The Intermediate Aquifer System contains three different aquifers, which are the lower zone of the Mid-Hawthorn Aquifer, the upper zone of the Mid-Hawthorn Aquifer, and the Sandstone Aquifer, that contains multiple production zones some of which could be defined as separate aquifers. The Surficial Aquifer System consists of the Lower Tamiami Aquifer and the water-table aquifer.

All of the aquifers occurring beneath Lee County have unique hydraulic properties. Many of these aquifers have high transmissivities and yield significant quantities of water. The aquifers with the highest current use are the Lower Hawthorn Aquifer (for reverse osmosis treatment to public supply and irrigation), the Sandstone Aquifer (for public supply and irrigation) and the water-table aquifer (for irrigation and public supply).

The geology, hydraulic characteristics, water quality, and potentiometric surface of each aquifer are summarized in this paper based on the current state of knowledge.

INTRODUCTION

The hydrogeology of Lee County is greatly influenced by its geographic position on the Florida Platform (Figure 1). It lies near the middle of the southern platform terminus, where the carbonate lithologic units are thick in the lower stratigraphic section and the siliciclastic units tend to separate the section into a generally larger number of mappable aquifers compared to other localities in Florida. All three of the regionally defined aquifer systems in Florida occur beneath Lee County. The terminology and aquifer definitions used in this paper conform to those adopted by the Southeastern Geological Society Ad Hoc Committee on Florida Hydrostratigraphic Unit Definition (Vecchioli and others, 1986) and Wedderburn et al. (1982).

Detailed investigation of the Lee County hydrogeology began in 1966 with the initial investigations conducted by Durward H. Boggess of the U. S. Geological Survey. A number of the fundamental problems related to the hydrogeology of the area were outlined in Boggess (1982). The initial aquifer names and general terminology used to describe the aquifer systems were first reported by Sproul et al. (1972). A series of hydrogeologic investigations conducted by the U. S. Geological Survey provided a framework and data base for hydrogeology of Lee County (Boggess, 1974a; Boggess, 1974b; Boggess and Missimer, 1975; Missimer and Boggess, 1974; Boggess and Missimer, 1975; Boggess et al., 1981; Boggess and O'Donnell, 1982; Boggess and Watkins, 1986). Wedderburn et al. (1982) published the first summary document on the hydrogeology of Lee County. Two consultants reports built upon the data base established by the U.S. Geological Survey and South Florida Water Management District for the purpose of groundwater resource development and management (Hole-Montes and Associates, Inc., 1981, and Montgomery Consulting Engineers, Inc., 1988). A very detailed investigation of the hydrogeology of Lee County was completed for the purpose of developing a raw water sup-

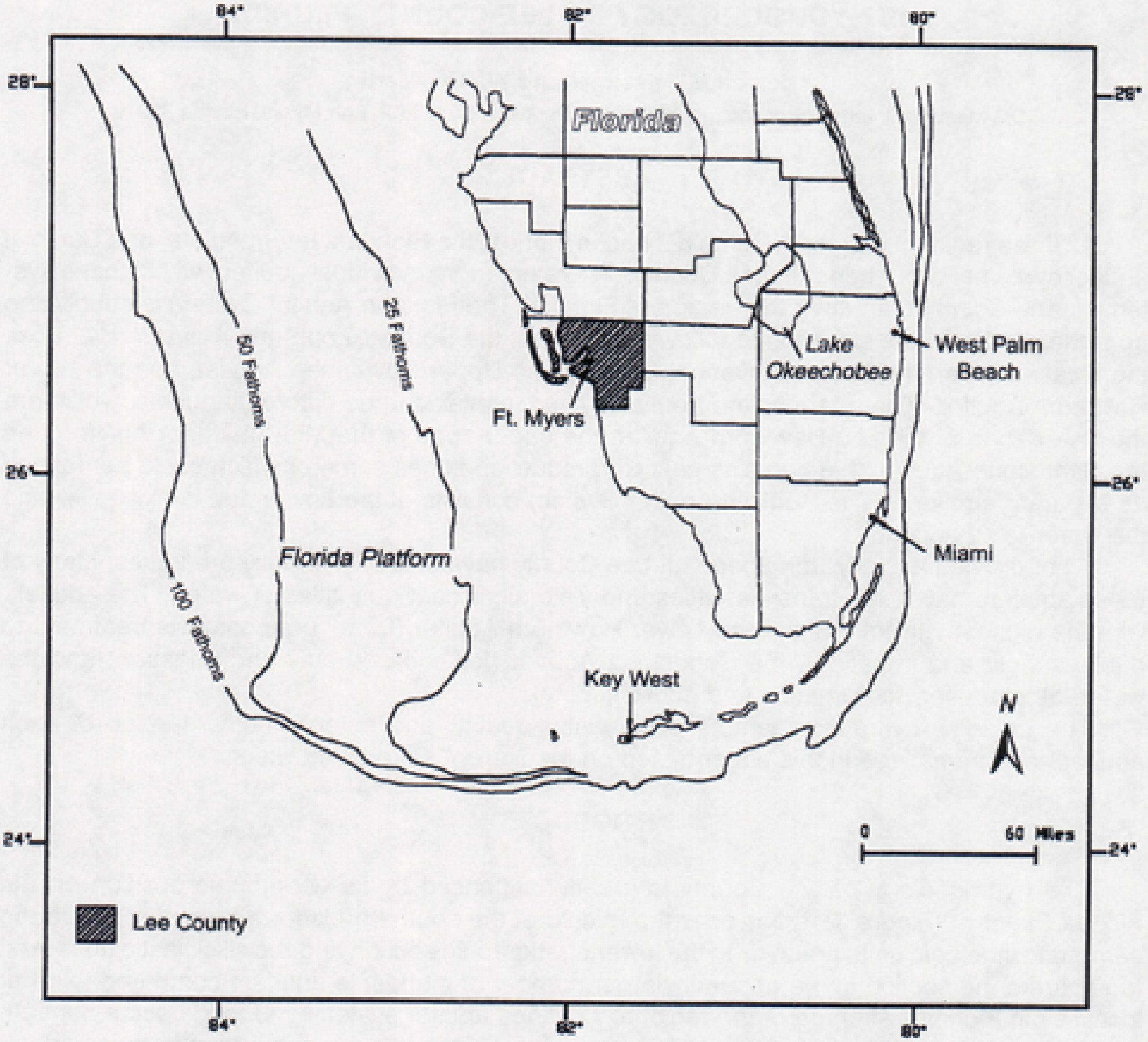

Figure 1. Map of Lee County showing the geographic locations discussed in the text.

ply plan of the area (Camp Dresser & McKee Inc./ViroGroup, Inc., 1993). The information contained in this report is the most comprehensive hydrogeologic data base compiled to date on Lee County and many of these data are used in this paper.

The hydrogeology of Lee County is very complex and there are many unanswered questions with regard to the horizontal connections between specific water-bearing zones. There is an overall pattern of lithologic unit pinch-outs from north to south that cause some aquifers to pinch out and others to merge into a single zone. These problems will be discussed in this text, but exact interpretations cannot be made based on the current data base.

GEOLOGIC FRAMEWORK AND AQUIFER NAMES

Sediments that contain sufficient hydraulic conductivity to provide some economic use for either disposal of liquid waste or for water supply occur above the top of the Paleocene-aged Cedar Keys Formation (Figure 2). The Cedar Keys Formation is predominantly an anhydrite

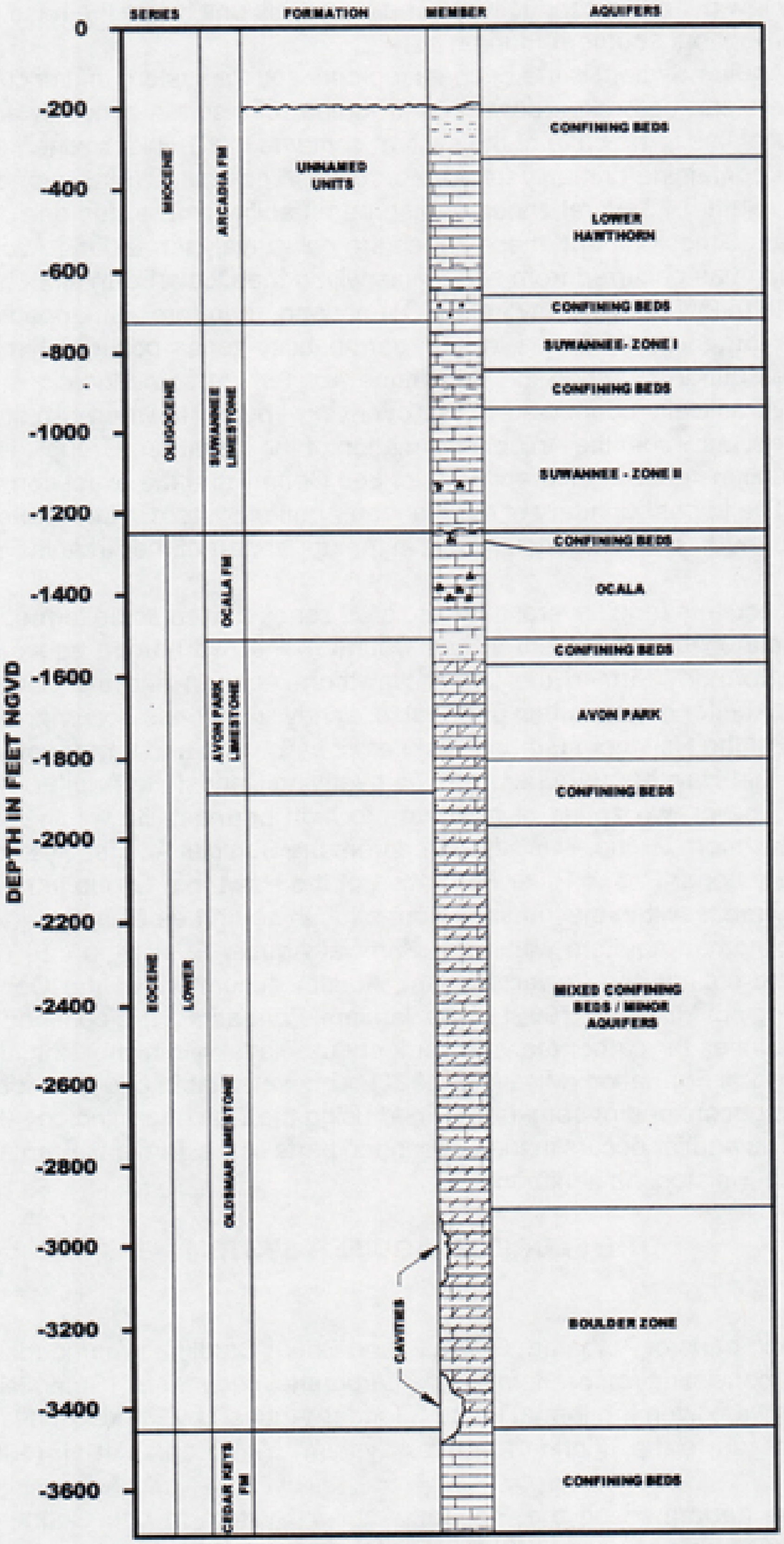

Figure 2. Generalized stratigraphic column showing the locations of the aquifers underlying Lee County, Florida.

unit, having a very low hydraulic conductivity. The top of this unit forms the base on the Floridan Aquifer System throughout southern Florida.

The Floridan Aquifer System is the deepest regional aquifer system that occurs beneath Lee County. The system can be broken down into a number of discrete zones or aquifers that are significant in terms of use. The base of the system contains the "boulder zone", which is a highly permeable zone containing primarily fracture porosity in dolomites (Maliva and Walker, 1998; Maliva et al., this volume). Several zones of high permeability limestones and dolomites occur within the Avon Park Limestone and these zones are collectively termed the Avon Park Aquifer. Localized production has occurred from sediments within the Ocala Formation, but the unit normally has moderate to low permeability in Lee County and, therefore, a mappable aquifer is not defined within this formation. A series of high-permeability zones occur within the Suwannee Limestone and the aquifer is termed the Suwannee Aquifer. At some locations the Suwannee Aquifer may be hydraulically connected to the overlying Lower Hawthorn Aquifer. The Lower Hawthorn Aquifer occurs within the Arcadia Formation of the Hawthorn Group. The aquifer contains several production zones in different parts of Lee County and the exact correlations are not currently defined. The upper boundary of the Floridan Aquifer System in Lee County occurs within mixed carbonate muds and terrigenous clays in the upper part of the Arcadia Formation of the Hawthorn Group.

There are two aquifers (and several other isolated zones that could be termed aquifers) lying within the Intermediate Aquifer System in Lee County. The two named aquifers are the Mid-Hawthorn Aquifer (formerly termed the Upper Hawthorn Aquifer) and the Sandstone Aquifer. The Mid-Hawthorn Aquifer occurs within permeable, sandy limestones occurring at the top of the Arcadia Formation of the Hawthorn Group. A series of carbonate and terrigenous clay confining beds separate the Mid-Hawthorn Aquifer from the overlying Sandstone Aquifer. The Sandstone Aquifer occurs as one or two zones of moderate to high permeability within the Peace River Formation of the Hawthorn Group. It is separated from the Surficial Aquifer System by clays and lime muds within the upper Peace River Formation of the Hawthorn Group in north and central Lee County and by muds within the Tamiami Formation in south Lee County.

There are two named aquifers within the Surficial Aquifer System in Lee County. In the southern part of the county, the Lower Tamiami Aquifer occurs within the Ochopee Member (using the terminology of Missimer, 1992) of the Tamiami Formation. It is confined from the overlying water-table aquifer by carbonate and terrigenous clays within the Bonita Springs Marl Member of the Tamiami Formation (Missimer, 1992). The water-table aquifer underlies nearly all of Lee County. It is unconfined or semi-unconfined using the Dutch terminology (Kruseman and DeRidder, 1970). The aquifer occurs in the unconfined parts of the Tamiami Formation and in the undifferentiated Plio-Pleistocene sediments.

THE FLORIDAN AQUIFER SYSTEM

Introduction

All of Florida and parts of Alabama, Georgia, and South Carolina are underlain by a regional aquifer system consisting of predominately carbonate sediments (Stringfield, 1966). In Florida, this aquifer was given the formal name "Floridan Aquifer" by Parker et al. (1955) and the name was later revised to the "Floridan Aquifer System" by Vecchioli et al. (1986) and Miller (1986).

Little work was performed on the Floridan Aquifer System in Lee County before 1974, because the data base was not good and the aquifer was not considered to be a viable source of water supply based on the treatment technology available at that time. The first published investigation on the Floridan Aquifer System in Lee County was Boggess (1974). Much of the compiled data on the Floridan Aquifer System of Lee County used in this paper comes from Camp Dresser & McKee Inc./ViroGroup, Inc. (1993). This data base was developed for the Lee County Regional Water Supply Authority as part of an area-wide groundwater management plan.

General Aquifer Framework

Lower Confining Beds

The base of the Floridan Aquifer System in Lee County is the top of the Paleocene-aged Cedar Keys Formation. This stratigraphic unit is primarily an anhydrite that is essentially impervious. It occurs at depths ranging from about 2,800 to 3,200 ft (853 to 975 m) below surface depending on the location.

High Permeability Zones within the Oldsmar Formation

The Oldsmar Formation is an early Eocene-aged unit that contains a series of bedded and interbedded limestones and dolomites. Both the limestones and dolomites tend to be fractured to some degree, but the fractures in the limestones are infilled with secondary cements and they do not usually have high permeabilities. Where the dolomites are highly fractured, zones of extremely high hydraulic conductivity occur, commonly called the "boulder zone" (Maliva and Walker, 1998; Maliva, et al., this volume). During well drilling the fractured zones tend to be mined and large parts of rock must be dredged from the wells, thereby, the analogy to boulders was coined. The porosity within the zones of high hydraulic conductivity is primarily fracture porosity and not dissolution or karst porosity. Although the zones of high hydraulic conductivity can occur at almost any depth interval within the formation, there is a greater probability for the zones to occur in the lower third of the formation. At the Sanibel Island injection well site, the zone of high hydraulic conductivity was a single interval at the very base of the formation, but at other locations, such as Fort Myers Beach, North Fort Myers, and Burnt Store Road, at least two zones of high hydraulic conductivity occur within a relatively low hydraulic conductivity interval in the middle of the formation.

The "boulder zone" has estimated transmissivities ranging from 1 to 20 million gpd/ft (12,400 to 248,000 m2/day). The boulder zone contains seawater and is used only for the disposal of treated, liquid wastes, such as treated domestic wastewater and the concentrate from desalination plants. The boulder zone is separated or confined from overlying high hydraulic conductivity zones within the Avon Park Formation by laterally continuous beds of fine-grained limestone or dolomite having low hydraulic conductivities (Maliva and Walker, 2000).

AVON PARK AQUIFER

Definition

There are several zones within the Avon Park Formation that contain high hydraulic conductivity. The porosity in these zones is primarily secondary dissolution porosity and not fracture porosity. Not much testing has been performed on this aquifer in Lee County, because it contains water with salinities ranging up to normal seawater with corresponding dissolved chloride concentrations of up to 19,000 mg/l. The most extensive testing of the Avon Park Aquifer occurred in the City of Cape Coral (Missimer & Associates, Inc., 1991), at a test site on Sanibel Island, a test well on North Pine Island, a test well near the Southwest Regional Airport off Daniels Parkway, and the injection well sites (Missimer & Associates, Inc., 1981c; 1982; 1986).

Hydraulic Properties

There is a large variation in the hydraulic conductivity of the various water-producing zones within the Avon Park Limestone that comprise the Avon Park Aquifer. Within deep injection wells and in areas to the northwest of Lake Okeechobee and in west-central Florida, the Avon Park Aquifer has transmissivities ranging from 500,000 to 4,000,000 gpd/ft (6,200 to 50,000 m/2day). However, no long-term aquifer performance test has been conducted on this aquifer in Lee County.

Water Quality

Water quality data has been obtained from a number of localities within the Avon Park Aquifer in Lee County. The most complete data sets are from the deep injection well sites at Burnt Store Road (near the Lee-Charlotte county line) (ViroGroup, Inc., 1995), the North Fort Myers Utilities site (Post, Buckley, Schuh & Jernigan, Inc., 1988), Fort Myers Beach Wastewater Plant (CH2M-Hill, Inc., 1999), and the Island Water Association site (Missimer International, Inc., 2000). Water quality at the very top of the aquifer improves with distance to the east away from the present shoreline. At Sanibel Island, the dissolved chloride concentration at the top of the aquifer is about 16,000 mg/l. This concentration reduces to 10,000 mg/l at Cape Coral (well LM-3509 (Missimer and Associates, Inc., 1991) and to about 4,000 mg/l near the Southwest Regional Airport (Missimer & Associates, Inc., 1981b). The water quality becomes more saline with depth at each of the injection well sites. Chloride concentrations of nearly 19,000 mg/l occur at each site at the base of the aquifer.

OCALA FORMATION AQUIFER

Definition

A series of grainstones and packstones within the Ocala Formation yield some water at various locations underlying Lee County. This formation contains sediments with hydraulic conductivities less than the bounding aquifers and there appears to be no laterally continuous aquifer within the formation. However, wells were drilled into this unit in the past and some irrigation water was developed for use. The top of the formation was mapped by Mobil Oil Corporation as part of a shallow structure-mapping project conducted between 1966 to 1968. Some water quality and minor hydraulic data were obtained from the formation during that time. The most extensive testing of the unit was conducted at the City of Cape Coral (Missimer & Associates, Inc., 1991) and additional hydrogeologic investigations were conducted at several other sites in Lee County (Missimer & Associates, Inc., 1981a; 1981b; 1982). Water quality data were obtained from this unit at each of the deep injection well sites previously referenced. The top of the aquifer occurs at depths ranging from 1,000 to 1,350 ft (305 to 412 m) below sea level depending on specific location.

Hydraulic Properties

The hydraulic properties of the Ocala "Aquifer" have been estimated from the hydrologic investigations conducted on the unit in Lee County. Missimer & Associates, Inc. (1991) calculated transmissivities ranging from 2,000 to 30,000 gpd/ft (25 to 370 m2/day) with an average value of 10,000 gpd/ft (125 m2/day) where the aquifer was productive. For modeling purposes, they used a transmissivity of 10,000 gpd/ft (125 m2/day), a storativity of 1 x 10-5, and a leakance of 5 x 10-4 gpd/ft3 (3.74 x 10-3 1/days). In the Lee County Regional Water Supply Model, an average hydraulic conductivity of 50 gpd/ft2 (2 m/day) was used for this aquifer (Camp Dresser & McKee Inc./ViroGroup, Inc., 1993). In this model, the leakance from the Avon Park Aquifer underlying it was estimated to be 0.001 gpd/ft3 (0.00748 1/days).

Water Quality

Water quality within the Ocala Aquifer varies greatly in Lee County. There is a distinct trend in water quality within the aquifer from chloride concentrations at or slightly above 19,000 mg/l (approximate seawater) near the coast to 1000 mg/l within the interior of the County (Figure 3). Some early farmers reported that deep wells within the Ocala Aquifer yielded nearly potable quality water in the late 1940's or early 1950's. Some U.S. Geological Survey data suggest that the quality of water in the aquifer could have been nearly potable at a few locations in the County, but the use of the water removed the low salinity water over time (replaced by vertical water leaked from below).

SUWANNEE AQUIFER SYSTEM

Definition

The Suwannee Aquifer System consists of a lower and an upper unit. The lower unit lies solely within the Suwannee Limestone and is confined from the upper unit by low permeability beds of clayey limestone or a "stiff" terrigeneous clay (i.e. Sanibel Island). The upper unit of the Suwannee Aquifer System lies primarily within the Suwannee Limestone, but it is hydraulically connected to the Arcadia Formation at certain localities, such as Sanibel Island (Missimer and Associates, Inc., 1979a; 1979b; 1980a; 1981d).

Hydraulic Properties

Some investigation has been performed on the hydraulic properties of the Suwannee Aquifer System, particularly in western Lee County, where it has a direct influence on water quality in the overlying part of the aquifer system. The lower part of the Suwannee Aquifer System has an estimated hydraulic conductivity of about 175 gpd/ft2 (7 m/day) and a thickness of 80 to about 205 ft (24.4 to 62.5 m) (Figure 4), which yields transmissivity values ranging from about 14,000 to 36,000 gpd/ft (174 to 447 m2/day). The transmissivity of the upper part of the Suwannee Aquifer System has a transmissivity range from 30,000 to 70,000 gpf/ft (372 to 868 m2/day) (Figure 5). Most of the transmissivity data are based on aquifer thickness data combined with measured hydraulic conductivities. This range of values is consistent with the measured specific capacities of wells tapping this zone and from a few aquifer stem tests conducted during testing for deep injection wells or aquifer storage and recovery projects. A very low transmissivity value for this part of the aquifer system, at about 5,000 gpd/ft (2.5 m2/day), was found at the Lee County North Water Treatment Plant site in northwest Lee County (Fitzpatrick, 1986). Because of the geologic changes from western to eastern Lee County, there is considerable uncertainty in the estimated transmissivity values shown in Figure 5 for all of eastern Lee County.

Based on limited aquifer performance test data and some reasonable estimates, the storativity of the lower aquifer is near 0.0001 and the upper aquifer has a range from 0.00007 to 0.0005. The estimated leakance between the underlying Ocala Aquifer and the lower Suwannee Aquifer is about 0.0005 gpd/ft3 (0.00374 1/days) and the leakance between the two Suwannee aquifers is estimated to be about 0.001 gpd/ft3 (0.00748 1/days) (Camp Dresser & McKee Inc./ViroGroup, Inc., 1993).

Water Quality

Water quality in the lower Suwannee Aquifer ranges from near seawater adjacent to the coast to slightly brackish in the up-gradient or northeast direction. Normal seawater in this region of the Gulf of Mexico has a dissolved chloride concentration of about 19,000 mg/l. Within the lower part of the aquifer system, measured chloride concentrations range from slightly under 1,000 to 13,000 mg/l (Figure 6). The water quality in the upper Suwannee aquifer is generally

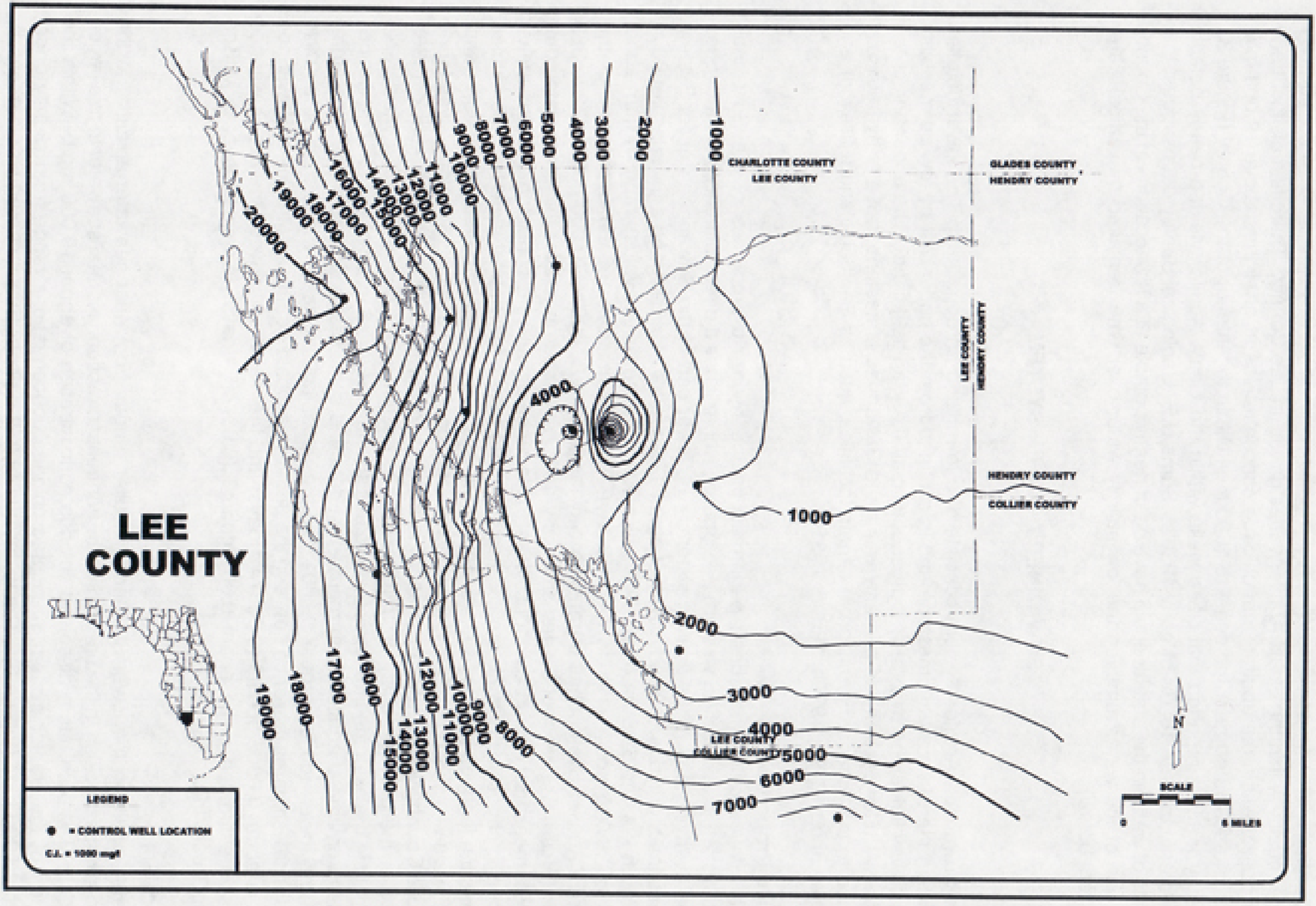

Figure 3. Dissolved chloride concentrations in the Ocala Aquifer (modified from Camp Dresser & McKee Inc./ViroGroup, Inc., 1993).

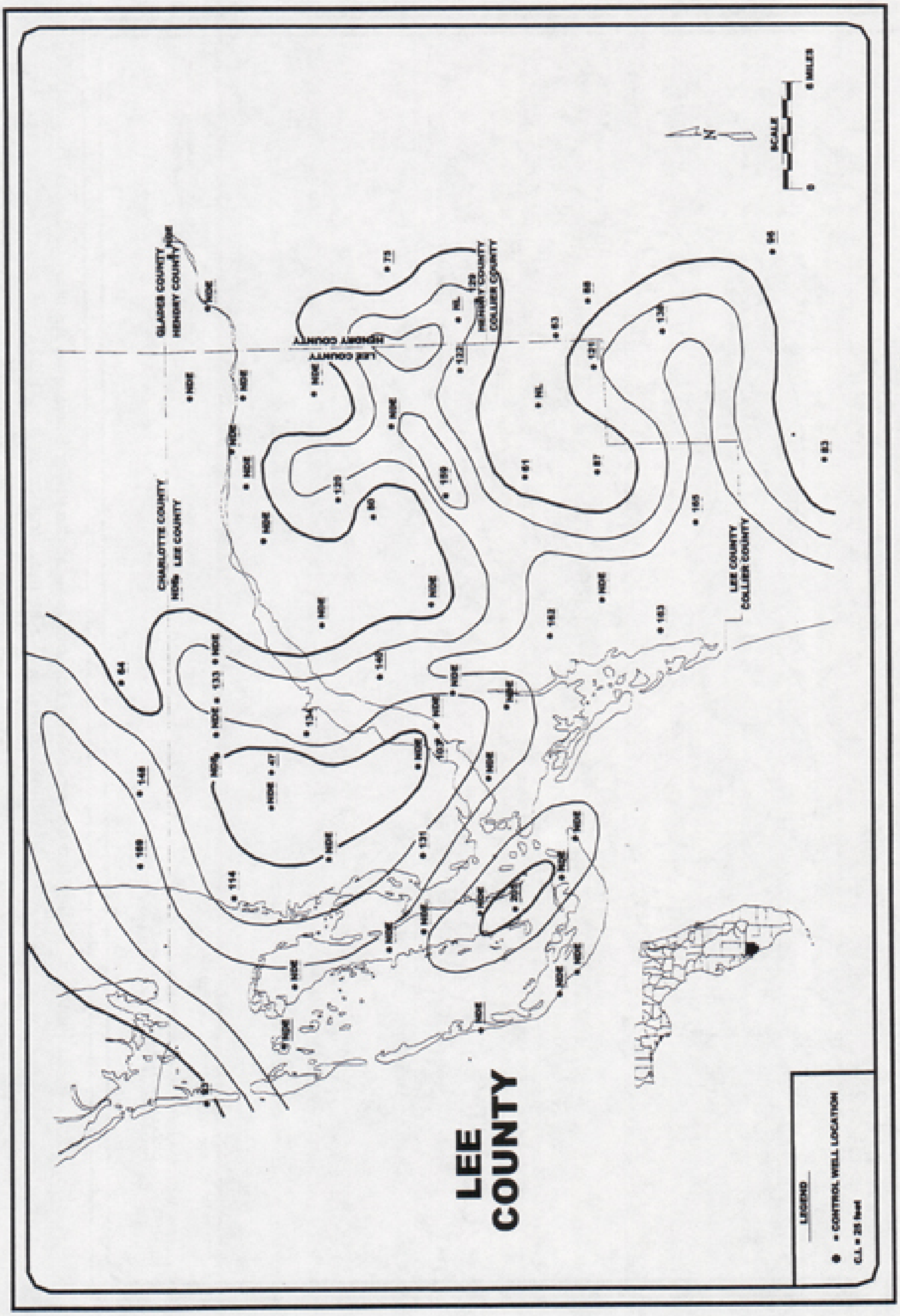

Figure 4. Thickness contour map of the lower Suwannee Aquifer (modified from Camp Dresser & McKee Inc./ViroGroup, Inc., 1993).

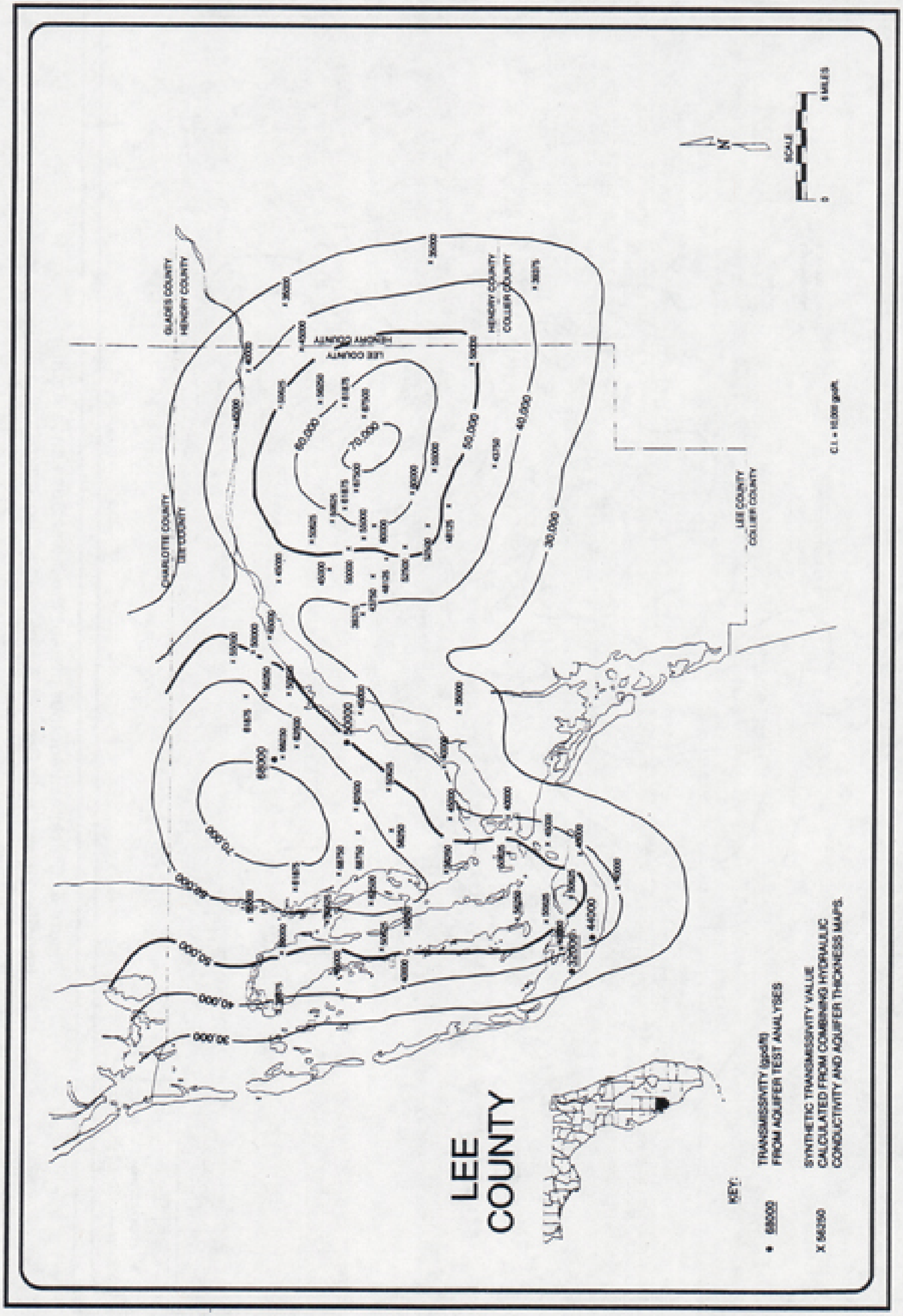

Figure 5. Estimated transmissivity contour map of the lower Suwannee Aquifer (modified from Camp Dresser & McKee Inc./ViroGroup, Inc., 1993).

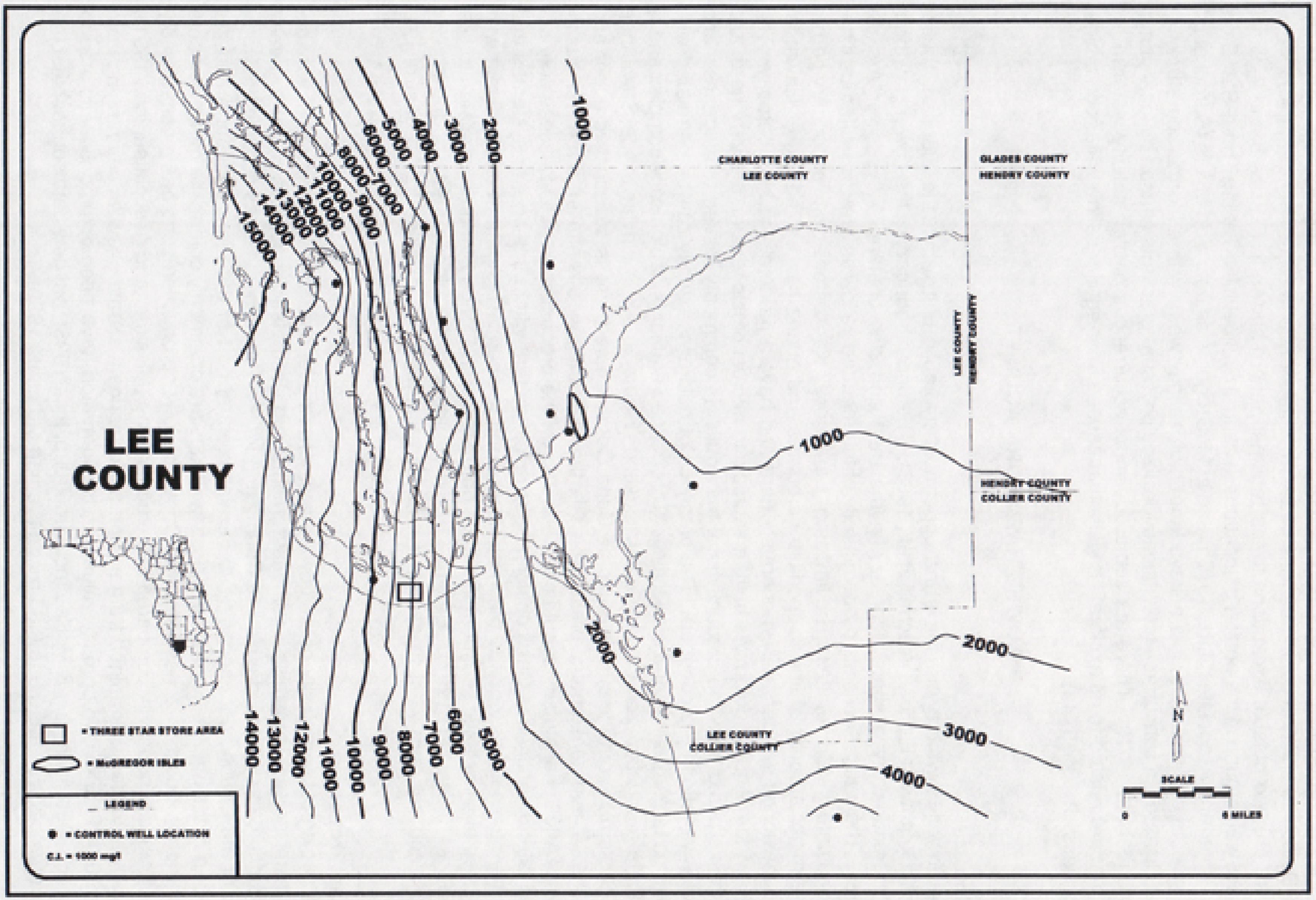

Figure 6. Dissolved chloride concentrations in the lower Suwannee Aquifer (modified from Camp Dresser & McKee Inc./ViroGroup, Inc., 1993).

less saline compared to the lower part of the aquifer, particularly in the western part of the County. Dissolved chloride concentrations range from about 800 to 5,000 mg/l (Figure 7).

There are two notable exceptions to the regional pattern shown in Figures 6 and 7, which are the seawater found in the aquifer at locations in central Sanibel Island at the Three-Star Store site (Missimer and Associates, Inc., 1979b) and at McGregor Isles near Fort Myers (Sproul et al., 1972). At both of these sites, it is believed that high salinity water with a high temperature has migrated upward via subsurface faults along localized pressure gradients caused by local pumping (Sproul et al., 1972). There are some additional occurrences of high salinity water in the aquifer that are related to oil exploration wells that caused inter-aquifer saline water contamination (Boggess, 1968; 1974a).

LOWER HAWTHORN AQUIFER

Definition

The Lower Hawthorn Aquifer is the uppermost hydraulic unit within the Floridan Aquifer System in Southwest Florida (Veccholi et al., 1986). The upper boundary of the Lower Hawthorn Aquifer is marked by a sharp decrease in the marl and clay content in the lower Arcadia Formation. The aquifer consists predominantly of interbedded yellowish-gray, fossiliferous limestones and pale olive dolomites. The limestones are mostly wackestones with secondary porosity and a minor amount of fine to medium carbonate and quartz sand. The Lower Hawthorn Aquifer limestones are generally moderately hard and have a moderate to high porosity. The Lower Hawthorn Aquifer dolomites have a sucrosic to microsucrosic texture, are very hard, and have variable porosities. The productivity of the aquifer is commonly related to diagenesis and small scale variations are common. The presence of dolomites usually can be correlated with areas of high transmissivity and productivity. This defined aquifer is geologically complex and is not a single production zone at any given location (Figure 8). It is similar to the Suwannee Aquifer System in some locations, such as Cape Coral, where there is a distinctive upper and lower zone. The potentiometric pressure within the different zones is similar, but water quality does vary. Additional studies should be conducted on the production zones to assess connectivity and lateral continuity. One consistent geological pattern within this aquifer system is that the internal confinement tends to pinch out from north to south. This pattern is consistent with the episodes of siliciclastic sediment influence onto the South Florida Platform as related to sea level changes (Missimer, 1997). Because of the structure of the Florida Platform, the aquifer tends to pinch out from west to east and it is not present some 30 miles to the east of Lee County.

Hydraulic Properties

The geological complexity of the Lower Hawthorn Aquifer creates a high degree of variability in transmissivity. Transmissivity measurements and estimates range from 5,600 to nearly 80,000 gpd/ft (69 to 992 m2/day) in Lee County (Figure 9). The highest values occur in the western part of the County, corresponding to the very central part of the Florida Platform and the thickest part of the aquifer. These transmissivity values are commonly composite measurements of two or more production zones. In Cape Coral, the lower production zone has a considerably higher hydraulic conductivity compared to the upper zone (Missimer and Associates, Inc., 1991).

Storativity values determined from aquifer performance test data show values ranging from 0.0001 to 0.001. Effective porosity values for the formation have been commonly estimated to be about 0.2 (Camp Dresser & McKee Inc./ViroGroup, Inc., 1993), but new data suggest that the values are probably in the 0.3 to 0.35 range (Yamamoto et al., 1999).

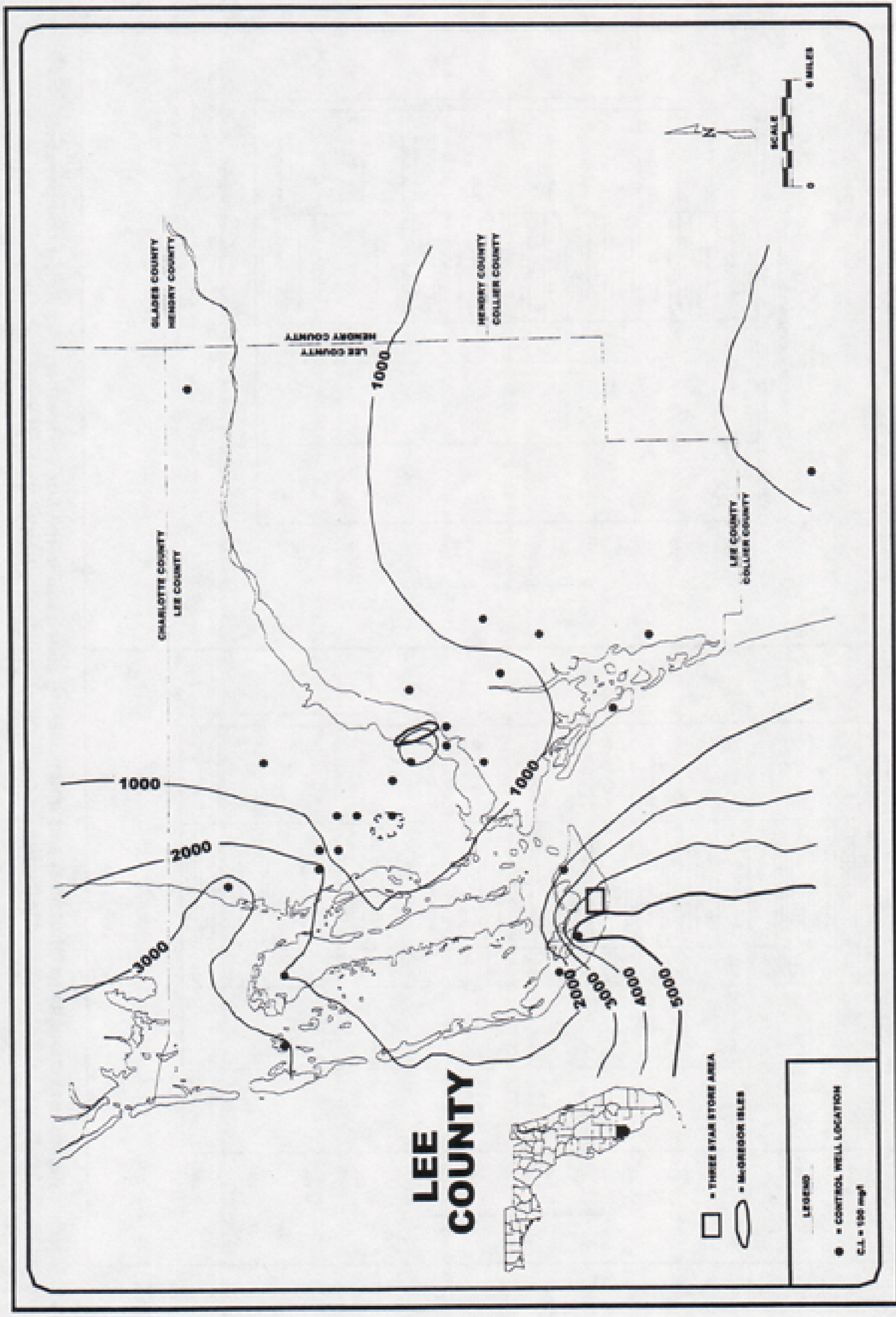

Figure 7. Dissolved chloride concentrations in the upper Suwannee Aquifer (modified from Camp Dresser & McKee Inc./ViroGroup, Inc., 1993).

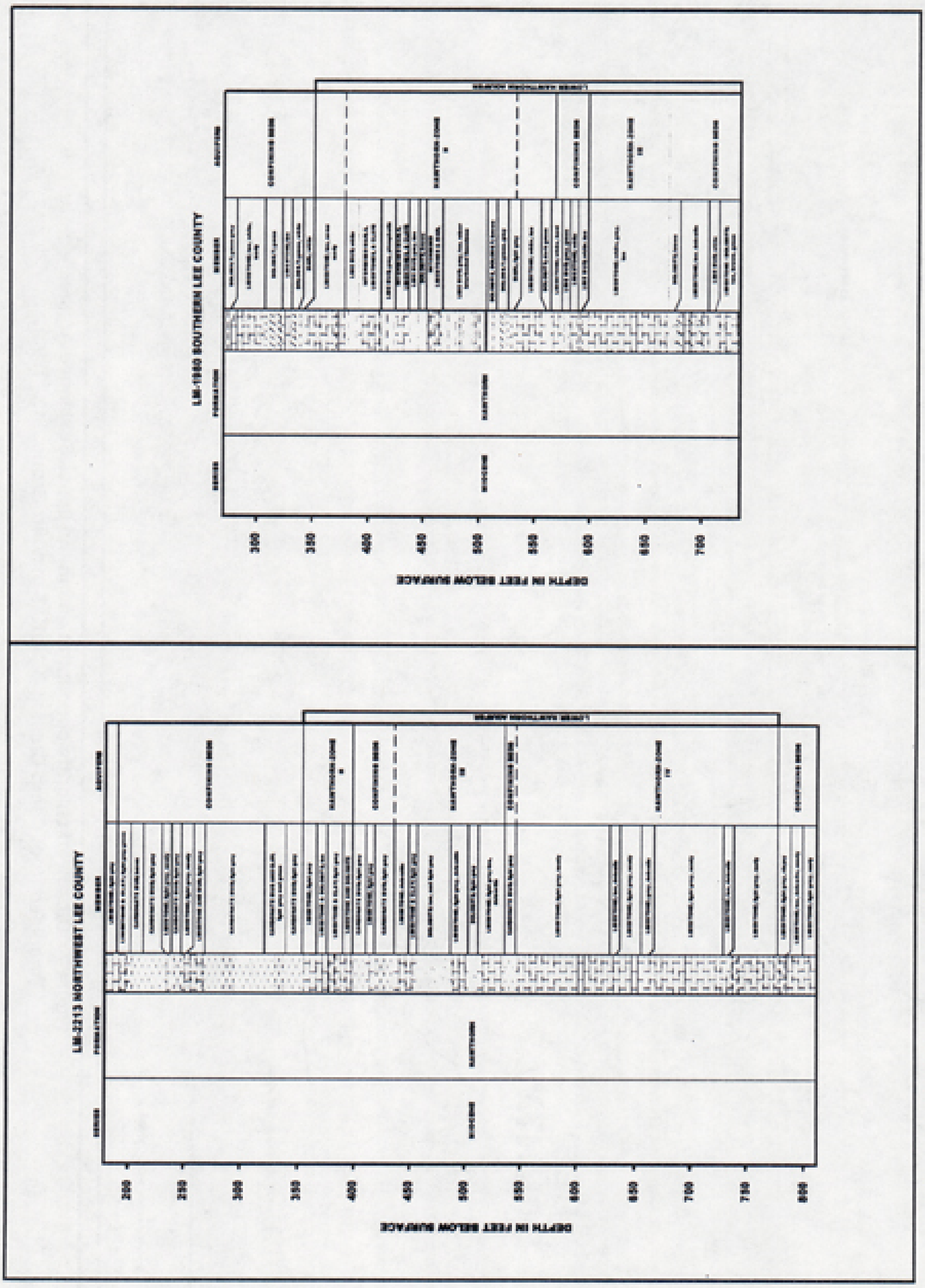

Figure 8. Variability in lithofacies and water-bearing zones within the Lower Hawthorn Aquifer, a comparison of the northern Cape Coral area to the Bonita Springs area.

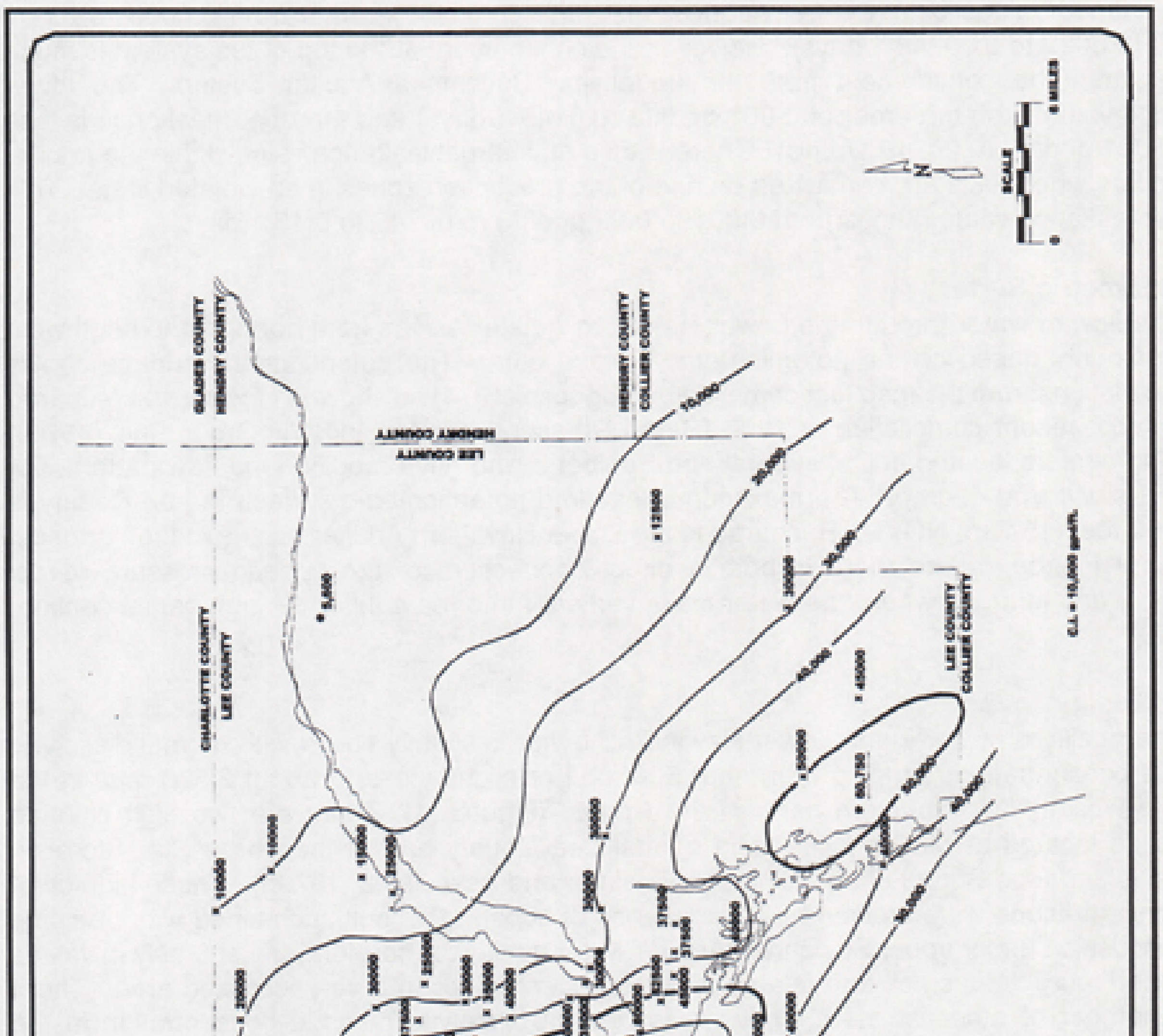

Figure 9. Transmissivity contour map of the Lower Hawthorn Aquifer (modified from Camp Dresser & McKee Inc./ViroGroup, Inc., 1993).

The leakance values obtained from aquifer test data commonly range from 0.0003 to 0.001 gpd/ft3 (0.0022 to 0.00748 1/days). However, the confinement at the top of the system is much greater than the confinement from the underlying Suwannee Aquifer System. The lower leakance value is on the order of 0.002 gpd/ft3 (0.0145 1/days) and the upper leakance is less than 0.001 gpd/ft3 (0.00748 1/days). There is also an internal leakance value within the aquifer that occurs when tests are conducted on one of the production zones in an isolated state. This internal leakance value ranges from 0.001 to 0.02 gpd/ft3 (0.00748 to 0.15 1/days).

Potentiometric Surface

The flow of water through the Lower Hawthorn Aquifer moves from northeast to southwest in Lee County based on the potentiometric surface data. The potentiometric surface shows some variations from the map first compiled by Boggess (1974) as shown in Figure 10 compared to the most recent compilation in 1990 (Camp Dresser & McKee Inc./ViroGroup, Inc., 1993). Pumping centers located in Cape Coral and Sanibel Island have modified the flow pattern, but not to a significant degree. The maximum measured potentiometric surface in Lee County is about 50 feet (15.2 m) NGVD. Recharge to the Lower Hawthorn Aquifer occurs to the northeast in central Florida, where there is both a direct connection to atmospheric pressure (direct recharge) and in areas where the water leaks vertically into the aquifer through partial confinement.

Water Quality

The quality of water in the Lower Hawthorn Aquifer is slightly saline with normal dissolved chloride concentrations ranging from near 500 mg/l or slightly less to about 2,500 mg/l in the extreme western and southern parts of the County (Figure 11). There are two high chloride anomalies located at McGregor Isles in central Lee County and at the Three Star Store on Sanibel Island (see Sproul et al., 1972 and Missimer and Associates, 1979b). These high chloride concentrations were caused by the presence of subsurface faults combined with pumping (see discussion under upper Suwannee Aquifer water quality). Therefore, the anomaly in values shown in Figure 11 is small and related only to concentrations in a very localized area. There are a number of other isolated, small areas of high dissolved chloride concentration in the aquifer. These point sources are the result of old oil test wells, improperly plugged and abandoned, that have allowed high salinity water to migrate upward into the aquifer. Only a few of these old well sites have been recorded. The water in the Lower Hawthorn Aquifer is a very good source for reverse osmosis treatment to produce drinking water.

UPPER CONFINING BEDS

A thick sequence of low hydraulic conductivity beds separates the Floridan Aquifer System from the Intermediate Aquifer System. There is a distinct change in potentiometric pressure and water quality from the top aquifer in the Floridan Aquifer System to the lowest unit in the Intermediate Aquifer System. In most cases, the confining bed thickness is over 200 feet and there is essentially no water movement between the two aquifer systems. However, there are some minor stratigraphic units within the confining beds that locally may yield some low salinity water. These units are not delineated, because they are quite local and do not occur in a regional setting.

THE INTERMEDIATE AQUIFER SYSTEM

The Intermediate Aquifer System was originally defined by Veccholi et al. (1986) to define a

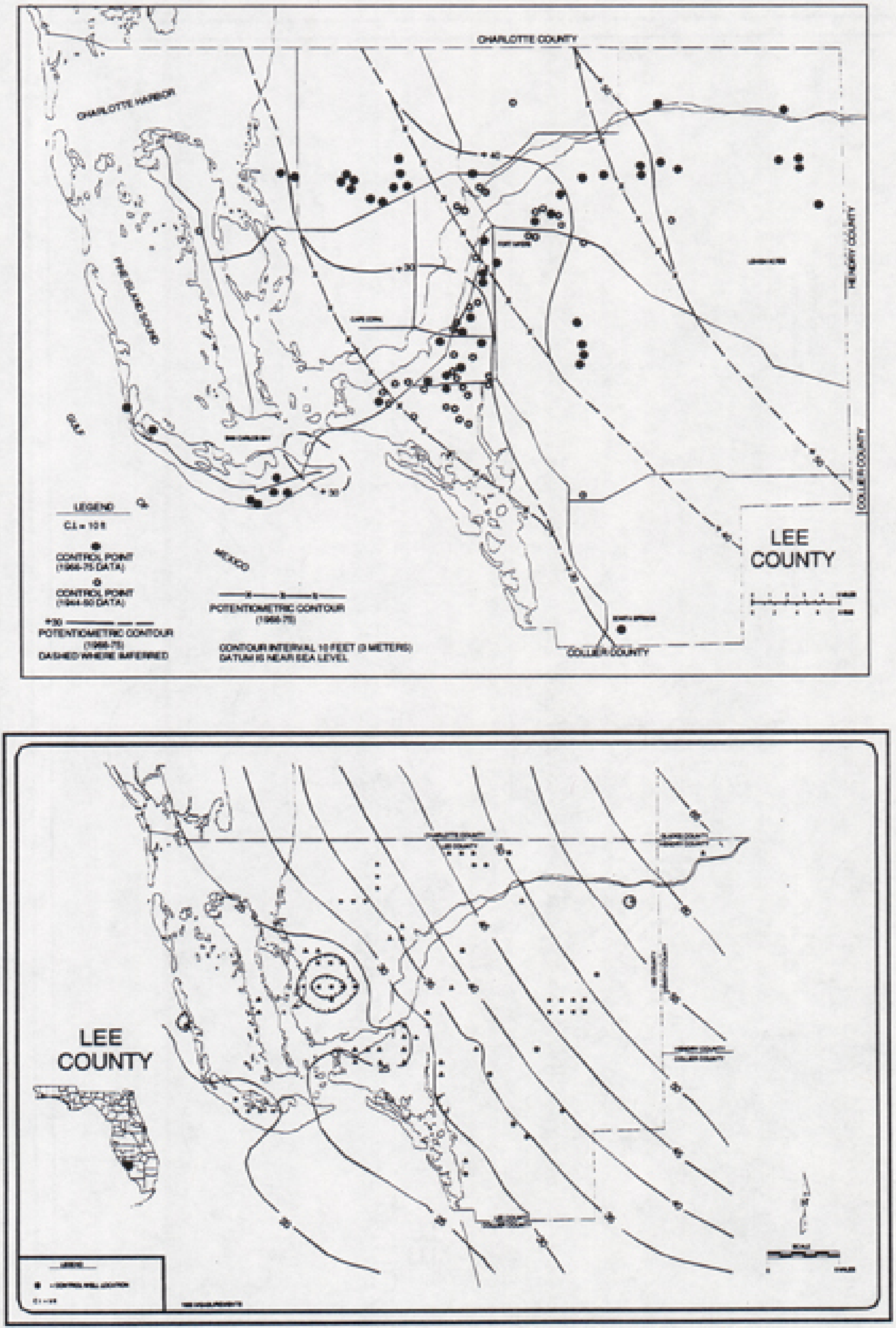

Figure 10. A comparison of the potentiometric surface of the Lower Hawthorn Aquifer from 1944-50 data (Boggess, 1974; 1990; Camp Dresser &McKee Inc./ViroGroup, Inc., 1993).

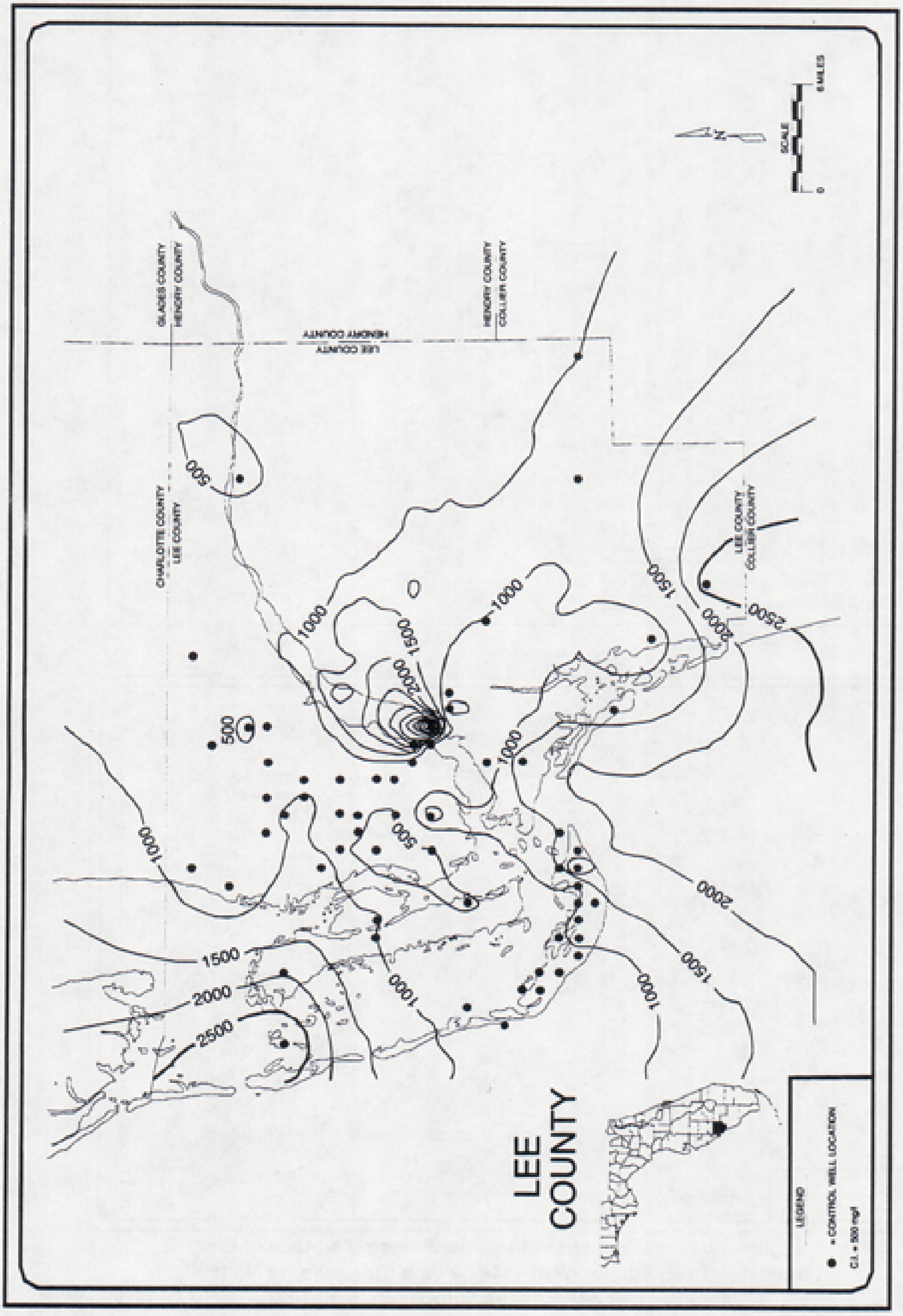

Figure 11. Dissolved chloride concentrations in the Lower Hawthorn Aquifer (Camp Dresser & McKee Inc./ViroGroup, Inc., 1993).

system of significant aquifers that occur within the confining beds between the Floridan and Surficial Aquifer systems. The Intermediate Aquifer System is best defined in southwestern Florida, where there are several complex regional aquifers that yield significant quantities of water for a variety of uses. Within Lee County, the aquifers contained within the Intermediate Aquifer System are geologically complex and are generally misunderstood. There are disagreements between various authors with regard to both geologic correlation of units and the hydraulic continuity of water-bearing zones. A northwest to southeast generalized cross-section of this aquifer system is given in Figure 12 to show our interpretation with regard to the hydraulic continuity and stratigraphic correlation of these units. The significant new features of this section are: 1) there are two different and distinct water-bearing zones within the Mid-Hawthorn Aquifer with unique potentiometric surfaces and water qualities, 2) the upper part of the Mid-Hawthorn Aquifer does not occur in south Lee County, 3) the confining beds between the Surficial Aquifer System and the Intermediate Aquifer System (the Cape Coral Clay Member of the Peace River Formation) pinch out from north to south near Estero in south Lee County, and 4) the Sandstone Aquifer becomes insignificant as an aquifer from north to south, where its remnants become hydraulically connected to the Lower Tamiami Aquifer of the Surficial Aquifer System.

MID-HAWTHORN AQUIFER

Definition

The Mid-Hawthorn Aquifer occurs within the upper part of the Arcadia Formation of the Hawthorn Group (Figure 2). Recent studies of the Mid-Hawthorn Aquifer show that it is much more complex than previously believed (Wedderburn et al.,1982). It contains two production zones that are hydraulically separated. The predominant lithologies within the aquifer are very light gray to pale olive limestones interbedded with thin layers of dolomite and quartz sand. All lithologies in the aquifer contain quartz sand, particularly in the upper part of the section. The limestones are mostly fine-grained sandy, wackestones cemented to variable degrees. The sandy limestones are moderately hard and have moderate to high porosity (both intergranular and moldic porosity). Sand-sized phosphate grains are present throughout the aquifer.

The lower part of the Mid-Hawthorn Aquifer occurs predominantly in the southern part of the County. The unit is a limestone with a relatively homogeneous internal lithology. Although the unit is believed to be within the Intermediate Aquifer System, the confinement between this unit and the underlying Lower Hawthorn Aquifer tends to pinch out somewhere to the south of Lee County in Collier County. This connection to the south causes the water quality to be saline within the aquifer and the flow gradient is reversed in the southern part of Lee County (potentiometric pressure increases from south to north). An attempt made to map this unit by Camp Dresser & McKee Inc./ViroGroup, Inc. (1993), modified version shown in Figure 13, is not considered to be accurate. The hydraulic correlations of this unit to permeable sediments within the upper confining beds of the Floridan Aquifer System in eastern and northeastern Lee County are not believed to be accurate (no hydraulic connection).

The Mid-Hawthorn Aquifer (upper) that contains freshwater lies at the very top of the Arcadia Formation in the northwestern part of the County. This unit was originally named the AUpper Hawthorn Aquifer@ by Sproul et al. (1972). A map showing the thickness of the aquifer is shown in Figure 14. In some parts of western Lee County the aquifer is over a hundred feet thick, but it is a very inhomogeneous unit that contains interbedded limestone, sandstones, and lime muds. The top of the upper Mid-Hawthorn Aquifer is shown in several hydrogeologic sections given in subsequent figures (sections A-A', B-B', C-C', and D-D').

In general, the aquifer is most productive in the western part of Lee County, where it is used

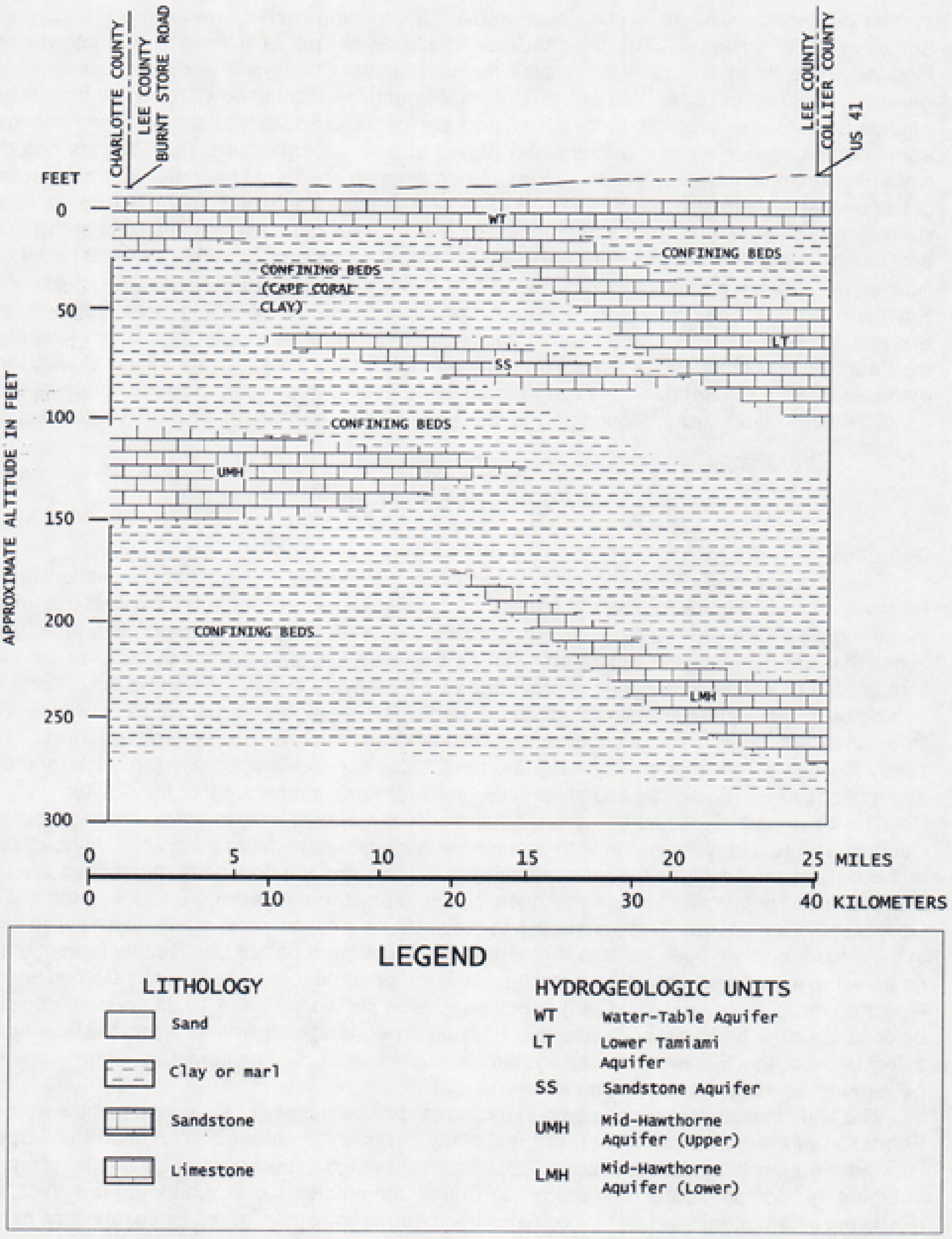

Figure 12. Generalized correlation of the aquifers within the Intermediate and Shallow Aquifer systems.

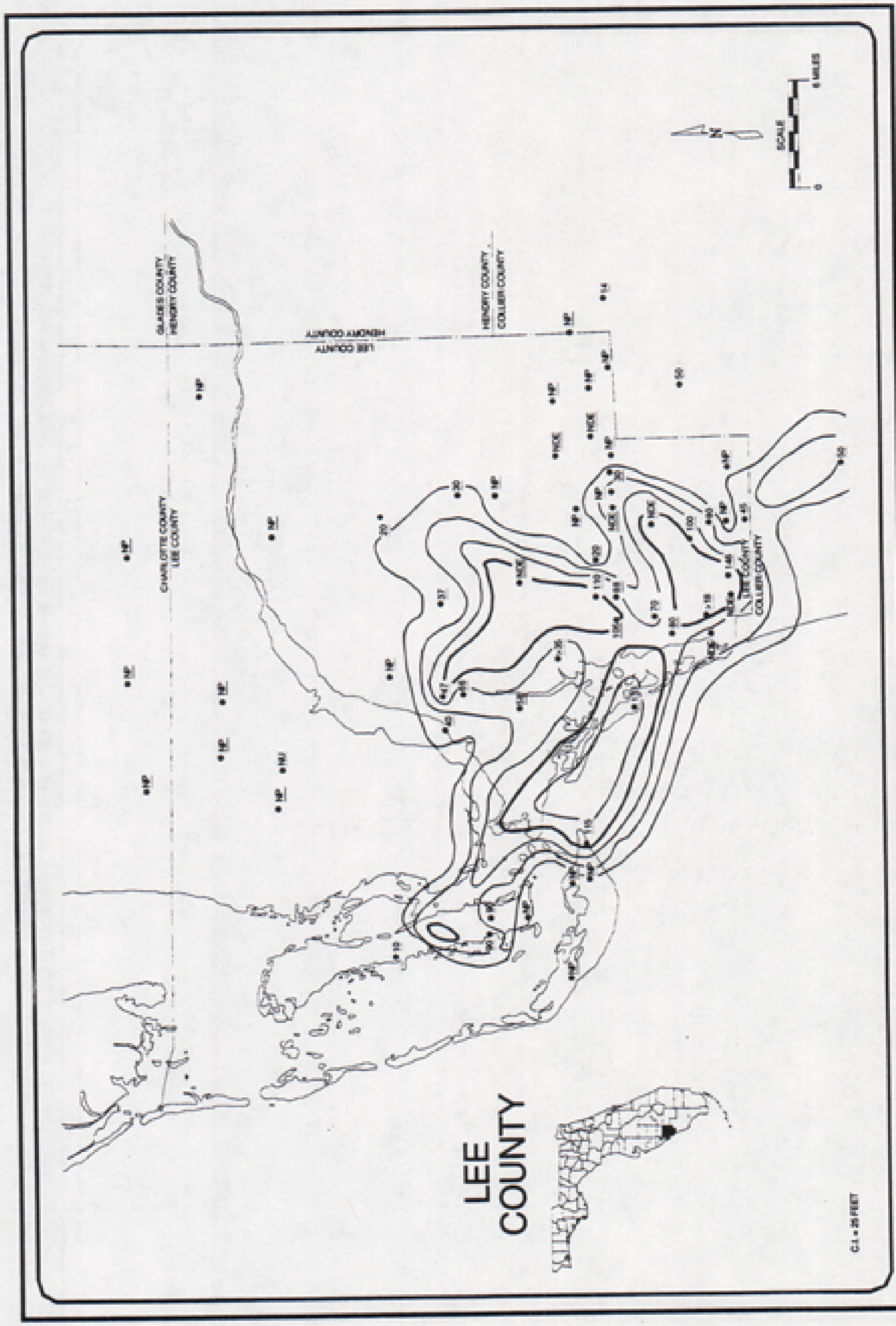

Figure 13. Generalized thickness contour map of the lower zone of the Mid-Hawthorn Aquifer (estimated) (modified from Camp Dresser & McKee Inc./ViroGroup, Inc., 1993).

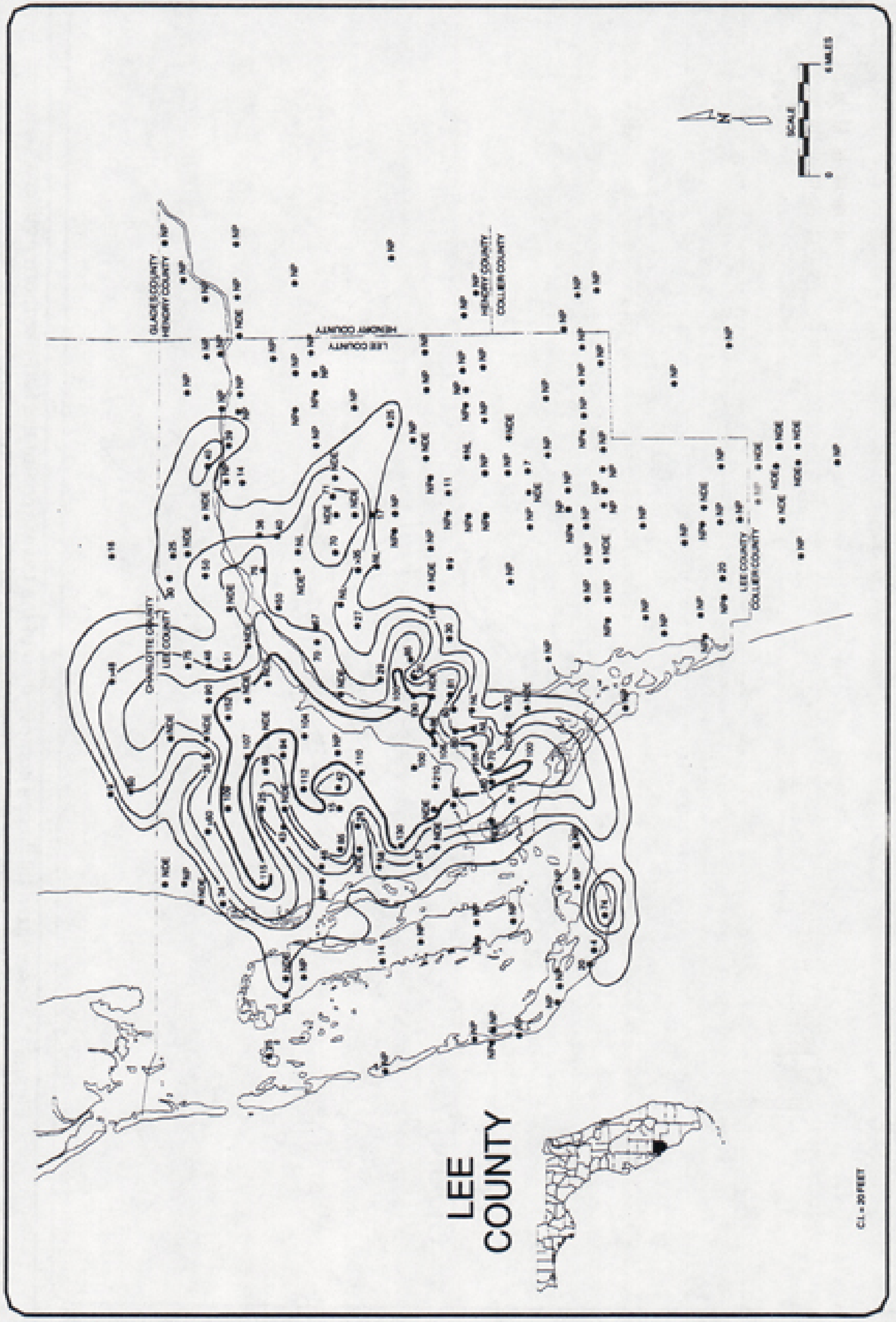

Figure 14. Thickness contour map of the upper zone of the Mid-Hawthorn Aquifer (modified from Camp Dresser & McKee Inc./ViroGroup, Inc., 1993).

extensively for domestic and irrigation from small diameter wells. In western Lee County, the unit does not exist.

Hydraulic Properties

A number of aquifer performance tests have been conducted on both the lower and upper Mid-Hawthorn aquifers in Lee County (Layne-Western, 1970; Missimer and Associates, Inc., 1978c; Missimer and Associates, Inc., 1980b; Missimer and Associates, 1981e). The aquifer test data for the lower zone of the Mid-Hawthorn Aquifer produced internally consistent results with three aquifer coefficients being obtained. The highest transmissivity was obtained in Bonita Springs at about 70,000 gpd/ft (868 m2/day) with a corresponding storativity of 0.00005, and a leakance of 0.00001gpd/ft3 (0.00000748 1/days) (Missimer and Associates, Inc., 1981e). Subsequent hydrogeologic investigations of the aquifer in the immediate area yielded lower transmissivity values in the range from 3,000 to 25,000 gpd/ft (37 to 310 m2/day).

Investigations of the hydraulic properties of the upper Mid-Hawthorn Aquifer were primarily restricted to northwestern Lee County. Investigations conducted by Layne-Western, Inc. (1970) in the late 1960's found that the aquifer had a transmissivity of 5,000 to 15,000 gpd/ft (62 to 186 m2/day) in the Cape Coral area. These tests yielded a storativity of about 0.0001, but a leakance value could not be obtained. Other aquifer tests conducted both to the north and east of Cape Coral yielded transmissivities ranging from 2,400 to 8,000 gpd/ft (30 to 99 m2/day). The kriged tranmissivity for the upper zone of the Mid-Hawthorn Aquifer developed by Camp Dresser & McKee/ViroGroup, Inc. (1993) is shown in Figure 15. Storativity values for the aquifer have a range of about 0.00005 to 0.0003. Despite the performance of numerous long-term aquifer performance tests, no leakance value has been obtained, because of the deviation of the drawdown curve above the Theis curve.

Water Quality

The quality of water within the lower zone of the Mid-Hawthorn Aquifer varies from nearly fresh in the northern extreme occurrence of the aquifer to about 2,500 mg/l of dissolved chloride in the Bonita Springs area of south Lee County. A compilation of water quality characteristics of this aquifer has not been made.

Historically, water quality within the upper zone of the Mid-Hawthorn Aquifer was fresh in most areas of the County with the possible exception of the western extreme area on the outer islands. Background dissolved chloride concentrations ranged from 80 to 200 mg/l depending on location. During the past 30 years, heavy pumping of the aquifer combined with poor well construction techniques have caused large areas of the aquifer to become contaminated with saline water (Boggess, 1968; Sproul et al., 1972; Boggess et al., 1977, McCoy, this volume).

Potentiometric Surface

The potentiometric surface of the lower zone of the Mid-Hawthorn Aquifer ranges from 26 to 21 feet (7.9 to 6.4 m) NGVD where it has been measured in south Lee County. These values are well above land surface and 5 to 10 feet (1.5 to 3 m) above the potentiometric pressure in the overlying upper zone of the Mid-Hawthorn Aquifer at locations where both zones occur stratigraphically in the subsurface (south of Fort Myers in the Gladiolus Road area). In Bonita Springs, the potentiometric pressure within the lower zone decreases from south to north. This opposite pressure gradient to the normal north to south gradient is likely caused by the pinching out of confining beds between sediments within the upper Floridan Aquifer and the lower Mid-Hawthorn Aquifer to the south of Lee County. The reverse gradient is therefore caused by pressure coming from the inter-aquifer connection to the south.

The potentiometric surface of the upper part of the Mid-Hawthorn Aquifer has been greatly

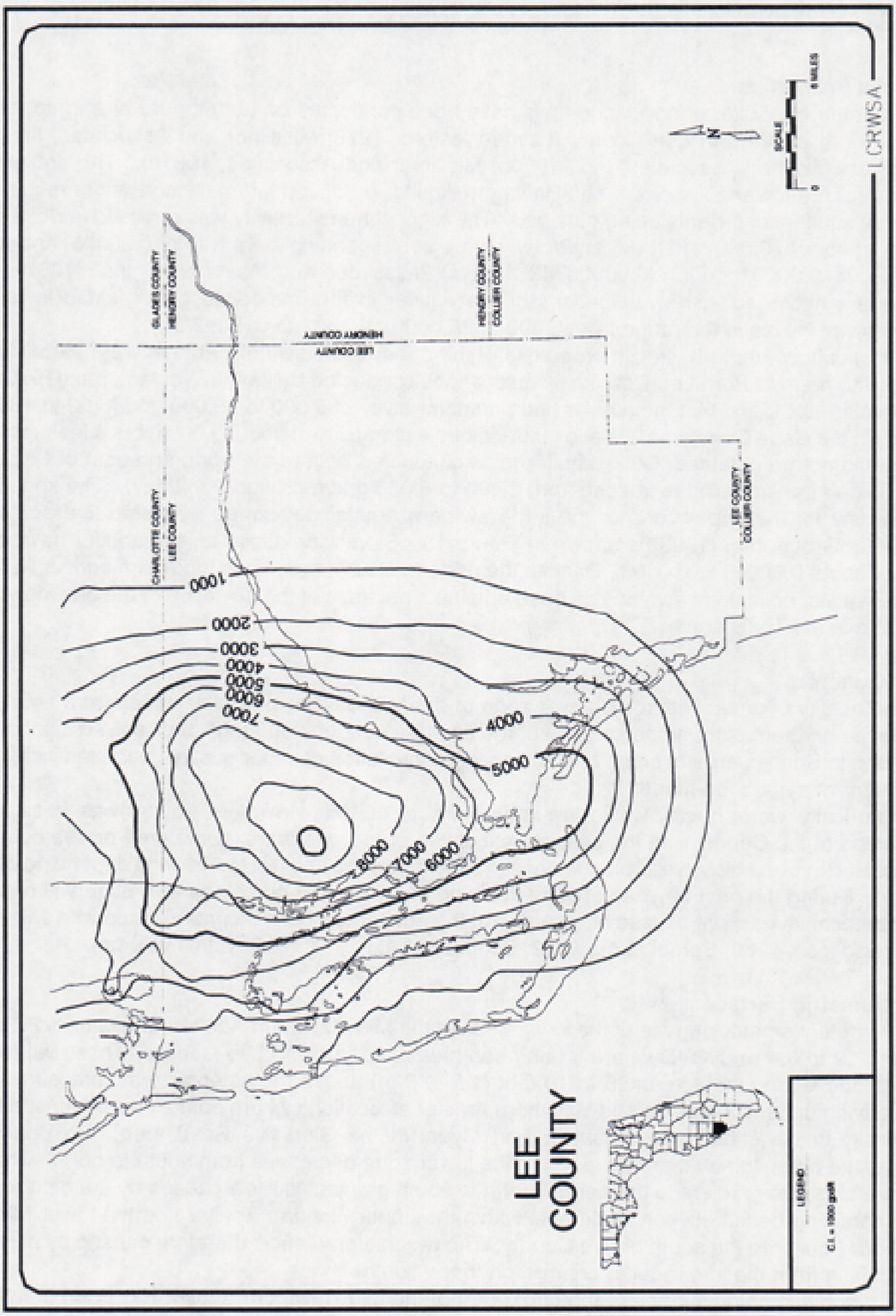

Figure 15. Transmissivity contour map of the upper zone of the Mid-Hawthorn Aquifer (modified from Camp Dresser & McKee Inc./ViroGroup, Inc., 1993).

affected by pumpage. Historically, the potentiometric pressure within this zone was at 10 to 12 feet (3 to 3.7 m) NGVD in the north part of the County and the aquifer typically flowed at land surface. In the late 1970's and early 1980's, the potentiometric pressure within the aquifer declined to nearly 100 feet (30 m) below land surface in a large area of western Lee County (Wedderburn et al., 1982). Failure of wellfields and individual wells along with the development of alternative water supplies have caused the aquifer potentiometric surface to recover to some degree.

SANDSTONE AQUIFER

Definition

The Sandstone Aquifer was first defined and named by Sproul et al. (1972) and substantial work was performed on the aquifer by Durward Boggess (Boggess et al., 1981; Boggess and Watkins, 1986) and later by Wedderburn et al. (1982). Although the Sandstone Aquifer is officially listed as part of the Intermediate Aquifer System, it has virtually no hydraulic connection to the underlying Mid-Hawthorn Aquifer and most of the recharge to the aquifer comes from the overlying water-table aquifer. The aquifer is directly recharged via a hydraulic connection to atmospheric pressure in southwestern Hendry County. The aquifer consists of moderate to low hydraulic conductivity quartz sands, sandstones, and sandy limestones.

The Sandstone Aquifer is a semi-confined aquifer that regionally underlies some of Charlotte County, Glades County, western Hendry County, all of Lee County, but the southwestern part, and much of central Collier County. The aquifer is most productive in eastern Lee County and western Hendry County. The aquifer thins to the west and the sediment comprising the aquifer have a generally lower hydraulic conductivity. The aquifer lies solely within the Peace River Formation of the Hawthorn Group. The aquifer is confined from the underlying Mid-Hawthorn Aquifer by a series of low permeability clay and lime mud units and is confined from the overlying water-table aquifer by muds within the deltaic part of the upper Peace River Formation. The upper confining unit pinches out from north to south (Figure 12; Missimer, 1999). The geology of the aquifer is shown in a series of east-west cross sections (reference map Figure 16; sections in Figures 17 to 21). In Lee County, the aquifer is commonly separated into two water-bearing zones; a lower limestone unit and an upper sand or sandstone unit. In north-central Lee County, the lower and upper zones are hydraulically connected, but separate from west to east (Figures 17 to 19). There is a subsurface structure in south-central Lee County in which some limestone units occur as separate zones at greater depth within the Peace River Formation. These units form other water-bearing zones within the aquifer and they are isolated within the structure (Figures 20 and 21). Correlation of the aquifer from north to south is given in Figure 12. The aquifer pinches out in general from east to west and occurs only on the eastern limb of the Florida Platform as shown in Missimer (1997).

The Sandstone Aquifer is primarily recharged via vertical flow from the overlying water-table aquifer in Lee County. Some recharge also occurs from the underlying Mid-Hawthorn Aquifer, where it has a naturally-occurring higher potentiometric pressure. The aquifer is directly recharged at some locations in southwestern Hendry County, where there is a direct hydraulic connection to the water-table aquifer.

Hydraulic Properties

Although there are two or more water-bearing zones that comprise the aquifer, aquifer hydraulic data has been reported only from the aquifer as a whole. Because of the complexity of the different water-bearing zones, future work needs to be accomplished to provide a more comprehensive characterization of the aquifer hydraulics.

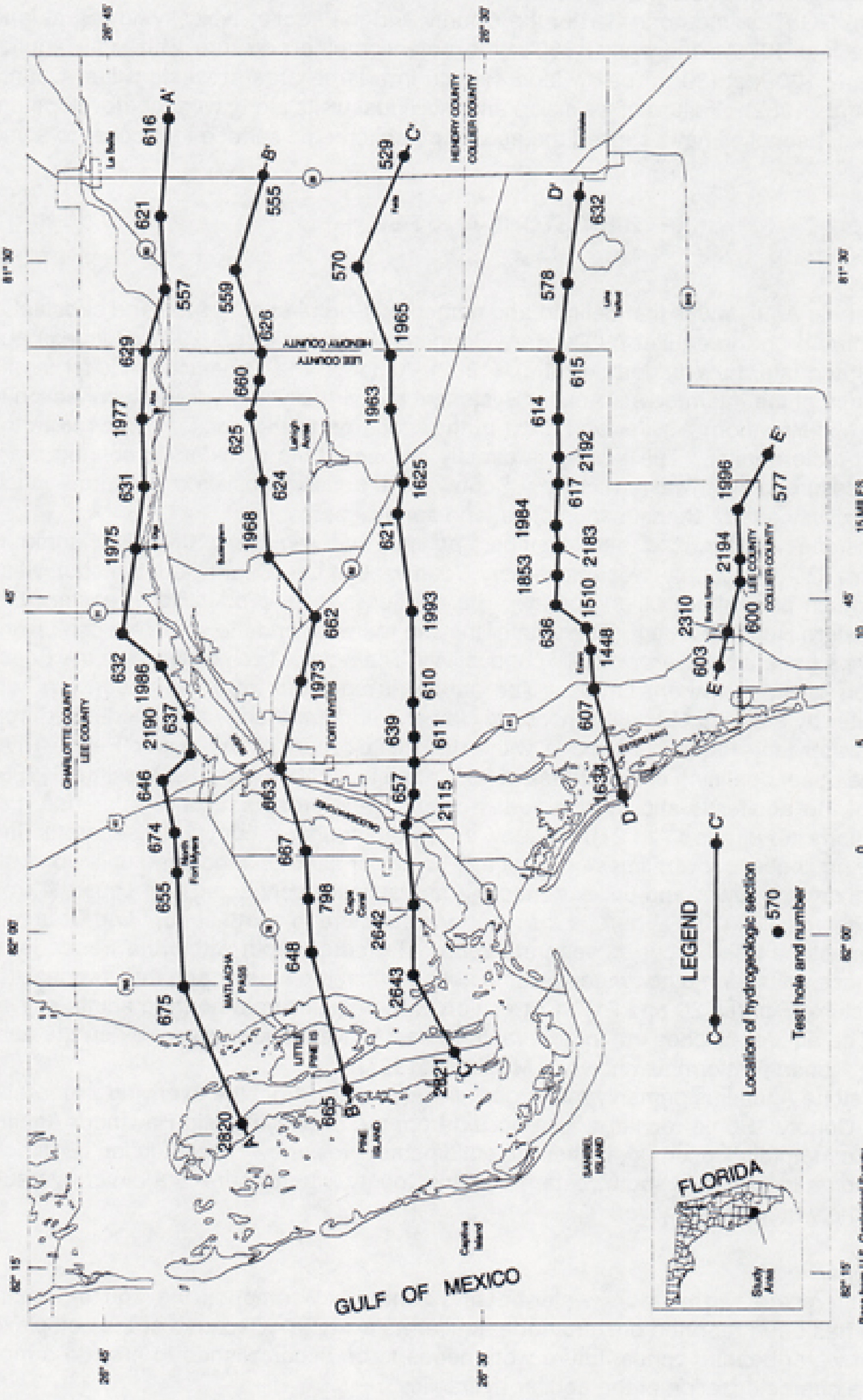

Figure 16. Index map showing the well locations for a series of hydrogeologic sections across Lee County.

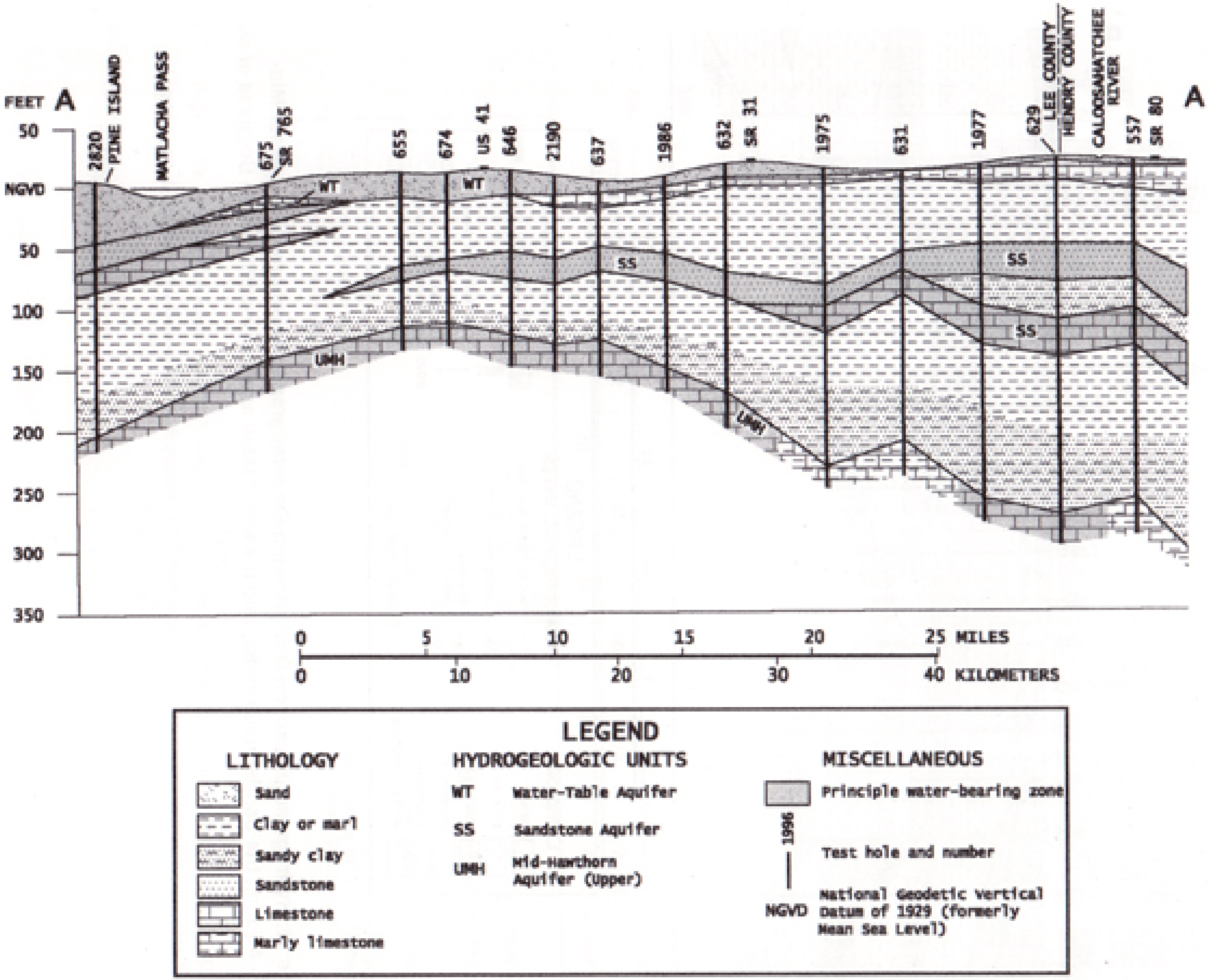

Figure 17. Hydrogeologic section A-A' showing the stratigraphic locations of the upper Mid-Hawthorn Aquifer, the Sandstone Aquifer, and the water-table aquifer (modified from Boggess et al., 1981).

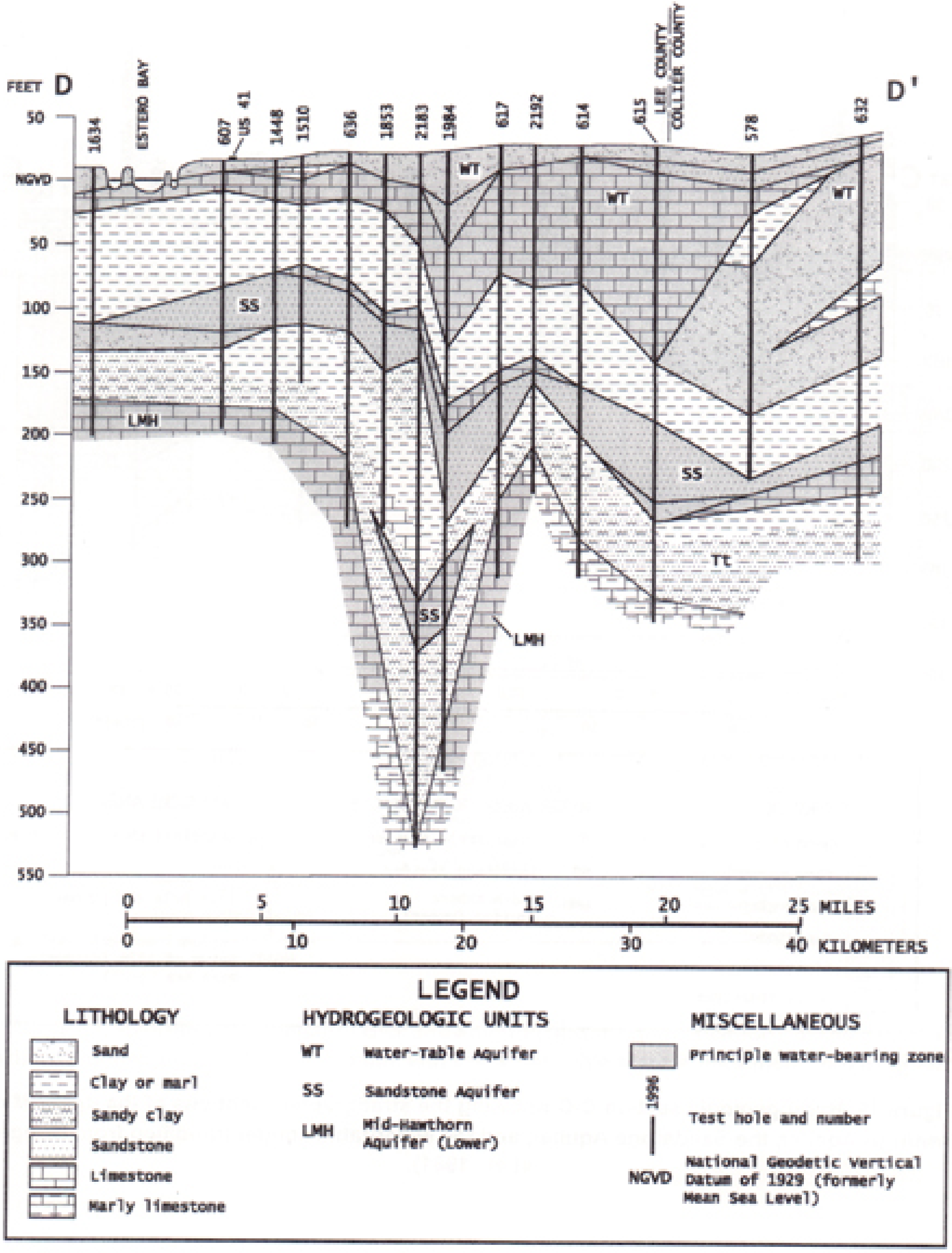

Figure 20. Hydrogeologic section D-D' showing the stratigraphic locations of the lower Mid-Hawthorn Aquifer, the Sandstone Aquifer, water-table aquifer (modified from Boggess et al., 1981).

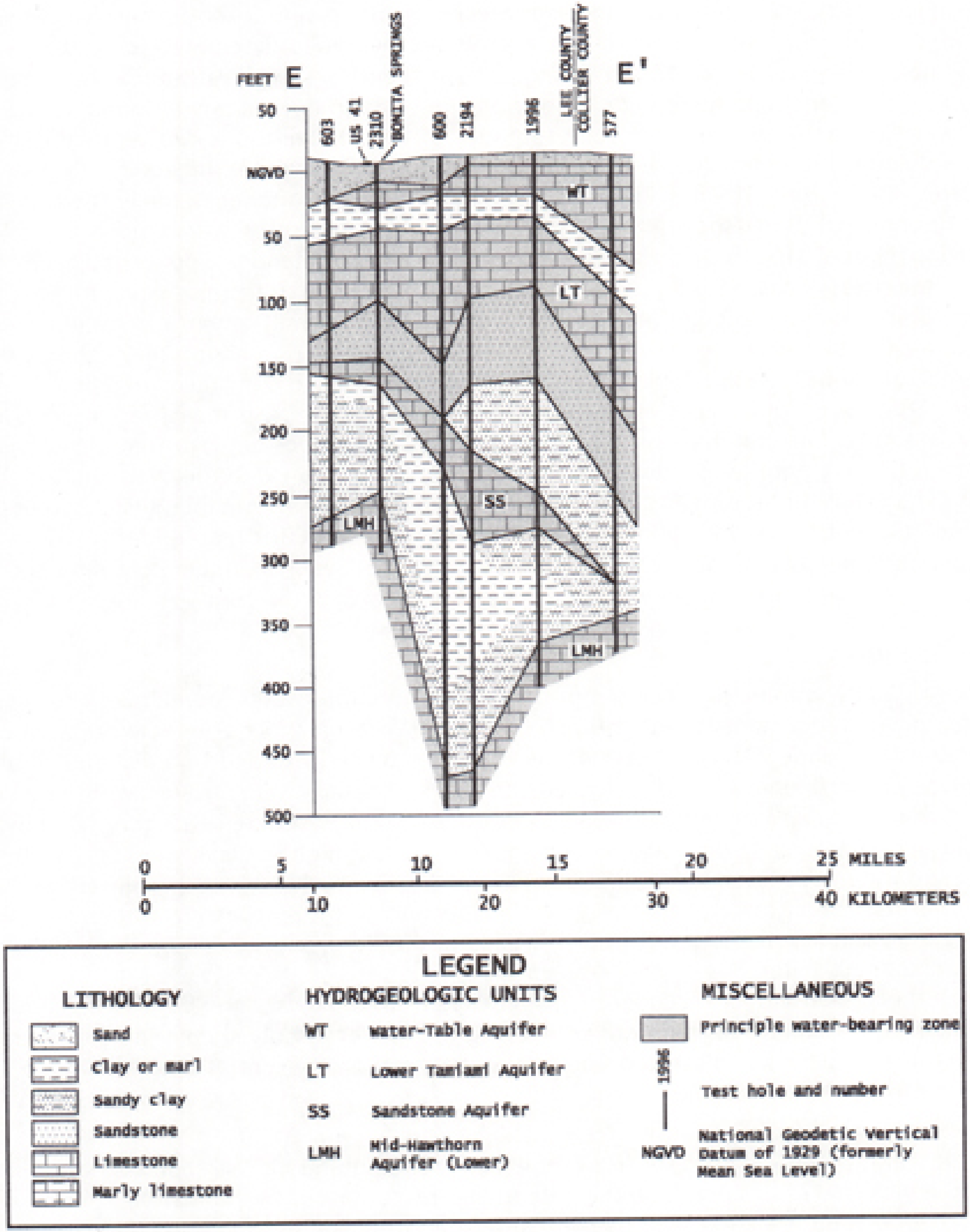

Figure 21. Hydrogeologic section E-E' showing the stratigraphic locations of the lower Mid-Hawthorn Aquifer, the Sandstone Aquifer, the water-table aquifer (modified from Boggess et al., 1981).

A large number of aquifer performance tests have been conducted on the upper part of the aquifer in Lee County. The transmissivity derived from these tests ranges from 500 to 373,000 gpd/ft (6.2 to 4625 m2/day). The aquifer has a relatively high transmissivity in western Lee County (Figure 22). The aquifer is either not present or has a very low transmissivity in western Lee County. Sediments that comprise the aquifer are hydraulically connected to the overlying Lower Tamiami Aquifer in the Bonita Springs area of southwestern Lee County, because of the pinchout of the upper confining beds. The anomalously high transmissivity found at one site in central Lee County (Gateway) is not representative of the aquifer and is caused by the presence of some dolomitized limestone and related secondary porosity within the aquifer (Missimer and Associates, Inc., 1984). The highest transmissivities within the aquifer occur in the central area of the County and are associated with the occurrence of thicker accumulations of sediments within a structural trough and diagenesis. In southwestern Hendry County, adjacent to Lee County, the two zones within the aquifer have a combined transmissivity of slightly over 100,000 gpd/ft (1240 m2/day) with about 50,000 gpd/ft (620 m2/day) in each aquifer.

The measured storativity in the Sandstone Aquifer ranges from about 0.0003 to 0.001 with an average of about 0.0005. The leakance of the aquifer has also been measured at a number of locations. However, some relatively high leakance values have been measured at several sites where the aquifer has multiple water-bearing zones. These values are representative of internal leakance within the aquifer and do not reflect the true connection with the overlying water-table aquifer. The range in leakance values obtained from aquifer performance tests is 0.00004 to 0.02 gpd/ft3 (0.003 to 0.15 1 /days). A realistic leakance value for the aquifer, particularly for the upper confining beds is about 0.001 gpd/ft3 (0.007 1/days). The upper confining bed thickness is greater than 30 ft (9.1 m) in most of Lee County, except the southern area.

Water Quality

Water quality within the aquifer normally meets potable water standards. The dissolved chloride concentration ranges from 40 to 200 mg/l. However, there are some areas where the aquifer contains saline water. Beneath of the Caloosahatchee River and to a distance of about 2 miles (3.2 km) north and south of the river, the aquifer contains saline water with the dissolved chloride concentration ranging from 250 to 700 mg/l. It is postulated that this saline water is hydraulically trapped connate water remaining from the last high sea level stand (125,000 years age). Saline water also occurs in the aquifer in the San Carlos Park area of central Lee County. The aquifer has a very low transmissivity at this location and it pinches out to the west. Therefore, the high salinity of the water in this area is also most likely caused by the occurrence of unflushed connate water.

Since the aquifer is recharged locally by leakage from the overlying water-table aquifer, the water chemistry is similar to that aquifer with slightly higher dissolved chloride concentrations, higher hardness, but lower dissolved iron and organic carbon concentrations.

Potentiometric Surface

The natural potentiometric surface of the Sandstone Aquifer closely follows the water-table position in most of Lee County. Both the potentiometric surface of the Sandstone Aquifer and the water-table position are controlled by land surface altitude and local surface drainage features. The potentiometric surface of the aquifer lies below the potentiometric surface of the overlying water-table aquifer in most of Lee County. Therefore, there is a downward gradient, which produces localized recharge. In many areas of Lee County, the potentiometric surface of the underlying Mid-Hawthorn Aquifer is also higher than the potentiometric surface of the Sandstone Aquifer, therefore, causing an upward hydraulic gradient. It is not clearly understood how this aquifer can be receiving recharge from two directions, and yet it appears to pinch out toward the

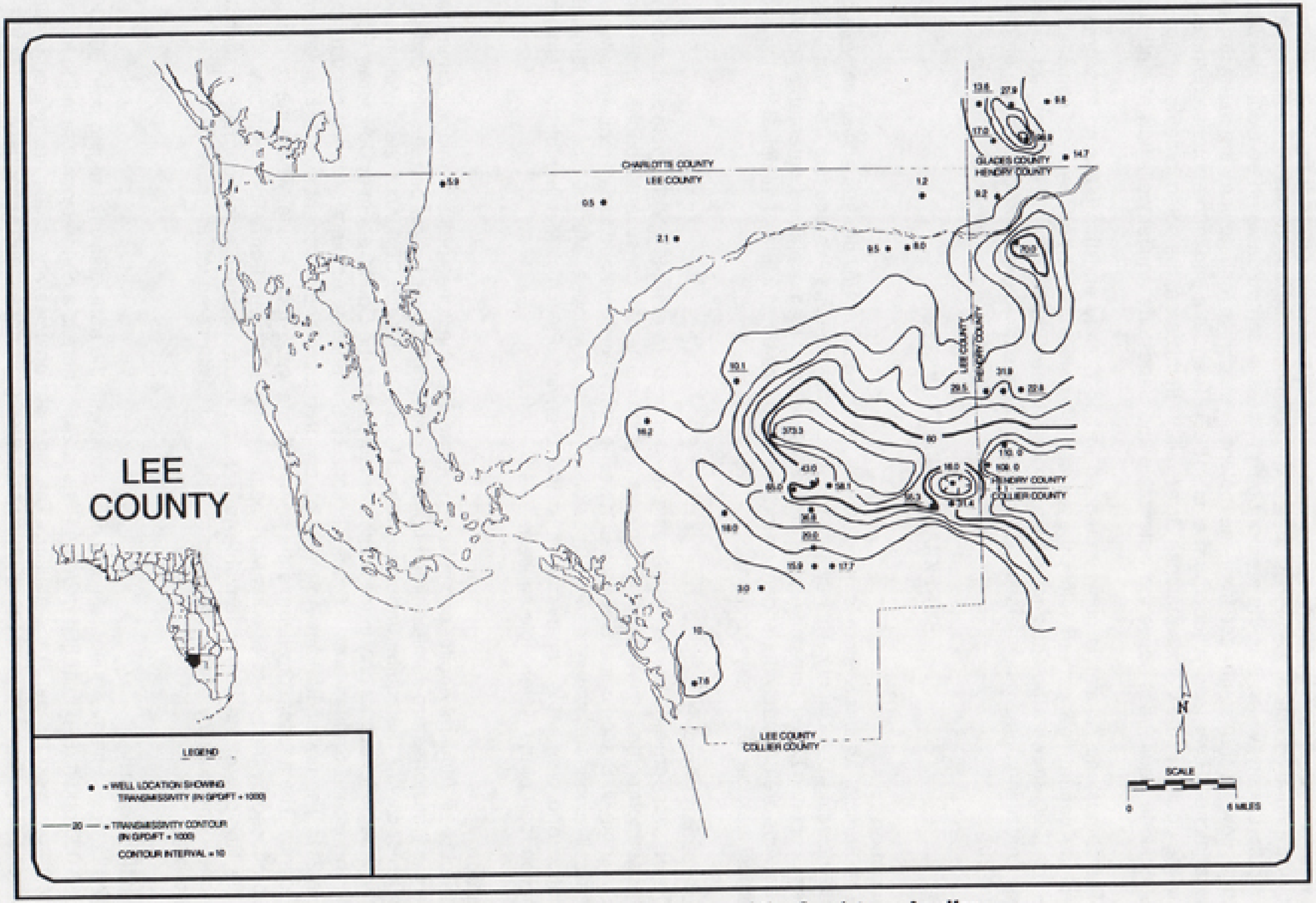

Figure 22. Transmissivity contour map of the Sandstone Aquifer (modified from Camp Dresser & McKee Inc./ViroGroup, Inc., 1993).

west with no clear discharge point.

In the natural condition, the highest area of the potentiometric surface lies at the highest altitude in Lee County, which is in the area of Lehigh Acres in central eastern Lee County. Water tends to flow to the southwest from the potentiometric high and toward the north to the Caloosahatchee River (see Wedderburn et al., 1982). There is a sag in the potentiometric surface of the aquifer in the Calossahatchee River valley. In this area, the potentiometric surface of the Sandstone Aquifer lies above the water table and Sandstone Aquifer wells flow at land surface.

The Sandstone Aquifer is heavily pumped in Lee County and this pumping has greatly altered the natural flow pattern within the aquifer. A poteniometric surface map compiled in March of 1990 shows a potentiometric high in central Lee County with the eastern part of the County containing numerous intersecting troughs and cones of depression caused by pumping (Figure 23).

SURFICIAL AQUIFER SYSTEM

Introduction

The Surficial Aquifer System is a regional hydrostratigraphic unit that underlies nearly all of Florida including Lee County. This system in Lee County contains two aquifers, the first being the semi-confined Lower Tamaimi Aquifer and the other being the unconfined water-table aquifer. Both aquifers are ultimately dependent on local recharge via direct inflow of rainfall at the top and by vertical leakage to the lower aquifer.

Lower Tamiami Aquifer

The Lower Tamiami Aquifer was named by Wedderburn et al. (1982) to replace the commonly used term "Tamiami Aquifer", which was used in numerous consultants reports and informally in some U. S. Geological Survey reports. The name was changed to differentiate between hydraulically-confined, water-bearing limestones in the Ochopee Member of the Tamiami Formation and permeable sediments within the overlying Pinecrest Member of the Tamiami Formation (part of the water-table aquifer).

Definition

The Lower Tamiami Aquifer occurs within permeable limestones of the Tamiami Formation, where the limestones are semi-confined from the overlying aquifer by low permeability carbonate muds or clays. The aquifer underlies parts of Lee, Hendry, and Collier counties. Within Lee County, the aquifer occurs only in the southernmost part of the County south of Corkscrew Road and in the Bonita Springs area. Cross sections of the shallow aquifers show its occurrence (Figure 21). The Lower Tamiami Aquifer is a very productive and important aquifer in southern Lee County. The aquifer correlates to the north with the water-table aquifer where the confining beds produced by the Bonita Springs Marl member of the Tamiami Formation pinch out.

The lithology of the Lower Tamiami Aquifer is a predominantly, highly permeable, sandy limestone. The porosity of the aquifer is mostly moldic with some intergranular porosity in the grainstones.

Hydraulic Properties

The Lower Tamiami Aquifer is highly productive with the transmissivity ranging from 50,000 to 1,360,000 gpd/ft (620 to 16864 m2/day) (Figure 24). There is a general increase in the transmissivity from west to east in the aquifer. The highest transmissivity values are related to the occurrence of specific sediment facies, such as coarse grainstones, and secondary alteration of

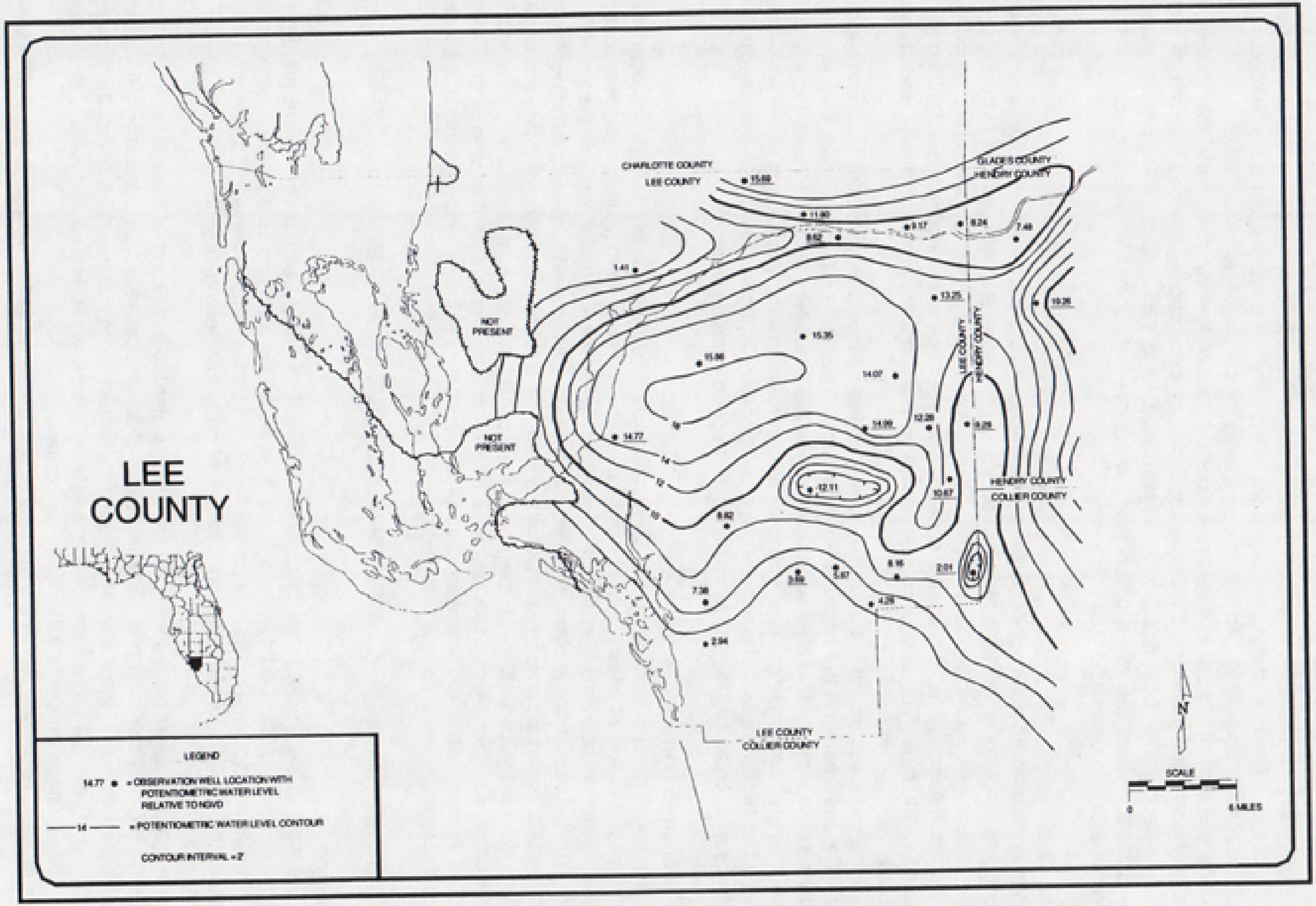

Figure 23. Dry season (March, 1990) potentiometric surface map for the Sandstone Aquifer (modified from Camp Dresser & McKee Inc./ViroGroup, Inc., 1993).

the limestones, which has caused the formation of interconnected small cavities.

Based on a number of aquifer performance tests, the storativity of the aquifer ranges from 0.0005 to 0.05. The high storativity values are found near the area where the aquifer becomes unconfined (north boundary). An average storativity for the aquifer is about 0.002.

The leakance of the Lower Tamiami Aquifer is directed downward, because the underlying clays are thicker and have very low permeabilities. Leakance values obtained from aquifer performances tests range from 0.002 to 0.25 gpd/ft3 (0.015 to 1.87 1/days). The highest values were obtained where the overlying confining muds are very thin. An average value for the aquifer is about 0.004 gpd/ft3 (0.03 1/days).

Water Quality

Water quality within the aquifer is strictly dependant on the distance from tidal water and on the occurrence of some saline water within proximity to existing surface drainage features, such as the Imperial River and the Cocohatchee River (Collier County). In areas unaffected by the occurrence of saline water, the aquifer contains dissolved chloride concentrations ranging from about 40 to 100 mg/l. The aquifer contains relatively high concentrations of organic carbon and dissolved iron.

Saline water occurs within the aquifer from the coast inland up to several miles in some locations. The area beneath the Imperial River and the Cocohatchee Canal (Collier County) also contains saline water. The saline water occurrence in the aquifer adjacent to tidal water is natural, but heavy pumping of the aquifer has caused some eastward migration of saline water into formerly freshwater areas. The occurrence of saline water in the vicinity of the tidal reaches of the rivers is probably natural and is hydraulically trapped connate water.

Potentiometric Surface

The potentiometric surface of the Lower Tamiami Aquifer generally follows the overlying water table. It occurs at a lower altitude and thus there is a downward hydraulic gradient, causing the aquifer to be recharged from the overlying water-table aquifer through the confining muds. The potentiometric surface of the aquifer fluctuates seasonally similar to the water table, but there is a lag time between the rise of the water table after a rainfall event and the corresponding rise in the potentiometric surface of the aquifer. A potentiometric surface map of the aquifer constructed for March, 1990 shows a horizontal flow gradient from east to west (Figure 25). The western part of the potentiometric surface lies below sea level and therefore, the potential for saline-water intrusion is a real issue.

WATER-TABLE AQUIFER

Definition

The water-table aquifer is the unconfined aquifer throughout Lee County. There are, however, some areas of the County where there is some minor confining soils or sandy clays that cause the aquifer to behave like it is partially confined by temporarily impeding the vertical flow of water. The aquifer is a very important source of both potable and irrigation water.

The water-table aquifer occurs from the top of the water table (or zone of saturation) to the first significant regional confining bed. The thickness of the aquifer varies seasonally with the position of the water table. The water table-aquifer is thickest in the southeastern part of the County (Figure 26). There are some parts of western Lee County, where the aquifer is quite thick, but the aquifer is filled with saline water at those locations.

Permeable sediments within the uppermost part of the Tamiami Formation, the undifferenti-

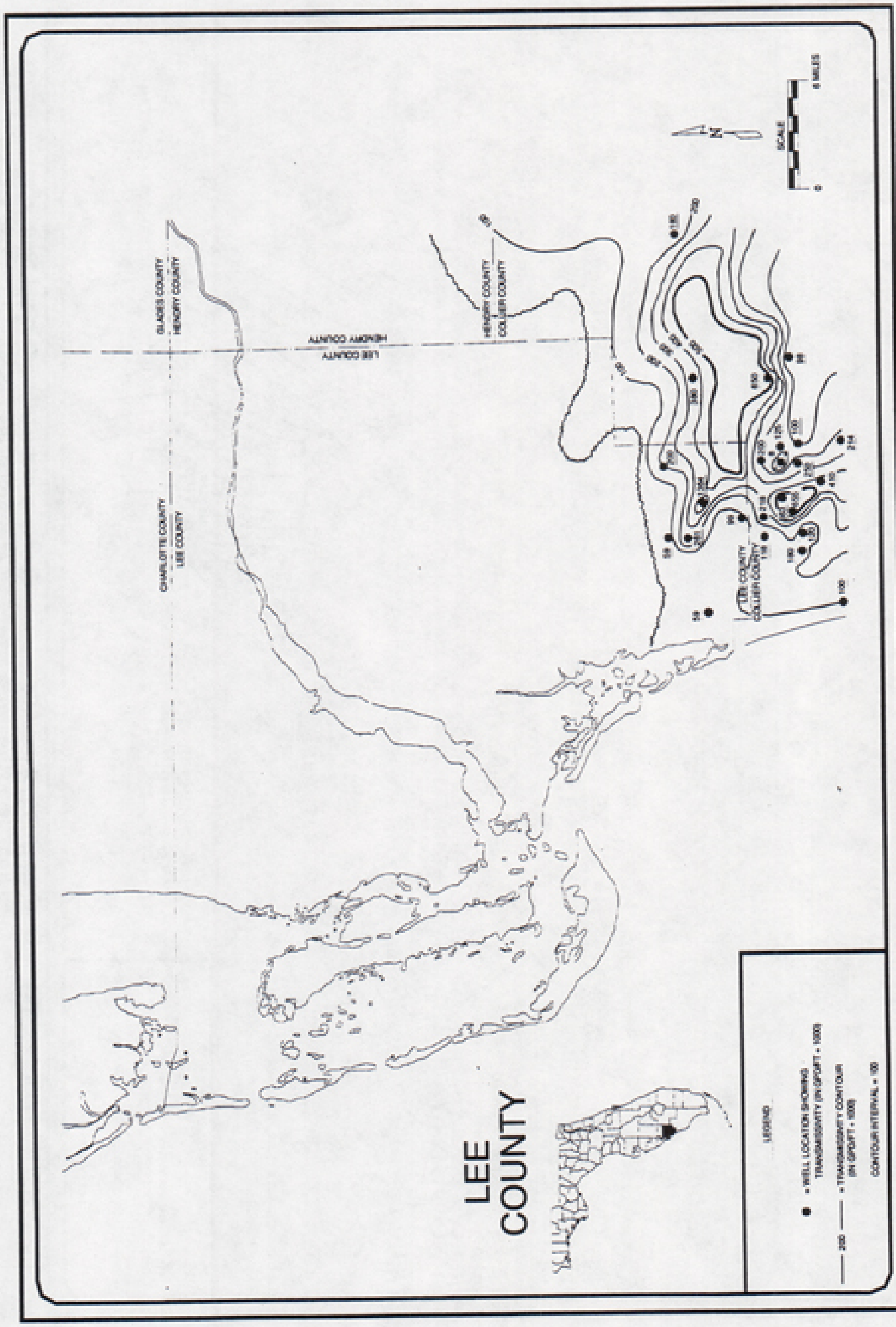

Figure 24. Transmissivity contour map of the Lower Tamiami Aquifer (modified from Camp Dresser & McKee Inc./ViroGroup, Inc., 1993).

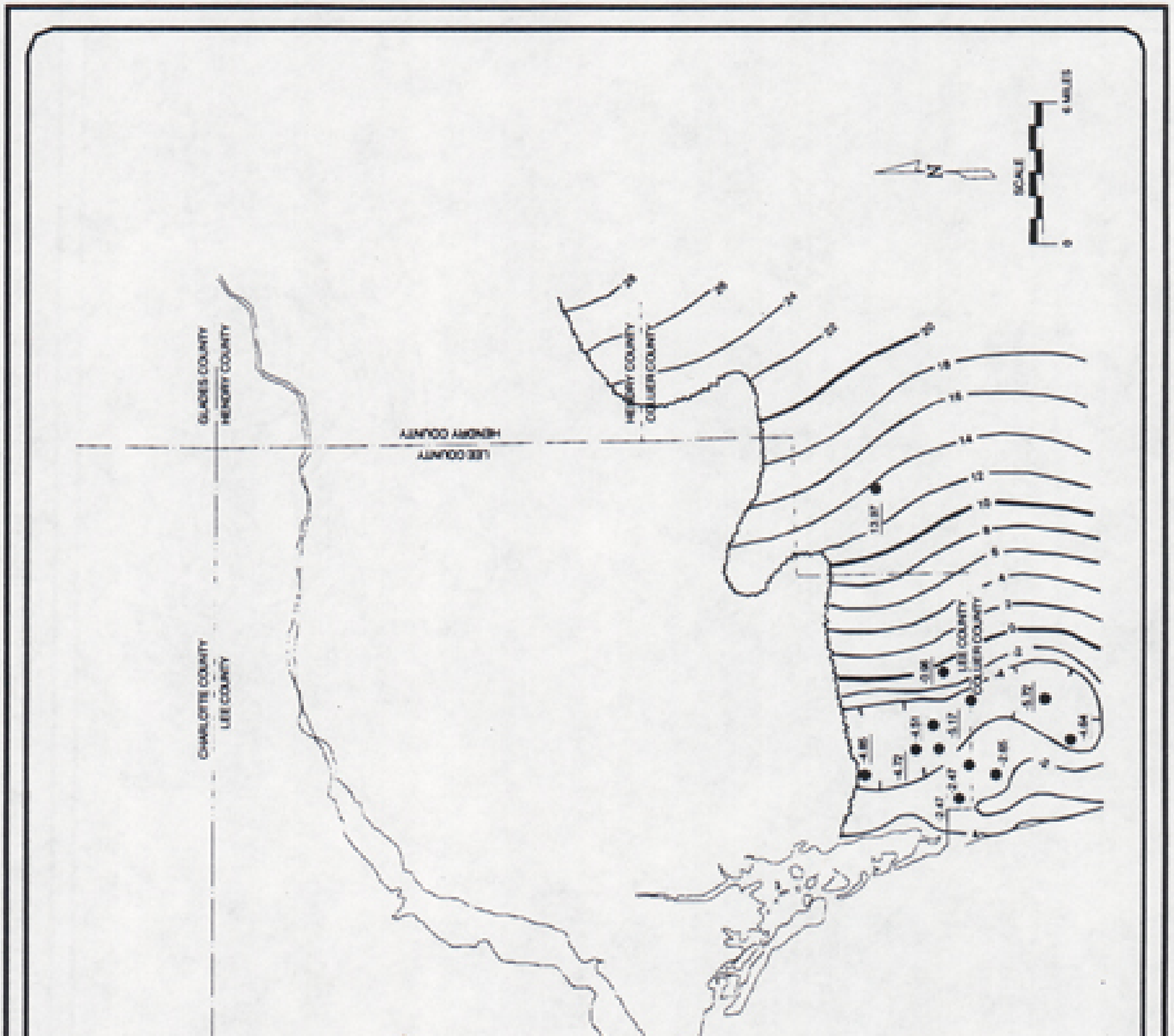

Figure 25. Dry season (March, 1990) potentiometric surface map of the Lower Tamiami Aquifer (modified from Camp Dresser & McKee Inc./ViroGroup, Inc., 1993).

ated Caloosahatchee and Fort Thompson formations, form the aquifer. Where the aquifer is most productive, it occurs in sandy, fossiliferous limestones in the upper Tamiami Formation. The limestone unit is characterized by secondary dissolution of aragonitic shell that creates moldic porosity. The aquifer is also characterized by abrupt changes in thickness and facies-controlled changes in hydraulic conductivity. The aquifer is less productive where it occurs in the Fort Thompson Formation shelly limestone and quartz sands.

Hydraulic Properties

The hydraulic properties of the water-table aquifer are more controlled by sediment facies than by aquifer thickness. The most productive area of the aquifer lies in southeastern Lee County. There are however, localized areas of high productivity where the aquifer is less than 20-ft (6 m) in thickness. In areas where the aquifer consists primarily of quartz sand, shell and thin limestone layers, the transmissivity may be as low as 5,000 gpd/ft (62 m2/day). In areas of the County where the limestones are thick, transmissivity values of over 100,000 gpd/ft (1240 m2/day) are common.

The aquifer hydraulic conductivity has been measured at numerous locations throughout the County (Figure 27). The measured hydraulic conductivity values are very high throughout the County, but these values do not necessarily represent aquifer productivity. For example, in many areas of the County, the highest hydraulic conductivity values occur very near to land surface, where a surface rock feature commonly contains large cavities within 3 to 5 ft (0.9 to1.5 m) of surface. An aquifer performance test or slug test conducted in the wet season will show a very high hydraulic conductivity and corresponding transmissivity (aquifer hydraulic conductivity times aquifer thickness). However, the normal seasonal fluctuation of the water table is up to 5 ft (1.5 m) and if the zone of highest hydraulic conductivity is not saturated, then the overall aquifer may have low productivity. The highest overall aquifer productivity in Lee County is in the central and southeastern areas, where there is a good combination of high average hydraulic conductivities and a large aquifer thickness. Transmissivity values commonly range from 50,000 to 300,000 gpd/ft (620 to 3720 m/day) in these areas.

Not many accurate values for specific yield have been measured in the water-table aquifer in Lee County. Aquifer performance tests cannot be conducted for time periods sufficient to overcome the effects of delayed yield on the drawdowns measured. Commonly, values of between 0.1 and 0.3 are used to estimate the specific yield of the aquifer. However, recent measurements of aquifer properties using sophisticated new techniques, suggest that the specific yield number commonly used may be low. These data suggest that for sand aquifers values should be 0.25 and for carbonate aquifers with secondary porosity the values should be 0.3 to 0.4 (Yamamoto et al., 1999).

Water Quality

The quality of water in the water-table aquifer in Lee County, where not affected by tidal water is fresh with dissolved chloride concentrations ranging from 10 to 70 mg/l. The water tends to have high concentrations of organic carbon and dissolved iron. The hardness varies greatly and depends on the lithology of the aquifer at a given location.

Potentiometric Surface

The potentiometric surface of the aquifer, commonly termed the water table, generally follows the topography of land surface. The water table position is affected by both naturally-occurring and man-created surface drainage features. The highest positions of the water table occur at the highest land surface altitudes in the County, which are located in the eastern part of the

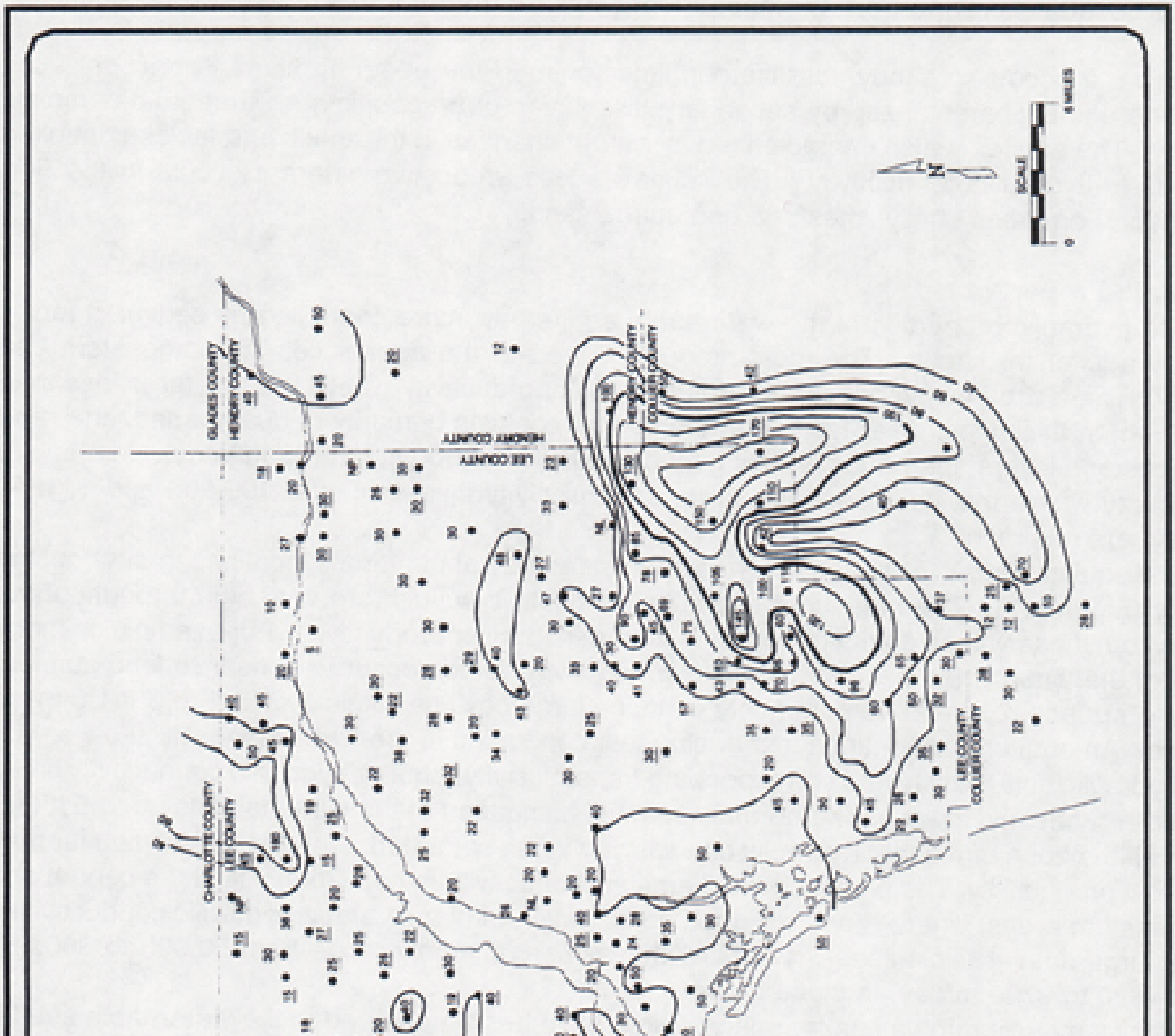

Figure 26. Thickness contour map of the water-table aquifer (modified from Camp Dresser & McKee Inc./ViroGroup, Inc., 1993).

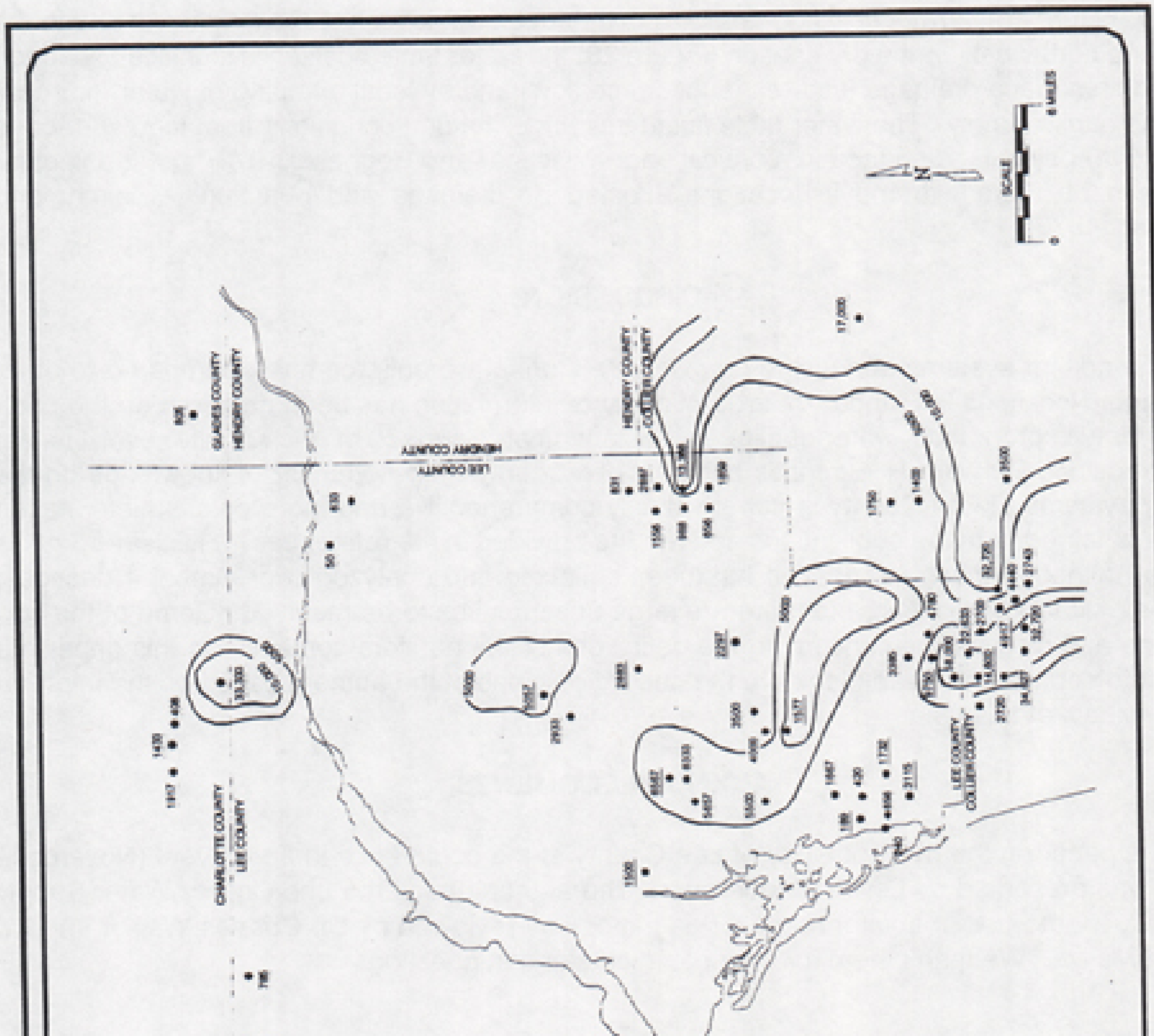

Figure 27. Hydraulic conductivity contour map of the water-table aquifer (modified from Camp Dresser & McKee Inc./ViroGroup, Inc., 1993).

County (Figure 28). Water flows generally from the topographic high to the southwest and to the north and northwest. In the dry season (Figure 28) the water table position is significantly affected by both surface drainage features (subsurface flow) and by local pumping of water for irrigation and public supply. The water table fluctuates under natural conditions from land surface to 5 ft (1.5 m) below land surface in a typical year (Missimer and Boggess, 1973), but the fluctuations can be more extreme in locations affected by drainage and pumping (Missimer and Boggess, 1973).

DISCUSSION

The aquifer systems underlying Lee County, Florida are quite complex compared to other geographic locations in Florida. A large quantity of information has been gathered on the geology, hydraulic properties, water quality, and potentiometric surface of each aquifer over the last 34 years since Durward H. Boggess came to Lee County. This summary of knowledge on the aquifer systems of Lee County is not absolutely comprehensive and more detailed information can be obtained from the publications and reports provided in the references. It is clear from this text that although much information has been collected and analyzed over almost 4 decades, there is much to be learned and there are large uncertainties to be resolved. Some of the correlations and discussions concerning the definitions of the aquifers contained in this paper are subject to debate, but these ideas are the current opinions of the authors based on the information available at this time.

ACKNOWLEDGMENTS

The paper on the hydrogeology of Lee County at the conference in Fort Myers (November, 1999) was presented by Leslie Wedderburn. The authors thank the Lee County Water Supply Authority for the use of aquifer maps. This paper was reviewed by Dr. Charles Walker and Dr. Robert Maliva. We thank them for their comments and suggestions.

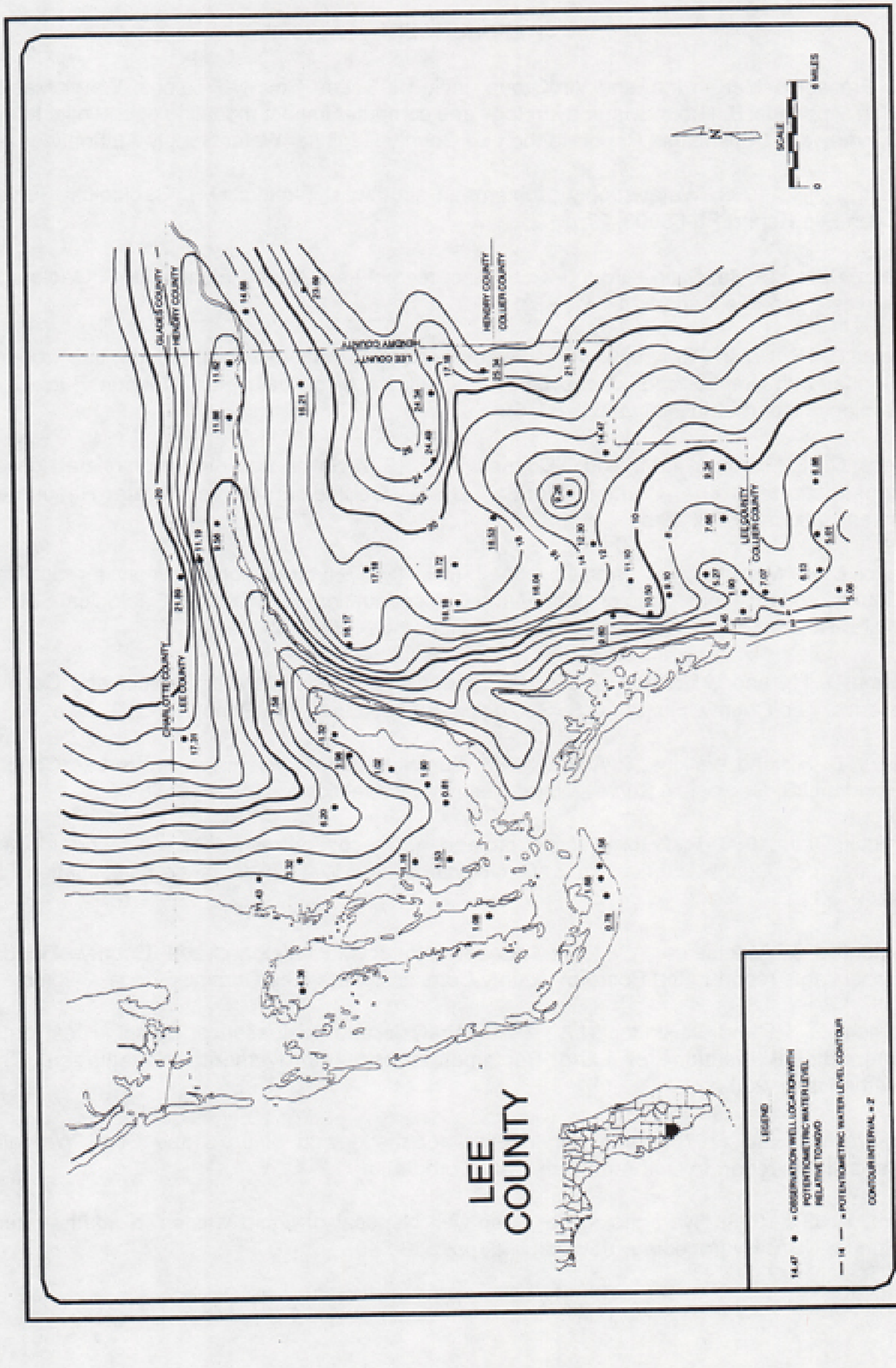

Figure 28. Dry season (March, 1990) potentiometric surface map of the water-table aquifer (modified from Camp Dresser & McKee Inc./ViroGroup, Inc., 1993).

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WATER LEVEL ELEVATION MAPS OF THE PRIMARY AQUIFERS IN THE LOWER WEST COAST OF FLORIDA

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ABSTRACT

Water table and potentiometric surface maps were prepared for the primary aquifers of southwest Florida including the water-table, Lower Tamiami, sandstone and Mid-Hawthorn aquifers. The maps cover the Lower West Coast Planning Area of the South Florida Water Management District and were based on May 1999 data. The data were from multiple agencies that collect water levels with field personnel and/or automated systems. Geostatistical methods were used to evaluate spatial variation in the data and kriging is the interpolator used in estimating the potentiometric surfaces. The water table surface was generated using the same approach but has additional refinements to reflect physical features not present in the observed water level data. Temporal variation recorded at continuous monitoring sites was not evaluated and the consequence of having multiple sampling dates and times in the map data sets was not established. At the time of sampling, much of the mapped area was under Phase I Water Shortage Restrictions declared by the South Florida Water Management District (SFWMD). The maps depict a regional view of water levels under dry hydrologic and recent water use conditions and serves as useful reference in resource availability studies and water supply planning.

INTRODUCTION

The U. S. Geological Survey (USGS), South Florida Water Management District (SFWMD), Lee and Collier County governments and others perform extensive monitoring of groundwater levels in the southwest Florida area. Previous spatial and temporal analyses of data from these sources have identified areas of significant change and time-related trends, but regional depictions of wet and dry season potentiometric surfaces have not been developed for many years (Knapp et al., 1986, Smith and Adams, 1988; Montgomery; 1988). Local variability of the area hydrogeology, and short- and long-term temporal changes in water levels present difficulties in producing good potentiometric surface maps. Resource planners and regulators who need a regional perspective may not gain it from interpreting separate data sets from individual ground water stations. Development of potentiometric surface maps provides fundamental information for assessing water availability under water shortage and future demand conditions, and for water use permitting. Potentiometric surface maps also provide useful reference surfaces for comparison with simulation results from numerical flow models.

The western portion of the SFWMD has three main surface-water basins that are grouped into the Lower West Coast (LWC) Planning area, and includes all or parts of Charlotte, Glades, Hendry, Lee, Collier and Monroe Counties in southwest Florida (Figure 1). Within the LWC area, water supply for potable and irrigation demands is primarily met with surface and groundwater sources that include the Caloosahatchee River and the water-table, Lower Tamiami, sandstone and Mid-Hawthorn aquifers (Figure 2). Each aquifer has distinct characteristics that may be highly variable, both vertically and laterally. Only the Water-Table aquifer is found throughout the LWC area and is the only aquifer that is considered regionally unconfined. The LWC has

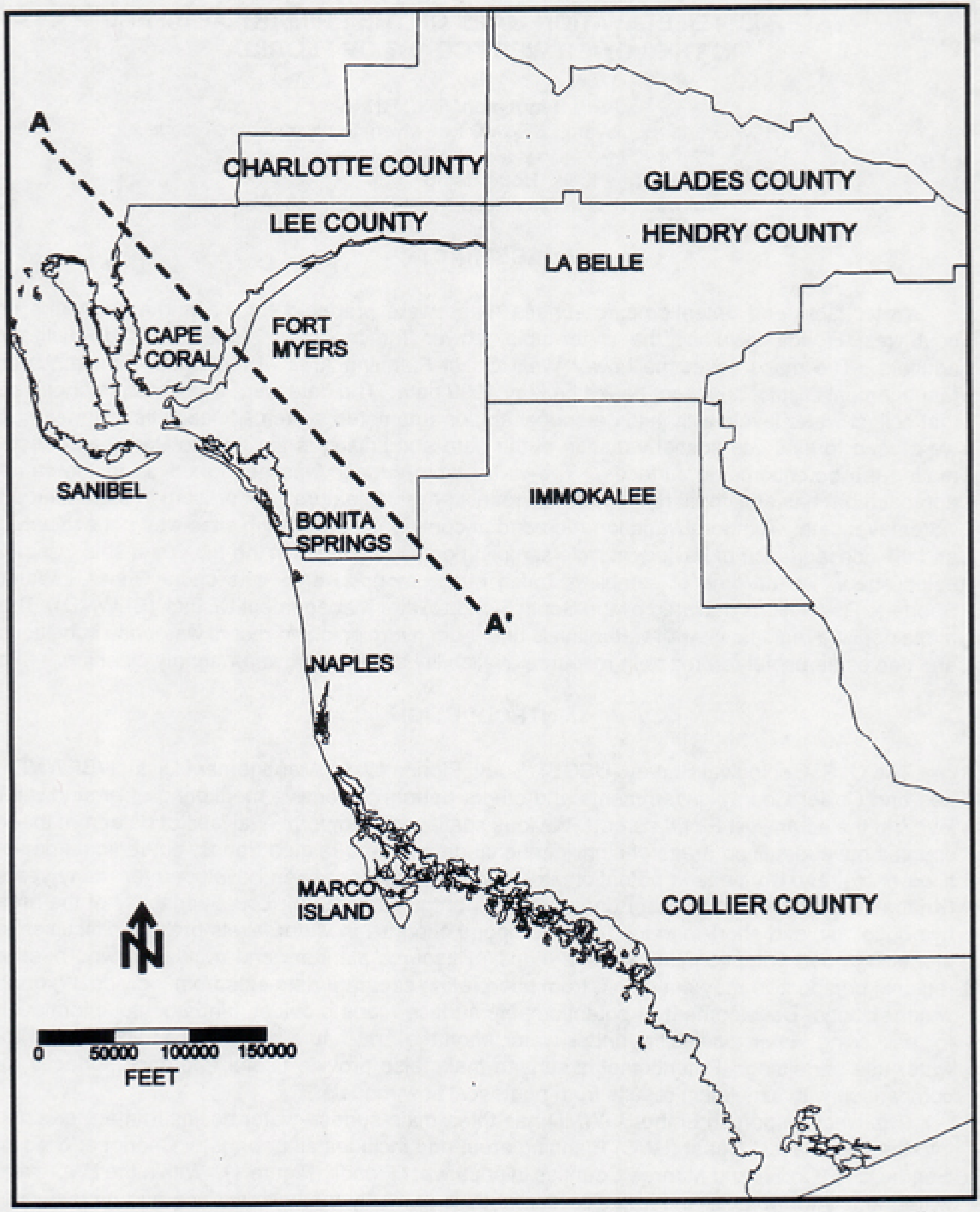

Figure 1. Location map of the Lower West Coast Planning Area.

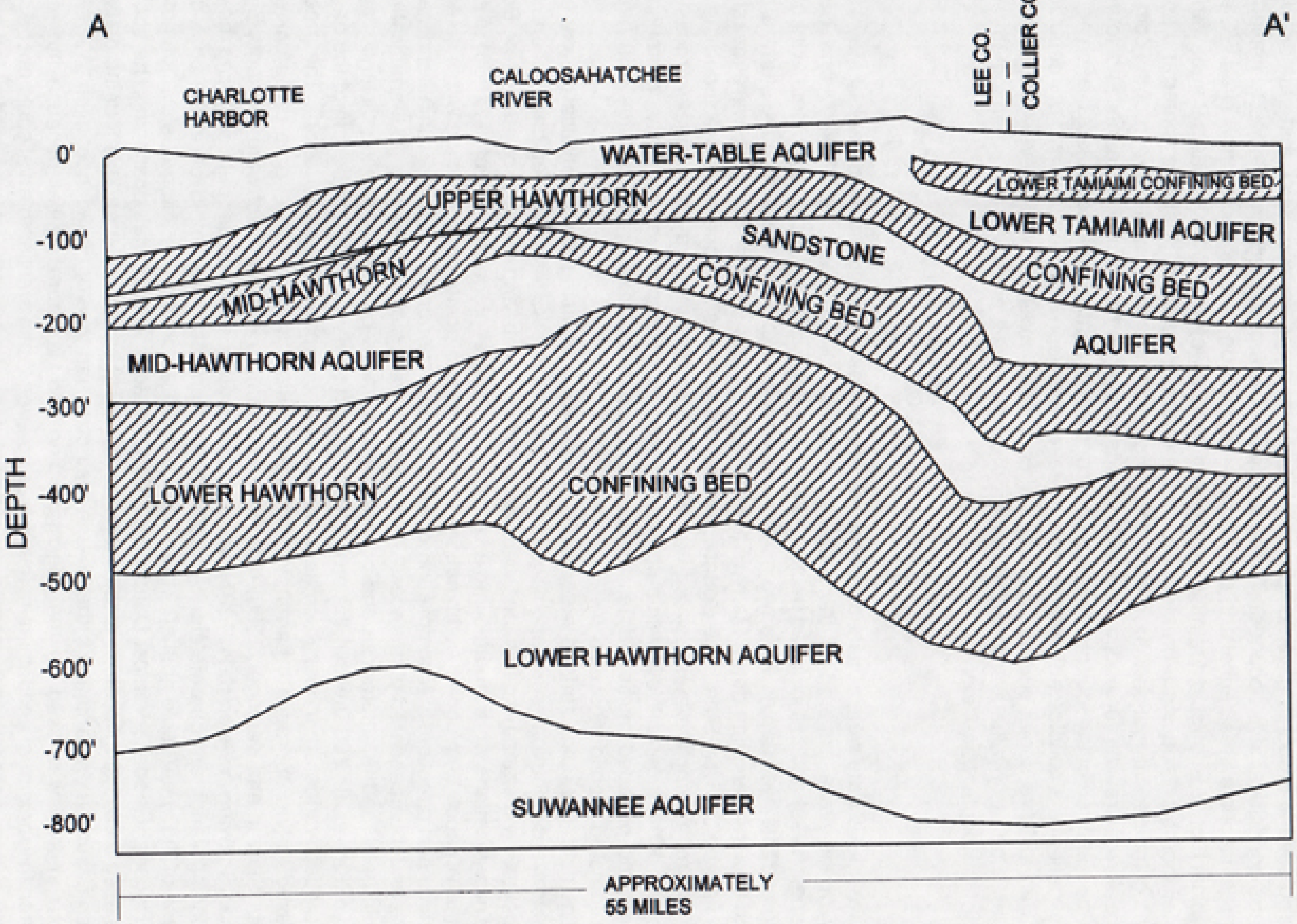

Figure 2- General hydrogeology of the Lower West Coast Planning Area (after Bower et al., 1990)

expanding water use demands that are primarily from population growth along the coast and agricultural developments inland. The past decade has experienced a significant rise in water use, and several droughts have compounded stress on these aquifers, such that periodic water shortage conditions have occurred. These conditions have prompted the SFWMD to implement water restrictions on residential and commercial irrigation on several occasions. The LWC area has typical Florida subtropical rainfall, which averages between 50 to 54 inches per year with the summer months producing a greater percentage of the annual total than the winter and spring months combined. Irrigation withdrawals occurring during the winter and spring months coincide with peak withdrawals for public supply demands caused by seasonal residents and tourists. Even though three of the four aquifers are semiconfined to tightly confined systems, each aquifer may experience a considerable range in water levels between seasonal wet and dry conditions.

In an effort to depict current dry seasonal conditions, available water level data from May 1999 are used to evaluate spatial distribution of water levels and map the potentiometric surfaces of the primary aquifers.

METHODOLOGY

Water level data were obtained from available sources targeting the third week of May 1999. Many of the wells are part of the monitoring network established by SFWMD and USGS (Switanek, 1999) and are included because they have established station parameters. Unknown casing and total well depths were two primary reasons for excluding wells from the study; a third reason was the sampling date. Many of the monitoring wells used in this study were measured in the field by the USGS and Lee County. The sampling dates of those wells precluded the use data from monitoring wells associated with water use permits that are predominately measured at the end of the month. Wells with automated recorders were accessed remotely or through file transfer and provided multiple dates for selecting consistent measurement dates with nearby nonautomated monitoring wells.

The data, excluding surface water levels, were evaluated using basic statistical measures to characterize distribution within each aquifer. The data was transformed to log base 10 and outliers beyond two standard deviations were excluded. The data and their associated State Plane coordinate locations were inputted into a variogram computer program (Kim, et al., 1985) to evaluate the variance between all combinations of pairs of data points or data points within selected distances and directions. A compilation of results listed the number of pairs within set distance ranges and mean squared differences. These results were plotted to seek a mathematical relationship between the differences and distance. An iterative process of varying distance, angle and dip (Kim et al., 1985) within the program was used to visually find the best fit of the data to a theoretical variogram model, such as spherical, linear, exponential or gaussian. The process was used to find appropriate parameters for interpolating the water level data using universal kriging (Skrivan and Karlinger, 1980). The kriging algorithm within the software package, Surfer (Golden Software, version 6.04, 1997), was used to contour each aquifer data set using the corresponding variogram parameters. Another iterative process was employed in the contouring process of the water-table aquifer, where additional data points with assumed elevations of 0.0 feet, National Geodetic Vertical Datum (NGVD) were added in coastal locations. The contour maps used a consistent scale to display a regional view of each aquifer and contour intervals are chosen based on presentation rather than a restricting variance or confidence level. A five-foot contour interval was used on the sandstone and Mid-Hawthorn aquifer because the range between the maximum and minimum levels was so large that a smaller interval could not be adequately shown on the chosen map scale. The two-foot contour interval was used in the water-table and Lower Tamiami maps because the ranges were smaller.

RESULTS

At least 30 wells with known station parameters and water levels were measured in each aquifer during the third or fourth week in May. The water-table aquifer potentiometric surface was constructed using 130 wells, 15 surface water stations, and 15 additional arbitrary points with assumed water levels of 0.0 feet, NGVD. The additional data points are included in the data set to improve contouring near the coast. Many of the water levels are recorded on May 18 or 19, 1999, however the entire sample period includes data recorded from May 17 through 31, 1999.

Since each aquifer has some negative readings (below sea level), every value is adjusted by an equal amount to increase the minimum value to above zero. Each aquifer data set proved to be lognormally distributed with the exclusion of one to three readings that were beyond two standard deviations from the mean. Many hydrogeologic parameters have data sets that are lognormally distributed to some base (Delhomme, 1980).

Multiple attempts were made to fit the variograms to a spherical model to find an appropriate nugget value, range and sill, under the assumption that the data sets were stationary. Isotropic and anisotropic attempts were tested based on topographic slope and previous potentiometric maps. The data sets for the water-table and sandstone aquifers appeared to loosely fit the expected spherical model, while the Lower Tamiami and Mid-Hawthorn data sets proved to fit only a linear model. Fitting a variogram to the spherical model was somewhat subjective. Knudsen and Kim (1978) showed that there are methods to evaluate fit and verify the appropriate theoretical model, however, these methods were not employed in this study. Both water-table and sandstone aquifer variograms could be made to fit a linear model with the proper anisotropic orientation. The linear variograms had their ranges set by the maximum distance between sampling points since sill values were not determined. In either the linear or spherical variograms, nugget values were always present indicating an inherent sampling error or uncertainty. The average variance from the variograms ranged from 1.14 to 1.48 feet.

The potentiometric surface maps have contour intervals that fit the range in water levels and map scale; they are set by practical reasons rather than statistical (Figures 3-6). A consistent map scale of 1:1,130,000 is used in each map for a regional view of the LWC Planning Area. The kriging interpolation used derived nugget values to allow some smoothing at data point locations and extrapolated to distances set by the variogram ranges. The northern extent of extrapolation for the water-table aquifer was truncated due to the lack of data and physiographic changes in Charlotte and Glades Counties. The northern and eastern extents of the Lower Tamiami potentiometric surface are also truncated due to the lack of data or pinching out of the aquifer. The surfaces represent dry seasonal hydrologic conditions and corresponding high ground water usage for irrigation and public consumption.

DISCUSSION

Fitting the variograms to linear models indicates that the data are related to each other within the distances of the collected data. The linear models do not establish the distance at which data points become unrelated. This result may indicate that there is insufficient data defining the aquifers, or that is there is a large-scale drift in the data. Delhomme (1979) describes the effects of a dipping aquifer slope on hydraulic head and by using a method of least squares an estimate of drift can be used to factor out its effects on the data set. Complex drift resulting from a 'hilly aquifer' may require polynomial filtering. Excluding the Water Table aquifer, each aquifer has a general dip and thickening to the southwest that may influence the data as described by Delhomme (1979). Each aquifer also has local variability in thickness and lithology that may

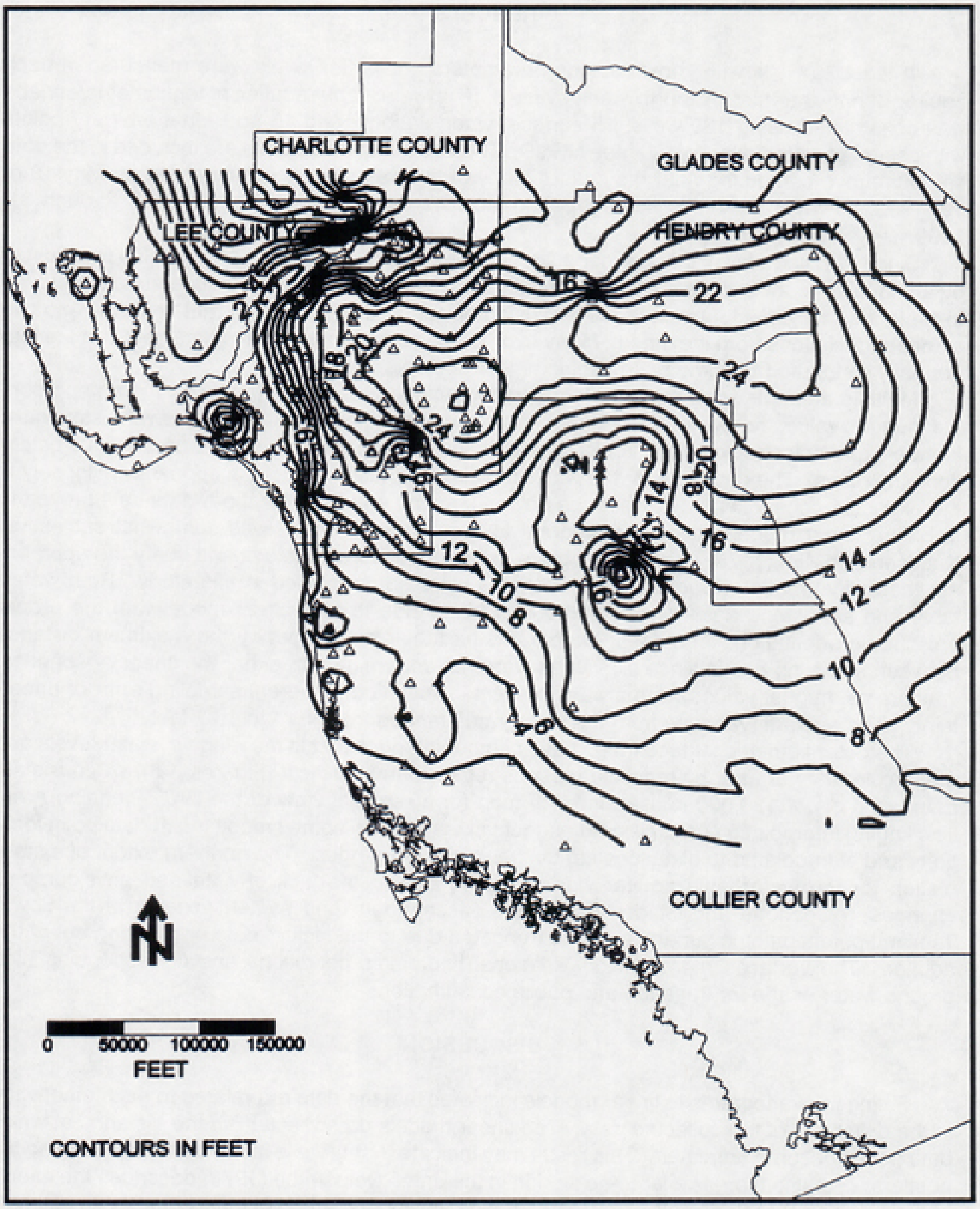

Figure 3. May 1999 potentiometric surface of the water table aquifer.

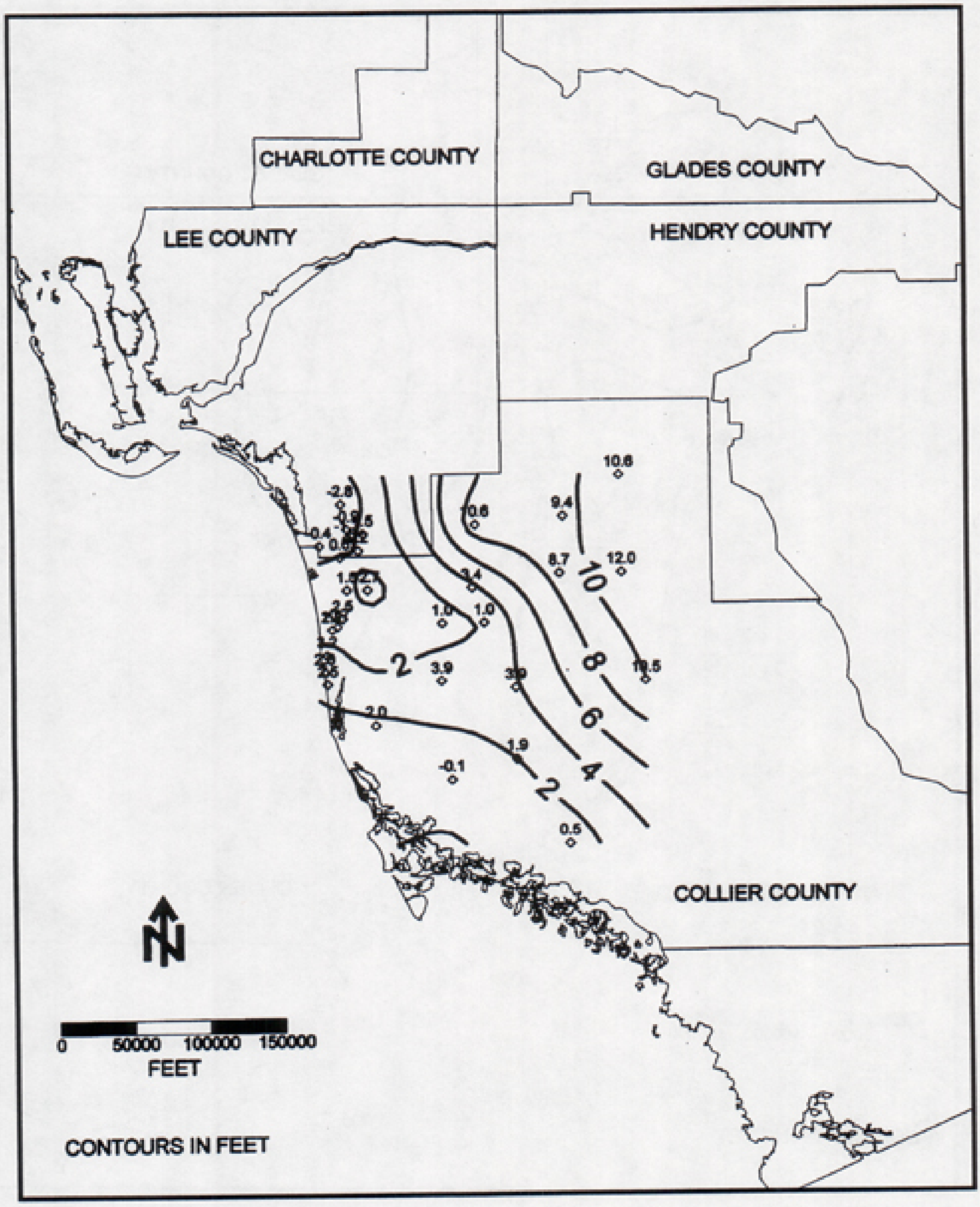

Figure 4. May 1999 potentiometric surface of the lower Tamiami aquifer.

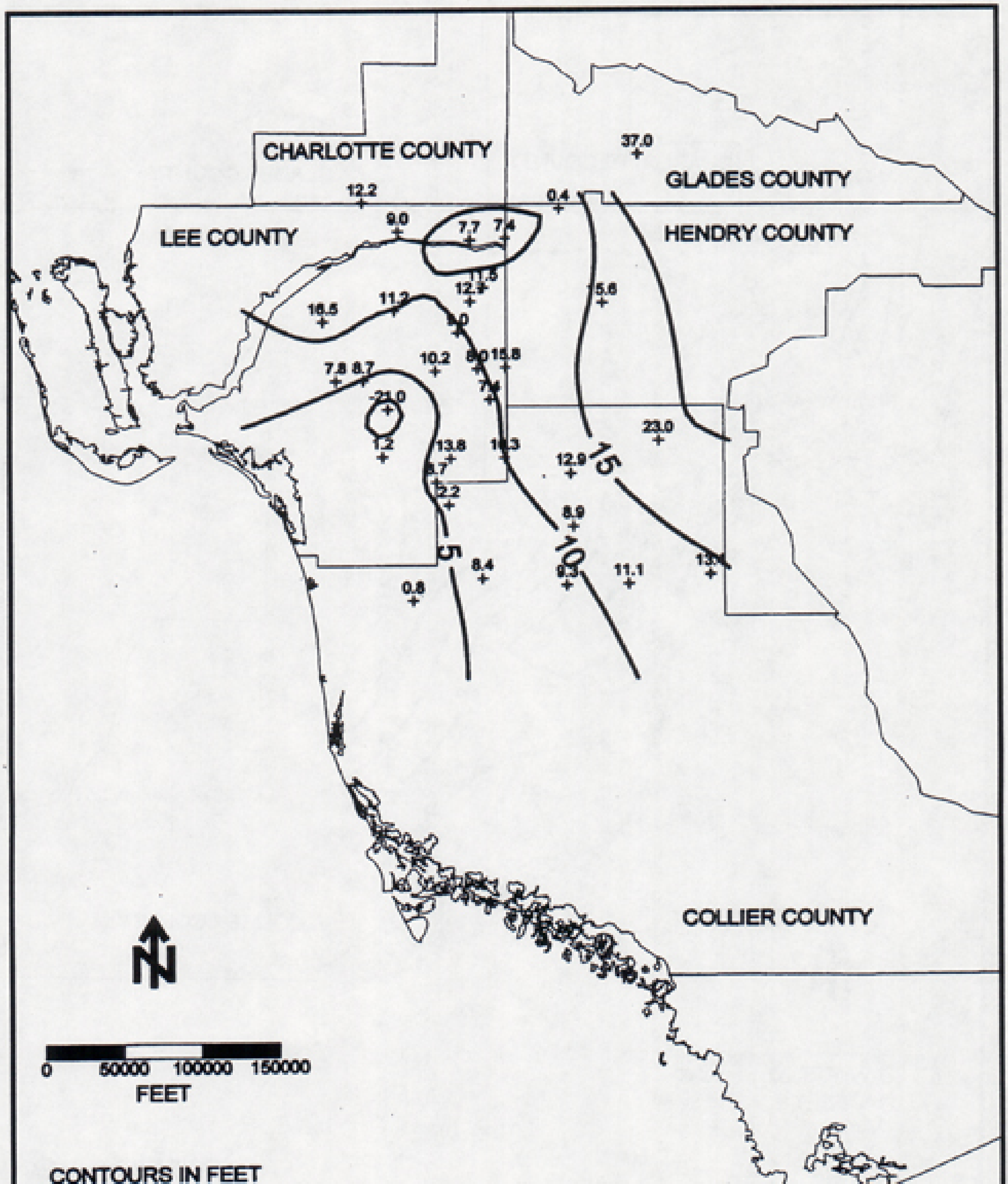

Figure 5. May 1999 potentiometric surface of the sandstone aquifer.

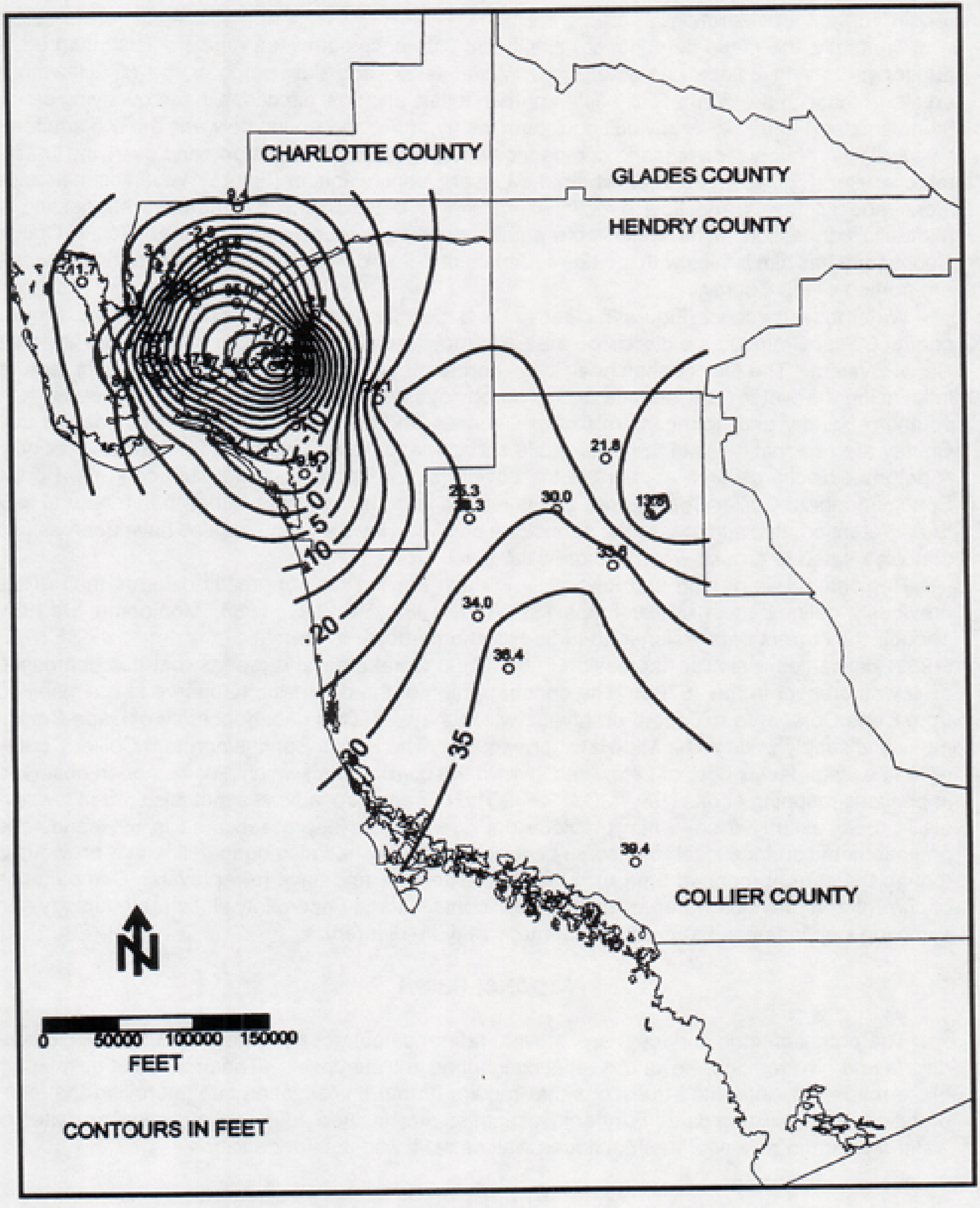

Figure 6. May 1999 potentiometric surface of the mid-Hawthorn aquifer.

require further consideration.

Generally, the maps demonstrate significant differences between aquifers illustrating each aquifer as having unique characteristics. Water levels and flow paths in the Mid-Hawthorn aquifer (Figure 6) are dramatically different than levels and flow directions in the overlying sandstone aquifer (Figure 5), clearly distinguishing the hydraulic separation between the two aquifers.

A similar observation is made comparing water levels in the sandstone and overlying water-table aquifer (Figure 3). In areas where the Lower Tamiami aquifer (Figure 4) overlies the sandstone aquifer, levels and flow directions are similar between the two aquifers suggesting a hydraulic connection. The water-table aquifer overlies the Lower Tamiami aquifer in Collier County and has similarities with the Lower Tamiaimi in flow direction and water levels in the western portion of the County.

Water table contours (Figure 3) clearly reflect the influence of the Corkscrew Swamp (north-central Collier County) as a discharge area and may also show influences from the Big Cypress Canal System. The Caloosahatchee River (northern Lee County) is another dominant feature influencing the water table surface and is an obvious discharge area. The Immokalee High in southern Hendry and northeastern Collier Counties and the plateau area in southeastern Lee County are regional highs in the water table surface, and flow radiates out from these locations. A potential discharge area appears in the Lower Tamiami potentiometric surface in the Bonita Springs/northern Collier County area and is related to pumping stress rather than a natural feature. Potentiometric surfaces in the sandstone and Mid-Hawthorn aquifer also have depressions that are related to ground water withdrawals.

Regional areas of high and low levels in each aquifer are not greatly different than areas previously delineated in earlier maps (SFWMD, 1982; SFWMD, 1986; Montgomery, 1988). Though the current depression in the Mid-Hawthorn aquifer is dramatic, it is not new. SFWMD (1982) delineates a similar depression in the Cape Coral area and reports that this depressed area was present in the 1970's. The central portion of the depression appears to have shifted from Cape Coral area to south Fort Myers, which may reflect the abandonment of Cape Coral's municipal supply wells in the Mid-Hawthorn aquifer. The Bonita Springs/northern Collier County area has water levels near or below sea level in the current map, which also has been observed in previous mapping efforts (SFWMD, 1986). The current map indicates that this area of low levels is more extensive now than previous depictions. The depressed area in the sandstone potentiometric surface located in south central Lee County has also been delineated previously, though the current mapped area may be more extensive and have lower levels. Comparisons of current and previous water level conditions contain some uncertainty since methodology and sampling locations used to produce the maps may be different.

CONCLUSION

The potentiometric surface maps provide reference surfaces for May 1999 hydrologic conditions and give regional views of spatial distribution in water levels. The process of developing these maps has generated questions that require further investigation into improving the interpretation of the existing data. Further investigation may include additional statistical analyses of water levels and review of the monitoring well network and aquifer definition.

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HYDROGEOLOGIC IMPLICATIONS OF URANIUM-RICH PHOSPHATE IN NORTHEASTERN LEE COUNTY

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ABSTRACT

Shallow groundwater in the Alva area of northeastern Lee County contains unusually high concentrations of dissolved uranium, which is locally a health concern. This paper describes the results of a study conducted to identify the uranium source. Most of the dissolved uranium is apparently leached from phosphatic sand and gravel present in the Pliocene age Buckingham Marl Member of the Tamiami Formation. This phosphorite contains very high concentrations of easily mobilized uranium, which may be caused by its high hexavalent uranium content. Stratigraphic evidence indicates the uranium-rich phosphate accumulated in a sedimentary trough where the Buckingham Marl is unusually thick.

The study also investigated a geochemical problem dealing with the fractionation of 238U and its daughter isotope 234U in sediment and groundwater. These results indicate that uranium valence behavior plays an important role in the fractionation process within the study area and perhaps in other hydrogeologic systems.

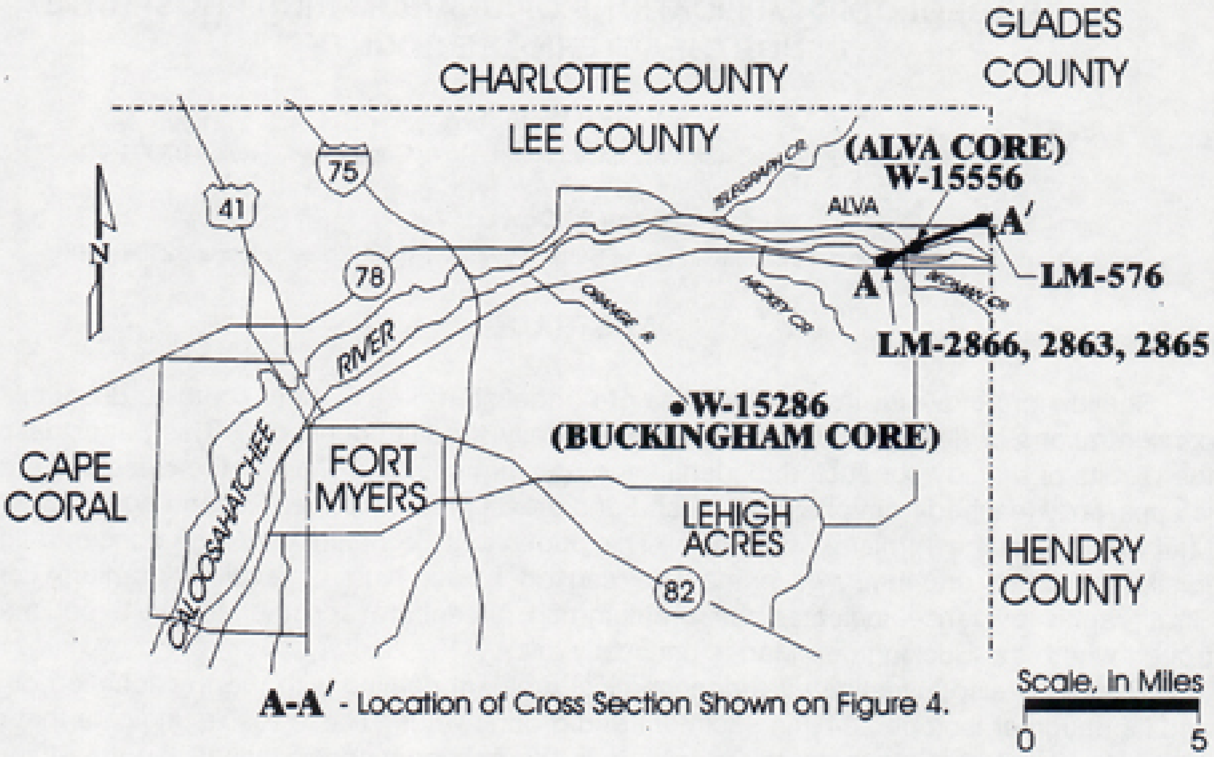
INTRODUCTION

n 1981 the Lee County Health Department conducted an investigation that identified unusually high concentrations of dissolved uranium in samples collected from shallow wells used for domestic and some public water supply in the community of Alva, northeastern Lee County (Pellicer and O'Connell, 1981). Levine (1988) studied dissolved uranium distribution in the area as part of a countywide groundwater survey and confirmed that high concentrations of uranium are present in the surficial aquifer near Alva. He reported dissolved uranium at concentrations up to 460 parts/billion (ppb) and concluded that it was supplied by a rich accumulation present in the local sediments.

This paper describes the results of a subsequent study that examined uranium characteristics and distribution in shallow sediments of the Alva area and surrounding north-central Lee County (Figure 1). The goal was to identify the specific uranium host material and gain a better understanding of the geochemical and hydrologic factors contributing to the high dissolved uranium concentrations found at Alva compared with other parts of the region. This information was used to help evaluate the potential for other uranium "hot spots" to be present in Lee County.

The United States Environmental Protection Agency may soon establish a 20 ppb maximum contaminant level for uranium in drinking water, because it is a carcinogen and has been linked with kidney disease (ATSDR, 1990; USEPA, 1998). Uranium, at the levels found in the Alva drinking water supply, poses a potential health risk to consumers. An improved understanding of the type of uranium deposits present in the region and how it is mobilized into the groundwater system would be a useful tool for managers in planning future development of the surficial aquifer.

A second part of the study examined a geochemical problem related to the behavior of two naturally-occurring isotopes of uranium; 238U and its daughter 234U. These two forms of ura-



A-A' - Location of Cross Section Shown on Figure 4.

Figure 1. Locations of cores and cross section wells.

nium, although similar in their properties, tend to have a different fate in nature. Most natural waters contain an excess of 234U, which is apparently mobilized from uranium-bearing minerals (Cherdyntsev, 1971). The cause of this fractionation process is a subject of scientific interest because 234U/238U system dynamics are applied in important fields such as sediment dating, uranium prospecting, and natural tracer studies of groundwater systems such as the south Florida "Boulder Zone" (Broecker, 1963; Cowart, et al., 1978; Roe and Burnett, 1985). It is likely that several different mechanisms are involved in the fractionation process, the effectiveness of each being dependent on local environmental conditions.

Levine (1988) showed that shallow groundwater in much of Lee County, including the Alva area, has an unusual composition of uranium isotopes typified by a relative shortage of 234U. This feature, as will be seen, makes conditions favorable for investigating how 234U/238U fractionation occurs in the study area and potentially in other hydrologic systems. The main focus in this part of the study was to examine the role uranium valence behavior plays in the overall fractionation process.

ANALYTICAL PROCEDURES

Samples for uranium analyses were collected from two cores drilled in 1982 by the Florida Geological Survey (Figure 1). The Alva core was drilled on the north side of the Caloosahatchee River in the general area shown to have maximum dissolved uranium levels. The Buckingham core came from a site located approximately eight miles southwest of Alva where uranium concentrations in the surficial aquifer were reported to be about 1 ppb.

The general procedures for extracting uranium from the sedimentary matrix followed the methods of Clarke and Altschuler (1958) and Kolodny and Kaplan (1970). These procedures enabled uranium to be separated into its two main valence states (U+4 and U+6), as was necessary to examine valence behavior. This work was done in a glove bag under a nitrogen atmosphere to reduce the potential for inadvertent sample oxidation due to experimental methods.

Uranium spikes (internal standards) in both valence states were added at the beginning of each experiment. Spike behavior was then used to estimate the amount of sample uranium valence crossover that had occurred. Some oxidation and to a lesser extent reduction of sample uranium apparently took place during all of the experiments. The analytical results were corrected for these influences.

Purified uranium was plated on a stainless-steel planchet and analyzed by alpha spectrometry. Repeated experiments were performed using a marine phosphate standard rock (NBS 120b) as a quality assurance check. Our results compared closely with those reported by Roe and Burnett (1985).

HYDROGEOLOGY

The hydrogeology of the study area was investigated because it controls both the mode of uranium accumulation and how it is mobilized by groundwater. The following section briefly describes the shallow hydrogeology of the Alva area. Comparisons with other parts of the county are made later in the paper. The important hydrostratigraphic units in the upper 220 feet of the Alva core are shown on Figure 2. The terminology used conforms with the unit designations adopted by Wedderburn, et al., 1982; Missimer, 1984; and Scott, 1988)

Pleistocene to Recent age terrace deposits consisting mainly of clean quartz sand form the upper several feet of sediment cover. The terrace deposits are underlain by the Pliocene age Buckingham Marl Member of the Tamiami Formation. The Buckingham Marl consists of gray to light green carbonate mud with variable amounts of quartz sand, marine fossils, and some phosphatic sand and gravel. Up to several feet of moldic limestone occurs in the upper part of the Buckingham Marl, and lenses of dolostone are locally present in the lower half of the unit.

The surficial aquifer in the Alva area is comprised of permeable strata in the Buckingham Marl and to some extent the overlying terrace sands. Productivity is generally low because the thicker limestone members of the Tamiami Formation, present in many other areas of Lee County, are absent. The base of the surficial aquifer is confined by dolomitic clays in the upper part of the Miocene to late Pliocene age Peace River Formation (Hawthorn Group). Phosphatic sand and gravel are common components of the Peace River Formation.

The Sandstone aquifer is the uppermost artesian aquifer in the region. It occurs within sandstones and carbonate rocks of the Peace River Formation at depths ranging from 115 to 195 feet below land surface in the Alva area. The Sandstone aquifer contains fresh water in much of Lee County, but mildly brackish water is present at Alva and adjacent parts of the Caloosahatchee River Valley. Dissolved mineral content generally increases with depth in the deeper aquifers that underlie the Sandstone aquifer.

Unlike most of Lee County, Alva is not serviced by municipal water supply. Due to the limited fresh water resources available, residents rely on shallow wells completed in the Buckingham Marl for their potable needs. This is one of the few places, or perhaps the only place, in Lee County, where the Buckingham Marl is used for potable water supply.

DISSOLVED URANIUM SOURCE

Uranium Distribution in Sediment

Mean uranium concentrations for groups of samples based on stratigraphic unit designation for both cores are given in Figure 3. Analytical results in tabular form are listed in Table 1. Many of the geologic formations studied contain granular phosphate. When practical, phosphatic sand and gravel were sorted out of the sample matrix for separate analysis. Phosphate sample results

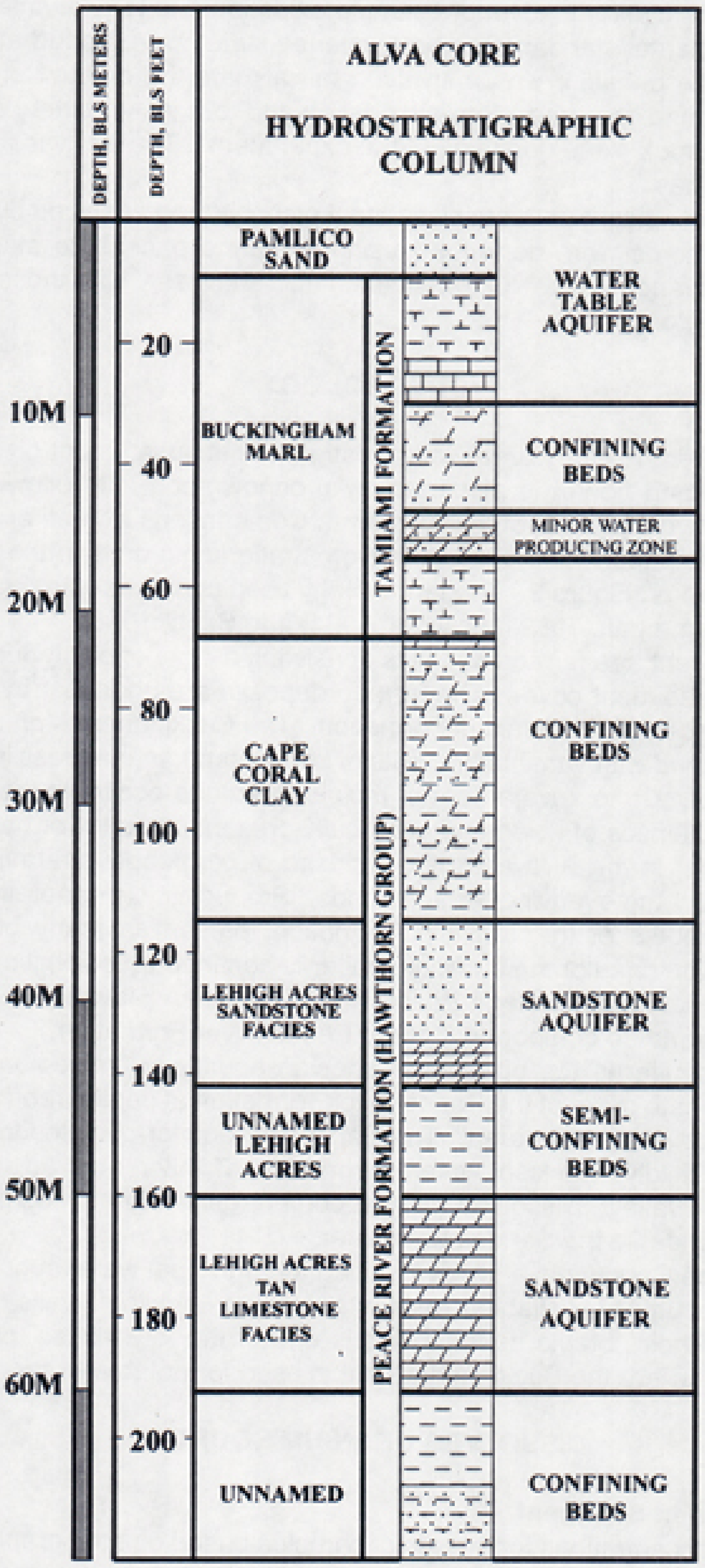


Figure 2. Hydrostratigraphic column, Alva core.

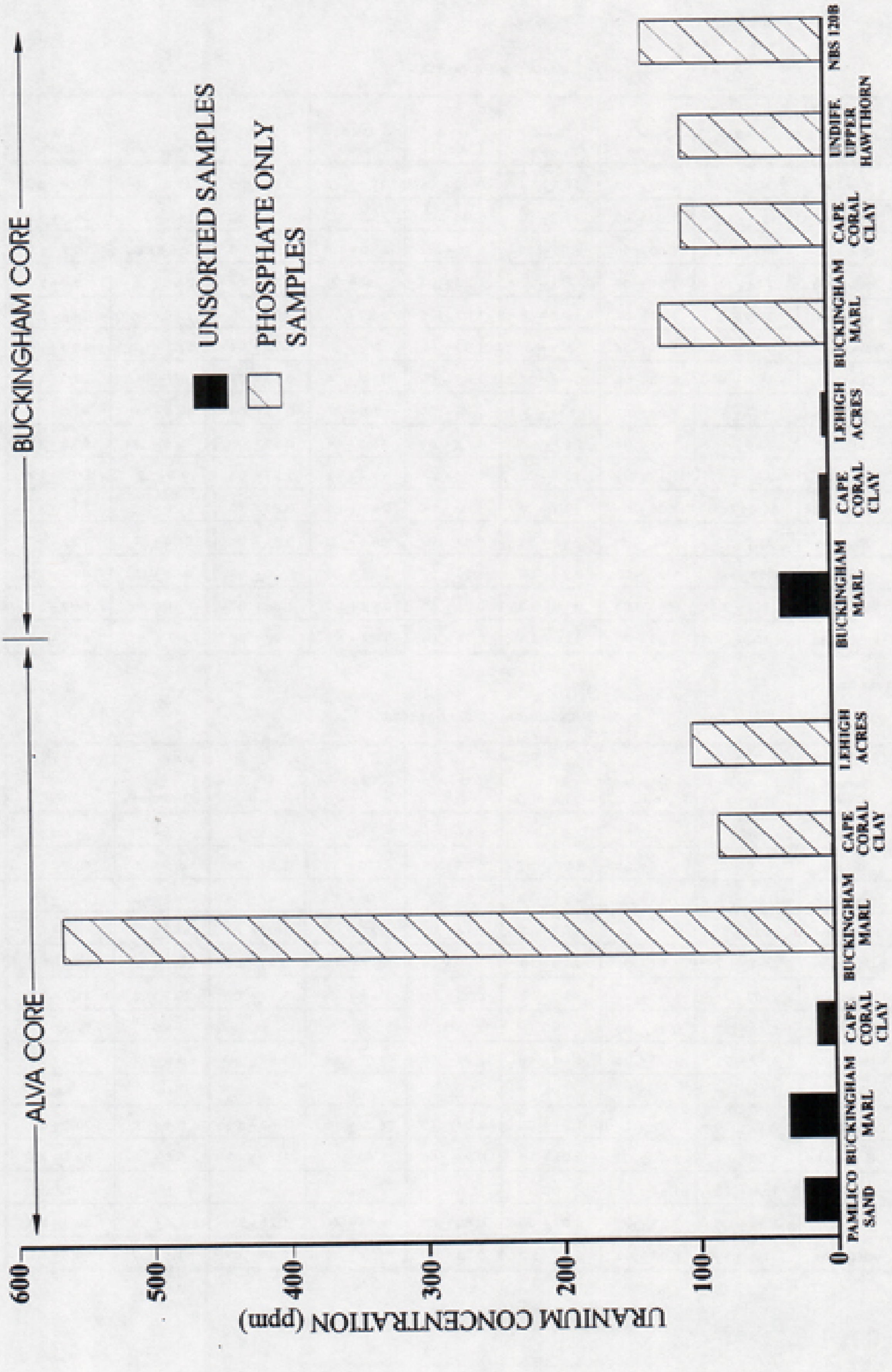


Figure 3. Bar graph of mean Uranium concentrations, Alva and Buckingham core samples grouped stratigraphically.

TABLE 1.

ALVA CORE ANALYSES

Sample Depth (feet)	Sample Type	Total U (ppm)	Total U A.R.	U+4 (ppm)	U+4 A.R.	U+6 (ppm)	U+6 A.R.	% Oxidation	% U(IV)
5	Unsorted	26.8±.5	0.95±.03	15.7± .4	0.96±.05	11.1± .2	0.93±.03	11.0± .2	58.6±2.3
15	Unsorted	45.4±1.2	1.06±.05	16.1± .6	1.06±.05	29.3±1.2	1.06±.08	14.5±2.1	35.5±3.9
25	Unsorted	44.0±1.6	1.00±.06	8.00±.28	1.10±.07	36.0±1.6	0.97±.08	8.6±1.0	18.4±5.0
31	Phosphate	729±10	1.16±.02	331± 4	1.39±.03	398± 7	0.98±.03	34.8± .8	45.4±1.8
35	Unsorted	38.9±.8	1.01±.04	14.6± .5	1.07±.05	24.3± .7	0.98±.05	12.6± .4	37.5±2.7
40	Phosphate	507±7	1.05±.02	245± 3	1.39±.03	262± 6	0.72±.04	37.1±1.0	48.3±1.9
45	Unsorted	25.6±.6	1.18±.05	14.6± .4	1.43±.05	11.0± .4	0.83±.07	9.7± .6	57.0±3.1
45	Phosphate	457±6	1.05±.02	192± 3	1.75±.04	265± 5	0.54±.04	48.4±1.0	42.0±1.8
55	Unsorted	17.8±.5	1.12±.06	5.50± .30	1.48±.08	12.3± .4	0.97±.06	10.5± .3	30.9±3.7
65	Unsorted	22.9±.4	1.17±.04	11.5± .3	1.07±.04	11.4± .3	1.27±.04	9.3± .2	50.2±2.4
69	Phosphate	84.4±1.8	1.06±.04	59.7± .9	1.10±.04	24.7±1.4	0.96±.10	51.5±1.8	70.7±3.1
75	Unsorted	21.2±.6	1.02±.05	2.59±.12	2.47±.09	18.6± .6	0.81±.05	31.4± .7	12.2±3.7
90	Unsorted	5.95±.14	1.28±.06	3.74±.09	1.27±.07	2.21±.09	1.28±.07	34.5± .3	62.7±3.1
118*	Phosphate	102±3	0.96±.03	86.6±3.3	0.83±.03	15.6±4.7	1.68±.07	ND	84.7±3.9
137	Phosphate	102±2	0.98±.03	83.8±2.1	0.75±.04	18.1±1.0	2.03±.08	8.9± .9	82.2±2.7

*uncorrected results

BUCKINGHAM CORE ANALYSES

Sample Depth (feet)	Sample Type	Total U (ppm)	Total U A.R.	U+4 (ppm)	U+4 A.R.	U+6 (ppm)	U+6 A.R.	% Oxidation	% U(IV)
8	Unsorted	ND	ND	ND	ND	ND	ND	ND	ND
15	Unsorted	12.0±.2	1.14±.04	5.87± .17	1.03±.05	6.13±.17	1.24±.06	2.5± .1	48.9±2.3
17	Unsorted	12.0±.3	1.15±.05	3.96±.13	1.53±.07	8.04±.27	0.97±.06	4.2± .3	33.0±3.4
17	Phosphate	122±1	1.12±.02	82.9± .8	1.14±.03	39.0±1.0	1.09±.04	34.5± .7	68.0±1.3
21	Unsorted	64.1±1.7	1.02±.04	28.0± .8	1.13±.06	36.1± 1.4	0.94±.06	25.1±1.2	43.7±3.5
25	Phosphate	107±2	1.04±.04	76.1± .9	0.98±.03	30.9± 1.9	1.17±.08	36.7± .9	71.2±2.7
34	Unsorted	6.18±.27	0.99±.06	ND	ND	ND	ND	ND	ND
43	Unsorted	6.47±.21	1.00±.06	4.40±.18	0.76±.08	2.07±.11	1.61±.10	6.8± .2	68.3±4.3
50	Unsorted	ND	ND	ND	ND	ND	ND	ND	ND
70	Unsorted	3.26±.10	1.72±.10	1.24±.06	2.04±.13	2.02±.09	1.53±.09	6.4± .1	38.0±4.1
90	Unsorted	4.60±.11	1.26±.06	2.92±.09	0.99±.06	1.68±.07	1.73±.09	5.6± .2	63.5±3.1
110	Unsorted	5.90±.22	1.14±.05	ND	ND	ND	ND	ND	ND
130	Unsorted	3.21±.08	1.15±.05	0.97±.03	0.88±.06	2.24±.08	1.28±.06	5.4± .1	30.2±3.4
161	Phosphate	108±1	0.98±.03	91.5±2.0	0.73±.03	16.6± .9	2.44±.07	11.5± .7	84.6±1.5

are designated with a shaded pattern on the bar graph. The remaining results reflect samples where no sorting was conducted.

Some clear patterns are evident from the data. Unsorted samples from all stratigraphic units contain low to moderate amounts of uranium, with mean determined values ranging from 4 to 32 parts/million (ppm). Uranium concentrations in the Buckingham Marl are slightly higher than the other stratigraphic units.

Phosphate samples, excluding those from the Buckingham Marl Member of the Alva core, form a second group of analytes. They have fairly consistent uranium concentrations ranging from 84 to 122 ppm. Typical values for marine phosphorite around the world are in the range of 50 to 150 ppm (Clarke and Altschuler 1958; Kolodny & Kaplan, 1970).

Phosphate samples from the Buckingham Marl Member of the Alva core have anomalous high uranium concentrations. Measured values range from 457 to 729 ppm, with a mean uranium content of 564 ppm. These are some of the highest values for marine phosphorite reported in the literature. Maximum uranium concentrations occur in the upper part of the Buckingham Marl then progressively decrease with core depth.

Analytical results indicate that uranium-rich phosphate present in the Buckingham Marl Member of the Tamiami Formation is the likely source for the unusually high amounts of dissolved uranium present in shallow groundwater in the Alva area. This contrasts markedly with the Buckingham area, where there is no evidence of significant uranium enrichment in phosphate from the Buckingham Marl Member, and dissolved uranium concentrations in groundwater are only about 1 ppb.

Uranium Mobility

Uranium in marine phosphorite is normally not very soluble (Wagner, 1988). However, for some reason, uranium in phosphate from the Alva area seems to be easily mobilized by shallow groundwater. Leaching experiments were conducted on selected samples to help determine if this is true. One sample consisted of uranium-rich phosphate from Alva; the other was a sample of "normal" phosphorite from the Peace River Formation. Samples were powdered and immersed in a mild basic solution (0.2N potassium carbonate) for 96 hours. Solids were then separated from the solution by vacuum filtration and each phase analyzed for uranium content.

Analytical results, reported in Table 2, indicate that the uranium-rich phosphate sample from the Alva core contained approximately 517 ppm of uranium. Of this, 175 ppm, or nearly 34%, was leached into the aqueous phase. In contrast, the Peace River Formation sample contained approximately 60 ppm of uranium and only 4.5% (2.7 ppm) was leached. These results demonstrate that uranium present in the uranium-rich phosphate at Alva is unusually soluble.

X-ray diffraction (XRD) analyses were conducted on most phosphate samples to determine if variations in mineralogy could help explain the unusual properties of the uranium-rich phosphate. Carbonate fluorapatite was the dominant mineral phase found in all samples, which is typical for marine phosphorite. No significant differences in peak width or intensity were observed that might indicate varying degrees of sample crystallization. The only other minerals identified were quartz, calcite, and dolomite, which all represent the relatively low uranium concentration matrix sediments.

One significant difference in uranium property that was identified is that uranium-rich phosphate samples from the Alva area were found to contain from 50 to 60% U+6. In comparison, phosphate samples from Buckingham Marl Member of the Buckingham core and the Peace River Formation in both cores only contained 15-30% hexavalent uranium. The much higher solubility of U+6 compared with that of U+4 may in part explain why uranium in the uranium-rich phosphate is so easily mobilized.

TABLE 2.

COMPARISON OF LEACHING TEST AND URANIUM ISOTOPE OXIDATION STATE ANALYSIS RESULTS

Sample #	Description	Uranium Conc. (in ppm)	234U/238U A.R.	% Uranium Mobilized	Total U (ppm)	Total U A.R	U+4 A.R.	U+6 A.R.
Alva 23	Leach Solution	175± 7	0.66±.10	N/A	N/A	N/A	N/A	N/A
Alva 24	Leached Rock Sample	342± 6	1.25±.01	N/A	N/A	N/A	N/A	N/A
Combined Leach Solution and Leached Rock Results		N/A	N/A	33.8±.4	517± 9	1.05±.04	N/A	N/A
Alva 13	Equivalent Oxidation State Analysis Sample	N/A	N/A	N/A	507± 7	1.06±.02	1.39±.03	0.72±.04
Buck 20	Leach Solution	2.68±.07	2.12±.05	N/A	N/A	N/A	N/A	N/A
Buck 21	Leached Rock Sample	56.9±1.2	1.00±.02	N/A	N/A	N/A	N/A	N/A
Combined Leach Solution and Leached Rock Results		N/A	N/A	4.5±2.2	59.6±1.2	1.05±.04	N/A	N/A
Buck 16	Equivalent Oxidation State Analysis Sample	N/A	N/A	N/A	108± 1	0.98±.03	0.73±.03	2.44±.07

N/A = Not Applicable

Notes: 1) Independent samples, not sample splits, from the same sampling horizon were used in leaching tests and uranium isotope oxidation state analysis.

2) Liquid phase uranium concentrations are based on initial rock sample weights.

Stratigraphic Controls

While the specific properties that give the uranium-rich phosphate its unusual characteristics cannot be fully explained, there is good evidence to help answer the question of why it is present in the Alva area. A west-to-east geologic cross section through the area is illustrated on Figure 4. Locations of geologic control points used to prepare the section are shown on Figure 1. To the west and east of Alva, the Buckingham Marl ranges from 15 to 30 feet thick, which is typical of the region. The unit thickens to about 60 feet at Alva and apparently infills a trough in the Peace River Formation sediments. It is suspected that this trough led to the deposition of uranium-rich phosphate in the Alva area.

The Buckingham Marl Member is continuous throughout most of north and central Lee County. It apparently pinches out in southern Lee County and is replaced by a quartz sandy facies of the Tamiami Formation in the western part of the county. The area where the Buckingham Marl subcrops represents the likely boundaries of other uranium-rich deposits in Lee County, if they do occur.

Natural Gamma Log Survey

Natural gamma logs for the boreholes of the Alva and Buckingham cores are compared on Figure 5. The uranium-rich phosphate-bearing sediments at Alva have a distinctively high gamma signature, with up to 340 API counts/second (cps) through the interval. Maximum gamma activity for the Buckingham Marl Member interval at the Buckingham core site is only about 100 API cps. This occurs near the base of the unit where mixing with highly phosphatic sediments in the Peace River Formation apparently occurred due to bioturbation.

These observations suggest that other rich uranium deposits, if present in the region, can be identified based on their high gamma signature. With this in mind, the logs for 34 other wells in Lee County were examined. The only other boreholes found with unusually high gamma activity within the Tamiami Formation were also from the Alva area. Thirty-four examples only represent an initial screening of the county. The results do not prove that the conditions at Alva are unique, but they at least suggest that other rich uranium accumulations are not widespread. If they do exist, the natural gamma log seems to be an effective screening device to help identify them.

URANIUM ISOTOPE FRACTIONATION

Introduction

There are two naturally occurring isotopes of uranium in the 238U decay series; parent 238U and its daughter 234U. Research conducted during the past few decades has shown that the fate of these two chemical species is different in nature, despite the fact that they are only separated in the 238U decay series by short-lived isotopes of thorium and protactinium (234Th and 234Pa). Most surface and groundwaters contain an excess of 234U that tends to be balanced by a relative shortage of it in uranium-bearing minerals (Cherdyntsev, 1971; Osmond and Cowart, 1976). This general relation suggests that 234U is preferentially mobilized into the aqueous phase.

The natural partitioning of radionculides produced by decay of the same parent atom is referred to as fractionation. Radioactive decay tends to produce a system in equilibrium, while differences in chemical and physical properties can fractionate isotopes of the same element. The degree of fractionation in any system can be quantified in terms of the relative radioactivity level of one isotope compared with another. The 234U/238U activity ratio (A.R.) is of importance in this discussion.

In a closed geochemical system, radioactive decay occurring at different rates will cause a state of secular equilibrium to develop between a short-lived daughter and long-lived parent isotope within several half-lives of the daughter. Both isotopes at equilibrium will decay at the same rate and their A.R. will equal 1.0. It had been assumed that 234U/238U A.R.s in most natural systems would be at equilibrium, since the half-life of 234U (2.48 x 105 years) is relatively short compared with the much greater age of most earth materials. In fact, the excess of 234U in most natural waters causes 234U/238U A.R.s to be greater than 1.0 in many groundwater systems. Uranium-bearing minerals, which have a depleted supply of 234U, typically have A.R.s less than 1.0.

Levine (1988) showed that the surficial aquifer in much of Lee County, including the Alva area, has an unusual uranium isotope composition in that there is a relative shortage of 234U. Shallow groundwaters in the region are characterized by 234U/238U A.R.s significantly less than 1.0. Potential mechanisms responsible for the formation of this low A.R. groundwater are described next.

Fractionation Mechanisms

Some researchers, including Kigoshi (1971) and Osmond and Cowart (1976), attribute at least part of the excess of 234U in natural waters to the process of alpha recoil. 238U decays by emission of an alpha particle to 234Th. A recoil energy is imparted to the daughter that can propel it up to a few hundred angstroms through the rock matrix and potentially eject it into the pore water system. Subsequent decay of thorium to 234U would then explain its excess in the hydrosphere. Decay-caused damage to the host mineral or displacement of 234Th to vulnerable sites within the rock matrix would also leave 234U more susceptible to mobilization.

The formation of low A.R. groundwater is not directly explained by the recoil mechanism. However, Osmond and Cowart (1976) theorize that the process may involve uranium leaching from mineral surfaces subject to prior 234U loss caused by long periods of alpha recoil and little uranium dissolution, as might occur in a reducing aquifer. An environmental change from reducing to more oxidizing conditions would mobilize (in an isotopically non-selective way) and transfer the uranium from the solid into the aqueous phase.

Another explanation for the relatively high mobility of 234U was first proposed by Chalov (1959), who suggested that decay-produced 234U is preferentially oxidized to the hexavalent state. Mobilization of 234U would then be favored, since U+6 is several orders of magnitude more soluble than U+4 (Langmuir, 1978). More recent research (Chalov and Merkulova, 1966; Kolodny and Kaplan, 1970; Burnett and Veeh, 1977) has confirmed that U+6 A.R.s in many minerals, including marine phosphorites, are significantly higher than U+4 A.R.s, which supports Chalov's theory.

Proposed explanations for this valence behavior fall into two general categories. One theory (Rosholt, et al., 1963; Dooley, et al., 1966) attributes the process to electron-stripping and other physical behavior directly related to radioactive decay (hot atom effects). A competing idea suggests that 234U is oxidized after decay, when it is displaced to a site in the mineral lattice with higher oxidation potential (Cherdynstev, 1971).

Kolodny and Kaplan (1970) conducted an important study bearing on this issue. They found convincing evidence that about 30% of the 234U present in marine phosphorites from various ocean basins is oxidized to U+6. They noted a close comparison of their findings with those of Ku (1965), who reported a 30% 234U deficiency in marine pelagic sediments, and reasoned that 234U escape from the sediments might be caused by its oxidation and subsequent mobilization. Kolodny and Kaplan concluded that 234U oxidation was probably controlled by environmental factors. However, the fact that valence fractionation trends are so consistent, even though redox conditions in the different depositional environments studied are not, suggests that hot atom effects may be important.

Like alpha-recoil, valence fractionation as described above would tend to enrich the aqueous phase in 234U and therefore does not explain the formation of low A.R. groundwater. Since recoil and valence fractionation processes both normally act in a complimentary manner, it is difficult to determine which is the more important in nature. A better comparison could be made if conditions were found where the two processes oppose each other.

Such conditions were reported by Roe and Burnett (1985), who found high U+4 and low U+6 A.R.s in insular phosphorites (avian guano source) from Pacific island sites. This apparent reduction of 234U, according to the authors, is possibly due to the high organic carbon content of the sediment. Whatever the cause, mobilization of U+6 from these sediments would generate low A.R. uranium in the agueous phase. In leaching experiments with different types of phosphate samples, Roe and Burnett showed that A.R.s of the mobilized uranium fraction closely matched the U+6 A.R. of the phosphate, regardless of whether the A.R. was high or low.

Roe and Burnett's results, and similar findings by others, suggested that valence fractionation might be an important factor in the development of dissolved uranium A.R.s in some hydrologic systems, and, under certain conditions, could generate low A.R. groundwaters. This mechanism introduced a possible explanation for the low A.R. uranium present in the surficial aquifer in the study area. The importance of this process was examined by analyzing U+4 and U+6 A.R.s in core samples and by conducting leaching experiments. The results, which are described in the following sections of the paper and shown in Tables 1 and 2, indicate that valence fractionation does offer a reasonable explanation for the dissolved uranium A.R. trends found in the region.

Total Uranium A.R.s

The term "total uranium A.R." (total A.R.) refers to the 234U/238U A.R. in the entire sample, regardless of valence. Total A.R.s in approximately 70% of the samples exceed 1.0, indicating an overall excess of 234U compared with secular equilibrium. Phosphate samples in both cores show consistent trends, with total A.R.s decreasing steadily from about 1.16 in the upper part of the Buckingham Marl Member to 0.98 in the deepest samples from the Peace River Formation. Unsorted sample A.R.s are more variable.

Seawater has a constant A.R. of 1.14, as does phosphate when initially formed in the marine environment. One interpretation of the phosphate results is that young uranium is present in the upper sediments of the Buckingham Marl and that progressive aging toward secular equilibrium occurs with depth. A recent uranium source seems unlikely considering the Pliocene age of the Buckingham Marl Member.

A marine transgression covered the region with seawater about 125,000 years ago, raising some possibility that uranium enrichment may have occurred at that time, "resetting the A.R. clock". However, it is more likely that the comparison with seawater A.R.s is simply coincidental.

Valence Fraction A.R.s

234U/238U A.R.s measured in the U+4 and U+6 fractions of the Alva core samples show two different data trends. Buckingham Marl Member samples generally have high U+4 and low U+6 A.R.s, with the degree of valence fractionation increasing with depth. This is particularly true of the phosphate samples, where U+4 A.R.s progressively increase from 1.39 to 1.75, while U+6 A.R.s decrease from 0.98 to 0.54 within this stratigraphic interval. These results suggest an apparent reduction of 234U in the Buckingham Marl Member.

Valence fractionation trends reverse in samples from the underlying Peace River Formation of the Alva core, which are mainly characterized by low U+4 and high U+6 A.R.s. The degree of fractionation again increases with depth, but toward opposite endpoints. U+4 and U+6 A.R.s in the deepest phosphate sample analyzed are 0.75 and 2.03, respectively. Preferential oxidation of 234U is apparently the dominant process in the Peace River Formation.

The Buckingham Marl Member is only 14 feet thick in the Buckingham core. There seems to be a shift toward high U+4 and low U+6 A.R.s with depth, but the trend is not well defined, perhaps because the unit is so thin. Similar to the Alva core, Peace River Formation samples from the Buckingham core are characterized by low U+4 and high U+6 A.R.s that become progressively more fractionated with depth.

These results indicate that preferential mobilization of U+6 from the Buckingham Marl would tend to produce low A.R. groundwater, particularly in the Alva area, where the highest dissolved uranium concentrations have been reported. The region of low A.R. shallow groundwater identified by Levine (1988) does in fact closely coincide with the subsurface occurrence of the Buckingham Marl Member in Lee County. In contrast, U+6 mobilized from the Peace River Formation would form high A.R. groundwater, which again matches the water quality data reported by Levine.

Leached Uranium A.R.s

Leaching experiment results, initially described in a previous section of this paper, provide direct evidence that hexavalent uranium present in sediment in the study area is in fact more mobile than U+4. The U+4 and U+6 A.R.s measured in the uranium-rich phosphate sample from the Alva core studied were found to be 1.39 and 0.72, respectively (see Table 2). A large amount of uranium (175 ppm) with an A.R. of 0.66 was leached from this sample.

Measured U+4 and U+6 A.R.s in the Peace River Formation phosphate sample were 0.73 and 2.44. In this case, only a modest amount of uranium (2.7 ppm) with an A.R. of 2.12 was leached. In both experiments, dissolved uranium A.R.s correlate closely with the U+6 fraction of the phosphate, but not with U+4 or total uranium A.R.s

Uranium Oxidation Potential

Investigation results suggest that both oxidation and reduction of 234U may be occurring in different stratigraphic intervals within the study area. The behavior of uranium spikes introduced during the experiments reveals some interesting, although enigmatic, information regarding this process. Spike tracking indicates that some uranium oxidation, and to a lesser extent reduction, occurred during all of the experiments. The amount of oxidation was fairly consistent for samples of the same type and stratigraphic position, but varied considerably between different sample types. This suggests that the sediments have inherent oxidation potentials that vary depending on mineralogy or perhaps trace constituent content.

In the case of phosphate samples from the Buckingham Marl Member and the upper part of the Peace River Formation in both cores, a large amount of uranium (35 to 50%) was oxidized based on spike behavior, indicating that these sediments have a high potential for oxidizing 234U. However, the data indicate that 234U reduction is the dominant process within this interval.

Only about 10% of the uranium present in phosphate from deeper strata in the Peace River Formation was oxidized, yet these samples show evidence for considerable 234U oxidation. The negative correlation in both cases suggests that either the redox potential of the sample matrix is not an important determinant in 234U valence behavior, or, if it is, the influence operates in a complex manner that is not presently understood.

CONCLUSIONS

Results of this investigation indicate that marine phosphorite with a very high content of extremely soluble uranium is present in the Buckingham Marl Member of the Tamiami Formation near Alva. Leaching of this naturally-occurring uranium is apparently the source for the unusually high dissolved uranium concentrations found in the surficial aquifer in that area. Uranium mobility, at least in part, seems to be due to its relatively high U+6 content.

Alva may be the only place in Lee County where the Buckingham Marl is used for potable water supply. This implies that other rich uranium deposits could be present in the region, but are unrecognized because wells are not normally completed in the unit. The uranium-rich phosphate at Alva apparently accumulated in a sedimentary trough. If other rich uranium deposits do occur in Lee County, they may have formed under similar conditions. Therefore, suspect areas would be places where the Buckingham Marl is particularly thick.

The uranium-rich phosphate interval has a distinctively high borehole natural gamma signature. A review of 34 other gamma logs from different parts of Lee County failed to identify any significant uranium deposits in the Tamiami Formation outside of the Alva area. While this cannot be taken as proof that conditions around Alva are unique, it at least suggests that other rich accumulations are not widespread. Site screening using the natural gamma log appears to be an effective device that can be used to help identify them.

A second part of this study examined the role uranium valence behavior plays in the fractionation of 238U and its daughter 234U. Evidence was found indicating that decay produced 234U is oxidized in phosphorite and other sediments from the Peace River Formation, but is apparently reduced in the Buckingham Marl Member. These differences in valence behavior produce distinct stratigraphic intervals containing either a shortage or abundance of hexavalent 234U. This then creates an opportunity for 234U/238U fractionation to occur due to the much higher solubility of hexavalent uranium.

Valence fractionation provides a reasonable explanation for the unusual isotopic trends identified in dissolved uranium in the study area. Groundwaters with high 234U/238U activity ratios were found to occur in aquifer sediments characterized by 234U oxidation, while low A.R. groundwaters are associated with intervals of 234U reduction. In both cases, mobilization of hexavalent 234U seems to be an important factor in the fractionation process. Leaching experiments provide direct evidence that valence fractionation does play an important role in producing dissolved 234U/238U activity ratio signatures in the study area. These findings should be considered when evaluating 234U/238U fractionation mechanisms in other hydrologic systems.

ACKNOWLEDGMENTS

This project was originally conducted as part of a masters thesis from the Florida State University (Weinberg, 1992). It builds upon the comprehensive study of dissolved radionuclide distribution in Lee County done by Barry Levine during an earlier thesis investigation at FSU. The great value of Barry's work is reflected in the number of times he is referenced in this text.

The authors would also like to express their appreciation to the FSU faculty members who provided valuable direction and editorial review during this project. Particular thanks go to Drs. Kenneth Osmond, William Parker, and William Burnett for their suggestions. The research was financially supported in part by a Banks/Parker Award and an Amoco Oil Company fellowship. The work would not have been possible without the cooperation of the Florida Geological Survey who made the cores available for sampling.

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HYDROGEOLOGY OF THE LOWER FLORIDAN AQUIFER "BOULDER ZONE" OF SOUTHWEST FLORIDA

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ABSTRACT

The "Boulder Zone" of the lower Floridan aquifer is perhaps that the most unusual feature in the subsurface of Southwest Florida. The fractured dolomites that constitute the Boulder Zone have extraordinarily high transmissivities, which make them an ideal zone for the underground disposal of liquid wastes. The Boulder Zone is not a stratigraphic feature, but is rather a regional diagenetic facies that occurs at varying depths and stratigraphic positions between wells. In the Floridan aquifer system of southwest Florida, dolomite and the Boulder Zone facies tend to occur at progressively greater depths and lower stratigraphic positions from north to south. However, the Boulder Zone facies is discontinuous and high transmissivity intervals do not occur at the same stratigraphic positions in injection wells at nearby sites or in some instances at the same site.

Prediction of the presence of the Boulder Zone facies is further complicated by the presence of anhydrite cements which may occlude fracture networks. High transmissivity fractured dolomites and subsidiary limestone, for example, are present in the Fort Myers Beach Wastewater Treatment Plant (WWTP) injection well between approximately 2,492 and 2,984 ft bls below land surface (bls). The fractures in the same depth interval were filled with anydrite at the Island Water Association Sanibel injection well, located approximately12 miles to the west-southwest. A partially fractured zone (3033 to 3232 ft bls) below the anhydrite has adequate transmissivity for the well=s design capacity of 6 Mgd even though the typical cavernous Boulder Zone facies is not present.

INTRODUCTION

Deep well injection is increasingly being used for the disposal of liquid wastes in Southwest Florida because the technology has been proven to be reliable, environmentally safe, and cost effective. The earliest deep injection wells in Southwest Florida were brought into service in the 1940's and were used for the disposal of brines brought to the surface during oil production (Vernon, 1970). Underground disposal of liquid wastes by local utilities began in 1988 with the construction of the North Fort Myers Utilities, Inc. injection well. Over the past 11 years municipal deep injection wells have been constructed at 11 sites in Charlotte, Lee, and Collier counties (Figure 1). The municipal injection wells are used to dispose of treated effluent from wastewater treatment plants, concentrate from reverse osmosis water softening and filtration pants, and leachate from a landfill. All fluids injected are non-hazardous.

The principal injection zone in Southwest Florida is an extremely high transmissivity interval of the early Eocene-age Oldsmar Formation, which is referred to as the "Boulder Zone" (Figure 2). The transmissivity of the Boulder Zone is typically on the order of 106 gpd/ft or greater. Despite its economic importance and hydrogeologic interest, the Boulder Zone has long been one of the most enigmatic features in the subsurface of Southwest Florida. However, in recent years voluminous data has been collected on the lower Floridan aquifer and Boulder Zone during the construction and rigorous testing of deep injection wells.

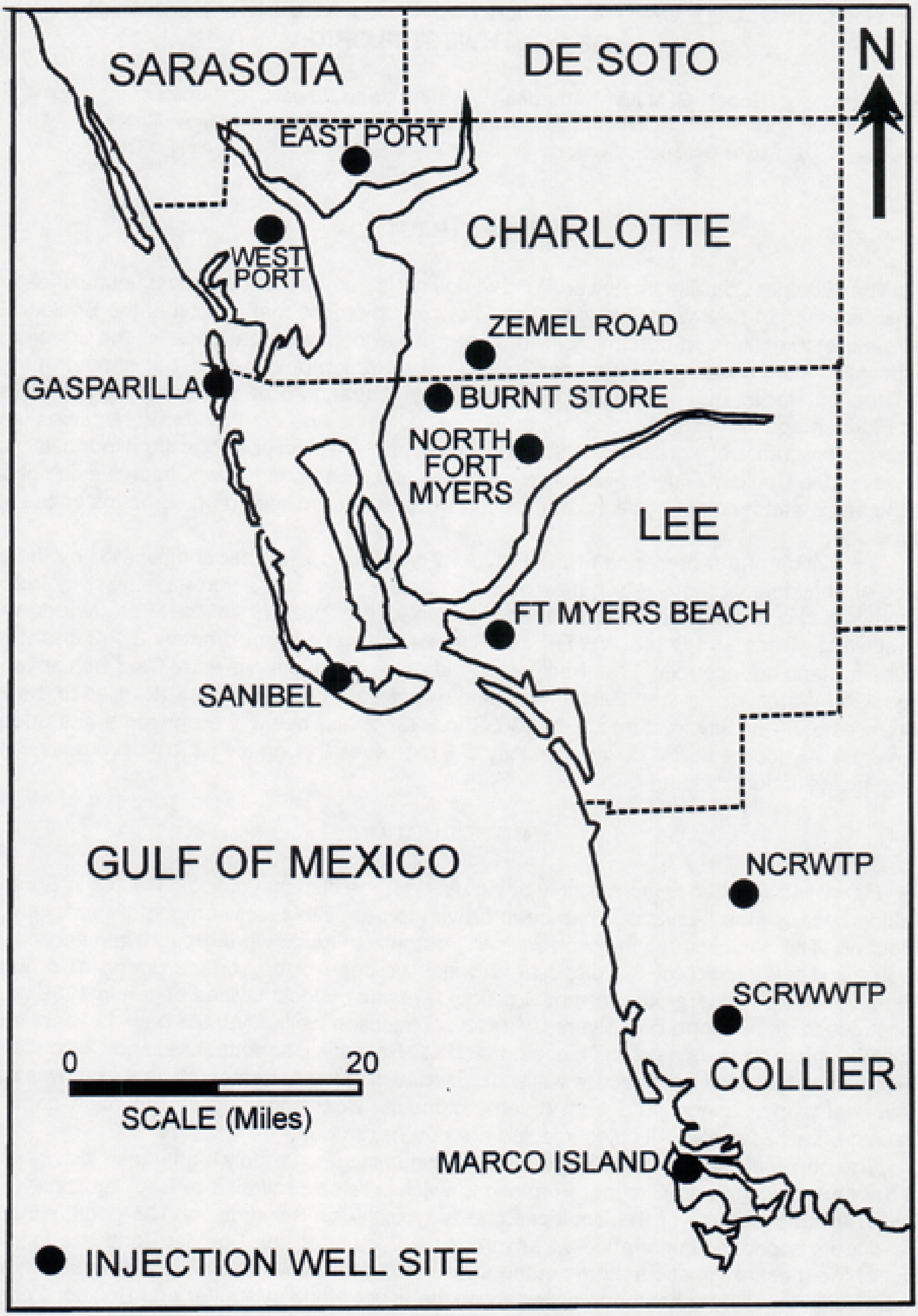

Figure 1. Map showing the location of Southwest Florida injection well sites.

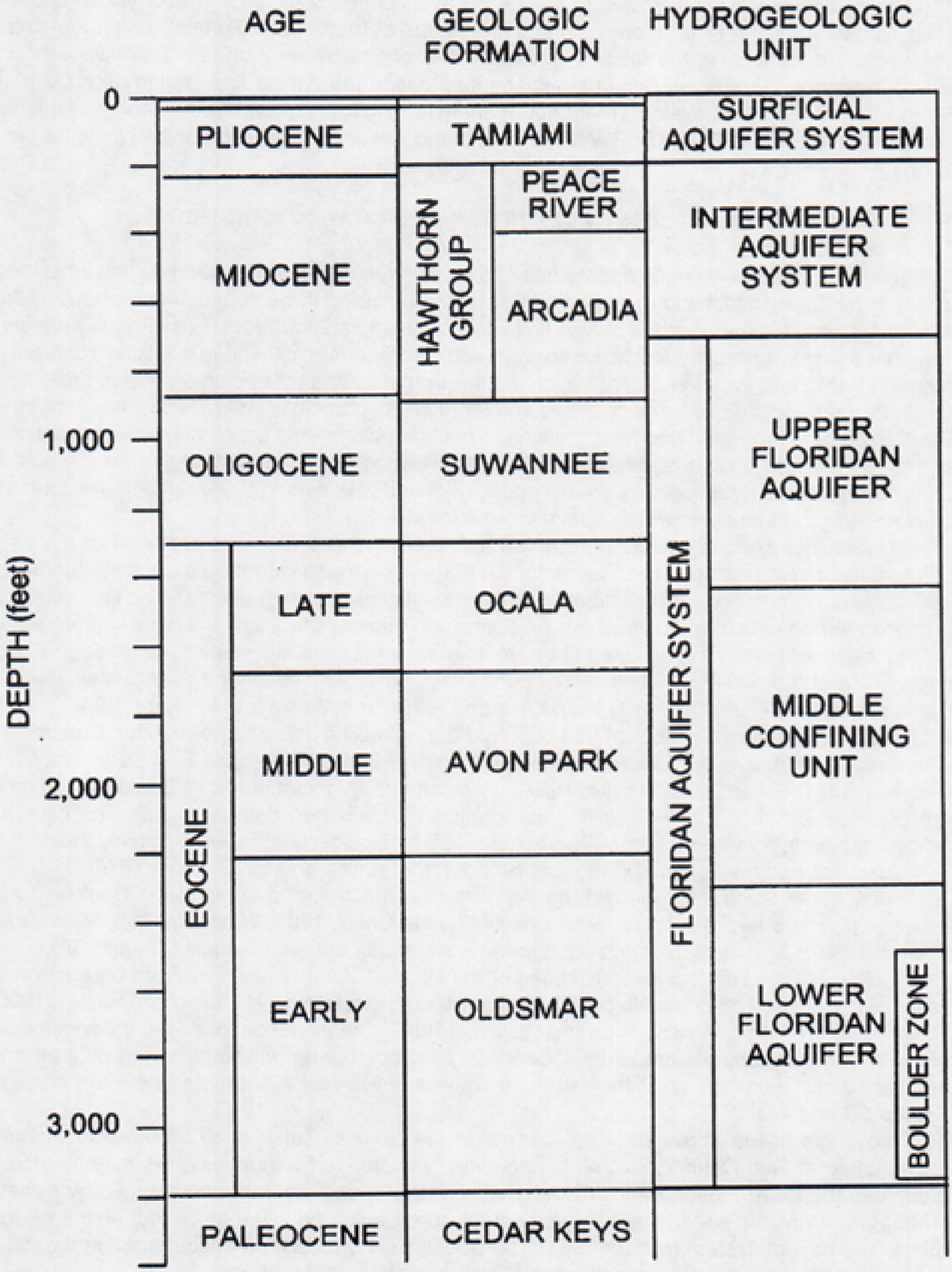

Figure 2. Regional stratigraphy and hydrogeology. Depths are from the Collier NCRWTP site.

The objective of this study was to review the available geological and geophysical data for what insights they can provide on the origin and nature of the Boulder Zone and high transmissivity zones in general in the lower Floridan aquifer of Southwest Florida. This investigation relied heavily on the authors personal experiences during the drilling and testing of the Collier North County Regional Water Treatment Plant (NCRWTP), Collier South County Regional Wastewater Treatment Plant (SCRWWTP), and Island Water Association (Sanibel) injection well systems.

BOULDER ZONE - DEFINITION AND CHARACTERISTICS

The Boulder Zone was originally defined as an interval of cavernous dolomite and limestone in which the drilling action of the bit was similar to that of drilling through boulders (Kohout, 1965; 1967). Vernon (1970) described the Boulder Zone as being an enormously cavernous area and suggested that it formed by calcite dissolution and dolomite precipitation in a mixing zone environment. Puri and Winston (1974) described the Boulder Zone was being a zone of great permeability characterized by a intricate vug and large cavity porosity. Miller (1986) noted that the Boulder Zone has no stratigraphic significance because cavernous conditions are not confined to a single discrete zone or stratigraphic position. He suggested instead that the term "Boulder Zone" can be used hydrologically as an "operational unit". Winston (1996) defined the zone as boulder-producing dolomites that contain cavities or wall collapse zones.

The Boulder Zone is defined here as an hydrogeologic and diagenetic facies that consists of intervals of very high transmissivity dolomite that are characterized by greatly enlarged borehole diameters, long sonic transit times, and borehole collapse during drilling. The later process produces the so-called boulders of the Boulder Zone facies. Fractured intervals without borehole enlargement are not considered to be Boulder Zone facies in this study. The geological and geophysical characteristics of the Boulder Zone facies have been described by Haberfeld (1991), Safko and Hickey (1992), Duerr (1995), Winston (1996), and Maliva and Walker (1998).

The most spectacular incident that occurred during drilling through the Boulder Zone facies was a reported 96 foot drill bit drop into a cavern in the Sun Oil Company Red Cattle Co. 32-2 well (Kohout, 1965; 1967; and Burke, 1967). Winston (1996) documented 13 Boulder Zone cavern occurrences during oil well drilling, as identified by reported drill bit drops. The caverns ranged in height from 5 to 96 feet. The boulders of the Boulder Zone were originally thought to be blocks that had fallen from the roof of open caverns (e.g., Puri and Winston, 1974).

Subsequent studies recognized the importance of fracturing in creating the Boulder Zone facies (e.g., Haberfeld, 1991; Safko and Hickey, 1992; Duerr, 1995; Winston, 1996; Maliva and Walker, 1998). Fracturing is common in the lower Floridan aquifer dolomites (Figure 3A). The vast majority of the large cavernous zones of the Boulder Zone facies form from borehole wall collapse of fractured dolomite after drill bit penetration (Haberfeld, 1991; Safko and Hickey, 1992; Duerr, 1995; Winston, 1996; Maliva and Walker, 1998). The evidence for a wall collapse origin of the cavernous zones is the usual absence of bit drops during drilling and the fractured and angular blocky morphology of the borehole wall as revealed by borehole television surveys (Figure 3B and 4A).

The origin of the apparent large caverns in the Boulder Zone, such as the 96 ft feature encountered at Red Cattle Co. 32-2, is uncertain. Isolated large open caverns may be locally present in the lower Floridan aquifer. Alternatively, the open "caverns" documented by Kohout (1965) and Winston (1996) may be vertical fractures enlarged by solution rather than large rooms in a cavern system (Miller 1986). The Boulder Zone facies, as encountered in the deep injection wells studied in this investigation is clearly not a karst features.

In addition to the open fractures that result in the extremely high transmissivities of the

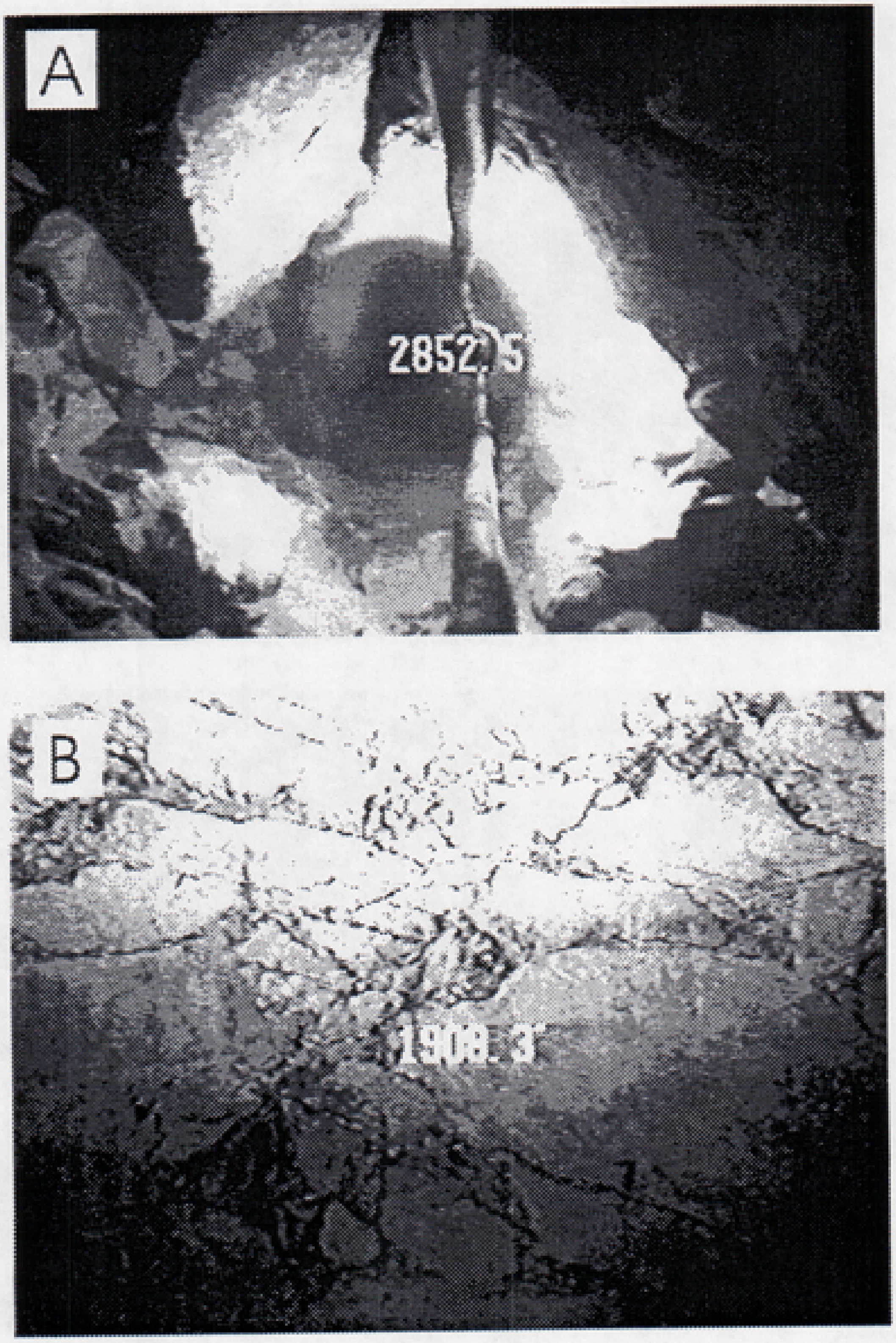

Figure 3. Borehole video survey photographs of the Boulder Zone facies. A) Well-developed fractures above a cavernous zone at the Collier SCRWWTP (2979 ft). B) Borehole wall collapse zone from the Fort Myers Beach WWTP injection well (2627.4 ft). Note the angular, blocky borehole wall.

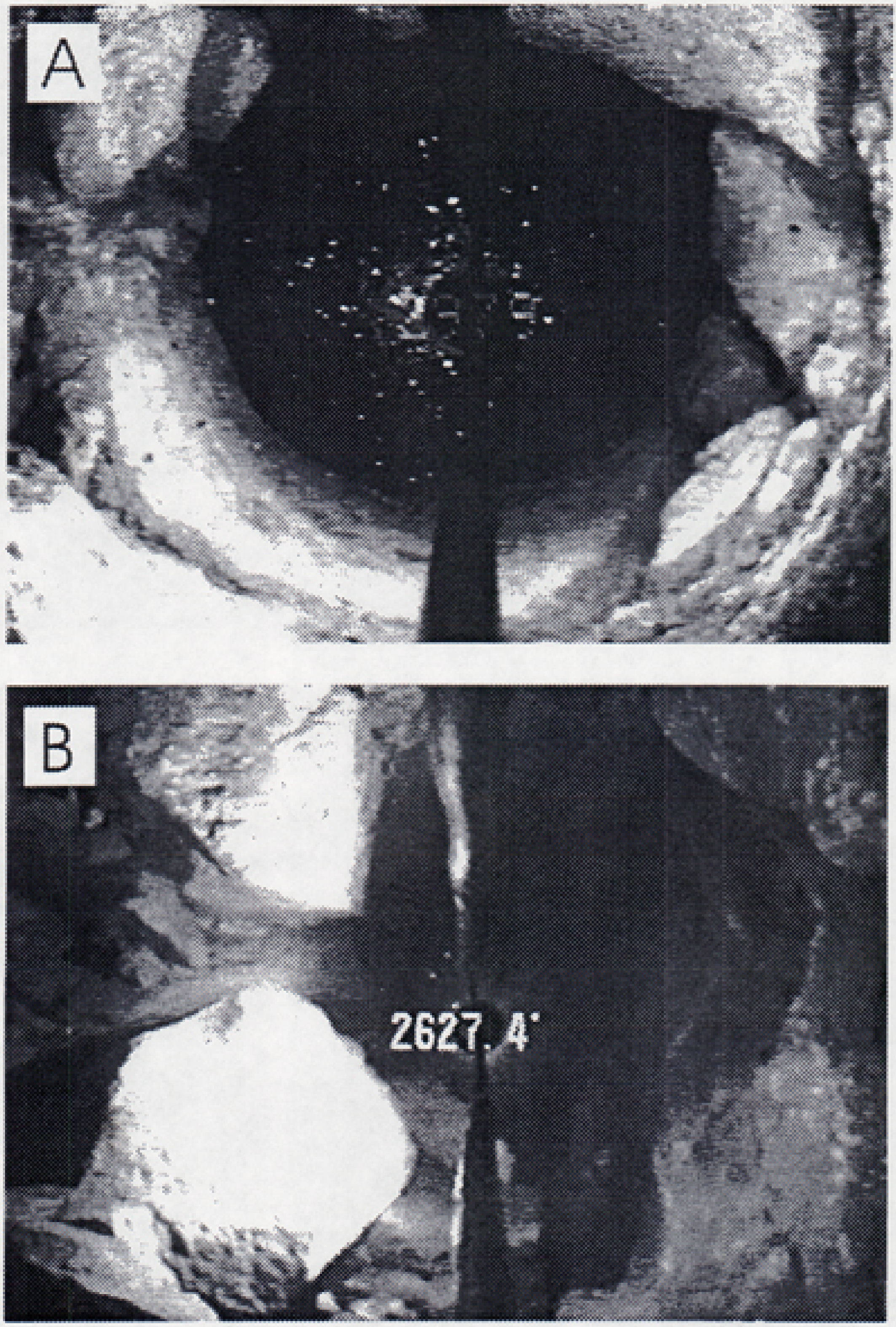

Figure 4. Borehole video survey photographs from Southwest Florida injection wells. A) Boulder Zone facies from the Fort Myers Beach WWTP injection well (2852.5 ft). The borehole wall is mostly fracture surfaces. Fractures are evident in the lower right and upper left corners. B) Lateral camera view of healed brecciation from the Sanibel injection well (1908.3 ft).

Boulder Zone facies, earlier generations of healed fractures and brecciation are common in the lower Floridan aquifer (Figure 4B). Flowmeter logs indicate that the zones of healed fractures and brecciation are not high transmissivity intervals. The fracturing that produced the Boulder Zone facies is the last of several generations of fractures in the lower Floridan aquifer.

DISTRIBUTION OF THE BOULDER ZONE FACIES IN SOUTHWEST FLORIDA

Prediction of the presence and location of the Boulder Zone facies is of obvious importance for the successful design and construction of deep injection well systems. The Boulder Zone facies has been ubiquitous at Southwest Florida injection well sites, but its location is highly variable. The location of the Boulder Zone facies in the Southwest Florida muncipal injection wells are shown in Figure 5. The Gasparilla Island injection well was not included in this investigation because it is a shallow well (1,918 ft) and does not penetrate the lower Floridan aquifer. The location of the Boulder Zone facies in each well was determined primarily from caliper and sonic logs.

There is a general overall trend for the Boulder Zone facies to occur at greater depths from north to south in Southwest Florida. The main Boulder Zone facies zone in the Collier SCR-WWTP and Marco Island injection wells occur at greater depths than in the Lee and Charlotte County wells. Intervals of the Boulder Zone facies are commony present between 3,000 feet (below land surface) and the bottom of the Floridan aquifer (. 3,200 to 3,250 ft) across the study area.

Great variation in the location of the Boulder Zone also occurs between closely spaced wells. Injection wells IW-1 and IW-2 at the Collier NCRWTP are located approximately 280 feet part. Thick intervals of the Boulder Zone facies were encountered between 2,570 and 2,830 ft in well IW-1. The Boulder Zone facies of IW-1 has the typical characteristics of long sonic transit times (Figure 6) and greatly enlarged borehole diameters. Borehole wall collapse was extensive, as evidenced by weeks of dredging during drilling. The 2,570 to 2,830 ft Boulder Zone facies intervals were unexpectedly absent in well IW-2 (Figure 6). A deeper interval of Boulder Zone facies was present between 2,886 and 3,016 ft in well IW-2 that was capable of accepting the well=s design capacity of 6.3 Mgd. The available geological and geophysical data provide no evidence for the origin of the pronounced variation in the location of the Boulder Zone facies between the two closely spaced wells. There is no evidence of faulting or local solution collapse structures.

The Boulder Zone facies is well-developed in the Fort Myers Beach Wastewater Treatment Plant (WWTP) injection well which was drilled in 1988. Intervals of the Boulder Zone facies are present between 2,099 and 2,200 ft and between 2,492 and 2,984 ft. The sonic log of the above-noted intervals show the typical Boulder Zone facies long sonic transit times and absence of early formation returns on the variable-density log (Figure 7). The Island Water Association (IWA) Sanibel Island injection well was drilled in 1999 approximately 12 miles west of the Fort Myers Beach WWTP well. It was expected during the design and drilling of the Sanibel well that intervals of the Boulder Zone facies would also be present between 2,100 and 3,000 ft. However, the typical Boulder Zone was not detected below 2,000 ft. Two fractured intervals with borehole enlargement are present from approximately 1,900 to 1,905 ft and 1,916 to 1,920 ft and other fractures were evident between 1920 and 2000 ft. The sonic logs of the 2,200 to 3,000 ft interval showed no evidence of enhanced porosity or fracturing. The borehole video of the Sanibel injection well revealed that fractures and small cavities are present, but are filled with anhydrite (Figure 8). The anhydrite in the Sanibel well was present mostly between 2,240 and 2,430 ft and between 2,550 and 2,900 ft . Anhydrite was largely absent between 2,900 and the top of the Cedar Keys Formation, which is located at approximately 3,232 ft.

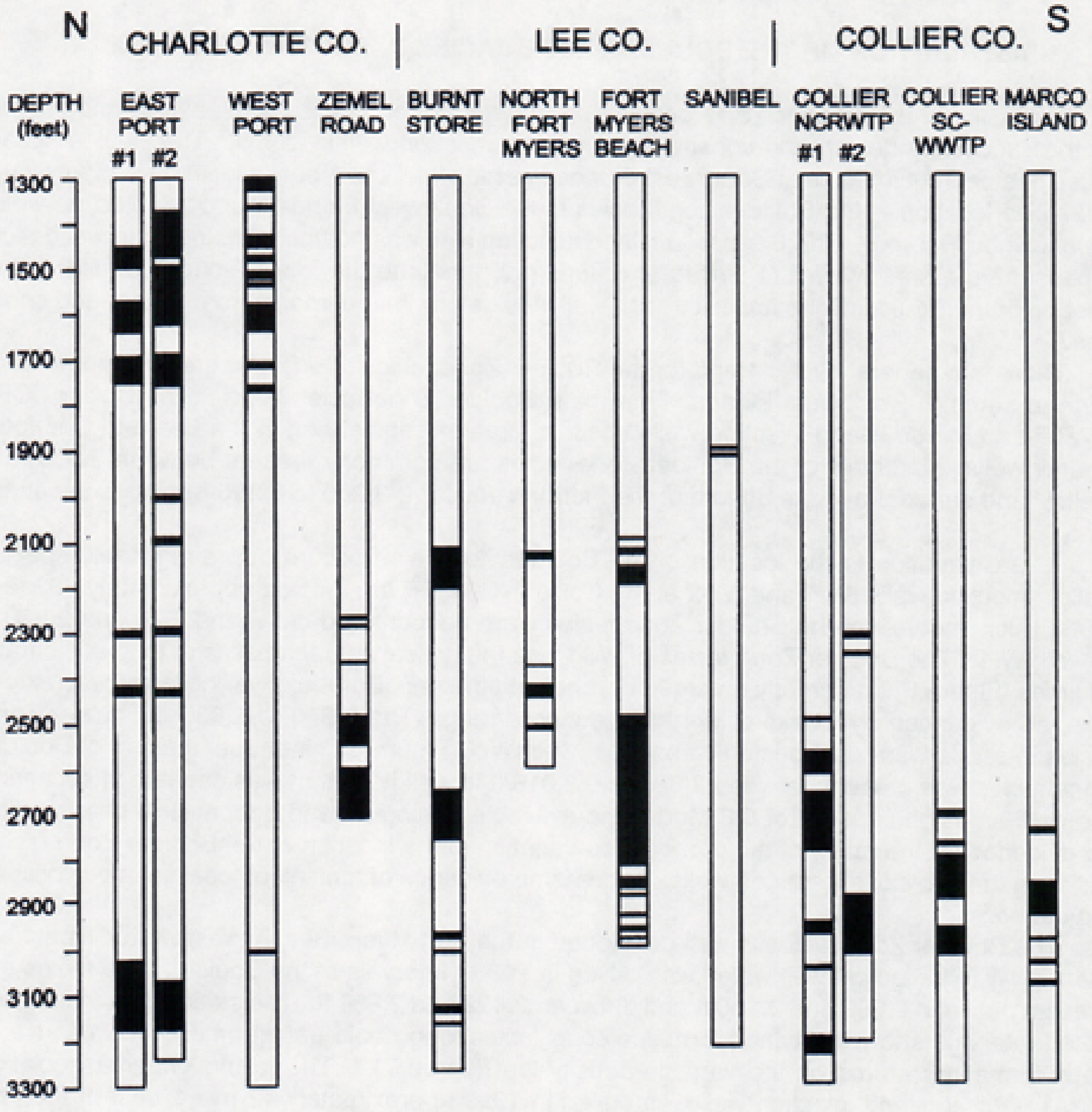

Figure 5. Locations of the Boulder Zone facies (shaded areas) in Southwest Florida municipal injection wells. The Boulder Zone facies intervals were identified by a greatly enlarged borehole diameter and long sonic transit time.

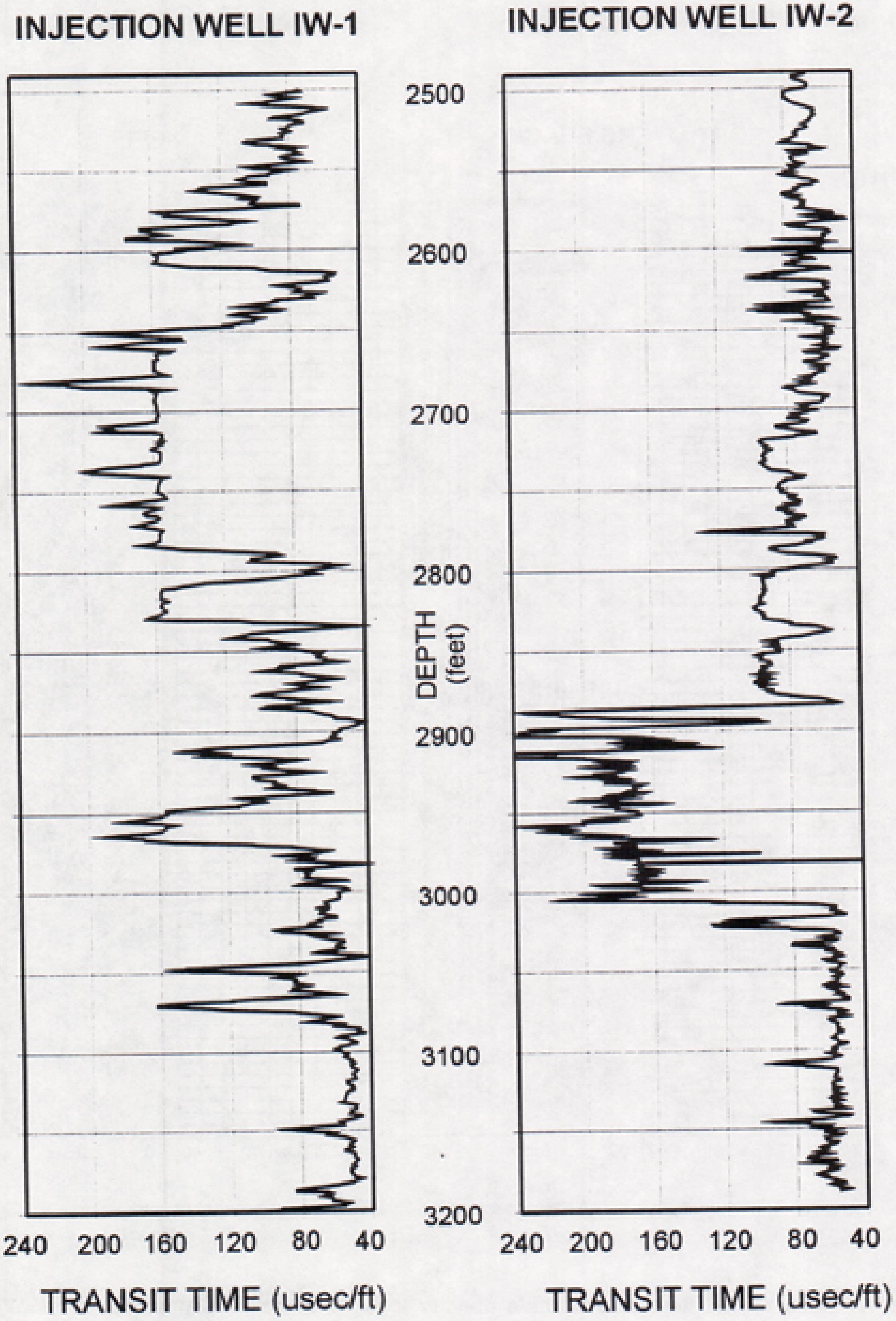

Figure 6. Sonic transit time logs for the Collier NCRWTP injection wells IW-1 and IW-2. The Boulder Zone facies in the injection wells has high (> 150 µsec/ft) sonic transit times. The Boulder Zone facies cannot be correlated between the wells, which are only 280 ft apart.

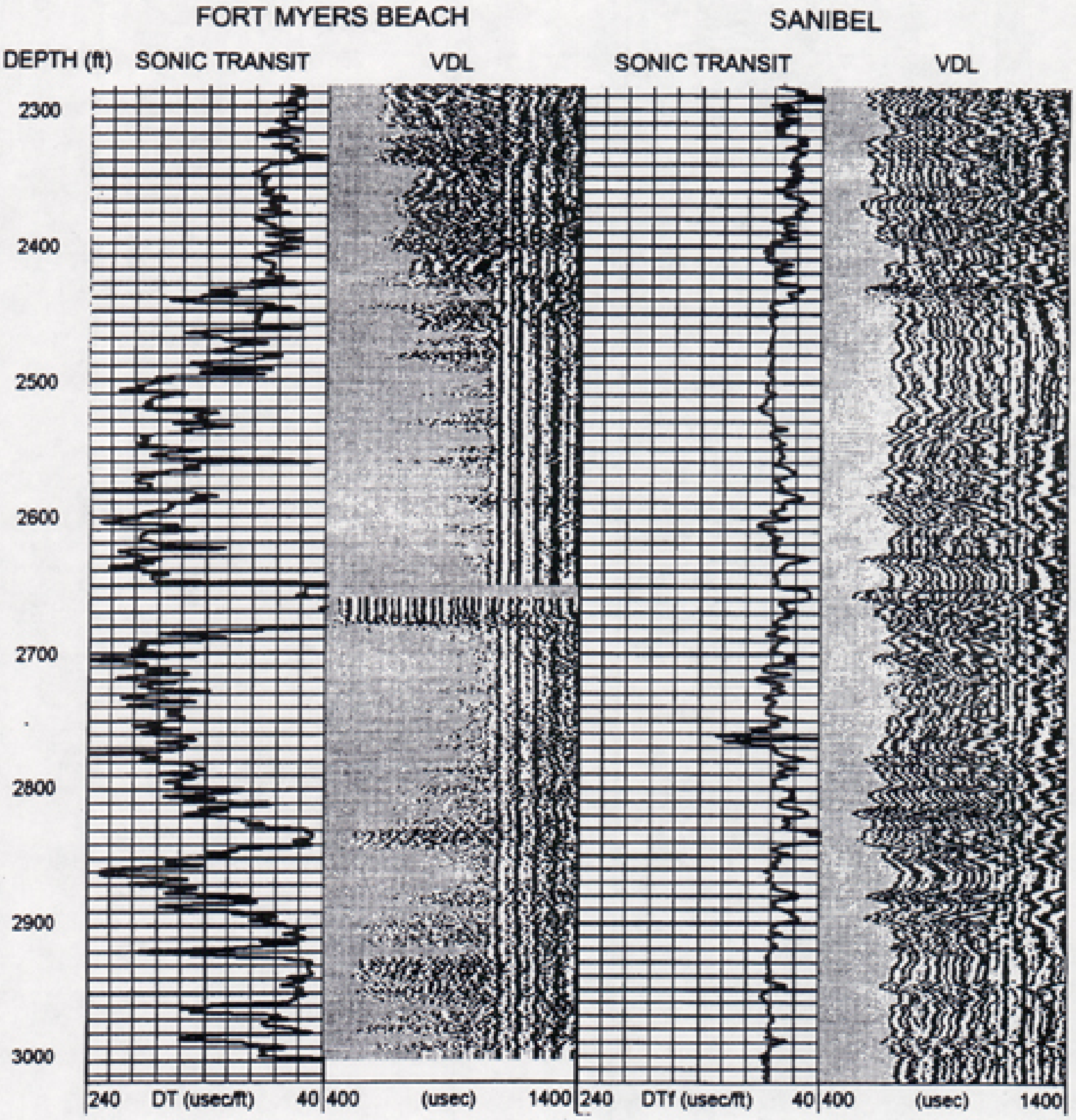

Figure 7. Sone transit time and variable density logs from the Fort Myers Beach WWTP and Sanibel injection wells. The well-developed Boulder Zone facies intervals in the Fort Myers Beach well, as expressed by long sonic transit times, are absent in the Sanibel well.

Figure 8. Laterial camera borehole video photograph of vugs filled with anhydrite from the Sanibel injection well (2817.2 ft). The vugs are on the order of 1-2 inches high.

Several small fractured intervals were detected in dolomites present below 3,033 ft in the Sanibel injection well pilot hole, as evidenced in the geophysical logs by slight increases in borehole diameters and sonic transit times (Figure 9). The fractured intervals detected below 3,033 ft are not associated with significant borehole collapse and are therefore not considered to be Boulder Zone facies, as defined in this study. The fractures between 3,033 and 3,232 ft were the best prospect for an adequate injection zone being present in the Sanibel injection well.

SANIBEL MINI-INJECTION TEST PROGRAM

In order to evaluate the injection potential of the fractured dolomite present below 3,033 ft bls in the Sanibel injection well, a new mini-injection test procedure was implemented. The tests were set up to record flow and bottom hole pressure in the injection well pilot hole at selected depths in order to evaluate the potential of different depth intervals to serve as injection zones. For each test a single inflatable packer was set in the pilot hole. A self-contained pressure transducer and data recorder were attached to the bottom of a flow meter logging tool, and the assembly was lowered down the drill pipe and through the packer. Water was then injected through the drill pit and packer at a rate of approximately 1,050 gpm, while flow rate, and bottom hole and wellhead pressures were recorded. The packer was set at approximately 2,950 ft for test

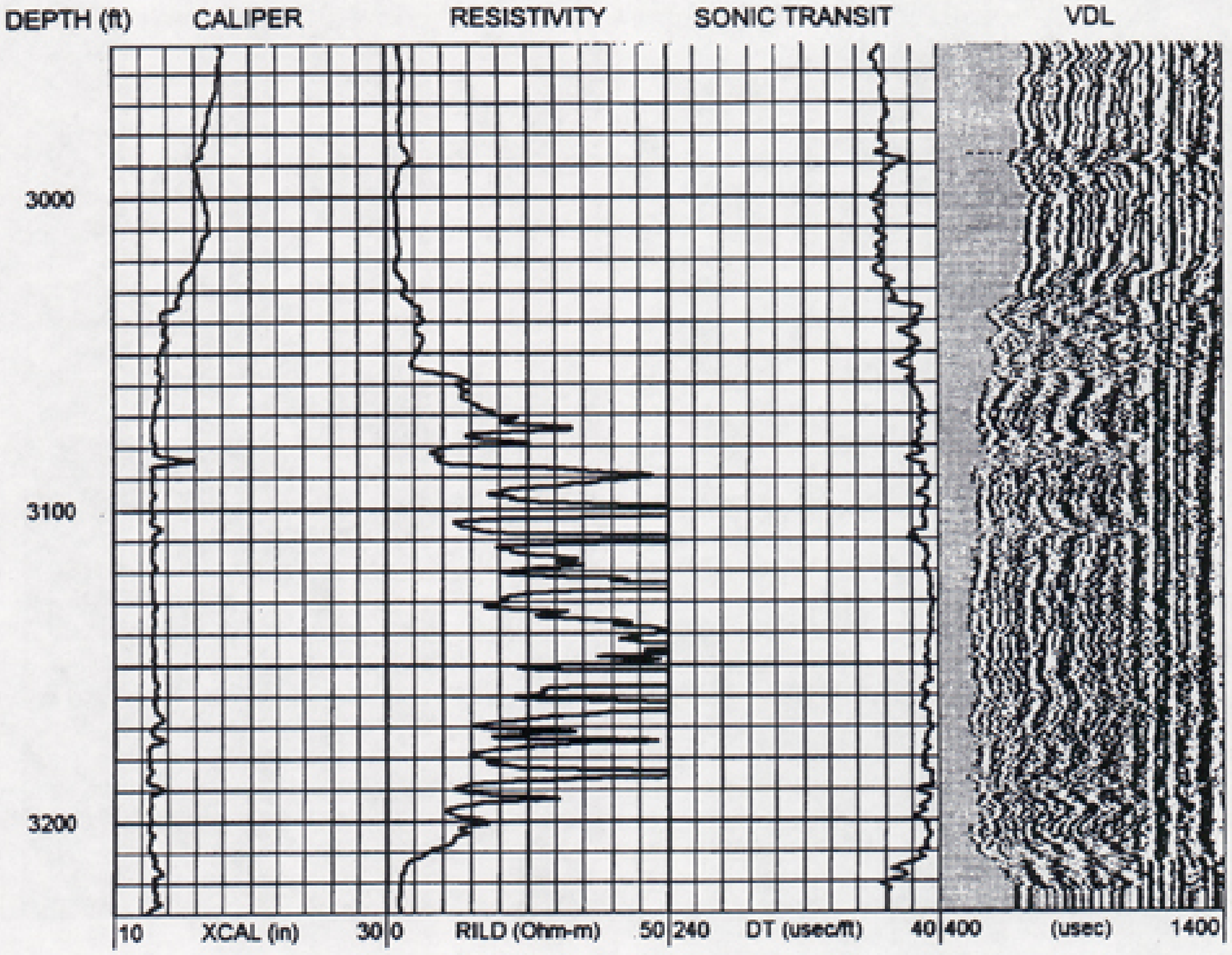

Figure 9. Geophysical logs from the lower part of the Sanibel injection well. Fractures are evident by minor increases in borehole diameter and sonic transit times. No cavernous zone are evident. The dolomite beds have high resistivities.

#1 and pressure and flow rates were measured at about 3,100 (station #1), 3,000 (station #2), and 2,610 (station #3) ft (Figure 10). The results of test #1 showed that nearly 100% of the injected flow passed stations #3 and approximately 85% of the flow passed station #1. Bottom hole pressure increased by approximately 1 psi at station #1. A high transmissivity for the 3,100-3,232 ft interval is indicated by the formation accepting a flow rate of approximately 890 gpm (85% of 1050 gpm) with only a minimal increase in bottom hole pressure.

For mini-injection test #2, the packer was moved up to 1,885 ft in order to evaluate the injection potential of the upper fractured intervals (1900-2200 ft). The flow meter and pressure transducer assembly was placed at 2,300 (station #4), 2,100 (station #5), and 1898 (station #6) ft (Figure 10). Flow calculations indicate that over 85% of the flow passed both the upper fractured interval and station #4. The down hole pressure buildup at 2,300 ft was about 8 psi. Most of the 8 psi down hole pressure buildup resulted from friction loss in the borehole from 2,300 ft down to the injection zones below 3,100 ft. A standard dynamic flow meter log conducted from the bottom of the hole up to the packer shows that the bulk of the injected flow entered the borehole below 3100 ft (Figure 11). No flow into the anhydrite invaded zone is evident in the flow meter log. The mini-injection test results thus indicate that the fractured dolomite intervals located

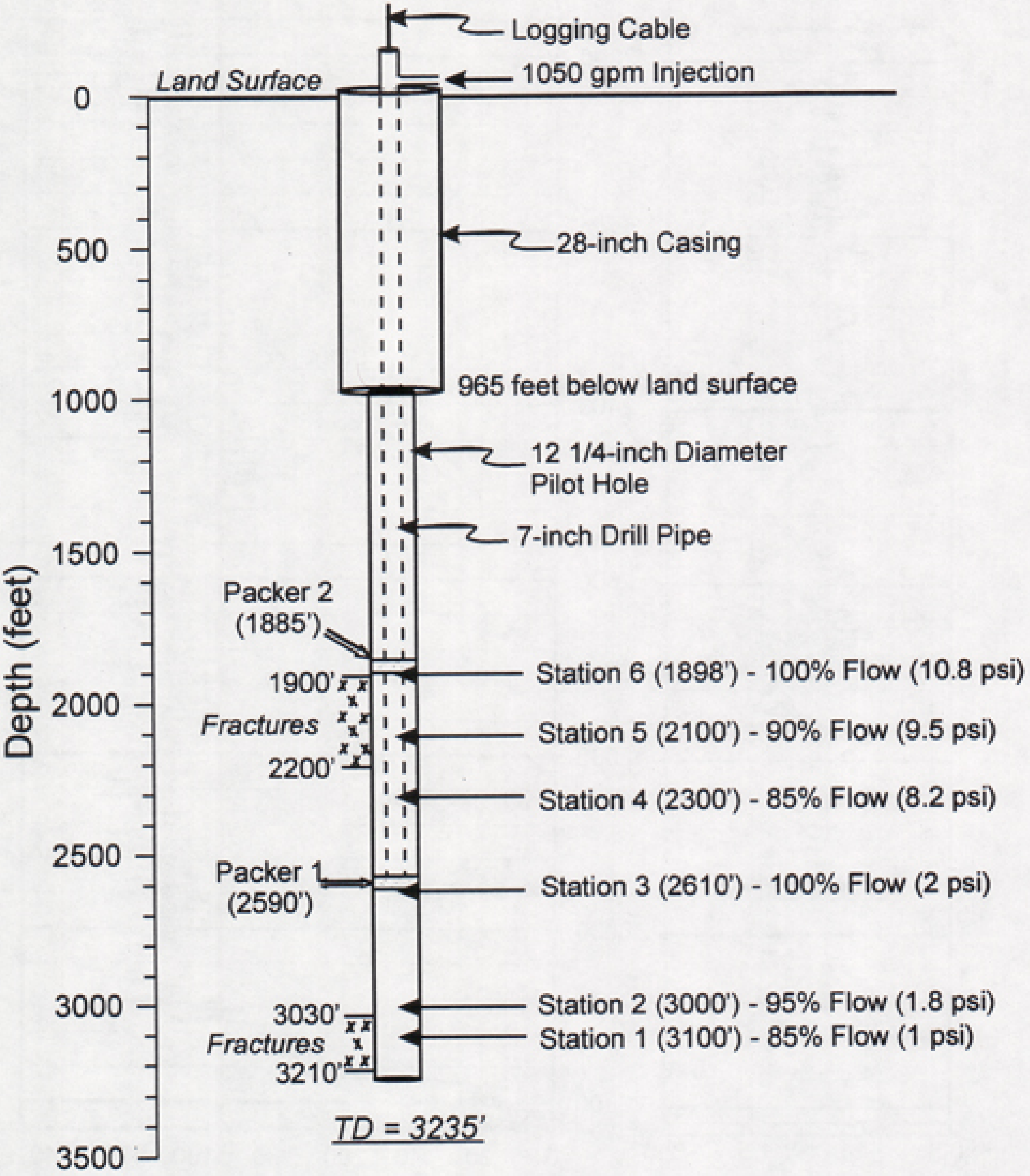

Figure 10. Sanibel mini-injection test diagram. The percent of flow and bottom hole pressures for test #1 (recording stations #1-3) and test #2 (recording stations #4-6(are shown. The bulk of the injected flow entered the formation below 3,100 ft.

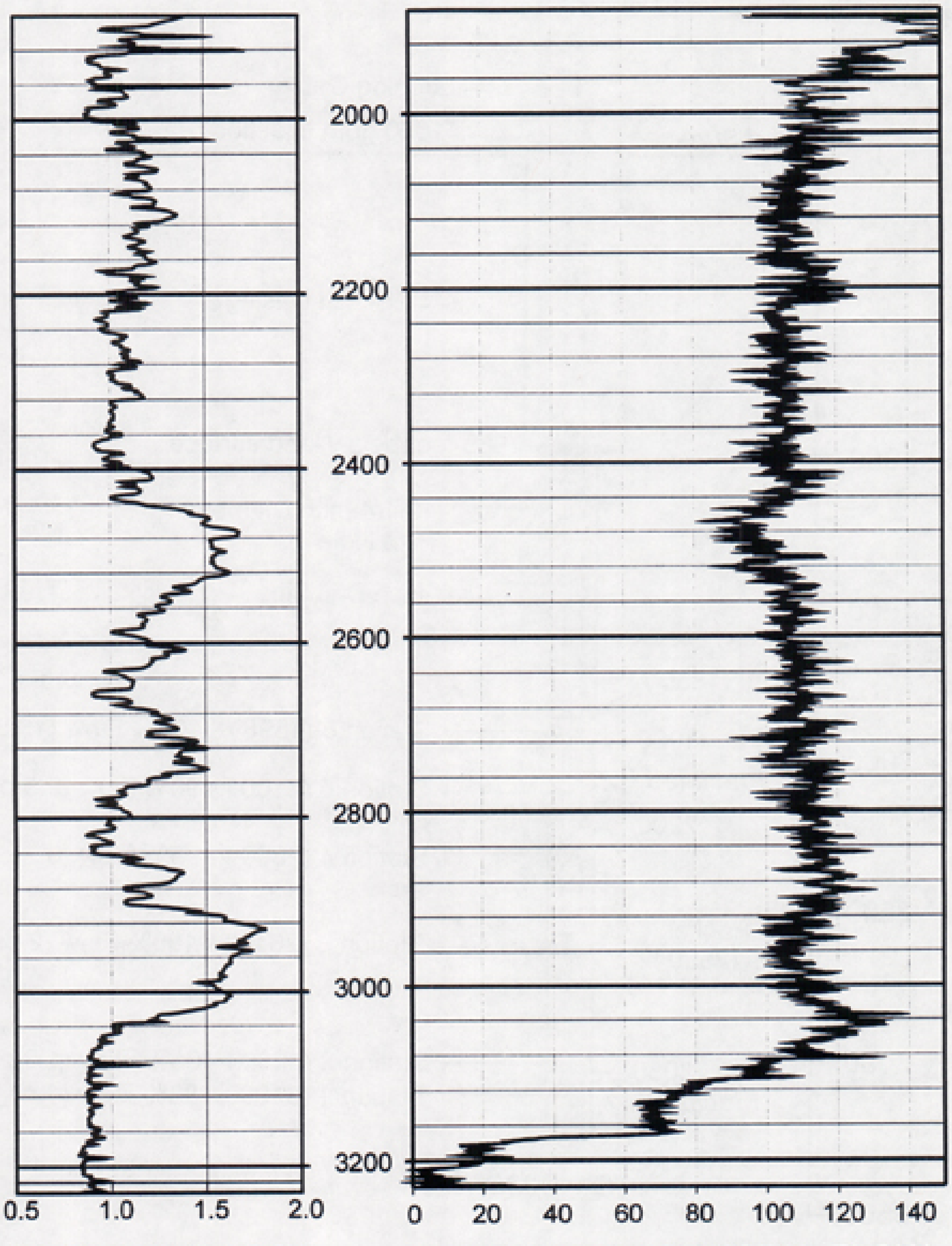

Figure 11. Results of dynamic flow meter log of the Sanibel injection well pilot hole below 1885 ft. Percentage of flow was calculated from the flow meter tool reading and the borehole area. The bulk of the flow entered the formation below 3,100 ft.

below 3,100 ft in the Sanibel injection well are capable of serving as an injection zone even though a typical cavernous Boulder Zone facies is not present.

CONCLUSIONS

The Boulder Zone facies in Southwest Florida deep injection wells is a fracture rather solution (karst) feature. Open fractures in the lower Floridan aquifer tend to occur most commonly in dolomite rather than limestone beds. The fracture networks have a great horizontal extent as evidenced by the networks being able to accept millions of gallons of water a day for years. Borehole wall collapse occurs during drilling where fracturing in dolomite is most intense, resulting in the development of the typical cavernous Boulder Zone facies. The results of the testing of the Sanibel injection well demonstrated that some fractured intervals may have high transmissivities, and be able to serve as injection zones, even though Acaverns@ did not develop during drilling. The cavernous nature of the Boulder Zone facies in itself contributes little to the high transmissivity of the zone.

The location of the Boulder Zone facies and other intervals of fractured dolomite is highly variable between wells. Part of the variation in the vertical location of the Boulder Zone facies at different injection well sites is due to variations in the location of the dolomite intervals. Dolomite in the lower Floridan aquifer tends to occur at greater depths and lower stratigraphic positions from north to south in Southwest Florida, which explains in part the tendency of the Boulder Zone facies to occur at greater depths from north to south (Maliva and Walker, 1998). However much of the vertical variation in the location of the Boulder Zone facies between wells is unknown.

Significant questions still remain concerning the origin of the Boulder Zone facies. The depositional and diagenetic history of the lower Floridan aquifer dolomites in Southwest Florida and the relationship between the dolomite and anhydrite has received very little study. Multiple generations of fracturing and brecciation are present in the lower Floridan aquifer in South Florida. Only the last generation appears to contribute to the extremely high transmissivities locally encountered. The origin of the fracturing in the lower Floridan aquifer has not been rigorously explored. The fracture producing stresses may resulted from basinal subsidence, regional tectonic activity, and/or dissolution of underlying evaporite beds. Evidence of the later process has not been documented in the Oldsmar Formation of Southwest Florida.

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CALOOSAHATCHEE BASIN INTEGRATED SURFACE -GROUNDWATER MODEL

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ABSTRACT

In its effort to ensure an adequate supply of water for all existing and future competing uses within the Caloosahatchee Basin, the South Florida Water Management District initiated the Caloosahatchee Water Management Plan in 1997. The plan, which was completed in 2000, addressed water supply issues in the fresh water portion of Caloosahatchee Basin. The Caloosahatchee Basin receives water from Lake Okeechobee, runoff from the watershed and through baseflow from the Surficial Aquifer System. The hydrology of the Caloosahatchee Basin is influenced by significant interactions between groundwater and surface-water systems. Simulation of these interaction processes by either a surface-water model or a groundwater model alone can produce inaccurate results that could lead to inefficient resource management recommendations. The Caloosahatchee Basin Integrated Surface-water / Groundwater Model (ISGM) of the freshwater portion of the Caloosahatchee River basin in southwest Florida, developed by DHI and the South Florida Water Management District (SFWMD), employs a more accurate representation of the surface-water / groundwater interactions and is more appropriate for planning in the Caloosahatchee Basin. This paper summarizes the modeling approach, model set-up, model calibration, and results.

INTRODUCTION

The Caloosahatchee Basin is located in south Florida and extends from Lake Okeechobee to the mouth of the Caloosahatchee River on the West Coast of Florida. The freshwater portion of the Caloosahatchee Basin extends from Lake Okeechobee to the Franklin Lock and Dam. The basin is located in the Lower West Coast planning region of the South Florida Water Management District (SFWMD) and represents one of the channelized outlets for Lake Okeechobee, which is located in the Lower East Coast planning region. The basin therefore plays an important role in both the Lower West Coast and the Lower East Coast water supply plans of the SFWMD.

The Caloosahatchee Water Management Plan (CWMP) was initiated in 1997 to study water resource characteristics of the Caloosahatchee Basin and provide a linkage between the SFWMD's Lower West Coast and Lower East Coast Water Supply Plans. The plan addresses a number of issues, a few of which are summarized below.

1) *Increased demand*: Projected increases in both agricultural activity and population will result in significant increase in demand for water within the Caloosahatchee Basin by the year 2020.
2) *Limited sources*: Meeting the projected increase in demands from the existing surface-water and groundwater sources would result in water level decline with potential impact to natural systems such as estuaries and wetlands, especially during the dry season. Effects of anticipated reduced inflows from Lake Okechobbee to the Caloosahatchee Basin also need to be investigated.
3) *Need for storage*: As with most of South Florida, a significant amount of the rains that fall in the rainy season flow through the canals and rivers and are discharged to tide and

therefore not available for use in the dry season. The recently completed Central and Southern Florida Comprehensive Review Study (USACE, 1999) identified the need to store the wet season flows for dry season uses.

To adequately address these issues, several analytical tools were developed. This paper describes the development and application of an Integrated Surface-water Groundwater model (ISGM) to address the identified issues, and provide a means of evaluating alternative scenarios to meet the future water needs of the basin.

MODEL CODE SELECTION

Water used within the Caloosahatchee Basin is drawn from both surface and groundwater sources. The potential impact of these withdrawals on the resources, as well as the need to quantify the effect of management measures, demand the capability to simulate both surface and groundwater changes. The model code for this study therefore had to be capable of (1) simulating surface-water flows within the Caloosahatchee Basin, (2) simulating groundwater response within the Caloosahatchee Basin and (3) simulating surface-water / groundwater interactions. The MIKESHE/MIKE11 model code is capable of meeting these requirements and was selected for the study.

MODEL OBJECTIVE

In order to meet the needs of the study, the model developed should in addition to simulating surface-water / groundwater interactions, be well calibrated for a wide range of flows, with emphasis on the low flows. This would enhance the models ability to simulate the effects of low flow or drought conditions. The model calibration would also emphasize surface and shallow groundwater and to a lesser degree deeper groundwater responses.

MODEL DESIGN

An integrated surface-water / groundwater model of the freshwater portion of the Caloosahatchee Basin was developed using the Danish Hydraulic Institute's distributed finite difference code, MIKESHE (Abbott et al, 1986a, 1986b, MIKESHE, 1993). The model area encompasses approximately 1050 square miles (2720 square kilometers) and extends from Lake Okeechobee at the upstream end to the Franklin Lock and Dam (Structure 79) at the downstream end (Figure 1).

MIKE SHE is modular in nature and consists of a number of components that may be combined to simulate simple or complex hydrologic systems. By varying the modules used, the model is capable of simulating the entire land-based portion of the hydrologic cycle. For the Caloosahatchee watershed, the close linkage between rivers, ditches, canals, and aquifers necessitated the inclusion of modules that represent both surface water and groundwater. The Caloosahatchee model thus simulates major flow processes within the basin including:

- Overland sheet flow and depression storage
- Infiltration and storage in the unsaturated zone
- Groundwater flows, storage, and potential heads
- River/canal flows and water levels
- Evapotranspiration losses
- Effects of drainage
- Effects of irrigation water allocation (conjunctive use)

- Dynamic exchange between unsaturated zone-groundwater (recharge)
- Dynamic exchange between aquifers and wetlands/rivers/canals (seepage)
- Dynamic flow exchange between flood plains, rivers, overland, and wetlands.

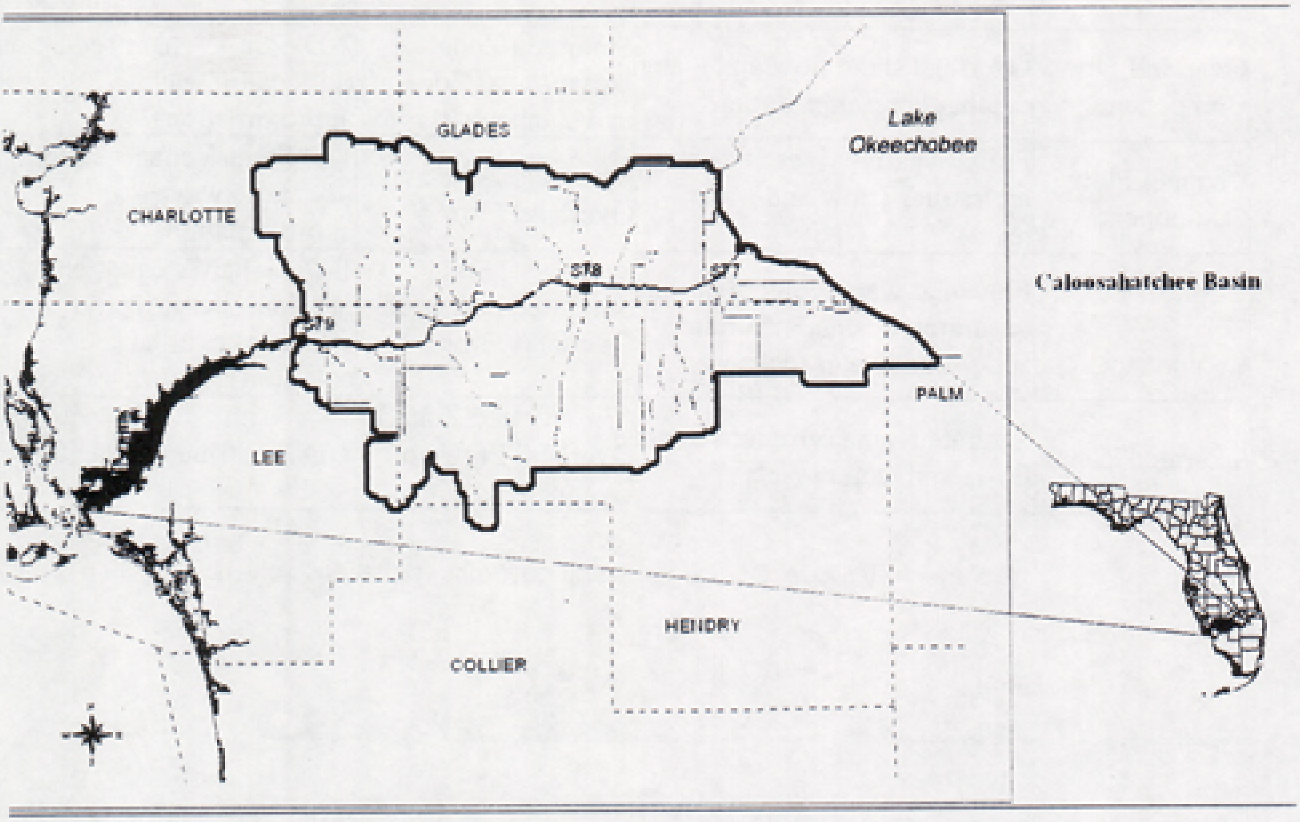

Figure 1: Study area map showing model boundary

A fully three-dimensional, multi-layer representation of the shallow and intermediate aquifer system, consistent with the generalized geology of the area, was used in the model. The Water Table, Tamiami, and Sandstone aquifers were represented in the model with two computational layers that cover the entire model area and two lenses that extend over portions of the model area consistent with the extent of the Tamiami and Sandstone aquifers. A one-dimensional representation of the unsaturated zone and a two dimensional representation of overland flow was employed. Channelized flow was simulated using the MIKE 11 package, which solves the one-dimensional Saint-Venants equation. The various model components are dynamically coupled as described in Table 1, which also summarizes the relationship of the model components and the governing equations solved.

A uniform grid size of 1500 by 1500 feet (457x457m) was selected for the model. This resolution was found to be adequate to represent major features within the Caloosahatchee Basin. It was also consistent with the density of available input data. While a finer grid resolution may be more desirable to better describe the basin in detail, the increased computer cost would limit its applicability. The selected model grid represents a compromise between detailed model output and computer capacity. Figure 2 shows the model grid superimposed over a map of the study area.

Model Component	Description	Coupling	Governing Equation
Overland Flow Component	Overland sheet flow and water depth, depression storage	Saturated Zone, Unsaturated Zone and Cannelized Flow	2-D Saint-Venants equation (kinematic wave approximation)
Channel Flow Component	Fully dynamic river and canal hydraulics (flow and water level)	Saturated Zone and Overland Flow	1-D Saint-Venants equation (dynamic wave approximation)
Unsaturated Zone Component	Flow and water content of the unsaturated zone, infiltration and groundwater recharge	Saturated Zone and Overland Flow	1-D Richard's equation / gravitational flow (no effects of capillary potential)
Saturated Zone	Saturated zone (groundwater) flows and water levels	Unsaturated Zone, Overland Flow and Channelized Flow	3-D Boussinesqs equation

Table 1. Key Model Components and governing equations solved.

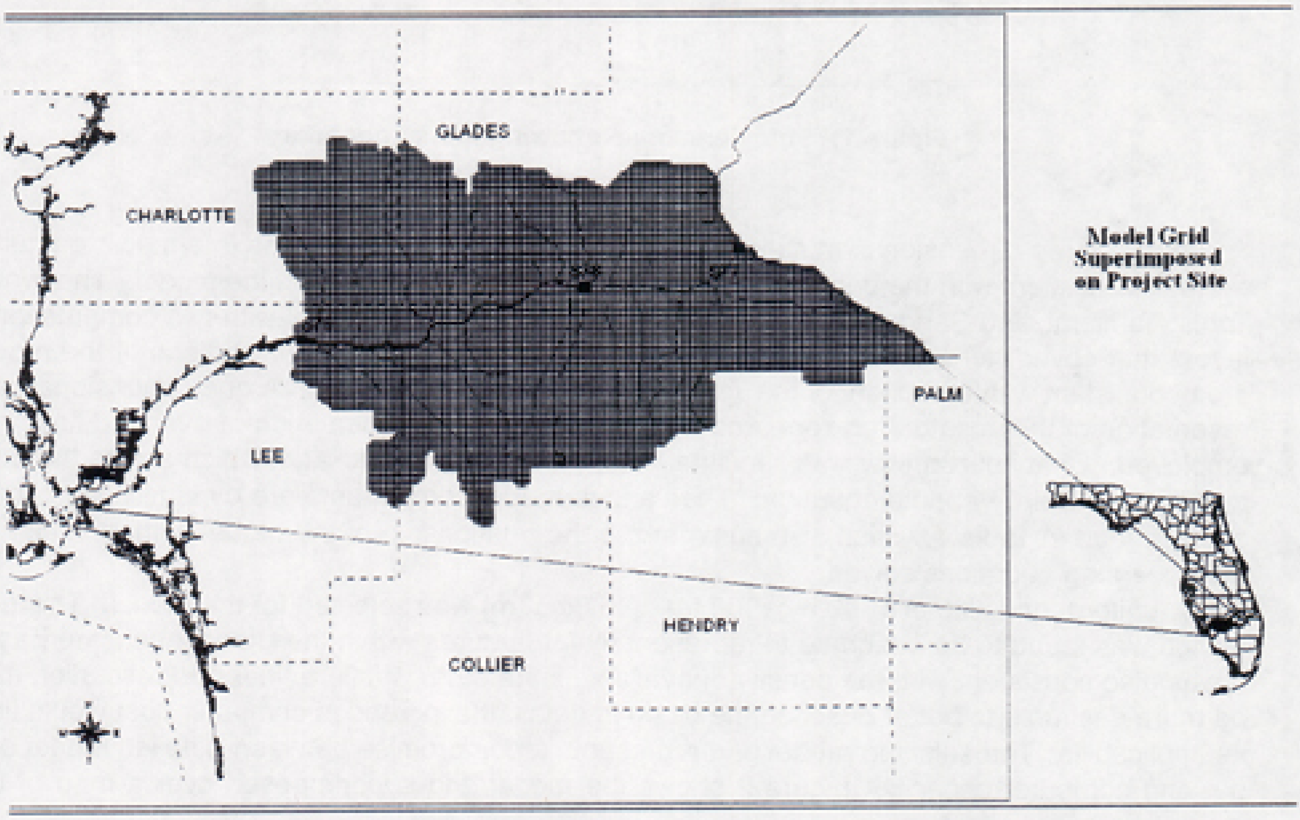

Figure 2. Model Grid Superimposed on Site Map

MODEL DEVELOPMENT

A varied array of input data was required to populate the model and properly describe the various flow components. The data required by component is summarized below. A detailed description can be found in the Basin Integrated Surface Water / Ground Water Model Final Report (DHI 1999).

Saturated Zone

The model simulates dynamic groundwater flow and potential heads in the saturated zone. The data requirements for this component of the model include information necessary to describe the extent, thickness, and elevation of the top of the major geological units comprising the Surficial and Intermediate Aquifer System. In addition, aquifer parameters, initial and boundary conditions, also had to be specified. The four aquifers represented in the model are the Water Table, Lower Tamiami, Mid Hawthorn, and Sandstone aquifers. These aquifers were assumed to account for the exchange of flows between the river and canal network, and the aquifers. They also constitute the major sources of groundwater in the model area. The impact of the Floridan Aquifer on surface-water flows was considered limited within the study area. The Floridan Aquifer was therefore not included in the model.

Lithologic information from previous work in Lee, Hendry, and Collier Counties (Bower, Adams, Restepo, 1990) was used to describe the aquifers. In portions of Charlotte and Glades Counties where data were limited or not available, layer thickness was extrapolated based on data from Lee and Hendry Counties using spatial interpolation techniques.

Aquifer parameters were specified based on reported values for the various aquifers. The initial values were modified during model calibration. For this study, a simplified approach assuming homogeneity within each model layer was implemented. The impact of specified aquifer parameters on model results was investigated through sensitivity analyses as part of a separate work effort. Future improvement to the model may be achieved by specifying spatially variable hydrogeologic parameters for each of the aquifers.

The model was run for a warm-up period to develop a potentiometric surface that was used as initial conditions in subsequent model runs. The starting water level for the warm-up run was based on spatially interpolated observed potentiometric data from monitoring wells in the study area.

Groundwater boundary conditions were specified for all layers in the model. For the upper layer it was assumed that surface-water and groundwater divides coincide. Subsequently a no-flow boundary was applied. A no-flow boundary was applied to most of the lower layer as well. In the southern portion of the model, where groundwater withdrawals close to the model boundary result in drawdown and groundwater inflow into the model area, a head dependent flow boundary was specified. Time series data from 3 observation wells close to the head dependent boundary were used to generate a dynamic head boundary incorporated into the model for the lower aquifer.

.The assumptions made in specifying the boundary conditions could be violated under some conditions such as high pumpage close to the model boundary, however, due to the density of canals, ditches, and surface-water features within the study area, the impact of boundary errors would be limited to areas close to the specified boundaries.

Unsaturated zone

The development of the unsaturated zone component of the model was based on horizontal and vertical distribution of soil physical parameters. Representative retention curves and hydraulic conductivity curves of various soil types were used in the computation of fully distributed soil water content profiles and vertical flow. Most of the soils of southwest Florida are shallow and sandy with high water tables. They are characterized by high to very high permeability, high porosity and little or no capillary rise. The texture and hydraulic properties of the soils varies both on local and regional scale. To provide a horizontal and vertical distribution of soil physical parameters, characteristic soil types were identified from landscape classifications. For the purpose of this study, soils were classified into different hydrologic response groups with similar properties. These are flatwoods, marshes and ponds, sloughs, depressions, and rock (shallow soils underlain by limestone).

Surface water

The surface-water component of the model comprises both the overland and the channelized flows. Detailed topographic information and canal geometry are important for the development of this component of the model. In addition, data describing water control structures such as weirs, locks, culverts, and pumps, and their operation, are required to properly represent these features in the model.

The study area is generally flat with a number of flood plains or depressions (sloughs and swamps) adjacent to the river branches. At high water levels following rainfall events, the river inundates the floodplains. When the river water levels recede, water accumulated on the floodplain drains back to the river. Dynamic floodplain simulation of the river/floodplain interaction was determined to be important in order to describe flow attenuation and surface-water storage in such areas as Lake Hicpochee and Telegraph Swamp, which are connected to the Caloosahatchee River and Telegraph Creek respectively.

The Caloosahatchee River and its major tributaries were included in the river hydraulics model. Locks, weirs, culverts, and pumps on the Caloosahatchee River and its major tributaries were also incorporated into the model. The river network implemented in the model included both irrigation and drainage canals. The irrigation canals are those canals within the basin from which pumpage for agricultural irrigation purposes was possible. Where such information was available, documented canal geometry obtained from permit records and previous surveys, was used to describe canal cross sections within the model. For those canals or canal reaches for which actual geometry was unknown, approximate cross sections were developed based on best available information.

The drainage and irrigation network within the Caloosahatchee Watershed is controlled by a large number of structures. Many of the secondary branches are canals, which have been constructed to provide sufficient conveyance capacity for drainage, sufficient storage capacity for irrigation, or both. To supply surface water to the upstream parts of the basin during dry periods, the water is pumped upstream from the Caloosahatchee River and held back by weirs or gates. The pumps are usually situated next to a weir. The pumps are activated when the water level upstream of the weir drops below the minimum acceptable level for irrigation. Water is diverted from the main secondary irrigation canals to the farm fields by pumps or by tertiary ditches and canals. The operations of the agricultural pumps and weirs were represented in the model.
Lake Okeechobee inflows represent the primary surface-water inflow to the model area. The historic measured inflows from Lake Okeechobee, measured at the Moore Haven Lock (S-77) were specified as surface-water boundary condition for the model. The downstream boundary of the Caloosahatchee River was specified west of the Franklin lock and Dam (S-79) and represents the discharge to tide from the river. The measured level downstream of S-79 was applied to the tidally influenced portion of the Caloosahatchee River west of S-79 in the model.

In addition to the data that describes the saturated, unsaturated, overland, and channelized flows, meteorological information, and data on water use within the study area, were required for model development.

Meteorological Data

The rainfall distribution in the study area, as in most parts of Florida, is highly variable in both time and space. Local thunderstorms account for considerable rainfall volumes. Rainfall data from nine stations were selected to represent the rainfall input in the model area. The measured time series were gap-filled by transferring values from neighboring stations and distributed areally using Thiessen polygons. Daily rainfall data is provided as input to the model.

Evapotranspiration accounts for a significant portion of the water losses from the Caloosahatchee Basin and was therefore an important component of the model. Potential evapotranspiration and crop cover were used within the model to compute actual evapotranspiration. Penman estimates of potential evapotranspiration from three stations within and close to the study area were provided as input into the model. Land use data were used to distribute vegetation characteristics over the model area. The model considered interception and evaporation from vegetation cover, soil and free water surface evaporation, and plant transpiration from the root zone in simulating the actual evapotranspiration rate. Additional discussion of the MIKESHE ET Module can be found in MIKE SHE Water Movement user Guide (DHI 1998.)

Water Uses

Irrigation and public water supply withdrawals from surface-water and shallow groundwater sources within the Caloosahatchee Basin were represented in the model. The public water supply withdrawal points were located just upstream of S-79 and were represented in the model by pumps withdrawing specified volumes of water directly from the Caloosahatchee River upstream of S-79. The simulated withdrawn were determined from water use records for the City of Fort Myers and Lee County Utilities.

The model calculated irrigation water demand for each time step of the simulation. The simulated irrigation water demand was based on soil water deficit in the root zone, which is specified as the field capacity minus the actual water content. The irrigation water demand is thus a

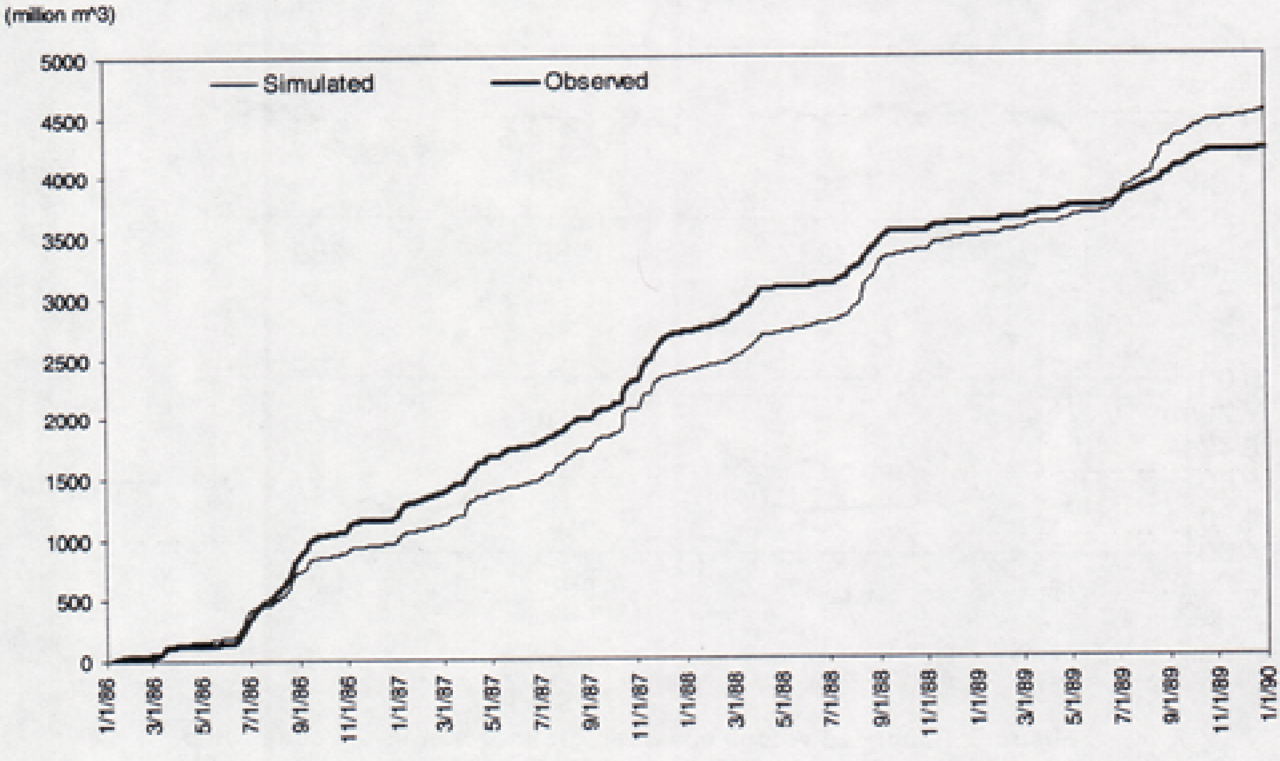

Figure 3: Simulated versus observed cumulative discharge at S78 (1986 - 1990)

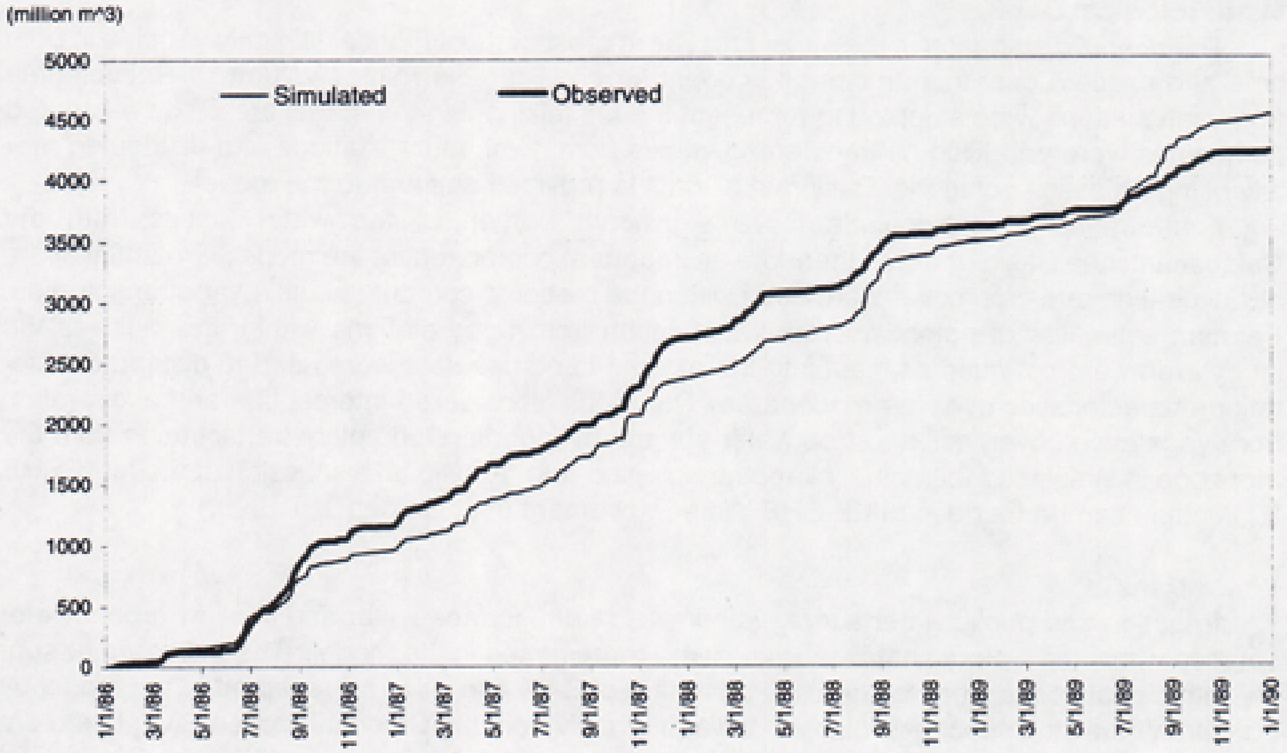

Figure 4: Simulated versus observed cumulative discharge at S79 (1986 - 1990).

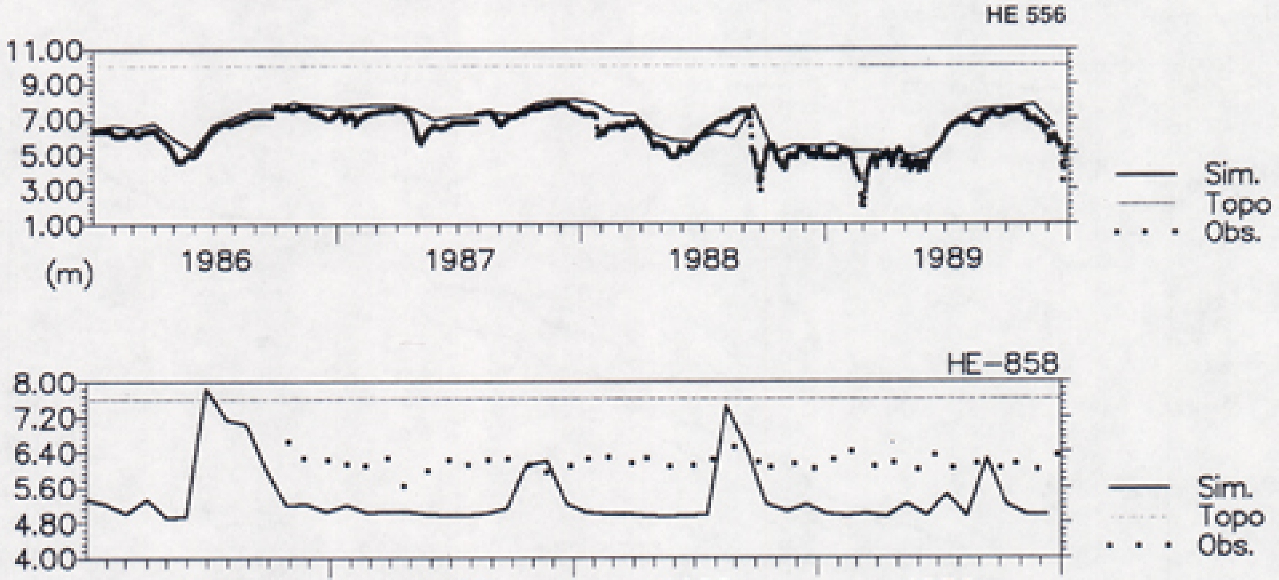

Figure 5: Simulated versus observed groundwater levels at selected calibration wells (1986 - 1990).

simulation result that depends on soil, vegetation, and meteorological data rather than a predefined input. The simulated irrigation needs were taken from groundwater or surface water sources based on information available in water use permit records for the individual farms. Where the data shows that both surface water and groundwater sources were used to meet the irrigation requirements, the model was developed to utilize surface water sources first and then groundwater sources when surface sources became limited.

CALIBRATION AND VALIDATION

Data for the four-year period between January 1, 1986 and January 1, 1990 were used to develop and calibrate the model. This period represents both dry and wet conditions within the study area and would provide insight into the models performance during low flow and high flow conditions. In addition, suitable data such as water level at wells and discharge at major structures were available to calibrate the model for this period. The emphasis of the model calibration was on simulated discharge at the Ortona Lock (S-78) and the Franklin Lock and Dam (S-79). A reasonable match of simulated water levels to observed groundwater levels at monitoring wells within the study area was also required.

Calibration was performed in an iterative process with surface water and groundwater parameters within the model varied until simulated flows at S-78 and S-79 and simulated groundwater levels at the calibration wells closely matched the observed values. Figures 3 and 4 show the match between cumulative observed and simulated discharge at S-78 and S-79 respectively. Both Figures show a reasonable match. Figure 5 shows the match between simulated groundwater level and observed groundwater level at two monitor wells within the study area. A

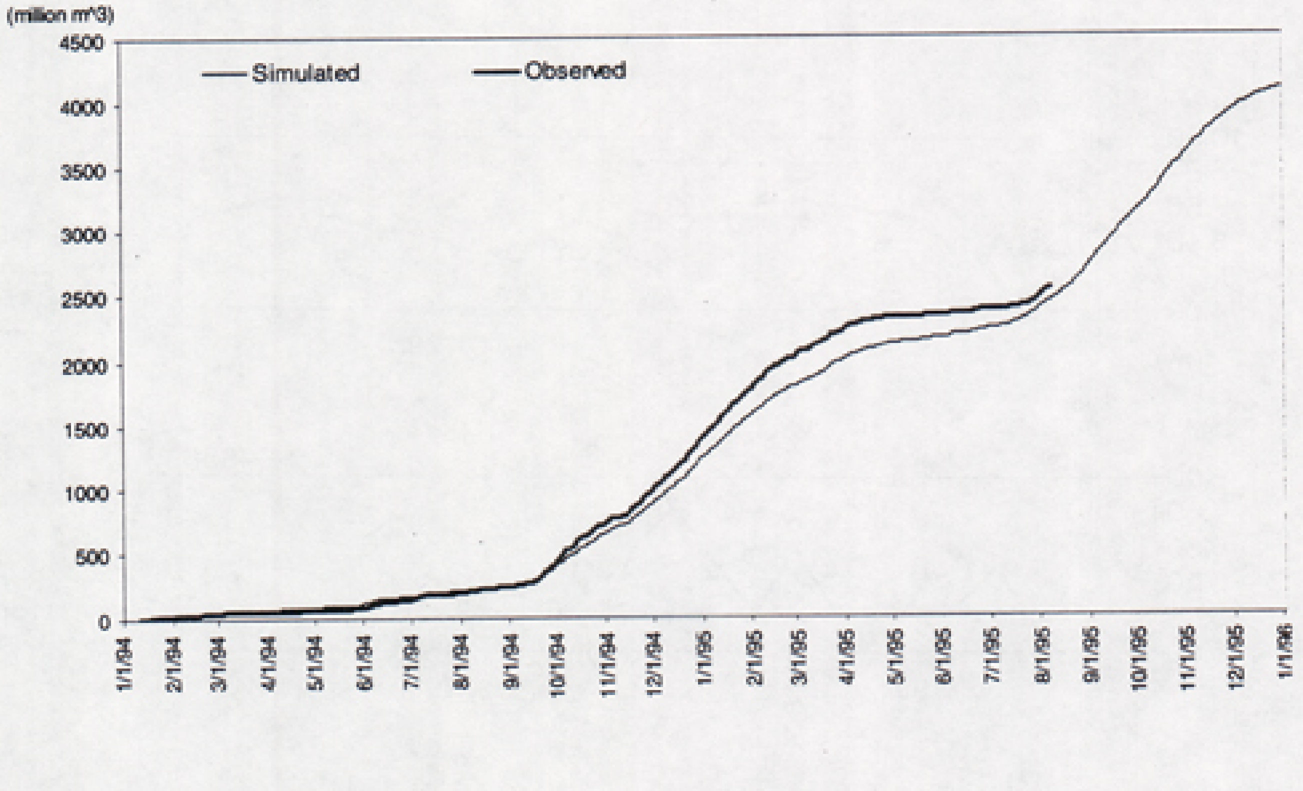

Figure 6: Simulated versus observed cumulative discharge at S78 (1994 - 1996).

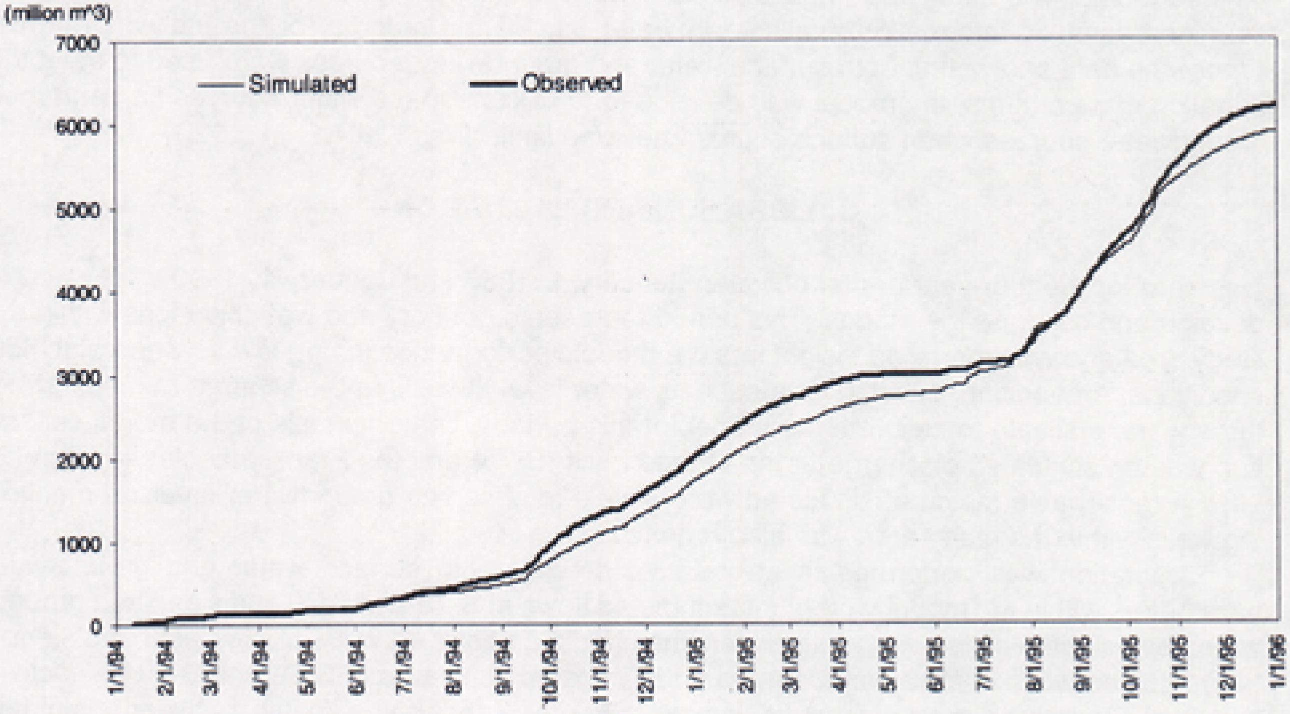

Figure 7: Simulated versus observed cumulative discharge at S79 (1994 - 1996).

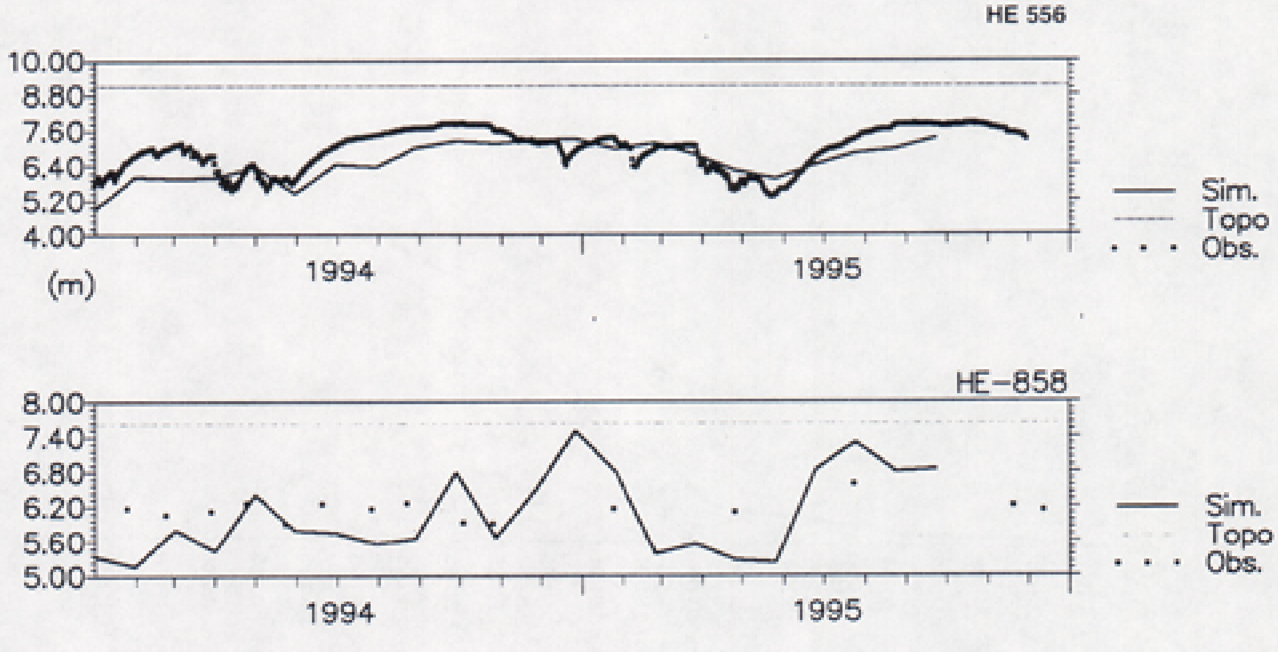

Figure 8: Simulated versus observed groundwater levels at selected calibration wells (1994 - 1996).

review of these and similar plots for other monitor wells show that the model-simulated water levels did not match the dynamics and magnitude of water level changes that were observed in many locations.

The quality in the fit, both in discharge and groundwater levels, could be affected by several factors. Primary among these is the uncertainty associated with distribution of rainfall within the basin. There is also uncertainty associated with agricultural pumping practices and rates within the study area. The size of the model grid (1500 feet by 1500 feet), the lumping of parameters within the grid cells, poor vertical resolution, and the use of homogeneity assumption about the aquifers are other factors that could also contribute to a poor fit of model simulated to observed groundwater levels. The model will benefit from a more detailed representation of the aquifers, use of smaller grid cells and distributed aquifer parameters based on properly designed field testing.

Following the model calibration, data from the period between 1994 and 1996 was used for model validation. The quality of the model prediction for data not used in the model development and calibration, while retaining the parameters selected based on the model calibration, provide insight into the models ability to properly represent field conditions. Simulated discharge at S-78 and S-79 and simulated groundwater level at selected monitor wells were compared to observed data for the new simulation period. Figures 6 and 7 show the match between cumulative simulated and observed discharge at S-78 and S-79. Both Figures show a reasonable match. Figure 8 shows the match between simulated groundwater level and observed groundwater level at two monitor wells within the study area. In all cases the simulated results match well with the observed data and the quality of the match is comparable to the matches obtained during model calibration. Based on the calibration and validation results, the model was considered suitable for simulating field conditions within the Caloosahatchee Basin and meets the primary objective of obtaining a close agreement with respect to canal low flows and acceptable groundwater head levels and dynamics.

DESCRIPTION OF MODEL APPLICATION

The model was used for alternative evaluation during development of the Caloosahatchee Water Management Plan. The model was run using projected agricultural and public water supply demands in order to evaluate impacts of the anticipated demands on the environment. The various scenarios were evaluated based on several performance criteria including water supply, watershed environmental and resource protection, and estuarine protection.

The Caloosahatchee model was run using the 1995 land use and public water demand data with precipitation and evapotranspiration corresponding to the 8-year period between 1988-1995. This simulation represented that 1995 base case scenario. A similar simulation using projected 2020 land use data with precipitation and evapotranspiration corresponding to the same 8-year period was performed. This scenario incorporated future demand without development of new infrastructure and represents the 2020 base case scenario. A comparison of both base case scenarios showed that 2020 projected demands could not be met for significant parts of the simulated period and flows to the estuary was significantly impacted with extended period of low discharge to the estuary. The model results also showed areas within the watershed with water management problems and opportunities. Several management alternatives were developed to address the problems and take advantage of the opportunities for meeting the future water needs. The strategies included such actions as development of surface or subsurface storage within the Caloosahatchee Basin to store water during the wet season and to augment water supply during the dry season. Regional reservoirs, distributed small-scale reservoirs, aquifer storage and recovery (ASR) facilities, additional water control structure in the Caloosahatchee

River, and water harvesting were specific storage or management components considered. The Caloosahatchee model was used to evaluate these water management strategies within the Caloosahatchee Basin. Nine alternatives, made up of one or more storage or water management component, were compared on the basis of the performance measures. The alternatives that best met agricultural, public water supply and estuary flow requirements with minimum environmental impact were identified as preferred alternatives. A detailed description of the alternative evaluation process and a presentation of the results can be found in the Caloosahatchee Water Management Plan (SFWMD, 2000.)

CONCLUSION

An Integrated Surface-water and Groundwater Model of the Caloosahatchee Basin was developed using MIKE SHE/MIKE 11. The model, which simulates surface-water and groundwater responses to changes in management, land, and water uses and other hydro-meteorological stresses, was developed as a tool for evaluating impact of water management alternatives developed as part of the Caloosahatchee Water Management Plan.

The model was developed and calibrated using data from 1986 to 1990 and was validated with data from 1994 to 1996. The calibration and validation results show a good match between simulated and observed surface-water discharge and acceptable match between simulated groundwater levels and observed groundwater levels.

The model was used to evaluate water resources management alternatives aimed at ensuring adequate water supplies within the Caloosahatchee Basin up to the year 2020. Based on the model results it was determined that the Caloosahatchee Basin will not be able to meet agricultural, public water supply and environmental demands by the year 2020 without the addition of surface and sub-surface storage within the basin.

The integrated surface-water groundwater model represents an improvement over traditional modeling approaches, which utilize surface-water models or groundwater models to simulate the extensive groundwater surface-water interactions observed in the Caloosahatchee Basin.

The integrated model is comprehensive in its representation of the entire land based portion of the hydrologic system. The data requirements are significant and could introduce uncertainty to the model results.

The calibration and validation exercise show that improvement in the groundwater representation is desirable. Application of distributed aquifer parameters, use of additional layers, and a finer grid resolution would improve the model and is recommended as part of future development work on the model.

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SURFACE WATER MANAGEMENT IN LEE COUNTY

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ABSTRACT

Historically, development in Lee County began along the Caloosahatchee River. The first roads, such as McGregor Boulevard and Palm Beach Boulevard, evolved along the topog-raphical break line where flat inland prairies began to slope steeply to the river. As development moved inland away from these first roadways and relatively well-drained steeper lands, problems began to arise. The flatter inland prairies were more difficult to drain and stable downstream creeks were incapable of passing significantly increased flows. The approach to solving these problems and some examples of solutions are further described. Durward Boggess' contributions to these solutions are outlined. Early stream gauging techniques to record high water marks and more recent gauging technology is discussed. Significant flood events such as in the early 1970's and in 1995 are described. The stormwater portion of the National Pollutant Discharge Elimination System (NPDES) program will have significant impact on surface water manage-ment in Lee County. The NPDES program's objective is improving water quality by reducing or eliminating pollutants discharged via surface runoff. Rainfall and water elevation data collection is important in this regard and is joined with estimation of flow and testing of water quality. The combination of this data allows annual pollutant and sediment loadings to be calculated. The gaug-ing techniques Durward Boggess helped establish are valuable to monitor and manage systems for maintenance or improvements as needed.

SURFACE WATER MANAGEMENT IN LEE COUNTY

History

Historically, the first settlers of Fort Myers concentrated near the Caloosahatchee River, where ground slopes were relatively steep and drainage was good. Early roads such as Palm Beach Boulevard and McGregor Boulevard evolved along "ridge lines" basically par-alleling the River. These road locations generally followed the topographic break where wet inland prairies began a steeper slope directly to the River. An example of this steeper slope to the River is along the Winkler Canal route. The slope from the Ten Mile Canal Dike west to McGregor Boulevard is six feet in two miles. The slope from McGregor Boulevard to the Caloosahatchee is twelve feet in one half mile. Many areas downstream of Palm Beach Boulevard and Bayshore Road (north of the river) show this similar steep gradient.

Early development in Lee County also generally occurred along the Caloosahatchee and then along the estuaries and bays where upland areas were easily accessible. As the areas between the ridge line roads and the River became more intensely populated, development moved inland. Small creeks that heretofore drained simply from ridge roads such as McGregor Boulevard to the River were subjected to drainage from large inland watersheds that became more impervious each year. In the 1960's when much of this development began to occur, no water management districts had been formed to oversee surface-water management in Lee County. When the original communities were planned along the River in the early 1900's, little thought was given to the effect that later upstream developments would have on downstream runoff.

The Basic Problem

Unfortunately, the historical development pattern was "in reverse" from a drainage standpoint. Natural downstream drainageways traversed developed and stable residential areas. In most cases, rights-of-way were by occupation and previous use only. Attempts to improve small downstream channels were met with many obstacles, including high costs and opposition of adjacent land owners. If downstream channels were not altered in conjunction with uncon-trolled upstream development, "bottleneck" situations occurred. The downstream constrictions obstructed the passage of upstream water as well as causing severe bank erosion in their own localized area.

Lee County's First Watershed Study

Lee County's first comprehensive watershed study was performed by the Sarasota engineering firm of Smally, Wellford and Nalven (1961). They divided the County into four general watershed areas (See Figure 1):

North Coastal
North Caloosahatchee
South Caloosahatchee
South Coastal

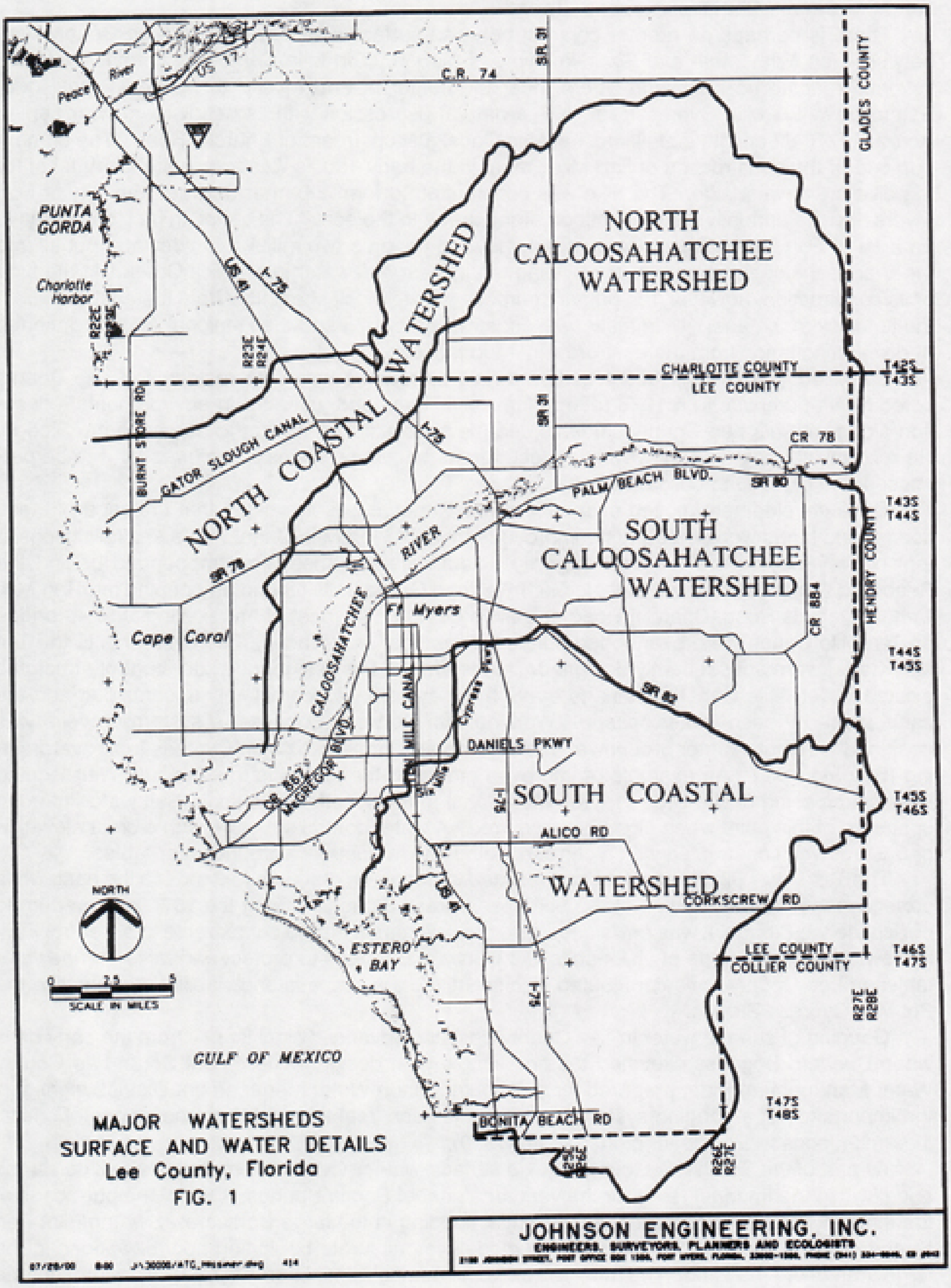
Three main zones could usually be distinguished in each watershed: (1) a flat, coastal marsh generally ranging in elevation from one to two feet above sea level, (2) a relatively steep transitional zone between the downstream coastal marsh and the upstream prairie area, and (3) a flat inland prairie in the upstream portions of watersheds.

Surface Water Studies - 1972 and 1979

Johnson Engineering performed surface water studies for Lee County in 1972 and 1979. It was during this period that Johnson's staff began meeting with Durward Boggess to acquire background data and advice. Discussions at these meetings usually centered around proposed surface-water con-veyances, the potential impact on groundwater and how to protect and enhance the groundwater table. One of the first issues to be discussed was Gator Slough and the need for a water control structure in the vicinity of Burnt Store Road. Boggess reasoned that Burnt Store Road was a logical location for a system of weirs to deter direct salt water intrusion into upstream canals and lakes. Use of Burnt Store Road as a barrier also provided opportunity to conserve fresh water upstream in the Cape Coral surface water system. Boggess strongly lobbied for a barrier weir on Gator Slough at Burnt Store Road and that the crest be set at elevation 2.5 feet NGVD. After several meetings, developers and regulatory agencies agreed with Boggess' recommendations. One of the first Lee County crest gauges was installed in 1973 on Gator Slough at Burnt Store Road. This gauge contributed to documentation used in later modeling of Gator Slough.

A crest gauge system was initiated in 1973 by Lee County on many of the major streams. Durward Boggess advised from his USGS experience on the type of crest gauge that would be economical and effective in Southwest Florida. A simple steel pipe with ground cork floating inside was used. As water levels rose, the cork would be deposited on a wooden lath strip inside the pipe. The lath was later removed and read to determine the surface-water elevation at its crest. The crest gauge information was used to establish many key road elevations such as:

Daniels Road @ Ten Mile Canal and @ Six Mile Cypress
Six Mile Cypress Parkway
Summerlin Road



MAJOR WATERSHEDS SURFACE AND WATER DETAILS
Lee County, Florida
FIG. 1

JOHNSON ENGINEERING, INC.
ENGINEERS, SURVEYORS, PLANNERS AND ECOLOGISTS

Ten Mile Canal / Six Mile Cypress Slough

There is perhaps no greater contrast between surface-water systems in Lee County than between Ten Mile Canal and Six Mile Cypress Slough. Ten Mile Canal is a channelized conveyance running from Hanson Street, near the center of Fort Myers, to Mullock Creek, near Estero Bay. Six Mile Cypress Slough is a natural depression with its headwaters near Lehigh Acres at S.R. 82 and its outfall into Ten Mile Canal just upstream of Briarcliff Road. The primary purpose of the construction of Ten Mile Canal in the early 1900's was to acquire fill material for the dike on its west side. The dike was constructed to form a barrier between the City of Fort Myers and the annually inundated flood prone areas to the east. The canal, in fact, originates in an area of Fort Myers where it would only have to traverse two miles to a tidewater outfall into the Caloosahatchee River versus traveling ten miles to tidewater in Mullock Creek. At the time of its construction, however, the primary purpose was to block sheet flow from the east, not drain the lands from the east. Ultimately, with construction of I-75 and the Regional Airport, drainage of developing lands from the east grew in importance.

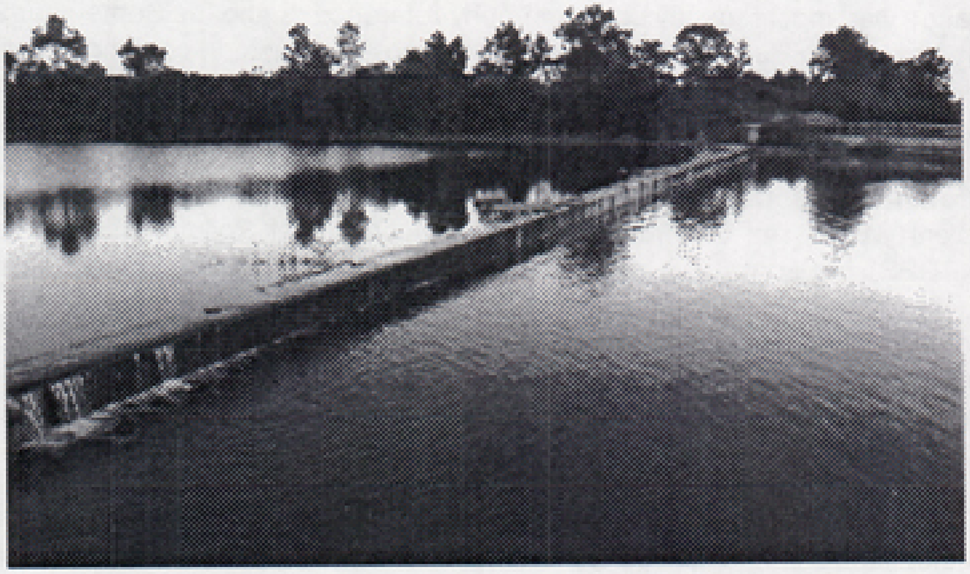
Six Mile Cypress was recognized as a natural treasure when the residents of Lee County voted for its purchase in a 1976 referendum. Bill Hammond, a leader in environmental education along with his Lee County students, led the successful campaign to purchase the Slough. He recognized that the only way to protect it from piecemeal development was for it to be purchased and placed in public ownership.

Once development moved east of Ten Mile Canal, it was inevitable that drainage of these flood prone lands would need to be improved. In 1974, Ten Mile Canal was a shallow inconsistent conveyance with a low flow capacity. Southwesterly sheet flow impounded behind the Seaboard Coast Line (now Seminole Gulf) Railroad Grade until it found an opening into Ten Mile Canal. Daniels Road, Briarcliff Road and even Old U.S. 41 (east of the existing U.S. 41 bridge on Ten Mile Canal) were overtopped during the summer wet season. Improvements to the Ten Mile Canal were subsequently designed. At the time of the design, no water control structures existed in Ten Mile Canal. Drainage through the system was completely uncontrolled and the canal went dry each winter season. Working with Durward Boggess, a system of weirs was designed to restore winter groundwater levels and also protect Six Mile Cypress from overdraining (See Figure 2). An example of improved groundwater control is the Tamiami Weir located near the crossing of Old U.S. 41. Ten Mile Canal at this location was tidal. Salt water intruded upstream of this point when high tides occurred. A water control structure with a crest elevation of 5.5 feet was constructed with a corresponding rise in upstream groundwater tables.

The Ten Mile - Six Mile system has resulted in adequate drainage for lands to the east, while protecting the natural function of the Six Mile Cypress Slough. During the 1976 referen-dum to pur-chase the Slough, it was envisioned as a green emerald strand comparable to a Central Park in New York City. Efforts of visionaries like Durward Boggess to protect and raise groundwater tables in Lee County have contributed significantly to the success and viability of areas like the Six Mile Cypress Slough.

Gauging of surface water in Lee County has also advanced significantly from the early days when Durward Boggess sketched the first simple pipe design. The recent South Lee County Water Management Plan, prepared for the South Florida Water Management District, highlights the importance of a gauging system that provides near "real time data" on the stages of critical streams (Johnson Engineering, Inc., et al., 1999).

As part of the South Lee County Plan, a surface-water model was created to simulate stages and flows in the Imperial River for the vast area east of Bonita Springs. One of the pur-poses of the model was to predict stages and potential flooding in the large Corkscrew Swamp/Flint Pen Strand area. Key to the reliability of this model was accurate beginning pool elevations in the large area being modeled. The most reliable data comes from historical U.S.G.S. records for the



Gator Slough at Burnt Store Road.

Six Mile Cypress Weir at Ten Mile Canal.

Figure 2.

Imperial - Estero Rivers (Kenner and Brown, 1956) and the existing continuous U.S.G.S. recorder on the Imperial River/Kehl Canal just upstream of I-75 at the Orr Road Bridge (U.S. Geological Survey, 1999). This gauge was used to both assist in model calibration and also to provide an on-going reference as to the model's predictive accuracy.

The gauge was most recently used for hourly reference during the September 21, 1999 period when tropical storm Harvey passed through the area. Its use, in conjunction with the predictive model, was instrumental in avoiding an unnecessary 1999 evacuation of Bonita Springs, which was so adversely impacted in the 1995 floods.

National Pollutant Discharge Elimination System

The Clean Water Act of 1968 established the National Pollutant Discharge Elimination System (NPDES) program. It is administered by the United States Environmental Protection Agency (EPA). The NPDES program covers all types of water-borne pollution that is discharged to waters of the United States. The initial thrust of this program was to decrease pollutant loadings from point sources. These point sources were mainly wastewater treatment plants and industrial waste process water. Great strides in pollutant reduction have been made over more than 30 years of this program.

Storm-water runoff was included in the original legislation, but was not an early target for specific regulation. The EPA was sued by several environmental groups in the mid-1980's. The result was that in 1987, EPA started regulating storm-water runoff, which is also referred to as a potential non-point source of pollutants. Municipalities with a population of more than 100,000 as of 1980 were included in the first phase of the stormwater regulation part of the pro-gram. An additional group of municipalities was included following the 1990 census. In this phase, construction sites where land is disturbed in quantities greater than five acres were considered an industrial activity regardless of the final land use. Permitting of these sites became required as a result. Most of the rules are similar to those already required by the Florida Department of Environmental Protection and the Water Management Districts. The major difference is the record keeping that is required.

Lee County was subject to the NPDES permit requirements on construction sites when the permit became available. A general permit for Florida became available on October 1, 1992. Initially the applicant was either an individual or group applicant. Under the general permit, a one page application known as a Notice of Intent (NOI) is utilized and requires a Storm Water Pollution Prevention Plan (SWPPP). The latter out-lines each site activity that may contribute to polluted runoff and procedures undertaken by the developer to minimize transporting pollution offsite.

The NPDES permit addresses surface water quality and not groundwater. Here in Southwest Florida, the surface water and the surficial aquifer are directly linked. Durwood Boggess' work with the groundwater system of this area can be related directly to the local surface waters. Most of the local surface waters ultimately discharge to waters of the United States, especially in the wet season when most of the runoff occurs. During the dry season, runoff may not go directly to an outfall, but enters the surficial aquifer instead.

Mr. Boggess recognized the importance of water quality early in his work here in Southwest Florida. He was a strong supporter of maintaining both surface-water quality and water quality in the aquifers. Much of his work centered on saltwater intrusion along the coast. He understood the connection between the surface water and the surficial aquifer. Using this knowledge he was an early pro-ponent of not breaching confining layers during the construction of lakes or borrow pits.

Durward Boggess has left a legacy that is effective in enhancing the public safety and welfare of Lee County even today.

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SEAGRASS MEADOW HOURLY DISSOLVED-OXYGEN RECORDINGS CENTRAL ESTERO BAY, LEE COUNTY

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ABSTRACT

Dissolved-oxygen (DO) concentrations and other physical water quality parameters were measured hourly, from June 1996 to the present day using a programmed continuous digital recorder deployed in a major *Thalassia, Syringodium,* and *Halodule* seagrass meadow at Starvation Flats in the shallow waters of central Estero Bay. The daily recorded DO concentrations, more than 19,000 measurements, showed a rapid increase between the hours of 1000 and 2000 (10 am to 8 pm) with a near-dawn low and a gradual lowering over the 5 year period. In general, during the wet-season (April through October), the near-dawn hourly-measured maximum DO concentrations (mg/L) were well below the Florida Department of Environmental Protection (FDEP) standard 1983 minimum of 4 mg/L. The DO production appeared to be directly related to water depth, wave action, water temperature, and water clarity, that is, the shallower the depth, the greater the sunlight penetration, and only indirectly to salinity and other physical parameters. Rainfall analysis showed that heavy rainfall appeared to have only a dampening effect on dissolved-oxygen production over the seagrass beds, which may be due to cloud cover and the slight lowering of water temperature during the rain storms. Dissolved-oxygen is an essential component in the aquatic environment. Of all the parameters that characterize an estuary, the level of dissolved-oxygen in the water is one of the best indicators of estuarine health. An estuary with little or no oxygen in its waters cannot support healthy levels of animal or plant life. DO concentrations of 5.0 mg/L or higher are able to support a well-balanced, healthy biological community. However, when concentrations fall below the current FDEP value of 4.0 mg/L, some researchers consider that a complete alteration of the estuarine biotic assemblage occurs. The health of an estuary can, to a large degree, be determined by observing the near-dawn dissolved-oxygen concentrations as well as the range of DO. For example, the DO (mg/L) continuous recordings made in central Estero Bay show DO levels that range from 0.05 to 12.10 mg/L during the wet and dry seasons of 1996-1997, with more than 120 days a year violating State standards (>4.0 mg/L). From this data, it would appear that Estero Bay may be more stressed than that recorded in Hillsborough Bay. This stress may account for the loss and changes in size of seagrass beds in Estero Bay as surveyed over the last 24 years. Near-dawn DO sags are probably the most important water quality variable affecting both the general health of the bay and species abundance and diversity. Daytime or one-time sampling gives both over-optimistic values and erroneous assessments of water quality. As near-dawn DO concentrations in central Estero Bay regularly experienced values below 2.0 mg/L, far below the recommended FDEP minimum, it is highly recommended that DO concentrations be taken hourly over a 24 hour period, rather than at one time, to assess the health of the estuary. In summary, this study investigated the hourly changes in DO mg/L for monthly periods at different times of the year over a period of 4 years to determine the validity of the hypothesis that near-dawn hourly DO measurements better reflect stresses within the bay than one-time site-specific data-point measurements. From these results, it can be seen that the one-time daytime sampling cannot take into account near-dawn sags, or daytime high DO concentrations, which are the most important indicator of the health of the bay. However, it may be mathematically possible to extrapolate the one-

time data, by using constructed monthly averaged-hourly curves and the time of the sampling to obtain the correct minimums and maximum DO concentrations. This study is still ongoing, and it is hoped that further future investigations will determine the long-term maximum and minimum DO patterns that may be helpful in bay management decisions as to the health of this estuary.

INTRODUCTION

The health of an estuary can, to a large degree, be determined by observing dissolved-oxygen concentrations (DO) (Friedemann and Hand, 1989). Oxygen enters estuarine waters from both the atmosphere and through aquatic plant and phytoplankton photosynthesis. Currents and wind-generated waves boost the amount of oxygen entering the water by putting more water in contact with the atmosphere. Oxygen solubility in water is poor, however, and even well-aerated, freshwater at zero degrees centigrade can only hold 14.2 mg/L of oxygen when fully saturated (Friedemann and Hand, 1989). Saltwater can absorb even less oxygen than freshwater. Similarly, warm water, fresh or salt, holds less oxygen than cold water (Friedemann and Hand, 1989). A vast array of organisms are dependent upon adequate levels of DO for survival. Most animals and plants can grow and reproduce unimpaired when DO levels exceed 5 milligrams per liter (mg/L). However, if DO levels fall under 2 mg/L, a condition known as *hypoxia*, many mobile species will move elsewhere while non-mobile species may die. A second condition, known as *anoxia*, occurs when the water becomes totally depleted of oxygen (<0.5 mg/L) and results in the death or avoidance by any organism that requires DO for survival. Although excess nutrients from human activities can be a major cause of *hypoxia* or *anoxia*, these conditions may also occur in estuaries relatively unaffected by humans. Usually, under the latter conditions, the severity of low DO and the length of time that low oxygen conditions persist are less extreme. The consequences of these changes frequently have both ecological and economic significance. It should also be noted that some systems, such as swamps, can exhibit naturally low dissolved-oxygen concentrations, without adverse effects on some of the biota. The breakdown of organic matter is an integral part of an estuarine ecological cycle, and, like animal and plant respiration, also consumes oxygen. Decomposition of large quantities of organic matter by bacteria can severely deplete the water of oxygen and make it uninhabitable for other species (Friedemann and Hand, 1989). An overload of nutrients from wastewater treatment plants or runoff from residential developments also adds to the problem by fueling the overgrowth of phytoplankton. Phytoplankton ultimately die and fall to the bottom where they decompose, using up oxygen in the waters of the estuary (Friedemann and Hand, 1989).

The measurement of DO concentration is an important indicator of existing water quality as it reflects the ability of a body of water to support a healthy and diverse biological community. It can be based on the saturation in the water, taking into account the temperature and conductivity, both of which affect its capacity to hold oxygen. Diurnal variation in DO levels is generally higher in estuaries than in streams due to the higher rates of primary productivity in estuaries (Friedemann and Hand, 1989). At the surface of an estuary, the water at mid-day is often close to oxygen saturation, due both to mixing with air and the production of oxygen by plant photosynthesis. As night falls, photosynthesis ceases and plants consume available oxygen, forcing DO levels to decline (Friedemann and Hand, 1989). Cloudy weather may also cause surface water DO levels to vary over short time periods, since reduced sunlight slows photosynthesis. The DO levels in deeper parts of an estuary fluctuate according to the rate of oxygen diffusion from the upper layer and the amount of mixing caused by storms, wind, currents, and the circulation of water temperature differences between the layers. Stratification is quite effective in blocking the transfer of oxygen and nutrients between the upper and lower layers. In a well-stratified estuary, very little oxygen may reach the lower depths and the deep water may remain at a fairly constant lower level of DO until the stratification disintegrates with the changing of tides, seasons, or a large storm (Friedemann and Hand, 1989). Although one may think of water as homogeneous and non-changing, its chemical constitution does, in fact, vary over time. Oxygen levels, in particular, may change sharply in a matter of hours, making it difficult to assess the significance of any single DO value. Daytime and mean measurements of dissolved-oxygen may have limited significance, since nocturnal respiration and other episodic instances of low dissolved-oxygen have a significant impact on aquatic biota. Diurnal dissolved-oxygen studies are a necessity for gaining a full understanding of the oxygen cycle in a particular body of water (Friedemann and Hand, 1989). The consequences of a rapid decline in DO (less than 2.0 mg/L) sets in quickly and animals must move to areas with higher levels of oxygen or perish. This impact makes measuring the level of DO an important means of assessing the status of water quality. This study investigated the hourly changes in DO mg/L for monthly periods at different times of the year to determine the validity of the hypothesis that hourly DO measurements better reflect stresses within the bay than a one-time site-specific data-point measurement.

Estero Bay Aquatic Preserve

The study site was located within a large seagrass meadow in the tidal circulation area of Big Carlos Pass within the Estero Bay Aquatic Preserve, Lee County, Florida (Figure 1). This preserve was the first aquatic preserve to be established in Florida in 1966, and was brought under standard management by the Florida Aquatic Preserve Act in 1975. The Preserve covers an area of about 4,525 hectares (11,200 acres) with a drainage basin encompassing 758.5 km2 (293 mi2), located approximately 24 km (15 mi) south of Fort Myers and about 26 km (16 mi) north of Naples, along the western coastline of, and entirely within, Lee County (Godschalk & Associates, 1988). It has experienced significant urban growth surrounding the Preserve and also receives sudden natural flood amounts of freshwater input in the northern, central, and southern portions of the Bay related to stormwater runoff. Some of the human activities in the Bay area responsible for decreased water quality include dredge and fill projects, nonpoint source pollution, road runoff, septic systems (nearly all are on central sewer today, except for some trailer parks and houses on the Estero River), fueling marinas, housing and dock developments, and scarring and turbidity from boat propellers. Along with these developments has come a decline in seagrasses and an abundance of algae in the Bay, as noted in surveys performed in 1972 by McNulty et al. (Estevez et al., 1981), in 1974 by Tabb et al., (1974), in 1991 by Lee County Environmental Laboratory (unpublished GIS maps available from Lee County Tax Office in Fort Myers), and in 1996, 1997, and 1998 by Mitchell-Tapping et al. (1996; 1997; 1998).

The shallow surface water area of Estero Bay (Figure 2) is more than 38 km2 (15 mi2). The estuary complex began to form approximately 5,000 years ago when a rise in sea level drowned the Preserve area. The clastic sediment from offshore were transported by the longshore currents south to be deposited as barrier islands bounding the present Estero Bay and also filled the bay to its present shallow depth. The strong tidal and storm influences formed a large tidal delta inside of Big Carlos Pass and smaller deltas bayside of former and present-day inlets. Within the bay, there are hundreds of low-lying islands and oyster bars, many covered with mangroves. These back-bay islands have no upland areas, except on Mound and Dog keys. Mangrove trees are by far the most dominant vegetation in the estuarine island complex and extensive marine grassbeds are found only in certain protected well-circulated shallow areas of the bay (Mitchell-Tapping et al., 1996, 1997, 1998, 1999).

The middle and lower reaches of all the rivers and creeks are tidal, while freshwater characteristics of the bay vary in response to the daily, seasonal, and long-term forces, and the many and varied conditions found in each of the minor streams from 10 watersheds flowing into the

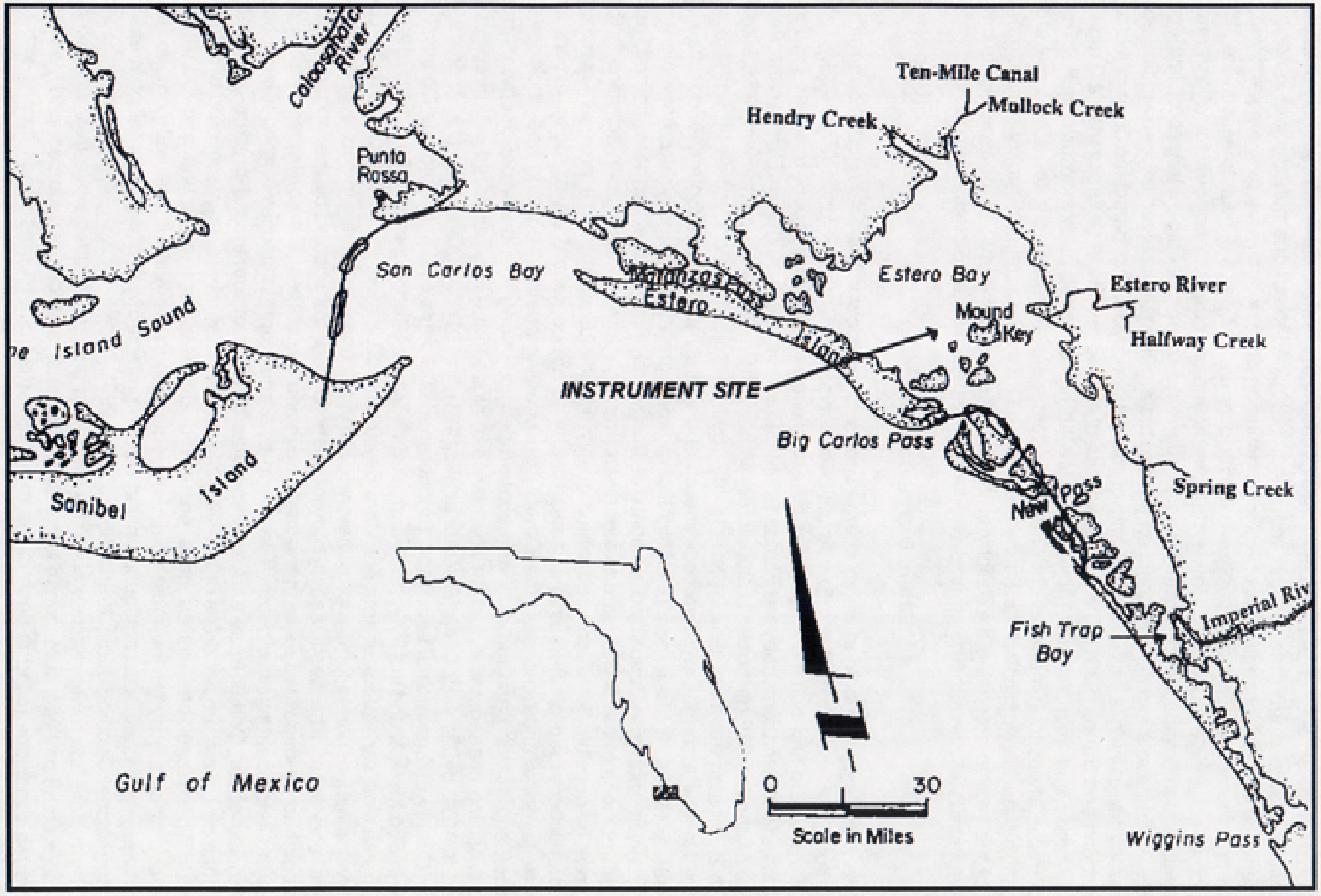

Figure 1. Location of the instrument deployment site in Estero Bay, Lee County, Florida.

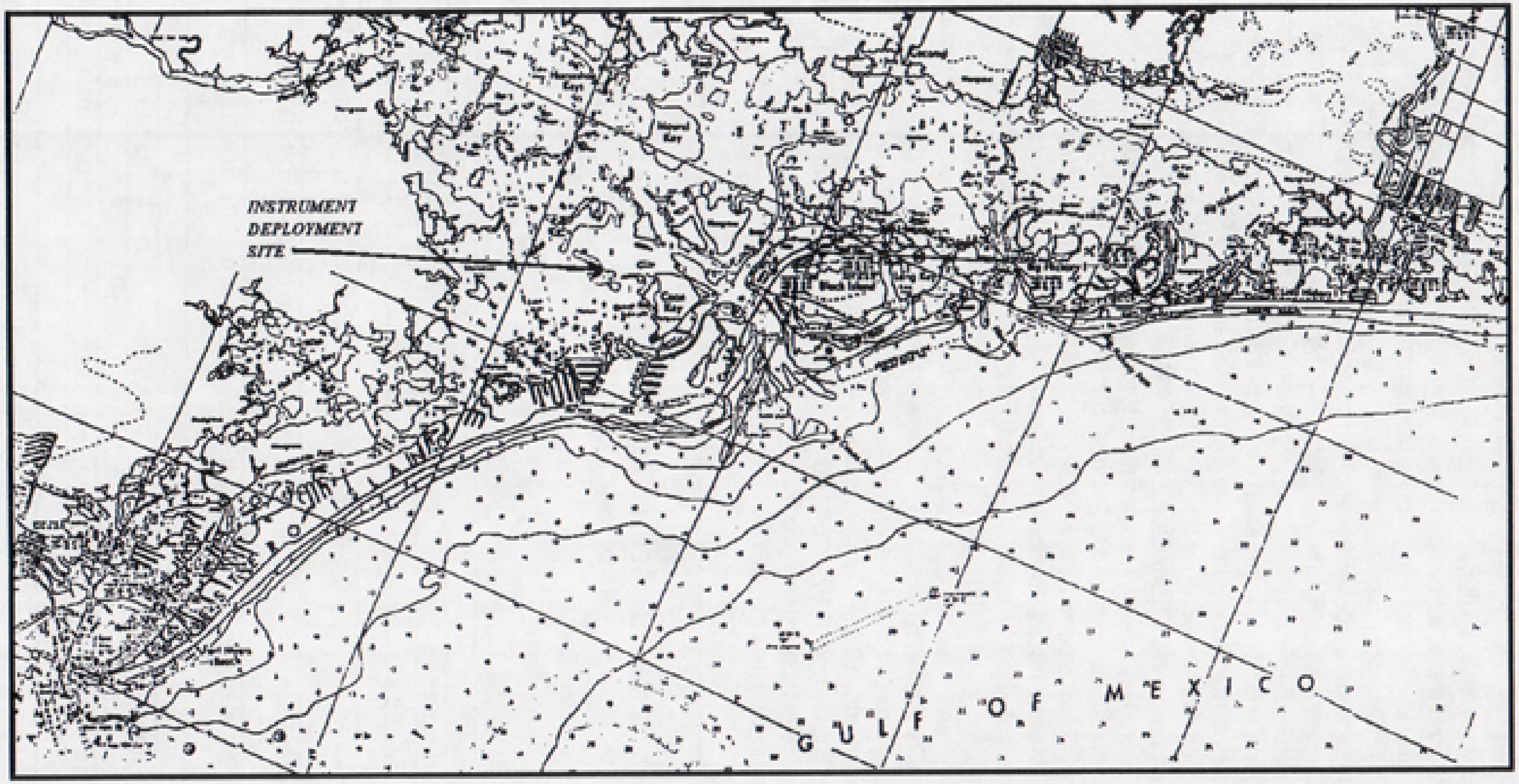

Figure 2. Bathymetric chart of Estero Bay showing the instrument deployment site in a seagrass meadow.

estuary. In the northern portion of the bay, Cow Creek, sometimes called Cow Slough, and No Name Slough both flow into small bays, while Hendry Creek and Mullock Creek and Ten-mile Canal input waters from the southern and eastern portions of the city of Fort Myers. In the central area, Halfway Creek, a former Pleistocene swale between dunes, flows into the Estero River. Spring Creek, also a Pleistocene swale area, flows into the south-central part of the bay and is affected by nearby residential development. In the southernmost part of the bay, the Imperial River drains the largest watershed in Lee County. The lower reaches of this river basin near Bonita Springs have experienced large developments that have affected the watershed. In October 1995, the Imperial River watershed measured a record runoff of 243 x 106 m3 (197,400 acre-ft) of water during a period of heavy rain-storms that recorded 444.75 mm (17.51 inches), while long-term runoff (1940-1995) for this watershed averaged 87.2 x 106 m3 (70,940 acre-ft) which includes past hurricane stormwater (USGS, 1996).

The tides in Estero Bay have a tidal range of approximately 0.94 times the open coast range at Naples (based on calculations and a Suboceanic Consultants hydrographic tide observation study of the Hickory Pass area in February 1978). EBML uses a tidal calculation computer program called *Tide Master* for all its observations in the Bay. Suboceanic Consultants (1978) recorded tidal data obtained at sites at Naples Pier and Little Hickory Island from tide gage records, while the data from Estero Bay inlets were obtained from tide staffs observations at approximately 15-minute intervals at each location (Table 1). The average bay tide range during ebb on February 8, 1978 was 1.77 ft., while the Gulf range was 1.87 ft (Suboceanic Consultants, 1978). Tides in the area are of the mixed-type and have a period of 12.25 hours (Suboceanic Consultants, 1978). Tidal range (0.54 m or 1.77 ft) is approximately, that is, 0.94 times the open coastal range (0.57 m or 1.87 ft) (Suboceanic Consultants, 1978). Area of calculated tidal influence, which extends up rivers to US41, within the Bay is: 0.3 x 108 m2 (3.29 x 108 ft2) (Suboceanic Consultants, 1978).

TABLE 1. TIDAL RANGES, INLET SIZE, AND CURRENT VELOCITIES

(Suboceanic Consultants, 1978).

Inlet	Tide range	Flood tide	Ebb tide
Big Carlos Pass	1.08 m (3.56 ft)	8.18×10^8 ft^3	5.75×10^8 ft^3
New Pass	1.08 m (3.56 ft)	2.71×10^8 ft^3	2.02×10^8 ft^3

Inlet	Throat Width	Hydraulic Radius	Cross-sectional area
Big Carlos Pass	494 m (1,620 ft)	3.9 m (12.85 ft)	1,933.3 m^2 (20,810 ft^2)
New Pass	250.7 m (822 ft)	2.7 m (8.88 ft)	678.2 m^2 (7,300 ft^2)

Inlet	Flood tide	Ebb tide
Big Carlos Pass	0.75 m/s (2.46 fps)	0.09 m/s (2.66 fps)
New Pass	0.78 m/s (2.57 fps)	0.65 m/s (2.12 fps)

Estero Bay has had eight tidal inlets in the past (Little Carlos, Big Hickory and Little Hickory Passes have a historical record of periodic closure). These are from north to south:

Matanzas Pass (affects only the northwestern area)
Hurricane Pass (closed) formerly lead to Hurricane Bay
Mid Island Pass (closed) formerly lead to Hell Peckney Bay
Big Carlos Pass (affects only the north and north-central central area)
Little Carlos Pass (closed) formerly affected the central-southern area.
New Pass (affects only the southern and south-central central area)
Big Hickory Pass (was reopened in 1988, affects only the southern local area)
Little Hickory Pass (closed) formerly affected the southern part.

Tidal current circulation is of utmost importance to Estero Bay in that it plays a dominant role in transporting, flushing, and diluting various contaminants from their sources to seaward locations. The understanding and quantifying of the circulation in an estuary is the first step toward developing a management plan for estuarine resources. Estero Bay is characterized by areas of strong currents that are very pronounced in and around the passes, and by null zones, that is, areas of very low currents, located at dead-end zones or where two tidal waves propagating in from different inlets meet (Figs. 3a, 3b, and 3c). Analysis of these currents show that the primary null flow-tide zones are located north of Ostego Bay and south of Hell Peckney Bay, that is, in the northern portion of Estero Bay, and near the entrance of the former Little Carlos Pass, that is, between Big Carlos Pass and New Pass, in the central part of the bay. The amount of water that flows through the various passes during each tidal cycle varies significantly. The locations of the null zones within the system have a significant effect on the biota and the flushing characteristics of the different segments within the bay and therefore the water quality (Fig. 4). Residual circulation patterns can have a significant effect on water quality within the bay through the transport of material to areas not necessarily near the point of input origin.

Many hours have been spent investigating the current patterns (Mitchell-Tapping et al., 1997) and have determined that there are changes in the location of ebb and flow null zones in the bay that have shown different flushing capabilities of the tidal currents. Tidal current circulation in the Estero Bay system is forced by the tides at Matanzas Pass, Big Carlos Pass, New Pass and Big Hickory Pass (when open, it is very restricted). Tides at the open boundaries are composed of semi-diurnal and diurnal components with relatively low tidal amplitudes (40-80 cm) and slight shifts in the tidal phases. Tidal amplitudes and tidal phases do not vary significantly within the Estero Bay. However, tidal currents show significant spatial variation. The shallower depth and more constricted geometry of the central part of Estero Bay result in more tidal dissipation. During flood and ebb tides, water enters and leaves the bay through all the passes including the Matanzas Inlet, creating strong flood and ebb currents on both sides of the inlets. EBML uses a tidal calculation computer program called *Tide Master* for all its observations in the Bay.

Currents within the bay between the passes are generally much weaker than currents in the passes, due to the presence of null zones. The interaction between the tidal waves entering in the various bay inlets creates a complex circulation pattern characterized by areas of strong currents near the passes and null zones in the bay between inlets. The null zone is characterized by near-zero water flow and direction. Null points may vary and actually be a wider zone at certain times of the year due to changes in tidal height, stormwater runoff quantity, and opening and closing of inlets. The location of the null zone also depends significantly on the location and configuration of the passes, and may shift dramatically if a new pass is opened or an existing pass is closed, such as Big Hickory Pass. Changes in water-quality parameters are also affected by residual flow and tidal flushing. There are four major segments in the Bay (Mitchell-Tapping et

Figure 3a. Northern portion of Estero Bay showing Matazas Pass tidal inflow circulation patterns and null points.

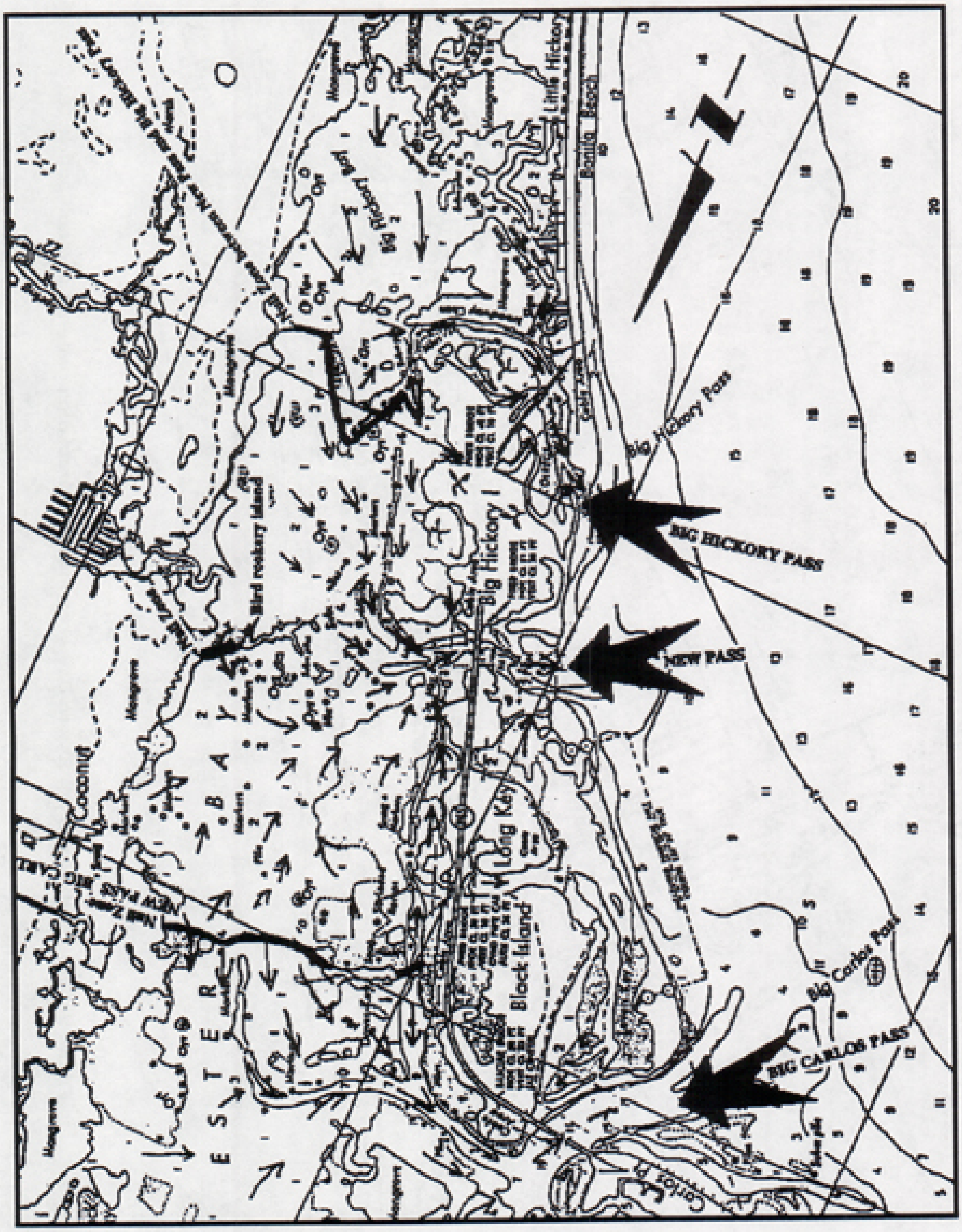

Figure 3b. Central Estero Bay Big Carlos Pass tidal inflow circulation patterns and null points.

Figure 3c. Southern portion of Estero Bay showing inlet circulation patterns and null points.

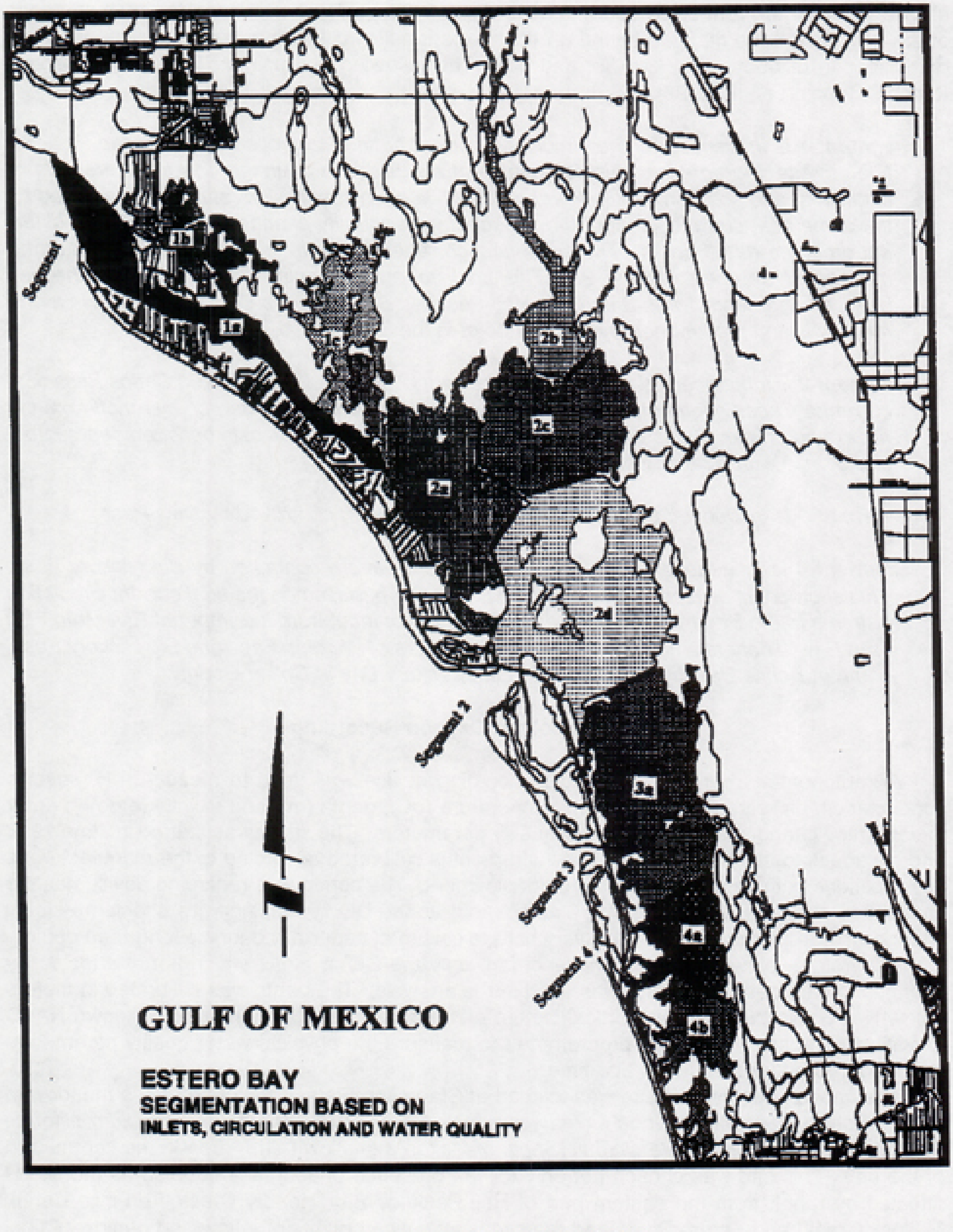

Figure 4. Estero Bay segmentation.

al., 1997) which are further divided into subdivisions. The major boundaries for each segment of the bay have been mapped based on tidal current null-circulation patterns by observing the drift direction of buoys (Fig. 3a, 3b, and 3c). The following null points have been observed (Mitchell-Tapping et al., 1997):

Segment 1 *is influenced by the circulation current pattern controlled by Matanzas Pass for tide ingress and egress. This segment controls the main drainage flow input areas from southwest and southern South Fort Myers, while each subdivision, although influenced by the same tidal currents, control the seasonal water quality changes that are due to different drainage runoff areas. There are tidal current null points in Hurricane Bay and at the meeting of Segments 1 and 2. This tidal current null point stretches across the bay between segments 1 and 2 and into Hell Peckney Bay as far as Dog Key. There is a bird rookery island present nearby this null point in the Bay.*

Segment 2 *is influenced by the circulation current pattern controlled by Big Carlos Pass tidal currents. These segments are influenced to a greater and lesser degree by runoff from the rivers and creeks in this area. Another tidal current null point exists between segments 2 and 3, also with a nearby bird rookery.*

Segment 3 *is influenced by the circulation current pattern controlled by New Pass.*

Segment 4 *is influenced by the circulation current pattern controlled by Big Hickory Pass. This segment is divided into two divisions,* ***4a*** *and* ***4b****, based on the tidal current circulation patterns in the Bay from Hogué Channel and the of input from the Imperial River into Fish Trap Bay. There is a null point between the waters of Wiggins Pass and Big Hickory Pass, south of Bonita Beach Road bridge in Little Hickory Bay in Collier County.*

Hourly Dissolved Oxygen Recordings

An autonomous, remote, continuous-recording device was used to measure pH, specific conductance, dissolved oxygen (mg/l), temperature (oC), depth (m), and salinity (o/oo) in order to determine changes in physical water-quality parameters. The study was started in June 1996 and continues to the present day. The instrument is calibrated according to the manufacturer's specifications both before and after each deployment. The continuous recording device has the capacity to measure DO in both mg/L and %, but as the DO % readings are affected by local changes in barometric pressure, it is very hard to calibrate, especially during a long-term deployment, therefore, although both were recorded, only the DO in mg/L, which is not affected by changes in barometric pressure, was used in the analysis. The depth was calibrated in meters below NAVD (North American Vertical Datum of 1988) using a survey marker of known NAVD elevation. The instrument was programmed to measure the physical water quality parameters every hour for at least a month at a time.

The chosen deployment site was located at Starvation Flats, a major seagrass meadow in central Estero Bay, with abundant *Thalassia testudinum (Turtle-grass), Syringodium filiforme (Manatee-grass)*and *Halodule wrightii (Shoal grass),* in a shallow (<1m) area in the central part of the bay. This site was chosen not only for the presence of seagrass but also as the site is affected by runoff from the eastern part of Hell Peckney Bay, Hendry Creek, Ten-mile Canal, Mullock Creek, and Estero River, and the site is influenced by major inflow and outflow of tidal water into the central part of the bay. Seagrasses are not true grasses, but flowering plants with stems, leaves, roots and flowers, and are more closely related to lilies (Fonseca, 1995).

Seagrasses serve as a good indicator of water quality because they are very sensitive to environmental change (Virnstein and Morris, 1996).

At the site, the instrument was suspended about 5 cm above the seafloor inside a capped (to prevent rainfall effects) protective perforated PVC pipe supported within a tripod and marked with two mooring posts either side of the pipe (Figs. 5). At the end of each deployment, usually for 2 or 3 months at a time, the instrument was recovered and the recordings downloaded into a computer spreadsheet program. The data is then plotted and charted monthly in 24 hour time periods.

A few problems with recordings did occur. Some records showed that during a period of low-low tide the probes of the instrument had been exposed to air, while others showed that sanding (re-suspended micro-sized quartz sediment during rough weather) of the probe had occurred for a short period, thereby giving false readings for that period. In the analysis of the data, these erroneous records were excluded. On one occasion during a deployment (late August, September, and October 1996) the instrument recorded every 2 hours due to an error in programming. November 1996 data was not recovered due to damage of the instrument in the field requiring factory repairs. During 1998, the glass-tipped pH probe was damaged by a crab thereby preventing further recordings of this one parameter.

The data results are presented monthly in 24-hour graphic chart form (Figs. 6, 7 and 8), and show curves of the concentration of dissolved-oxygen in central Estero Bay that increase rapidly between the hours of 1000 and 2000 (10 am to 8 pm) and decrease to a near-dawn sag. Near-dawn sags and daytime high DO concentrations are considered the most important indicators in the assessment of the health of the bay. The charts of DO (mg/L) during the wet and dry seasons show that the daylight maximum DO is sometimes less than 1 mg/L, and the near-dawn sag is well below 0.5 mg/L.

Lewis and Estevez (1988) have reported a maximum DO low in June to August, but had a maximum high during January in a study of Hillsborough Bay. Lewis and Estevez (1988) also reported ranges of DO (mg/L) for other Florida west-coast bays (Tables 2, 3, and 4). None of the recorded DO ranges of these bays (Table 2) are as great as that experienced in Estero Bay (Table 3) which show a range from 0.4 to 13.12 mg/L during the wet and dry seasons of 1999-2000. Lewis and Estevez (1988) state that Hillsborough Bay has the most oxygen stress of all the bays and that the DO levels violate existing State standards 60-90 days a year. Based on these conclusions and as Estero Bay DO levels exhibit a greater range and have more than 220 days a year violating State standards (>4.0 mg/L)(Table 5), one could conclude, based on this dissolved oxygen data, that Estero Bay may be more stressed than Hillsborough Bay, which may also account for the loss of seagrasses within the bay (Mitchell-Tapping et al., 1996; 1997; 1998; 1999; 2000).

Charts were also constructed to show the effect of rainfall precipitation on DO (mg/L) during the wet season. An analysis shows that heavy rainfall appears to have only a dampening effect on dissolved-oxygen production over the seagrass beds and this may be due to a lowering of temperature and increase of cloud cover during rainstorms (Fig. 9). Further analysis of the charts shows that daytime one-time DO sampling gives both over-optimistic values and erroneous assessments of existing water quality. Studies of Estero Bay in 1995 and 1996 (Mitchell-Tapping et al., 1996), taking daytime site-specific one-time weekly samples at more than 15 locations within the bay and also offshore Lovers Key in the Gulf of Mexico, showed higher DO concentrations that gave an over-optimistic view of the health of the bay. However, using a continuous recording device, programmed for hourly sampling over the seagrass meadow in the central portion of the bay, measurements show DO concentrations that show some reason for concern (Table 4).

From these recordings, it can be seen that the one-time daytime sampling cannot take into

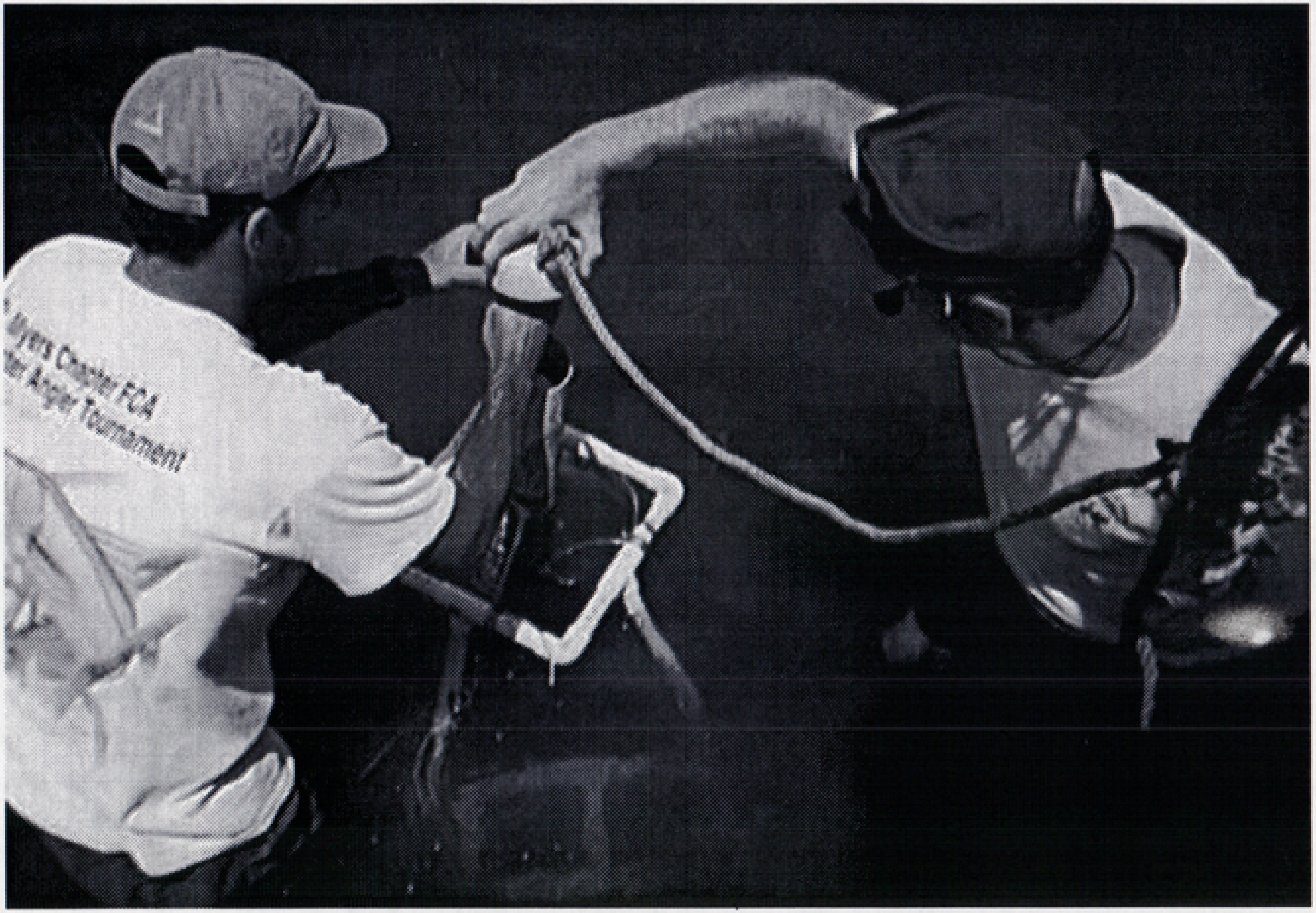

Figure 5. Instrument being deployed at site in a seagrass meadow in central Estero Bay.

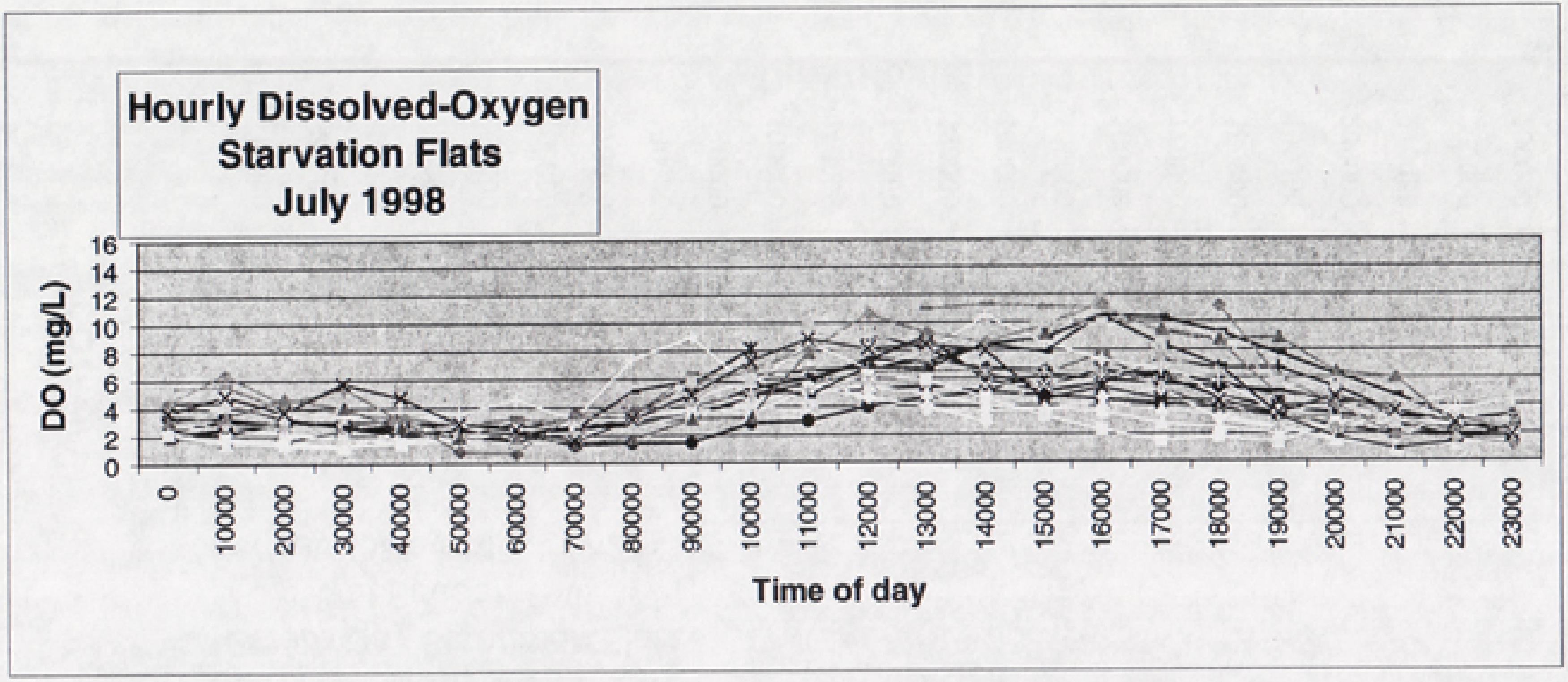

Figure 6. Hourly dissolved oxygen concentration chart for August 1998 showing the near-dawn sag and the daytime high.

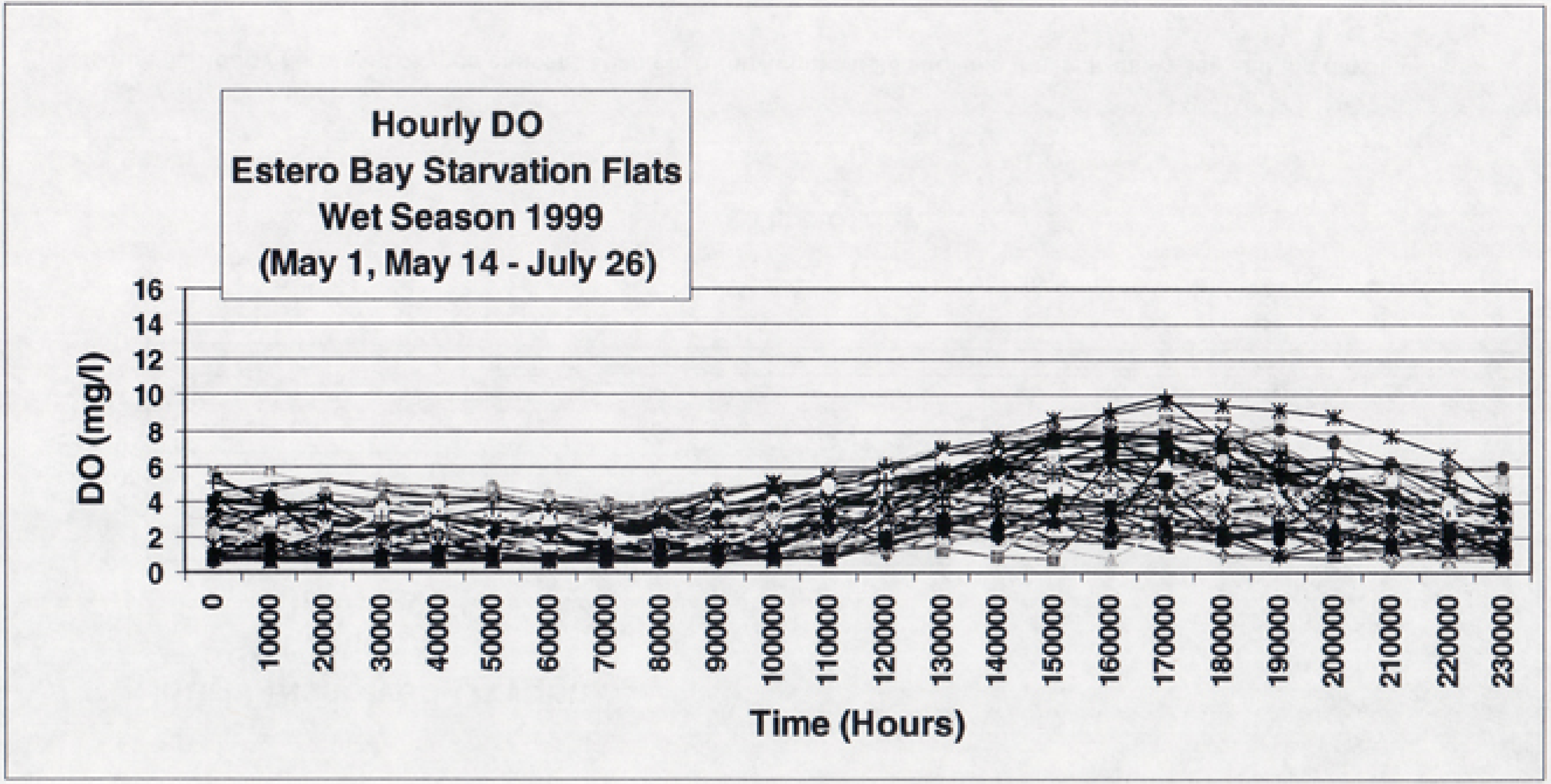

Figure 7. Hourly dissolved oxygen concentration chart for May, June, and July 1999 showing the near-dawn sag, below 4mg/L, and the daytime high.

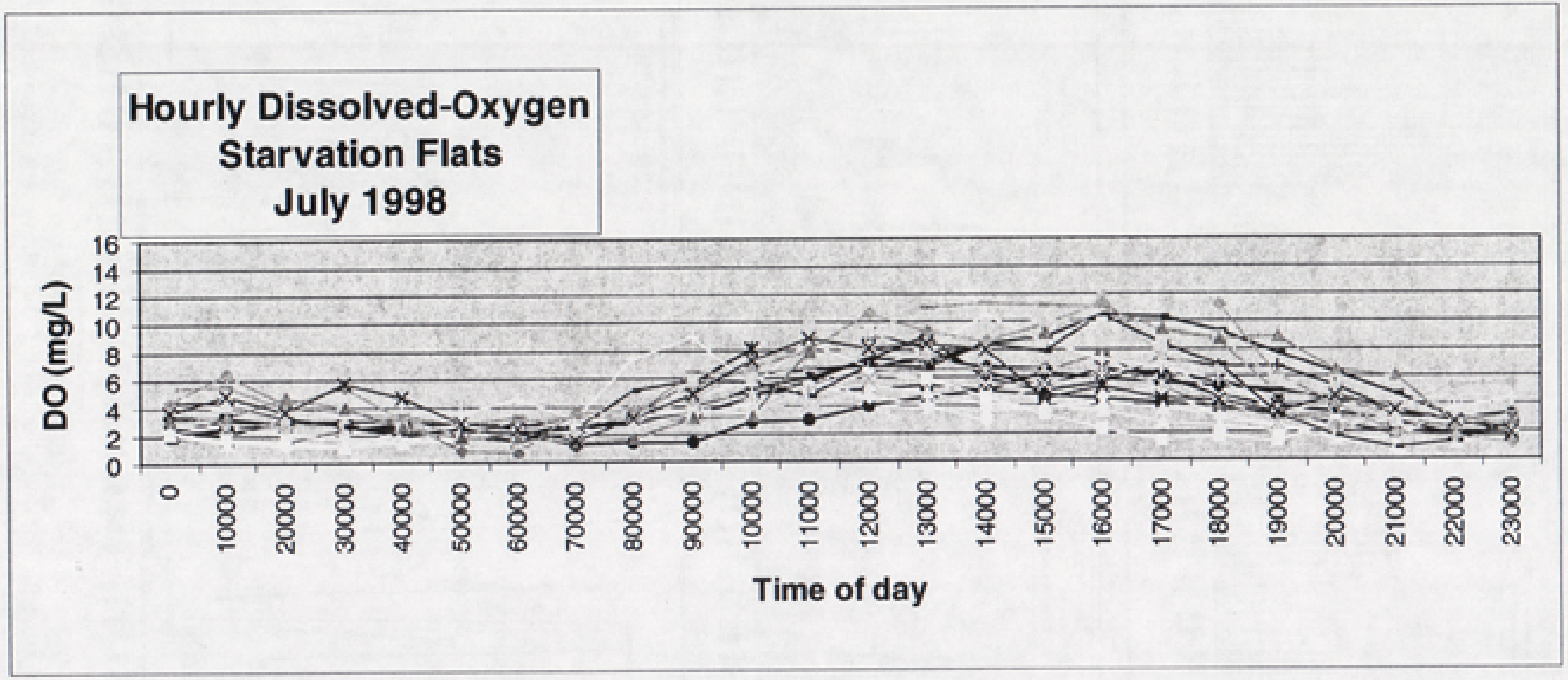

Figure 8. Hourly dissolved oxygen concentration chart for July 1998 during the seagrass growing season.

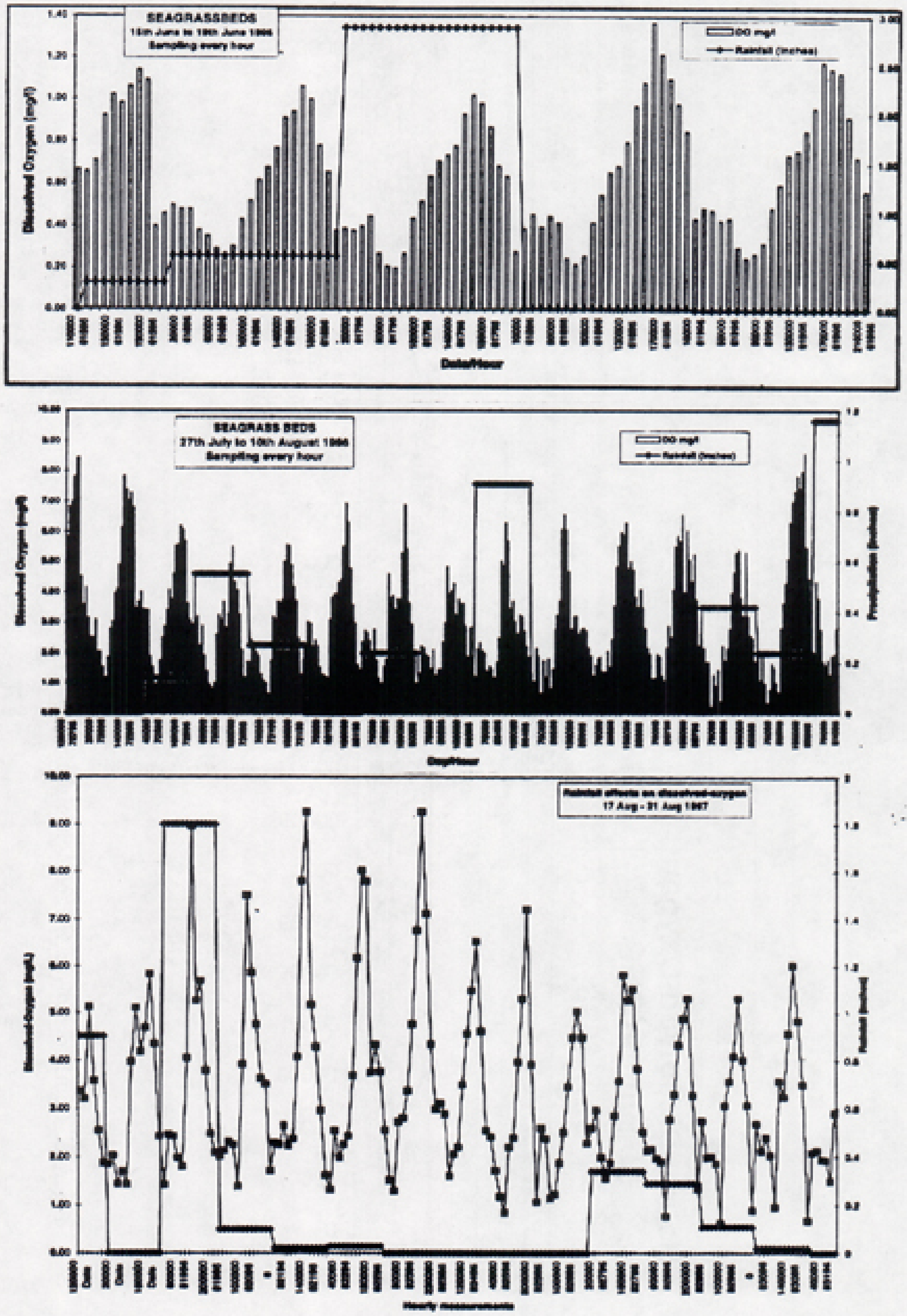

Figure 9. Rainfall effects on DO during the wet season.

Table 2. Florida West Coast Bay Rangess of DO (mg/L)
(as recorded in the literature)

Location	Range (mg/L)
Hillsborough Bay	0.9 - 11.6
Old Tampa Bay	2.7 - 10.6
Upper Tampa Bay	1.1 - 8.1
Lower Tampa Bay	1.4 - 8.5
Boca Ciega Bay	1.6 - 10.6

Table 3. Central Estero Bay dissolved oxygen (mg/L)

Location	Range (mg/L)
Estero Bay 1996 wet season	0.05 - 11.91
Estero Bay 1996-7 dry season	0.33 - 11.32
Estero Bay 1997 wet season	0.31 - 12.95
Estero Bay 1997-8 dry season	0.91 - 17.50
Estero Bay 1998 wet season	0.28 - 13.08
Estero Bay 1998-9 dry season	1.09 – 15.06
Estero Bay 1999 wet season	0.40 - 10.77
Estero Bay 1999-2000 dry season	0.76 – 13.12

Table 4. Hourly dissolved oxygen concentration (mg/L) statistical data 1996-2000.

Season	Dry 1999-2000	Wet 1999	Dry 1998-9	Wet 1998	Dry 1997-8	Wet 1997	Dry 1996-7	Wet 1996
Average	3..97	2.82	8.02	5.15	5.17	4.88	4.84	2.28
Median	4.13	2.63	7.30	4.67	5.20	3.67	4.69	1.68
Maximum	13.12	10.77	15.86	13.08	12.60	12.95	11.32	11.91
Minimum	0.76	0.40	1.09	0.28	0.77	0.94	0.33	0.05
StDeviation	***1.5***	***1.71***	***3.31***	***2.21***	***1.50***	***2.67***	***2.01***	***2.17***
# samples	***2,721***	***3,722***	***3,305***	***1,889***	***1,508***	***3,523***	***1,528***	***1,280***

Table 5. The range of Estero Bay data as compared to typical water quality percentile values for Florida's estuaries.

(FDEP data from Friedemann et al., 1989)	Temp (°C)	pH	DO (mg/l)	Specific Conductance
FDEP Florida Estuaries 5 percentile	18.4	7.0	4.2	0.85 mS/cm
FDEP Florida Estuaries 50 percentile	25.0	8.0	6.8	37.125 mS/cm
FDEP Florida Estuaries 90 percentile	28.6	8.3	8.5	49.05 mS/cm
Estero Bay 1996 Wet Season Range	26.97 - 29.35	7.34 - 8.50	2.22 - 6.94	0.67 - 46.85 mS/cm
Estero Bay 1996/7 Dry Season Range	10.89 - 27.79	7.06 - 8.13	2.09 - 9.16	29.90 - 55.60 mS/cm
Estero Bay 1997 Wet Season Range	15.88 - 37.20	6.15 - 8.89	0.27 - 14.74	26.30 - 64.60 mS/cm
Estero Bay 1997/8 Dry Season Range	12.13 - 28.69	7.78 - 8.49	0.90 - 12.60	22.20 - 48.70 mS/cm
Estero Bay 1998 Wet Season Range	23.77 - 37.45	7.69 - 9.09	0.28 - 13.08	34.90 - 50.10 mS/cm
Estero Bay 1998/9 Dry Season Range	10.87 - 32.15	No data	1.09 - 15.90	19.90 - 55.50 mS/cm
Estero Bay 1999 Wet Season Range	23.56 - 35.35	No data	0.40 - 10.77	16.70 - 54.80 mS/cm
Estero Bay 1999/2000 Dry Season Range	10.87 - 32.15	No data	1.09 - 15.90	19.90 - 55.50 mS/cm

account near-dawn sags or daytime highs which are the most important indicators of the health of the Bay. However, it may be mathematically possible to extrapolate the one-time data, by using constructed monthly averaged-hourly curves and the time of the sampling, to obtain the correct minimums and maximum DO concentrations.

CONCLUSIONS

Dissolved-oxygen (DO) is an essential component in the aquatic environment. Of all the parameters that characterize an estuary, the level of dissolved-oxygen in the water is one of the best indicators of estuarine health. An estuary with little or no oxygen in its waters cannot support healthy levels of animal or plant life. The health of an estuary can, to a large degree, be determined by observing the hourly DO concentrations. Usually waters with DO concentrations of 5.0 mg/L or higher can support a well-balanced, healthy biological community. However, some species cannot tolerate even slight depletion in DO, and when concentrations fall below this level the result is often a complete alteration of the biocommunity and ecosystem structure.

The DO (mg/L) continuous recordings in central Estero Bay (Table 4) show DO levels that range from 0.05 to 15.86 mg/L, during both wet and dry seasons, from 1996 to 2000, and that for more than 120 days a year the waters are violating State standards (>4.0 mg/L). From this data, it would appear that central Estero Bay may be more stressed than Hillsborough Bay (Table 5).

Near-dawn DO sags are probably the most important water quality variable affecting both the general health of the Bay and species abundance and diversity. Daytime or one-time sampling gives both over-optimistic values and erroneous assessments of existing water quality. If continuous recording devices are not readily available, then hourly 24hr DO curves should be constructed for each month of the year and then the daytime or one-time values can be plotted on the curves to determine by extrapolation the near-dawn DO sags for water quality evaluation. Although this hourly diel study is still ongoing, further future investigations are considered necessary to determine the DO patterns that may be helpful for long-term bay management decisions as to the health of Florida's first Aquatic Preserve.

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THE LEE COUNTY ABANDONED WELL PROGRAM

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ABSTRACT

The Lee County Abandoned Well Program started in 1989 in cooperation with the South Florida Water Management District. The purpose of the program was to protect the quality of ground-water resources by plugging approximately 5000 unused large diameter (usually six inches or larger) wells in the District's 13 county area. The number of abandoned wells in Lee County was thought to be about 1000. It was anticipated that the vast majority of these wells were old farm wells with corroded steel casings or wells with insufficient casing depths. Most of these wells tapped aquifers containing salty water under enough pressure to cause the water to move up the borehole and into fresh-water aquifers with lower pressures.

Initially, the District funded the program, which paid for both the plugging of the wells and the salaries of County well inspectors while they are searching for and assisting with the plugging of the wells. Lee County funded a similar program for small diameter wells. The cost for plugging a large-diameter well ranged from about $600 to $55,000; the cost for the small diameter, from about $300 to $1500.

The District halted the program near the end of 1991 after plugging about 2000 wells, 115 of which were in Lee County. Since the beginning of 1992, Lee County has funded both programs. To date, about 50 more wells have been plugged under the large-diameter program and more than 1000 under the small-diameter program.

Lee County requires the water well contractor to collect a water sample from a well during development and the water is analyzed for chloride concentration. The comparison of the chloride concentration of water from wells drilled before and after plugging a nearby deep well indicates that the abandoned well programs are successful and will be continued depending on the availability of funds.

DISCUSSION

An artesian well is defined in Florida Statute 373.203 (2) as A...an artificial hole in the ground from which water supplies may be obtained and which penetrates any water-bearing rock, the water in which is raised to the surface by natural flow, or which rises to an elevation above the top of the water-bearing bed. An abandoned artesian well is defined as one that taps an artesian aquifer and has one or more of the following:

1) Does not have a properly functioning valve;
2) Use has been permanently discontinued;
3) Does not meet current well construction standards;
4) Is discharging water containing greater than 500 milligrams of chlorides into a drinking water aquifer;
5) Is in such a state of disrepair that it cannot be used for its intended purpose without having an adverse impact upon an aquifer which serves as a source of drinking water or which is likely to be such a source in the future; or
6) Does not have a proper flow control on or below the land surface.

Florida has attempted to regulate uncontrolled flowing wells since the early 1950's. State legislation in 1953 required working valves or caps on all flowing wells. In 1957, Florida Statute Chapter 373.021 - 373.061 was passed, which provided for the plugging of all artesian wells that were in violation of the law.

The regulation and control of abandoned flowing wells was the responsibility of various state and local agencies until the formation of the five water management districts in 1972. In 1974, rules and regulations governing water wells were adopted. The Florida Department of Environmental Regulation (now Environmental Protection) and the water management districts were given the regulatory responsibility for the implementation of the rules and regulations. Abandoned wells were addressed in the rules by 1) the implementation of a permitting system by the districts to regulate the plugging of abandoned wells, 2) the elimination of wells that allow interchange of water between aquifers or the uncontrolled loss of artesian pressure, and 3) the establishment of minimum criteria for the plugging of abandoned wells.

The South Florida Water Management District implemented its own well plugging program in 1978. The District decided that only one county would be selected so that the program could develop from the results of the initial project. Several conditions were considered in selecting the county: 1) the type and extent of the problem caused by the abandoned wells, 2) the number of offending wells available for plugging, 3) the availability of an accurate inventory, and 4) selecting an area where the program would give the maximum social and economic benefit.

One report estimates 2500 to 3000 deep artesian wells in Lee County (Sproul et al., 1972). The U.S. Geological Survey statewide inventory of uncontrolled flowing wells (Healy, 1978) identified five counties in the South Florida Water Management District with more than 200 uncontrolled wells and listed 742 in Lee County. A later report suggested that 1850 flowing wells occur in Lee County (Burns, 1983). Several reports have documented the adverse effects of saline water from offending wells on three fresh-water aquifers in Lee County (Sproul et al., 1972, Boggess, 1973; 1974; Boggess et al., 1977). Because of the foregoing and the projected rapid growth in southwest Florida, Lee County was chosen for the initial well plugging program. Under the cooperative program with the District, Lee County inventoried additional large diameter (over three inches) wells qualifying for plugging. The total number was increased to over 900.

The vast majority of these wells were abandoned farm (mostly gladiolus) wells with corroded steel casings or wells with short casings. Almost all of these wells tapped aquifers containing salty water (chloride concentration greater than 500 milligrams per liter) under enough pressure to cause the water to move up the borehole and into fresh-water aquifers. The program paid for both the plugging of the wells and the salaries of County well inspectors while they were searching for and assisting with the plugging of the wells. Lee County funded a similar program for plugging abandoned small-diameter residential wells. The cost for plugging a large-diameter well ranged from about $600 to $55,000 and for a small diameter well from about $300 to $1500.

Chapter IV of the AWater Quality Assurance Act of 1983" legislation calls, in part, for the water management districts to accomplish the plugging of all known abandoned wells before January 1, 1992.

About 115 wells were plugged in Lee County from 1979 through 1991. Since then, Lee County has continued the program and about 50 additional wells have been plugged under the large-diameter program and more than 1000 under the small-diameter program.

Lee County requires the water well contractor to collect a water sample from a well during development and the water is analyzed for chloride content. The comparison of the chloride content of water from wells drilled before and after plugging a nearby deep well indicates that the abandoned well programs are successful and will be continued depending on the availability of funds.

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